Title	Glossary of interest to earthquake and engineering seismologists
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1 Introduction

This is a preliminary glossary, still under development, revision and amendment, also with respect to co-authorship. **Comments, corrections as well as proposals for complementary entries are highly welcome and should be sent to the editor, P. Bormann.** He has compiled the current version by combining, harmonizing, amending and sometimes correcting entries from three major earlier published glossaries of terms that are (see References):

1) frequently used in seismological observatory practice (glossary in the first edition of the IASPEI New Manual of Seismological Observatory Practice (NMSOP; Bormann, 2002 and 2009; see http://nmsop.gfz-potsdam.de);
2) of interest to earthquake and engineering seismologists (glossary compiled by Aki and Lee, 2003, for the International Handbook of Earthquake and Engineering Seismology (see Lee et al., 2003a);
3) now widely used in some rapidly developing new fields such as rotational seismology, (compiled by Lee, 2009).

The following glossary includes some 1,500 specialized terms. Not included were abbreviations and acronyms (with the exception of just a few that required more explanation). Acronyms have been added as an extra file to this Manual (see NMSOP-2 website cover page). Alphabetization is strictly letter-by-letter of the glossary terms (in bold face), ignoring hyphenation and space between words. Words included in parenthesis are also ignored in the alphabetization. Words which are written in *italics* in the explanatory text refer to other glossary terms for which more explanation is given elsewhere.

Terms in this glossary may be encountered when reading literature in seismological observatory practice, earthquake and engineering seismology and related fields. The purpose of the glossary is to provide a short definition and/or a starting point for readers to learn more from cited references. Although rather extensive, this glossary is by no means complete. We attempt to give commonly used definitions, understandable also for non-specialists. But readers should realize that terms may be differently defined in some literature. We avoid giving mathematical formulas (except for a small number of cases). For key formulas in seismology we refer to Yehuda Ben-Zion (2003), as well as to Aki and Richards (2002 and 2009).

When compiling the above mentioned earlier main glossaries many earlier and widely scattered ones were consulted, such as glossaries published by the US Geological Survey (http://www.usgs.gov/), the Montana Bureau of Mines and Geology (http://www.mbmg.mtech.edu/), the International Data Center of the CTBTO (http://www.ctbto.org), and in addition several standard reference sources, including Aki and Richards (1980, 2002 and 2009), Ben-Menahem and Singh (2000), Bormann (2002), Clark (1966), EERI (1989), Hancock and Skinner (2000), Jackson (1997), James and James (1976), Lee and Stewart (1981), Lide (2002), Meyers (2002), Naeim (2001), Richter (1958), Runcorn (1967), Sigurdsson (2000), USGS Photo Glossary (2002), and Yeats *et al*. (1997). Some glossary terms and texts have also been contributed by chapter/section/entry authors of this Manual, amongst them J. Schweitzer, T. Diehl and L. Kueperkoch, as well as by authors of the International Handbook of Earthquake and Engineering Seismology (eds. Lee et al., 2002 and 2003a) and of the BSSA special issue on rotational seismology (eds. Lee et al., 2009, Lee et al., 2009a, and 2009b), amongst them (for the latter) R. DeSalvo, J. R. Evans, E. F. Grekova, C. R. Hutt, H. Igel, C. A. Langston, B. Lantz, E. Majewski, R. Nigbor, J. Pujol, P. Spudich, R. Teisseyre, M. D. Trifunac, R. J. Twiss, and Z. Zembaty. Further terms and/or suggestions for revisions were provided by R. Adams, J. Anderson, J. Andrews, Y. Ben-Zion, M.G. Bonilla, D. Boore, K. Campbell, Ch. Chapman, C.B. Crouse, A. Curtis, A. Douglas, L. Esteva, B. Hall, D. Hill, B. Hutt, P. Irwin, K.-H. Jäckel, R. Jeanloz, P. Jennings, C. Kisslinger, O. Kulhanek, A. McGarr, M. Pirli, C. Prodehl, H. Sato, J. Savage, J. Schweitzer, A. Snoke, K. Suyehiro, B. Tilling, and S. Uyeda. More names may be added here with future entries.

Nevertheless, words of caution are required at this point. Although precise definitions are critical for fostering collaboration and reducing misunderstanding between different disciplines, there are no unique definitions of terms. Every scientific field seems to develop its own “jargon” that is sometimes difficult for outsiders to understand. Even within a given field, different authors often define technical terms differently, or a given term has different usage. This is particularly the case in rapidly developing new fields such as rotational seismology. Therefore, the compilers tried to use a usage that they judged to be “common”, or to indicate different meanings of the same term in different fields of Earth or technical sciences and sometimes by providing references to alternative and more specialized sources. With respect to rotational seismology these are especially the tutorials by Peters (2009), Pujol (2009), Teisseyre (2009), and Zembaty (2009b), and the review by Trifunac (2009). Evans et al. (2010) describe notation conventions for rotational seismology, while Grekova and Lee (2009) provide suggested readings in continuum mechanics (including elasticity theories), and earthquake seismology.

2 Glossary terms

A

aa

A common type of *lava flow* composed of a jumble of *lava blocks*, with a rough, jagged, spiny, and generally clinkery or slaggy surface. Of Hawaiian origin, the term aa is applied also to similar lava flows at other volcanoes.

acausal filter

See *zero-phase filter*.

acausal signal

Output signal that exists also for times prior to the application of an input *signal*, a non-physical phenomenon of digital data processing.

acceleration

When an object, e.g., a car, changes its speed from one speed to another, it is accelerating (moving faster) or decelerating (moving slower). This change in *velocity* is called acceleration. In seismology this term specifically means the rate of change of *ground motion* particle velocity per unit time when the ground is shaking due to an *earthquake* or another kind of *seismic source* process. The peak acceleration is the largest acceleration recorded by a particular station during an earthquake. In *strong-motion* seismology the ground acceleration is commonly expressed as a fraction or percentage of the acceleration due to gravity (g) where g = 981 cm/s^2. For the strongest earthquakes ground accelerations of more than 1.5 g have been recorded. Since the weight of an object, e.g., of a building, is equal to its mass multiplied by the gravity g, the additional acceleration due to ground shaking causes an extra load. This extra load may exceed the strength of the building and may cause damage or collapse.

accelerogram

A record (time history) of ground *acceleration* as a function of time produced by an *accelerograph* during a seismic event.

accelerograph

A compact, rugged, and relatively inexpensive *seismograph* designed to record the *signal* from an *accelerometer*, especially of strong ground shaking on ground or in structures, caused by nearby large earthquakes (see, e.g., Trifunac, 2009. Film used to be the most common analog recording medium. Modern accelerographs, however, record digitally with much larger *dynamic range*. Whereas a traditional *strong-motion* accelerograph begins recording when the motion exceeds a certain specified trigger level, at present, some *seismic networks* record acceleration within a large dynamic range continuously.

accelerometer

A sensor or *transducer* that converts *acceleration* of its base into an analog trace or electrical *signal*. The acceleration signal is normally obtained from the feedback current necessary to maintain an *inertial sensor* at its mechanical zero point. As in a linear actuator the current is equal to the applied force, this current is proportional to the acceleration within the bandwidth limits of the feedback. Outside the band the acceleration can still be extracted from the position signal, normally through a complicated *transfer function*. Accelerometers may be enclosed within a self-contained *accelerograph*, but for studies of structural response they can be located remotely, with their signals being transmitted to a central recorder. Unless otherwise specified, an accelerometer measures translational acceleration. However, accelerometers are also sensitive to *rotational ground motions*.

acceptable risk The probability associated with a social or economic consequence of an earthquake that is low enough (in comparison with other risks) to be judged acceptable by appropriate authorities. It is often used to represent a realistic basis for determining design requirements for engineered structures, or for taking certain social or economic actions. What kind and level of risk is considered to be acceptable by a society depends also on its socio-economic and political conditions.

ACH method ACH stands for Aki, Christoffersson and Husebye (1977) who developed a method for determining the three-dimensional structure of the Earth using the *teleseismic* observations from a two-dimensional *seismic array*. The method was extended to the *local earthquake* data by Aki and Lee (1976). It opened one way to the research area now called “*seismic tomography*”.

accretionary prism See *accretionary wedge*.

accretionary wedge *Trench* sediments and volcanics that accumulate and deform where oceanic and continental *plates* collide. These sediments are scraped off the top of the downgoing oceanic crustal plate and are added as a generally wedge-shaped mass to the leading edge of the continental plate (Von Huene and Scholl, 1991; Duff, 1993; see *subduction* and *tectonic plates*).

accuracy According to Bevington and Robinson (2003) a measure of how close the results of an experiment (observed values or values calculated from observations via model assumptions) come to the “true” value.

acoustic emission A term in rock mechanics indicating *seismic wave* radiation from dynamic formation of a microcrack. Due to the small crack lengths, the *frequencies* of the radiated waves are in the kHz (acoustic or ultrasound) range.

acoustic impedance Product of wave propagation *velocity* v and *density* ρ of the medium in which the accoustic (or elastic seismic) waves propagate. See *seismic impedance* and *impedance contrast*.

active fault A *fault* that is considered likely to undergo renewed movement within a period of concern to humans. Faults are commonly considered to be active if they have moved one or more times in the last 10,000 years, but they may also be considered active when assessing the hazard for very critical installations such as nuclear power plants even if movement has occurred in the last 500,000 years. Although faults that move in earthquakes today are active, not all active faults generate earthquakes - some are capable of moving aseismically (see *creep, silent earthquake, slow earthquake*; also, e.g., Johnston and Linde, 2002). More precise attempts (usually unsatisfactory) have been made to define "active" faults for legal or regulatory purposes. See Yeats et al. (1997, p. 449).

active margin A continental margin that is also a *plate boundary* with earthquakes and/or volcanic activity.

active tectonic regime A term that refers to regions where *tectonic deformation* is relatively large and earthquakes are relatively frequent, usually near *plate boundaries*.

active tectonics *Tectonic* movements that are expected to occur or have occurred within a time span of concern to society.

active volcano By a widely used but poor definition, an active volcano is one that is erupting or has erupted one or more times in recorded history (see Decker and Decker, 1998). Active and potentially active (i.e., presently dormant) volcanoes occur in narrow belts that collectively comprise less than 1 percent of the Earth's total surface (Simkin et al., 1994).

aftershock An earthquake occurring as a consequence of a larger earthquake (referred to as the *mainshock*) at roughly the same location**.** Aftershocks are smaller than the mainshock and within 1-2 *fault lengths* distance from the mainshock fault. The sequence of such earthquakes following a larger one generally shows a regular decrease in the rate of occurrence, first discovered by Omori (1894), indicating a stress relaxation and redistribution process as the rocks accommodate to their new post-earthquake state. Aftershocks can continue over a period of weeks, months, or years, decreasing in frequency with time. In general, the larger the mainshock, the larger and more numerous the aftershocks, and the longer they will continue. See Utsu (2002b), and Eq. (7.4) in Ben-Zion (2003).

afterslip The increase in *displacement* on a *fault* by *creep* following a sudden *coseismic slip*.

AIC Akaike Information Criterion, applied in statistical modeling to get the most appropriate probability distribution that describes the observed data. Definition:

$$AIC = -2 \cdot \max(L) + 2(p),$$

where $\max(L)$ is the maximum likelihood function and p the number of free parameters. See Akaike (1970, 1971).

airgun A non-explosive *seismic source* normally used at sea. Compressed air (about 15 MPa) is fed into an air chamber of variable size (1-30 L) and is repetitively released into water to generate sound waves to be emitted.

air-coupled surface wave Despite the great *density* contrast between air and ground, atmospheric *pressure* disturbances traveling over the Earth's surface can produce *surface waves* if the *phase velocity* is equal to the acoustic velocity in the air. Such a coupling with air has been observed for flexural waves in ice sheets floating on the ocean and for *Rayleigh waves* in ground with low-velocity surface layers. A simultaneous arrival of *air waves* and tidal disturbances was observed after the well known explosion of the volcano Krakatoa in 1883.

air wave Audible sounds or *infrasound* waves are sometimes generated by earthquakes; a *local earthquake* may sound like distant thunder, canon shots or the rumbling from a passing truck or tank on a bumpy road. Instrumental measurements show that these sounds arrive simultaneously with the first *P waves* (Hill et al., 1976). More long-*period* (seconds to hours) acoustic-gravity waves may also be excited by *great earthquakes*, as well as by volcanic explosions, meteorite falls, and nuclear blasts in the atmosphere. See Ben-Menahem and Singh (2000).

Airy phase Portions of dispersed wave trains associated with the maxima or minima of the *group velocity* as a function of *frequency*. The Airy function can be used for an approximate calculation of the *waveform*. Examples are continental *Rayleigh waves* at *periods* around 15 seconds, *mantle* Rayleigh waves at periods of 200 to 250 seconds, and *surface waves* of periods between some 6 and 10 seconds which travel across an ocean at a velocity near 1 km/sec. (see Fig. 2.10 of Chapter 2 in this Manual). See also Kulhanek (2002, p. 345), and Aki and Richards (1980, p. 256).

Akaike Information Criterion See *AIC*.

aleatory uncertainty The uncertainty in *seismic hazard analysis* due to inherent random variability of the quantity being measured. Aleatory uncertainties cannot be reduced by refining modeling or analytical techniques. See *epistemic uncertainty*.

aliasing A serious error in the *analog-to-digital conversion*, pointed out by Blackman and Tukey (1958), that occurs when the sampling rate is less than twice the highest *frequency* (*Nyquist frequency*) contained in the *signal* to be digitized. A long *period* ghost which does not exist in the original *signal* may appear after digitization (see Chapter 6 of this Manual; also Aki and Richards, 1980, p. 576-579).

alluvium Loose gravel, sand, silt, or clay deposited by streams after the last ice age (see *Holocene*).

Alpide belt Mountain belt with frequent earthquakes that extends from the Mediterranean region, eastward through Turkey, Iran and northern India.

altitude of ambiguity The topographic relief (or error) required to create one fringe in an *interferogram*. The height of ambiguity is expressed in units of meters.

ambient noise See *noise*.

amplification (by seismograph) Most earthquakes are relatively small, in fact, so small that no one feels them. In order for seismologists to see the recording of the ground movement from smaller earthquakes, the recording has to be made larger. Modern *seismographs* are able to magnify the *ground motion* 10^6 times or even more, i.e., they are able to resolve ground motion *amplitudes* as small as the diameter of molecules or even atoms. The frequency-dependent amplification of a *seismograph* depends on the input spectrum of the *seismic signal*, the *eigenfrequency* and *attenuation* of the *seismic sensor* or *seismometer*, and of the filter parameters and gain of the *seismic recorder* (see Chapters 4 to 6 of this Manual).

amplification (by recording site) The term is also used to describe the increase in *amplitude* of *seismic waves* and/or levels of shaking at the site of recording or observation. Increase (or decrease) of amplitudes may be due to focusing (or defocusing) of seismic wave energy caused by the geometry/*heterogeneity* of the *velocity structure* of sediments and other rock formations, by basin subsurface topography, or by surface topography. Most *seismographs* are installed at a site on or near the surface with irregular topography and lithologic structures of heterogeneous material created by aeons of weathering, erosion, deposition and other geological processes. These complex near-surface structures also tend to amplify the amplitude of incident seismic waves (see *site effect* and *site response*). The degree of amplification is usually dependent on the *frequency* and thus on the *wavelength* of the *seismic signal* with respect to the linear dimensions of the surface and subsurface heterogeneities.

amplitude The size of the wiggles on an earthquake recording; more general and correct in a physical sense the height of a wave-like disturbance - such as the seismic record trace (called *waveform*) - from the medium (zero) level to its peak, respectively trough. When measured from peak to trough it is called double or "peak-to-peak" (more correct "peak-to-trough") amplitude. In seismology *ground motion* amplitudes are usually measured in nanometers (10^{-9} m) or micrometers (10^{-6} m).

amplitude response In general, the complex *frequency response* (e.g., calculated as *Fourier transform* of the output *signal* divided by that of the input signal) of a system. Specifically, the frequency-dependent amplification and phase response of *ground motion* by a *seismograph*, a site, a building etc., depending on their eigenoscillation and *attenuation* properties (for *seismographs* see Chapters 4 and 5 and for *site response* Chapter 14).

analog-to-digital converter An electronic device that converts a voltage produced by a sensor to digital values by applying specific digitization rates depending on the frequency content of the original signal.

anelastic attenuation *Amplitude* reduction of a *signal* (e.g., a seismic or electro-dynamic wave) due to energy dissipation (friction, heat). See *intrinsic attenuation*.

anelasticity Loss of *strain* energy in a stressed medium due to internal *friction* caused by imperfections in the elasticity of the medium. A dimensionless measure of the internal friction or anelasticity of a medium is the *quality factor Q*.

angular coherence function Measure of *coherency* of two transmitted *wave fields* as a function of incidence angles.

anisotropic A medium is anisotropic if its physical properties depend on the direction. See *seismic anisotropy*.

annual probability (of exceedence) The probability that a given level of *seismic hazard* (typically some measure of *ground motion*, e.g., seismic *magnitude*, *intensity* or ground *acceleration*), or *seismic risk* (typically economic loss or casualties) can be equaled or surpassed within an exposure time of one year.

ansatz A German word used by mathematicians to describe an initial or trial solution.

anthropogenic earthquake An *earthquake* that is a byproduct of human activities.

anticline A fold, generally convex upward, whose core contains the stratigraphically older rocks.

anti-plane strain Assumed two-dimensional symmetry, used to simplify mathematical analysis or numerical calculation, in which *displacement* depends on only two spatial coordinates and its direction is perpendicular to the plane of those coordinates. *Strike-slip* displacement that does not vary along strike is an example of anti-plane *deformation*. Examples are a Love wave from a line source and mode 3 crack (see Figure 6 in IS 3.1., *plane strain*, *mode 3 crack*, *Love wave*, and Love, 1944).

aperture Largest horizontal distance between two sensors of a *seismic array*. See *array aperture*.

apparent stress Defined by Wyss and Brune (1968) as the product of the *rigidity* and the ratio of the *seismic energy* to the *seismic moment* for an earthquake. It is the fictitious *stress* (radiation resistance) which acting through the actual earthquake *slip* would do the work equivalent to the seismic energy radiated in the faulting. More simply, it is the product of the *seismic efficiency* and the average absolute stress as explained in Aki and Richards (2002, p. 55). See also Chapter 3.

apparent velocity If T (in s) and D (in km) denote the *travel time*s and *epicentral distance*s, respectively for a *seismic phase* arriving at points of the Earth's surface, then the apparent velocity v_{app} is defined as dD/dT. The apparent velocity is for a spherical Earth model the reciprocal of the seismic *ray parameter* p or more generally the reciprocal of the horizontal (radial) component s_R of the *slowness vector* **s** (see Chapters 2 and Chapter 9 of this Manual).

arc See *volcanic arc*.

Archaean An eon in geologic time, from 4 to 2.5 billion years ago. Archaean is from Greek and means "beginning" (see *geologic time*).

Arias intensity A *ground-motion* parameter derived from an *accelerogram* and proportional to the integral over time of the acceleration squared. Expressed in units of *velocity* (m/s or cm/s). More specifically a broadband measure of the strength of strong ground motion observed in an accelerogram, defined by the integral over all *natural frequencies* of the energy input to a damped *single degree of freedom* oscillator in response to an accelerogram.

array (seismic) See *seismic array*.

array analysis The joint analysis of *seismograms* recorded in a network of *seismometers*, which all record with a common time base. *Seismic arrays* allow the estimation of the propagation direction of *seismic waves* and also the estimation of the *wave field*'s gradient and thus the estimation of various components of the *strain tensor* and the vector of *rotational motions*. See Chapter 9 in this Manual.

array aperture The size of an *array* measured by the maximum separation between pairs of *seismometers* in an array. Traditionally arrays are divided up into small aperture (maximum separation around 3 km), medium aperture (maximum separation 10-25 km), and large aperture (maximum separation 100-200 km) depending on their size (see Chapter 9 in this Manual).

array beam The result of the summation of the output from several elements of an *array* (*beamforming* by *delay-and-sum processing*) to enhance *signals* with a given *apparent velocity* (or *slowness*) and *backazimuth* of approach. By choosing velocity and azimuth expected for a *hypocenter* of the source, this process can enhance *seismic waves* coming from this particular source location (see Chapter 9 in this Manual).

array processing Techniques of *array analysis*, which are mainly based on *wave field coherence* and *correlation* techniques (see Chapter 9 in this Manual).

arrival The appearance of a particular *seismic phase* (e.g., *P wave*) on a *seismogram*.

arrival time The time of the first *onset* of a *seismic wave* (e.g., *P wave*) as recorded by a *seismograph*. Arrival times are the basic data for locating earthquake *hypocenters* and for determining seismic *velocity* structures of the Earth.

ASC See *Asian Seismological Commission.*

Asian Seismological Commission The second regional commission of *IASPEI*. The ASC was founded in 1996, has Member States from all over Asia and holds General Assembly meetings every second year since its foundation. See http://www.asc1996.com.

aseismic In seismology, an adjective for characterizing a *fault* (an area) on which (where) no earthquakes have been observed and are not likely to occur. Aseismic behavior may be due to lack of *shear stress* across the fault, a *locked fault* condition with or without shear stress, or release of stress by fault *creep*. In earthquake engineering, an adjective for structures which are designed and built to withstand earthquakes.

aseismic slip *Slip* on a *fault* which is not associated with the radiation of *seismic waves*. See *fault creep*.

ash See *volcanic ash*.

ashfall See *fallout*.

asperity A region on a *fault* of higher strength than the surroundings, at which stress concentrates prior to fault rupture. In seismology, this term (and also the term barrier) is often used to describe the *heterogeneity* of a fault. It was first introduced by Lay and Kanamori (1981) to describe regions of earthquake ruptures where relatively high release of *seismic moment* or release of *seismic energy* occurs [see *barrier*; Scholz (2002)] or it may refer to locked sections of the fault that cause fault *segmentation*. An asperity may be produced by one or more of the following conditions: increased *normal stress*, high *friction*, low *pore pressure*, or geometric changes in the fault such as fault bends, offsets, or roughness.

association (of arrivals) To assign a seismic wave *arrival* to a specific *seismic event*.

asthenosphere The *ductile* part of the Earth's *upper mantle*, just below the brittle *lithosphere*. More specifically, the weak lower portion of the near-surface *thermal boundary layer* and underlying mantle which undergoes significant ductile *deformation* under long-term loads.

asymptotic ray theory The mathematical theory used to describe high-frequency *seismic rays*. The ray *ansatz* is constructed as a series in inverse powers of *frequency* in the frequency domain, or integrals of the source impulse in the time domain, with *amplitude* coefficients and *travel times* only as functions of position along the ray. See *Maslov asymptotic ray theory*.

attenuation Waves are largest where they are formed and gradually get smaller as they move away from their generating source. The decrease in wave *amplitude* is caused by *geometrical spreading* and by attenuation of wave energy. The latter is due to two different processes: a) intrinsic attenuation (also termed anelastic attenuation or absorbtion) in different Earth materials and/or b) *scattering* of *seismic energy* at *heterogeneities* in the Earth (e.g., *faults* or small-scale anomalous geological bodies; see Figures 2.37 and 2.38 in Chapter 2). Q and κ (kappa) are attenuation parameters used in modeling the attenuation of *ground motion*s (see section 2.5.4.2 in Chapter 2).

attenuation relation Term used particularly in the fields of *strong ground motion* and earthquake engineering to describe the decay of peak spectral ground motion parameters (such as displacement, *peak* velocity, or *acceleration*) as a function of distance from the *source* or a ruptured *fault*, its *magnitude*, fault type, and sometimes also the specific travel path and site conditions. Its coefficients are usually derived from statistical analysis of earthquake records (see, e.g., Chapter 15 in this Manual and

Campbell (2003). Similar relations are expected for peak ground rotation parameters.

attribute (of an arrival) A quantitative measure of a seismic *arrival* such as *onset* time, (*back)azimuth*, direction of first motion, *slowness*, *period* and *amplitude*.

A-type earthquake Earthquakes with clear *P* and *S waves*, occurring beneath volcanoes. They are indistinguishable from normal shallow *tectonic earthquakes*. In the original definition by Minakami (1961), it was contrasted to the *B-type earthquake* attributed to an extremely shallow *focal depth*. In recent years the contrast has been attributed to the source process, and it is more often called volcano-tectonic (VT), or *high-frequency* (HF) *earthquake* (see Chapter 13 of this Manual).

autocorrelation Calculating the *correlation* function of a *signal* with itself.

autocorrelation coefficient Parameter that describes the *correlation* between values of a function or samples of a discrete time series separated by time shifts in case of continuous functions or time lags in case of discrete time series. The autocorrelation c is the autocovariance normalized by the variance in case of a stationary process.

autoregressive process Model of a time series, where the actual value x_j is described by a linear combination of the p predecessors:

$$x_j = \sum_{i=1}^{p} a_i x_{j-i} + e_j \,,$$

where a_i denotes the $j-$th autoregressive (AR) coefficient and e_i denotes white noise or the prediction error. p denotes the order of the AR process.

average annualized loss (AAL) The average economic loss expected per year for a specific property, portfolio of properties, or region as a result of one or more damaging earthquakes.

axial deformation A *deformation* having an axial symmetry, characterized by a lengthening or shortening parallel to a given direction or axis, with a shortening or lengthening perpendicular to the axis that is the same in all directions.

axis of rotation An axis parallel to the *rotation vector*. Each rotation can be presented in terms of angle of rotation and axis of rotation. See *rotation tensor*.

axial tensor, vector or scalar A tensor (vector or scalar) object which changes the sign when we change the orientation of a system of coordinates from right-handed to the left-handed or vice versa. They do not depend on the coordinate system itself. For instance, *couple stress tensor, Levi-Civitta tensor, torque, rotational velocity*, and mixed product of basis vectors of the coordinate system are axial objects. Many axial objects are related to (see different entries under) *rotation*. Axial objects sometimes are called pseudo objects. They cannot be equal to polar objects, which do not depend on the orientation of a coordinate system.

azimuth In general, a direction measured clock-wise in degrees against the North. In seismology, used to measure the direction from a *seismic source* to a *seismic station* recording this event. The azimuth in the opposite direction from the station to the source is called *backazimuth*.

azimuthal anisotropy A term used when the *seismic wave* properties depend on the azimuth of propagation in the horizontal plane. For example, *Pn waves* in the neighborhood of an oceanic spreading center exhibit azimuthally anisotropic velocity but also *SKS* and *SKKS waves* due to *upper mantle* flow anisotropy (see Fig. 2.8 in Chapter 2 of the Manual).

B

back arc The region adjacent to a volcanic arc, and on the opposite side of the oceanic *trench* and subducting *plate* (see also *volcanic arc*).

back-arc basin A basin floored by oceanic *crust* behind a *volcanic arc* (See *back arc*; also Duff, 1993; Uyeda, 1982).

backazimuth The direction from the *seismic station* towards a *seismic source*, usually measured in degrees clock-wise from North (cf. *azimuth*). The backazimuth of shear energy can be estimated from co-located measurements of *translation* and *rotations*.

background noise Permanent movements of the Earth as seen on seismic records caused by ocean waves, wind, rushing waters, turbulences in air-pressure, etc. (ambient natural noise), and/or by traffic, hammering or rotating machinery, etc. (man-made noise). See *microseisms*.

background seismicity *Seismicity* that occurs at a more or less steady rate in the absence of an *earthquake sequence*, such as a *swarm* or *foreshock-mainshock-aftershock* sequence. In *seismic hazard analysis*, it is the seismicity that cannot be attributed to a specific *fault* or source zone.

back-scattering See *scattering* and *scattering theory*.

backstop Continental rocks in the *back arc* that are landward from the trace of the *subduction thrust fault* and that are strong enough to support *stress* accumulation. These rocks are both igneous and dewatered, lithified, consolidated sediments that probably were part of the *accretionary wedge*. The softer accretionary-wedge rocks are strongly deformed as they accumulate against the backstop. The exact position and dip direction of the backstop is not well determined, and more than one backstop may exist.

ballistic projectiles A collective term for fragmental volcanic products (*tephra*) of diverse shapes greater than 64 mm in size. Such projectiles can exit the volcanic vent at speeds of tens to hundreds of meters per second on trajectories that are little affected by the eruption dynamics or the prevailing wind direction; thus, they are typically restricted to within 5 km of vents. See *bomb, volcanic, block, volcanic*, and *cinder*.

band-pass filter A *filter* which removes low and high *frequency* portions of the input *signal* outside of the *passband* (see, e.g., Figs. 4.10, 4.14, 4.16, 4.18, and 4.42-4.45 in Chapter 4 of this Manual).

bandwidth A range between high-pass and low-pass cut-off frequencies (see *high-pass filter* and *low-pass filter*). In seismology, bandwidth is often meant as the portion of the *frequency-response* amplitude spectrum that is approximately flat; and it is often defined as the frequency band between the upper and lower frequencies, where the amplitude falls 3 *dB* below its maximum value (called the -3 dB points).

barrier A site on a *fault* surface of higher strength than the surroundings that is capable of terminating rupture or across which rupture may jump. In seismology, this term (and also the term *asperity*) is often used to describe *heterogeneity* of a fault, and was first introduced by Das and Aki (1977) to construct a two-dimensional fault model. See Scholz (2002).

basalt A general term for mafic igneous rocks (or corresponding melts) produced by partial melting of the *upper mantle*, and comprising most of the *crust* beneath the oceans.

base isolation A technique to reduce the earthquake forces in a structure by the installation of horizontally flexible devices at the foundation level. Such devices greatly increase the lowest natural periods of the structure for horizontal motions and thereby lower the accelerations experienced by the structure. The most common applications of base isolation are to old historic buildings, hospitals and bridges.

base-line correction A term used in the processing of time series analysis. It corrects a recorded *signal* for the bias in the zero value, and any long-period drift in the zero level that may arise from *instrumental noise*, or from the digitization of analog signals.

basement In geology, the igneous and metamorphic rocks that underlie the sedimentary deposits and extend downward to the base of the *crust*.

base shear The horizontal shearing force at the base of the structure. The maximum base shear, typically in the form of a fraction of the weight of the structure, is an important parameter in earthquake response studies and in earthquake resistant design.

base surge Highly turbulent, dilute cloud of *volcanic ash*, air, and steam, which expands radially away from the base of an *eruption column* at high velocity. It commonly forms when an eruption starts in a lake or coastal environment and involves the explosive interaction of hot *magma* with water.

basin-induced surface wave *Surface waves* generated at the edges of a basin or at a strong lateral *discontinuity* inside the basin by incident *body* (*S* or *P*) *waves*. Their *amplitudes* and *waveforms* depend on the basin structure along the ray path from the edge (or the discontinuity) to the site. If the site lies in the central part of a large sedimentary basin, the basin-induced surface waves appear much later than the direct and reverberated S waves. The term "secondary surface waves" sometimes used for them is not appropriate since their amplitudes can be of primary importance**.**

basin-transduced surface wave *Surface waves* transduced at edges of a basin or at a strong lateral *discontinuity* inside the basin from incident surface waves. They are distinguished from *basin-induced surface waves* by the difference in incident waves. These surface waves are observed if the earthquake source is shallow and distant. *Refraction* and mode conversion of both *Love* and *Rayleigh waves* and transformation among them occur at the edge of a basin.

Bayesian method Any method accepting not only the interpretation of a probability as the limit of an experimental histogram, but also as the representation of subjective information. See Mosegaard and Tarantola (2002), and the biography of Thomas Bayes in Howell (2003).

beamforming See *array beam*, *delay-and-sum processing* and Chapter 9 of this Manual.

bedrock A relatively hard, solid rock that commonly underlies soil or other softer unconsolidated sedimentary materials. The bedrock is a subset of the *basement*.

bending-moment fault *Fault* formed due to bending of a flexed layer during folding. *Normal faults* characterize the convex side, placed in tension, and *reverse faults* characterize the concave side, placed in compression.

Benioff zone Also called *Wadati-Benioff zone* (see also *subduction zone*).

blind fault A *fault* that does not extend upward to the Earth's surface, being "buried" under the uppermost layers of sediments or rock in the *crust* with no surface evidence. It usually terminates upward in the axial region of an *anticline*. If its *dip* is <45º, it is a blind thrust. The Northridge thrust fault responsible for the 1994 Northridge, California, earthquake is an example of a blind fault. See Yeats et al. (1997).

block-and-ash flow Small-volume *pyroclastic flow* characterized by a large fraction of dense to moderately vesicular juvenile blocks in a matrix of the same composition. Such flows are typically associated with collapse of *Vulcanian eruption* columns or are produced from partial or complete collapse of unstable, viscous *lava domes* as they over-steepen at their fronts during active growth (e.g., as during the eruption of Unzen Volcano, Japan, in 1991). See Freundt et al. (2000).

block (or blocky) lava A term sometimes applied to all *lava flows* with fractured surfaces and are covered with angular fragments (including *aa*). However, as emphasized by Macdonald (1972), the term is more appropriately restricted to those lava flows, which, even though similar in overall structure to aa, lack the jaggedly spinose features of aa and have fragments characterized by more regular forms (often approaching cube-like) and smoother surfaces.

block rotation Rotation of crustal blocks in continental areas. Block rotation about a vertical axis is common along *strike-slip faults*, but horizontal-axis block rotation commonly occurs in *thrust* and *normal fault* systems, and presumably oblique-axis block rotation can occur along *oblique-slip faults*. See Twiss et al. (1993).

block, volcanic A ballistic projectile (> 64 mm in size) but more angular in shape than volcanic bombs, indicating that it was thrown out in a state too solid to allow any changes in shape during flight. See *bomb, volcanic*.

body wave Waves that propagate through the interior of a body are called body waves, as opposed to *surface waves*, which propagate along the boundary surface of a body. In seismology, the Earth is usually considered an infinite, linear elastic and *homogeneous* continuum. In such a medium there exist only two basic types of seismic body waves with different *polarization*: (1) dilatational (or *longitudinal*) *P waves* and (2) translational (*shear*) *S waves* (see Chapter 2 in this Manual).

body-wave magnitude Earthquake *magnitude* calculated from *amplitude*/*period* ratios of *body waves*. mB and mb are based on data recorded by relatively broadband and short-period *seismographs*, respectively. The original body-wave magnitude introduced by B. Gutenberg (1945) and Gutenberg and Richter (1956) is denoted by m_B. It has been determined by measuring the largest ratio of displacement amplitudes and periods of vertical and/or horizontal component *P* and *PP waves* as well as horizontal component *S waves*. Different from this, the more or less equivalent new IASPEI (2011) standard, denoted mB(BB) or mB_BB, is based only on direct measurement of the largest vertical component broadband velocity amplitude in the whole P-wave train (Bormann and Saul, 2008). Body-wave magnitudes assigned by USGS and ISC were up to 2011 only short-period mb (denoted Mb by the ISC), however, both agencies will in future additionally determine mB_BB. Also mb has been re-defined in a unique way (IASPEI 2005 and 2013) in order to avoid the sometimes significant differences between the mb values issued by different agencies. See Chapter 3 and IS 3.3 in this Manual, Bormann et al. (2009) and Bormann (2011).

bomb, volcanic A ballistic projectile greater than 64 mm in size that is erupted in a semi-solid state and fluid enough to change shape aerodynamically while flowing through the air. Volcanic bombs can take on a great variety of shapes (see also *block*, *volcanic*).

borehole sensor A sensor installed below the Earth's surface in a borehole (see, e.g., section 7.4.6 in Chapter 7 of this Manual).

Born approximation A perturbation method that iteratively solves an *inhomogeneous* wave equation, where waves are decomposed into primary waves which satisfy the *homogenous* wave equation and scattered waves of small *amplitude*. See Sato et al. (2002), and the biography of Max Born in Howell (2003).

branch (of travel-time curve) Term used in seismology for "branching" *travel-time curves* that are related to discrete ray paths of the same type of wave and due to strong velocity *gradients* and/or *low-velocity layers* in the Earth's interior. For a *prograding* travel-time branch the rate of travel time t increases with increasing *epicentral distance* D (in km) (or Δ in degree), i.e., the derivative dt/dD = *ray parameter p* = horizontal component of *slowness* s_R is decreasing, in contrast to a *retrograde* (or *receding*) travel-time branch, for which this derivative is increasing. This is equivalent with dD/dp < 0 for prograde and dD/dp > 0 for retrograde branches. Thus, at the distance where the prograde and the retrograde branches merge (i.e., where the sign of dD/dp changes), wave energy is focussed, resulting in strongly increased amplitudes (*caustic point*; see also Figs. 2.30 - 2.33 in

Chapter 2 of this Manual). Retrograde branches may be formed by strong positive velocity increases with depth. When this gradient weakens again at larger depth, a new prograde branch is forming. Such a sequence of prograde, retrograde and prograde travel-time branches in the order of decreasing dt/dD = p for the same wave type is called a *triplication*. Examples are the two *P wave* triplications due to the *upper mantle discontinuities* (strong velocity gradient zones) at 410 km and 660 km depth (see Figs. 2.32 and 2.5.3.2 in Chapter 2 of this Manual) and the *PKP* triplication with the branches PKPab, PKPbc, PKiKP and PKPdf (Fig. 11.73 in Chapter 11) due to the strong velocity increase from the outer to the inner Earth *core* (see Fig. 2.79 in Chapter 2. For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

breccia A coarse-grained clastic rock composed of angular broken rock fragments in a fine-grained matrix.

brittle Unable to accommodate inelastic *strain* without loss of strength and tending to break.

brittle-ductile boundary See *brittle-plastic transition*.

brittle-ductile transition A zone in the Earth´s *crust* across which the thermo-mechanical properties of the crust change from *brittle* behavior above (tending to break) to *ductile* behavior below (plastic or quasiplastic, tending to bend). Its depth is usually identified as the maximum focal depth of local earthquakes and occurs at depths at which the temperature lies between 200 to 400 degrees. This is typically around 15 km but depends on the *heat flow* conditions and age of the crust. Most earthquakes initiate at or above this depth on steep (high-angle) *faults*. Below this depth, fault slips may be *aseismic* and may grade from high angle to low angle faulting (e.g., Ito 1990).

brittle-failure (BF) earthquake Sometimes used in *volcano seismology* (see Chapter 13 of this Manual) to distinguish earthquakes dominated by *brittle* processes (frictional slip or formation of a tensional crack) from those in which fluids are thought to play an active role (such as *“LP” earthquakes* or “*harmonic tremor*”. The designation “BF earthquake” is generally synonymous with “high-frequency”, “*volcano-tectonic*”, or “*A-type*” earthquake.

brittle-plastic transition A simplified, more precise model of the *brittle-ductile transition* in which the plastic fracture is considered as the *deformation* mechanism in the *ductile* part.

broadband magnitude *Body-wave* and *surface-wave magnitudes* that are based (in contrast to *amplitude*/*period* ratios measured on more or less narrow-band records of ground *displacement*) on direct measurements of ground motion velocity on broadband records. Examples are the IASPEI (2011) recommended *P-wave* magnitude standard mB(BB) or mB_BB, measured in the period range between 0.2s to 30 s, and the new *surface-wave* magnitude standard Ms(BB) or Ms_BB, measured at periods between 3 s and 60 s. As compared to more narrow-band magnitudes, such as mb, measured at periods around 1 s, and the surface-wave magnitude Ms, measured at periods around 20 s, broadband magnitudes are less prone to the underestimation of magnitude for large *seismic events* (in the case of mb) or smaller events (in the case of Ms(20) = Ms_20). See Chapter 3 and IS 3.3 in this Manual and Bormann et al. (2009).

broadband seismogram *Seismograms* recorded by a *broadband seismograph*. See Chapter 5 of this Manual.

broadband seismograph To avoid the strong *ambient noise* caused by ocean waves (*microseisms*), two types of *seismograph* have traditionally been used to record seismic *signals*: one for *periods* longer than about 10 s and the other for those shorter than 3 s. However, this kind of filtering may result in significant signal distortions and underestimation of earthquake *magnitude*. A broadband seismograph can record faithfully seismic signals in a *frequency* range of 3 decades or some 10 octaves (e.g., between 0.1 s to 100 s) or even wider, thanks to the improved linearity range of the seismometer and *dynamic range* of the recorder. See Chapter 5 of this Manual.

broadband seismometer *Seismic sensor* used in a *broadband seismograph***.**

Brownian (molecular) motion Completely irregular (stochastic) motion of smallest particles suspended in a liquid or gas, first described by the British botanist Robert Brown (1773-1858). The diffusion intensity of B.m.m. increases with temperature and is explained in a physically and mathematically tractable form by the theories of Albert Einstein (1879-1955) and Marian Smoluchowski (1872-1917). It plays a role in the temperature-dependent diffusive internal *friction* and thus *anelasticity* of Earth materials, the related *attenuation* of *seismic waves*, and may also be one of the causes of *instrumental noise* of *seismic sensors* (see Section 5.5.5 in Chapter 5 of this Manual).

Brune model The omega-squared circular-crack model proposed by Brune (1970). The physical basis of this model was refined by Madariaga (1976), who solved the mathematical problem of seismic wave radiation from an expanding circular crack that stops. See *omega-squared model*, Chapter 3, Fig. 3.5 in this Manual and Aki and Richards (2002 or 2009, p. 560-565),

***b*-slope** Another name for *b-value*.

B-type earthquake Earthquakes occurring under volcanoes with emergent onset of *P waves*, no distinct *S waves*, and a lower *frequency* content as compared with the usual *tectonic earthquakes* of the same *magnitude*. In the original definition by Minakami (1961) its character difference from the *A-type earthquake* was attributed to the extremely shallow *focal depth* (< 1 km). More recently the difference has been attributed to the source process and now called more often *long-period (LP)* or *low-frequency earthquakes*. See Chapter 13 in this Manual.

bulk density The mass of a material divided by its volume, including the volume of its pore spaces.

bulk modulus The modulus of volume elasticity which relates a change in volume to a change in hydrostatic pressure. It is the reciprocal of *compressibility*. See Birch (1966) for an introduction and a compilation of values, section 2.2 in Chapter 2 of this Manual and Eq. (1.6) in Ben-Zion (2003).

Burridge & Knopoff model A spring-and-block model proposed by Burridge and Knopoff (1967) for earthquakes. See Madariaga and Olsen (2002, p. 176-7).

***b*-value** A coefficient in the frequency-magnitude relation, log $N(M) = a - bM$, obtained by Gutenberg and Richter (1941; 1949), where M is the earthquake *magnitude* and $N(M)$ is the number of earthquakes with magnitude greater than or equal to M. Estimated *b-values* for most seismic zones fall between 0.6 and 1.1, but may be higher in volcanic regions, earthquake *swarms* and sometimes in *aftershock* sequences. See also the biographies of Beno Gutenberg and Charles Francis Richter in Howell (2003).

Byerlee's law The common observation from laboratory *friction* experiments that the coefficients of friction for nearly all rocks that comprise the *lithosphere* fall in the range 0.6 to 1.

C

c This symbol is used to indicate the *reflection* at the *core-mantle boundary* for waves incident from the *mantle*. For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

$_{14}$C age date An absolute age obtained for geologic materials containing bits or pieces of carbon using measurements of the proportion between the radioactive carbon ($_{14}$C) and the non-radioactive carbon ($_{12}$C). These dates are independently calibrated with calendar dates. The method is used to determine when past earthquakes occurred on a fault. See *paleoseismology*.

caldera A circular or ovoid depression, generally 5 to 20 km in diameter, formed by collapse or subsidence of the central part of a volcano, often associated with large explosive eruptions.

calibration (of seismograph) The process of determining the *response function* and *sensitivity* of a seismic instrument. See Chapter 5 in this Manual.

calibration pulse An electronic *signal* used to calibrate seismic instruments. See *calibration*.

capable fault A mapped *fault* that is deemed a possible site for a future earthquake with *magnitude* greater than some specified threshold.

cascade model of earthquakes An extended version of the *characteristic earthquake model* in which several consecutive *fault segments* can rupture in a variety of combinations. The *slip* on each segment is assumed to be characteristic to the segment.

catalog of earthquakes A chronological listing of earthquakes. Early catalogs were purely descriptive, i.e., they gave the location and date of each earthquake and some description of its effects. Modern catalogs are usually quantitative, i.e., earthquakes are listed as a set of numerical parameters describing *origin time*, *hypocenter* location, *magnitude*, *moment tensor*, etc. See Engdahl and Villasenor (2002) for an instrumentally determined earthquake catalog (1900-1999), Utsu (2002a) for a catalog of deadly earthquakes (1500-2000), and Ambraseys et al. (2002, p. 759-761) and Schweitzer and Lee (2003) for a discussion of historical and modern earthquake catalogs and *seismic bulletins*.

causal signal An output *signal* that does not exist for times prior to the application of an impulsive input. In other words, an impulse response h(t) that vanishes for t<0. See *impulse response, linear system* and *convolution*.

caustic point A point on the Earth's surface where the rate of change of the *epicentral distance* traveled by a *seismic ray*, respectively of its *slowness*, with the change of its *take-off angle* changes its sign. A large concentration of arriving *seismic energy* will generally be observed at the caustic point. See Figs. 2.30 to 2.3 in Chapter 2 of this Manual.

Cenozoic An era in geologic time, from 66.4 million years ago to the present. See *geologic time*.

cgs system of units An obsolete system of units based on: (1) centimeter for length, (2) gram for mass, and (3) second for time. Some derived cgs units with special names are: (1) force in dyne (cm g s^{-2}), (2) energy in erg (cm^2 g s^{-2}), and (3) acceleration of free fall in gal (cm s^{-2}). See *international system of units*.

channel In observational seismology, it is the *signal* output of a component of a *seismic sensor*. Modern seismic recorders (see *data logger)* are able to record simultaneously the signals from many channels.

chaos A term that had been used since antiquity to describe various forms of randomness. It is now a commonly accepted technical term referring to the irregular, unpredictable, and apparently random behavior of deterministic dynamic systems. Solutions to deterministic equations are chaotic if adjacent solutions diverge exponentially in phase space. See Socolar (2002) or Wolfram (2002) for a general discussion of chaos, and Turcotte and Malamud (2002) for an application in seismology.

characteristic earthquake model A fault-specific earthquake model in which a given *fault segment* generates an earthquake of a size and mechanism determined from the geometry of the segment. At a specific location along a fault, the *displacement* (*slip*) is the same in successive characteristic earthquakes. Other earthquakes occurring on the fault are much smaller than these. In its application to *seismic hazard analysis*, it refers to an earthquake of a specific size that is known or inferred to recur at the same location, usually at a less frequent rate than that extrapolated from the frequency-magnitude relation for smaller earthquakes in the area. See Aki (2002, p. 44-45), Grant (2002, p. 482-484), and Eq. (7.3) and Figure 15 in Ben-Zion (2003).

characteristic function Non-linear transformation of the *seismogram*, its information being exploited by a picking algorithm. Introduced by Rex Allen (1978). See Chapter 16 in this Manual.

Christoffel matrix A symmetric real-valued matrix, whose eigenvalues give the seismic *velocities* and eigenvectors give the *polarization* directions of the waves. See Chapman (2002), Cara (2002), and the biography of Elwin Brun Christoffel in Howell (2003).

cinder A common fragmental volcanic product (*tephra*), classified as ranging between 2 and 64 mm in size.

cinder cone A relatively small, cone-shaped hill or mountain, rarely exceeding 1 km in height, that nearly always has a truncated top in which there is a bowl-shaped crater (see Macdonald, 1972). As its name implies, this volcanic edifice is built entirely of *tephra* ejected during moderately explosive eruptions. See *cinder*.

circular fault *Fault plane* geometry in which the rupture front starts from a point on the fault and spreads as a circle. See *rupture front* and *Brune model*.

Circum-Pacific belt The zone surrounding the Pacific Ocean that is characterized by frequent and strong earthquakes and many volcanoes, as well as high *tsunami* hazard. Also called the *Ring of Fire.*

classical continuum An idealized material medium that is assumed in classical mechanics (see e.g., Goldstein, 1950). The medium has a continuously distributed mass, and the *stress* is a function of 6 independent strain measures, characterizing purely *translation*al (volumetric and shear one) *strain*.

clip level The maximum output of a *seismograph*. A “hard clip” is defined as the maximum voltage output of a *seismometer* regardless of input. A “soft clip” is defined as the *amplitude* at which the output begins to distort into a nonlinear representation of the input waveform. For an ideal sensor, the two clip levels are (nearly) the same, with no distortion or nonlinearity before the hard clip is reached.

coda The “tail” of a *seismic signal*, which follows a well defined wave *arrival*. For example, the teleseismic P-coda follows the arrival of teleseismic *P waves*. Coda waves are due to *scattering* and superposition of multi-path arrivals, with usually exponentially decaying *amplitudes* (e.g., Figs. 2.44 and 2.45 of Chapter 2 and Figure 1b of DS 11.1 in this Manual, and Kulhanek (2002, p. 333-334).

coda attenuation See *coda Q* .

coda normalization method A method to use the power of local earthquake S-coda at a given lapse time as a measure of earthquake radiation energy, which is used for measurements of *site amplification* factors, *attenuation* per unit travel distance, and source energy. This method is based on the assumption of a uniform spatial distribution of coda energy density of a local earthquake at a long lapse time measured from the earthquake *origin time*. See Sato et al. (2002, p. 200-201).

coda Q A parameter characterizing the *amplitude* decay of S-coda of a local earthquake with the *lapse time* defined by Aki and Chouet (1975) assuming single S to S *scattering*. The coda lasts longer for higher coda Q.

coda phase A *detection* of a single phase of unknown path found within the coda signal envelope, designated as tx, Px or Sx.

coda waves The *seismograms* of an earthquake usually show some vibrations long after the passage of relevant *body wave* and *surface wave onsets* in the considered distance range. This portion of the *seismogram* to its end is called the *coda*. Coda waves are believed to be *back-scattering* waves due to *inhomogeneities* in the Earth. They have been extensively used to obtain source spectra, as well as to measure seismic *attenuation* and *site amplification* factors by the *coda normalization method*. See Sato et al. (2002; p. 198-201). Measurements of *rotations* in the coda *wave field* may help to separate P and S energy (see Pham et al., 2009).

coefficient of friction (μ_f) Coefficient of the linear relationship between *shear stress* (τ) and *normal stress* (σ_n) on a *fault* or joint that is slipping $\tau = S_o + \mu_f \sigma_n$. See Lockner and Beeler (2002, p. 506), and section 5 in Ben-Zion (2003).

coherent *Seismic signals* detected on various *seismic sensors* of an *array* or network of *seismic stations* are said to be coherent if they are related to each other in time, *amplitude* and *waveform* shape because they come from the same *seismic source*.

coherence or **coherency** The degree to which two *wave fields* are in *phase* and similar in shape. Mathematically it is the normalized cross-power spectrum of the two wave fields. It is the *frequency-domain* counterpart of the "*correlation*" in the *time domain*. See Sato et al. (2002).

cohesion (S_o) The inherent shear strength of a *fault* or joint surface; shear strength at zero *normal stress* in the equation $\tau = S_o + \mu_i \sigma_n$. See Lockner and Beeler (2002, p. 506).

cohesionless Referring to the condition of a sediment whose shear strength depends only on *friction* because there is no bonding between the grains. This condition is typical of clay-free sandy deposits. See *cohesion*.

cohesive force The force that acts in the cohesive zone of a crack located between the freely slipping crack surface and the intact elastic body ahead of the crack tip. The existence of a cohesive zone removes the *stress* singularity at the crack tip. See Aki and Richards (2002, p. 548-552).

collision zone A zone where two continents collide. Continental collision is the cause of mountain building or *orogeny*. See Uyeda (2002), and Duff (1993).

colluvial wedge A prism-shaped deposit of fallen and washed material at the base of (and formed by erosion from) a *fault* scarp or other slope, commonly taken as evidence in outcrop of a scarp-forming event.

colluvium Loose soil or rock fragments on or at the base of gentle slopes or hillsides. Deposited by or moving under the influence of rain wash or downhill *creep*.

column collapse A condition that occurs when an explosive *eruption column*, composed of volcanic gases, *tephra*, and air, becomes denser than the ambient atmosphere and collapses to ground level.

compatibility condition The ability of two or more fields to fulfill the required mutual relationship. For example, a condition imposed on the *strain* field so that it can be expressed by the derivatives of the *displacement* field.

compensated linear-vector dipole The force system representing a crack opening or closing under the constraint of no volume change. The corresponding *moment tensor* has zero trace (purely deviatoric). Traditionally called “cone-type mechanism” in Japan. See Sipkin (2002).

complex site effect Dynamic *amplification* effects, e.g., those arising from a *resonance* condition, generated by propagation of earthquake waves in 2D/3D near-surface geological configurations, such as sedimentary valleys, and topographic irregularities. See Chapter 14 of this Manual, and Faccioli and Pessina (2003).

component (1) One dimension of a three-dimensional *signal*, (2) The vertically- or horizontally-oriented (north or east) sensor of a *seismic station*.

composite volcano Synonymous with *stratovolcano*.

compressibility Reciprocal of *bulk modulus*.

compressional tectonic setting A region undergoing lateral contraction and for which the vertical *principal stress* is the minimum. See McGarr et al. (2002).

compressional wave See *P wave*.

compressional stress The *stress* that squeezes something. It is the stress component normal to a given surface, such as a *fault plane*. It results from forces applied perpendicular to the surface or from remote forces transmitted through the surrounding rock.

compressive strength The maximum compressive stress that can be applied to a material before failure occurs. See *strength*.

confidence ellipsoid In *hypocenter* location calculations, an ellipsoid surrounding the computed hypocenter within which the true hypocenter is (formally) located at some specified level of confidence (see IS 11.1 in this Manual).

conical wave See *head wave*.

Conrad discontinuity Seismic boundary between the upper and middle *crust* that is usually defined by an increase in seismic *velocity* from 6.2-6.4 km/sec to about 6.6-6.8 km/sec. The term has fallen into disuse in recent years due to the lack of universality of such a *discontinuity*. See Mooney et al. (2002), and the biography of Victor Conrad in Howell (2003).

constitutive equation For continuous media, an equation relating basic physical quantities characterizing the state of the material - for instance, the relation between *strains*, temperature, the gradient, and *stresses* of a continuum. Constitutive equations define the behavior of the material, and they are different for different materials.

continental deformation A term usually used to emphasize the contrast between deforming zones in the oceans and on the continents (see *continental tectonics*).

continental drift A theory that continents have displaced thousands of kilometers in the last few hundred million years, first proposed by the German meteorologist and geophysicist Alfred Wegener (1912 a and b). See Uyeda (2002), and biography of Alfred Wegener in Howell (2003).

continental tectonics A term used to include the large-scale motions, interactions and deformation of the continental *lithosphere*. It is often used in contrast to *plate tectonics*. Whereas deforming zones in the oceanic *plates* are usually narrow and confined, on continents they are often spread over wide areas, requiring a different approach to their description and analysis. See Jackson (2002).

contractional jog A stepover between *en échelon fault* strands where *slip* transfer involves contraction and increased mean compressive *stress* within the *stepover*. See Sibson (2002).

contractive soils Granular soils that decrease or tend to decrease in volume during large *shear deformation*. The tendency to contract increases pore water pressures in undrained saturated soils during shear. Slopes and embankments underlain by contractive soils may suffer catastrophic strength loss and flow failure during earthquake shaking. See Youd (2003).

controlled-source seismology Seismic investigations that utilize man-made *seismic sources*, such as chemical explosions detonated in boreholes or water, vibrators at land or *airguns* in water. See Mooney et al. (2002).

convergent margin *Plate boundary* zone where two *plates* are converging to one another. Either plate may subduct under, collide into, or obduct over the other plate. See Suyehiro and Mochizuki (2002).

conversion relationships Statistical relationships between parameter data of similar kind, e.g., different types of *magnitude* estimates. Such relationships are used for converting, with some uncertainty, one type of data into the other one, e.g., *body* and/or *surface-wave magnitude* values into the equivalent *moment-magnitude* values. This is common practice in efforts to create *homogeneous* - with respect to magnitude - *earthquake catalogs*. Usually, conversion relationships are derived via *least-square* standard *regression analysis*, although for data afflicted with comparable measurements and initial errors, as is the case with many types of magnitude data, Chi-squared or *orthogonal regression* relationships are preferable. See, e.g., Stromeyer et al. (2004), Castellaro et al. (2006), Castellaro and Bormann (2007), Gutdeutsch et al. (2011), Lolli and Gasperini (2012).

converted waves Conversion of *P* to *S waves* and S to P waves occurs at a *discontinuity* for non-normal *incidence angle* (see Figs. 2.34, 2.35 and 2.52 in Chapter 2 of this Manual). Converted waves sometimes show distinct *arrivals* on *seismograms* (e.g., Figs. 2.25 and 2.52 in Chapter 2; 11.65, 11.67 and 11.70 in Chapter 11) and may be used to determine the location of the discontinuity.

convolution A mathematically equivalent operation that describes the action of a linear (mechanical and/or electronic) system on a signal, such as that of a *filter* on a *seismic signal*. The convolution of two functions $x(t)$ and $h(t)$ is often written as $x(t) * h(t)$, and is defined mathematically as $y(t) = x(t) * h(t) = \int x(\tau)\, h(t- \tau)\, d\tau$. In signal processing, $y(t)$ represents an output of a *stationary linear system* in terms of the input $x(t)$ and impulse response $h(t)$ of the system. See *linear system* and *impulse response*.

core (Earth's) Central part of the Earth's interior with upper boundary at a depth of about 2900 kilometers. It represents about 16% of the Earth's volume with about 33% of the Earth´s mass. It is divided into an inner, solid core, and an outer, fluid core. The outer core extends from about 2900 to about 5120 km below the Earth's surface and consists in its main components of a mixture of liquid iron and nickel. The inner core is the central sphere of the Earth with a diameter of about 1250 km and consists of solid metal. For wave *velocity*, *density* and *attenuation* distribution in the core, as compared to the Earth´s *mantle*, see Fig. 2.79 in Chapter 2 of this Manual. For further information see Jacobs (1987), Lay (2002), and Song (2002).

core-mantle boundary (CMB) Sharp *discontinuity* between the bottom of the Earth´s *mantle* and the Earth´s *core*, characterized by a decrease of the *P-wave velocity* v_P from 13.7 to 8.0 km/s and of the *S-wave* velocity from 3.44 to 0 km/s (see Fig. 2.79 in Chapter 2 and Tables in DS 2.1 of this Manual).

core shadow zone A gap in the emergence of *P waves* that have traveled directly through the Earth extending for short-period P waves from *epicentral distances* of about 103^o to 114^o. This gap or shadow of the core is caused by the sharp decrease in the P wave velocity at the *core-mantle boundary*. Note, however, that long-period mantle P waves may be diffracted around the curvature of that boundary, thus feeding mantle P-wave energy of strong earthquakes into this shadow beyond 140° (see *diffracted P (Pdif)*, Figs. 2.55 of Chapter 2 and 11.73 and 11.74 of Chapter 11 in this Manual, and Kulhanek (2002, p. 340).

Coriolis force Inertia force named after the French engineer and physicist Gaspard Gustave Coriolis (1792-1843), which describes mechanical processes in rotating reference systems. The C.f. always acts perpendicular to the momentary direction of movement and the axis of *rotation* defined by the *rotation vector* $\boldsymbol{\omega}$. It acts on each mass moving on the Earth surface and results in a rightward drift on the northern hemisphere and a leftward drift on the southern hemisphere. The C. f. needs to be taken into account, e.g., in the analysis of the spectral splitting of *free oscillations* when investigating lateral inhomogeneities of the Earth´s structure (see Lay and Wallace, 1995, p. 162; Aki and Richards, 2002, p. 375).

corner frequency The *frequency* at which the curve representing the *Fourier amplitude spectrum* of a recorded *seismic signal* abruptly changes its slope and drops by -3 db from the spectral plateau. In earthquake source studies, a parameter characterizing the *far-field body-wave displacement* "source spectrum", being related to *fault* size, *rupture velocity*, *source duration* and *stress drop* in the source. See *omega-squared model*, Fig. 3.5 in Chapter 3 of this Manual, and Figure 7 and Eq (6.1) in Ben-Zion (2003). In *seismometry* the frequency at which the *transfer function* (*magnification curve*) of a recording system changes its slope and drops by -3 dB from its plateau (maximum) level. See Figures in IS 5.2 in this Manual, also *bandwidth* and *band-pass filter*).

corrected acceleration An *acceleration* time history that has been "corrected" from the raw data recorded by an *accelerograph*. The correction typically involves removing *drift*, spikes, and any distorting effects created by the instrument or digitizing process. See Shakal et al. (2003).

corrected penetration resistance A measure of an in-situ property of soil, important for interpreting geotechnical and seismic *site response* data. It is based on a penetration test, such as standard penetration-test resistance, corrected for the influence of overburden *pressure*, hammer energy, rod length, borehole diameter, and sampler type; or cone penetration resistance, corrected for the influence of overburden pressure. See Youd (2003).

correlation The degree of relative correspondence, as between two sets of data, expressed, e.g., by the *correlation coefficient***.** See also *autocorrelation* and *crosscorrelation*.

correlation coefficient In statistics a descriptive index applied to two sets of numbers (x,y), the value of which serves to specify the overall dependence (in per cent) exhibited by the data between the variables x and y.

correlation techniques Different mathematical methods and numerical algorithms to estimate the *coherence* between data sets and time-series by investigating their *auto*- and *cross-correlation* relationships.

coseismic Occurring at the same time as an earthquake.

Cosserat continuum A continuum, whose point bodies (infinitesimal particles) possess both *translational* and *rotational* degrees of freedom. In the Cosserat continuum, the *stress tensor* is asymmetric, and there exists a *couple-stress tensor*. Apart from the full Cosserat continuum, there exists a Cosserat pseudo-continuum, in which *translations* and *rotations* are not independent (in the linear approximation, the *rotation vector* equals curl **u**/2**,** where **u** is the *translational displacement*), and a reduced Cosserat continuum, in which rotations and translations are independent but the *couple-stress tensor* is zero.

Cosserat elasticity An elasticity theory introduced by the Cosserat brothers (Eugène and François Cosserat, 1909), in which each material point has six degrees of freedom, three of which correspond to *translation*, as in the classical theory, and the other three to *rotation*. See Pujol (2009).

Cosserat length A characteristic length associated with a rotation independent field, and defined for the given type of continuum.

Coulomb friction In a constitutive law (see *constitutive equation*) governed by Coulomb friction, a *slip* occurs when *shear stress* exceeds strength defined by a coefficient of *friction* (a constant) times the *normal stress*. In contrast, the rate-and-state dependent law involves the coefficient of friction, which is not a constant but depends on the sliding speed (rate) and contacts (state) on the *fault plane*. See Harris (2003), and Eq. (5.1) in Ben-Zion (2003). See also the biography of Charles Augustin de Coulomb in Howell (2003).

couple stress tensor Let **n** be the unit vector corresponding to the normal to an elementary material surface. A tensor **μ** of second rank is called the couple-stress tensor, if **n • μ** gives the *torque* acting upon this surface. The couple-stress tensor plays the same role for *torques* as the *stress tensor* does for forces.

Crary waves Crary waves are a train of sinusoidal waves with nearly constant *frequency* observed on a floating ice sheet (Crary, 1955). They are multi-reflected *SV waves* with horizontal *phase velocities* near the speed of compressional waves in ice.

crater A bowl- or funnel-shaped depression, generally in the top of a volcanic cone, often the major vent for eruptions; the distinction between the terms crater and *caldera* is blurred, but caldera tends to be applied to depressions with diameters >5 km.

creep Slow, more or less continuous movement occurring on *faults* due to ongoing *tectonic deformation*. Also applied to slow movement of *landslide* masses down a slope because of gravitational forces. Faults that are creeping release shear strain without significant radiated seismic energy, i.e., they do not tend to have large earthquakes. This fault condition is commonly referred to as *unlocked*. See Lockner and Beeler (2002).

creep events Episodic *slip* across a *fault* trace observed at the surface over minutes to days. See Jonston and Linde (2002).

creep meters Instruments for measuring *displacement* across a *fault* trace on the Earth's surface, usually with a baseline of length around 10 meters. See Johnston and Linde (2002) and IS 5.1 on *strainmeters* in this Manual.

creep waves Regional strain waves propagating along *active faults* as suggested by Savage (1971). However, these slip waves have not yet been directly observed. See Johnston and Linde (2002).

Cretaceous pulse of spreading During the Cretaceous period (124-83 Ma) when there was no *geomagnetic reversal*, *sea-floor spreading* was 50-75% faster than in other periods. This phenomenon is interpreted as caused by *mantle* superplume activity. See Uyeda (2002), and Larson (1991).

critical damping Critical damping exists if the *damping* coefficient of the special damping device of an harmonic *oscillator* (nicknamed "dashpot"; see Fig. 5.5 in Chapter 5) is h = 1. This value marks the transition of free vibration of the oscillator from the under-damped case of exponentially decaying harmonic motion to a-periodic motion that decays without changing algebraic sign. Widely used classical *seismometers* had damping values ranging from about 0.5 (WWSSN short-period and the Russian Kirnos *seismographs* SKM-III and SKD), 0.7 (modern electrodynamic seismometers such as GS13, CMG-3T or STS-2 and the re-calibrated Wood-Anderson standard response according to Uhrhammer and Collins, 1990), up to near critical 0.98 (WWSSN long-period). Systems with very low *attenuation* may experience damage when excited to *resonance*.

critical facilities Man-made structures whose ongoing performance during an emergency is required or whose failure could threaten many lives. May include (1) structures such as nuclear-power reactors or large dams whose failure might be catastrophic, 2) major communication, utilities and transportation systems, (3) high-occupancy buildings such as schools or offices, and (4) emergency facilities such as hospitals, police and fire stations, and disaster-response centers.

critically stressed crust A state of *stress* in the Earth's *brittle crust* balanced by the frictional strength of the Earth's crust.

cross-axis sensitivity (rotation and translation) The susceptibility of a *sensor* to produce an additional *signal* in response to motion other than that for which the sensor is intended to be sensitive. It is often due to limitations in the design or manufacture of the mechanical suspension in the sensor, or misalignment of the *components* within the sensor. There are five cross-axis sources for every sensitive axis of an *inertial sensor* (Nigbor *et al*., 2009). A translational *accelerometer* may be sensitive to both off-axis translational axes and to *rotations* about any axis. See Trifunac and Todorovska (2001).

cross-correlation coefficient Parameter, that describes the correlation between the values of two functions or independent samples of a discrete time series, separated by time shifts in case of continuous functions or time lags in case of discrete time series. See also *autocorrelation* and *correlation*.

crossover The distance from an event where two different *phase*s arrive at the same time, allowing constructive interference that sometimes enhances the *signal amplitudes*.

cross-talk The appearance of a *signal* on a *channel* due to electrical leakage from a signal on an adjacent channel. It is often due to electrical problems with shielding, grounding, etc. See Shakal et al. (2003).

crust (Earth's) The outmost layer of the Earth above the *Mohorovičić discontinuity* ("*Moho*" for short). The crust in continental regions is about 25-75 km thick, and that in oceanic areas is about 5-10 km thick. (For global cross section see Fig. 2.10 in Chapter 2 of this Manual). It represents less than 0.1% of the Earth's volume, with rocks that are chemically different from those in the *mantle*. The uppermost 15-35 km of the crust is *brittle* enough to produce earthquakes. The seismogenic crust is separated from the lower crust by the *brittle-ductile boundary*.

The crust is usually characterized by *P-wave velocities* below 8 km/s (average velocity of about 6 km/s). See also *mantle (Earth's)*, Mooney et al. (2002), and Minshull (2002).

cultural noise Seismic *noise* generated by various human activities such as traffic, construction works, industries, etc. See Chapter 4, Sub-Chapter 7.2 and IS 7.3 of this Manual and Webb (2002).

cumulative seismic moment The sum of the *seismic moments* of earthquakes which have occurred in a region from a fixed starting time till time t, as a function of t. It can be related to the cumulative *tectonic displacement* across a *plate boundary* lying in the region, or to the cumulative tectonic *strain* within the region.

curl In mathematics, the curl is the vector operator describing the "*rotation*" of a vector field. Curl **A**, or rot **A**, is equal to $\nabla\times \mathbf{A}$, the vector product of the gradient operator and vector or tensor **A**. In seismic *wave fields* based on linear *isotropic elasticity*, the curl operator separates out the *S-wave* field because the curl of the *P-wave* field is zero.

cyclic mobility A condition in which *liquefaction* occurs and flow *deformation* commences in response to static or dynamic loads but deformation is arrested by dilation at moderate to large shear strains. See Youd (2003).

Cyclic Resistance Ratio (CRR) The capacity of a granular soil layer to resist *liquefaction*, expressed as a ratio of the dynamic *stress* required to initiate liquefaction to the static effective overburden *pressure*. See Youd (2003).

Cyclic Stress Ratio (CSR) The seismic load placed on a granular soil layer, expressed as the ratio of the average horizontal dynamic *stress* generated by an earthquake to the static effective overburden *pressure*. See Youd (2003).

D

D" A ~ 200 km thick layer surrounding the fluid *core* of the Earth occupying the lowermost *mantle*. D" had been defined by Keith Bullen (1950) and is believed to be a region of strong thermal and chemical *heterogeneity*. See Lay (2002).

damage probability matrix A matrix giving the probabilities of sustaining a range of *losses* for various levels of a ground-motion parameter.

damage scenario A representation of the possible damage caused by an earthquake to the built environment in an area, in terms of parameters useful for economical and engineering assessment or post-earthquake emergency management. See Faccioli and Pessina (2003).

damping The reduction in *amplitude* of a *seismic wave* or *oscillator* due to *friction* and/or the internal absorption of energy by matter. In seismometry, a specific damping device (symbolized as a "dashpot"; see Fig. 5.5 in Chapter 5 in this Manual) is added in the design of a *seismometer* to diminish the effects of *resonance* and of the transient *free oscillation*. Fig. 5.22 in Chapter 5 of this Manual shows the dependence of normalized resonance curves on the damping coefficient h. In vibration analysis, a term that indicates the mechanism for the dissipation of the energy of motion. Viscous damping, which is proportional to the velocity of motion and is described by linear equations, is used to define different levels of *response spectra* and is commonly used to approximate the energy dissipation in the lower levels of earthquake response. See *critical damping*.

damping constant A parameter quantifying the effect of damping.

data Series of observations, measurements or facts.

data acquisition Process of acquiring and storing *data*.

database Systemized collection of *data* that can be manipulated by data processing systems for specific purposes.

data logger A digital *data acquisition* unit, usually for multi-*channel* recordings.

data processing Handling and manipulating of *data* by computer.

debris avalanche A flowing mixture of debris, rock, and moisture that moves down-slope under the influence of gravity. Principally differs from debris flows in that they are not water saturated. Debris avalanches are almost always associated with sector collapse at volcanoes. See Vallance (2000).

decibel (**dB**) A logarithmic measure of relative *signal* power, defined as 10 log(P/P_o), or 20 log(A/A_o), where P_o is the power and A_o the signal *amplitude* at some reference level, typically the minimum or maximum signal resolvable by the recording instrument ($P_o = A_o^2$). The *dynamic range* of seismic recorders is expressed in units of dB.

declustering (**of earthquake catalogs**) The procedure for removing dependent earthquakes such as *foreshocks* and *aftershocks*. A declustered *earthquake catalog* contains only *mainshocks* and isolated earthquakes. The largest shock in each earthquake sequence is considered as the mainshock and remains in the catalog. See Utsu (2002b).

deconvolution A procedure that removes the unwanted effects of *convolution* on a *signal*.

delay-and-sum processing A procedure for forming an *array beam*. Time delays are applied to the output of each of the *seismometers* of an array to bring the desired *signal* recorded at the different seismometer positions into phase, followed by summing of the outputs with appropriate weights**.** See Chapter 9 of this Manual.

defining (of an arrival) An arrival *attribute*, such as *arrival time*, *azimuth*, *slowness*, or *amplitude* and *period*, which is used in the calculation of location or magnitude of the *seismic source*.

deformation A change in the original shape and/or volume of a material due to *stress* and *strain*.

density Either (1) the quantity of something per unit measure such as unit length, area, volume, or *frequency* (see, for example, *power spectral density*), or (2) the mass per unit volume of a substance under specified conditions of *pressure* and temperature.

depth phases (pP, pwP, pS, sP, sS) Depth phases are called all *seismic waves* which propagated upward from the *hypocenter*, turned into downward propagating waves by *reflection* at the free surface. These phases are useful for an accurate determination of the focal depth and their *phase names* (codes) indicate their phase type before and after the reflection. For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011). Further see section 2.6.3 of Chapter 2, Figure 7 in IS 11.1 of this Manual, Kulhanek (2002), Engdahl and Villasenor (2002).

design earthquake The postulated earthquake (commonly including a specification of the *design ground motion* at a site) that is used for evaluating the earthquake resistance of a particular structure.

design ground motion A level of ground motion used in structural design. It is usually specified by one or more specific *strong-motion* parameters or by one or more time series. The structure is designed to resist this motion at a specified level of response, for example, within a given *ductility* level. See Borcherdt et al. (2003).

design spectrum The specification of the required strength or capacity of the structure plotted as a function of the *natural period* or *frequency* of the structure and of the *damping* appropriate to earthquake response at the required level. Design spectra are often composed of straight line segments and/or simple curves, for example, as in most building codes, but they can also be constructed from statistics of *response spectra* of a suite of ground motions appropriate to the *design earthquake*(s). To be implemented, the requirements of a design spectrum are associated with allowable levels of *stresses*, *ductilities*, *displacements* or other measures of response. See *response spectra*; also Housner (1970).

detection Identification of an *arrival* of a *seismic signal* with *amplitudes* above and/or waveform and spectral content different from seismic *noise*.

deterministic earthquake scenario A representation, in terms of useful descriptive parameters, of an *earthquake* of specified size postulated to occur at a specified location (typically an *active fault*), and of its effects. See Faccioli and Pessina (2003).

deterministic methods Refers to methods of calculating *ground motion*s for hypothetical earthquakes based on earthquake-source models and wave-propagation algorithms that exclude random effects.

deterministic system A dynamic system whose equations and initial conditions are fully specified and are not *stochastic* or random. See Turcotte and Malamud (2002).

deviatoric moment tensor A *moment tensor* with no *isotropic* (explosive or implosive) component. The sum of its eigenvalues is zero (see IS 3.9 of this Manual).

dextral fault See *right-lateral fault*.

differential pressure gauge A device for measuring long period (0.1 to 2000 seconds) *pressure* fluctuations on the seafloor. See Webb (2002).

differential travel time The difference between the *arrival time* of one *seismic phase* and that of another phase recorded at the same station from the same source. Differential travel times are often used to eliminate the uncertainty in the event *origin time* and to reduce the influence of the *velocity* structure near the source or receiver.

diffracted P (Pdif) The *P wave* that follows a ray path from the *seismic source* that grazes the Earth's *core*, is diffracted along the *core-mantle boundary*, and emerges at an *epicentral distance* of about 97° on. Diffracted P waves are observed, especially longperiod ones, in the *shadow zone* beyond distances of 100° up to about 140° (see Figs. 2.60 and 2.61 of Chapter 2 and Figs. 11.74 and 11.77 of Chapter 11 in this Manual as well as Aki and Richards (2002, p. 456-457). For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

diffracted S (Sdif) The *S wave* that follows a ray path from the *seismic source* that grazes the Earth's *core*, is diffracted along the *core-mantle boundary*. See the analogues phase *diffracted P (Pdif)* and for this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

diffraction A wave propagation phenomenon, which can be explained by the principle of Huygens-Fresnel but not by the high-frequency approximation of geometrical optics theory. Diffraction commonly occurs when the size of an obstacle becomes comparable with (and thus can be "sensed" by) the *wavelengths* of the *incident wave*.

diffusion A process describing transport of mass or heat caused by differences in chemical potential, pressure or temperature. It can also describe *seismic energy* transport in randomly *heterogeneous* elastic media. See Sato et al. (2002), and Johnston and Linde (2002).

digital accelerograph See *digital seismograph*.

digital filter A mathematical tool designed to modulate the *frequency* characteristics of a discrete time series by means of numerical calculations on a computer. See Scherbaum (2002), and Kinoshita (2003).

digital seismograph A *seismograph* in which the analog output *signal* from a *seismometer* is first converted to digital samples and then stored as time-series data in digital form. This contrasts with an analog seismograph, which directly records the analog output signal on paper, film, or magnetic tape.

digital signal processor (DSP) The processor implements mathematical operations, such as a *Fast Fourier transform*, numerically. Recent electronic *analog-to-digital converters* use DSP's to attain high resolution and to remove *aliasing*. See Chapter 6 of this Manual.

digitization The conversion of an analog waveform, e.g., a *seismogram* recorded on film, to a series of discrete x-y values corresponding to time-acceleration pairs, for use in subsequent computer processing. See Shakal et al. (2003).

digitization noise See *noise* and *least significant bit*.

dilatancy Inelastic increase of a volume of rock caused by the formation of cracks. Dilatancy may occur in a rock mass prior to an earthquake with some observable effects, such as changes in elevation, local wave propagation *velocity*, electrical conductivity, changes in well or ground water levels, spring discharges and effects of temporary hardening against *fault* rupture.

dilative Granular soils that increase or tend to increase in volume during shear.

dilatometers Borehole *strainmeters* measuring volumetric *strain*. See Johnston and Linde (2002).

dip Inclination of a planar geologic surface from the horizontal (measured in degrees).

dip slip The component of the *slip* parallel with the *dip* of the fault. See *fault*.

dip-slip fault A *fault* in which the *slip* is predominantly in the direction of the *dip* of the fault.

Dirac tensors The invariant tensors defined in four dimensions with use of the numbers: 0, 1, -1 and the imaginary unit i or -i. These tensors remain unchanged under any transformation in 4-D and help to define the invariant fields. These tensors are symmetric, anti-symmetric or asymmetric.

directivity A concept in *seismic source* studies that was introduced by Ben-Menahem (1959). An effect of a propagating *fault* rupture whereby the *amplitudes* and *frequency* of the generated *ground motion*s depend on the direction of wave propagation with respect to fault orientation, *slip* direction(s) and rupture velocity. The directivity and thus the radiation pattern is different for *P* and *S waves*. See also *radiation pattern*, *source directivity effect* and *Doppler effect*, Eq. (3.8) and Figure 6 in Ben-Zion (2003), section 9.1.1 in Lay and Wallace (1995), and the animations in Chapter 3 of this Manual.

directivity focusing The variation in wave *amplitude* as a function of azimuth relative to *strike* or *dip* of the *fault* source caused by the propagation of the *rupture front*. See animations in Chapter 3 of this Manual and *directivity*.

directivity pulse A concentrated pulse-like *ground motion* generated by constructive interference of *S waves* traveling ahead of the tip of a rupturing *fault*. See *directivity*.

direct wave A *seismic wave* that travels directly from the *seismic source* to the recording *station*, without being reflected or refracted at *interfaces* within the Earth. Observation of local, direct *P and S waves* are of particular interest for *focal depth* determination.

disaster Accidental or uncontrollable event, actual or threatened, in which individuals or society undergo severe danger or damage that disrupts the social structure of a society.

discrete wavenumber method A simple and accurate method for calculating the complete *Green's function* for a variety of problems in elastodynamics. See Bouchon (2003) for a review.

discontinuity A boundary (*interface*) between adjacent media of different physical properties, such as *density*, wave propagation *velocity* and/or others (e.g., the *Mohorovičić discontinuity*). One may differentiate between sharp first order discontinuity (with rapid or step-like changes) and second order discontinuities with gradual changes of such properties. It depends on the ratio between *wavelength* λ and the thickness d of the transition zone between the two media whether seismic waves "sense" a discontinuity as being "sharp" (λ >> d) or gradual (d >> λ).

discriminant A characteristic feature of a seismic or other *signal* that can be used for *discrimination*.

discrimination The work of identifying different types of *seismic events*, and specifically of distinguishing between earthquakes, mining or quarry blasts, and underground nuclear explosions, and/or between underground nuclear and chemical explosions. See Chapter 17 and IS 11.2 in this Manual, Richards (2002) and Richards and Wu (2011).

disk loop A storage device that continuously stores new *waveform data* while simultaneously deleting the oldest data on the device.

dislocation In seismology, the *displacement discontinuity* (*slip*) associated with faulting on an internal surface. In physics, dislocation generally refers to the line bounding of an internal surface subject to uniform slip, in which case the segments of the dislocation may be described as edge, screw, or mixed depending upon whether the slip is perpendicular, parallel, or oblique to the line. See Agnew (2002), Madariaga and Olsen (2002), Teisseyre and Majewski (2002), and Johnston and Linde (2002), and Savage (1980). See also *dislocation modeling*.

dislocation modeling Determining the dislocation distribution that would produce the observed surface *deformation* of an earthquake. See *dislocation*.

dispersion Spreading of wave duration with propagation distance due to *frequency*-dependent *velocity*. See Chapter 2 in this Manual.

dispersion relations See *Kramers-Kronig relations*.

displacement (rotational) It is often used as a synonym for *rotation* vector.

displacement (translational) A vector from the point where a material particle initially was located, to its location after an increment of motion. Unless otherwise specified, it means *translational* displacement in seismology. In earthquake geology, a general term for the movement of one side of a *fault* relative to the other; the amount of displacement may be measured in any chosen direction, usually along the *strike* and the *dip* of the fault. In *seismometry* displacement is the *ground motion* commonly inferred from a *seismogram*. For example it may be calculated by double integration of an *accelerogram* or a single integration of a velocity-proportional recording with respect to time. It is expressed in units of length, such as nanometer, micrometer or millimeter. In geology, displacement is the (quasi-) permanent offset of a geological or man-made reference point along a fault or a *landslide*. In geodesy, movement of a point on the Earth's surface; traditionally defined in a local (east, north, up) coordinate system centered at a reference point fixed to the Earth. In space geodesy, the reference point can be attached to the inertial frame. In *strong-motion* seismology and earthquake engineering, it is the time-dependent position of a material particle during earthquake shaking relative its position at rest, typically obtained by doubly integrating the acceleration records. Recovering the long-period part of the displacement history accurately from velocity or acceleration sensors is difficult because of the sensitivity of translation sensors to rotational ground motions (Trifunac and Todorovska, 2001).

dome

See *lava dome*.

Doppler effect

A shift in the *frequency* of a *signal* due to relative motion between the signal source and the sensor measuring the signal. The observed frequency is shifted from the source frequency depending on the direction with respect to the moving direction.

dormant volcano

By a widely used but inadequate definition, a dormant volcano is one that is not presently erupting but is considered likely to do so in the future. Volcanoes can remain dormant for hundreds, thousands, and, in rare cases, millions of years before reactivating to erupt again. In general, the longer a volcano remains dormant, the greater the likelihood that its next eruption will be large (Simkin and Siebert, 1994).

double couple

A force system consisting of two opposing (or orthogonal) couples with the same *scalar moment* and opposite direction (or sign). Its equivalence to a dynamic *fault slip* was first shown by Maruyama (1963) for an *isotropic* elastic medium. The force system equivalent to fault slip for an anisotropic medium was obtained by Burridge and Knopoff (1964). See Aki and Richards (2002, p. 42-48).

double-difference

In InSAR (see *satellite interferometry*), this term denotes the difference of two *interferograms*, each of which is the difference of two radar images. In GPS, this term describes a linear combination of four ray paths involving two satellites and two receivers. An equivalent is the so-called double-difference relative precision location algorithm in seismology (Waldhauser and Ellsworth, 2000).

double frequency microseisms Describes microseismic noise on the Earth generated by ocean waves with the main spectral peak at half the wave period (hence the seismic noise is at double frequency) as explained by Longuet-Higgins (1950). See Chapter 4 of this Manual, and Webb (2002).

drift For a structural engineer, “inter-story drift” means cord rotation defined by the difference in horizontal offsets between two elevations (floors) of a given structure. To instrumentalists, it means a change in the sensor offset by time caused by e.g., a fluctuation of temperature, tilting of the base, and instability of mechanical or electronic elements of the instrument. Finally, to a geologist it means a type of glacial deposit.

ductile Able to accommodate inelastic *strain* without loss of strength.

ductility The property of an object, a structure or a structural component that allows it to continue to have significant strength after it has yielded or begun to fail. Typically, a well-designed *ductile* structure or component will show, up to a point, increasing strength as its deflection increases beyond yielding or cracking in the cases of reinforced concrete or masonry. See Jennings (2003).

ductility ratio The ratio of the maximum deflection (or rotation) of a structure or structural component to the deflection (or rotation) at first yielding or cracking.

duration magnitude The logarithm of the duration of a local earthquake *seismogram* is generally proportional to earthquake *magnitude* calculated from *direct-wave amplitudes*. Its physical basis is given by the *back-scattering* theory of *coda waves*, after which the duration must be measured from the earthquake origin time. More often it is measured from the *onset* of *P waves*, requiring an additional minor, usually neglected correction for the *epicentral distance*. See Chapter 3 of this Manual, Aki (1987), Lee and Stewart (1981, p. 155-157), Havskov and Ottemöller (2010).

dynamic range The squared *amplitude* ratio between the amplitudes of the output and input *signal*, e.g., of an amplifier, or between the largest and the smallest signal that can be faithfully recorded by a sensor-recording system such as a *seismograph* or of the range of amplitude variations with respect to a reference amplitude; usually expressed in *decibel* (see Chapters 4 to 6).

dynamic ray equations The dynamic ray equations govern the properties of a *paraxial ray*, which is defined as a ray generated by perturbing the source position or take-off direction of a central ray. They are expressed as ordinary differential equations for certain characteristics of a *wave field* and are related to the amplitude and curvature of wave front in the vicinity of the central ray as a function of the *travel time* or the ray path length. See Chapman (2002) and Červený (2001).

dynamics (of seismic source) A term concerned with the *stresses* or forces responsible for generating seismic motion. See *kinematics (of seismic source)*; also Aki and Richards (2002, Box 5.3, p. 129).

dynamic stress drop A term in earthquake source physics; the space-time history of *stress drop* while the *fault* is slipping, affected by the detailed processes of *friction* sliding and *seismic wave* radiation. It is more difficult to estimate from observations than *static stress drop*. See Madariaga and Olsen (2002), Ruff (2002, p. 550-551), and Figure 14 in Ben-Zion (2003).

E

early warning system (EWS) Any installation, which can inform with very short time delay public and/or authorities or trigger automatically certain safety or mitigation operations after a potentially catastrophic event. Examples are: Earthquake Early Warning Systems (EEWS), with response times typically within a few seconds after *origin time* (OT) and thus triggering only automatic operations; Tsunami Early Warning Systems (TEWS) with issued warnings or alarms within a few to 10 minutes after OT and lead times before the arriving tsunami waves of minutes to hours, such as the Pacific Tsunami Warning Center (PTWC) in Honolulu or the German Indonesian Tsunami Early Warning System (GITEWS) in Jakarta; Volcano Eruption Early Warning Systems with sometimes even longer lead times. For a review of existing or planned EEWS systems and concepts see Allen et al. (2009) and Gasperini et al (2007) and for TEWS see http://www.gitews.org and http://www.tsunami.gov.

Earth The third planet from the Sun in the solar system. It has a mean radius of 6371 kilometers (km), a surface area of 5.1×0^{8} km^2, a volume of 1.08×10^{12} km^3, and a mass of 5.98×10^{24} kilograms. Its internal structure consists of the *crust*, the *mantle*, and the *core*.

Earth eigen modes See Earth *normal modes*.

Earth normal modes Comprise the fundamental mode (with lowest frequency) and higher (frequency) modes (or “overtones”) of the *free oscillations* of the Earth as being measurably excited by very strong earthquakes. They comprise *spheroidal* modes and *toroidal* modes. The longest *period* (about 54 minutes) has the spheroidal mode ${}_0S_2$, nicknamed “rugby” mode. The toroidal mode ${}_0T_2$ corresponds to a purely horizontal twisting motion between the northern and southern hemisphere and has a period of about 44 min. See section 2.4 in Chapter 2 of this Manual and *normal modes*.

earthquake A shaking of the Earth that is either *tectonic* or volcanic in origin or caused by collapse of cavities in the Earth. A tectonic earthquake is caused by *fault slip*.

earthquake catalog See *catalog* (catalogue) of earthquakes.

earthquake energy change The total change in energy associated with an earthquake. This includes changes in elastic energy, gravitational potential, energy radiated in *seismic waves*, frictional dissipation (heat), and surface energy of newly created surfaces. See Brune and Thatcher (2002, p. 571-572), and Eq. (6.3) in Ben-Zion (2003). See also Scholz (2002).

earthquake engineering The field of earthquake engineering is defined as encompassing man's efforts to cope with the harmful effects of earthquakes It may be subdivided into three parts; (1) a study of those aspects of seismology and geology that are pertinent to the problem, (2) an analysis of the dynamic behavior of structures under the action of earthquakes, and (3) the development and application of appropriate methods of planning, designing and constructing of man-made structures, installations or systems to resist earthquakes. It overlaps with Earth sciences on one hand and with social scientists, civil engineers and planners, and with industry and government on the other hand.

earthquake faulting The disruption and displacement of rocks along a *fault* in conjunction with an *earthquake* rupture. For basic types of earthquake faulting see Figures and Animations in Chapter 3 of this Manual.

earthquake focal mechanism A description of the orientation and sense of *slip* on the causative *fault plane* derived seismologically from the *radiation pattern* of *seismic waves* (traditionally by the sense of the *first P- wave motion* and *polarization* of *S-wave* motion, and now the *moment tensor* inversion of *waveforms*). From the seismic radiation pattern alone it is not possible to distinguish between the fault plane and the auxiliary plane orthogonal to the slip direction. See Sub-chapters 3.4 and 3.5 and Exercises 3.2 and 3.5 of this Manual. See also *fault-plane solution* and *focal mechanism*.

earthquake focus See *hypocenter*.

earthquake hazard Any physical phenomena associated with an earthquake (e.g., *ground motion*, ground failure, *liquefaction* and *tsunami*) and their effects on land use, man-made structure and socio-economic systems that have the potential to produce a *loss*. More correct and less ambiguous is the probabilistic definition now generally accepted and used in the hazard community: Earthquake hazard *H* is the probability of occurrence of an event with a specified type and level of ground shaking and thus disaster potential within a defined area and interval of time. This definition does not relate to specific effects and loss potential (see *earthquake risk*). They come into play only when *H* is convolved with the *exposure E* to *earthquake hazard* and the *vulnerability V* of the objects and persons exposed. See also Somerville and Moriwaki (2003), and Giardini et al. (2003).

earthquake intensity See *seismic intensity*.

earthquake, local Although there exists no standard definition for the characterization of earthquakes according to distance, in this Manual (see Chapter 11) an earthquake is considered as local if the *direct* crustal *phases Pg* and *Sg* arrive as first *P*- and *S-wave onsets*. The corresponding distance range varies from region to region and ranges between about 100 and 250 km.

earthquake precursor Anomalous phenomenon preceding an earthquake. For overviews see Kanamori (2003) and Bormann (2010).

earthquake prediction The statement, in advance of the event, of the time, location, and magnitude of a future earthquake. Earthquake prediction programs have been promoted in Japan, China, the United States, the former Soviet Union, and other countries. See, e.g., Kanamori (2003), and Bormann (2010).

earthquake, regional Usually, the distance range in which phases *Pn* and *Sn* appear as first *P*- and *S-wave arrivals* on seismic records. The actual range varies from region to region, as in the case of local earthquakes, between about 100 and 1000 km. The distance range between about 1000 and 2000 km is often called far-regional. See *earthquake, local*, and Chapter 11 of this Manual.

earthquake risk Earthquake risk *R* is the expected (or probable) total loss of life, injury, building and infrastructure damage and their socio-economic consequences in the case of an earthquake and thus, the cumulative product of *H* with the *elements at risk RE* and their *vulnerability V:*

$$R_i = H_i \sum_{j=1}^{m} RE_j * V_j \;.$$

However, in common language, *earthquake risk* and *earthquake hazard* are occasionally used interchangeably, which might be misleading.

earthquake sequence A series of earthquakes originating in the same (wider) locality, such as *aftershocks*, *earthquake swarms*, but sometimes also a sequence of consecutive *mainshocks*. See Utsu (2002b).

earthquake source parameters The parameters specified for an earthquake source depend on the applied model. They are *origin time*, *hypocenter location*, *magnitude*, *focal mechanism* and *moment tensor* for a *point source* model. They include *fault* geometry, *rupture velocity*, *rupture duration*, *stress drop*, *slip distribution*, etc. for a finite fault model. See Section 6 in Ben-Zion (2003).

earthquake source spectrum In the far-field measured *spectra* of seismic *P* or *S waves* that have been corrected for propagation *path* and source *radiation pattern effects* so as to approximate best the primary spectrum radiated by the *seismic source*. The shape of the source spectrum is mainly characterized by its plateau value, *corner frequency* and high-frequency roll-off, which are controlled by the geometry and size (*seismic moment*), kinematics (*slip* and *rupture velocity*) and dynamics (*stress-drop*, radiated *seismic energy*) of the *earthquake rupture*. Values of these source parameters can therefore, based on reasonable model assumptions, be roughly inferred from the parameters of the source spectrum.

earthquake storms A sequence of large earthquakes, occurring over a period of a few years to tens of years over distances of hundreds of kilometers. For example, along the North Anatolian fault between 1939 and 1999; the Mojave region between 1950 and the present, or the eastern Mediterranean between about 340 AD and 380AD. See Nur (2002).

earthquake stress drop See *static stress drop* and *dynamic stress drop*, and Figure 14 in Ben-Zion (2003).

earthquake swarm A series of earthquakes occurring in a limited area and time period, in which there is not a clearly identified main shock of a much larger magnitude than the rest. See Utsu (2002b) and *swarm (of earthquakes)*.

earthquake thermodynamics A branch of physics of *earthquakes* that deals with consequences of the second law of thermodynamics on rock fracture and *earthquake faulting*. See Teisseyre and Majewski (2002).

earth tides Periodic *strains* primarily at diurnal and semi-diurnal periods generated in the solid Earth by the gravitational attraction of the Sun and the Moon, firstly observed by Ernst von Rebeur-Paschwitz (1892, 1893).

edge dislocation See *dislocation*.

edge effect (on ground motion in a basin) A special amplification effect found near the edge of a basin. In a two- or three-dimensional model of basin, basin-induced *diffracted waves* and *surface waves* generated at the edge by an incident *body wave* meet together in phase at some point causing constructive interference. As a result the *amplitude* of *ground motion* there becomes much larger than in the case of a simple one-dimensional model. The edge effect contributed importantly to the damage concentration in Kobe during the Hyogo-ken Nanbu earthquake of 1995. See also Chapter 14 of this Manual and Kawase (2003).

effective normal stress The *normal stress* minus the *pore pressure*. See Nur and Byerlee (1971), and McGarr et al. (2002).

effective stress In soil mechanics, the sum of the inter-particle contact forces acting across a plane through a soil element divided by the area of the plane. On a horizontal plane, the effective stress is defined as the total overburden pressure minus the instantaneous pore water pressure. In rock mechanics, it also means the *stress* above the *pore pressure*. See Lockner and Beeler (2002), and Youd (2003).

effusive eruption Non-explosive extrusion of *lava* at the surface; typically produces *lava flows* and *lava domes***.**

eigenperiod From the German word “Eigenperiode”; see *fundamental period* and *natural period*.

eigenfrequency The inverse of *eigenperiod* or *natural period* or *fundamental period*.

eikonal From the Greek word “eikon” which means “image”. It was introduced by Heinrich Bruns (1848-1919) to describe the phase function (or *travel time*) in wave solutions that can usefully be written $A(x)$ exp[i $\psi(x)$]. Constant values of the eikonal represent surfaces of constant phase, or *wavefront*s. The *eikonal equation* is a partial differential equation for the eikonal.

eikonal equation Consider a *wavefront* originating from an impulsive source at a point, and define the *travel time* in space as its *time of arrival*. The eikonal equation in this case equates the magnitude of *gradient* vector of the travel time to the reciprocal of the local wave speed. The term was also used in relation to Hamilton’s equations in analytical dynamics, which has some similarity with equations in the *ray theory*. See Chapman (2002), and the biography of William Rowan Hamiltion in Howell (2003).

elastic dislocation theory In *seismology*, the theoretical description of how the elastic Earth responds to *fault slip*, as represented by a distribution of *displacement discontinuities*.

elastic energy (or **strain energy)** The internal energy contained in an elastic material and caused by its *translational* and/or *rotational strain*. Elastic energy is a function of materially objective *strain tensors* (rotating together with the material and independent of its rigid translations). Knowing this function, one may obtain the *constitutive equations* of the elastic material. In the linear material, elastic energy is a quadratic form of the linear strain tensors (materially objective in the linear approximation). See *principle of material objectivity*.

elasticity The property of a body to recover its shape and size after being deformed.

elastic rebound model A model of the overall earthquake genesis process first put forth by H. F. Reid in 1910. It says that the energy that is released in a *tectonic earthquake* accumulates slowly in the vicinity of the *fault* in the form of elastic *strain* energy in the rocks, until the *stresses* on the fault exceed its strength and sudden rupture occurs. The rock masses on the two sides of the fault move in a direction to reduce the strain in them. At the time this model was proposed, the source of the accumulating strain was not known.

elastic wave A wave that is propagated by some kind of elastic *deformation*, that is, a deformation that disappears when the deforming forces are removed. A *seismic wave* is a type of an elastic wave.

elastodynamic equation The basic equation governing the dynamic deformation of a solid body. It is derived from Newton’s law on force and *acceleration*, generalized Hooke’s law on *stress* and *strain*, and the assumption of the existence of the strain energy function. For an infinitesimally small *displacement*, it can be reduced to a form equating *density* times the second time-derivative of the displacement to the sum of the body force and the divergence of the stress tensor (written in terms of the space-derivatives of the displacement). See Aki and Richards (2002, p. 11-36), Teisseyre and Majewski (2002), and Eqs. (1.7) and (1.8) in Ben-Zion (2003). See also the biographies of Isaac Newton and Robert Hooke in Howell (2003).

electromagnetic Coupled electric and magnetic field effects. For electromagnetic *transducers* and *seismographs* see Chapter 5 of this Manual.

elements exposed to risk Endangered elements RE_j (j = 1, ..., m) within a defined area, e.g., number of persons, value of property, level of economic activity etc., which constitute the elements of an "*exposure model*".

elliptic crack *Fault plane* geometry in which the *rupture front* starts at a point on the fault and spreads as an ellipse. See also Aki and Richards (2002, p. 509-510, 552-560).

elliptic fault See *elliptic crack*.

empirical Green's function method A method for calculating *ground motions* for a large earthquake using actual records of small earthquakes originating on or near the same *fault plane* as *Green's function* representation for the propagation *path effects*.

EMS-98 See *European Macroseismic Scale*.

en echelon An overlapping or staggered arrangement, in a zone, of geologic features (such as *faults*) that are oriented obliquely to the orientation of the zone as a whole. The individual features are short relative to the zone. See *en echelon faulting*.

en echelon faulting Faulting type which produces typical *en echelon* features with repeated oblique *fault* offsets. Often observed along the surface rupture trace of large *strike-slip* faults (see *faulting*).

energy magnitude (Me) The radiated *seismic energy* Es by an earthquake can nowadays be estimated routinely by integrating over a wide range of *periods* the squared *velocity amplitudes* recorded by *broadband seismographs* and correcting them for wave propagation effects. See Chapter 3 in this Manual and Bormann and Di Giacomo (2011), also for the relationship between Me and *moment magnitude* Mw.

engineering seismology That part of seismology which aims primarily at providing seismological data for *earthquake engineering*, *earthquake hazard* and *earthquake risk* applications. Such data are *ground-motion* parameter data (*intensity*, peak values of ground *displacement*, *velocity* and *acceleration*), *time series* and *spectra* of *ground motions* for *response* modeling of structures, for assessing spectral *site-amplification* effects, *ground shaking scenario modeling*, *liquefaction* potential, etc. See Chapter 15 of this Manual and Campbell (2003).

envelope broadening Phenomenon where a wave envelope which has been impulsive at the time of radiation from the source is broadened with increasing travel distance because of *diffraction* and *scattering* by distributed *heterogeneities*. See Sato et al. (2002).

epicenter The point on the Earth's surface vertically above the earthquake-rupture initiation point (the *focus* or *hypocenter*).

epicentral area The area around the epicenter of an earthquake, often characterized by the largest *macroseismic intensity* I of *ground shaking*. See *epicentral intensity*.

epicentral distance Distance from a site (usually a recording *seismograph* station) to the *epicenter* of an earthquake. It is commonly given in kilometers for local earthquakes (see *earthquake, local*), and in degrees (1 degree is about 111 km) for *teleseismic* events.

epicentral intensity The *intensity* of *macroseismic* shaking observed at (or inferred to be) the *epicenter* of a strong earthquake, usually abbreviated as I_o. See Chapter 12 of this Manual.

episodic tremor and slip (ETS) The coupled phenomena of *non-volcanic tremor* and slow volcanic tremor (Rogers and Dragert, 2003). See also *non-volcanic tremor*, *slow slip-events*.

epistemic uncertainty The analysis uncertainty due to imperfect knowledge in model parameterization and other limitations of the methods employed. Epistemic uncertainty can be reduced by improvements in the modeling and analysis. See *aleatory uncertainty* and Anderson (2003).

equivalent linearization The process of selecting a linear system and its parameters so that it approximates the response of a nonlinear system.

erg A cgs unit for energy; 1 erg = 10^{-7} joule. Now an obsolete, non-standard unit but commonly used in older seismological literature. See *Joule*.

eruption A general term applied loosely to any sudden expulsion — explosive or non-explosive — of material (solid, liquid, or gas) from *volcanic vents*. Some volcanologists, however, prefer that the term be restricted only to ejections of *lava* and (or) fragmental solid debris, thereby distinguishing them from aqueous or gaseous emissions devoid of particulate matter. Such a distinction is important in the assessment of volcano hazard and in the communications of volcano-hazard information during a volcanic emergency.

eruption column A vertical plume of *tephra* and gases mixed with air that forms above a *volcanic vent* during an explosive volcanic *eruption*; may rise to stratospheric heights (tens of kilometers) and can last for many hours.

ESC See *European Seismological Commission*.

Euler pole See *Euler vector*.

Euler vector Rotation vector describing the relative motion between two *tectonic plates* along the Earth’s surface. The magnitude of the Euler vector is the rotation rate, and its intersection with the Earth's surface is the Euler pole. The linear velocity at any point on the *plate boundary* is the vector product of the Euler vector and the radius vector to that point.

European Macroseismic Scale A twelve-degree *macroseismic intensity* scale with the acronym EMS. In 1988 the European Seismological Commission initiated a major revision and elaboration of the *MSK Scale*, which resulted finally in the publication of the

European Macroseismic Scale 98 (*EMS-98*; Grünthal, 1998). Although this new scale is largely based and compatible with the *MSK Scale*, its organization is very different. Most importantly, its guidelines for practical use, supported by illustrations, tables, vulnerability classification of building types and worked examples, are very elaborate and unique in comparison with all other widely used *macroseismic intensity* scales. Since its publication the EMS-98 has been widely adopted inside and also outside Europe.

European Seismological Commission (ESC) A regional commission of *IASPEI*. The ESC was founded after World War II and had its first General Assembly in 1952, has more than 30 member states in the region covering an area from the Mid-Atlantic Ridge to the Urals and the Arctic Ocean to northern Africa. It holds ever since its foundation General Assembly meetings every second year. See http://www.esc-web.org.

event association See *signal association*.

event, seismic See *seismic event*.

event horizon A term in *paleoseismology* indicating the ground surface at the time of an earthquake in the geologic past. See Grant (2002).

exceedance probability Probability that a specified value of a *strong-motion* parameter, e.g., the *intensity* of shaking or the *peak ground acceleration*, is exceeded by a future earthquake occurrence within a specified period of time. See Campbell (2003).

exploration seismology Application of seismological methods by using mostly artificial *seismic sources* (e.g., explosions, vibrators) and thus waves of higher frequencies within shorter distance ranges for a more detailed imaging of structures in the upper Earth´s *crust* with exploratory interest. See Sheriff and Geldart (1995) and *seismic exploration*.

explosion earthquake A term in volcanology; *seismic events* associated with explosive volcanic activities. In addition to the usual *seismic waves* such as *P* and *S* waves, they often also generate acoustic waves travelling through the air (see *infrasound*) and are transmitted back into the ground in the vicinity of the seismometer. See Ben-Menahem and Singh (1981) and McNutt (2002).

exposure model A more or less quantified model of the number and distribution of persons and objects of different degree of *vulnerability* in a given area which are exposed to hazard (such as *earthquake hazard*).

exposure time The time period used in the specification of probabilistic *seismic hazard* and *seismic risk*. It is usually chosen to represent the design or economic life of a structure.

extensional tectonic setting A region in which the *crust* is undergoing lateral expansion and for which the maximum *principal stress* is vertical. See McGarr et al. (2002).

extinct volcano By a widely used, but inadequate definition, an extinct volcano is one that is not erupting and is not expected to do so in the future (see Decker and Decker, 1998).

F

failure envelope Boundary of *stress* conditions associated with rock failure, as defined in *shear stress* versus *normal stress* space. Typically the slope of the failure envelope $d\sigma/d\sigma_n$ is steepest at low normal stress (σ_n). The slope is also referred to as the "pressure dependence" of failure strength. See Lockner and Beeler (2002, p. 508).

fallout The settling and deposition of *tephra* from the atmospheric plume of an explosive volcano *eruption*.

far field See *near field and far field*.

Fast Fourier transform (FFT) A computer algorithm that transforms a time domain sample sequence to a frequency-domain sequence which describes the spectral content of the *signal*. This efficient algorithm for computing the Fourier transform was first introduced by Cooley and Tukey (1965). See Brigham (1988), Hutt et al. (2002), and Scherbaum (2002).

fault A fracture or fracture zone in the Earth along which the two sides have been displaced relative to one another parallel to the fracture. The accumulated *displacement* across a fault may range from a fraction of a meter to many tens or hundreds of kilometers. The type of fault is specified according to the orientation and sense of *slip* and the inclination (*dip*) of the *fault plane* (Aki and Richards, 1980; Yeats et al., 1997). If the block opposite an observer looking across the fault moves to the right, the slip style is termed *right lateral* (*dextral*), if the block moves to the left, the motion is termed *left lateral* (*sinistral*). *Dip-slip* faults are inclined fractures along which rock masses have mostly shifted vertically. If the rock mass above an inclined fault moves down (due to lateral extension) the fault is termed *normal*, whereas if the rock above the fault moves up (due to lateral compression), the fault is termed *reverse* (or *thrust*). *Oblique-slip* faults have significant components of both slip styles (i.e., *strike slip* and *thrust* or dip slip). See Figs. 3.105 and

3.106 and EX 3.2 in this Manual, and for more specific explanations and definitions Aki and Richards (1980, 2002, 2009) and the entries *normal fault*, *reverse fault*, *thrust fault* and *strike-slip* fault.

fault, active: See *active fault*.

fault breccia A fault-rock made up of angular rock fragments derived from *brittle* fragmentation in a fine-grained or hydrothermal matrix. See Sibson (2002).

fault creep Quasi-static *slip* on a *fault*; slip that occurs so slowly that radiation of *seismic waves* is negligible. See *creep* and *creep events*.

fault dip The inclination of a *fault plane* relative to the horizontal in degrees. A dip of 0 degree is horizontal, 90 degrees is vertical. See Figs. 3.104 to 3.107 and 3.111 in Chapter 3 of this Manual.

fault-fracture mesh A mesh structure of interlinked minor *faults* (shear fractures) and extension fractures occupying a substantial volume of the rock-mass. See Sibson (2002).

fault gouge A clayey, soft material formed when the rocks in a *fault zone* are pulverized during slippage. Textures range from essentially random-fabric to foliated.

fault length See *rectangular fault*.

fault model (of an earthquake) A model of an earthquake source in which a slip across a *fault plane* causes the *ground motion*. See Aki (2002), Madariaga and Olsen (2002), Das and Kostrov (1988), and Scholz (2002). See also *Brune model*, *Burridge and Knopoff model*, *Haskell model*, *Knopoff model*, *Kostrov model*, *omega-squared model* and *specific barrier model*.

fault plane The surface along which there is *slip* during an earthquake. In simplified mathematical approximations and *fault-plane solutions* assumed to be planar (flat).

fault-plane solution A simplified geometric-mathematical way of presenting an earthquake *fault* and the direction of *slip* on it, using circles with two orthogonally intersecting curves for the two potential *fault planes* that look like “beach balls” (see Figs. 3.105 and 3.106 of Chapter 3 in this Manual). A fault-plane solution is found by an analysis using stereographic projection or its mathematical equivalent to determine the attitude of the causative fault and its direction of slip from the *radiation pattern* of *seismic waves* using earthquake records at many stations. The most common analysis uses the direction of *first motion* of *P-wave* onsets and yields two possible orientations for the fault rupture and the direction of seismic slip. Other techniques use in addition the *polarization* of teleseismic *S waves* and/or *amplitude* ratios between P and S waves. From these data, approximate inferences can be made concerning the principal axes of stress in the region of the earthquake. The *principal stress* axes determined by this method are the *compressional* axis (also called the P-axis, i.e., the axis of greatest compression, or s_1), the *tensional* axis (also known as the T-axis, i.e., the axis of least compression, or s_3), and the intermediate axis (s_2). See also *focal mechanism* and *earthquake focal mechanism*.

fault rake A parameter describing the *slip* direction on a *fault*, measured as an angle in the *fault plane* between the *fault strike* and the slip vector. Slip in the direction of the maximum slope (i.e., the *dip*) of the fault plane is a rake of 90º, positive for *reverse faults*, negative for *normal faults*. See Fig. 3.111 in Chapter 3 of this Manual; also Aki and Richards (2002, Fig. 4.13, p. 101), and Figure 13 in Ben-Zion (2003).

fault-rock A rock whose textural/micro-structural characteristics (usually involving grain-size reduction from the *protolith*) developed through deformation within a *fault zone* at depth. See Sibson (2002).

fault sag A narrow *tectonic* depression common in *strike-slip fault zones*. Fault sags are generally closed depressions in the order of a hundred meters wide and approximately parallel to the fault zone.

fault scarp Step-like linear landform coincident with a *fault trace* and caused by geologically recent *slip* on the fault.

fault slip The relative *displacement* of points on opposite sides of a *fault*, measured on the fault surface. See Figs. 3.100 to 3.102, 3.107, and 3.111 of Chapter 3 in this Manual; also Aki and Richards (2002, Fig. 4.13, p. 101), and Figure 13 in Ben-Zion (2003).

fault slip rate The rate of *displacement* on a *fault* averaged over a time period encompassing several earthquakes.

fault strike The azimuthal direction of the horizontal in the *fault plane*. See Figs. 3.30 and 3.31 in Chapter 3 of this Manual; also Aki and Richards (2002, Fig. 4.13, p. 101), and Figure 13 in Ben-Zion (2003).

fault trace The intersection of a *fault* with the Earth's surface or with a horizontal plane; indirectly also the line commonly plotted on geologic maps to represent the surface exposure of a fault.

fault, unlocked See *creep*.

fault width See *rectangular fault*.

fault zone The *fault plane* of the geometric-mathematical model of an earthquake is usually a planar surface in an elastic medium. The actual fault is a zone of finite width, comprising also secondary fault branches (see Fig. 3.8 in Chapter 3 of this Manual), in which non-elastic processes occur during the earthquake, sometimes also called a break-down zone or cohesive zone. The fault zone includes the *fault gouge*.

fault-zone head wave A seismic *P* or *S wave* propagating along a material interface in a *fault zone* structure with the *velocity* and motion polarity of the corresponding *body waves* on the faster side of the fault. See *head waves*.

fault-zone trapped mode Seismic *guided waves* trapped in the low-velocity *fault zone*. They are useful for studying the three-dimensional structure of the fault zone. They have been also used to find temporal changes in the physical characteristics of fault zones.

feedback The addition of part of the output signal of a linear system like an amplifier to the input signal in order to modify the response. Mostly used to stabilize the system (negative feedback). See Chapter 5 of this Manual.

felt area The area of the Earth's surface over which the effects of an earthquake were humanly perceptible. See Chapter 12 of this Manual.

filter Electronic device or numerical algorithm which acts on an input signal to produce an output signal with a desired modification in spectral characteristics. See *digital filter*; also Chapters 5 and 6 as well as IS 5.2 in this Manual, and Scherbaum (2002).

filtering *Attenuation* or downgrading of certain frequency components of a (*seismic*) *signal* as compared to others. For a recorded signal, the process can be accomplished mechanically, electronically or numerically in a computer. Filtering also occurs naturally as *seismic waves* are attenuated in a frequency-dependent way during their pasage through the Earth.

final prediction error Criterion proposed by Akaike (1970) for selection of the order of an *autoregressive process*. The final prediction error (FPE) is defined as:

$$FPE = \frac{n + p + 1}{n - p - 1} E_s^2$$

where n is the number of observations, p the corresponding chosen model order, and E_s^2 the sum of squares of prediction errors. FPE and the *Akaike Information Criterion* (AIC) are related, as, with regard to *autoregressive models*, a model is obtained that approximately minimizes the FPE by minimizing the AIC. Another method for selection of the order of an *autoregressive process* is the use of the *partial autocorrelation function* (PACF).

finite element

A geometrical subdivision, generally small, of a larger structure or medium. Finite elements are commonly used in numerical studies of the response of complex media or structures to earthquake excitation. Typical finite elements include triangles and rectangles for analysis of two-dimensional problems, and tetrahedrons for three-dimensional problems. In applications, a structure is divided into many finite elements and field quantities such as *density* and *displacement*, for example, are assumed to vary over each element in a prescribed manner (e.g., linearly varying displacement). Thus the displacements and associated *stresses* and *strains* within each element are determined by the displacements at its corners or nodes. The displacements of the nodes of the finite elements then become the unknown vector in a matrix equation that is solved numerically. See Hall (2003).

FIR filter

Finite Impulse Response filter, also named *acausal*- or, in their symmetrical realization, *zero-phase filter*.

first motion

The first half-cycle of a *body wave*, usually the *direct P wave*. On a *seismogram*, the first discernible displacement of the record trace caused by the *arrival* of a P wave at the *seismometer*. The direction (*polarity*) of first motion, which for the P wave is either away from source (called compression) or towards it (called dilatation), is assumed to be conserved along the ray path from the focus to a given station, given that corrections have been made for any polarity changes due to *reflection* of the wave at any boundary between source and receiver. First motions of P arrivals are often used for determining the *earthquake focal mechanism*. However, when the *seismic signal* arrives in the presence of *seismic noise* the proper polarity of the first motion may be distorted and difficult to recognize.

fissure eruption

A volcanic eruption fed by one or more fissure vents, rather than by a central (point-source) vent or a tight cluster of central vents. See *volcanic vent*.

f-k analysis

Frequency (f) versus *wavenumber* (k) analysis is a key *array processing* technique that maps the power of seismic waves observed at an *array* as a function of the wave propagation *azimuth* (or *backazimuth*) and the horizontal *slowness* component for a given frequency band. F-k analysis is also used to identify *seismic phases* on the basis of their distance-dependent *slowness* differences and to locate seismic events.

See *wavenumber filtering, wavenumber vector, slowness, array beam, and slowness vector* and Chapter 9 in this Manual.

flank eruption An eruption that takes place away from the summit area of a volcano (e.g., on rift zones or flanks of the volcano); synonymous with lateral eruption.

fling step The permanent *displacement* of the ground at or near a ruptured *fault*.

flow deformation Shear *deformations* in soil that occur with little resistance within a liquefied layer or element. Deformations may be of limited excursion, as occurs in *dilative* soils, or unlimited excursion, as occurs in *contractive* soils. See Youd (2003).

flow failure *Liquefaction*-induced failure of a slope or embankment underlain by contractive soils leading to large, rapid ground *displacements*. These failures are characterized by large loss of shear strength, large lateral displacements (several meters or more), and severe disturbance to the liquefied and overlying soil layers. See Youd (2003).

fluid overpressure Fluid-pressure exceeding the *hydrostatic pressure* value appropriate to the depth.

fmax Above a limiting *frequency*, fmax, the observed spectrum of a typical local earthquake decays more steeply with increasing frequency than is expected from the standard *omega-squared model*. This was first recognized by Hanks (1982) and has been attributed to the earthquake *source effect* (e.g., Kinoshita, 1992), as well as to attenuation of the shaking by unconsolidated sediments underlying the recording site (e.g., Anderson and Hough, 1984). See also *omega-squared model*.

focal depth The conceptual "depth" of an *earthquake focus*. If determined from the *first motion arrival-time* data, this represents the depth of rupture initiation (the *hypocenter depth*). If determined from waveforms that are long compared to the *fault* dimension, the depth represents some weighted average of the moment release in the earthquake (the "centroid" depth. See Romanowicz (2002, p. 153), and Lee and Stewart (1981, p. 130-139).

focal mechanism See *fault-plane solution* and *earthquake focal mechanism*.

focal sphere Hypothetical (conceptual) sphere around a seismic *point source* (i.e., a source with linear dimensions smaller than the diameter of the focal sphere). It is used for calculating the *take-off angles* under which the *seismic rays* leave the source through the surface of this sphere towards the seismic stations and to reconstruct the *fault-plane solution* (i.e., the type and spatial orientation of the earthquake rupture) from the stereographic projection of these ray “penetration points” through the focal sphere and their associated *first-motion polarities*, *polarisation* and *amplitude* ratios.

focal zone The rupture zone of an earthquake. In the case of a *great earthquake*, the focal zone may extend several hundreds of kilometers in length and several tens of kilometers in width.

focus That point within the Earth from which the first *displacement* of an earthquake and radiation of its *elastic waves* originates. See *hypocenter*.

focusing effect (in local site amplification) Special amplification of *ground motion* found just above the corner of the basin bottom or layer interfaces. In a two- or three-dimensional basin with strong lateral variation, rays of an incident *body wave* are warped at these interfaces and constructive (or destructive) interference takes place at some point on the surface. See Chapter 14 of this Manual and and Kawase (2003).

footwall The underlying side of a non-vertical *fault* surface. See *hanging wall*, Figure 3.107 in Chapter 3 of this Manual, Grant (2002), and Figure 13 in Ben-Zion (2003).

force-balance accelerometer A *seismometer* that compensates the inertial force acting on its suspended mass with a negative *feedback* force, and thereby keeps the mass at rest relative to the ground. Modern broadband seismometers make use of this feedback system. See Chapter 5 in this Manual.

fore arc The region between the *subduction thrust fault* and the *volcanic arc*.

forensic seismology Seismology applied to problems involving legal issues, such as, e.g., the verification of compliance with any treaty limiting the testing of nuclear explosions. See Chapter 17 in this Manual and Richards (2002).

foreshock Relatively smaller earthquake that precedes the largest earthquake (which is termed the *mainshock*) in an *earthquake sequence*. Foreshocks usually originate at or near the *focus* of the mainshock and may precede the latter by seconds to weeks. Not all mainshocks have foreshocks. See also *aftershock* and Utsu (2002b).

forward problem A typical problem in physical science is that of the modeling of natural phenomena. Through such a modeling, and given some parameters describing the system under study, one may predict the outcome of some possible observables. Solving a forward (also called “direct”) problem requires model parameters → model → prediction of observed data. See *inverse problem* and

Fig. 1.1 of Chapter 1 in this Manual; also Mosegaard and Tarantola (2002), and Menke (1984).

forward scattering See *scattering* and *scattering theory*.

Fourier amplitude spectrum See *Fourier transform (spectrum).*

Fourier phase spectrum See *Fourier transform (spectrum).*

Fourier transform (spectrum) An integral transform mapping *signals* defined in the time domain *f(t)* into the complex frequency domain *F(ω)* by multiplying exp*(iωt)* and integrating over t from minus infinity to plus infinity. The Fourier spectrum consists of two complementary parts, the *amplitude-frequency* and the *phase-frequency spectrum*. See equation (4.2) in Chapter 4 of this Manual as well as Scherbaum (2002), and the biography of Jean Baptiste Joseph Fourier in Howell (2003).

Fourier analysis The mathematical operation that resolves a time series (for example, a recording of *ground motion*) into a series of numbers that characterize the relative *amplitude* and *phase* components of the *signal* as a function of *frequency*.

fractal A geometrical structure or object which is self-similar on all scales (i.e., *scale invariance*), and is quantified by a fractional (instead of an integer) dimension. See Mandelbrot and Frame (2002) for a general review of fractals.

fractal dimension A statistical quantity in *fractal* geometry that indicates how completely a fractal appears to fill space, as one zoomes down to smaller and smaller scales. Although there exist many specific definitions, the fractal dimension may be estimated from the exponent of a power law distribution such as the *Gutenberg-Richter relation*. Its *b-value* is about half of the fractal dimension of the considered complete random ensemble of earthquakes of different *magnitude*. Values of b = 1.5, 1 or 0.5, respectively, would indicate that the governing earthquake rupture process would be 3D, 2D or 1D (linear). b-values may vary with time and tend to be larger for *aftershocks* and *swarm* earthquakes than for *mainshocks* of larger magnitudes. Values $0.7 < b < 1.4$ have been reported by Neunhöfer and Güth (1989) within a major earthquake swarm.

fractal statistics A statistical distribution in which the number of objects has a power-law dependence on their size. See Turcotte and Malamud (2002), and Vere-Jones and Ogata (2003). See also *fractal* and *fractal dimension*.

fracture A general term for *discontinuities* in rock; includes *faults*, joints, and other breaks. See Section 4 in Ben-Zion (2003).

fracture toughness A measure of the energy expended in an increment of *fracture*. It is more difficult to propagate a fracture in a material with high fracture toughness than with low fracture toughness. See Teisseyre and Majewski (2002), and Lockner and Beeler (2002).

fracture zone An elongated zone of unusually irregular topography that separates regions of different water depths in the ocean floor. It is commonly found to displace the magnetic lineations and the axes of mid-ocean ridges, and it is interpreted as a *transform fault*. See Wilson (1965), and Uyeda (1978).

fragmentation *Deformations* and failures in which the structures in the material undergo micro-crushing or crushing under high compressive load.

free-field motion Strong *ground motion* that is not modified by the earthquake caused motions of nearby buildings or other structures or geologic features. In analyses, often defined as the motion that would occur at the interface of the structure and the foundation if the structure were not present. A fully instrumented building site typically includes one or more *accelerographs* located some distance from the structure to obtain a better approximation of the free-field motion. See Jennings (2003).

free oscillations See *normal modes*.

frequency The frequency is the number of cycles of a periodic motion per unit time, or per unit *period* (as the reciprocal time). In the context of the *Fourier transform*, “frequency” is also used for the angular frequency, which is 2π times the frequency defined above. The frequency unit is Hertz (Hz).

frequency domain A *seismic signal* that has been recorded in the *time domain* (as a *seismogram*) can be decomposed by means of *Fourier analysis* into its *amplitude* and *phase* components as a function of frequency (see *spectrum*). The representations of a seismic signal in the *time domain* and in the frequency domain are mathematically equivalent. For some procedures of data analysis the time-domain representation of seismic records is more suitable, while for others the frequency-domain approach is more appropiate and efficient.

frequency of occurence The number of times something happens in a certain *period* of time, e.g., the (average) number of *earthquakes* in a given *magnitude* range per year or per century, also termed *occurrence rate*.

frequency response *Fourier transform* of the output signal of a linear system divided by the Fourier transform of the input signal. The frequency response of a linear system equals the Fourier transform of its *impulse response*. For a typical inertial *seismometer* (e.g., an *accelerometer* or *rotational-motion sensor*), the *frequency response* is the complex *transfer function* relating the input ground motion (translational acceleration or *rotational velocity*) to the output signal (usually voltage). This transfer function is typically measured in terms of *amplitude* and *phase spectra*. For analog-output sensors, the measured frequency response is generally modeled in the Laplace domain with a best-fit pole-zero model (Nigbor et al., 2009).

frequency-wavenumber analysis See *f-k analysis*.

friction The ratio of shear *stress* to *normal stress* on a planar *discontinuity* such as *fault* or joint surface. See Douglas (2002, p. 506), and section 5 in Ben-Zion (2003).

frictional instability A condition that arises during quasi-static *fault slip* when the reduction of fault strength with *displacement* exceeds the elastic stiffness of the region surrounding the fault; under these conditions the *slip rate* accelerates rapidly. See Lockner and Beeler (2002, p. 517), and material below Eq. (5.4f) in Ben-Zion (2003).

frictional (FR) regime That portion of the *crust* or *lithosphere* where *fault* motion is dominated by unstable (velocity weakening) pressure-sensitive frictional sliding. See Sibson (2002).

friction-melting Melting as a consequence of high temperature generated by *friction* during rapid localized *fault slip*. See Sibson (2002).

frozen waves In the *epicentral area* of a *great earthquake*, walls, embankments, and the like are sometimes left in the form of a wave. These “frozen waves” are attributed to the ground cracking open at the crests of the waves, sometimes with the emission of sand and water. Frozen waves are also seen on the surface of the Moon, concentric with very large impact craters.

fully-decoupled explosion An underground explosion, carried out within a cavity large enough that the walls of the cavity are not stressed beyond their elastic limit. See Richards (2002).

fundamental period The longest *period* for which an object, e.g., a *seismometer*, a structure, the sub-surface underground or the whole planet Earth shows a maximum response. Also termed *eigenperiod* or *natural period*. The reciprocal is the *natural frequency* or *eigenfrequency*.

G

g A commonly used unit for the *acceleration* of a free falling mass due to the *gravity* of the Earth (9.81… m/s²). When there is an *earthquake*, the accelerations caused by the shaking can be measured as a fraction or percentage of gravity (%g).

Ga An abbreviation for billion (10^9) years ago.

gain Commonly used to describe an amplifier or *filter* gain, not the sensitivity of a sensor.

gal A unit of *acceleration* (1 gal = 1 cm/s², or approximately one thousandth of 1 g).

Gaussian distribution (of measurement values) According to Carl Friedrich Gauss (1777-1855), a symmetric, bell-haped distribution of randomly sampled measurement values about their mean value due to random measurement errors/fluctuations with a specified *standard deviation* SD. About 67% of the values deviate less than ±1×SD from the mean value, and about 95% less than 2×SD.

Gaussian noise spectrum The spectrum of a time history whose sample values are generated by random selection from a statistical population that has a specified mean and a standard deviation. Accordingly, the ordinate values follow a *Gaussian distribution* about their mean. In earthquake studies, this type of spectrum is commonly multiplied by a theoretical *earthquake* source *spectrum* to obtain predicted *ground-motion* spectra for hypothetical earthquakes.

Geiger's method A commonly used method to determine the *hypocenter* and the *origin time* of an earthquake or any other *seismic source* by using *arrival times* of *seismic waves*, assuming the knowledge of their *travel-times* within the Earth. Geiger (1910) applied the Gauss-Newton method (a linearized *least-squares fit* algorithm) to solve the earthquake location problem, but his method was not practical until the advance of computers in the late 1950s. See *linearize*, IS 11.1 in this Manual, Lahr (2003), Klein (2003), Lee et al. (2003b), Lee and Stewart (1981, p. 132-139), and the biographies of Ludwig Geiger, Karl Friedrich Gauss, and Isaac Newton in Howell (2003).

genetic algorithm (GA) A learning algorithm used to maximize the adaptability of a system to its environment. It is often used as a computer algorithm in function optimization or object selection problems. See McClean (2002) and Sambridge (2003).

geochronology Science of dating earth materials, geologic surfaces and processes. See Grant (2002).

geodesy The science of determining the size and shape of the Earth and the precise location of points on its surface as well as of the dynamical processes and forces leading to the observed shape.

geodetic Referring to the determination of the size and shape of the Earth and the precise location of points on its surface.

geodetic moment Geodetic estimate of the *seismic moment*. See Feigl (2002, p. 616-617).

geodynamics Study of the dynamics of the Earth's interior including heat transfer and convection currents.

geodynamo Magneto-hydrodynamic convection in the Earth's *core* that is responsible for the generation of the Earth's main magnetic field. See Song (2002).

geoid Surface of constant potential energy, representing the balance between gravitational and rotational forces; corresponds to an idealization of the Earth's actual surface. In practice, deviations of the geoid from a reference ellipsoid are presented as the geoid.

geology The study of the planet Earth - the materials it is made of, the processes that act on those materials, the products formed, and the history of the planet and its life forms since its origin.

geologic time The time since the Earth was formed 4.6 billion years ago (Ga), and encompasses the entire geologic history of the Earth. It is usually divided chronologically into the following hierarchies of time units: eon, era, period and epoch. The eons are: (1) *Hadean* (4.6 – 4 Ga), (2) *Archaean* (4-2.5 Ga), (3) *Proterozoic* (2.5- 0.545 Ga), and (4) *Phanerozoic* (545 million years ago to the present). The Phanerozoic eon is divided into the following eras: (1) *Paleozoic* (545-245 Ma), (2) *Mesozoic* (2.45-66.4 Ma), and (3) *Cenozoic* (66.4-0 Ma). The Cenozoic era is divided into following periods: (1) *Tertiary* (66.4-1.6 Ma), and (2) *Quaternary* (1.6 Ma-present). The Quaternary period is divided into the following epochs: (1) *Pleistocene* (1.6 Ma – 10,000 years ago), and (2) *Holocene* (10,000 years ago to the present). For a detailed discussion of geologic time, see Eicher (2002), and Hancock and Skinner (2000).

geomagnetic polarity epoch A period of *geologic time* during which the Earth's magnetic field was essentially or entirely of one polarity. Short period of opposite polarity within a polarity epoch is called "event".

geomagnetic pole The point where the axis of the calculated best-fit dipole cuts the Earth's surface in the northern or southern hemisphere.

These poles lie opposite to each other and wander with time. See *magnetic poles (of the Earth)*.

geomagnetic reversal A change of the Earth's magnetic field between normal polarity and reversed polarity. These reversals occur at different time intervals.

geomagnetism The study of the properties, history, and origin of the Earth's magnetic field. See Merrill and McFadden (2002).

geometrical spreading Decrease of wave energy per unit area of *wavefront*, and thus of the *amplitudes* of waves, due to the expansion of the wavefront with increasing distance.

geomorphology The study of the character and origin of landforms, such as mountains, valleys, etc.

geophone A term commonly used for a relatively inexpensive, robust, light weight and small size *seismometer*, usually a mass-spring system with electrodynamic *transducer*, that responds to high-frequency (usually > 1 Hz) ground motions (see Fig. 5.3 and section 5.3.8 in Chapter 5 of this Manual). Even smaller and cheaper versions with *natural frequencies* typically between about 5 and 25 Hz are commonly used in exploration *geophysics*.

geophysics The study of the Earth and its sub-systems by physical methods (seismic, gravimetric, magnetic, electric, thermic, radioactive and others).

geosyncline A crustal down-warp that is several hundreds or thousands of kilometers long and contains an exceptional thickness of accumulated sediments, on the order of 10 to 15 km.

geotechnical Referring to the use of scientific methods and engineering principles to acquire, interpret, and apply knowledge of Earth materials for solving engineering problems.

geotechnical engineering The branch of engineering that deals with the analyses, design and construction of foundations and retaining structures on, within, and with soil and rock. Common examples include structural foundations and earth or rockfill dams.

geotechnical zonation A mapping that portrays specified ground characteristics or mechanical properties in an area, typically showing zones that correspond to pre-defined geotechnical units. For example, a map of *shear wave velocities* derived from soil profile classifications. See Faccioli and Pessina (2003).

geotherm A profile of temperature as a function of depth inside the Earth. See *geothermal gradient*.

geothermal gradient The rate of increase in temperature with depth in the Earth. By convention, this quantity is positive when increasing downward.

geyser A fountain of hot water and steam ejected intermittently from a source heated by *magma* or hot rocks. See King and Igarashi (2002).

global plate motion model A set of *Euler vectors* specifying relative *plate* motions. Such models can be derived for time spans of millions of years using rates estimated from sea-floor *magnetic anomalies*, directions of motion from the orientations of *transform faults*, and the *slip* vectors of earthquakes on transforms and at *subduction zones*. They can also be derived for time spans of a few years using space-based geodesy. See Stein and Klosko (2002).

global tectonics See *tectonics*.

glowing avalanche Incandescent and turbulent mixture of *pyroclasts*, *volcanic gases*, and air that flows under *gravity* down the flanks of a *volcano*; essentially synonymous with *nuée ardente*, *pyroclastic flow*, and *pyroclastic surge*.

Gondwana The proto-continent of the southern hemisphere in the late *Paleozoic* (see *geologic time*). It included Australia, South America and Antarctica, as well as India, before they were drifting away from one another. It was named by the Austrian geologist Eduard Suess after Gondwana, a historic region in Central India. See Uyeda (2002), Duff (1993), and Hancock and Skinner (2000).

graben A down-dropped block in the Earth's *crust* resulting from extension, or pulling, of the *crust*. See also *horst*.

gradient The rate of change, e.g., of the *seismic velocity* with depth in the Earth.

gradiometry (seismic wave) The study of the compatibility relationship between a *wave field* and its spatial and temporal *gradients*. Spatial gradients of the wavefield may be constructed using a dense *seismic array* of instruments or obtained from *strain* or *rotation* measurements. The compatibility relationship requires a model for a propagating seismic wave in 1, 2, or 3 dimensions that can be used to determine wave propagation *azimuth*, *wave slowness*, change in *geometrical spreading*, and change in azimuthal *radiation pattern*. See Langston (2007).

gravity The attraction between two masses, such as the Earth and an object on its surface. Commonly referred to as the *acceleration* of *gravity g*. Changes in the gravity field can be used to infer information about the structure of the Earth's *lithosphere* and *upper mantle*. Interpretations of changes in the gravity field are generally applied to gravity values corrected for extraneous effects. The corrected values are referred to by various terms, such as free-air gravity, Bouguer gravity, and isostatic gravity, depending on the number and kind of corrections made.

gravity anomaly The difference between the observed *gravity* and the theoretically calculated value based on a model.

gravity loads In *earthquake engineering*, the vertical loads created in the elements of a structure by the force of *gravity*. Gravity loads are sometimes separated into dead load (the weight of the structure) and live load (the weight of furnishings and other contents). See Hall (2003).

gravity waves *Normal modes* in a surface layer with very low *shear-wave velocity*, such as unconsolidated sediments, may be affected significantly by *gravity* at long periods like by a *tsunami* in the ocean. Waves similar to the gravity waves in a fluid layer are possible in addition to the shortening of *wavelength* of normal modes by gravity. So-called "visible waves" with large *amplitude* and relatively long *periods* observed in the *epicentral area* of a *great earthquake* have been suggested to be gravity waves. See Satake (2002, p. 442-443) and Ben-Menahem and Singh (1981, p. 776-796).

great earthquake An earthquake with *magnitude* greater than about 7 ¾ (or 8) is often called "great".

Green's function In seismology, the vector displacement field generated by an impulsive force applied at a point in the Earth. When combined with the source function describing the discontinuities in *displacement* and traction across an internal surface, a Green's function can represent the seismic displacements caused by earthquake *faults* and explosions. Green's function was first introduced by George Green (1793–1841) as a solution to an inhomogeneous hyperbolic equation for a point source in space and time. See Aki and Richards (2002, p. 27–28).

ground failure A general reference to *landslides*, *liquefaction*, *fault displacement*, lateral spreads, and any other lasting consequence (permanent deformation) of shaking that affects the stability of the ground. See Youd (2003).

ground motion Vibration of the ground, primarily due to *earthquakes* or other *seismic sources*. Ground motion is produced by *seismic waves* that are generated, e.g., by sudden *slip* on a *fault*, the collapse of sub-surface cavities or sudden pressure released by *explosions*, and - after traveling through the Earth - arrive at its surface. It is measured by a *seismograph* that records *acceleration*, *velocity* or *displacement*. In *engineering seismology*, it is usually given in terms of a *time series* (an *accelerogram*), a *response spectrum* or *Fourier spectrum*. See Chapters 2, 4 and 15 of this Manual and Anderson (2003).

ground motion relation See *attenuation relation*.

ground-motion (strong-motion) parameter In *engineering seismology*, a parameter characterizing ground motion, such as *peak acceleration*, peak velocity, and peak displacement (peak parameters) or ordinates of *response spectra* and *Fourier spectra* (spectral parameters). See Chapter 15 of this Manual and and Campbell (2003).

ground oscillation A geotechnical term specifying a ground condition in which *liquefaction* of subsurface layers decouples overlying non-liquefied layers from the underlying firm ground, allowing large transient *ground motions* or ground waves to develop within the liquefied and overlying layers. See Youd (2003).

ground roll A term used in exploration seismology to refer to *surface waves* generated from explosions. They are characterized by low *velocity*, relatively low *frequency*, and high *amplitude*, and are observed in regions where the near-surface-layering consists of poorly consolidated, low-velocity sediments overlying more competent beds with higher velocity.

ground settlement Permanent vertical *displacement* of the ground surface due to compaction or consolidation of underlying soil layers. See Youd (2003).

ground shaking scenario A representation for a site or region depicting the possible ground shaking level or levels due to earthquake, in terms of useful descriptive parameters. See Chapter 15 of this Manual, and Faccioli and Pessina (2003).

ground truth A jargon coming from the nuclear-test detection seismology, referring to information about the location of a *seismic event* that is derived from information not usually available to an analyst studying the event with a typical monitoring network. The ground truth can come from satellite observations, or from *fault traces* that break out at the Earth's surface, or from operation of a local network, drilling site or similar. Ground truth (GT) locations are sometimes associated with a number, e.g., “GT5”, meaning a location believed to be accurate to within 5 km, obtained from ground truth. Today, ground truth events are essential for testing *seismic source* location algorithms and to validate seismic velocity models. See IS 8.5, 8.6 and 11.1 in this Manual and Richards (2002).

group velocity For dispersive waves with frequency-dependent *phase velocity*, $c(\omega)$, the wave packet or energy propagates with the group velocity given by $d\omega/dk$, where k is the *wave number* given by *ω/c(ω)*. See Aki and Richards (2002, p. 253-254) and Fig. 2.10 in Chapter 2 of this Manual.

guided waves Guided waves are trapped in a waveguide by total *reflections* or bending of rays at the top and bottom boundaries. An outstanding example is the acoustic waves in the *SOFAR channel*, a low-velocity channel in the ocean. Since the absorption coefficient for sound in seawater is quite small for frequencies in the order of a few 100 Hz, transoceanic transmission is easily achieved. If the Earth's surface is considered as the top of a waveguide, *surface waves*, such as *Rayleigh*, *Love*, and their higher modes, are guided waves. The fault-zone trapped mode is a guided wave in the *low velocity fault zone*. Where they can exist, guided waves may propagate to considerable distances, because they are effectively spreading in only two spatial dimensions.

Gutenberg discontinuity The seismic velocity discontinuity marking the *core-mantle boundary* (CMB) at which the velocity of *P waves* drops from about 13.7 to about 8.0 km/s and that of *S waves* from about 7.3 to 0 km/s. The CMB reflects the change from the solid *mantle* material to the fluid outer *core*. See Fig. 2.79 in Chapter 2 of this Manual and Lay (2002).

Gutenberg-Richter relation An empirical relation expressing the *frequency (of occurrence)* distribution of *magnitudes* of *earthquakes* occurring in a given area and time interval. It is given by $\log N(M) = a - bM$, where M is the earthquake magnitude, $N(M)$ is the number of earthquakes with magnitude greater than or equal to M, and a and b are constants (See *b-value*). It was obtained by Gutenberg and Richter (1941; 1949), and is equivalent to the *power-law* distribution of earthquake energies or moments. See Utsu (2002b, p. 723), and Eqs. (7.1) - (7.2) in Ben-Zion (2003).

G-waves (Gn) Another name for very long-period *Love waves*. Because the group velocity of Love waves in the Earth is nearly constant (4.4 km/sec) over the period range from about 40 to 300 seconds (see Fig. 2.10 in Chapter 2 of this Manual), their *waveform* is rather impulsive, and they have received this additional name. They are called G-waves after Gutenberg. It takes about 2.5 hours for G-waves to make a round trip of the Earth. After a large earthquake, a sequence of G-waves may be observed. They are named G1, G2, …, Gn, according to their arrival times. The odd numbers refer to G-waves traveling in the direction from epicenter to station, and the even numbers to those leaving the *epicenter* in the opposite direction and approaching the station from the antipode of the epicenter. See section 2.3.4, Fig. 2.19 in Chapter 2 of this Manual and Kulhanek (2002, p. 346).

gyroscope (Gyro) — A device, which contains a fast rotating axial-symmetric body, measuring or compensating for *rotational motions*; commonly used for navigation. The principle of its action is based on the law of balance of *kinetic moment*. Because this term can mean both a stable platform and a *rotational sensor*, it should be avoided or defined by the authors.

H

Hadean — An eon in *geologic time*, from 4.6 to 4 billion years ago. It is named after Hades, the underworld of Greek mythology.

Hales discontinuity — See *N discontinuity*.

half-life — The time required for a mass of a radioactive isotope to decay to one half of its initial amount. See King and Igarashi (2002).

halfspace — A mathematical model bounded by a planar surface but otherwise infinite. Properties within the model are commonly assumed to be *homogeneous* and *isotropic*, unlike the Earth itself, which is heterogeneous and anisotropic. Nevertheless, the half space model is frequently used to perform theoretical calculations (forward modeling) in seismology.

hanging wall — The overlying side of a non-vertical *fault* surface. See *footwall* and Figure 3.107 in Chapter 3 of this Manual.

harmonic tremor — Oscillatory *ground motion* sustained for minutes to days or longer, commonly associated with volcanic *eruptions* and often observed during the precursory phase of eruptive activity. The spectral content of harmonic tremor is commonly dominated by one or two spectral peaks in the frequency range 1 to 5 Hz. See *volcanic tremor*; also Chapter 13 of this Manual and McNutt (2002).

Haskell model — A representation of the earthquake source by a ramp-function *slip* propagating unilaterally at a uniform velocity along the long dimension of a narrow *rectangular fault* surface (Haskell, 1964). It is specified by 5 parameters, i.e., *fault length*, *fault width*, final slip, *rupture velocity* and *rise time*. See Aki and Richards (2002, p. 498-503), and Purcaru and Berckhemer (1982) for a compilation of earthquakes with these parameters determined by various authors. See IS 3.1 in this Manual, Udias (2002, p. 99-100), and Eq. (3.8) in Ben-Zion (2003).

Hawaiian eruption — Eruption of highly fluid (low-viscosity) *magma* that commonly produces *lava fountains* and forms thin and widespread *lava flows*, and generally very minor *pyroclastic deposits* around the *vent*.

hazard See *earthquake hazard* and *volcano hazard*.

hazard master model A type of master model of earthquakes in which the *Probabilistic Seismic Hazard Analysis* (PSHA) is used for unifying multi-disciplinary data regarding earthquakes in a given region. The integration of the multi-disciplinary data is done in the end product, in contrast to a physical master model. See Aki (2002).

head waves Head waves are interface waves observed in a *halfspace* that is in welded contact with another halfspace with higher velocity when the *seismic source* is located in the lower-velocity medium. The wave enters the higher velocity medium at the critical *incidence angle* and, after traveling along the interface at the higher velocity, re-enters the lower velocity medium at the critical angle. The *wavefront* in the lower-velocity halfspace is a part of the surface of an expanding cone. For this reason, head waves are sometimes called “conical waves.” See section 2.5.3.5 and Figs. 2.36 and 2.37 in Chapter 2 of this Manual and Aki and Richards (2002, p. 203-209).

heat flow In geophysics, heat flow usually means the rate of heat flowing from the Earth’s interior per unit area of the surface. It is measured near the Earth’s surface as the product of thermal conductivity and vertical temperature gradient. The average heat flow of the Earth is estimated to be about 2 µcal cm^{-2} sec^{-1}, corresponding to about 84 mW m^{-2} (milli-Watt per square meter) in SI units. Heat flow conditions have a great influence on the *rheological properties* and thus on the depth of the *brittle-ductile transition* and the occurrence of earthquakes in the *Earth’s crust*. See also *heat flow unit* and *thermal conductivity*, Chapter 81.4 in Lee et al. (2002), and Morgan (2002).

heat flow unit (HFU) Terrestrial *heat flow* values are commonly given in the SI units mW m^{-2} (milli-Watt per square meter). However, in older publications and maps the heat flow is usually given in cgs units of µcal/cm^2 sec, or 10^{-6} cal cm^{-2} sec^{-1}. The conversion relationship is 1 µcal cm^{-2} sec^{-1} = 41.84 mW m^{-2}. Occasionally some authors used the term “heat flow unit” or “HFU” for “µcal cm^{-2} sec^{-1}”.

helioseismology Study of the Sun's *free oscillations* (both acoustic and gravity modes), typically through spatially resolved Doppler spectroscopy (see *Doppler effect*).

hertz (Hz) The *SI* derived unit for frequency; expressed in cycles per second (s^{-1}). It is named after Heinrich Rudolph Hertz (1857-94) who discovered electromagnetic waves.

heterogeneity A medium is heterogeneous when its physical properties change along the space coordinates. A critical parameter affecting seismic phenomena is the scale of heterogeneities as compared with the seismic *wavelengths*. For a relatively large wavelength, for example, an intrinsically *isotropic* medium with oriented heterogeneities may behave as a *homogeneous* anisotropic medium. See Cara (2002).

hexagonal symmetry Symmetry by rotation of 60° around one axis, the 6-fold symmetry axis. Hexagonal symmetry and cylindrical symmetry are equivalent for the elastic properties. There are 5 independent elastic parameters in hexagonal symmetry systems. See Cara (2002).

higher order statistics Assuming the expectation of a continuous distribution as

$$E[X] = \int_{-\infty}^{\infty} xp(x)dx$$

with the distribution function $p(x)$ of the random variable x, the central statistic moment m of order k is given by $m_k = E\left[(X - E[X])^k\right], k > 1$. The second central moment is the variance, the third central moment normalized by the variance is the *skewness* S, and the fourth central moment normalized by the variance is the *kurtosis* K:

$$S = \frac{m_3}{m_2^{3/2}}$$

$$K = \frac{m_4}{m_2^2}$$

Skewness and kurtosis are parameters that describe deviations of a time series or a random value distribution from a *Gaussian distribution*.

high-frequency (HF) earthquake In volcano seismology, generally synonymous with "volcano-tectonic", "brittle-failure", or "*A-type*" *earthquake*. See Chapter 13 in this Manual and McNutt (2002). In general, earthquakes that radiate more than (magnitude-dependent) average of high-frequencies are characterized by higher than average *stress drop* and/or *rupture velocity*.

high-pass filter *Filter* which removes the low frequency portion of the input signal. See IS 5.2 of this Manual and Scherbaum (2002).

hodograph In the early era of seismology, the term sometimes used for the time of *arrival* of various *seismic phases* as a function of *epicentral distance*.

Holocene The most recent epoch in the *geologic time*, from 10,000 years ago to the present.

Holocene fault Applied to *faults*, this term indicates the time of most recent fault *slip* within the *Holocene*. Faults of this age are commonly considered *active*, based on the observation of historical or *palaeoseismic* activity on faults of this age in other locales.

homogeneous Being uniform, of the same nature; the opposite of *inhomogeneous*. Although the real Earth as a whole is largely inhomogeneous and weakly *anisotropic*, it can be considered for *seismic modeling* in a first approximation, at least in parts, as being homogeneous and isotropic.

horizontal-to-horizontal spectral ratio *Spectral ratio* of horizontal components at a target site to those at a reference site. If a reference site is virtually *site-effect* free, this corresponds to the true *site amplification* of the target site. Care must be taken to use a deep borehole station as a reference site, because seismic motions at depth are modified by the presence of the free surface differently from those at the surface. See Chapter 14 of this Manual and Kawase (2003).

horst An upthrown block lying between two steep-angled *fault* blocks.

hot spot A long-lived volcanic center that is thought to be the surface expression of a persistent rising *plume* of hot *mantle* material. The position of hot spots is used in many *plate* movement studies as reference coordinate system. See Uyeda (2002, p. 59-61) and Olson (2002). See also *melting anomaly*.

hummocks A term in volcanology, referring to characteristic topographic features for *debris-avalanche* deposits (e.g., hummocky topography), as demonstrated during the 18 May 1980 eruption of Mount St. Helens, Washington State; their occurrence provides tell-tale evidence for one or more sector collapses of a volcanic edifice in its eruptive history.

H/V spectral ratio Ratio of the *Fourier amplitude spectra* of horizontal and vertical components of *ambient noise*, or of earthquake *ground motions*, recorded at a site. Typically used to identify the presence of site-specific dominant frequencies in such motions. If this technique is applied to *microtremor* data, it is sometimes called "*Nakamura method*". If applied to the P and S portion of seismic data from distant sources to invert for a one-dimensional structure, it is called the "*receiver function method*". See Chapter 14 of this Manual and Faccioli and Pessina (2003).

hyaloclastic rocks A general term for a wide variety of glassy volcanic rocks formed by the fragmentation of *magma* or *lava* in the presence of water. The adjective hyaloclastic has Greek roots (hyalos, "glass"; klastos, "broken").

hybrid earthquake — In volcano seismology, an earthquake with characteristics of both "*high-frequency*" and "*long-period" earthquakes*. Often applied to earthquakes that have an impulsive, high-frequency onset with distinct *P* and *S waves* followed by an extended, low-frequency coda. Usage is variable.

hydroacoustic — Pertaining to compressional (sound) waves in water, in particular in the ocean. Hydroacoustic waves may be generated by explosions, volcanic eruptions, *airgun* shots or earthquakes. See *T-phase* and *SOFAR channel*.

hydrology — The science that deals with water on and under the ground surface, including its properties, circulation, and distribution.

hydrophone — A device for measuring *pressure* fluctuations in water using a piezoelectric sensor.

hydrostatic pressure — There are two variations on the usage of this term. In one usage, it simply refers to a *stress* state that is *isotropic*, i.e., shear stresses are zero. Another common usage is that "hydrostatic pressure" is a special case of "*lithostatic pressure*" where the density of the overlying column is chosen to be water density. See Ruff (2002).

hypocenter — A point in the Earth (also called *earthquake focus*) where the rupture of the rocks initiates during an earthquake. Its position, in practice, is determined from *arrival times* of the *seismic phase onsets* recorded by *seismographs*. The point on the Earth's surface vertically above the hypocenter is called the *epicenter*. See Lee and Stewart (1981, p. 130-139).

hypocentral distance — Distance from an observation point to the *hypocenter* of an earthquake.

I

I, i — The symbol I is used to indicate that part of a *ray* path that has traversed the Earth's *inner core* as a *P*-wave. On the other hand, i is used to indicate *reflection* at the boundary between outer and inner core in the same manner that c is used for reflections at the *core-mantle boundary*. For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

IASPEI — An acronym for the International Association of Seismology and Physics of the Earth's Interior (http://www.iaspei.org/). See Adams (2002) and Engdahl (2003).

IASPEI magnitude standards Standards for *magnitude* measurements elaborated by an international working group of the Commission on Seismic Observation and Interpretation (IASPEI, 2005 and 2013). These standards aim at a) the reduction of measurement errors due to the application of different procedures for calculating magnitudes of the same type, b) the wider use of *broadband magnitudes* from *body* and *surface waves* that are in better agreement with original definitions and c) maximizing the benefits of modern digital broadband records, simulation *filters* and signal processing tools for collecting many more globally compatible *amplitude*, *period* and magnitude data for research and other applications.

identity tensor A tensor of second rank, possessing the following property: the scalar product (from right or left side) of this tensor and of any vector (tensor) gives the same vector (tensor). The identity tensor is equal to **ii** + **jj** + **kk**, where **i**, **j**, **k** are orthogonal unit vectors, and the sign of the tensor product is omitted.

igneous rock A rock that has formed from molten or partly molten material. See Christensen and Stanley (2003), and Press and Siever (1994).

impedance In seismology, the product of *seismic wave velocity* and *density* ($v\rho$).

impedance contrast The ratio of the *impedances* $v\rho$ at the *disontinuity* (or *interface*) between two adjacent media: $v_1\rho_1/v_2\rho_2$. It largely controls, besides the *incidence angle*, the *refraction angle*, the *reflection* and transmission coefficients at the discontinuity. For the ratio of the *amplitudes* A_1 and A_2 of an acoustic wave group travelling through two adjacent media (neglecting *geometrical spreading* and *attenuation*) holds $A_1/A_2 = [(v_2\rho_2)/(v_1\rho_1)]^{1/2}$.

impulse response Output *signal* of a stationary linear system to an impulsive (delta function) input.

incidence angle i The angle between a seismic *ray*, incident on an *interface*, and the vertical (normal) to this *discontinuity*. See also *reflection angle* and *refraction angle*.

incident wave The wave that propagates toward an *interface*.

induced earthquake An earthquake that results from changes in crustal *stress* and/or strength due to man-made sources (e.g., underground mining and filling of a high dam), or natural sources (e.g., the *fault slip* of a major earthquake). As defined less rigorously, “induced” is used interchangeably with “*triggered*” and applies to any earthquake associated with a stress change, large or small. See *triggered earthquake*; also McGarr et al. (2002).

inertial sensor A *translational* or *rotational ground motion sensor* sensitive to *accelerations*, *velocities* or *displacements* affixed and referenced to some stated frame (generally to the non-inertial frame of the rotating, gravitating Earth or a built structure), and generally measuring one of the six degrees of freedom of whole-body motion. Inertial sensors respond to accelerations but, because of the inductive readout method, often output a signal proportional to ground-motion velocity or ground motion. A well built inertial sensor has a bob moving "freely" in only one degree of freedom and is sensitive to accelerations for signal frequencies (much) smaller than the *eigenfrequency* of the sensor or displacements for frequencies (much) larger than the sensor´s eigenfrequeny in that degree of freedom (see Fig. 5.3 upper left and lower left in Chapter 5 of this Manual). Because of hinging effects, very often inertial sensors intrinsically mix the linear and angular acceleration. To make sure that this does or does not happen, one has to examine the hinging mechanism of the sensor.

inertia tensor See *tensor of inertia.*

infragravity waves Infragravity waves are the component of ocean waves at *periods* longer than 25 seconds. Infragravity waves control long period (>30 seconds) vertical component seismic *noise* levels at the seafloor and at coastal sites on land. Infragravity waves are trapped along shorelines as edgewaves (see *edge effect*) or surfbeat and are generated by nonlinear mechanisms by the interaction of shorter period (wind driven) ocean waves along coastlines. See Webb (2002, p. 307).

infrasonic Pertaining to low-frequency (sub-audible) compressional (sound) waves in the atmosphere (see *infrasound*).

infrasound Acoustic waves at *frequencies* approximately from the seismic to the audible range. Typical for sound waves is that they propagate over great distances through the atmosphere and that the propagation conditions strongly depend on the changing parameters in the dynamic medium. See Chapter 17 of this Manual and Richards (2002, p. 370).

inhomogeneous The opposite of *homogeneous*.

inhomogenous plane waves *Plane waves* with *amplitudes* varying in a direction different from the direction of propagation. The propagation velocity is lower than that for regular plane waves. For example, *Rayleigh waves* are composed of inhomogeneous *P* and *SV waves* propagating horizontally with amplitudes decaying with depth. They are also called "evanescent waves." See Aki and Richards (2002, p. 149-157).

inner core The central part of the Earth's *core*. It extends from a depth of about 5200 km to the Earth's center. It has non-zero *rigidity*, in contrast to the outer core and was discovered in 1936 by Inge Lehmann.

inner core anisotropy Refers to elastic anisotropy of the *inner core*. The P velocity along the north-south direction in the inner core is about 3% faster than along east-west directions although the amount appears to vary spatially. See Song (2002).

inner core rotation The *geodynamo* is expected to force the *inner core* to rotate relative to the *mantle*. The observational evidence for such a differential inner core rotation has been reported but it is still under debate. See Chapter 56 in Lee et al. (2002).

instrumental noise Unwanted data part originating from the instrument used for the measurement. See *self noise*.

instrument response In order to recover the *ground motion* at a recording site, one must deconvolve (see *deconvolution*) the contribution of the recording instrumentation. A modern instrument response can be broken down into two stages: a) the transformation of ground motion to an electrical energy followed b) by the transformation of that electrical energy into an output *signal* which can produce a permanent record (historically paper or photographic record, today mostly a digital stream recorded on a computer storage unit). See Chapter 5 of this Manual, as well as Wielandt (2002), Scherbaum (2002) and Eq. (3.10) in Ben-Zion (2003).

intensity, macroseismic A cumulative measure of the effects of an *earthquake* at a particular place at the Earth's surface on humans and (or) structures and thus a measure of the strength of earthquake shaking. Different from *magnitude*, the intensity at a point depends not only on the earthquake strength (released *seismic energy*) or earthquake size (released *seismic moment*), but also on the *epicentral distance*, the *focal depth*, the position of the observation point with respect to the type of *focal mechanism* and its *directivity*, and the local site conditions. Intensity values are usually given as integer Roman numerals ranging from 0 to 12 (see *intensity scales, macroseismic*). Although coarse, they are a valuable complementary analogue for physical *ground motion parameters*, correlating best with ground velocity. Moreover, intensity of shaking, based on the assessment of real post-event damage, is a suitable site-related empirical risk estimator for scenario calibrations. See Chapter 12 of this Manual. Intensity is now also quantitatively estimated using ground motion measurements; such quantitative intensity measurement is called "Instrumental Intensity" to distinguish it from the qualitative seismic intensity. See Musson (2002).

intensity scales, macroseismic *Macroseismic intensity* assessments assign integer numerals to observed physical damages and perceived motions, thus classifying the shaking strength observed at a site. When these intensity classes are arranged in a systematic and mutually linked reasonable way they form a macroseismic scale. Macroseismic intensity scales can be considered as an analogue to the 12-degree Beaufort wind-strength scale which is also based on perceptions and physical effects. The first, also internationally widely used macroseismic intensity scale was the ten-degree Rossi-Forel Scale of 1883. The scale of Sieberg (1912, 1923) became the foundation of all modern twelve-degree scales. A later version became known as the *Mercalli-Cancani-Sieberg Scale*, or *MCS Scale* (Sieberg, 1932). It was translated into English by Wood and Neuman (1931), becoming the *Modified Mercalli Scale* (*MM Scale*), and after an extensive revision by Richter (1958) the "Modified Mercalli Scale of 1956" (MM56). Since the 1960s, the *Medvedev-Sponheuer-Karnik Scale* (*MSK Scale*, Sponheuer and Karnik, 1964) was widely used in Europe. It was based on the MCS, MM56 and previous work of Medvedev (1962) in Russia, but greatly developed the quantitative aspects of the scale. Since the late 1990s the much more elaborated *European Macroseismic Scale 98* (*EMS-98*; Grünthal, 1998) has essentially replaced the usage of the old MSK scale although content-wise the EMS is more or less compatible with it. A more recent modification of the *MM Scale*, termed *MMI*, was proposed by Stover and Coffman (1993). All these scales have twelve degrees of intensity. Only the scale used in Japan, the *JMA intensity scale*, uses less degrees, originally 6, and since recent modifications (JMA 1996, 2009) 10 degrees. See Chapter 12 of this Manual, the specific entries in this glossary for the specific scales, and Musson et al. (2010) for a comparison between the scales and a discussion on their evolution.

interface In a continuum, a surface of *discontinuity* that separates two different media.

interference In physics, interference is the phenomenon in which two waves superpose each other to form a resultant wave of greater or lower *amplitude*. Interference usually refers to the interaction of waves that are *coherent* with each other, either because they come from the same source or they have the same or nearly the same *frequency*. When two waves with the same frequency combine, the resulting pattern is determined by the *phase* difference between the two waves.

interferogram The photographic or digital record of the *interference* pattern of electromagnetic or other types of superposing waves that has diagnostic potential to decipher the original state and/or the travelpath history of the interfering waves.

interferometry Refers to a family of techniques in which electromagnetic waves are superimposed in order to extract information about the waves, respectively about the position and/or shape of the object(s) that receive(s) or reflect(s) the electromagnetic waves radiated from an electromagnetic source. Interferometry is an important investigation technique in many fields, amongst them astronomy, engineering and optical metrology, remote sensing, seismology, oceanography, nuclear and particle physics.

interferometry, 2-pass differential Approach to calculating *interferograms*, which uses two radar images and a digital elevation model (DEM). Also called DEM-elimination. See Feigl (2002).

interferometry, 3-pass Approach to calculating *interferograms*, which uses three radar images, but no elevation model. See Feigl (2002).

International System of Units (SI) An internationally agreed system of units, which is abbreviated as SI for “Système International d’Unités”, and is recommended for use in all scientific and technical fields (NBS, 1981). The international system of units is comprised of 7 base units: (1) length in meter (m), (2) mass in kilogram (kg), (3) time in second (s), (4) electric current in ampere (A), (5) thermodynamic temperature in kelvin (K), (6) amount of substance in mole (mol), and (7) luminous intensity in candela (cd). It also has a number of derived and supplementary units. Some derived units with special names are: *frequency* in hertz (Hz), force in newton (N), *pressure* or *stress* in pascal (Pa), energy, work, or quantity of heat in joule (J), power in watt (W), electric charge in coulomb (C), and electric potential in volt (V). See Lide (2002) and NBS (1981) for a detailed review of SI and conversion factors.

interplate Interplate pertains to processes between *lithospheric plates* (see *lithosphere*).

interplate coupling The qualitative ability of a *subduction thrust fault* to lock and accumulate *stress*. Strong interplate coupling implies that the fault is locked and capable of accumulating stress whereas weak coupling implies that the fault is unlocked or only capable of accumulating low stress. A fault with weak interplate coupling could be *aseismic* or could slip by *creep*. See *locked fault*.

interplate earthquake An earthquake that has its source in the *interface* between two lithospheric *plates*, such as in a *subduction zone* or on a *transform fault*.

intraplate Intraplate pertains to processes within the Earth’s lithospheric *plates* (see *lithosphere*).

intraplate earthquake An earthquake that has its source in the interior of a lithospheric *plate*. Often the reason for the specific location of such an earthquake or its relation to an identifiable *fault* is not evident.

intrinsic attenuation *Attenuation* of *seismic waves* due to intrinsic absorption caused by internal *friction* (anelasticity). See Section 5.5 in Aki and Richards (2002, p. 161-177).

inverse problem A problem in which the intent is to infer the values of the parameters characterizing a system, given some observed data. Solving an inverse problem may be summarized as → observed data → model → estimates of model parameters. An inverse problem is the opposite of a *forward problem*; it can be formulated as a problem of iterative data fitting or, more generally, as a problem of probabilistic inference. Usually, there is no direct and unique solution to the inverse problem. A rare exception is the solution of the *Wiechert-Herglotz* formula under strict conditions. See *inversion*, Mosegaard and Tarantola (2002), Curtis and Snieder (2002), Menke (1984), and Tarantola (2005).

inverse refraction diagram (for tsunami) A *refraction* diagram drawn from coastal observation points. Iso-time contours correspond to the *travel time* encompassed by the ray path to each station from the source region on the map. See Suyehiro and Mochizuki (2002, p. 443).

inversion Given a model hypothesized for explaining a set of observed data, inversion is a procedure for determining the model parameters from the observed data. Various issues involved in this procedure, such as the evaluation of the resolution and error in the estimated parameters, constitute the *inverse problem*. In contrast the prediction of observables for a model with assumed parameters is called the *forward problem*. See Mosegaard and Tarantola (2002), Curtis and Snieder (2002), Menke (1984) or Tarantola (2005).

Ishimoto-Iida's relation An empirical relation expressing the *frequency of occurrence* of the maximum *amplitudes* of earthquakes recorded at a *seismograph* station obtained by Ishimoto and Iida (1939). Although the concept of *magnitude* was not known to them, the power law found for the amplitude distribution is reducible to the power law for earthquake energy implied in *Gutenberg-Richter's* frequency-magnitude *relation*. They recognized the significance of its departure from the Boltzmann exponential law for statistical energy distribution. See Utsu (2002b), and Eqs. (7.1) - (7.2) in Ben-Zion (2003).

isochron In seismology, a line on a map or a chart connecting points of equal time or time interval, e.g., *arrival times* of the *onset* of *seismic waves* from a source. In *geochronology,* a line connecting points of equal age. In marine geophysics, the *magnetic lineation* with equal age, often abbreviated as chron. See Cox (1973), Uyeda (1978), and Duff (1993).

isopach As used in *volcanology*, a line joining points of equal thickness in a *pyroclastic* deposit.

isopleth As used in *volcanology*, a line joining points where the sizes of the largest *pyroclasts* are the same.

isoseismal A closed curve bounding the area within which the *intensity* from a particular earthquake was predominantly equal to or higher than a given value. See Chapter 12 of this Manual and Musson and Cecić (2002).

isostasy The application of the principle of buoyancy on the Earth's *lithosphere*. If the mass of any column of rocks above a specified level is everywhere the same, this part of the lithosphere is in isostatic equilibrium. Dynamic processes can destroy this balance, but buoyancy will force to restore the equilibrium.

isotope Various species of atoms of a chemical element with the same atomic number, but different atomic weights.

isotropric Means the physical properties of a medium, e.g., its *density* or *velocity* of *seismic wave* propagation, are independent on any direction in space.

J

J The symbol J is used to indicate that part of a *ray* path which has traversed the Earth's *inner core* as an *S wave*. Unambiguous observations of such waves have not yet been achieved, but they may be possible in future. For this and other such symbols used in *seismic phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

jerk Rate of change of *acceleration*.

JMA magnitude (M_J) *Magnitude* for earthquakes in Japan and its vicinity, assigned by JMA using data from the JMA network. M_J is fairly close to *Ms* for shallow earthquakes and *mB* for intermediate and deep earthquakes. See Chapter 3 in this Manual and Chapter 44 in Lee et al. (2002).

JMA intensity scale The *macroseismic intensity scale* used by the Japanese Meteorological Agency (JMA). Modified four times since its first definition in 1884. From 1996 onward, the scale has 10 grades designated as 0, 1, 2, 3, 4, 5-, 5+, 6-, 6+, and 7. See *intensity scale*, Chapter 12 in this Manual, and Musson et al. (2010).

joint transverse-angular coherence function Measure of *coherency* between two transmitted *wave fields* as a function of *incident angles* and the transverse-separation of receivers. See Sato et al. (2002, p. 202).

joule (J) The *SI* derived unit for energy, or work, or quantity of heat, expressed in m^2 kg s^{-2}, or Newton meter (Nm). It is named after James Joule (1818-89), who established the mechanical equivalence of heat, and is today used instead of the outdated unit calorie (1 cal = 4.184 J).

Julian day As used in seismology, the number of a day during the year (also referred to as Day-Of-Year, DOY), counted continuously from January 1 as Day 1. For example, February 2 is Julian day 33 in this method of counting. Note that for non-leap and leap years, the Julian Day for the 28^{th} of February differs by one day.

juvenile An adjective commonly used to describe eruptive materials produced from the *magma* involved in the *eruption*, in contrast to *lithic* materials derived from preexisting rocks, volcanic or non-volcanic. See *lithics*.

K

K *Seismic phase* symbol that stands for the *P waves* lag of *seismic waves* that traveled through the outer *core* (with K for the German word for core = Kern). For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

kelvin (K) A base unit of thermodynamic temperature in the *international system of units (SI).* The official definition is: “The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.” See NBS (1981).

kilogram (kg) A base unit of mass in the *international system of units (SI).* The official definition is: “The kilogram is the unit of mass; it is equal to the mass of the international prototype of mass of the kilogram.” See NBS (1981).

kiloton An energy unit, now defined as 4.184 trillion (10^{12}) Nm (or Joules, J). The term originates from an estimate of the energy released by the explosion of a thousand tons of the chemical explosive Trinitrotoluol (TNT). See Richards (2002).

kinematic Referring to the general movement patterns and directions, usually expressed in physical units of *displacement* (m), *velocity* (m/s) or *acceleration* (m/s^2).

kinematic units See *kinematic*.

kinematic ray equations The ordinary differential equations governing the geometry of a *ray* path. The independent variable is typically the *travel time* or ray path length, and the dependent variables, the ray position and direction. See Chapman (2002).

kinematics (of seismic source) A description of the *deformation* or motions within a *seismic source* region in geometrical terms such as *fault slip* or transformational *strain*, without reference to the *stresses* or forces that are responsible. See *dynamics* (*of seismic source*); also Aki and Richards (2002 or 2009, Box 5.3, p. 129).

kinetic moment Rotational analogue of impulse. It is equal to the sum of moments of momentum and of proper kinetic moment (sometimes called "dynamic spin"). Kinetic moment of a body is calculated relatively to a fixed point in a system of reference and depends upon the chosen "pole" (another point, fixed in the body). For a rigid body, if its center of mass is taken as a "pole," and the origin of an inertial system of reference is taken as a fixed point, the kinetic moment is equal to **r x p + J ω,** where **r** is the radius-vector of the center of mass, **p** is the momentum (impulse) of the body, **J** is the *tensor of inertia* calculated relative to the center of mass, and **ω** is the angular velocity of the body. The time derivative of the kinetic moment represents the inertial term in the law of balance of *torque* (the *torques* must be calculated relative to the same fixed point). In *micropolar* theories, the existence of proper kinetic moment of particles and resistance of the medium to their rotation causes the existence of *rotational waves*.

Kirchhoff surface integral method This method originates from Kirchhoff's solution of the Cauchy problem, i.e., finding a solution of the wave equation for given initial conditions on the wave function and its time derivative defined for the whole space. The solution was expressed as a surface integral of functions given as initial conditions, properly time-shifted and weighted over a spherical surface centered at the observation point. It can be generalized to an integral over a non-spherical surface enclosing the region where the homogeneous wave equation is valid. It can be used, for example, to represent scattered waves from a rough surface as a surface integral. The integral reduces to ray-theoretical solution for the planar surface. See Chapman (2002), and biographies of Augustin Louis Cauchy and Gustav Kirchhoff in Howell (2003).

Knopoff model — A shear crack model for earthquakes investigated by Knopoff (1958). See Madariaga and Olsen (2002), and Scholz (2002). See also *fault model*.

Kostrov model — A self-similar circular rupture model for earthquakes introduced by Kostrov (1966). See Madariaga and Olsen (2002), Das and Kostrov (1988). See also *fault model*.

Kramers-Kronig relations — Also called *dispersion relations*. Relationships between the *amplitude* and *phase* of the frequency response resulting from the requirement that the corresponding impulse response is causal. See *frequency response*, *impulse response* and *causal signal*. See also Aki and Richards (2002 or 2009, p. 167-169).

kurtosis — A quantitative measure of the deviation of a random value distribution from the "normal" bell-shaped *Gaussian distribution.* Kurtosis is a measure of the bulge of the distribution. It is 3 for normally distributed random variables. Positive (negative) deviations from 3 indicate widening (narrowing) of the distribution. See *higher-order statistics*.

L

L (LQ, LR) — The symbol L is used to designate long-*period surface waves*. When the type of surface wave is known, LQ and LR are used for *Love* and *Rayleigh waves*, respectively. For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

lahar — A widely used Indonesian term for volcanic debris flow. See *mudflow*.

Lamé constants — Two physical constants, λ and μ, that linearly relate *stress* to *strain* in a *homogeneous* and *isotropic* elastic solid in the classical elasticity theory. μ is the *rigidity* (*shear modulus*) and λ a combination between *bulk modulus* κ and rigidity μ ($\lambda = \kappa - 2\mu/3$). See section 2.2.2 in Chapter 2 of this Manual.

landslide — The down-slope movement of soil and/or rock.

lapilli — Of Italian origin (meaning "little stones"), a term given to *tephra* ranging in size between 2 and 64 mm.

Laplace transformation — An integral transform mapping signals $r(t)$ defined in the positive *time domain* ($r(t) = 0$ for $t<0$) into the complex domain by multiplying by $\exp(-st)$ and integrating over t from 0 to infinity. See section 5.2.2 of Chapter 5 in this Manual and Scherbaum (2002).

lapse time — Time measured beginning from the earthquake *origin time*.

Late Quaternary faults *Faults* of this age, between the present and 500,000 years before the present, are sometimes considered *active* based on the observation of historical or *palaeoseismic* activity on faults of this age in some locales.

lateral blasts Sharing the characteristics of *pyroclastic flows* and *surges*, such phenomena have in addition an initial low-angle component of explosive energy release; they are often associated with sudden decompression of a highly pressurized magmatic system upon *sector collapse*, as was well documented for the 18 May 1980 eruption of Mount St. Helens, Washington State.

lateral-force coefficient A term in *earthquake engineering* referring to a numerical coefficient, specified in terms of a fraction or percentage of the weight of a structure, used in earthquake resistant design to specify the horizontal seismic forces to be resisted by the structure. See Borcherdt et al. (2003).

lateral spread and flow Terms referring to *landslides* that commonly form on gentle slopes and that have rapid fluid-like flow movement, like water.

lateral spread in ground failure Lateral displacement of the ground down gentle slopes or toward a free face as a consequence of *liquefaction* accompanied by flow within subsurface granular layers. See Youd (2003).

Laurasia The proto-continent of the northern hemisphere in the late *Paleozoic* time. It included most of North America, Greenland, and most of Eurasia (excluding India), before they were drifting away from one another. See Duff (1993), and Hancock and Skinner (2000).

lava An all-inclusive term for any *magma* once it is erupted from a *volcano*; rocks and deposits formed from lava can vary widely in texture and appearance depending on chemical composition, gas and (or) crystal content, eruption mode (effusive or explosive), and depositional environment.

lava cone A relatively small *volcanic* edifice built largely of *lava flows* around a central *vent*, but it is distinguished from a *lava shield* by having a slightly concave upward profile becoming steeper toward the top — similar to those of *cinder cones* or *stratovolcanoes*. Depending on the viscosity of the lava flows involved, there can be a continuum in characteristics between lava cones and lava shields.

lava delta A wide, fan-shaped area of new land created by prolonged *lava* entry — commonly via a *lava-tube* system — into the ocean, as demonstrated by the 1983-present eruption at Kïlauea Volcano in Hawaii. Such new land is usually built on sloping layers of loose lava fragments and flows.

lava dome Roughly symmetrical and hemispherical mound of *lava* formed during extrusion of *magma* that is so viscous that it accumulates over the *vent*.

lava flow A stream of molten rock that pours from a *volcanic vent* during an *effusive eruption*; lava flows can exhibit wide differences in size, fluidity, textures, and physical aspects depending on *lava* viscosity and eruption rates.

lava fountain A pillar-like, uprushing jet of incandescent *pyroclasts* that falls to the ground near the *vent*; lava fountains can also occur as sheet-like jets from one or more fissure vents ("curtain of fire"). Lava fountains can attain heights of hundred of meters. See *Hawaiian eruption*.

lava lake (or pond) An accumulation of molten *lava*, usually *basaltic*, contained in a *vent*, *crater*, or broad depression. It describes both lava lakes that are molten and those that are partly or completely solidified. If one or more vents sustain a lava lake, it can remain active for many months to years.

lava shield A broadly convex, gently sloping volcanic landform built by multiple thin flows of fluid *lava* from a *volcanic vent* or a cluster of closely spaced vents. While the term applies to such landforms of any size, the larger lava shields tend to be called *shield volcanoes*.

lava tube Lava tubes are natural conduits through which *lava* travels beneath the surface. They form by the crusting over of lava channels and flows. A broad *lava-flow* field often consists of a main lava tube and a series of smaller tubes that supply lava to the front of one or more separate flows.

Layer 2 (and 1 of the oceanic crust) Upper part of the oceanic *crust*, characterized by *velocities* lower than about 6.5 km/sec and by high velocity *gradients* (typically 0.5-1.0 km/sec per kilometer). Layer 1 in this nomenclature is the water layer itself. See Minshull (2002).

Layer 2A (of the oceanic crust) A layer of particularly low *velocities* (typically 2-4 km/sec) found in the vicinity of ocean ridge axes, bounded by a sharp velocity increase at its base, and commonly interpreted as an extrusive *basalt* layer. See Minshull (2002).

Layer 3 (of the oceanic crust) Lower part of the oceanic *crust*, characterized by *velocities* normally in the range 6.5-7.2 km/sec and by low velocity *gradients* (typically 0.1-0.2 km/sec per kilometer). See Minshull (2002).

leaking modes — *Normal modes* in a layered *halfspace*, in general, have cutoff *frequencies* below which the *phase velocity* exceeds the P and/or S velocities of the halfspace, and the energy leaks through the half-space as *body waves*. Because of the leakage, the *amplitude* of leaking modes attenuates exponentially with distance. See Aki and Richards (2002 or 2009, p. 312-324).

Least Significant Bit (LSB) — The smallest change in value that can be represented in the output of an *analog-to-digital converter* (digitizer).

least-squares fit — An approximation of a set of data with a curve such that the sum of the squares of the differences between the observed points and the assumed curve is a minimum.

left-lateral fault — A *strike-slip fault* across which a viewer would see the block on the other side moves to the left. Also known as a *sinistral fault*. See *right-lateral fault*.

left-lateral movement — See *left-lateral fault*.

Levi-Civitta tensor — A tensor that is equal to $-\mathbf{I} \times \mathbf{I}$, where $\mathbf{I}$ is the *identity tensor*. Its components are known as Ricci symbols. It appears in expressions including vector products.

Lenz's law — An induced electric current in a circuit always flows in a direction so as to oppose the change that causes it. This law was deduced in 1834 by the Russian physicist Heinrich Friedrich Emil Lenz (1804–65).

Lg waves — Originally, short-period (1-6 seconds) large *amplitude arrivals* with predominantly transverse motion (Ewing et al., 1957). The maximum energy within the Lg-wave group propagates along the surface with *velocities* around 3.5 km/s, which is close to the average shear velocity in the upper part of the continental *crust*. Lg waves are observed with frequencies up to 5 or 10 Hz and caused by superposition of multiple *S-wave* reverberations and *SV* to *P* and/or P to SV conversions inside the whole crust. The waves are observed only when the wave path is entirely continental and not disturbed by abrupt changes in crustal thickness or lithological composition along major *tectonic* boundaries. As little as 2° of intervening ocean can be sufficient to eliminate the waves. See Kulhanek (2002, p. 336-337). For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

lifelines — Man-made structures that are important or critical for a community to function, such as roadways, pipelines, power lines, sewers, communications, and port facilities.

linear analysis — A calculation or theoretical study that assumes material properties stay within their linear ranges and that the deflections are small in comparison to characteristic lengths. These assumptions permit the response to be described by linear differential or matrix equations. See Chapter 2 of this Manual and Jennings (2003).

linearity In mathematics, a function F is linear if $F(ax) = aF(x)$, and $F(x+y) = F(x) + F(y)$, where x and y are variables and a is a constant. A system is linear if its output can be expressed as the *convolution* of the input and the *impulse response*. When the input is a function of time in a linear system, the output can be obtained from using its frequency response alone. See *convolution* and *frequency response*. See Section 5.7 of Chapter 5 in this manual and Wielandt (2002, p. 297) for testing the linearity of seismometers.

linearize To linearize an equation means to use a linear approximation to that equation, often found by keeping only the first-order terms in the *Taylor expansion*, or, in equivalent linearization, by choosing the parameters of a linear system to minimize the difference between some measure of the responses of a nonlinear system and its linear approximation.

linear system A system which is completely determined by its frequency response. When the frequency response is time-invariant, it is called *stationary linear system*. See *linearity* and *frequency response*.

liquefaction Process by which water-saturated sediment or soil temporarily loses strength and acts as a fluid. The transformation of a granular material from a solid state into a liquefied state is caused by increased pore water pressures and reduced *effective stress*. This effect can be caused by *ground motion* (earthquake shaking) and be associated with *sand boil*. See Youd (2003).

lithics Non-juvenile fragments in *pyroclastic* deposits that represent preexisting solid volcanic or non-volcanic rock incorporated and ejected during explosive *eruptions*.

lithology The description of rock composition and texture.

lithosphere The rigid upper portion of the near-surface thermal boundary layer of the *Earth* at temperatures below about 650°C that can store elastic energy under long-term loads. This definition may or may not agree with the seismic lithosphere, which is composed of the *crust* and the uppermost *mantle* “lid” above the *low velocity layer*. The lithosphere is about 100 km thick, although its thickness depends on age and *heat-flow* conditions (older and cooler lithosphere is thicker). At some locations the lithosphere below the crust is *brittle* enough to produce earthquakes by faulting, such as within subducted oceanic *plates*. See Lay (2002) and Mooney et al. (2002).

lithosphere-asthenosphere boundary The (gradual) transition between the rigid-brittle *lithosphere* and the ductile (partially molten) *asthenosphere* in the Earth´s *upper mantle*.

lithospheric plates See *tectonic plates*.

lithostatic pressure See *hydrostatic pressure*.

lithostatic stress There are two variations on the usage of this term. One usage, also called the "lithostatic load" or "*lithostatic pressure*", gives the vertical *normal stress* as a function of depth due to the gravitational force of the overlying rock column. Another usage, the "lithostatic stress state", combines the "lithostatic load" with assumptions about the *strain* history and rheology of the rock column to produce the complete *stress tensor*. See Ruff (2002).

Li-waves These are similar to *Lg-waves*, but their existence is not as widely accepted as that of Lg. The *velocity* of Li-waves is 3.8 km/sec (as compared to 3.5 km/sec for Lg) and may be associated with the lower continental *crust* (Båth, 1954).

local magnitude (M_L) A *magnitude* scale introduced by Richter (1935) for earthquakes in southern California. M_L was originally defined as the logarithm of the maximum *amplitude* of *seismic waves* on a *seismogram* written by the Wood-Anderson *seismograph* (Anderson and Wood, 1925) at a distance of 100 km from the *epicenter*. In practice, measurements are reduced to the standard distance of 100 km by a *calibration* function established empirically. Because Wood-Anderson seismographs have been out of use since the 1970s, M_L is now computed with simulated Wood-Anderson records and a slightly modified standard formula. The original M_L scale calibration function is only valid for the seismic wave *attenuation* conditions in California. Therefore, when adapting the M_L scale to other regions, many authors use the original Richter definition together with a modified calibration function. See the biography of Charles Francis Richter in Howell (2003), Chapter 3, DS 3.1 and IS 3.3 in this Manual, the IASPEI (2013) magnitude standards, and Bormann (2011).

local site conditions Qualitative or quantitative description of the topography, geology and soil profile at a site which affect ground motions at that site during an earthquake. See Chapter 14 of this Manual and Campbell (2003).

locked fault A *fault* that is not slipping because frictional resistance on the fault is greater than the *shear stress* across the fault. Such faults may store *strain* for extended periods, which is eventually released in an earthquake when frictional resistance is overcome. In contrast, a *fault segment* which slips sometimes without the occurance of an earthquake is called creeping segment. See *creep events*.

log-periodic behavior Power-law (fractal) behavior when the power is not real, but complex. See Turcotte and Malamud (2002).

longitudinal waves Another name for *P waves*. See section 2.2.3 in Chapter 2 of this Manual.

long-period In traditional *seismometry* with limited *dynamic range*, *seismographs* were naturally divided into two types; long-period seismographs for *periods* above the spectral peak (periods around 5 seconds) of the microseismic noise (see *microseisms*) generated by ocean waves and short-period seismographs for periods below it. See Chapters 4 and 5 in this Manual.

long-period earthquake Small, local *seismic events* occurring under volcanoes with emergent *onset* of *P waves*, no distinct *S waves*, and a low-*frequency* content (1 to 5 Hz) as compared with the usual *tectonic earthquakes* of the same *magnitude*; also called *B-type* or *low-frequency earthquake*. The observed features are attributed to the involvement of fluid such as *magma* and/or water in the source process. See Chouet (1996a) for the review of relateded observations and their interpretation, Chapter 13 in this Manual, and McNutt (2002).

long (oceanic) wave A kind of oceanic gravity wave. When the *wavelength* is much larger than the water depth, it is called long wave or shallow water wave. Most *tsunamis* can be treated as long waves. See Satake (2002).

look vector A vector parallel to the line of sight between a radar and its target on the ground. See Feigl (2002).

loss In earthquake damage, an adverse economic or social effect (or cumulative effects) of an earthquake (or earthquakes), usually specified as a monetary value or as a fraction or percentage of the total value of a property or portfolio of properties.

loss function A mathematical expression or graphical relationship between a specified *loss* and a specified *ground-motion* parameter (often the *seismic intensity*) for a given structure or class of structures.

Love-Rayleigh wave discrepancy Observed *phase velocities* of *Love* and *Rayleigh waves* require a *transverse isotropy* of seismic *velocities* in the *crust* and the uppermost *mantle*. Love waves are observed to be faster than predicted for *isotropic* models, which are based on the inversion of Rayleigh waves. This still not totally understood discrepancy was first discovered by Aki and Kaminuma (1963) for Japan, and has been found universally, both in tectonically active and stable regions. See Cara (2002).

Love wave *SH-waves* trapped near the surface of the Earth and propagating along it. Their existence was first predicted by A. E. H. Love (1911) for a *homogeneous* layer overlying *halfspace* with an S velocity greater than that of the layer. They can exist, in general, in vertically *heterogeneous* media, but not in a homogeneous halfspace with a planar surface. See Chapter 2 in this Manual, Malischewsky (1987), Malischewsky and Scherbaum (2004), Kulhanek (2002), and the biography of Augustus Edward Hough Love in Howell (2003).

lower mantle Lowermost part of the Earth's *mantle*. It contains the *D"* zone, which is located directly above the *core-mantle boundary*.

low-frequency earthquake (LFE) A term introduced by the Japan Meteorological Agency (JMA) to differentiate a new class of events in their *seismicity* catalog. LFEs occur as part of an extended duration *tremor signal* in *subduction* environments and the visible *arrivals* of LFEs are primarily *S-waves*. *Cross-correlation* methods can be used to accurately locate source regions of LFEs and evidences exist that LFEs originate from shear failure on the *plate interface* in-between locked and slipping portions of the interface (Shelly et al., 2006). See also *non-volcanic tremor* and *long-period earthquake*.

low-pass filter *Filter* which removes the high *frequency* portion of the input *signal*. See IS 5.2 in this Manual and Scherbaum (2002).

low velocity layer/zone Any layer in the Earth in which *seismic wave velocities* are lower than in the layers above and below. The wider low-velocity zone in the *upper mantle* with seismic velocities lower than in the overlying lid of the uppermost layer of the mantle is termed *asthenosphere* and is commonly associated with the presence of partial melt and *ductile* flow. See section 2.5.3.3 and Fig. 2.33 in Chapter 2 of this Manual and Lay (2002).

Lyapunov exponent Solutions to deterministic equations are chaotic if adjacent solutions diverge exponentially in phase space; the exponent is known as the Lyapunov exponent. Solutions are chaotic if the exponent is positive. See *chaos*.

M

Ma An abbreviation for one million years ago (Megaannum).

macroscopic precursor An *earthquake precursor* detected by human sense organs, for example, anomalous animal behavior, gush of well water, earthquake lights, and rumbling sounds. See Rikitake and Hamada (2002).

macroseismic Pertaining to the observed (felt) effects of earthquakes. See Chapter 12 of this Manual, and Musson and Cecić (2002).

macroseismic intensity See *intensity* and *intensity scales*.

macroseismology The study of any effects of earthquakes that are observable without instruments, such as felt by people, *landslides*, fissures, knocked-down chimneys, etc. See Chapter 12 in this Manual.

magma Molten rock that forms below the Earth's surface; contains variable amounts of dissolved gases (principally water vapor, carbon dioxide, sulfur dioxide) and crystals (principally silicates and oxides).

magmatism Production of molten igneous rock called "*magma*". The magma either erupted at the Earth's surface as *lava* or *ash* (volcanism), or trapped in subterranean chambers within the *crust* or *upper mantle* as rock bodies termed intrusions (plutonism).

magnetic anomaly The difference between the observed value of the magnetic field and the calculated value based on a standard model of the Earth's magnetic field. See Uyeda (2002, p. 55-56).

magnetic lineation Stripe patterned *magnetic anomalies* observed in oceanic areas. They are generally 10-20 km wide and many hundred kilometers long with amplitudes of many hundred nT (nano Tesla). Their origin is explained by the Vine-Matthews-Morley theory (Vine and Matthews, 1963, Morley and Larochelle, 1964). See Uyeda (2002), Raff and Mason (1961), Cox (1973), Uyeda (1978), Duff (1993), and Merrill et al. (1998).

magnetic poles (of the Earth) They correspond to a point on the Earth's surface where the magnetic inclination is observed to be +90º and -90º, respectively. The North Pole and the South Pole are not exactly opposite each other and their positions wander with time due to changes in the geomagnetic dynamo in the Earth's *core*. As of 2005 the position of the North Pole was calculated to lie at 82.7°N and 114.4°W, and that of the South Pole at 64.5ºS and 137.7ºE. See Merrill et al. (1998). See *geomagnetic pole, geodynamo*.

magnetic quiet zone An area of the sea-floor without *magnetic lineations*, because the Earth's magnetic field did not reverse its polarity for a long interval, e.g., during the long Cretaceous normal magnetic epoch. See Chapter 6, and Larson and Pitman (1972).

magnetic reversal A change of the Earth's magnetic field to the opposite polarity that has occurred at irregular intervals during *geologic time*. Polarity reversals can be preserved in sequences of magnetized rocks and compared with standard polarity-change time scales to estimate geologic ages of the rocks. Rocks created along the *oceanic spreading ridges* (*sea-floor spreading*) commonly preserve this pattern of polarity reversals as they cool, and this pattern can be used to determine the rate of ocean-ridge spreading. The reversal patterns recorded in the rocks are termed sea-floor magnetic lineaments. See *magnetic lineation*.

magnification curve A diagram showing the *amplification*, e.g., of the seismic ground motion by a *seismograph*, as a function of *frequency*. See *amplification* and *amplitude response*.

magnitude, of earthquakes In seismology, a quantity intended to measure the size of *earthquakes* and is independent of the place of observation. The Richter magnitude or *local magnitude* (M_L) was originally defined by Charles F. Richter (1935) as the logarithm of the maximum *amplitude* in micrometers of *seismic waves* in a *seismogram* written by a standard Wood-Anderson *seismograph* at a distance of 100 km from the *epicenter*. Empirical tables were constructed to reduce measurements to the standard distance of 100 km (see also *magnitude calibration function*) and the zero of the scale was fixed arbitrarily to fit the smallest earthquake then recorded. The concept was extended later to construct magnitude scales based on other data, resulting in many types of magnitudes, such as *body-wave magnitude* (*mB* and *mb*), *surface-wave magnitude* (*Ms*), *moment magnitude* (*Mw*) and *energy magnitude* (*Me*). In some cases, magnitudes are estimated from seismic *intensity* data, *tsunami* data, or the duration of *coda waves*. The word "magnitude" or the symbol M, without a subscript, is sometimes used when the specific type of magnitude is clear from the context, or is not really important. According to Hagiwara (1964), earthquakes may be classified by magnitude (M) as: *major* if $M \geq 7$, as *moderate* if M ranges from 5 to 7, as *small* if M ranges from 3 to 5, as *micro* if M ranges from 1 to 3, and as ultra-micro < 1. Later usages include: as nano if $M < 0$, as *great* if $M \geq 8$ (or sometimes 7 ¾), and as mega if $M \geq 9$. In principal, all magnitude scales could be cross calibrated to yield the same value for any given earthquake, but this expectation has proven to be only approximately true, thus the need to specify the magnitude type as well as its value. For details also on other specific types of magnitudes, on IASPEI recommendations for standard magnitude measurement procedures, as well as cross-correlations of magnitude scales see Chapter 3 and IS 3.3 of this Manual, Kanamori (1983), Utsu (2002b), Bormann and Saul (2009), Bormann et al. (2009), Bormann (2011), and IASPEI (2013).

magnitude calibration function That a *magnitude* becomes a defined and comparable quantity, which relates to the size or strength of an *earthquake* independent of the place of observation, one has to correct the related measured values such as *amplitude*, *period*, *duration*, *waveform*, *moment* or *energy* content for *path effects* (*geometrical spreading*, *intrinsic attenuation*, *scattering*, …), source mechanism, and/or recording *site effects*. These correction terms are then accounted for in a magnitude calibration function. Because of the complexity of all these effects and the difficulty to model them theoretically, especially for short-period data, these "functions" are usually derived as average functions or tabulated values from large empirical data sets. For a commented summary of calibration functions and tables see DS 3.1.

mainshock The largest earthquake in an *earthquake sequence*, sometimes preceded by one or more *foreshocks*, and almost always followed by many *aftershocks*.

major earthquake An earthquake with *magnitude* equal to or greater than 7 is often called "major". See *magnitude*.

mantle (Earth's) Zone of the *Earth's* interior below the *crust* and above the *core*. The mantle represents about 84% of the Earth's volume and is divided into the *upper mantle* and the *lower mantle*, with a transition zone between. See Fig. 2.79 in Chapter 2 and Figs. 11.65 and 11.66 in Chapter 11 of this Manual, Lay (2002), and Jeanloz (2002).

mantle convection The slow overturning of the solid, crystalline *mantle* by subsolidus *creep*, driven by internal buoyancy forces. The term subsolidus creep refers to the fact that mantle convection occurs in a crystalline solid. The hot interior of the mantle deforms like an elastic solid on short time scales but like a viscous fluid on *geologic time* scales. The primary surface expression of mantle convection is *plate tectonics* and *continental drift*. See Uyeda (2002) and Olson (2002).

mantle magnitude Mm The mantle *magnitude* Mm uses *surface waves* with *periods* between about 60 s and 410 s that penetrate into the Earth´s *mantle*. The concept has been introduced by Brune and Engen (1969) and further developed by Okal and Talandier (1989 and 1990). Mm is firmly related to the *seismic moment* M_o and does not, or only marginally, saturate even for *great*, *slow* or complex *earthquakes*. Therefore, it is routinely used for rapid magnitude determination of great earthquakes within about 10 min after *origin time* in the context of *tsunami* early warning. See Chapter 3 of this Manual, Okal and Talandier (1989 and 1990), Weinstein and Okal (2005).

mantle plume A concentrated *mantle* upwelling that forms a *hot spot* in the Earth's surface. See Uyeda (2002), and Olson (2002). See also *melting anomaly*.

mantle Rayleigh waves (R waves) Just as long-period *Love waves* are given another name, *G-waves*, long-period *Rayleigh waves* are sometimes called "mantle Rayleigh waves" or R waves. See Figs. 2.20 and 2.21 in Chapter 2 of this Manual.

marine microseisms An ever-present, nearly periodic *seismic signal* originating from ocean waves and surf. Its *amplitude* is typically between 0.1 and 10 μm and its *period* between 4 s and 8 s. The marine microseisms divide the spectrum of seismic signals into a short-period and a long-period band. See *double frequency microseisms* and *microseisms*.

Maslov asymptotic ray theory The traditional *ray* theory breaks down at *caustics* as the rays are focused and the equation for the *amplitude* predictions becomes singular. V. P. Maslov's asymptotic ray theory (1965) generalizes the ray theory by using an *ansatz*, which integrates over neighboring rays with appropriate phase delays. The Maslov asymptotic ray theory remains valid at caustics but reduces to the original ray theory when the latter is valid. See Chapman (2002).

master model of earthquakes A concept developed at the Southern California Earthquake Center to use as a framework for integrating multi-disciplinary earth science information regarding earthquakes in Southern California for the purpose of transmitting it to people living there. A first generation master model for southern California is described in WGCEP (1995). See Aki (2002).

maximum credible earthquake (MCE) The maximum earthquake, compatible with the known tectonic framework, that appears capable of occurring in a given area**.** See Faccioli and Pessina (2003).

maximum probable earthquake (MPE) The maximum earthquake that could strike a given area with a significant probability of occurrence**.** See Faccioli and Pessina (2003).

Maxwell material A theoretical viscoelastic material in which the short-time response to an applied force is that of an elastic solid, while the long-time response is that of a viscous fluid. See also *viscoelasticity*.

Maxwell's equations A set of four partial differential equations that describe the large-scale electromagnetic phenomena by the behavior of the electric and magnetic vectors and how the electric and magnetic fields are related to each other. These equations were formulated by James Clerk Maxwell (1831-1879) based on the experimental results of Ampere, Coulomb, Faraday, and Lenz. See Maxwell (3^{rd} edition, 1991), Stratton (1941).

mb See *body-wave magnitude*.

mB See *body-wave magnitude*.

MCS scale See *Mercalli-Cancani-Sieberg scale*.

Medvedev-Sponheuer-Karnik scale A *macroseismic* twelve-degree intensity scale (abbreviated MSK). It was based on MCS, MM56 (see *intensity scales*) and previous work by Medvedev (1962) in Russia. Published first in 1964 (Sponheuer and Karnik, 1964), it received several later minor modifications. The MSK developed greatly the quantitative aspects of the scale, thus making it more powerful than its predecessors. It became widely used in Europe. See Chapter 12 of this Manual and Musson et al. (2010).

melting anomaly Another name for *hot spot*. A region on Earth (often in an *intraplate tectonic* setting) of anomalously high rates of volcanism over many millions of years, presumably sustained by a persistent source of hot *mantle* material; the Hawaiian melting anomaly (or hot spot) is arguably the best example.

MEMS devises Sensor devices based on microelectromechanical systems. Originally developed for use in airbags, they are nowadays built-in in smartphones, harddisks, Wii stations, etc. Of special interest for *seismic exploration*, *seismology* and *engineering seismology* are *accelerometers* based on MEMS technology. Mechanical components and required electronic circuits are often integrated on a silicon chip that means small dimensions and often low costs. Low g chips have a resolution of about 1 mg at costs of a few $. They can be used for *strong-motion* sensing (e.g., in earthquake *early warning systems* such as SOSEWIN, Fleming et al., 2009);) There is also some progress in the development of high resolution accelerometers for different applications. The resolution is up to ~100ng/sqrt(Hz). Other applications are in strong-motion seismic sensing with high *dynamic range* of 120dB or more and in *seismic prospection* where MEMS accelerometers combined with 24 bit digititizer modules result in a modern replacement for classical *geophones*. Costs of these high resolution sensors are still high (several 100$ per unit), due to a more expensive technology. It is not likely that MEMS can replace *broadband seismometers* in near future since their sensitivity at very low *frequencies* is more than 2 orders less than for broadband velocity-meters.

Mercalli-Cancani-Sieberg scale A *macroseismic* twelve-degree *intensity scale* (abbreviated *MCS*). It is essentially based on the earlier developed and upgraded twelve-degree scale by August Sieberg

	(Sieberg, 1912, 1923). Sieberg's version of 1923 has been translated into English by Wood and Neumann (1931), becoming the *Modified Mercalli Scale* (*MM Scale*).
Mesozoic	An era in *geologic time*, from 245 to 66.4 million years ago.
metamorphic facies	A set of metamorphic rocks characterized by particular mineral associations, indicating origin under a specific pressure-temperature range.
metamorphic rock	A rock derived from pre-existing rocks by mineralogical, chemical, and/or structural changes, essentially in the solid-state, in response to changes in pressure, temperature, shearing stress, and chemical environment.
meter (m)	A base unit of length in the *international system of units (SI)*. The official definition is "The meter is the length of the path traveled by light in vacuum during a time interval of 1/299792458 of a second". See Lide (2002).
Metropolis method	A general method for sampling a probability, including high-dimensional spaces. See Mosegaard and Tarantola (2002).
microcontinent	An isolated, relatively small mass of sialic *crust* surrounded by oceanic crust. It is commonly plastered onto continents at a *convergent margin* where it becomes a part of the orogenic belt identifiable as an exotic terrane or "suspect terrane."
microcrack	An ensemble of tiny cracks that can join to form a crack. See Teisseyre and Majewski (2002).
microearthquake	An *earthquake* that is not perceptible by man and can be recorded by *seismographs* only. Typically, a microearthquake has a magnitude of 2 or less on the Richter scale.
micromorphic (continuum)	A continuum in which each material point is equipped with a kind of micro-structure, described in a local system of coordinates, whereby each of its "points" comprises a microvolume with micro-*displacements*, micro-*rotations*, micro-*deformations*, and micro-inertia tensor (see *tensor of inertia*). A number of material constants permit the description and solution of many complicated problems in which materials display non-classical responses to applied external loads (Eringen, 1999).
micropolar (continuum)	A synonym for the *Cosserat continuum* (Pujol, 2009). A continuum defined similarly to the *micromorphic continuum*, but for which only micro-*displacements* and micro-*rotations* of the microelements are permitted, but not micro-*deformations*, i.e., the microelements are taken to be rigid. Each material point is equipped with three degrees of freedom for rigid rotation in

addition to the classical translational degrees of freedom (Eringen, 1999).

microseisms Continuous *ground motion* constituting the background *noise* for any seismic measurement. Microseisms with *frequencies* higher than about 1 Hz are usually caused by artificial sources, such as traffic and machinery, and are sometimes called “microtremors”, to be distinguished from longer-period microseisms due to natural disturbances. At a typical station in the interior of a continent, the microseisms have predominant *periods* of about 6 seconds. They are caused by surf pounding on steep coastlines and the pressure from standing ocean waves, which may be formed by waves traveling in opposite directions in the source region of a storm or near the coast (Longuet-Higgins, 1950). Also called *double frequency microseism* and *marine microseism*. See Chapter 4 in this Manual, Webb (2002), Kulhanek (2002); also Aki and Richards (2002 or 2009), p. 616-617).

microzonation The identification and mapping at local or site scales of areas having different potentials for hazardous earthquake effects, such as *ground shaking intensity*, *liquefaction* or *landslide* potential.

mid-ocean ridge An undersea mountain range extending through the Arctic Ocean, the North and South Atlantic Oceans, the Indian Ocean, and the South Pacific Ocean, and consists of many small and slightly offset segments. Each segment is characterized by a central *rift* where two *tectonic plates* are being pulled apart and new oceanic *lithosphere* is being created. See Cox (1973), Uyeda (1978), Duff (1993), Hancock and Skinner (2000), and Uyeda (2002).

mitigation The proactive use of information, land use, technology, and societies' resources to prevent or minimize the effects of disasters on society. See O’Brien and Mileti (2003).

mixed dislocation See *dislocation*.

Mm See *mantle magnitude*.

modal A term referring to natural modes of vibration or their properties, for example, modal *damping*. See Jennings (2003).

mode 1 crack An opening crack in which *displacement* is directed normal to the crack surface. See section 4 and Figure 9 in Ben-Zion (2003).

mode 2 crack A shear crack in the plane strain mode. See *plane strain*, and section 4 and Figure 9 in Ben-Zion (2003).

mode 3 crack A shear crack in the anti-plane strain mode. See *anti-plane strain*, and section 4 and Figures 9 - 10 in Ben-Zion (2003).

moderate earthquake An earthquake with magnitude that ranges from 5 to 7 is often called "moderate". See *magnitude*.

mode shape The shape a structure assumes when it oscillates solely at one of its *natural frequencies*. Mathematically, a mode shape is an eigenvector of the eigenvalue problem posed by linear, free vibration of a structure. See Jennings (2003).

Modified Mercalli scale A *macroseismic* twelve-degree *intensity scale* (I to XII) published by Wood and Neumann (1931) (abbreviated MM). It is based on the translation into English by Wood and Neumann (1931) of the macroseismic scale published by Sieberg (1923), which in its later version (Sieberg, 1932) became widely known as the *Mercalli-Cancani-Sieberg scale*. Therefore, the name Modified Mercalli scale is inappropriately chosen. Even more, after Richter (1958) overhauled the Wood and Neumann version completely, thus becoming the "Modified Mercalli Scale of 1956" (MM56), which is only very remotely linked to Mercalli. Reference to the MM scale is further complicated by recent modifications introduced by Stover and Coffman (1993) to the 1931 version of the MM in conjunction with the revision of the *seismicity* of the United States between 1568 and 1989. This latest upgrade is now referred to as *MMI*. The MM scale is widely used, not only in the USA (although MMI has become there now most popular because of the "Did you feel it?" system maintained by the USGS), but also in many countries in and outside of North America**.** For details see Chapter 12 of this Manual, Musson et al. (2010) and Atkinson and Wald (2007).

MM scale See *Modified Mercalli scale*. A later revision by Richter (1958) became known as the version MM56.

MMI scale Recently modified version of the *MM scale* proposed by Stover and Coffman (1993). See *Modified Mercalli* seismic intensity *scale*.

Moho The abridged "knickname" for *Mohorovičić discontinuity*.

Mohorovičić discontinuity A *discontinuity* in seismic *velocities* that defines the boundary between *crust* and *mantle* of the Earth. Named after the Croation seismologist Andrija Mohorovičič (1857-1936) who discovered it. The boundary is at a depth of 20 to 60 km beneath the continents and 5 to 10 km beneath the ocean floor. See Fig. 2.11 in Chapter 2 of this Manual, Mooney et al. (2002), Minshull (2002), and the biography of Andrija Mohorovičič in Howell (2003).

Mohr diagram A two dimensional diagram of a particular plane (Mohr plane) of the three dimensional *stress* state. The Mohr plane contains two of the *principal stresses* $\sigma_i > \sigma_j$, and depicts the shear and *normal stresses* on planes of all possible orientation whose normals lie in the Mohr plane. Details on use and construction of Mohr diagrams can be found in Jaeger and Cook (1971). See Lockner and Beeler (2002).

moment connection A connection between elements of a structure that is capable of transmitting moment as well as shear force. In a *moment frame*, the joints between the beams and columns are typically designed to take the full moment developed in the beam. See Hall (2003), Dowrick (1977), and Salmon and Johnson (1996).

moment frame An unbraced planar frame. Moment frames resist lateral forces by flexure of the comprising beams and columns. See Hall (2003), and Dowrick (1977), Park and Paulay (1975), and Salmon and Johnson (1996).

moment magnitude (Mw) A non-saturing *magnitude* computed using the *scalar seismic moment* (M_O). It was introduced by Kanamori (1977) via the Gutenberg-Richter magnitude-energy relation. See Chapter 3 in this Manual and Bormann and Di Giacomo (2011) for details, also with respect to the relationship of Mw to the *energy magnitude* Me and the problem of *saturation (of magnitude scales).*

moment of force The tendency of a force applied to an object to cause the object to rotate about a given point, and this tendency is expressed by the equation, **N** = **r x F**, where **N** is the *torque*, **r** is the position vector from the origin to the point of application of force, and **F** is the total force acting on the point.

moment of inertia A component of *tensor of inertia J***,** calculated as **k*J*k,** is called moment of inertia relative to the axis with unit vector **k.**

moment tensor A symmetric second-order tensor that characterizes an internal *seismic* point *source* completely. For a finite source, it represents a point source approximation and can be determined from the analysis of *seismic waves* whose *wavelengths* are much greater than the source dimensions. See IS 3.9 of this Manual, Aki and Richards (2002 or 2009 p. 49-58), Sipkin (2002), and Section 2 in Ben-Zion (2003).

monitoring system A system for monitoring *earthquakes*, volcanic *eruptions*, *tsunami*, and/or other phenomena, usually consisting of a network of *seismic stations* and/or *arrays*, sometimes complemented by other types of sensors.

monogenetic volcano A small volcano that is of a type that generally has a single *eruption*, or short-lived eruptive sequence, during its lifetime.

Monte Carlo method Any mathematical method using at its core a random (or, more frequently, pseudo-random) generation of numbers. Monte Carlo methods are typically used to randomly explore high-dimensional spaces, where a systematic exploration is unfeasible. See Mosegaard and Tarantola (2002) and Tarantola (2005).

moveout The time difference between *arrivals* (such as P) at different stations, or between different arrivals at the same stations (like P and pP), which is also known as *step-out*.

M_S See *surface-wave magnitude*.

MSK scale See *Medvedev-Sponheuer-Karnik scale*.

Mt See *tsunami magnitude*.

mudflow Essentially synonymous with volcanic debris flow and *lahar*.

multi-degree of freedom A term applied to a structure or other dynamical system that possess more than a single degree of freedom. The number of degrees of freedom of a complex system is equal to the number of independent variables needed to fully describe the spatial distribution of its response at any instant. See Jennings (2003).

multiple lapse time window analysis A method to measure *scattering* loss and *intrinsic absorption* from the analysis of whole *S-wave seismogram* envelopes. This method is based on the radiative transfer theory for S-wave propagation through *scattering* media. See Sato et al. (2002), and Sato and Fehler (1998, p. 189).

Mw See *moment magnitude*.

mylonite A cohesive, penetratively foliated (and usually lineated) *fault*-rock (L-S tectonite) with at least one of the major mineral constituents (usually quartz) having undergone grain-size reduction through dynamic recrystallization accompanying crystal plastic flow. The mylonite series (protomylonite - mylonite - ultramylonite) reflects progressive reduction in grain size, generally under greenschist facies *metamorphic* conditions. See Sibson (2002, p. 458).

mylonitic gneiss A comparatively coarse-grained, banded mylonitic *fault*-rock (L-S tectonite) developed in a high-*strain ductile* shear zone under amphibolite facies *metamorphic* conditions, in which most of the mineral constituents have undergone dynamic recrystallization. See Sibson (2002).

N

Nakamura method See *H/V spectral ratio* and *spectral ratio*.

natural frequency The discrete *frequency* at which a particular elastic object or system vibrates when it is set in motion by a single impulse and not influenced by other external forces or *damping*. The reciprocal of *fundamental period*.

natural period The reciprocal of *natural frequency*.

N discontinuity A seismic boundary within the continental *lithosphere* at a depth of 60-120 km reported particularly in Eurasia. Also called "*Hales discontinuity*". See Mooney et al. (2002, p. 898).

Nakamura method See *H/V spectral ratio*.

near field and **far field** A *seismic source* radiates different types of *seismic waves* with different *amplitude* decays. Some of these seismic waves can only be observed in the vicinity of the source. In theoretical seismology usually all seismic wave types with an amplitude decay of r^{-1}, are called "far-field" terms, while those with a amplitude decay of r^{-2} are called "near-field" terms. If the *hypocentral distance* is large enough for the "near field" terms to become negligible one is in the "far field". The exact hypocentral distance, which separates "far field" and "near field", depends on the *frequency* of the seismic waves. Usually a distance of a few *wavelengths* from the source is considered as "far field", and a distance within a fraction of a wavelength is "near field", with intermediate distances requiring the examination of the effects of the individual terms (Aki and Richards, 1980, p. 88 and eqns. 4.23 and 4.35). However, in geology and earthquake engineering a simpler approach is taken: Locations more than about ten source dimensions from the source are in the *far field*, and those within one to several dimensions are in the *near field*.

neotectonics The study of the post-Miocene structures and structural history of the Earth's *crust*. The Miocene ended about 5 million years ago.

Newmark analysis A numerical technique that models a potential *landslide* as a rigid block resting on a frictional slope, describing dynamic forces on the block from assumed *ground shaking* records in order to calculate the expected *displacement* of the block.

newton (N) The SI derived unit for force. It is defined as the force which accelerates a mass of 1 *kilogram* to 1 *meter* per *second* per second, i.e., 1 N = 1 kg m s^{-2}. It is named after Isaac Newton (1642-1727) who formulated the three laws of motion.

noble gas A gas in group 0 of the periodic table of the elements (Neon, Argon, Krypton, Xenon, and Radon); it is monatomic and chemically inert. See King and Igarashi (2002).

node A reference point, typically a corner, in *finite element* analysis. Because the variation of field quantities of interest, such as *displacement*, *strain*, *velocity*, etc., are assumed to vary within finite elements in specified ways, their values become functions of values of key variables at the nodes. See *finite element* and Hall (2003).

noise In general: Unwanted part of data superimposed on a wanted *signal*. Noise is often modeled as a stationary random process, but may also contain signal-dependent components. One man's noise can be the other man's signal. More specific in seismology: Incoherent, natural or artificial perturbations caused by a diversity of agents and distributed sources. One usually differentiates between *ambient* background *noise* and *instrumental noise*. The former is due to natural (ocean waves, wind, rushing waters, animal migration, ice movement, etc) and/or man-made sources (traffic, machinery, etc.), whereas instrumental (internal) noise may be due to the "flicker" noise of electronic components and/or even Brownian molecular motions in mechanical components. Digital *data acquisition* systems may add *digitization noise* due to their finite discrete resolution (*least significant bit*). Very sensitive seismic recordings may contain all these different noise components, however, usually their resolution is chosen so that only *seismic signals* and to a certain degree also the ambient noise are resolved. Disturbing noise can be reduced by selecting recording sites remote from noise sources, by underground installation of seismic sensors (e.g., in boreholes, tunnels or abandoned mines) or by suitable *filter* procedures (improvement of the *signal-to-noise ratio*). See Chapter 4 of this Manual, Webb (2002), and Wielandt (2002).

noise level (of an instrument) See s*elf noise*.

non double-couple earthquake An earthquake produced by a source that includes *displacement* components other than simple shear displacements along a *fault plane* (a *double-couple* earthquake). Common examples include the abrupt extensional opening of a crack, the collapse of a cavity or a *compensated linear vector dipole* (CLVD). See Julian et al. (1998).

non-linear analysis In *earthquake engineering*, a calculation or theoretical development that includes material changes such as yielding or cracking, or the non-linear effects of large *displacements* such as the increased *moment* at the base of a structure caused by lateral displacements of floor masses. These effects cannot be considered within the framework of linear equations. See Jennings (2003).

nonstructural The parts of a building system that do not support loads (e.g., partitions, exterior claddings, lighting fixtures, etc.).

non-volcanic tremor Non-volcanic tremor is characterized by long lasting wave-trains of low-*frequency* components between 1 and 10 Hz and lack of distinct *P* or *S phases*. Unlike the frequently observed deep, low-frequency micro-earthquakes beneath active volcanoes, non-volcanic tremors are extremely large phenomena characterized by long time duration from hours to weeks and a wide source area, over 600 km in length (Obara et al., 2004). Non-volcanic tremor was first detected within *subduction zones* in southwest Japan and Cascadia and appears to be related to *slow-slip events* in these regions. Similar tremor is also observed in other *fault* settings such as the San Andreas fault system. Non-volcanic tremor is often associated with *aseismic slip*. See also *low frequency earthquakes, slow slip-events, episodic tremor and slip.*

normal distribution (or errors) Synonym for *Gaussian distribution*.

normal fault A *fault* that involves lateral extension, where one block (the *hanging wall*) moves over another (the *footwall*) down the *dip* of the *fault plane*, i.e., the movement of the hanging wall is downward relative to the footwall. The maximum compressive stress is vertical; the least compressive stress is horizontal. See *reverse fault*; also Figs. 3.105 and 3.106 in Chapter 3 of this Manual, Jackson (2002), and Figure 13 of Ben-Zion (2003).

normal modes Normal modes were originally defined as the linear, free vibrations of a system with a finite number of degrees of freedom, such as a finite number of mass particles connected by massless springs. Each mode is a simple harmonic vibration at a certain frequency called an “*eigenfrequency*” or *natural frequency*. There are as many independent modes as the number of degrees of freedom. An arbitrary motion of the system can be expressed as a superposition of normal modes. Free vibrations of a finite continuum body, such as the Earth, are also called normal modes. In this case, there are an infinite number of normal modes, and an arbitrary motion of the body can be expressed by their superposition. The concept of normal modes has been extended to wave-guides in which free waves with a certain *phase velocity* can exist without external force. Examples are *Rayleigh waves* in a *halfspace* and *Love waves* in a layered halfspace. In these cases, however, one cannot express an arbitrary motion by superposing normal modes. See Udias

(2002, p. 90-92), Lognonne and Clevede (2002), and Aki and Richards (2002 or 2009, Chapters 7 and 8).

normal stress Force per unit area exerted upon an infinitesimal area in the direction of the normal to that area. In most disciplines, tension across the area is reckoned positive; in geology, the opposite convention may be used. See also *shear stress*, Ruff (2002), and Figure 1 in Ben-Zion (2003).

nuée ardente A French term ("glowing cloud") that was first used to describe the deadly 1902 eruption of Montagne Pelée (Island of Martinique) that devastated the port city of St. Pierre (Lacroix, 1904). A nuée ardente is a density current consisting of hot *pyroclastic* fragments, volcanic gases, and air that flows at high speed from the *crater* region of a volcano — generally associated with the collapse of an eruption column or unstable *lava dome*. See *glowing avalanche*, *pyroclastic flow*, and *pyroclastic surge*.

Nyquist frequency Half of the digital sampling rate. It is the minimum number of counts per second needed to define unambiguously a particular *frequency*. If the *seismic signal* contains energy in a frequency range above the Nyquist frequency the signal distortions are called *aliasing*.

O

oblique slip A combination of *strike slip* and *normal slip* or *reverse slip*.

occurrence rate See *frequency of occurrence*.

ocean bottom seismometer/hydrophone (OBS/OBH) A receiver for seismic signals which is located at or near the seabed. An OBH is commonly moored a few meters above the seabed and has a single *hydrophone* sensor. An OBS commonly rests on the seabed and has in addition to a hydrophone a three-component *seismograph*, which may be inside the recording package or deployed as a separate package for better coupling. See sub-Chapter 7.5 of Chapter 7 in this Manual, and Minshull (2002).

oceanic spreading ridge A fracture zone along the ocean bottom that accommodates upwelling of *mantle* material to the surface, thus creating new *crust*. A line of ridges, formed as molten rock reaches the ocean bottom and solidifies, topographically marks this fracture. See *mid-ocean ridge* and *sea-floor spreading*.

oceanic trench A narrow and elongated deep depression of the sea-floor associated with a *subduction zone*. See Uyeda (1978), and Duff (1993).

octave (filtering) A term coming from music, defining distance between the eighth full tone above (or below) a given reference tone. The *frequency* doubles (or halves) between two tones separated by one octave. S*eismographs* typically record (filter) *ground motion* oscillations within a range of one (narrow-band) to 12 octaves (very broadband).

Okada model Closed form of analytic solutions for the static *displacement* field due to shear and tensile *faults* in a *homogeneous halfspace*. It has become a standard model used for calculating the displacement field for earthquake *fault slips* and *pressure* sources beneath volcanoes. See Okada (1985), and Feigl (2002, p. 612-613) with a computer program included on the attached Handbook CD#1, under the directory \37Feigel.

omega-squared model A widely used earthquake source model associated with the *far-field body-waves*. It is based on the *displacement amplitude spectrum* and is characterized by having a flat low-*frequency* part and a *power law* decay (with the power of -2) in the high-frequency part, separated by the *corner frequency*. The level of the flat low-frequency part is proportional to the *seismic moment* and the corner frequency is inversely proportional to the linear dimension of the source. See Hanks (1979) and Aki and Richards (2002, Chapters 10 and 11) for its observational and physical bases. The observed seismic spectra tend to be lower than predicted by this model at frequencies higher than a limit called *fmax*. A practical procedure for computing the time history of strong ground motion, including the *fmax* effect, was given by Boore (1983) based on this model. See *Brune model*, *seismic moment*, *corner frequency*, *fmax*, Fig. 3.5 in Chapter 3 of this Manual or on p. 1871 in Bormann et al. (2009), and Eq. (6.1) in Ben-Zion (2003).

Omori's relation (Omori's law) A relation expressing the temporal decay of the *frequency of occurrence* of *aftershocks*. Occasionally called “hyperbolic law”. The modified Omori relation generalizes it to a *power law* dependence on time with the power allowed to deviate from –1. See Utsu (2002b), and Eq. (7.4) in Ben-Zion (2003), and the biography of Fusakichi Omori in Howell (2003).

one-dimensional amplification of seismic waves In *site effect* studies a one-dimensional structure means a structure varying only in the vertical direction. It is also called a horizontally-layered structure. The *amplification* for incident *body waves* can be theoretically calculated by considering multiple transmission and *reflection* at each interface of horizontal layers including the free surface. There is no amplification for *surface waves* incident on such a structure since it is assumed to be *homogeneous* in the horizontal directions. See Kawase (2003).

onset (of seismic wave) The first appearance of an seismic *wavelet* on a record.

ophiolite A suite of mainly ultramafic and mafic rocks formed at *mid-ocean spreading centers* and along zones of convergence of oceanic crustal *plates*. On-land exposures of tectonically accreted sections of ophiolite are a primary means of studying the rocks that make up the oceanic *crust* and uppermost *mantle*. See Minshull (2002) and Dickinson (2002).

optimal survey design Optimal design of experiment or survey based on the *inverse* theory. See Curtis and Snieder (2002, p. 868-870).

organized noise Seismic *noise* whose power spectrum is not uniformly distributed, but is concentrated at particular *wavenumbers* and *frequencies*. See Douglas (2002).

origin time The instant of time when an earthquake begins at the *hypocenter*. It is usually determined from *arrival times* of *seismic waves* by the *Geiger's method*.

orogenesis See *orogeny*.

orogeny The process of crustal uplift, folding, and faulting by which systems of mountains are formed. See Uyeda (2002, p. 62-64).

orthogonal regression See *regression analysis*.

orthorhombic symmetry Symmetry with respect to three mutually orthogonal planes. There are 9 independent elastic parameters for an orthorhombic material. Olivine crystals are orthorhombic. See Cara (2002).

oscillator A mass that moves with oscillating motion under the influence of external forces and one or more forces that restore the mass to its stable at-rest position. In *earthquake engineering*, an oscillator is an idealized damped mass-spring system used as a model of the *response* of a structure to earthquake *ground motion*. A *seismograph* is also an oscillator of this type. See *single-degree-of-freedom* (SDOF) system.

outer rise Upward flexure of the oceanic *plate* before subducting beneath the *trench*.

outer arc ridge A zone landward from the trace of the *subduction thrust fault* of elevated sea floor probably related to the compression of the rocks in the *accretionary wedge*. Also referred to as the outer arc high.

oversampling A sampling technique in which the analog input *signal* is first sampled at a sampling rate much higher than the final sampling rate and subsequently decimated digitally. See Chapter 6 of this Manual and Scherbaum (2002).

P

P	General symbol for a *P-wave*. For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).
P'	Alternative phase name for PKP. For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).
pahoehoe	A common type of fluid *lava flow* produced by *Hawaiian eruptions*, pahoehoe in solidified form is characterized by a continuous, smooth, billowy or ropy surface. Like *aa*, the term is also of Hawaiian origin; both aa and pahoehoe have become universally accepted to describe lava flows of similar appearance and characteristics in the world over.
paleoearthquake	An ancient, usually prehistoric earthquake.
paleomagnetics	The study of the geomagnetic field existing at the time of formation of a rock, based on the remanent magnetization that was induced in the rock at the time of its formation and is still preserved today. See Uyeda (2002, p. 52-54), and Merrill and McFadden (2002).
paleomagnetic pole	An estimate of the geomagnetic pole of the Earth at a certain time in the past by averaging the paleomagnetic field over a sufficient long period of time, e.g., 10^4 to 10^5 years, from rocks which acquired the paleomagnetic field at that time. See Uyeda (2002), and Merrill et al. (1998).
paleomagnetism	All rocks exhibit magnetic properties imparted to them by the Earth's magnetic field at the time they were formed, and preserved to the present time as remanent magnetism. Paleomagnetism is the study of these properties, or the properties themselves. See Merrill and McFadden (2002).
palaeoseismic	Referring to the prehistoric seismic record as inferred from ruptural *displacements* in young geologic sediments in combination with $_{14}C$ *age* dating.
paleoseismic event	A *paleoearthquake* that caused surface faulting, *displacements* in young sediments, or other near-surface phenomena such as *liquefaction*. See Grant (2002).
paleoseismology	The study of (usually prehistoric) *paleoearthquakes*, i.e., centuries or millennia after their occurrence. See Grant (2002), and McCalpin and Nelson (1996).

Paleozoic An era in *geologic time*, from 545 to 245 million years ago.

Pangea A supercontinent (including most of the continental *crust* of the Earth) that was postulated by Alfred Wegener in 1912 to have existed from about 300 to 200 million years ago. Pangea is believed to have split into two protocontinents – *Gondwana* in the south and *Laurasia* in the north, from which the modern continents are.

parabolic approximation An approximation to the wave equation in which the second derivative with respect to the global *ray* direction is neglected. It can be justified when the *wavelength* is much smaller than the characteristic length of the *heterogeneity*. The wave equation then becomes parabolic in type. This approximation includes *diffraction* and *forward scattering*, but neglects *back-scattering*. See Sato et al. (2002).

parameter data A quantitative *attribute* of a seismic *arriva*l, such as *onset* or *arrival time*, *(back)azimuth*, *slowness*, *polarisation*, *period*, and *amplitude*.

paraxial ray Originally defined for an optical system with a symmetrical axis of *rotation*. A light ray near this axis and which has only a small inclination to the axis is called a paraxial ray. In *seismic ray* theory it is defined as a ray generated by perturbing the source position or take-off direction of a central ray. The *dynamic ray equation* governs the properties of the paraxial ray. See Chapter 9 in Lee et al. (2002).

partial autocorrelation function (PACF) Plays an important role in data analyses aimed at identifying the extent of the lag in an autoregressive model (see *autoregressive process*). The use of this function was introduced as part of the Box-Jenkins approach (Box et al., 2008) to time-series modeling, where by plotting the partial autocorrelative functions one could determine the appropriate lags **p** in an autoregressive AR(**p**) model or in an extended AutoRegressive Integrated Moving Average ARIMA(**p**,**d**,**q**) model. See Wikipedia.

participation factor A factor that apportions scaled versions of the input to a *multi-degree of freedom* system to the various modes of the system. The factor is not unique and depends on how the mode shapes are normalized. In one common normalization scheme the participation factors add to unity; in this case the participation factor for a mode is the fraction of excitation that mode receives. See Jennings (2003).

pascal (Pa) The *SI* derived unit for *pressure* or *stress*, named after Blaise Pascal (1623-62) for his pioneering work on hydrostatics. It is defined as a force of one *newton* per square *meter* (N m^{-2}), or (m^{-1} kg s^{-2}). In older seismological literature the unit for pressure and stress is usually expressed in the cgs unit bar, with 1 MPa (i.e., 10^6 Pa) = 10 bar.

passband The portion of the *frequency spectrum* that a *filter* passes with less than 3-*decibel attenuation*. See Ballou (1987).

passive margin A continental margin that is not a *plate boundary*, formed, for example, as *sea-floor spreading* carries the continental block away from the spreading center. If earthquakes occur on such a margin, they are *intraplate* events (q.v.). See also *active margin*.

passive-source seismology Seismic investigations that utilize data from naturally occurring *seismic events*. See Mooney et al. (2002).

path effect The effect of the propagation path on seismic *ground motions*. It is implicitly assumed that the *source*, path and *site effects* on ground motions are separable.

Pb, P* Designates *P waves* critically refracted (see *refraction*) through an intermediate layer in the Earth's *crust* with a *velocity* between ~6.5 and ~7.5 km/sec. The upper boundary of this layer has been called the *Conrad discontinuity*. An alternative, still accepted phase name is P*. For these and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

P coda The portion of *P waves* after the *arrival* of the primary waves. They may be due to P-to-S-wave *conversions* at *interfaces* or to multiple *reflections* in layers or to *scattering* by three-dimensional *inhomogeneities*.

peak acceleration See *peak ground acceleration*.

peak ground acceleration The maximum *acceleration amplitude* measured (or expected) in a strong-motion *accelerogram* of an earthquake, abbreviated PGA. See Anderson (2003).

pedogenic Pertaining to processes that add, transfer, transform, or remove *soil*.

Peléan eruption A type of eruption named after the 1902 eruption of Montagne Pelée, Martinique. It is associated with relatively viscous *magmas* (e.g., andesitic to rhyolitic compositions). The most violent and destructive activity generally occurs early in the eruption and commonly involves *nuées ardentes*, followed by emplacement of *lava domes* and thick *lava flows*.

pendulum In relation to the design of an *inertial sensor*, a pendulum is either (1) a mass moving strictly in a translational manner (Figure 1, bottom), as in most simple *geophones*; or (2) a mass attached by a rigid arm to a pivot axis orthogonal to that arm and to the active axis of the sensor, as in many *accelerometers* and broadband velocity sensors (Figure 1, top). A mass moving on a simple cantilever, as in many *MEMS devices*, is equivalent to (2), whereas the restoration of classical pendulums derives solely from the gravitational force, with springs.

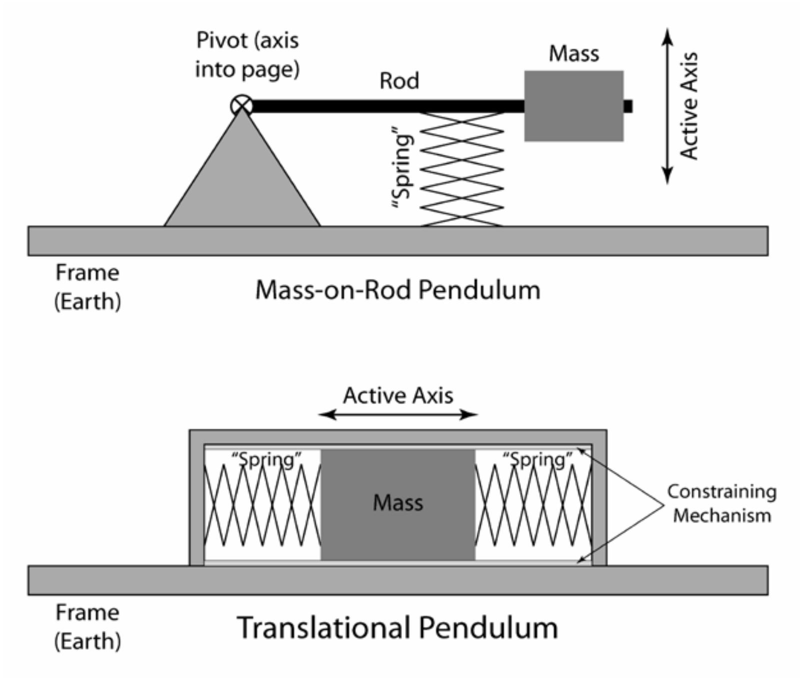

Figure 1. Schematic diagrams of a mass-on-rod pendulum (*top*) and a translational pendulum (*bottom*). The mass-on-rod pendulum moves in a circular arc about its pivot, here pointing into the page, and is parallel to the putative active axis only while at zero deflection. The translational pendulum is constrained by its suspension to move only in the active-axis direction. "Spring" is shorthand for all mechanical and force feedback restoring forces in combination.

They provide, either acting alone or in conjunction with *gravity*, the restoring force in common seismic pendulums. Nearly all pendulums are purposely damped by some means. The intended direction of (infinitesimal) mass motion relative to the instrument frame (thus the ground) is the *active axis* of the pendulum. Most seismic sensors are based on one or the other of these forms of constrained pendulums, although a few are based on magneto-hydrodynamic and other phenomena. In the simple or common pendulum, the mass is below the pivot, and constrained to move in a vertical plane; in the inverted pendulum, the mass is directly over the pivot; and in the horizontal pendulum, the mass is to one side of the pivot, and is constrained to move in a nearly horizontal circle. See Chapter 5 (pp. 15-18 and Fig. 5.4-5.7) in this Manual.

pendulum (gravitational) A classic instrument first studied by Galileo and Newton, a structure without springs, in which the line between the *rotation* axis (in the original, a fixed point) and the center of mass oscillates with dampened simple harmonic motion (in the linear approximation) about the direction of the local gravitational field of the Earth. Its equilibrium orientation is the plumb line. See Fig. 5.5 in Chapter 5 of this Manual.

pendulum (mass-on-rod) A pendulum (Figure 1, top) that rotates about some axis with the mass on the other end of a rigid rod, or with the mass at the end of a stiff cantilever spring (the pendulum of many modern force-balance *accelerometers* and *broadband seismographs*). Because the rod can also rotate away from the normal to the activeaxis, this design may be affected by translational accelerations along the axis of the rod while it is offset, although such offsets are minimized in force-feedback and stiff (e.g., *MEMS*) designs. Mass-on-rod pendulums also are directly affected by *rotational accelerations* about the pivot axis. See also Figs. 5.4 to 5.7 of Chapter 5 in this Manual.

pendulum, translational A mass-on-spring pendulum (Figure 1, bottom) where the mass moves only along a linear translational path relative to the sensor's case (the mass and multiple constraining cantilever springs of a common geophone or a few *MEMS devices* in which multiple cantilevers and careful design obviate any effects of rotation). This design has minimum sensitivity to off-axis translational and *rotational accelerations* but is sensitive to *Coriolis forces*.

peridotite Rock comprising the uppermost *mantle*, composed mainly of olivine [(Mg, Fe)2SiO_4] and pyroxene [(Mg, Fe, Ca)SiO_3]; other minerals, such as garnet, can also be present.

period The length of time required to complete one cycle or a single oscillation of a periodic process. See *natural period* or *natural frequency*.

period (of a signal) Most *seismic signals* are aperiodic but can be mathematically represented as a superposition of periodic sinusoidal signals. The "period of a seismic signal" usually means the period of the dominant sinusoidal signal.

permeability (hydraulic) Rate of fluid flow through rock per unit *pressure gradient*. See Johnston and Linde (2002), and Johnston (2002).

permeability (magnetic) A coefficient relating magnetic flux density to magnetic field intensity. See Johnston (2002).

permittivity A constant relating the force between two charges separated by a distance. See Johnston (2002).

perovskite A dense, high-pressure phase of pyroxene [[(Mg, Fe, Ca)SiO_3]; it is only stable at high *pressures* (above ~20 GPa), but is thought to be the predominant mineral of the Earth's *mantle*. See Jeanloz (2002).

Pg, $\overline{P}$

Travel-time curves at short distances (up to a few hundred km) for *seismic sources* in the Earth's *crust* usually consist of two intersecting straight lines; one with a *velocity* of about 6 km/sec at shorter distances and the other with a velocity of about 8 km/sec at greater distances. The former is attributed to direct *P waves* propagating through the crust and is designated as Pg, which stands for granitic layer. An alternative, older name has been $\overline{P}$**,** which is no longer standard. For these and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

PGA

See *peak ground acceleration*.

Phanerozoic

An eon in *geologic time*, from 545 million years ago to the present. It is from Greek and means "apparent life".

phase

(1) A stage in periodic motion, such as wave motion or the motion of an *oscillator*, measured with respect to a given initial point and expressed in angular measure. (2) A pulse, *wavelet* or group of seismic *body*- or *surface-wave* energy arriving at a definite time, which passed the Earth on a specific path (see also *phase nomenclature*). (3) Stages in the physical properties of rocks or minerals under differing conditions of *pressure*, temperature, and water content.

phase names

Seismograms consist of distinguished *onsets* of different *phases*. During the last 120 years, seismologists deciphered the principle character and the travel paths through the Earth of most of these onsets and developed a nomenclature to name them. The newest version of these naming rules was accepted by *IASPEI* in 2003 during its General Assembly in Sapporo. A detailed description of these rules, many examples of phase names and explaining plots to the different *seismic wave* paths can be found in IS 2.1 in this Manual or in Storchak et al. (2003 and 2011).

phase response

The phase of the complex *frequency response*, e.g., of a *seismograph*.

phase velocity

Frequency-dependent *velocity* of propagation of a specific *phase* position (angle) in a dispersive wave train, such as a *surface-wave* group. See also *group velocity*.

phreatic

Adjective of Greek origin (from phrear, "well") relating to ground water. Commonly applied to explosive *eruptions* triggered by interaction of water with *magma* or solidified but still hot volcanic rock that eject steam and fragments of preexisting solid rock (lithics), but not magma. “Phreatic” is synonymous with “*steam-blast*”.

phreatomagmatic eruption Volcanic *eruption* that results partly from the interaction of external water and *magma*, resulting in explosive conversion of water to steam and disruption of the erupted *lava*.

physical master model A type of *master model of earthquakes* in which universally applicable laws of physics and chemistry are applied to geologic processes to integrate earth science information regarding earthquakes in a given region. Its construction has been an ultimate goal beyond that of the hazard master model at the Southern California Earthquake Center. See Aki (2002).

piercing line A term in *paleoseismology* indicating a feature that crosses a *fault*. The point where a piercing line intersects a fault is called “piercing point”. See Grant (2002).

piezomagnetism Changes in rock magnetism resulting from *stress* loading. See Johnston (2002).

pillow lava Type of submarine *lava flow* resulting from underwater volcanic *eruptions*, or from the entry of lava erupted on land into the ocean, with formation of bulbous and tubular masses with glassy surfaces upon chilling in water.

pinned connection A connection that can transmit shear but not *moment*, like a hinge. Historically, actual pins were used in such connections, particularly in bridges, but in modern construction most such “pinned joints” are welded or bolted joints not designed to transmit significant moments. See Dowrick (1977), and Salmon and Johnson (1996).

PKIKP Symbol for a *P wave* transmitted through the outer and *inner core* of the Earth; an alternative phase name for the PKPdf branch. See Chapter 2, Fig. 2.54, Chapter 11, Figs. 11.73 and 11.77, Figures 1, 2 and 5 of EX 11.3 in this Manual; also Kulhanek (2002, p. 342), and Cara (2002, p. 880-881). For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

PKJKP A *P wave* that travels as a converted *shear wave* through the solid *inner core* (known as a J wave). The PKJKP phase, though ardently sought, has yet to be reliably observed. See Song (2002). For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

PKPpre PKP phases become the first geometric *arrivals* beyond the *core shadow*. However, sometimes on short period *seismograms* at a distance range of about 128º to 145º, clearly visible waves arrive a few to 10 seconds prior to the PKP phases. The addition pre stands for precursory. These precursors are explained by *scattering* at *heterogeneities* in the lowermost *mantle* (*D''*) or near or at the *core-mantle-boundary*. See Kulhanek (2002, p. 341-342), and Song (2002). For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

PKP triplication This *triplication*, which has three distinct *branches* of a *seismic phase* at the same distance, is the result of wave propagation through a zone of steep *velocity* changes with depth within the Earth's *core*. At distances between ~ 145° and 155° all three PKP phases PKPab, PKPbc, and PKPdf can be observed. (see Figs. 11.72, 11.73, 11.76 and 11.77in Chapter 11 of this Manual). For these and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

planar frame An assemblage of vertical columns and horizontal beams, with or without inclined braces, where all members lie in a single plane. See Park and Paulay (1975).

plane strain Also called in-plane *strain* in contrast to *anti-plane strain*; used to simplify mathematical analysis of elastic problem, in which *displacement* depends on only two spatial coordinates and its direction lies in the plane of those coordinates. *Dip-slip* displacement that does not vary along *strike* is an example of plane-strain *deformation*. Another example is a *Rayleigh wave* from a line source. See *anti-plane strain*; also Love (1944).

plane wave A wave for which the constant-phase surfaces are planes perpendicular to the direction of propagation. See *spherical wave*, *inhomogenous plane waves*; also Chapter 9 of this Manual, Aki and Richards (2002 or 2009, p. 119-187), and section 3 of Ben-Zion (2003).

plastic hinge A term given to a point on a structural element, typically a beam or column, where the element has yielded to the extent that increased curvature occurs without an increase in the resisting moment. See Bolt and Abrahamson (2003).

plastic strain rate Irreversible *strain* rate expressed by a tensor. See Teisseyre and Majewski (2002).

plate Here the same as *tectonic plate*. In *tectonics*, a plate is an internally rigid segment of the Earth's *lithosphere* which is in motion relative to other plates and to deeper mantle beneath the lithosphere. See *plate motion*, *plate tectonics*, and Uyeda (2002), and Stein and Klosko (2002).

plate boundary (zone) The zone of diffuse *deformation*, often marked by a distribution of *seismicity*, *active faulting*, and rough topography, within which relative *plate motion* is accommodated. Plate boundary zones are typically narrow under oceans and broad under continents. See Stein and Klosko (2002).

plate driving force A forces that drives the motion of Earth's *lithospheric plates*. Terms such as “*ridge push*”, “*slab pull*” and “basal shear” have been used to describe them. See Zoback and Zoback (2002).

plate motion The geometrical combination of three fundamental kinds of relative plate motions produces the observed *plate* patterns on Earth. Pairs of plates in contact at mutual boundaries either move apart (plate divergence), toward one another (plate convergence), or slip sideways past one another along structural ruptures (*transform faults*). The topology of *plate boundaries* on a sphere also dictates that three plates locally meet at common junctures (*triple junctions*), which may involve any of the three kinds of plate boundaries in any combination. The present Earth may be divided into six major and six smaller plates, with various additional “microplates” that jostle between the larger plates along some plate boundaries. See *Euler vector*. See also Uyeda (2002), and Stein and Klosko (2002), and Dickinson (2002).

plate tectonics The *lithosphere* of the Earth is broken into six major, and six smaller *plates* and various microplates that are in relative motion with respect to each other, over the underlying hotter and more fluid *asthenosphere*. Plate tectonics is the single coherent theory which reconciles *continental drift*, *sea-floor spreading* and deep focus earthquakes and explains (most) of the *tectonic* phenomena such as folding, faulting, rifting as well as related seismic and volcanic activity as the result of the interaction between or fragmentation (break-off) of lithosphere plates. Thus, plate tectonics provides a modern paradigm for the whole Earth science community. See Uyeda (2002), Stein and Klosko (2002), and Dickinson (2002). See also *plate motion*, *inter-plate* and *intra-plate*.

Pleistocene An epoch in *geologic time* between about 10,000 and 1,6 million years before present. As a descriptive term applied to rocks or *faults*, it marks the period of rock formation or the time of most recent *fault slip*, respectively. Faults of Pleistocene age may be considered active though their activity rates are commonly lower than for younger faults.

Plinian eruption Explosive *eruption* that generates a high and sustained *eruption column*, producing *fallout* of *pumice* and *ash*.

plume See *mantle plume*.

PL waves A train of long-*period* (30 to 50 seconds) waves observed in the interval between *P waves* and *S waves* for distances less than about 30°. They show normal *dispersion* (longer periods arriving earlier). They are explained as a *leaking mode* of the *crust-mantle* waveguide with P to *Rayleigh wave* conversion. See Aki and Richards (2002, p. 323). For these and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

Pn According to the *IASPEI* standard *phase name* list Pn is a *P wave* bottoming in the *upper mantle* or an upgoing P wave from a source in the uppermost mantle (see IS 2.1 in this Manual and Storchak et al. (2003 and 2011). This differs to some extent from earlier related definitions and considerations. Beyond a certain critical distance, usually beyond 100 to 200 km depending on crustal thickness and source depth, the first *arrival* from *seismic sources* in the *crust* corresponds to waves refracted under a (near) critical angle from the top of the mantle. The *amplitudes* of Pn waves are relatively small, with long-period motion followed by larger and sharper waves of shorter period called *Pg*, which propagated directly through the crust. Yet, at *epicentral distances* between some 300 to 600 km the *Moho* reflected PnPn may be the first strong arrival after Pn with sometimes rather large amplitudes. The Pn wave has long been interpreted as a *head* (*conical*) *wave* along the *interface* between two *homogeneous* media - namely, crust and mantle. The observed amplitude, however, is usually greater than that predicted for head waves, implying that the *velocity* change at the crustal base (*Mohorovičić discontinuity*; *Moho*) is not exactly step-like but has a finite *gradient* at or below the transition zone. The designation Pn is commonly applied to short-period P waves that propagate over considerable distances (even up to 20° in continental platform regions) with horizontal *phase velocities* in the range of ~7.5-8.5 km/s. This can also not been explained in terms of head wave propagation at the Moho (although the horizontal velocity and *travel times* would agree with it), because head waves must decay rapidly with distance. More likely is an explanation in terms of *guided waves*, within a high-Q layer several tens of kilometers in thickness at the top of the mantle. See *Sn*; also record examples in Chapter 2 (Figs. 2.17, 2.46 and 2.47), Chapter 11 (Figs. 11.58-11.60) and DS 11.1 of this Manual, Kulhanek (2002, p. 335-338), and Mooney et al. (2002). For these and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

point process A series of events distributed according to a probabilistic rule. See Utsu (2002b).

point rotation Rotational motions nominally of an infinitesimal point, generally measured by a dedicated *rotational sensor* either deployed on a small rigid pad or attached to some point in a structure.

point seismic array Co-located, inertial three-component *seismograph*, *rotational sensor*, and/or *strain meter* that can be used to perform seismic wave *gradiometry*. Although wave measurements are taken at a single observation point on the Earth, wave gradiometry produces estimates of wave parameters, such as horizontal *slowness* and *azimuth*, similar to large-aperture *arrays* of seismographs constructed for *beamforming* or *frequency-wavenumber analysis*. See *seismic array*.

point source Idealized, mathematical model of a *seismic source*, considered as the assumed startpoint (in time and space) of a rupture process.

point string deformation The point *deformation* with the simultaneous extension and contraction perpendicular to each other and of the equal values.

Poisson distribution A probability distribution that characterizes discrete events occurring independently of one another in time. See Vere-Jones and Ogata (2003).

Poisson process A point process in which events are statistical independently and uniformly distributed with respect to the independent variable, e.g., time. See Utsu (2002b).

Poisson's ratio An elastic body like a metal bar under uniaxial tension shows elongation along the tension axis and shrinkage in the transverse direction. The absolute ratio of the transverse *strain* to the longitudinal strain is called Poisson’s ratio. Poisson’s ratios for rocks are typically around 0.25. See Fig. 2.2 in Chapter 2 of this Manual as well as Christensen and Stanley (2003), Eq. (1.6) in Ben-Zion (2003), and the biography of Simeon Denis Poisson in Howell (2003).

polarity In *seismology*, the direction of *first motion* on a vertical component *seismogram*; either up (compression) or down (dilatation or relaxation).

polarity reversal In seismology, the occurrence of *waveforms* that are mirror images of their own, e.g., the waveforms of *depth phases* with respect to their primary *P* or *S waves*.

polarization Direction of particle motion relative to the direction of wave propagation. It differs for different types of *seismic waves* such as *P*, *S* and *surface waves* and may be ± linear or elliptical, prograde or retrograde. It is also influenced by *heterogeneities* and *anisotropy* of the medium in which the seismic waves propagate and depends on their *frequencies* or *wavelengths*, respectively. The polarization of *ground motion* may be reconstructed by analyzing three-component seismic recordings. See *Christoffel matrix*, *shear wave splitting*, *seismic anisotropy* and *earthquake focal mechanism*.

polarization anisotropy A term used (in contrast to *azimuthal anisotropy*) to refer to an *anisotropic medium* in which the *seismic-wave* properties depend apparently on the *polarization* of the waves, and not on the *azimuth* of their propagation direction. *SH*/*SV velocity* differences and *Love-Rayleigh wave* discrepancies are often referred to as "polarization anisotropy" while azimuthal velocity variations would be due to "azimuthal anisotropy". See Cara (2002).

polar tensor (vector or scalar) An object which does not depend on the orientation of a co-ordinate system. Examples of polar objects: *stress tensor,* force, translational velocity, and mass. Polar objects cannot be equal to axial objects and are often related to the translational motions.

polar wandering The movement of geographic or *paleomagnetic poles* over *geologic time*. See Uyeda (2002), Uyeda (1978), and Duff (1993).

poloidal See *spheroidal*.

polygenetic volcano A long-lived volcano that has erupted repeatedly throughout its lifetime, often in an episodic manner.

pore-fluid factor The ratio of fluid pressure to overburden *pressure* ($\lambda_v = P_f / \sigma_v$) employed as a measure of the degree of overpressuring. For typical rock *densities*, λ_v ~ 0.4 and λ_v = 1.0 denote hydrostatic and lithostatic fluid-pressure conditions, respectively. See Sibson (2002).

pore pressure In soil mechanics, the *pressure* within the fluid that fills voids between soil particles. In rock mechanics, the pressure due to liquids in formations that offsets the strengthening effect of *normal stresses* acting on a *fault*. At a given depth, the ambient pore pressure is often observed to be nearly equivalent to that of a column of water extending upward to the ground surface, a pore pressure regime termed the hydrostatic. See Johnston and Linde (2002), McGarr et al. (2002), and Youd (2003).

porosity The volume of voids per unit volume of a porous material usually expressed as a percentage.

poststack seismic data A term in *reflection seismology*; seismic data set reduced by the *stacking process* such that each surface location is represented by a single stacked seismic trace. See *prestack seismic data*.

potency See *seismic potency*.

power — In general terms, the source of physical or mechanical force or energy; in mathematics, the product of the multiplication of a quantity by itself (e.g., 4 is the second power of 2, i.e., 2^2); in a more general sense, the exponent to the base, which may also be a non-integer, and negative number.

power law — The mathematical relationship between two quantities X and Y, if $Y = X^n$ with a power (exponent) $n \neq 1$. E.g., when the frequency of occurrence of earthquakes varies as a power of earthquake size, then the *frequency* is said to follow a power law. Many physical, biological, geological, man-made and other phenomena follow a power law.

power spectral density — The power spectral density of a stationary time series is defined as the *Fourier transform* of its *auto-correlation function*. The power spectral density integrated over the whole *frequency* range is equal to the mean square of the time series, hence the name "spectral density". There is a factor 2 difference depending on whether the frequency range is taken from 0 to ∞ or $-\infty$ to $+\infty$. See Chapter 4 in this Manual and Aki and Richards (2002 or 2009, p. 610-611).

PP, PPP, PS, PPS etc. — Single, respectively double *reflection* (or *conversion to S*) at the free surface of a *P wave* leaving a source downward. See also *PzP*. For these and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

precision — The closeness with which separate observations (or parameter values calculated from observed data on the basis of a model) agree with each other. According to Bevington and Robinson (2003) a measure of how carefully a result is determined without reference to any "true" value (in contrast to *accuracy*).

precursor time — The time span between the onset of an anomalous phenomenon and the occurrence of the *mainshock.*

pre-event memory — In a triggered recording system of a digital *seismograph*, it refers to a signal buffering memory in the *data logger* from which the *ground motion* can be retrieved for a time segment prior to the time the instrument was triggered.

preliminary tremors — In early seismological studies, the term was used for the small motions at the start of an earthquake record. For *local earthquakes,* this corresponds to the waves arriving between the (in modern terms) first *P* and main *S arrival*. Omori found that its duration (or time difference between *S* and *P onset*) is proportional to the *epicentral distance* by a factor of about 8 km/sec; distance = 8 × (S – P onset time). See biography of Fusakichi Omori in Howell (2003).

pressure If a material element has zero "shear stress", then the *principal stresses* all share the same value; this value is the negative pressure. Any rotation of the coordinate system produces the same value for the *normal stresses*, hence a stress state with zero shear stress is *isotropic* and the *stress tensor* can be written as the product of the scalar quantity "pressure" and the identity matrix. Even if shear stresses are present, the isotropic component of the stress state can be extracted from the general stress tensor. The pressure is simply the average value of the three normal stresses regardless of the coordinate system orientation. See Ruff (2002).

pressure solution Water-assisted *ductile deformation* mechanism whereby minerals are sequentially dissolved from highly stressed regions, transported through fluid by diffusion or advection, and precipitated in low *stress* regions. See Lockner and Beeler (2002).

prestack seismic data A term in *reflection seismology* referring to the entire seismic data set before reduction by the *stacking process*. See *poststack seismic data.*

primary seismic station *Seismic station* or *array* of the International Monitoring System (IMS) that is part of the detection network to monitor compliance with the Comprehensive Test-Ban Treaty (CTBT). See Chapter 17 of this Manual.

principal axes In general, the principal axes are the eigenvectors of a symmetric tensor, i.e., the three orthogonal axes at which the rotated tensor has only diagonal elements. They can, for example, characterize the orientation of the *stress* and the *strain* at a point, and need not be tied to the geographic coordinate system. For example, in the case of the *seismic moment* tensor corresponding to a *double couple* source, the principal axes are called the compression axis, tension axis and null axis. With respect to seismic signals, as proposed by Penzien and Watabe (1975), the principal axes are a system of Cartesian coordinates on the ground surface for which three seismic signals, viewed as stochastic processes along respective axes $u_x(t)$, $u_y(t)$, and $u_z(t)$, are least correlated. The system of principal axes is expected to be situated in such a way that one of the three axes is perpendicular to ground surface and one is directed toward the *epicenter*.

principal displacement zone (PDZ) The zone of concentrated *slip* (sometimes referred to as the *fault* core) accommodating most of the *displacement* within the more distributed *deformation* (damage zone) defining a major *fault zone*. See Sibson (2002).

principal part (of seismogram) In early seismological studies, the term used for the largest motions seen on the *seismogram* from an earthquake. See Agnew (2002).

principal plane (of shear fracture) The most favorably oriented plane for shear fracture. Given planes of equal shear strength and of all possible orientations, the principal plane is that which minimizes the work done in shear. The orientation is given by $\tan 2\beta = 1/\mu_*$, where β is the angle between the greatest *principal stress* and the normal to the plane of interest, and μ_* is the coefficient of *friction* for a *fault* or the coefficient of internal friction for an intact rock. See Lockner and Beeler (2002, p. 508).

principal stresses The three *normal stresses* in the particular coordinate frame (principal axes) oriented so that the *stress* tensor reduces to diagonal form (i.e., no shear stresses). See Ruff (2002), Harris (2003), and Figure 1 in Ben-Zion (2003). See also *normal stress*, *shear stress*, and *principal axes*.

principle of material objectivity Also termed material frame indifference, because the constitutive laws governing the internal interactions between the parts of a physical system should not depend upon the external frame of reference used to describe them. For continuous media, this implies that *stress* and *couple-stress tensors* have to rotate together with the material when subjected to a rigid motion and not depend upon its translational part.

prior information The information one may have on the parameters characterizing a system, prior to any actual measurement. See Mosegaard and Tarantola (2002).

probabilistic earthquake scenario A representation, in terms of useful descriptive parameters, of earthquake effects with a specified probability of exceedance during a prescribed period in an area. See Faccioli and Pessina (2003).

probabilistic seismic hazard analysis (PSHA) Available information on earthquake sources in a given region is combined with theoretical and empirical relations among earthquake *magnitude*, distance from the source and local site conditions to evaluate the exceedance probability of a certain *ground motion* parameter, such as the *peak acceleration*, at a given site during a prescribed period. See Aki (2002), and Somerville and Moriwaki (2003).

probability density A function of a continuous statistical variable whose integral over a given interval gives the probability that the variable will fall within that interval. See Vere-Jones and Ogata (2003).

probability of exceedance The probability that, in a given area or site, an earthquake *ground motion* will be greater than a given value during some time period. See Giardini et al. (2003).

probable maximum loss (PML) A probable upper limit of the *losses* that are expected to occur as a result of a damaging earthquake, normally defined as the largest monetary loss associated with one or more earthquakes proposed to occur on specific *faults* or within specific source zones.

prograde branch See *branch (of travel-time curve).*

Proterozoic An eon in geologic time, from 2.5 billion to 545 million years ago. It is from Greek and means “first life”. *See geologic time*.

protolith The original rock from which a particular *metamorphic rock* is eventually formed.

PSD See *power spectral density*.

pseudotachylyte A black aphanitic *fault*-rock retaining evidence of a melt origin (relic glass, devitrification or quench textures) attributed to heat generated by localized *seismic slip*. Also developed in association with impact structures or at the base of some *landslides*. See Sibson (2002).

pseudo vector A quantity that behaves as a vector as long as the handedness of the coordinate system (i.e., it is right- or left-handed) remains unchanged. Changing the handedness changes the direction of the quantity. For this reason, vectors cannot be equated to pseudo vectors (see, e.g., Pujol , 2009) An example of a pseudo-vector is the vector product of two vectors. Pseudo vectors are also known as axial vectors. See a*xial tensor***,** *vector or scalar***.**

PSHA See *probabilistic seismic hazard analysis.*

pull-apart basin A topographic depression produced by extensional bends or stepovers along a *strike-slip fault*.

pumice Low-*density* fragments of silicate glass (generally of dacitic to rhyolitic composition) containing few crystals but a large fraction of gas bubbles (voids) due to exsolution of gas from *magma* during eruption. See *scoria*.

push over analysis An analysis used to estimate the capacity of a structure to resist collapse from strong *ground motion*. Typically used in earthquake resistant design studies, the analysis employs a selected force profile that is increased in intensity until the analysis indicates a structural element will fail or yield. That member is replaced by its yielding resistance, or removed if failed, and the force profile increased until another member yields or fails. The process is repeated until the overall structure has a constant or declining resistance under increased load. The deflection profile at this final stage approximates the structure's ultimate, non-linear, earthquake resistance. See Bolt and Abrahamson (2003).

p value The exponent of the time factor in the modified *Omori relation* showing the rate of decay of *aftershock* occurrence. A higher p value indicates more rapid decay. Estimated p values for most aftershock sequences fall between 0.9 and 1.5. In the original Omori relation, the p value is fixed as 1. See Utsu (2002b).

P wave A symbol for a *seismic body wave* that involves particle motion (alternating compression and dilatation) in the direction of propagation. P waves travel faster than *S waves* and, therefore, arrive earlier in the record of a *seismic event* (P stands for "unda prima" = primary wave). The particle *displacement* associated with P waves (for a classical linear elastic continuum in an *isotropic far field*) is parallel to the direction of wave propagation. For this reason, P waves are sometimes called longitudinal waves. See Chapter 2 in this Manual and Aki and Richards (2002, p. 122). In isotropic media, the *curl* of the P-*wave field* (i.e., rotational motion) is zero. However, this is not so in general, for instance, for anisotropic or *Cosserat continua*. For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

pyroclast A general term of any fragment of *lava* ejected during an explosive volcanic *eruption*; by definition, pyroclastic deposits are composed of pyroclasts.

pyroclastic Adjective of Greek derivation (from pyr, "fire"; klastos, "broken") relating to fragmental materials formed by the shredding of molten or semi-molten *lava* and (or) the shattering of pre-existing solid rock (volcanic and other) during explosive *eruptions*, and to the volcanic deposits they form.

pyroclastic flows Ground-hugging mixtures of hot, generally dry, pyroclastic debris and volcanic gases that sweep along the ground surface at extremely high velocities (< 250 km/h). A continuum exists between pyroclastic flow and *pyroclastic surge*, depending on the ratio of solid materials to gases. Because of its relatively high aggregate density, the movement of pyroclastic flows tends to be more controlled by topography, mostly restricted to valley floors.

pyroclastic surges Though part of a continuum with *pyroclastic flows*, pyroclastic surges have relatively lower ratios of solid materials to gases (lower aggregate *density*). In contrast to pyroclastic flows, the less dense, more mobile surges are less controlled by topography and can affect areas high on valley walls and even overtop ridges to enter adjacent valleys.

PzP This wave is like the surface *reflection PP*, except that the reflection occurs at an *interface* at depth z (expressed in kilometers, e.g., P600P) instead of at the surface. Similarly, for *conversions from P to S* one writes PzS (or vice versa). The new *IASPEI* phase name standards additionally differentiate with a + or – sign, whether this reflection/conversion occurred on the outer (upper) side (+) or on the inner (lower) side (-) of a *discontinuity*; e.g., P660-P is a P reflection from below the 600 km discontinuity, which means this phase is a precursory to PP For examples see Figs. 2.68-2.70 in Chapter 2 and for other such symbols used in *seismic phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

Q

Q factor So-called quality factor, which is a measure of the dissipative characteristics of a system or a material, proportional to the inverse of the fractional loss of energy per cycle of oscillation. See also *Q inverse* and Eq. (3.9) in Ben-Zion (2003).

Q inverse (Q^{-1}) The reciprocal of the *Q* value is the fractional loss (*attenuation*) of wave energy per cycle divided by 2π. It is called spatial Q^{-1} if measured from the *amplitude* attenuation with distance and temporal Q^{-1} *attenuation* if measured from that with time. They can be different for dispersive waves. See Aki and Richards (2002, Box 5.7, p. 162-163).

quasi-isotropic ray theory Quasi-isotropic ray theory describes *rays* in weakly *anisotropic* media and includes the coupling between quasi-shear rays. The quasi-isotropic ray *ansatz* depends on the *signal period* and the anisotropic part of the model parameters. See Chapman (2002).

quasi-plastic (QP) regime That portion of the *crust* or *lithosphere* where *fault* motion is governed by localized *ductile* shearing in which temperature-sensitive crystal plastic and/or diffusional flow mechanisms dominate. See Sibson (2002).

Quaternary A period in *geologic time*, from 1.6 million years ago to the present.

quiescence A significant decrease in the rate of background *seismicity* from the long-time average rate.

R

radar An acronym for RAdio Detection And Ranging. Synthetic aperture radar (*SAR*) *interferometry* is increasingly used by seismologists for analyzing the real surface *deformation* due to strong *earthquakes* and for deriving therefrom information about the rupture mechanism. See *satellite interferometry* and Feigl (2002).

radial anisotropy A term sometimes used to denote hexagonal symmetry with a vertical symmetry axis. Traditionally called *transverse isotropy*. See Cara (2002).

radiation damping The dissipation of energy through the transmission of vibratory energy that is not reflected or confined. Radiation *damping* occurs, for example, in the idealized problem of a vibrating structure imbedded in a linear, elastic *halfspace*, even when the material of the halfspace is not dissipative. See Jennings (2003).

radiation efficiency A term introduced by Husseini (1977), which corresponds to the ratio between radiated *seismic energy* and the potential energy available for *strain* release. In contrast to *seismic efficiency*, the radiation efficiency accounts only for strain energy loss due to fracturing but not due to the additional conversion into frictional heat and sound energy. Therefore, values of radiation efficiency are significantly larger than those of *seismic efficiency*. Whereas the former ranges for most earthquakes between 0.25 and 1 (although they may drop even below 0.1 for very slow rupturing *tsunami earthquakes*) the seismic efficiency is estimated to be only a few percent. See Kanamori and Brodsky (2004), Bormann and Di Giacomo (2011) and *seismic efficiency*.

radiation pattern Dependence of the *amplitudes* of seismic *P* and *S waves* on the direction and *take-off angle* under which their *seismic rays* have left the *seismic source*. It is controlled by the type of *source mechanism*, e.g., the orientation of the *earthquake fault plane* and *slip direction* in space. See *earthquake focal mechanism*, Chapter 3 and Ex 3.2 in this Manual, and Eq. (3.7b) in Ben-Zion (2003).

radiative transfer theory A phenomenological theory that describes a multiple *scattering* process based on causality, *geometrical spreading*, and the energy conservation law, which neglects the interference between wave packets. It is often applied to model the propagation of high-*frequency seismic-wave* energy in *heterogeneous* Earth media. See Sato et al. (2002), and Sato and Fehler (1998, p. 173).

radiocarbon dating *Geochronology* using radioactive ^{14}C *age dating*. See Grant (2002).

radiogenic heat production The rate of heat generated in a unit volume of rock by spontaneous radioactive decay of natural unstable isotopes in the rock. The primary heat producing isotopes in the Earth are ^{232}Th, ^{238}U, ^{40}K, and ^{235}U. See Morgan (2002).

radiometric Pertaining to the measurement of *geologic time* by the analysis of certain radioisotopes in rocks and their known rates of decay (see *$_{14}$C age date*).

random medium A mathematical model for a medium whose spatial variation in parameters is described by random functions. Their *autocorrelation* functions or *power spectral density* functions give their statistical properties. See Sato et al. (2002).

random vibration theory (RVT) A theory of the response of systems to probabilistic defined inputs. In *seismology*, a convenient way of estimating *time domain* properties, such as peak *amplitudes* and *frequency*, from the *Fourier spectrum* of *ground motion* and an estimate of the duration of the motion. For applications, see the review by Boore (2003).

random walk The typical path followed by a molecule in *Brownian motion*. By extension, the path followed in a parameter space when using a *Monte Carlo method*. See the biography of Robert Brown in Howell (2003), Mosegaard and Tarantola (2002), and Tarantola (2005).

range In satellite geodesy; distance along the line of sight between the satellite and the ground. See Feigl (2002).

rate and state dependent friction A class of constitutive relationships that describe sliding *friction* over a wide range of conditions and time scales, developed by Ruina (1983) and Rice and Ruina (1983) as a generalization of equations of Dieterich (1978, 1979). These relations consist of a base frictional resistance and depend on the sliding speed (rate) and contacts (state) on the *fault plane*. See Lockner and Beeler (2002, p. 521), Harris (2003), and Eqs. (5.4a)-(5.4f) and Figure 12 in Ben-Zion (2003).

rate strengthening A term used to describe a positive dependence of *fault* shear strength on sliding velocity; always produces *aseismic* fault *slip*. See Lockner and Beeler (2002, p. 521).

rate weakening A term used to describe a negative dependence of *shear* strength on sliding velocity; can lead to frictional instability (*seismic slip*) under some circumstances. See Lockner and Beeler (2002, p. 521), and material below Eq. (5.4f) in Ben-Zion (2003).

ray A trajectory along which the constituent components of a wave, e.g., *phase* and energy, propagates. See Chapman (2002), and Bleistein (2002).

ray expansion The complete seismic response can be expanded into a summation of terms associated with *rays*. Normally the response can be approximated by a limited number of rays in the time window and *amplitude* range of interest. See Chapman (2002).

ray Green's function The approximate *Green's function* obtained using asymptotic *ray theory*. See Chapman (2002), and the biography of George Green in Howell (2003).

Rayleigh damping A form of *damping* used in the matrix analysis of structures in which the damping matrix is a constant times the mass matrix plus another constant times the stiffness matrix. Rayleigh damping produces viscous damping factors in the modes that are dependent on the *natural frequencies* of the modes. The constants are chosen to produce desired damping factors over the important modes of response. See Jennings (2003), and the biography of Lord Rayleigh in Howell (2003).

Rayleigh wave Coupled *P* and *SV waves* trapped near the surface of the Earth and propagating along it. Their existence was first predicted by Rayleigh (1887) for a *homogeneous halfspace*, for which the *velocity* of propagation is 0.88 to 0.95 times the shear velocity, depending on the *Poisson's ratio*, and their particle motion is retrograde elliptic near the surface. They can exist, in general, in a vertically heterogeneous medium bounded by a free surface. See Udias (2002, p. 87-88), Kulhanek (2002, p. 334-335), Aki and Richards (2002 or 2009, p. 155-157), and the biography of Lord Rayleigh (1842-1919) in Howell (2003).

ray parameter p See *wavenumber vector k.*

ray theory Theoretical approach, which treats wave propagation like particles moving along *seismic rays*. It is a valid approximation when the medium properties such as wave *velocity*, *density* and *attenuation* vary smoothly within a *wavelength* (high-frequency approximation). See Chapman (2002) and Červený (2001).

ray-tracing method Computational method of calculating ground-shaking estimates that assumes that the *ground motion* is composed of multiple arrivals of *seismic rays* and related energy bundles (Gauss beams) that leave the source and are reflected or refracted at *velocity* boundaries according to *Snell's Law*. The *amplitudes* of reflected and refracted waves at each boundary are recalculated according to the energy conservation law.

receding branch See *branch (of travel-time curve).*

receiver function method See *H/V spectral ratio* and *receiver functions*.

receiver functions The spectral ratio of the horizontal component of *S waves* to the vertical component of *P waves* recorded at a single station from a *teleseismic* event. Assuming a horizontally layered structure beneath the station, it gives an estimate of the seismic *velocity* structure, particularly the nature of *discontinuities*, of the *crust* and the uppermost *mantle*.

record section A display of *seismograms* recorded from a source (e.g., an earthquake or an explosion) according to their distance from that source in a time-distance graph.

rectangular fault *Fault plane* geometry with a rectangular shape. The long and short side is, respectively, called *fault length* and *fault width*. The *rupture front* is a line segment parallel to the width. It starts at a point on the fault and propagate along the fault length. See IS 3.1 in this Manual and *Haskell model*.

recurrence interval The average time interval between consecutive events which occur repeatedly; also termed average return period. See Grant (2002).

recursive technique A computational technique based on a formula which relates certain coefficients, say for a *filter*, at the nth step with those at the (n-1)th step. Desired coefficients are obtained at the nth step by an iterative use of the formula starting with the initial values at the 0th step. See Sipkin (2002).

reduced travel time (T_r) The observed *travel-time* T minus the distance from a source X divided by a suitable *reduction velocity* (V_r).

reduction velocity (V_r) A suitable reduction velocity mostly used for controlled-source *P wave* crustal studies is 6 km/sec, for upper-*mantle* studies 8 km/sec, for *S wave* studies the reduction velocity is usually that for P wave studies divided by $\sqrt{3}$.

reflection The energy or wave from a *seismic source* that has been returned (reflected) from an *interface* between materials of different elastic properties within the Earth.

reflection angle The angle between a *seismic ray*, leaving an *interface* on the same side as reaching it, and the vertical (normal) to this *discontinuity*. See also *incidence angle* and *refraction angle.*

reflection coefficient The *amplitude* ratio of the reflected wave relative to the incident wave at an *interface*. In seismology, the coefficients are found by imposing boundary conditions that the seismic *displacement* and the traction acting on the *discontinuity* surface are continuous across the surface. These conditions physically mean a welded contact and absence of extra-seismic sources at the discontinuity. Coefficients have been defined for different normalizations and signs of the component waves, e.g., energy or displacement (Knott 1899; Zoeppritz, 1919). See *transmission coefficient*, Chapman (2002, p.110-112), and Aki and Richards (2002 or 2009, p. 128-149).

reflection seismology The study of the Earth's structure by the use of *seismic waves* originating from a near-surface source and reflected back to the surface from sub-surface *discontinuities*.

reflector An *interface* between materials of different elastic properties that reflects *seismic waves*.

refraction (1) The deflection, or bending, of the *ray* path of a *seismic wave* caused by its passage from one material to another having different elastic properties. (2) Bending of a *tsunami* wave front owing to variations in the water depth along a coastline.

refraction angle The angle between a *seismic ray*, leaving an *interface* after passing it, and the vertical (normal) to this *discontinuity*. See also *incidence angle* and *reflection angle.*

refraction diagram (tsunami) A chart indicating *wavefronts* of a *tsunami* from the source. It is used to predict tsunami *travel times* from a given source area. See Satake (2002).

refraction seismology The study of the Earth's structure by the use of *seismic waves* from a near-surface source refracted back to the surface after propagation along deep *interfaces*.

regional strain A description of the overall *deformation* of a region. See Jackson (2002).

regional waves *Seismic waves* which propagate laterally in the *crust* and uppermost *mantle*. Examples are *Pg, Pn, Sn, Lg* and *Rg*. These waves are distinguished from *teleseismic* waves which propagate in the deeper interior of the Earth. Regional waves typically propagate over *epicentral distances* up to 1500 km (somewhat further for Lg), and their travel speed can be very different for different regions. For example, a Pn wave, which travels along the top of mantle, can arrive 8 seconds earlier in some regions and 5 seconds later in other regions as compared to the global average *arrival time* for the same distance. See Richards (2002).

regression analysis A statistical technique applied to data to determine, for predictive purposes, the degree of *correlation* of a dependent variable with one or more independent variables, in other words, to see if there is a strong or weak cause-and-effect relationship between two or more parameters. More specifically, standard regression analysis considers one of the two compared variables as independent (given and error free) and the other one as dependent and error afflicted, in contrast to correlation analysis which considers both variables as being in error. In this sense, the so-called *orthogonal regression*, preferable for deriving regression relationships between different types of *magnitude* data, is a correlation analysis between magnitude data with comparably large initial errors. See Bormann et al. (2007, 2009) and Castellaro and Bormann (2007).

relative bandwidth The relative bandwidth (RBW) can be expressed by a number or in terms of *octaves* or decades. Increasing the *frequency* of a *signal* by one octave means doubling its frequency, and by one decade multiplying it by ten. Accordingly, a band-passed signal (or *filter*) with n octaves or m decades has a ratio between the upper and lower *corner frequencies* $f_u/f_l = 2^n = 10^m$ and a geometric *center frequency* $f_o = (f_u \times f_l)^{1/2} = f_l \times 2^{n/2} = f_l \times 10^{m/2}$. From this follows for the relative bandwidth

$$RBW = (f_u - f_l)/ f_o = (2^n - 1)/ 2^{n/2} = (10^m - 1)/10^{m/2}.$$

Note that signal and *noise amplitudes* can be made commensurate only when plotting them in a constant RBW over the whole considered frequency range. See Chapter 4 of this Manual.

relaxation theory A concept in which radiated *seismic energy* is released from stored *strain* energy during the *slip* along a *fault* until the adjacent fault blocks reach a new state of equilibrium.

renewal process A point process in which the statistical distribution of the intervals between consecutive events are statistically independent and stationary. See Utsu (2002b).

residual The difference between measured and predicted values of some quantity.

residual strength Shear resistance within cohesive soils at very large shear *deformations* or within contractive granular soils in the liquefied state. See Youd (2003).

resonance Strong increase in the *amplitude* of vibration in an elastic body or system when the *frequency* of the shaking force is close to one or more times of the *natural frequencies* of a shaking body.

response The motion in a system resulting from shaking under specified conditions.

response function See *amplitude response* and *frequency response*.

response-spectral ordinate A term in *engineering seismology*, indicating the *amplitude* of a *response spectrum* at a specified value of undamped *natural period* or *frequency*. See Campbell (2003).

response spectrum A curve showing the computed maximum *response* of a set of simple *single-degree-of-freedom* harmonic *oscillators* with chosen levels of viscous *damping* and different *natural frequencies* to a particular record of *ground acceleration*. Response spectra, commonly plotted on tripartite logarithmic graph paper, show the oscillator's maximum acceleration, *velocity*, and *displacement* as a function of oscillator frequency for various levels of oscillator's damping. A computational approximation to the response spectrum is referred to as the pseudo-relative velocity response spectrum (PSRV). These curves are used by engineers to estimate the maximum response of simple structures to complex *ground motion*s. See Anderson (2003).

retrograde branch See *branch (of travel-time curve).*

return period The average time between exceedance of a specified level of *ground motion* at a specific location; it is equal to the inverse of the annual probability of exceedance. See also *recurrence interval*.

reverse fault A *fault* that involves lateral shortening, where one block (the *hanging wall*) moves over another (the *footwall*) up the *dip* of the fault, i.e., the movement of the hanging wall is upward relative to the footwall. The maximum *compressive stress* is horizontal, and the least compressive stress is vertical. Reverse faults that dip less than about 30 degrees are often called "*thrust faults*". See also *normal fault,* and Jackson (2002).

reverse movement See *fault*.

Rg Originally a symbol for the fundamental-mode *Rayleigh waves* observed for continental paths in the *period* range 8 to 12 seconds (Ewing et al., 1957). Now applied to dispersed wave trains propagating in the Earth's *crust* with periods between about 0.1 and 4 second (e.g., Fig. 2.18 in Chapter 2 of this Manual and Figure 4 in Kulhanek, 2002, p. 337). For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

rheological properties The properties of rocks that describe their ability to deform and flow as a function of temperature, *pressure*, and chemical conditions.

Richter magnitude (of an earthquake) The magnitude value of an earthquake based on Richter´s *local magnitude* (M_L) *scale* (Richter, 1935). In popular use, the term is often mistaken for any magnitude. See *magnitude*.

Richter scale Also called *Richter magnitude* scale or *local magnitude* (M_L), introduced by Richter (1935). See *magnitude*.

ridge push Gravitational force acting on the edges of diverging *plates* at *mid-ocean ridges*, due to the uplift of the ocean-ridge crest caused by the hot *asthenosphere* underneath it.

rift (rift valley) An extended feature marked by a *fault*-caused trough that is created in a zone of divergent crustal *deformation*. Examples are the East African Rift Valley and the rift that often exists along the crest of a *mid-ocean ridge*.

rift zone An elongate system of structural weakness — defined by eruptive fissures, *craters*, *volcanic vents* and geologic *faults* — that has undergone extension (ground has spread apart) by movement, storage, and rise of *magma*.

right-lateral fault A *strike-slip fault* across which a viewer would see the block on the other side moves to the right. Also known as *dextral fault*. See *left-lateral fault*.

right-lateral movement See *right-lateral fault*.

rigidity Also termed *shear modulus*, is a measure of the resistance of the material to pure shearing, i.e., to changing the shape but not the volume of the material. See section 2.2 and Fig. 2.2 in Chapter 2 of this Manual.

Ring of Fire Another popular name for the *Circum-Pacific belt* whereabout 90% of the world's earthquakes occur. The next most seismic region (5-6 %) is the *Alpide belt*.

ring laser An instrument that detects the Sagnac beat frequency of two counter-propagating light beams (see *Sagnac effects*). This beat frequency is directly proportional to the *rotation rate* around the surface normal to the ring laser system.

ripple-firing, delay-firing, millisecond delay initiation These are all terms used to characterize quarry or mine-blasting activity, in which a particular shot is carried out as a series of separate charges, fired in a sequence instead of all together. Ripple-firing is the term commonly used, but experts usually refer to delay-firing and in some cases to millisecond delay initiation (where a specifically timed pattern of charges is executed that may entail delays that are designed for a particular blasting objective, such as fragmenting rock to a pre-determined size and moving the fragments a pre-specified distance). See Richards (2002).

rise-time In earthquake source studies, it refers to the time required for the completion of *slip* at a point on the *fault plane*. In the *Haskell model*, it is the parameter of ramp-function used for describing the slip time history. See *Haskell model*, and Eqs. (3.5b) and (3.8) in Ben-Zion (2003).

rocking *Rotation* about a horizontal axis or, as often used by engineers, of a whole structure about a horizontal axis. The term “rocking” should be used only with full, graphically supported definitions inclusive of frequency band, according to Evans et al. (2009).

root mean square Square root of the mean value of a set of squared values.

root n improvement More precisely, “square root of n” improvement in *signal-to-noise ratio*, as expected from *delay-and-sum processing* of n independent recordings with *noise* that has uniform power. See Chapter 9 in this Manual and Douglas (2002).

rotation(s) See *displacement (rotational)* and *rotation vector*.

rotation angles (rotational motions) The *rotational displacements* indicated θ_X, θ_Y, and θ_Z in Figure 1 of Evans et al. (2010). Terms like “*X*-rotation” may be used as shorthand though “rotation angle θ_X” is more formal. Authors are cautioned that the term “rotational displacement” has other meanings and should be defined (e.g., P. Spudich, written comm., 2008; B. R. Julian, oral comm., 2008). Rotation angles are generally given in units of radians. For example, “θ_X” is the right-handed rotation angle about the *X* axis. The *SI* abbreviation for “radians” is “rad,” and for “seconds” it is “s” (not “sec”); thus, units in the style “mrad/s” are preferred to “milli-radians/sec”. In continuum mechanics, rotation angle and axis of rotation define the *rotation tensor*.

rotation, average (volume or area) *Rotation* of an extended region or some extended portion of a structure, often inferred from measured *translational motions* at the periphery.

rotation, block See block rotation**.**

rotation, point See *point rotation*.

rotation rate In the linear approximation, the first time derivative of *rotational displacement*. “Angular velocity” and *rotational velocity* are acceptable synonyms for “*rotation rate*”. In the nonlinear theory, it is defined via the *rotation tensor***.**

rotation tensor A mathematical object that may refer to many kinds of “physical” *rotations*, in particular to the rotational part in the polar decomposition of the *gradient* of the radius vector in the classical continuum, to the (independent) rotation of a point body in the *Cosserat continuum*, or to any other rotation, for instance, to the rotation of a rigid body, of a co-ordinate system etc. In the following discussion, it is an orthogonal tensor characterizing rotation of vectors and rigid bodies. If **d** is a vector subjected to rotation, the rotated vector equals **d' = P d,** where **P** is the rotation tensor, det **P** = 1. Each rotation tensor may be represented via the *rotation angle* and axis of rotation (theorem by Leonhard Euler): **P** = (1 - cosθ) **n n** + cosθ **I** + sinθ **I** x **n**, where **I** is the identity tensor (**I d** = **d** for each vector **d**), **n** is the axis of rotation. For linear motions, **P** is approximately equal to **I** +θ **n** x **I**. In the literature, the rotation tensor is also called the "turn tensor". In *micropolar* media, one has to distinguish the rotation of the background continuum, related to the gradient of translational deformation, and the proper rotation of particles. In linear elasticity and seismology the rotation tensor refers to a different object, and the expression for **P** is simplified by the infinitesimal nature of the *rotation angle*, not the linear motion. See Pujol (2009).

rotation vector In continuum mechanics, it is the vector θ **n**, where θ is the *rotation angle* and **n** is the unit vector along the axis of rotation. It corresponds to the *rotation tensor*, **P** = (1 - cosθ) **n n** + cosθ **I** + sinθ **I** x **n.**

rotational acceleration The time derivative of the *rotational velocity*. In the linear approximation, the second time derivative of a *rotational displacement*. "Angular acceleration" is often used for "rotational acceleration."

rotational displacement It is often used as a synonym for *rotation vector*.

rotational ground motion The rotational components of *ground motion***.** In classical elasticity and assuming infinitesimal *deformations*, **ω** = ½ (∇× **u**(**x**)), where **ω** is a *pseudo vector* and represents the angle of rigid rotation generated by the disturbance, ∇× is the *curl* operator, and **u** is the *displacement* of a point at **x.** See e.g., Aki and Richards (2002 and 2009, p. 13), and Cochard et al. (2006, p. 394).

rotational-motion sensor The term rotational-motion sensor is widely used instead of *rotational sensor* in aerospace, automotive, and mechanical engineering. In earthquake studies, the term *rotational seismometer* is preferred.

rotational response spectrum A plot of maxima of rotational responses of *oscillators* as a function of their *natural periods* (or *frequencies*). It is generalized from the conventional, translational *response spectrum* (see, e.g., Kalkan and Graizer 2007, Zembaty 2009a).

rotational seismology An emerging field of inquiry for studying all aspects of *rotational ground motions* induced by earthquakes, explosions, and ambient vibrations.

rotational seismometer A *rotational sensor* specifically designed as a *seismometer* for measuring *rotational ground motions* associated with *seismic waves* from *earthquakes* or explosions.

rotational seismic solitons A finite number of rotational pulses excited in the earthquake source; they can have a form of spin or twist *solitons*. See Majewski (2006; 2008).

rotational seismic waves They are *rotational waves* excited in the *earthquake source* as a result of rotational vibrations, including rotational longitudinal waves, and rotational transverse waves. See Majewski (2006).

rotational sensor A *rotational sensor* (often generically known as a *gyroscope* or *inertial* angular *sensor*) that can measure angular displacement, velocity (often called "rate"), acceleration, or jerk (rate of change of acceleration). Such sensors may or may not have *response* down to zero frequency. See *rotational-motion sensor*.

rotational velocity The first-time derivative of *rotation angles*; an acceptable synonym for *rotation rate* and spin, if the latter term refers to the antisymmetric part of the velocity gradient tensor. In the nonlinear case, rotational velocity is defined as vector $\boldsymbol{\omega}$ satisfying the equation $d\mathbf{P}/dt = \boldsymbol{\omega} \times \mathbf{P}$, where $\mathbf{P}$ is the *rotation tensor*, t is time.

rotational waves Motions of a continuum, where the rotational dynamics is present. Term sometimes used in connection with *micropolar* media to describe rotation waves in a medium in which each point has degrees of freedom related to rotational motions. It is important not to confuse rotational waves with *rotational ground motions* appearing as the *curl* of the *wavefield* in linear elasticity with a symmetric *stress tensor* (e.g., *S waves*).

ROV An acronym for Remotely Operated Vehicle. See Suyehiro and Mochizuki (2002).

RSAM An acronym for Real-time Seismic Amplitude Measurement; widely used by many volcano observatories, the RSAM system enables the continuous monitoring of total *seismic energy* release during rapidly escalating *volcanic unrest*, when conventional seismic-monitoring systems are saturated. See Endo and Murray (1991) for details. Both the RSAM and *SSAM* systems, together with associated PC-based software for data collection and analysis, form the core of an integrated "mobile volcano observatory" (Murray et al., 1996), which can be rapidly deployed.

run-up The maximum height above a reference sea level of the water brought onshore by a *tsunami*. See *tsunami run-up height*.

rupture duration Time length of the rupture process.

rupture front The instantaneous boundary between the *slip*ping and *locked* parts of a *fault* during an earthquake. Rupture front propagation along the *fault length* of a *rectangular fault* from one end to the other is referred to as unilateral. If it starts in the middle of the fault and propagates toward its two ends, it is called bilateral. Rupture may expand outward in a circular or an elliptic form from its center. See *rectangular fault*, *circular fault*, *elliptic fault*, and Figures 9 and 10 in Ben-Zion (2003).

rupture velocity The velocity v_R at which a *rupture front* moves along the surface of the *fault* during an earthquake. Depending also on *stress drop*, v_R may vary in a wide range between some 20% and 95% of the *shear-wave velocity* v_S, yet being > 60% v_S for most of the large earthquakes. Occasionally, $v_R > v_S$ has been reported from so-called “super shear” earthquakes, whereas for *tsunami* earthquakes v_R may become < 30% of v_S. See Kanamori and Brodsky (2004).

Rytov method A method to find an approximate solution for the logarithm of the *wave field* (complex phase function) for waves in a smoothly varying *inhomogeneous* medium. In the Rytov approximation the second order term of the *gradient* of the complex phase function is often neglected. See Sato et al. (2002).

S

S General symbol for an *S-wave*. For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

$\bar{S}$ See *Sg*.

Sagnac effect (Sagnac interference) An interferometric phenomenon encountered in rotating systems, as in ring-laser and fiber-optic *gyroscopes*. In seismology most often described and measured in the *frequency domain* (a beat *frequency*) rather than in the spatial domain (interference fringes).

sag pond A *fault sag* that contains water.

sand boil Sand and water ejected to the ground surface during strong earthquake shaking as a result of *liquefaction* at shallow depth; the conical sediment deposit remains as evidence of liquefaction. See Bardet (2003).

satellite interferometry (InSAR) Modern technology to measure areal *crustal deformations* and to derive seismic *fault plane* solutions after strong earthquakes by interferometric superposition of images taken from synthethic aperture radar (*SAR*) satellites before and after the earthquake. See *interferometry*, Feigl (2002) and color plate 14 in Lee et al. (2002); also Fig. 3.14 and related text in Chapter 3 of this Manual.

SAR Abbreviation for Synthetic Aperture Radar. See Feigl (2002) and *satellite interferometry (InSAR)*.

saturation (of a magnitude scale) Above a certain *magnitude* level, the magnitude determined from the *amplitudes* or amplitude/*period* ratios of specified *seismic waves* recorded by a specific *seismograph* increases only slowly or does not further increase as the physical size of the earthquake (such as measured by the *moment magnitude Mw*) increases. This behavior, sometimes called saturation, is due to the shape of the *displacement* spectrum of a typical *seismic signal*, which is characterized by a *corner frequency* above which the displacement amplitude decreases rapidly. As the size of the earthquake increases, the corner frequency moves to lower frequencies. When the frequency at which a specific type of magnitude is calculated falls above this corner frequency, that magnitude scale tends to underestimate systematically the event magnitude. Saturation sets in at smaller magnitudes for scales based on records from short-period seismographs. Accordingly, magnitudes *mb* >6.5, M_L >7.0, *mB* >7.5, or *Ms* >8.0 are rarely reported. The new *IASPEI* (2005 and 2011) standards delay magnitude saturation for mb and mB to values above 7.0 and 8.0, respectively. The new IASPEI (2005 and 2013) standards delay magnitude saturation for mb and mB to values above 7.0 and 8.0, respectively. No saturation occurs for *Mw* or *mantle magnitude Mm*, because these scales (if properly applied) always use frequencies well below the corner frequency. See Chapter 3 of this Manual as well as Bormann et al. (2009) and Bormann (2011).

scalar seismic moment See *seismic moment*.

scale invariance Property of a phenomenon which appears identical at a variety of scales. See Turcotte and Malamud (2002).

scaling law of seismic spectrum The law governing the *frequency*-dependent growth of the seismic spectrum with the increase of earthquake *magnitude*. The *saturation of a magnitude scale* is one of its consequences. It is also important for (roughly) estimating strong *ground motion* for a large earthquake based on the observed data for smaller ones. However, depending on the actual *stress drop*, the *corner frequencies* may vary for equal *seismic moment* by about one order. This explains the sometimes large differences between seismic *moment magnitude Mw* and *energy magnitude Me*. See Aki and

Richards (2002 or 2009, p. 513-516), Chapter 3 in this Manual, Madariaga and Olsen (2002, p. 185-186), and Eq. (6.1) in Ben-Zion (2003), as well as Fig. 3.5 in this Manual or Fig. 1 in Bormann et al. (2009) and Fig. 2 in Bormann and Di Giacomo (2011).

scattering In physics, it refers to an alteration in direction of motion of a particle because of collision with another particle. In seismology, the particle is replaced by a wave, and it represents the change in wave properties such as *waveforms* and *ray* directions by inclusions or *heterogeneities* in the material properties of the medium. See Sato et al. (2002).

scattering coefficient Scattering power per unit volume of *heterogeneous* media having a dimension of the reciprocal of length. This quantity characterizes the *coda* excitation of a *local earthquake* and the strength of *scattering attenuation* in heterogeneous media. See Sato et al. (2002).

scattering theory Theory which develops models and algorithms suitable for synthesizing and (by inversion) interpreting observed scattering features in particle and wave physics. For seismic *scattering*, see Sato and Fehler (1998), and Sato et al. (2002).

scoria A porous glassy *pyroclast*, often containing more than 50 % void space, between 2 and 64 mm in size; it is generally darker in color and denser than *pumice*.

screw dislocation See *dislocation*.

ScS A symbol for *S waves* traveling through the *mantle* until reaching the *core-mantle boundary* and reflected there back to the surface. See Kulhanek (2002, p. 341), Cara (2002). For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual, and Storchak et al. (2003 and 2011).

sea-floor spreading A term introduced by Dietz (1961). It is now taken to be the creation of new oceanic *lithosphere* as *plates* separate at *mid-ocean ridges*, where upwelling *mantle* materials fills the growing gaps between the moving plates. See Uyeda (2002), and *magnetic reversal*.

sea-floor spreading hypothesis A hypothesis proposed by Dietz (1961) and Hess (1962) for the evolution of continents and oceans by the spreading of sea floor from *mantle convection*. See *sea-floor spreading*.

second (s) The base unit of time in the *international system of units* (*SI*). The official definition is "The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom." See NBS (1981).

sector collapse The sudden failure of a significant part of the summit and (or) flank of a volcano, typically triggered by intrusion of new *magma*, *phreatic* explosions, or an earthquake. Also called flank failure or edifice collapse, such processes result in associated *landsliding* and *debris avalanches*, often creating deposits with distinctive hummocky topography (e.g., at Mount St. Helens in May 1980). At island volcanoes, large sector collapses can produce destructive *tsunamis*. See *hummocks*.

secular Referring to long-term changes that take place slowly and imperceptibly. Commonly used to describe changes in elevation, tilt, and *stress* or *strain* rates that are related to long-term *tectonic deformation*. For example, a mountain that is growing is getting taller so slowly that we cannot see it happen, but if we measure the elevation in one year and then after, e.g., another time ten years later, we could see that it has grown taller.

sedimentary rock A rock formed from the consolidation of sediment. The sediment can be physically deposited by wind, water or ice, or chemically precipitated from bodies of water. See Press and Siever (1994).

segmentation The breaking up of a *fault* along its length into several smaller faults. This can happen as a result of other faults crossing it, topography changes, or bends in the *strike* of the faults. Segmentation can limit the length of faulting in a single earthquake to some fraction of the total *fault length*, thus also limiting the maximum possible size of an earthquake on that fault.

segment or segmentation model The assumption that earthquake *faults* are divided into discrete, identifiable sections that behave distinctively over multiple rupture cycles. See Grant (2002).

seiche A free oscillation (*resonance*) of the surface of an enclosed body of water, such as a lake, pond, or bay with a narrow entrance. They are sometimes excited by *earthquakes* and by *tsunamis*. The period of oscillation ranges from a few minutes to a few hours, and the oscillation may last for several hours to one or two days.

seismic albedo The ratio of the *scattering coefficient* to the total *attenuation* coefficient**,** i.e., the sum of absorption coefficient and scattering coefficient. This term derives from the original term “albedo” in astrophysics. See Sato et al. (2002).

seismic anisotropy A term used for effective material parameters which depend on the direction of propagation or *polarization* of *seismic waves*. It includes *isotropic* media with aligned small-scale *heterogeneities* that may behave *anisotropic* for seismic *wavelengths* longer than the heterogeneity scale. See Curtis and Snieder (2002), and Cara (2002).

seismic array — An ordered arrangement of *seismometers* distributed over the surface or volume (with bore-hole sites) of the Earth whose outputs are transmitted to and recorded at a central *data acquisition* and *data processing* unit. Since the 1950's many arrays have been constructed worldwide for detecting underground nuclear tests and for fundamental research in seismology. See Chapter 9 of this Manual, Douglas (2002), *array analysis*, *array aperture*, and *array beam*.

seismic belt — An elongate earthquake zone, for example, the *Circum-Pacific*, Mediterranean, Rocky Mountains earthquake *belt*.

seismic bulletin — A compilation or listing of parametric seismic data from different stations (mainly *phase arrival times*, *amplitudes* and *periods* of waves) associated with specific *seismic events*. When enough and consistent data are available, event locations and *magnitudes* are also computed and listed. The most complete global seismic bulletin for 1964 to the present is the "Bulletin of the International Seismological Centre (ISC)". Between 1913 and 1964 the most relevant global bulletins are those of the International Seismological Summary (ISS) and the Bureau Central International de Seismologie (BCIS). See Engdahl and Villasenor (2002), and Schweitzer and Lee (2003).

seismic catalog — A compilation or listing of earthquake focal parameters. The basic focal parameters reported by most seismic catalogs are: earthquake *origin time*, latitude, longitude, depth, and some indicator of the size (e.g., *magnitude*). Unlike *seismic bulletins*, seismic catalogs do not include the primary data measured at the *seismic stations* (mostly *phase arrival times*, *amplitudes* and *periods*) that were used to obtain the *hypocenter* location or the other focal parameters. See *catalog*.

seismic constant — In building codes dealing with *earthquake hazard*, an arbitrarily set quantity of steady *acceleration* (in units of *gravity g*) that a building must withstand.

seismic core phase — A general term referring to a *seismic body-wave phase* that enters the *Earth's core*. See section 2.6.2 in Chapter 2, sections 11.5.2 and 11.5.3 in Chapter 11, IS 2.1, Data Sheet DS 11.3 and exercise EX 11.3 of this Manual; also Song (2002).

seismic efficiency — For an earthquake**,** the ratio of the energy radiated in the *seismic waves* to the total energy released due to *fault slip*, or, equivalently, the ratio of *apparent stress* to the average stress acting on the fault to cause slip. Savage and Wood (1971) suggested that the seismic efficiency of earthquakes should not exceed 0.15 and a likely value would be about 0.07. The seismic efficiency is less than the *radiation efficiency*, because the latter neglects energy loss due to frictional heat and conversion of *strain* energy into acoustic energy. See Eq. (6.5) in Ben-Zion (2003); also Kanamori and Brodsky (2004) and Bormann and Di Giacomo (2011). See *radiation efficiency*.

seismic energy That part of the potential energy released during an *earthquake*, an explosion or another type of *seismic source* that is converted into elastic *seismic waves* that propagate away from the source through the Earth and cause vibrating *ground motions*. The ratio between seismic energy Es and *seismic moment Mo* is proportional to the *stress drop* $\Delta\sigma$ in the seismic source. (See also *radiation efficiency*).

seismic event A general term used for localized sources of different type which generate *seismic waves*, such as *earthquakes*, rock bursts, explosions (man-made or natural ones), impacts and cavity collapses.

seismic exploration Seismic exploration uses *seismic waves* of different types (mostly *reflected*, *refracted* and *converted body waves*) of usually higher *frequencies* between some 1 to 100 Hz and thus shorter *wavelengths* and higher spatial resolution than commonly recorded and analyzed in earthquake seismology. These high-frequency seismic waves are typically generated by controlled *seismic sources* such as explosions, vibrators, and *airguns* and recorded by *geophones* or *hydrophones*. S. e. aims at detailed imaging of layered, folded and faulted structures in the Earth's crust. Commercial s. e. is usually termed *seismic prospection* and aimes at finding structures with potential for exploitable natural deposits of oil, gas, acquifiers etc. in the uppermost *crust*.

seismic gap An area of a *seismic zone* in which large earthquakes are known to have occurred in the past, but in which none has occurred for a defined long time. Seismic activity is low compared to the neighboring areas of the same zone. Such an area is often considered to be the site of the next large earthquake following the idea of Fedotov (1965) who found that great earthquakes in the northern Pacific tended to occur in regions lacking earthquakes for several decades, and tended to rupture discrete segments which eventually fill the whole seismic zone without overlapping. See Kanamori (2003).

seismic hazard "Hazard H is the probability of occurrence of an event with disaster potential within a defined area and interval of time". It is also used - without regard to a *loss* - to indicate the probable level of ground shaking occurring at a given point within a certain period of time. See *earthquake hazard*, Somerville and Moriwaki (2003), and Giardini et al. (2003).

seismic hazard analysis (SHA) The calculation of the *seismic hazard*, expressed in probabilistic terms (see *probabilistic seismic hazard analysis*), as contrasted with deterministic seismic hazard analysis, for a site or group of sites. The result is usually displayed as a *seismic hazard curve* or *seismic hazard map*. See Somerville and Moriwaki (2003), Giardini et al. (2003), and Reiter (1990).

seismic hazard curve A plot of *probabilistic seismic hazard* (usually specified in terms of annual probability of exceedance) or average return period versus a specified *ground-motion parameter* for a given site.

seismic hazard map A map showing contours of a specified *ground-motion parameter* or *response spectrum* ordinate for a given *probabilistic seismic hazard* or average return period.

seismic impedance *Seismic wave velocity* multiplied by *density* of the medium. The contrast in seismic impedance across two media is the main factor governing the *reflection coefficient* at their boundary (see *impedance contrast*).

seismic intensity The degree of ground shaking estimated from its effect on people, houses, construction, and natural objects. The intensity scales are essential for assigning *magnitude* to earthquakes for which instrumental data are not available. See Chapter 12 of this Manual, *intensity scales*, *intensity (macroseismic)*, and Musson and Cecić (2002).

seismicity A term (used already by Willis, 1923) to describe quantitatively the space, time and *magnitude* distribution of earthquake occurrences. Seismicity within a specific source zone or region is usually quantified in terms of a *Gutenberg-Richter relationship*. See Utsu (2002b).

seismic lid The *mantle* part of the seismic *lithosphere* overlying the *asthenosphere*. See Lay (2002).

seismic line A set of *seismographs* usually lined up along the Earth's surface to record *seismic waves* generated by artifical or natural *seismic sources* for studying the internal structure of the Earth.

seismic migration In *exploration seismology*, a process which collapses *diffractions* and moves *reflections* to their proper location in the seismic image. See Sheriff and Geldart (1995).

seismic moment The magnitude of the component couple of the *double couple* that is the point force system equivalent to a *fault slip* in an *isotropic* elastic body. It is equal *to rigidity* times the fault slip integrated over the *fault plane*. It can be estimated from the *far-field* seismic spectrum or *waveform* fitting at *wavelengths* much longer than the source size. It can also be estimated from the *near-field* seismic, geologic and geodetic data, and the consistency among various observations. This was first demonstrated for the Niigata, Japan, earthquake of 1964, supporting quantitatively the validity of the fault origin of an earthquake. Also called "*scalar seismic moment*" to distinguish it from *moment tensor*. See *slip moment* and *geodetic moment*. See section 3.5 of Chapter 3 and exercises 3.4 and 3.5 in this Manual, Aki and Richards (2002 or 2009, p. 48-49), and section 2 in Ben-Zion (2003).

seismic multiples Seismic *arrivals* arising out of *reflections* between subsurface layers.

seismic network A network of *seismographs* deployed for a specific purpose. Modern means of regional and global data communication permit to design task-tailored temporary virtual seismic networks. See Chapters 8, 9 and 11 in this Manual; also Lahr and van Eck (2003).

seismic noise See *microseisms*.

seismic phase A pulse, *wavelet* or group of seismic *body*- or *surface-wave* energy arriving at a definite time, which passed the Earth on a specific path (see also Chapters 2 and 11, IS 2.1, DS 11.1 to 11.3, Storchak et al. (2003 and 2011) and *phase nomenclature*.

seismic potency A quantity (area times *slip*) that characterizes the inelastic *strain* in a faulting region. See Ben-Menahem et al. (1965), and section 2 in Ben-Zion (2003).

seismic prospection See *seismic exploration.*

seismic rays and tubes A seismic ray is a path in a 3D space along which *seismic energy* can be considered to propagate like a particle. For high-*frequency seismic signals*, this is often a useful approximation and simplification. The ray vector is oriented perpendicular to the *wavefront*, pointing into the direction of wave propagation, and marking behind it the "ray trace". The propagation of *seismic waves* can be easily modeled as the propagation of seismic rays following *Snell's Law* (see section 2.5.2 in Chapter 2 of this Manual). Neighboring rays form a ray tube and the energy flux is confined within its walls. See also Chapman (2002).

seismic recorder A devise for recording seismic *ground motions* in analog or digital form (see *seismograph*), usually as a *frequency*-filtered and amplified equivalent electronic *signal* (see *transducer* and *data logger*). See Chapter 6 of the Manual.

seismic refraction/wide-angle reflection profiles Also referred to as Deep Seismic Sounding (DSS) profiles. *Seismic velocity* structures in the *lithosphere* derived from data recorded with long offsets (100-300 km) between sources and receivers consisting of widely-spaced *geophones* (100-5,000 m). See Mooney et al. (2002).

Seismic Research Observatories (SRO) Name and acronym of a former global U.S. *seismic network*, operating between 1974 and 1993. The long-period SRO *responses* were very specific: a narrow 20 s bandpass with a 6 s noise notch-*filter* (see in Chapter 11 of this Manual Fig. 11.38 and Tab. 11.3 for the poles and zeros). Many record examples, in comparison with those from other *seismographs*, are given in Chapter 11, DS 11.2 and 11.3 of this Manual. The SRO-LP response has advantages for measuring the *IASPEI* standard Ms_20 *magnitude*. See Chapter 3 and IS 3.3 of this Manual, and Hutt et al. (2002).

seismic risk The risk to life and property from earthquakes. In probabilistic risk analyses, the probability that a specified loss will exceed some quantifiable level during a given exposure time. See *earthquake risk*, and Somerville and Moriwaki (2003).

seismic risk analysis (SRA) The calculation of *seismic risk* for a given property or portfolio of properties, usually performed in a probabilistic framework and displayed as a *seismic risk curve* or *seismic hazard map*. See Somerville and Moriwaki (2003).

seismic risk curve A plot of seismic risk (usually specified in terms of annual probability of exceedance or return period) versus a specified loss for a given property or portfolio of properties.

seismic sensor There are two basic types of seismic sensors: (1) *inertial seismometers* which measure *ground motion* relative to an inertial reference (a suspended mass), and (2) *strainmeters* or extensometers which measure the motion of one point of the ground relative to another. Inertial seismometers are generally more sensitive to earthquake *signals*, whereas strainmeters may outperform inertial seismometers when observing very long-*period free oscillations* of the Earth, tidal motions, and quasi-static *deformations* when it becomes increasingly difficult to maintain an inertial reference. See Chapter 5, DS 5.1 and IS 5.1 of this Manual.

seismic sequence Unconformity-bounded sequence of strata recognizable on seismic cross sections.

seismic signal A *coherent* transient *waveform* radiated from a definite, localized *seismic source* that is usually considered as a useful signal for the location of the source, the analysis of the source process and/or of the propagation medium (in contrast to *noise*). See *signal*.

seismic source A localized area or volume generating *coherent*, usually transient seismic *waveforms*, such as an *earthquake*, *explosion*, vibrator etc. See Ben-Zion (2003).

seismic source function See *source function*.

seismic spin solitons A kind of *rotational seismic waves* in a form of a finite number of spin pulses excited in the earthquake source as a result of spin vibrations. See Majewski (2006; 2008).

seismic station A facility devoted to the measurement and recording of earthquake motions. A modern seismic station has a weak motion sensor (e.g., a broadband *seismometer*), often a strong motion sensor (e.g., an *accelerometer*), and a *data logger* with GPS timing, onboard storage, and real-time communication devices. See Chapter 7 of this Manual, Lee (2002) and Hauksson et al. (2003). See also *station*.

seismic tomography An imaging method using a set of seismic *travel-time*, *amplitude* or *waveform* data obtained from *seismographs* distributed over the Earth's surface to deduce the 3D *velocity* and/or *attenuation*/*scattering* structure of the Earth's interior. In most cases, velocity structures are obtained from the travel-time data. Various computational techniques have been developed for data from different types of *seismic sources* including natural *earthquakes*, as well as controlled sources like explosions, *airguns* and bore-hole sources. However, it can be shown that collocated measurements of the ratio of *rotations* (or *strain*) and corresponding components of *translational motions* contain also information on the subsurface velocity structure (e.g., Fichtner and Igel, 2009). See also Curtis and Snieder (2002).

seismic trace See *trace*.

seismic twist solitons A kind of *rotational seismic waves* in a form of a finite number of twist pulses excited in the earthquake source as a result of twist vibrations. See Majewski (2006; 2008).

seismic wave A general term for waves generated by *earthquakes*, explosions or other types of *seismic sources*. There are many types of seismic waves. The principle ones are *body waves*, *surface waves*, and *coda waves*. See, e.g., Chapter 2 and IS 2.1 in this Manual, and Section 3 in Ben-Zion (2003).

seismic zonation Geographic delineation of areas having different potentials for hazardous effects from future earthquakes. Seismic zonation can be done at any scale – national, regional, local or site, the latter two often referred to as *microzonation*. See *seismic zoning map*.

seismic zone An area of *seismicity* probably sharing a common cause.

seismic zoning map A map used to portray *seismic hazard* or seismic design variables. For example, maps used in building codes to identify areas of uniform seismic design requirements.

seismite Sedimentary units or features resulting from earthquake shaking. See Grant (2002).

seismoelectric Electric fields generated by *crustal stress* changes during earthquakes. See Johnston (2002).

seismogenic Capable of generating earthquakes.

seismogenic thickness The thickness of the *brittle* layer within the *lithosphere* in which earthquakes occur. On the continents this thickness is typically 10 to 15 km, corresponding to the region at temperature lower than 300-400 degrees C. See Jackson (2002).

seismogenic zone That portion of the *crust* or *lithosphere* capable of generating earthquakes. See Sibson (2002).

seismogeodetic method A term introduced by Bodin et al. (1997) to describe the method used by Spudich et al. (1995) to infer the spatially uniform strain and rigid body *rotation* as functions of time that best fit ground translations recorded by a *seismic array*, essentially doing a geodetic inversion at every instant of time. The seismogeodetic method uses a generalized inversion of the data and accounts for the data covariances.

seismogram A record written by a *seismograph* in response to *ground motion*s produced by an earthquake, explosion, or any other *seismic sources* that generate oscillating *ground motions*. Such a record may be analog or digital. See diverse figures in Chapter 2 and in DS 11.1 to 11.4 of this Manual, Lee (2002) and Kulhanek (2002).

seismograph Instrument that detects and records *ground motions* (and especially vibrations due to earthquakes) along with timing information. It consists of a *seismometer*, a precise timing element, and a recording device or *data logger*. See Chapters 5 in the Manual and Wielandt (2002).

seismological parameter Parameter used to characterize a seismological property of the source, propagation path, or site-response. See, e.g., Campbell (2003).

seismology A branch of geophysics dealing with mechanical vibrations of the Earth caused by natural sources like earthquakes and volcanic *eruptions*, and controlled sources like underground explosions or any other *seismic source*.

seismomagnetic Magnetic fields generated by *crustal stress* changes during earthquakes. See Johnston (2002).

seismometer A sensor that responds to point *ground motions* or structural *acceleration* and usually produces a *signal* that can be recorded in terms of *displacement*, *velocity*, or acceleration of the seismometer mass with respect to the ground on which the seismometer is installed. A seismometer is usually a damped oscillating mass that is connected with a ground-fixed base and frame via a suspension, e.g., a spring (see *pendulum* with Figure 1). Thus the mass serves as an inertial reference for detecting and measuring seismic ground motion relative to the suspended mass. These relative motions are commonly directly recorded or transformed into an electrical voltage (see *transducer*), which was traditionally recorded analog on paper, film or magnetic tape. Nowadays, digital recording media are almost exclusively used. The seismometer record can mathematically be converted to a record of the absolute ground motion. For *inertial seismometers* (*sensors*), see Chapter 5 and DS 5.1 of this Manual. Another, non-inertial type of seismometers is *strainmeters* (see IS 5.1 in this Manual). Until recently, "seismometer" meant only a translational sensor that senses one of the three components of *translational motions*. More recently, a *rotational seismometer* may also be deployed to complement such translational seismometers and allow for measuring all six components of ground motion.

seismometer array See *seismic array* and Chapter 9 in this Manual.

seismometry The science of preparing for, making and understanding the effects instrumental seismic measurements. See Chapter 5 of this Manual.

seismoscope A device that indicates some feature of *ground motion* during an earthquake, but without producing the time-dependent record. Seismoscopes are forerunners of *seismographs* and were in use until about 1910.

self noise Also termed *instrumental noise*, is the *frequency*-dependent electronic and mechanical noise at the output of a *seismometer*, *seismic recorder* or *seismograph* in the presence of zero input signal (Lee et al., 1982). The self noise of a seismographic system is typically measured at a seismically quiet site using a single sensor (if the sensor noise is higher than the seismic noise) or two or three sensors (if the sensors' self noise is below the seismic noise). Weak-motion seismometers require two- or three-sensor methods to isolate self-noise from *ambient* Earth *noise*. Evans et al. (2010) provide a detailed definition and methods for measurement and analysis of *accelerometer* self noise and sections 5.5.5 to 5.5.7 in Chapter 5 of this Manual for different weak-motion seismometers. See also Sleeman et al. (2006).

self-organized criticality A system in a marginally steady state (at a critical point) in which the input is continuous and the output is a series of "avalanches" satisfying a *power-law* (*fractal*) *frequency*-size distribution. See Bak (1996) or Banzhaf (2002) or, for a general review, Wolfram (2002), and Turcotte and Malamud (2002) for application in seismology.

sensitivity (of seismic sensors) The scalar value used to convert the measured output *signal* (usually in voltage) to motion units. It is equivalent to the sensitivity scale factor of a normalized Laplace *transfer function*. For a sensor with a flat *frequency response*, the sensitivity corresponds to some mid-frequency level of the frequency-response *amplitude* for a specified frequency, often 1 Hz. Sensitivity has units of volts per input unit (e.g., volt per g for strong-motion *accelerometers*, volt per m/s for velocity meters or volt per rad/s for *rotational sensors*).

sensitivity kernels Term often used in connection with *seismic tomography*. Sensitivity kernels contain information about the possible resolution of a tomographic image. They are calculated as functions of space quantifying the influence of points in space on observable quantities (*arrival times*, translational or rotational *amplitudes*, or combinations of these) (or vice versa as functions of observable quantities vs. points in space).

separation A term in earthquake geology referring to the distance between any two parts of a reference plane (for example, a sedimentary bed or a geomorphic surface) offset by a *fault*, measured in any plane. Separation is the apparent amount of fault *displacement* and is nearly always less than the actual *slip*.

serpentinization A process by which the *upper mantle* reacts chemically with seawater to generate serpentine minerals. This process can cause substantial reductions in both *P*- and *S-wave velocities*. See Minshull (2002).

Sg *S waves* propagating through the *crust* like *Pg*. An older but not longer standard nomenclature for this phase is $\overline{S}$. At greater distances the *travel-time curve* of Sg is becoming (due to multiple paths all trapped in the crust) the *onset* of the *Lg-wave* group. Then both names are often alternatively used for the same seismic *onset*. For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

SH, SV

S-wave components with *polarization* direction in the horizontal and vertical planes with respect to the propagation direction of the S-wave *ray*. The *amplitude* ratio between the SH and SV component of the S-wave particle motion recorded at a *seismic station* depends on the *slip* direction in the *double couple source* with respect to the *take-off angle* from the source of the *seismic ray* arring at the station. For a vertically *heterogeneous* medium, the SV part of an S wave can be converted into a *P wave* and vice versa, The SH part of an S wave cannot interact with P-waves and is usually simpler than the SV part. In an *anisotropic* medium in which *shear-wave splitting* occurs, SH and SV are coupled, making this classification less meaningful or even useless.

shadow zone

Distance range along the Earth's surface in which a *direct phase* is not observed as a result of downward deflection of the *ray* path by a *low velocity zone* at depth. See section 2.5.3.3 and Figure 2.33 in Chapter 2 of this Manual, and Lay (2002).

shake map

A map of earthquake *ground motion* showing the geographical distribution of ground shaking as described by a specific parameter such as *peak acceleration*. See Hauksson et al. (2003).

shallow water wave

A kind of oceanic gravity wave. When the *wavelength* is much larger than the water depth, it is called a long wave or a shallow water wave. Most *tsunamis* can be treated as shallow water waves. See Satake (2002).

Shanidar

A cave in northern Iraq in which several Neanderthal skeletons were uncovered, dating back to 50,000 BP, presumably crushed by roof collapse caused by repeated earthquakes. They may be the oldest known casualties of earthquakes on Earth. See Nur (2002).

shear connection

A connection between a beam and a column designed to transmit only the shear force from the beam to the column and not the moment. In a steel frame building shear connections typically have the web of the beam welded or bolted to the column, but show gaps between the flanges of the beam and the surface of the column. See Dowrick (1977), and Salmon and Johnson (1996).

shear-coupled *PL*-waves

This is a long-*period* wavetrain that follows *S* for distances up to about 80°. It has been explained as being due to the coupling of S waves with a *leaking mode* of the *crust-mantle* waveguide, i.e., *PL-waves*. The coupling of PL-waves with *SS* and *SSS* has also been observed.

shear modulus The ratio of *shear stress* to shear *strain* of a material during simple shear (see *rigidity*, Fig. 2.2 and explanations in Chapter 2 of this Manual, and Birch, 1966).

shear stress Force per unit area exerted upon an infinitesimal surface in the direction tangential to that surface. There is some confusion over the usage of this term (see text for discussion in Ruff, 2002). In three-dimensions, there are two independent force components tangential to an area element, thus further specification is required. Another definition of shear stress cites the difference between two *principal stresses*, while still another definition cites half the difference between two principal stresses. The latter definition is compatible with the Mohr's Circle representation (see *Mohr diagram*) of the stress state. See *normal stress*; also Ruff (2002), and Figure 1 in Ben-Zion (2003).

shear wave Another name for *S wave*. See Section 2.2.3 in Chapter 2 of this Manual, and Eq. (1.9b) in Ben-Zion (2003).

shear-wave splitting Behavior of *S waves* in an anisotropic medium which shows a split into two *shear waves* with mutually perpendicular *polarization* directions and different propagation *velocities*. See Cara (2002), IS 11.5 (p. 16) and Fig. 2.8 of Chapter 2 in this Manual.

shield volcano Volcanic landform with broad, gentle slopes built by countless *eruptions* of fluid *lava*; classic example is Mauna Loa Volcano, Island of Hawaii. See *lava shield*.

short-period In traditional *seismometry* with limited *dynamic range*, *seismographs* were naturally divided into two types; long-period seismographs for *periods* above the spectral peak (periods around 5 seconds) of the *microseismic noise* generated by ocean waves and short-period *seismographs* for periods below it. A short-period seismograph *response* usually has a bandwidth from about 1 to 10 Hz. See Fig. 3.20 in Chapter 3, Section 4.5 in Chapter 4 of this Manual, and Wielandt (2002).

short-period body-wave magnitude (m_b) See *body-wave magnitude*.

shutter ridge (also shutterridge) A ridge that has been displaced by *strike-slip* or *oblique-slip faulting*, thereby shutting off the drainage channels of streams crossing the *fault* (after Buwalda, 1937 and Sharp, 1954).

SI An acronym for Système International d'Unités. See *international system of units*.

Sigma-Delta modulation A technique for *analog-to-digital conversion* commonly used in many modern seismic acquisition systems. See Chapter 6 in this Manual, and Scherbaum (2002).

signal The wanted part of given data. The remaining part is called *noise*. See *seismic signal*.

signal association A major problem in detection and location of *seismic events* using a *seismic network* is to sort out lists of *arrival times* from each station and correctly identify the sources of overlapping events. This work is called signal or *event association*. It is challenging particularly for global networks in producing reliable *seismic bulletins*, which commonly locate more than 100 events per day. See Richards (2002).

signal detection The detection of weak *signals* imposed upon *noise* can be accomplished by noting significant changes in *amplitude*, *frequency* content, *polarization* direction, signal shape, or wave propagation characteristics (*backazimuth* and *slowness*). If the signal to be detected has a *waveform* or a horizontal wave-propagation *velocity* that is known beforehand, for example, from a prior event in the same location and recorded at the same station, then *correlation* methods, matched filtering or velocity filtering can be applied for detection. See Chapter 9 and Section 4.4 in Chapter 4 of this Manual; also Richards (2002)

signal-to-noise improvement A measure of how well a wanted *signal* is enhanced by processing, relative to the *ambient noise* and unwanted signals. Assuming that the processing leaves the signal unchanged, the signal-to-noise improvement is often expressed as the square root of the ratio of the noise power (or its average over channels for an *array*) before processing to the power after processing. See Chapters 4 and 9 in this Manual, and Douglas (2002).

signal-to-noise ratio The comparison between the *amplitude* of the *seismic signal* and the amplitude of the *noise*; abbreviated as SNR. Often quantified as the ratio of the power (variance) of the signal to that of the noise for a given *frequency* band and measured in decibels (dB). See Chapters 4 and 9 in this Manual, Webb (2002), and Suyehiro and Mochizuki (2002).

signature The appearance of a *seismic signal* that is more or less unique to the kind of *seismic source*.

silent earthquake *Fault* movement not accompanied by seismic radiation. See Johnston and Linde (2002).

similarity (of earthquakes) Similarity of earthquake *waveforms* is a phenomenological property with a great latitude of definitions. High similarity is interpreted as the result of closely spaced *seismic sources* (*hypocenters*), reflecting the similarity of the *Green's functions* that characterize the source-receiver paths, and very similar source-radiation patterns. See, e.g., Geller and Mueller (1980), and Baisch et al. (2008) and references therein. Two similar events are called doublets, while a group of more than two similar events is known as a multiplet. A common way to investigate and express the similarity of earthquakes is through the application of waveform cross-correlation or matched filtering techniques, the correlation coefficient being a measure of the level of similarity between waveforms. See *correlation*, *correlation coefficient*, *cross-correlation*, and Chapter 9 in this Manual.

simulated annealing A trick used to solve optimization problems, taking its roots in a thermodynamical analogy. Simulated annealing is based on the *Metropolis* algorithm. See Mosegaard and Tarantola (2002) and Tarantola (2005).

single-degree-of-freedom (SDOF) system An *oscillator* or structure composed of a single mass attached to a spring and dashpot. This system has a single mode or *period* of vibration whose *response* is described by a single variable. See Chapter 5 and Fig. 5.5 in this Manual, and Campbell (2003).

single frequency microseisms A secondary peak near 14-second *period* in *seismic noise* related to the action of ocean waves which is usually 20-40 dB smaller than the main peak due to the *double frequency microseism*. Called the single frequency peak because the seismic noise is at the same *frequency* as the ocean waves. See Chapter 4 in this Manual, and Webb (2002).

sinistral fault See *left-lateral fault*.

site amplification See *site response*.

site category Category of site geologic conditions affecting earthquake *ground motions* based on descriptions of the geology, or measurements of the *S-wave velocity* standard penetration test, shear strength, or other properties of the subsurface. For example, in the USA, geologic site conditions were classified by NEHRP into 6 categories ranging from A (hard rock) to F (very soft soil) and different amplification factors were assigned for them. See Kawase (2003).

site classification The process of assigning a site category to a site by means of geological properties (e.g., crystalline rock, *Quaternary* deposits, etc.), or by means of a geotechnical characterization of the soil profile, e.g., standard penetration test and *S-wave velocity*. See Borcherdt et al. (2003).

site effect The effect of local geologic and topographic conditions at a recording site on *ground motions*. It is implicitly assumed that the source, *path* and site *effects* on ground motions are separable. See Chapter 14 in this Manual, and Kawase (2003).

site response — The modification of earthquake *ground motion amplitude*, *phase* and shape in the *time* or *frequency domain* caused by local site conditions. See Chapter 14 in this Manual, and Campbell (2003).

Skempton's coefficient — A poroelastic constant *B* relating changes in mean *stress* σ_m to *pore* fluid *pressure* p, $B = dp/d\sigma_m$. See Lockner and Beeler (2002, p. 526).

skewness — A quantitative measure of deviation of a random value distribution from the "normal" symmetric *Gaussian distribution.* The skewness is zero for symmetric distributions, it becomes negative (positive) if the distribution contains outliers to the left (right). See *higher order statistics.*

SKS — *Mantle shear wave* transmitted through the outer *core* (K) as a *P wave*. See Figs. 2.8 and 2.52 in Chapter 2 and Figs. 11.48, 11.68, and 11.69 in Chapter 11 of this Manual, as well as Kulhanek (2002, p. 341-343), Cara (2002), and Aki and Richards (2002 or 2009, Box 5.9, p. 181-182). For this and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

slab — Subducted oceanic *lithosphere plate* that underthrusts the continental plate in a *subduction zone* and is consumed by the Earth's *mantle*. Typically a dipping tabular region of relatively high seismic *velocity*, high *Q* and low temperature. Deep earthquakes only occur within subducted slabs, and such *seismicity* extends to depths down to 700 km. See Lay (2002).

slab pull — The force of gravity causing the cooler and denser oceanic *slab* to sink into the hotter and less dense *mantle* material. The downdip component of this force leads to downdip extensional *stress* in the slab and may produce earthquakes within the subducted slab. Slab pull may also contribute to stress on the *subduction thrust fault* if the *fault* is *locked*.

slickensides — A polished and smoothly striated surface that results from *slip* along a *fault* surface. The striations themselves are slickenlines.

slip — The relative *displacement* of formerly adjacent points on opposite sides of a *fault*. See *slip vector*, *fault slip*.

slip model — A kinematic model that describes the amount, distribution, and timing of a *slip* associated with an earthquake.

slip moment — A geological term for *seismic moment*. See Chapter 36 in Lee et al. (2002).

slip rate

How fast the two sides of a *fault* are slipping relative to one another, as derived from seismic records in case of an earthquake or determined, as a long-term average, from geodetic measurements, from offset man-made structures, or from offset geologic features whose age can be estimated. It is measured parallel to the predominant *slip* direction or estimated from the vertical or horizontal offset of geologic markers. See also *fault slip rate*.

slip vector

The direction and amount of *slip* in a *fault plane*, showing the relative motion between the two sides of the *fault*. See Figs. 3.30 and 3.31 in Chapter 3 and IS 3.1 in this Manual, Fig (13) in Ben-Zion (2003), Jackson (2002), and Aki and Richards (2002 or 2009, Fig. 4.13, p. 101).

slip waves

See *creep waves*.

slope-intercept method

A graphical technique used to infer seismic *velocities* and layer thicknesses from seismic *travel-time* data, based on the assumption that the *crust* is built up of uniform layers bounded by horizontal *discontinuities*. See Fig. 2.36 and section 2.5.3.5 in this Manual, and Minshull (2002).

slow earthquake

Fault failure occurring without significant seismic radiation due to very low *rupture velocity* and/or *stress drop*. See Johnston and Linde (2002). See *creep, creep event*.

slowness

The inverse of *velocity* v, often annotated as scalar *s*, related to vector **k** (the *wavenumber vector***)** and given in units seconds/degree or seconds/km.

slowness vector s

The slowness vector **s** points into the direction of wave propagation and has the absolute value s = 1/v with v = wave propagation *velocity*. See also *wavenumber vector*.

slow-slip event

Aseismic slip (no *seismic waves* are generated) on the *subduction interface* downdip from the seismogenic zone. Slow slip-events are detected by measuring crustal *deformation* with dense GPS or *tiltmeter* networks. Estimates of the time span for these events range from 6 to 15 days in the Cascadia subduction zone (Dragert et al. 2001). Recurrence rate for these events ranges from 13 to 16 months (Cascadia) to approximately six month in southwest Japan (Obara et al., 2004). Slow-slip events appear to coincide with the occurrence of major non-volcanic tremor activities. See also *creep, creep event, silent earthquake, non-volcanic tremor, episodic tremor and slip*.

small earthquake

An earthquake with magnitude that ranges from 3 to 5 is often called “small”. See *magnitude*.

Sn Early use of the designation Sn was in reference to short-*period S waves* that were presumed to propagate as *head waves* along the top of the *mantle*. The new *IASPEI* standard *phase names* define Sn as any S wave bottoming in the uppermost mantle or an upgoing S wave from a source in the uppermost mantle; see also the discussion about the analogues defined phase *Pn*. Quite commonly, the term is now also applied to a prominent *arrival* of short-period *shear waves* that may be observed (with a straight-line *travel-time* curve) at *epicentral distances* as great as 40°. Although Sn arrives at regional distances larger than 100 km usually as the first S-wave arrival, its *amplitudes* are, as compared to the later *Sg*, *SmS*, *Lg* arrivals, relatively small and often covered in the signal generated noise after *Pg*. For record examples see, e.g., Figs. 1a, 3a, 4a, 6a, and 6c in DS 11.1 of this Manual and Kulhánek (2002). For this and other such symbols used in seismic phase names see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

Snell's law In seismology, the law describing the angles of *seismic rays* reflected and transmitted (i.e., refracted) at an *interface* in the Earth. It is derived from the conservation of wave *slowness* parallel to the interface. This law was originally discovered in optics by the Dutch physicist Willebrord Snell in about 1621. See section 2.5.2 in Chapter 2 of this Manual, Chapman (2002), and Bleistein (2002).

SOFAR channel A depth region of low acoustic *velocity* within the ocean water column which allows sound waves to propagate over very large distances with very low *attenuation*. It is a very efficient waveguide for the seismic *T phase* from earthquake sources. See Kulhanek (2002).

soil (1) In geotechnical engineering, all unconsolidable material above the *bedrock*. (2) In soil science, naturally occurring layers of mineral and (or) organic constituents that differ from the underlying parent material in their physical, chemical, mineralogical, and morphological character because of *pedogenic* processes.

soil profile Vertical arrangement of soil horizons down to the parent material or to *bedrock*. Commonly subdivided into A, B and C horizons.

soil-structure interaction A term applied to the consequences of the *deformation* and forces induced into the soil by the movement of a structure. The common fixed-base assumption in the analysis of structures implies no soil-structure interaction.

solitons (or **solitary waves**) A special kind of localized waves that propagate undistorted in shape. They are essentially nonlinear waves, which can be treated as non-dispersive localized packets of energy moving with uniform *velocity*. Solitons are exact solutions of nonlinear wave equations. See Majewski (2006).

sound waves See *air wave*.

source See *seismic source*.

source depth Depth of an earthquake *hypocenter* (see *focal depth*) or of a buried explosion, mining collapse, or any other type of *source* that generates *seismic waves*.

source directivity effect The effect of the earthquake source on the *amplitude*, *frequency* content and duration of the *seismic waves* propagating in different directions, resulting from the propagation of *fault rupture* in one or more directions with finite speeds. Directivity effects are comparable to, but not exactly the same as the *Doppler effect* for a moving *oscillator*. See Faccioli and Pessina (2003), and material below Eq. (3.8), Figure 6 in Ben-Zion (2003) and Fig. 3.112 in Chapter 3 of this Manual

source duration Time length of *seismic energy* radiation from the *seismic source*.

source effect The effect of the earthquake source on seismic motions. It is implicitly assumed that the source, *path* and *site effects* on *ground motions* are separable. See, e.g., Aki (2002), and Eq. (3.5) in Ben-Zion (2003).

source function The *ground motion* generated at the *fault* during rupture, usually as predicted by a theoretical model and represented by a time history or *spectrum*. The terms Brune spectrum, Aki spectrum, and *Haskell model* refer to varying representations of the source function, each based on different assumptions, as devised by the scientist for which the model is named. Strictly defined, the source function is a compact space-time history of the earthquake source process that will give the observed *displacement waveforms* as its convolution with the *Green function* for the wave propagation in the Earth and the *instrument response* of the recording instrument. See Aki and Richards (1980), Ben-Menahem and Singh (1981), Das and Kostrov (1988).

source-to-site distance Shortest distance between an observation point and the source of an earthquake *hypocenter* that is represented as either a point (point-source distance measure) or a ruptured area (finite-source distance measure). See Campbell (2003).

source zone An area in which an earthquake is expected to originate. More specifically, an area considered to have a uniform rate of *seismicity* or a single probability distribution for purposes of a *seismic hazard* or *seismic risk* analysis.

space-based geodesy Space-based technologies to measure the positions of geodetic monuments on the Earth. A fundamental departure from the traditional geodesy is its reference to an inertial reference frame rather than those fixed to the Earth. Current accuracy of better than a centimeter for sites thousands of kilometers apart is good enough for measuring the present-day *plate motion*. See Stein and Klosko (2002), and Feigl (2002).

spasmodic burst A rapid-fire sequence of high-*frequency* earthquakes often observed in volcanic or geothermal areas presumably due to a cascading *brittle*-failure sequence along subjacent *faults* in a fracture mesh driven by transient increases in local fluid *pressures*. See Hill et al. (1990).

specific barrier model A *fault* model consisting of a *rectangular fault plane* filled with circular-crack sub-events developed by Papageorgiou and Aki (1983) for interpreting the observed power spectra of strong *ground motion* records. It is a hybrid of deterministic and stochastic fault model, in which the sub-event ruptures statistically independently from each other as the *rupture front* sweeps along the *fault length*. See Papageorgiou (2003) for its latest review.

spectral acceleration Commonly refers to either the *Fourier amplitude spectrum* of ground *acceleration* or the pseudo relative velocity response spectrum (PSRV); abbreviated as SA.

spectral amplification A measure of the relative shaking response of different geologic materials depending on the *frequency* of excitation; the ratio of the *Fourier amplitude spectrum* of a *seismogram* recorded on one material to that computed from a seismogram recorded on another material for the same *earthquake* or explosion.

spectral ratio The ratio of two *amplitude* (or *power*) *spectra*. In classical linear theory, the ratio between transverse *acceleration* and *rotation rate* for time windows containing *surface waves* is proportional to the *dispersion* curves, the *frequency*-dependent local *phase velocities* (see Lee and Trifunac 2009). The spectral ratio H/V of horizontal to vertical component records of ambient *seismic noise* (so-called *Nakamura method*) is used to estimate the fundamental *resonance* frequency of the sedimentary cover layers in *microzonation* studies (see Chapter 14 of the Manual).

spectrum Curves showing *amplitude* or *phase* of a *time-history* as a function of *frequency* or *period*.

spectrum intensity (S.I.) A broadband measure of the intensity of strong *ground motion* defined by the area under a *response spectrum* between two selected *natural periods* or *frequencies*. First introduced by

Housner (1952) as the area under the 20 per cent damped response spectrum between periods of 0.1 and 2.5 seconds.

spherical surface harmonics Analog of the two-dimensional Fourier series for the spherical surface. It combines Fourier harmonics and Legendre polynomials and is used to describe the Earth's *normal modes* of oscillation (among many other phenomena). See Aki and Richards (2002 or 2009, Box 8.1, p. 334-339).

spherical wave A wave for which the constant-phase surfaces are spheres perpendicular to the direction of propagation. See *plane wave*; also Aki and Richards (2002 or 2009, p. 190-217).

spheroidal A mode of vector field **u** in spherical coordinates for which the radial component of **rot u** is zero. See *toroidal*; also Aki and Richards (2002, p. 341).

spinor A geometrical object similar to a tensor that describes a rotational state. Some authors believe that spinors are more fundamental objects than tensors. See Majewski (2008).

spread The layout of *seismometer*/*geophone* groups from which data from artificial *seismic sources* (such as explosions, vibrators, *airguns*) are recorded simultaneously.

spread footing A support structure for a wall, column or pier that is essentially a horizontal mat, usually of reinforced concrete, lacking piles or caissons. The footing works by spreading the load over an area wide enough to reduce the bearing *stresses* to permissible levels. See Park and Paulay (1975).

SRSS (Square Root of the Sum of Squares) A technique used in earthquake engineering analysis and design (introduced by Rosenblueth, 1951), wherein the maximum contributions of different modes to a variable of interest, determined from a *response spectrum* or spectra, are combined by squaring them, adding, and taking the square root of the sum. The result gives an estimate of how the modal responses, whose time of maximum occurrence is not known, combine to produce the maximum total response. See also the biography of Emilio Rosenblueth in Howell (2003).

SSAM An acronym for real-time Seismic Spectral Amplitude Measurement; the SSAM system aids in the rapid identification of precursory *long-period (LP) volcanic seismicity* during rapidly escalating *volcanic unrest* (see Stephens et al., 1994, for details).

stable tectonic regime A term that refers to a region where *tectonic deformation* is relatively low and earthquakes are relatively infrequent, usually far from plate *boundaries*.

stacking process In *reflection seismology*, the process of summing several seismic traces that have been corrected for normal *moveout*. See Sheriff and Geldart (1995). See *beamforming* and *delay-and-sum processing*.

standard deviation A measure of how much a set of data is different from the curve it should make when plotted on a graph. Or, the square root of the average of the squares of deviations about the mean of a set of data. Standard deviation is a statistical measure of spread or variability.

state of tectonic stress The magnitude and orientation of *principal stress*es in the Earth. Principal stresses are usually aligned with horizontal and vertical. See Zoback and Zoback (2002).

static fatigue A laboratory observed phenomenon in mechanical engineering, material science and rock mechanics, consisting of an inherent time delay between the application of a *stress* increase and the occurrence of *brittle* failure (*stress drop*) induced by the stress change. See Lockner and Beeler (2002, p. 523).

static stress drop A theoretically well-defined quantity that compares the "before" and "after" *stress-strain* states of the elastic volume that surrounds the *fault*. The definition of the overall static stress drop reduces to a weighted integral over just the fault portion that slips during the earthquake. See *dynamic stress drop*; also Figure 10 in IS 3.1 of this Manual, Ruff (2002, p. 548-550), Brune and Thatcher (2002, p. 580-581), and Figure 14 in Ben-Zion (2003).

station In seismology, the site where geophysical instruments, e.g., *seismograph*s, have been installed for observations. Stations can either be single sites or specially grouped *arrays*.

stationary random process An ensemble of time series for which the ensemble-averaged statistical properties such as mean and variance do not vary with time. If the statistical averages taken over time for a single member of the ensemble are the same as the corresponding averages taken across the ensemble, the stationary random process is also ergodic.

stationary linear system See *linear system*.

station calibration For using *station* observations from all over the world in a common data center, these station observations should be corrected (if possible) for all very anomalous local effects such as significant azimuth- and distance-dependent *travel-time residuals*. The same applies to anomalously large or small *amplitudes* of relevant *seismic phases* due to strong *site effects* which systematically bias station *magnitude* readings with respect to the network average. See Richards (2002).

steady-state strength The shear resistance of contractive soil in the liquefied state. With respect to *liquefaction*, the steady-state strength and the residual strength are used interchangeably. See Youd (2003).

steam-blast See *phreatic*.

step-out The time between two seismic *phases*, such as pP and *P*, at a specific *epicentral distance* from a *station*. The step-out, if it increases or decreases as the distance increases, can be a characteristic determinant for phase identification.

stepover Region where one *fault* ends, and another *en echelon* fault of the same orientation begins; described as being either right or left, depending on whether the bend or step is to the right or left as one progresses along the fault.

stick-slip A periodic or quasi-periodic faulting cycle consisting of a relatively long period of static, predominately elastic loading followed by rapid *fault slip* seen on laboratory fault surfaces loaded at a constant rate of shear stressing; stick-slip is considered the laboratory time scale equivalent of periodic earthquake recurrence. See Lockner and Beeler (2002, p. 518).

stochastic process A physical process with some random or statistical element in its structure. See Turcotte and Malamud (2002), and Vere-Jones and Ogata (2003, p. 1577).

Stoneley wave Wave trapped at a plane *interface* of two elastic media. It is always possible at a solid-fluid interface with the *phase velocity* lower than the compressional velocity of the fluid. It can exist at a solid-solid interface only in restrictive cases. See Aki and Richards (2002, p. 156-157), as well as Webb (2002), and the biography of Robert Stoneley in Howell (2003).

strain (**strain tensor**) Change in shape and/or size of a infinitesimal material element per unit length or volume. In elasticity theory, the strain is generally referred to a reference state in which the material has zero *stresses* (natural configuration). For small *deformation*, the complete description of strain at a point in three dimensions requires the specification of the extensions (change in length/length) in the directions of each of the reference axes and the change in the angle between lines which were parallel to each pair of reference axes in the reference state. Diagonal components of the strain tensor describe normalized changes in length; off-diagonal components describe changes in angle. See Johnston and Linde (2002).

strain events Episodic *strain* transients recorded by *strainmeters*. See Johnston and Linde (2002).

strain hardening

The property of a material to resist post-yield *strains* with increasing *stress*, as opposed to the constant post-yield stress of a perfectly plastic material.

strainmeter

Strainmeters or extensometers are another basic type of *seismic sensor*. They measure the motion of one point of the ground relative to another, in contrast to inertial *seismometers* which measure the *ground motion* relative to an inertial reference such as a suspended mass. See IS 5.1 in this Manual.

strain rate

Strain measurements are computed from observed changes in length on the Earth's surface, commonly along multiple paths. Because the changes in length are observed over varying time periods and path lengths, they are expressed as the change in length divided by the measurement distance divided by the time period of measurement. This number, termed the strain rate, is expressed as the change in length per unit length per unit time. Strain rates vary widely in different *tectonic* environments, ranging from about 10^{-8}/year at highly active *plate boundaries* and 10^{-11} to 10^{-12} within stable continental platforms. These differences in strain rates control the average return period of earthquakes.

strain steps

Step-like changes in *strain* recorded by *strainmeters*. See Johnston and Linde (2002).

stratigraphy

The study of the character, form and sequence of layered rocks.

stratovolcano

Volcanic landform produced by deposits from explosive and non-explosive *eruptions*, resulting in a volcanic edifice built of interbedded layers of *lavas* and *pyroclastic* materials.

strength (of rock)

The ability of rock to withstand an applied *stress* before failure. It is measured in units of stress by means of the uniaxial and triaxial compression test. See Handin (1966), and Scholz (2002).

stress

Force, resolved into normal and tangential components, exerted per unit area on an infinitesimal surface. A complete description of stress (i.e., the *stress tensor*) at a point in a three dimensional reference frame requires the specification of the three components of stress on each of three surface elements orthogonal to one of the reference axes. Hence there are nine components of stress. However, in a *homogeneous*, *isotropic* medium (i.e., classical continua, consisting of point masses), the balance of *torque* implies the symmetry of the stress tensor and therefore reduces the stress description to six independent components: three normal components and three shear components. In *micropolar* theory, stresses may be non-symmetric. In contrast, *traction* is a force vector defined for a particular surface. See IS 3.1 in this Manual, as well as Ruff

	(2002), Zoback and Zoback (2002), Johnston and Linde (2002), and Figure 1 in Ben-Zion (2003).
stress corrosion	A *stress* degradation process that is related to the action of some chemical agents. See Teisseyre and Majewski (2002).
stress drop	The difference between the *stress* on a *fault* before and after an earthquake. A parameter in many earthquake source models that has a bearing on the level of high-*frequency* shaking radiated by the earthquake. Commonly stated in units termed bars or megapascals (1 megapascal (MPa) = 10^6 N/m^2 = 10 bars). See *static stress drop*, *dynamic stress drop*, Fig. 10 in IS 3.1 of this Manual, and Figure 14 in Ben-Zion (2003).
stress map	Map showing the orientation and relative magnitude of horizontal *principal stress* orientations. See Zoback and Zoback (2002).
stress shadow	A region where earthquakes are temporarily inhibited because the ambient *stress* has been decreased by a nearby earthquake. A *fault* can remain in a stress shadow until stress accumulation recovers the pre-earthquake stress state. See Harris (2003).
stress tensor	See IS 3.1 in this Manual and *stress*.
stretch modulus	Also termed *Young´s modulus*, describes the behavior of a cylinder of length L that is pulled on both ends.
strike	Trend or bearing, relative to North, of the line defined by the intersection of a planar geologic surface (for example, a *fault* or a bed) and a horizontal surface such as the ground. See *fault strike*, Fig. 3.107 in Chapter 3 of this Manual, and Figure13 in Ben-Zion (2003).
strike-slip	See *fault movement*.
strike-slip fault	A *fault* on which the movement is parallel to the *strike* of the fault, e.g., the San Andreas fault. The maximum and minimum *principal stresses* are both horizontal. See Yeats et al., (1997, p.167-248).
Strombolian eruption	Slightly more violent than *Hawaiian eruptions*, this type of activity is characterized by the intermittent explosion or fountaining of *lava* from a single *vent* or *crater*. Such eruptions typically occur every few minutes or so, sometimes rhythmically and sometimes irregularly.
strong ground motion	*Ground motion* of sufficient *amplitude* and duration to be potentially damaging to a building’s structural components, architectural features, or to its content. One common practical designation of strong ground motion is a *peak ground*

acceleration of 0.05 *g* or larger. See Anderson (2003), Bolt and Abrahamson (2003), and Campbell (2003).

strong motion See *strong ground motion*.

strong-motion accelerograph An *accelerograph* designed to record accurately the *strong ground motion* generated by an *earthquake.* They were originally developed by earthquake engineers, because the traditional *seismographs* designed by seismologists to record weak ground motions from earthquakes were too fragile and did not have sufficient *dynamic range* to record strong ground motions. A typical strong-motion accelerograph has a tri-axial *accelerometer*, which records *acceleration* up to 2 *g* on scale. See Anderson (2003), and Kinoshita (2003).

strong-motion instrument See *strong-motion accelerograph*.

strong-motion parameter A parameter characterizing the *amplitude* of *strong ground motion* in the *time domain* (time-domain parameter), or *frequency domain* (frequency-domain parameter). See Campbell (2003).

strong-motion seismograph See *strong-motion accelerograph*.

structural geology The study of geologic structures and their formation processes. Applied to earthquakes, it includes the relation between *faults*, folds and *deformation* of rocks on all scales. See Jackson (2002).

subduction A *plate tectonics* term for the process whereby the oceanic *lithosphere* collides with and descends beneath the continental lithosphere.

subduction thrust fault The *fault* that accommodates the differential motion between the downgoing oceanic crustal *plate* and the continental plate. This fault is the contact between the top of the oceanic plate and the bottom of the newly formed continental *accretionary wedge*. Also alternately referred to as the *plate-boundary* thrust fault, the thrust *interface* fault or the megathrust fault.

subduction zone A zone of convergence of two *lithospheric plates* characterized by thrusting of one plate into the Earth’s *mantle* beneath the other. Processes within the subduction zone bring about melt generation in the mantle wedge and cause buildup of the overlying *volcanic arc*. Subduction zones (where most of the world’s greatest earthquakes occurred) are recognized from the systematic distribution of *hypocenters* of deep earthquakes called *Wadati-Benioff zones*. See Uyeda (2002, p. 62-64), and biographies of Hugo Benioff and Kiyoo Wadati in Howell (2003).

subductology, comparative Comparative study of *subduction zones* emphasizing the differences between the Mariana-type and Chilean-type subduction zones, caused by difference in the degree of *plate* coupling. See Uyeda (1982) and Uyeda (2002).

subplinian eruption A small-scale *Plinian eruption* - intermediate in size and energy release between Strombolian and Plinian activity - that is characterized by *pumice* and *ash* deposits covering less than 500 km^2.

substructure Generally, that portion of a structure that lies below the ground, for example, the basement parking in a tall building. In analyses, the substructure can include a portion of the surrounding ground as well as all or part of the structural foundation. See Hall (2003).

summit (or central) eruptions General terms referring to *eruptions* that take place from one or more *vents* (fissural or cylindrical) located at or near the summit, or center, of the volcanic edifice, in contrast to eruptive outbreaks on the flanks of volcanoes downslope from the summit area. Compare with *flank* or lateral *eruption*.

superstructure That portion of a structure that is above the surface of the ground or other reference elevation at which a significant change in the structure occurs. See Hall (2003).

surface faulting Faulting that reaches the Earth’s surface; commonly accompanies moderate and large earthquakes having *focal depths* less than 20 km. The faulting is almost always *coseismic*, however it may also accompany *aseismic tectonic creep* or natural or man-induced subsidence. See Bonilla (1970).

surface P wave The *ray* path of surface P consists of two segments: a) an *S-wave* path from the source to the free surface with an apparent horizontal *velocity* equal to the *P-wave* velocity, and a P-wave path along the free surface to the receiver. Surface P-waves appear at the critical distance and can be a sharper *arrival* than the direct S waves, although they attenuate very rapidly with distance. In some respects they behave like *diffracted* or *head waves*.

surface reflections/conversions Waves leaving the source downwards and then undergoing one or more *reflections* or *conversions* (from P to S or vice versa) at the surface before arriving at the recording station, contrary to *depth phases*, which leave the source in an upward direction. Examples are *PP, PPP, SS, SSS, SP, PS, PPS, SP* etc. For these and other such symbols used in seismic *phase names* see IS 2.1 in this Manual and Storchak et al. (2003 and 2011).

surface wave *Seismic wave* that propagates along the surface of an elastic *halfspace* or a layered elastic halfspace. See *Love wave* and *Rayleigh wave*, Chapter 2 of this Manual and also Romanowicz (2002), and Kulhanek (2002).

surface-wave magnitude (*M_S*) An earthquake *magnitude* scale determined from surface wave records and introduced by Gutenberg (1945) uses maximum *amplitudes* of *surface waves* with *periods* around 20 seconds. In its *IASPEI*-recommended standard form, it is now termed Ms_20 and uses a slightly different *magnitude calibration function* than Gutenberg and amplitude readings on seismic records which simulate the long-period *WWSSN response.* Another IASPEI-recommended surface wave magnitude standard is the broadband version Ms_BB. It allows magnitude determinations in a wider range of periods (2 to 60 s) and distances (2° to 160°), is better tuned to the use of the IASPEI Ms standard *calibration* function and correlates better with the *moment magnitude Mw*. See *magnitude saturation*, Chapters 3 and IS 3.3 in this Manual, Bormann et al. (2009), and IASPEI (2013).

SV See *SH, SV*.

swarm (of earthquakes) A sequence of earthquakes occurring closely clustered in space and time with no dominant *mainshock*. See McNutt (2002) and Utsu (2002b).

swath bathymetry Seafloor bathymetry obtained by a multi-narrow beam echo sounder. One sounding sequence can provide bathymetry information over a width of more than 7 times the water depth. See Suyehiro and Mochizuki (2002).

S wave *Elastic waves* producing shear and no volume change are called S waves (S standing for Latin *Secundae* or “secondary”). In a *homogeneous*, *isotropic*, linear elastic medium the *velocity* of S waves is equal to $(\mu/\rho)^{-1/2}$, where μ and ρ are the *rigidity* and *density*, respectively. For a classical isotropic linear elastic medium (in an isotropic *far field*), the particle *displacement* associated with S waves is perpendicular to the direction of wave propagation, so they are sometimes called “transverse waves.” See Aki and Richards (2002, p. 122), and Ben-Zion (2003, Eq. (1.9b)). In an isotropic full space, only S waves generate *rotational motions*. For isotropic *Cosserat continua*, the S wave becomes a mixed shear-rotational wave. In anisotropic media, it couples also with *P waves*.

synthetic (ground motion) Time-history of a strong *ground motion* for engineering purposes calculated by a deterministic or stochastic simulation. See Boore (2003) for the latest review on simulation of ground motion using the stochastic model. See also Faccioli and Pessina (2003).

synthetic seismograms Computer-generated *seismograms* for models of *seismic source* and Earth's structure. Various methods are used for different purposes, encompassing the whole field of theoretical seismology. Those for the vertically *heterogeneous* one-dimensional Earth model have been well developed and described in many text books. Those for the 2D- and 3D-models are still under development. See Chapters 8 through 13 and 55 in Lee et al. (2002) and for examples Figs. 2.82, 2.83, and 2.85 of Chapter 2 and Figures 3 and 4 in IS 11.4.

T

take-off angle The angle under which a *seismic ray* leaves the *seismic source*, measured from the plum line clockwise or counter-clockwise. It is 0° when taking off in the direction of the plum line, 90° when leaving the source in horizontal direction and 180° when taking off vertically upward. The take-off angles from the source have to be known (respectively calculated on the basis of a certain model) when reconstructing seismic *fault-plane solutions* from observed *first motion polarities*, *amplitude* ratios or *polarization* analysis via stereographic projections of the *focal sphere*. See section 3.4.2 of Chapter 3 and EX 3.1 in this Manual.

tamped explosion An explosion in which the explosive is buried under the ground firmly to avoid venting into the atmosphere**.** See Richards (2002).

Taylor expansion A mathematical technique commonly used to linearize an equation. It is based on the Taylor's theorem which describes approximating polynomials for rather general functions and provides estimates for errors. It is named after the English mathematician and philosopher Brook Taylor (1685-1731). See James and James (1976).

tectonic Of, pertaining to, or designating the rock structure and external forms resulting from deep-seated crustal and subcrustal forces in the Earth.

tectonic earthquake An earthquake caused by the release of *strain* that has accumulated in the Earth as a result of broad scale *tectonic deformations* (as contrasted with volcanic earthquakes or impact earthquakes).

tectonic plates Large, relatively *rigid plates* of the *lithosphere* that move relative to one another on the outer surface of the Earth.

tectonic rotational solitons Rotational (spin or twist) *solitons* generated by past earthquakes and propagating slowly (about 1 km/day) along a fractured earthquake *fault* and triggering new earthquakes. See Majewski (2006).

tectonics The branch of Earth Science that deals with the structure, evolution, relative motion, and *deformation* of the outer part of the Earth, or the *lithosphere*, on a regional to global scale, for time scales ranging from very short up to thousands of millions of years. The term “active tectonics” refers to tectonic movements that occur on a time scale of up to thousands of years, and “neotectonics” to tectonic movements on a scale of thousands of years to a few million years. The lithosphere includes the Earth's *crust* and part of the Earth's upper mantle and averages about 100 km in thickness. Plate tectonics is a theory of global tectonics in which the Earth's lithosphere is divided into a number of spherical *plates* that undergo dominantly rigid-body translation on the sphere. The relative motions of these plates cause earthquakes and deformation along the plate boundaries and in adjacent regions.

tectonoelectric Electric fields generated by non-seismic crustal *stress* changes. See Johnston (2002).

tectonomagnetic Magnetic fields generated by non-seismic crustal *stress* changes. See Johnston (2002).

tectonophysics A branch of geophysics that deals with the *deformation* of the Earth.

teleseism A *seismic source* at an *epicentral distance* larger than about 20º or 2200 km from the observation site.

teleseismic waves *Seismic waves* observed at distances more than 20º (or about 2200 km) away from the *epicenter*. For record and ray path examples see, e.g., Fig. 1.6 in Chapter 1, section 2.6.2 of Chapter 2, sections 11.5.2 to 11.5.4 of Chapter 11 as well as record examples in DS 11.2 and 11.3 of this Manual.

tensile (tensional) stress The *stress* component normal to a given internal surface, such as a *fault plane*, that tends to pull the materials apart. See *compressive stress*, *normal stress*, Figure 3 in IS 3.1 of this Manual, and Figure 1 in Ben-Zion (2003).

tensor of inertia Rotational analogue of mass. This is a symmetric (maximum six components), positively defined tensor that describes the distribution of mass in a rigid body. This tensor rotates together with the body if it moves, and its eigenvalues are called principal moments of inertia (diagonal components of the symmetric tensor). The tensor of inertia multiplied by the vector of *rotational velocity* is a part of the *kinetic moment*. In *micropolar* theories, inertial characteristics of each particle are density and density of tensor of inertia.

tensor strainmeters Borehole *strainmeters* measuring three horizontal *strain* components from which the principal strain components can be derived. See Johnston and Linde (2002).

Tertiary A period in geologic time, from 66.4 to 1.6 million years ago. See *geologic time*.

tephra Collective term for airborne *pyroclastic* material, regardless of fragment size or shape, produced by explosive volcanic *eruptions*. Tephra can be of juvenile or lithic origin. See *lithics* and *juvenile*.

theoretical onset time Time at which the *arrival* of a seismic *phase* is expected to appear on a *seismic record*, based on the known location and depth of the *seismic source* and related theroretical *travel-time* calculations based on an assumed Earth model.

thermal boundary layer Layers at the top and bottom of a convecting fluid where heat advection and heat conduction are in balance.

thermal conductivity (of rock) The rate of *heat flow* in rock per unit area of the internal surface normal to the temperature *gradient* vector is proportional to the magnitude of the temperature gradient. This proportionality constant is the thermal conductivity.

thermal fluid pressurization Transient thermal pressurization of *fault zone* fluids as a consequence of heat generated during *seismic slip*. See Sibson (2002).

three-dimensional site amplification Traditionally, site *amplification* of *ground motion* has been modeled by means of a depth-dependent one-dimensional structure. Three-dimensional amplification considers a structure varying in all directions due to features such as irregular topography and sub-surface *interfaces*. The computational load increases dramatically as one proceeds from 1-D to 3-D through the intermediate 2-D approximation. See Kawase (2003).

thrust fault A *reverse fault* that dips at shallow angles, typically less than about 30 degrees. See also *fault* and Jackson (2002).

tilt A term that to some authors seems to mean long-period *rotations* about a horizontal axis, to others only static rotations, and to yet others rotations at any *frequency*. The term “tilt” should be used only with full, graphically supported definitions inclusive of frequency band, according to Evans et al. (2010).

tiltmeter An instrument designed to measure changes in the direction of (or angle to) the local surface normal. *Tilt* at the Earth’s surface is equivalent to the horizontal components of *rotation*.

Mechanically based tiltmeters are in general sensitive to horizontal *acceleration*, according to the separation distance of axis and center of mass. At very long *periods* (*Earth's eigenmodes*, *Earth tides*) the horizontal components of *ground motion* recorded by *inertial sensors* may contain substantial contributions due to tilts (see section 5.3.3 in Chapter 5 of this Manual).

tilt noise — A *noise* on a horizontal-component *seismogram* created by *rotation* (local *tilt*) around a horizontal axis. Slight tilts produce large apparent *accelerations* as a component of the acceleration of *gravity* is coupled into the horizontal components. See section 5.3.3 with Figs. 5.8 and 5.9 in Chapter 5 of this Manual, and Webb (2002).

time domain — A seismic record is usually presented in the time domain, i.e., as a display of varying *amplitudes* of *ground motion* as a function of time (in contrast to the equivalent representation in the *frequency domain*). See also *Fourier analysis*.

time history — The sequence of values of any time-varying quantity (such as a *ground motion* measurement) measured at a set of fixed times. Also termed time series. Examples are *accelerograms*, *seismograms* or recordings of the *displacement* of a point in a structure.

tomogram — An image of (usually a slice through) the interior of a body (in this case, the Earth) formed using *tomography*. See Curtis and Snieder (2002).

tomography — The science and technological art of creating images of the interior of a body. See *seismic tomography* for imaging the Earth, and Curtis and Snieder (2002).

topographic site effects — *Site effects* caused by surface irregularities such as canyons or mountains. In practice, it is difficult to separate topographic effects from effects caused by subsurface layering. See Kawase (2003).

tornillo — In *volcano seismology*, a term sometimes applied to *long-period* (*LP*) *volcanic earthquakes* with an especially monochromatic *coda* reminiscent of the profile of a screw (from the Spanish for "screw"). See McNutt (2002, Figure 4).

toroidal — A mode of vector field **u** in spherical coordinates for which both the radial component of **u** and div **u** vanish. See *spheroidal*, and Aki and Richards (2002 or 2009, p. 341).

torque — Torque is a cause of the *rotational motion* of a body (i.e., rotational analogue of force). Torque is equal to the *moment of force* plus proper torque, which does not depend upon forces.

Independent ("proper") torques were introduced for the first time by Leonhard Euler in the theory of rods. In *micropolar* theories, each elementary material volume is subjected to forces as well as to independent torques (which may be caused, for instance, by moment of forces on the next micro level, or may have another origin).

torque waves Knopoff and Chen (2009) showed that frictional torques accumulated in a *fault zone* of finite width are relaxed through the development of *torque* or *rotation* waves radiated as *shear waves* during the fracture process near the tips of advancing cracks.

torsion A term that seems to mean *rotations* or *strains* about the vertical axis of a structure (but with the same variance as **"***tilt***"** in the implied *frequency* band). The term "*torsion*" should be used only with full, graphically supported definitions inclusive of frequency band, according to Evans et al. (2010).

torsion balance Also called a torsion pendulum, an instrument used to measure small forces. Invented by John Michell, it was used by Coulomb to establish the electrostatic force law and by Henry Cavendish to measure the Earth's *density*. The Cavendish balance is also used to measure the universal gravitational (fundamental) constant, G. The restoring *torque* that acts on the boom of the balance depends upon the *shear modulus* of the fiber that supports it. An instrument similar to the classic torsion balance is the Wood-Anderson *seismometer*.

total overburden stress The vertical *stress* in a soil layer due to the weight of overlying soil, water, and surface loads. See Youd (2003).

T phase Tertiary wave (*T wave*) in seismology introduced by Linehan (1940), next to *P* (primary) and *S* (secondary) *waves*. It is generated by an earthquake in or near the oceans, propagated in the oceans as an acoustic wave guided in the *SOFAR channel* and converted back to *seismic wave* at the ocean-land boundary near the recording site. See Storchak et al. (2003 and 2011), Kulhanek (2002), Fig. 2.22 in Havskov and Ottemöller (2010), and Figs. 2.72 and 2.73 in Cahpter 2 of this Manual.

trace In observational seismology, a trace is a plot of the *time history* of seismic *waveforms* recorded by a channel of a *seismograph* or an *accelerometer*.

traction Force exerted per unit area of a particular internal or external surface by the body on one side (containing the normal vector) of the surface to that on the other. This is a vector in contrast to the *stress tensor*. See *stress*.

transducer

Any of various devices that transmit energy from one system to another, sometimes one that converts the energy in form. For recording seismic *ground motion*, the motion of the *seismometer* mass has to be transmitted either via a mechanical or optical lever system to the recorder (used in old classical *seismographs*) or to be converted into an equivalent electronic *signal* (as used in all modern seismometers). Transducers use different physical principles and devices such as coil-magnet systems, inductive bridges, capacity half-bridges, pieco-electric effects, interferometric-optical devices, etc. Accordingly, the output signal of the transducer may be proportional to ground *displacement*, *velocity* or *acceleration*.

transfer function

In general terms the *Laplace* or *Fourier transform* of the *impulse response* of a linear system (*filter*, sensor, etc.). It is equivalent to the Laplace or Fourier transform of a broadband output *signal* divided by that of the input signal. In seismology the transfer function of a seismic sensor-recorder system (= *seismograph*), or of the Earth medium through which *seismic waves* propagate, describes the *frequency*-dependent *amplification*, *damping* and *phase* distortion of *seismic signals* by a specific sensor-recorder devise (or the propagation medium). The amplitude (or absolute value or modulus) of the complex transfer function is termed the amplitude-*frequency response* function or *magnification curve* of a seismograph. The influence of the related phase response on the seismic wave forms is often ignored in the classical routine observatory practice of amplitude measurements, yet it has to be taken into account for correct simulation of the transfer function. See section 5.2.7 of Chapter 5 in this Manual and Scherbaum (2002).

transform fault

A *strike-slip fault* that connects segments of convergent or divergent *plate boundary* features, such as ridge-to-ridge, ridge-to-trench, etc. This type of fault was proposed by Wilson (1965), and confirmed by Sykes (1967). See Uyeda (2002, p. 57), and the biography of J. Tuzo Wilson in Howell (2003).

transition zone

A term in the study of the Earth's interior, referring to the depth range from 410 to about 800 km, in which solid-state phase transitions produce strong seismic *velocity gradients* and sharp *discontinuities*. Sometimes used only for the depth range 410-660 km between the two major discontinuities at those depths. See the depth range of TZ in Fig. 2.79 of Chapter 2 of this Manual; see also Lay (2002).

translation

See *displacement* and *translational motions*.

translational motions

The term "translational" is strongly preferred over "linear" because the latter conflicts with matters of linearity *versus* nonlinearity in soils, instruments, mathematics, and so forth. If *displacements*, *velocities*, and *accelerations* are not otherwise qualified, they are assumed to refer to translational motions. The in-line displacements are indicated u_X, u_Y, and u_Z in Figure 1 of Evans et al. (2010).

transmission coefficient The ratio of *amplitude* of the transmitted wave relative to the incident wave at a sub-surface *discontinuity*. The coefficient is found by imposing boundary conditions that the seismic *displacement* and the *traction* acting on the discontinuity surface are continuous across the surface. These conditions physically mean a welded contact and absence of extra-seismic sources at the discontinuity. Coefficients have been defined for different normalizations and signs of the component waves, e.g., energy or displacement (Knott, 1899, and Zoeppritz, 1919). See *reflection coefficient*, Chapman (2002, p. 110-112), and Aki and Richards (2002 or 2009, p. 128-149).

transmitting boundary In analytical studies, a boundary to a region of interest that approximates the effects of media outside the boundary. Transmitting boundaries or boundary elements are often used in *finite element* studies to include the effects of far extents of solid or fluid domains.

transport equation The ordinary differential equations describing the variation of the *amplitude* coefficients along a *ray*. See Chapman (2002).

transverse coherence function Measure of *coherency* of transmitted *wave field* as a function of the transverse-separation of receivers. See Sato et al. (2002).

transverse isotropy A term introduced by Love (1927) to describe a medium with one axis of cylindrical symmetry. In the geophysical literature, this axis is often implicitly considered as vertical, so that the *velocity* and *polarization* are independent of the *azimuth* of propagation in the horizontal plane. See Cara (2002).

travel time The travel time is the time taken for the *seismic waves* to propagate from one point to another along the *ray*. See Chapter 2 in this Manual, and Chapman (2002).

travel-time curve A graph of travel time of a considered *seismic phase* plotted against the epicentral distance of the recording *station*. Seismic *velocities* within the Earth can be computed from the slopes of the resulting curves. See Figs. 2.30, 2.32-2.33, 2.36/-2.37, and 2.59-2.61 in Chapter 2 of this Manual and the entries *travel time*, *epicentral distance*, *hodograph* and *Wiechert-Herglotz-Formula*.

tremor See *episodic tremor and slip (ETS)*, *non-volcanic tremor* and *volcanic tremor*.

trench In global scale it means *oceanic trench*. In *earthquake geology*, it means a trench excavated across a *fault trace* for investigating of the *fault zone* structure.

trench log A map of an excavation or *trench* wall that exposes geologic formations or structures for detailed study. Trench logs constitute primary data records for many *paleoseismic* investigations. See Grant (2002).

triaxial seismometer A set of three *seismic sensors* whose sensitive axes are perpendicular to each other. See Wielandt (2002).

triggered earthquake An earthquake that results from *stress* changes (e.g., those from a distant earthquake) that are considered small compared to ambient stress levels at the earthquake source. See *induced earthquake*. and McGarr et al. (2002).

triggering In seismometry, the turning on of an instrument, especially an *accelerograph*, by *ground motion* of a prescribed level. In soil mechanics, the onset of a liquefied condition. In earthquake seismology, an earthquake may be triggered due to *stress* redistribution in the wake or a preceding neighboring strong earthquake. A striking example for the latter has been the triggering of the November 12, 1999 M7.2 Düzce earthquake along a side branch of the North Anatolian Fault (NAF) in Turkey after the August 17, 1999 M7.6 Izmit earthquake on the main branch of the NAF. See also Youd (2003).

triple junction See *plate motion*.

triplication Behavior of the *travel-time curve* showing three *arrivals* for the same range of *epicentral distance* caused by a sharp increase of *velocity* with depth. This happens when a part of a *ray* path refracted from below the zone of velocity increase appears at shorter distances than that from above the zone. These two travel-time branches are connected by the so-called *receding branch* associated with ray paths through the zone. See Aki and Richards (2002, Fig. 9.19, p. 421). See *branch (of travel-time curve)*, *PKP triplication*, and P triplications in Figs. 2.30, 2.32, and 2.60 of Chapter 2 and Fig. 11.73 in Chapter 11 of this Manual.

tromometer Originally a simple-pendulum *seismoscope*, observed with a microscope, to measure background vibrations. Used through about 1900 as another term for *seismometer*. See Agnew (2002).

tsunami In Japanese meaning "wave (running into the) harbour". A train of gravity sea waves set up by a disturbance in the sea bed or water column, e.g., by a submarine earthquake, *landslide*, or explosion of a volcanic island. Tsunami *amplitudes* are typically small in the open ocean, but when running into shallow waters near the coast the tsunami wavefront sometimes piles up the waters 30 m or higher and sweeps up to several km into shallow land. The *tsunami run-up height* strongly depends on coastal profile and shape. Bays and cone-shaped river mouths increase run-up heights. See Benz et al. (2002).

tsunami earthquakes Earthquakes that generate much larger *tsunamis* than expected from their *magnitudes*. Tsunami earthquakes have much smaller than usual *rupture velocities* and *stress drops*. See Kanamori (1972), Satake (2002), Polet and Kanamori (2009), and Bormann and Di Giacomo (2011).

tsunamigenic earthquake An earthquake that causes a *tsunami*. Most large shallow earthquakes under the sea are tsunamigenic. See Satake (2002).

tsunami magnitude (M_t) The *magnitude* of an earthquake determined from the height of a *tsunami* wave at a given travel distance representing the strength of a tsunami source. The tsunami magnitude Mt, referenced to *moment magnitude Mw*, was introduced by Abe (1979). See Satake (2002), and Utsu (2002c).

tsunami run-up height The *tsunami* height on land above a reference sea level measured at the maximum inundation distance from the coast. See Satake (2002).

tube waves in a borehole In an empty cylindrical hole, a kind of *surface wave* can propagate along the axis of the hole with energy confined to the vicinity of the hole. They exhibit *dispersion* with *phase velocity* increasing with the *wavelength*. At wavelengths much shorter than the borehole radius, they approach *Rayleigh waves*. The phase velocity reaches the shear velocity at wavelengths of about three times the radius. Beyond this cutoff wavelength, they attenuate quickly by radiating *S waves*. In a fluid-filled cylindrical hole, in addition to a series of multi-reflected *conical waves* propagating in the fluid, tube waves exist without a cutoff for the entire *period* range. At short wavelengths, they approach *Stoneley waves* for the plane liquid-solid *interface*. For wavelengths longer than about 10 times the hole radius, the velocity of tube waves becomes constant, given in terms of the *bulk modulus* κ of the fluid and the *rigidity* μ of the solid, by $\upsilon = c / \sqrt{(1 + \kappa/\mu)}$, where c is the acoustic velocity in the fluid.

turbidite Sea-bottom deposit formed by massive slope failures of large sedimentary deposits. These slopes fail in response to, e.g., earthquake shaking or excessive sedimentation load.

T wave See *T phase*.

twistor A geometrical object that consists of a pair of *spinor* fields. Twistors describe rotational states. See Majewski (2008).

twist A term that is used to describe a shear *deformation* caused by torsional moment. It is widely used in the European literature**.**

two-dimensional site amplification A site effect calculated for a geologic structure varying in the vertical direction and in only one horizontal direction. In a purely two-dimensional case, incident waves are assumed to be *homogeneous* along the same horizontal direction. The case, in which the incident wave field is allowed to be three-dimensional, such as *spherical waves*, is sometimes called 2.5-dimensional. See Kawase (2003).

U

ultra-long-period (ULP) earthquake In volcano seismology, long-period earthquakes with *waveforms* having dominant *periods* of 100 seconds or longer. See Chouet (1996a).

unconformity Surface of erosion or non-deposition that separates younger strata from older rocks.

underplating Addition of igneous material to the base of the *crust*, a process thought to have occurred at volcanic rifted margins and beneath some ocean islands, or addition of material (including sediments) to the base of an *accretionary wedge* by thrusting at *subduction zones*. See Minshull (2002).

uniform hazard (response) spectrum In *probabilistic hazard analysis*, a *response spectrum* with ordinates having equal probability of being exceeded. See Campbell (2003).

uniform shear beam A beam with constant properties, but arbitrary cross-section, that can deform only in shear and whose response is described by a one-dimensional wave equation. A cantilevered shear beam is often used as a simplified model of a building. See Jennings (2003).

unreinforced masonry Construction that employs brick, stone, clay tile or similar materials, but lacks steel bars or other strengthening elements. See Jennings (2003).

upper mantle Uppermost part of the Earth's *mantle*, connected with mineralogical phase transformations and increase of seismic velocities at several *discontinuities*, located between the *Moho* and a depth of about 700 km.

UTC An acronym for the Universal Time Coordinated, a time scale defined by the International Time Bureau and agreed upon by international convention. Seismology is using UTC and the former Greenwich Mean Time (GMT) since more than 100 years as global time base for *seismic bulletins* and seismic *catalogues*.

V

VBB An acronym for very broadband, in reference to the 0.1-second to 360-second band of *seismic signals*. See Hutt et al. (2002).

velocity In reference to earthquake shaking, velocity is the time rate of change of ground *displacement* of a reference point during the passage of earthquake *seismic waves*, commonly expressed in nanometer or micrometer per second. However, velocity may also refer to the speed of propagation of seismic waves through the Earth, commonly expressed in kilometers per second.

velocity, apparent See *apparent velocity*.

velocity structure In seismology, a generalized local, regional or global model of the Earth that represents its structure in terms of the *velocities* of *P* and/or *S waves* as a function of depth and/or of its lateral distribution. See, e.g., Figs. 2.77, 2.79, and 2.80 in Chapter 2 of this Manual; Lay (2002), Mooney et al. (2002), and Minshull (2002).

very-long-period (VLP) earthquake In volcano seismology, long-period earthquakes with *waveforms* having dominant *periods* of 10's of seconds. See Chouet (1996a).

vent See *volcanic vent*.

vesicle Cavity formed in a volcanic rock as a result of exsolution and expansion of gas phase when the rock was still in a molten state, either below the surface as *magma* or during the slow cooling and solidification of thick *lava flows* or *lava lakes*.

virtual seismic network See *seismic network*.

viscoelasticity The property of a material that causes its *response* to an applied force to involve both elastic and viscous components. Several models of viscoelastic materials have been developed that depend on the initial and long-time response to a step in *stress*, such as Maxwell and Voigt models. The short-time response of a Maxwell material is that of an elastic solid, while the long-time response is that of a viscous fluid.

viscous damping The most commonly used type of *damping* for analytical or numerical studies of earthquake *response* of a structure. A viscous damper generates a force proportional to the relative velocity of its two attachment points in a direction that opposes the motion. Viscous damping is one of the few forms of damping that can be described by linear equations. See Jennings (2003).

visible earthquake waves Slow waves with long *period* and short *wavelengths* reported by eyewitnesses in the *epicentral area* of a *great earthquake*.

volatiles Chemical species or compounds that are dissolved in *magmas* at high *pressure* and that appear as low-*density* gases at low pressure; the most common ones in magmas are water, carbon dioxide and sulfur dioxide.

volcanic arc Long, arcuate chains of *volcanoes* that are created above *subduction zones*, and are currently active or were operative in the geologic past. It can form on land as volcanic mountains or in the sea as volcanic islands.

volcanic ash *Pyroclastic* fragments of rocks, minerals, and *volcanic glass* smaller than 2 mm in size produced during explosive *eruptions*; the pyroclastic deposit formed by the accumulation of such fragments.

volcanic block See *block, volcanic*.

volcanic bomb See *bomb, volcanic*.

volcanic chains Roughly linear alignments of a series of volcanoes, extinct, dormant, or active. Most volcanic chains are located along or near the boundaries of *tectonic plates*, but some can be of *intraplate* origin, the best-known example of which is the Hawaiian Ridge-Emperor Seamount Chain in the interior of the Pacific Plate.

volcanic degassing A collective term for the processes by which *volatiles* and *volcanic gases* escape from *magma* or *lava*. Degassing can occur continuously or discontinuously at highly variable rates before, during, and after *eruptions*.

Volcanic Explosivity Index (VEI) First proposed by Newhall and Self (1982), a now widely used, open-ended semi-quantitative classification scheme - based principally on the height of the *eruption column* and the erupted volume of *tephra* - to describe the size of explosive *eruptions*. The largest historical eruption (Tambora, Indonesia, in 1815) is assigned a VEI = 7; for comparison, the 18 May 1980 eruption of Mount St. Helens was ranked as VEI = 5. However, much larger explosive eruptions in the geologic past (e.g., voluminous *caldera*-forming events at Yellowstone volcanic system, Wyoming) can be assigned VEI = 8. Non-explosive eruptions are VEI = 0, regardless of size. As with earthquakes, small to moderate-size explosive volcanic events (< VEI = 5) occur much more frequently than large events (> VEI = 5); Simkin and Siebert (1994) have assigned VEI estimates for all the world's known eruptions during the last 10,000 years. In terms of the energy involved, the energy of the 1980 Mount St. Helens (VEI = 5) eruption has been estimated to be about $2x10^{16}$ J, which is roughly the amount of *seismic energy* released by an Mw = 8 earthquake. The energy of the 1815 Tambora eruption (VEI = 7) has been estimated to be about $1x10^{19}$ J, and is thus comparable to the seismic energy of the 1960 Chilean earthquake (Mw = 9.5), the largest instrumentally recorded earthquake so far.

volcanic gases Are produced from exsolution of *volatiles*, which were originally dissolved in *magma* at great *pressure* (depth), during magma rise into, and storage within, lower-pressure regions. Such gases are released from the magmatic system either passively (when the volcano is quiescent) or abruptly upon rapid expansion and *eruption*. Explosively expanding volcanic gases initiate and propel eruptions.

volcanic glass Quenched *lava* that contains no visible or only a few submicroscopic crystals.

volcanic plume Synonymous with *eruption column*, the term is also sometimes used to describe the quiescent degassing of water vapor and other gases above a *volcanic vent*.

volcanic tremor *Seismic signals* which are generated by volcanic activity and are highly variable in character, ranging from those indistinguishable from *tectonic earthquakes* to continuous vibrations with relatively low *frequencies* (0.5-5 Hz). The continuous vibrations are known as volcanic or harmonic tremors and are likely caused by the involvement of gas-fluid interaction. Harmonic tremors have a very uniform appearance, whereas spasmodic tremors are pulsating and consist of higher frequencies with a more irregular appearance. See McNutt (2002).

volcanic unrest A general term that applies to a *volcano*'s behavior when it departs from its usual or background level of activity, as evidenced by visible or instrumentally measurable changes - seismic, geodetic, or geochemical - in the state of the volcano from volcano-monitoring studies. However, not all episodes of volcanic unrest, which can last from a few days to a few decades, culminate in eruptive activity.

volcanic vent Surface opening at and through which volcanic materials are erupted, explosively or non-explosively; such openings can be fissures or point sources, vary widely in form and complexity.

volcano A mountain, hill, or plateau formed by the accumulation of materials erupted - effusively or explosively - through one or more openings (*volcanic vents*) in the Earth's surface; also refers to the vents themselves. However, some volcanoes have a negative topographic expression, such as *calderas* or *craters*.

volcano hazards Potentially damaging volcano-related processes and products that occur during or following eruptions. In quantitative hazard assessments, the probability of a given area being affected by potentially destructive phenomena within a given period of time. At the start of the 21^{st} century, more than half a billion of the world's population is at risk from volcano hazards. For general discussions of volcano hazards and their monitoring and mitigation, see Scarpa and Tilling (1996) and Tilling (1989, 2002).

volcano monitoring The general term applied to the systematic surveillance of the physical and chemical changes in the state of a volcano and its associated hydrothermal system, before, during, and after *volcanic unrest*.

volcano risk Relating to the adverse impacts of *volcano hazards*, generally involving the consideration of the general relation:

risk = *hazard* x *vulnerability* x value (what is at risk).

In probabilistic risk assessments, the probability or likely magnitude of human and economic *loss* is calculated from the same relation.

volcano seismology Seismological study of the structures and processes beneath volcanoes. For reviews see McNutt (2002) and Chouet (1996b and 2003).

volcano-tectonic (VT) earthquake Often used to refer to ordinary (high-*frequency* or *brittle*-failure earthquakes) in a volcanic environment. This usage reflects an ambiguity whether the *stresses* leading to the earthquake are a result of regional *tectonic* processes or local magmatic processes, such as dike intrusion, or some combination thereof. See *A-type earthquake*.

Volume (Vol. n) A defined stage of the operations of processing *strong-motion* data, typically consisting of Vol. 1 (raw *acceleration* data), Vol. 2 (corrected acceleration data), Vol. 3 (*response spectra*), and Vol. 4 (*Fourier spectra*). See Shakal et al. (2003).

Vulcanian eruption Term is taken from descriptions of *eruptions* on the Island of Vulcano (the home of the Roman god Vulcan), Italy, in the late 19^{th} century. Characterized by discrete, violent explosions lasting second to minutes in duration, Vulcanian activity is generally considered to be more energetic than Strombolian activity (see *Strombolian eruption*).

vulnerability V Expected degree of loss ($0 < V < 1$; 0 - no loss/damage, 1 - total loss/damage) due to a disaster event such as strong earthquake shaking (see *earthquake hazard*, *elements exposed to risk*, *loss* and *loss function*).

W

Wadati-Benioff zone A dipping planar (flat) zone of earthquakes that is produced by the interaction of a downgoing oceanic crustal *plate* with a continental plate. These earthquakes can be produced by *slip* along the *subduction thrust fault* (thrust *interface* between the continental and the oceanic plate) or by slip on *faults* within the downgoing plate as a result of bending and extension as the plate is pulled into the *mantle*. Slip may also initiate between adjacent segments of downgoing plates. Wadati-Benioff zones are usually well developed along the *trenches* of the *Circum-Pacific belt*, dipping towards the continents. See also *subduction zone*.

watt (W) The *SI* derived unit for power, or radiant flux, expressed in meter^2 kilogram second^{-3} (m^2 kg s^{-3}), or joule per second (J/s). It is named after James Watt (1736-1819) who invented the modern steam engine.

water table The upper surface of a body of unconfined ground water at which the water *pressure* is equal to the atmospheric pressure.

wave field A general term used to describe the whole group of different propagating *seismic waves* radiated from one *seismic source*.

waveform (data) The complete analog or sufficiently dense sampled digital representation (i.e., without *aliasing*) of a continuous wave group (e.g., of a seismic *phase*) or of a whole wave train (*seismogram*) in contrast to *parameter data*. Accordingly, waveform data allow to reconstructing and analyzing the whole seismic phase or earthquake record both in the *time* and *frequency dom*ain whereas *parameter data* describe the *signal* only by a very limited number of more or less representative measurements such as *onset time*, maximum signal *amplitude* and related *period*.

waveform inversion A term used both in Earth structure and earthquake source studies, indicating the use of the whole *waveform data* instead of their particular parameter characteristics. Various inversion procedures can be used for estimating the model parameters of Earth structure and earthquake source, by minimizing the misfit between the observed and *synthetic seismograms* based on trial parameters. See Jackson (2002).

wavefront A wavefront is a 3D surface in space with the same travel time from a common source point. See *travel time*.

wavelength The spatial distance between adjacent points of equal *phase* of wave motion (e.g., crest to crest or trough to trough). See Fig. 2.5 in Chapter 5 of this Manual.

wavelet A "little wave", wave ripple, or short wave group related to a distinct *seismic phase*.

wavelet transform The wavelet transform can be used to decompose time-series. It gives information in both the *time* and *frequency domains*, and is therefore useful for describing non-stationary *signals* like *seismograms*. The wavelet transform decomposes the signal at different scales, thus characterizing its components at different resolutions. Wavelet coefficients at high resolutions show the fine structure of the time series, and those at low resolutions characterize its coarse features. Possible applications for wavelet transform are de-noising of seismograms (e.g., Galiana-Merino et al., 2003) or automatic phase detection (e.g., Zhang et al., 2003).

wavenumber The ratio between angular frequency $\omega = 2\pi f$ and the wave propagation *velocity* v, i.e., $k = \omega/v$. See *wavenumber vector*.

wavenumber filtering A technique for processing recordings from an *array* of *seismometers* to enhance *signals* with a given range of angular frequency ω and of the radial component $\mathbf{k_R}$ of the *wavenumber* vector $\mathbf{k}$ in the horizontal (azimuthal) direction of wave propagation. The *wave field* is then assumed to be composed of plane harmonic waves with frequency ω propagating along the surface with horizontal *slowness vector* $\mathbf{k_R}/\omega$. The reciprocal of the absolute value of $\mathbf{k_R}/\omega$ is the *apparent velocity* v_{app}. See Chapter 9 of this Manual, and Douglas (2002).

wavenumber vector k **k** is the vector in wave propagation direction, i.e., perpendicular to the propagating *wavefront*, with the scalar amount of the *wavenumber* k. See Chapter 9 and this Manual and Douglas (2002).

WGS84 An acronym for World Geodetic System, 1984. A system of coordinates conventionally used and distributed by GPS as GPS coordinates. Includes an ellipsoid with inverse flattening $1/f$ = 298.25722 and semi-major axis = 6378.137 km (DMA, 1987). The flattening f is defined as the difference between the equatorial and polar radius of the Earth divided by the former. All *seismic stations* should report their positions in WGS84 coordinates. See Feigl (2002).

wide-angle seismic method A term used for seismic experiments in which the source and receiver are widely separated compared to the target depth. This term is preferred over the traditional "*seismic refraction*" method because of the recognition that much of the information on crustal structure in modern experiments comes from reflected phases. See Minshull (2002).

Wiechert-Herglotz inversion In the case that the *wave velocity* v = f(z) increases monotonously with depth z in the Earth a continuous *prograde travel-time curve* exists because all *rays* return to the surface. In this case an exact analytical solution of the *inverse problem* exists, i.e., when knowing the *apparent* horizontal *velocity* v_{app} at any point of *epicental distance* D, we can calculate the velocity v_{zp} at the turning point of the ray that returns to the surface at D. The inversion formulas have been derived by Herglotz (1907) and Wiechert (Wiechert and Geiger, 1910). They permit to calculate 1D Earth models by assuming that lateral variations of velocity are negligible as compared to the vertical velocity variations. See section 2.5.3.6 in Chapter 2 of this Manual and Schweitzer (2003).

Wiener filter Optimal *filter* after Wiener (1949) to remove *noise* from *signal* under the assumptions that the time series is ergodic, that noise and signal somehow differ, and that certain information on noise and/or signal are given, at best the signal itself or the *autocorrelation functions* of signal and noise. Wiener proposed to minimize the expectations of the squared differences between desired and actual filter output.

Wilson cycle A successive recurrence of opening and closing of ocean basins due to *plate motions* on a time scale of about 100 million years. It was proposed by Wilson (1968). See Uyeda (2002, p. 63) and Dickinson (2002).

WKBJ approximation A method for approximate solution of wave propagation through an *inhomogeneous* medium, in which the *velocity* variations are relatively weak and occur over distances large compared with the *wavelengths* of interest. This method is named after Gregor Wentzel, Hendrik Kramers, Leon Brillouin, and Harlod Jeffreys. See Aki and Richards (2002 or 2009, Box 9.6, p. 434-437), and the biographies of Wentzel, Kramers, Brillouin and Jeffreys in Howell (2003).

W phase The term W phase was introduced by Kanamori (1993) to describe the complex interference of multiple *reflections* and/or *P-to-S* or *S-to-P conversions* of long-period *body waves* of large earthquakes. The W phase appears as a long-*period* (approximately 100 -1000 s) phase in the *seismogram* between *P* and *S waves*. Recently, this phase came into focus as a strong candidate for deriving in real-time operation stable and non-saturating *moment magnitude* and *source mechanism* estimates of large earthquakes without waiting for *surface wave* information. This is of great advantage for *tsunami early warning systems*. See Kanamori and Rivera (2008) and Hayes et al. (2009).

WWSSN An acronym for the World-Wide Standardized Seismograph Network, established in the early 1960s and equipped with narrow-band short-*period* and long-period *seismographs* (see *magnification curves* in Fig. 3.20 of Chapter 3 in this Manual). Later, several stations were upgraded for digital data acquisition, also in an intermediate period band, and operated as DWWSSN between 1981 and 1993. See Hutt et al. (2002).

X

xenolith A piece of preexisting solid *mantle* or crustal rock that is picked up, and incorporated into, flowing *magma*; also sometimes called inclusion. It is a direct sample of the uppermost mantle and the *crust*.

Y

Young`s modulus See *stretch modulus*.

Z

zero-frequency earthquakes A term sometimes used for *silent earthquakes*, i.e., very slow *fault* movements which release energy without perceptible seismic radiation over periods of hours to months rather then within seconds to minutes that are characteristic of “normal” earthquakes.

zero-initial-length spring A helical spring that is pre-stressed so that the force it exerts in extension is proportional to the distance between the points of attachment, rather than the difference between that distance and the initial length of the spring. Originally developed by L. LaCoste for use in gravimeters, it found important applications in the design of long-period vertical *seismographs* that can theoretically achieve an infinite *period* without instability. See Aki and Richards (2002 or 2009, p. 602-603).

zero-phase filter A *filter*, which causes no time shift (or time shift is corrected for) and no *phase* distortions of the *signal*. Usually, such filters have symmetrical *impulse response* and are therefore called two-sided or *acausal filters*. When applied to a very impulsive signal, the symmetry of the filter may lead to precursory ('acausal') oscillations, making it hard to identify the true *onset* (see Scherbaum, 2002 and Figure 7 in IS 11.4).

z-transform A discrete equivalent of the *Laplace transform*. See Scherbaum (2002) and Claerbout (1976, p. 1-8).

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