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Seismology and Environment

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Definitions

Environmental Seismology	Field using seismic waves for investigating phenomena at the interface of solid and fluid Earth.
Anthropic Seismology	Field using seismic waves for investigating phenomena induced by anthropogenic activity (nuclear explosions, triggered seismic events in industry, mines, oil reservoirs, quarries, traffic,. . .).
Glacial Earthquakes	Earthquakes occurring in glaciers or ice polar caps, often associated with calving of icebergs at glacier terminus or at the discontinuity between bedrock and glaciers (specific class of icequakes with large magnitude).
Hurricanes, typhoon	Violent wind with a circular movement originating in tropical zones.
Landslides	Destabilization of rocks or soils from a sloping area such as a mountain, a cliff, or a volcano.
Microseisms	Small earth tremor whose sources are related to the ocean-wave activity. Primary microseisms are oscillating at the characteristic ocean-wave periods (approximately between 10 and 20 s periods) and result from the interaction of these waves with the shallow sea floor. Secondary microseisms are generated by interactions among ocean waves and have the double of their frequency.
Seismic hum	Continuous excitation of the Earth in the absence of earthquakes (at periods longer than 50 s) created by the interaction of long period ocean waves (infragravity waves) and the sea floor. This signal is weak but nevertheless large enough to excite the earth-free oscillations.
Snow avalanches	Destabilization of a mass of snow from a sloping topography turning into a flow of snow particles or aggregates that stop downslope.
Very long period noise	For periods larger than 200 s, the noise results from gravitational attraction changes induced by local pressure perturbations.

Introduction

Seismology is usually devoted to the investigation of tectonic earthquakes and imaging of the solid structure of the Earth. But with the improvement of seismometers and the explosion of the continuous recording of the ground motion by broadband seismic networks, other phenomena can be investigated. Since seismometers are sensitive to any kind of ground displacement, small events hidden in the noise can be detected. A large part of these small events is related to the interaction or the coupling of the surface of the solid Earth with its surficial unconsolidated solids, fluid/gas envelopes (ocean and atmosphere). Iceberg calving, glacier dynamics, landslides, snow avalanches, hurricanes, and ocean waves belonging to this kind of environmental events are able to generate observable seismic signals. Microseisms permanently excited by the interaction of gravity waves and swells in oceans, fluvial seismic signals, make it necessary to use statistical approaches for extracting useful information on the source processes in a broad frequency range. In contrast to microseisms, some events are episodic, deterministic; some of them well located in space and time and can be individually

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investigated. The study of all these natural phenomena giving rise to observable seismic signals constitutes the field of environmental seismology.

Due to the faintness of the associated signals, new methods and techniques have been used. For deterministic events, beamforming methods, time-reversal methods or their less general form, and back-projection technique (see Larmat et al., this issue for all references) have been applied to locate them in space and time. Microseisms were investigated by Wiechert (1904), and physical processes to explain them were proposed many decades ago (Longuet-Higgins 1950; Hasselmann 1963). For a stochastic approach of ambient noise, the cross-correlation methods of signals between two seismic stations are now routinely used and make it possible to retrieve the empirical Green's function (impulse response of the propagating medium) between these two stations (see Campillo et al. this issue). They are particularly well suited for monitoring physical parameters such as variation in the subsoil temperature, aquifers, and climate and global changes.

Environmental seismology can be distinguished from "anthropic seismology," including the study of seismic signals associated with anthropic activity, such as nuclear, mining explosions, attacks, triggered events, and urban seismology (traffic, footquakes, etc.), even though similar methods can be used to study them.

Broadband Seismic Noise

Seismic noise has several and various origins. It is present in the whole seismic frequency range 50 Hz–1 mHz (or period range 0.02–1000 s). It is classical to divide the frequency (or period) range of seismic noise into four bands:

- Frequency higher than 1 Hz (periods smaller than 1 s), noise is mostly related to local sources, impulsive natural events of various origins, and it also corresponds to the area of expertise of anthropic seismology.
- Frequency band between 1 Hz and 0.05 Hz (period range 1–20 s) corresponds to the classical **microseismic** band.
- Frequency range between 0.05 Hz and 0.01 Hz (period range 20–100 s), sometimes named the noise notch where the noise is minimum.
- Very low frequency range (frequency < 0.01 Hz) or very long-period range (period $T > 100$ s) where the seismic **hum** is the best observed.

The high frequency range ($T < 1$ s), where the anthropic sources are the most visible, is routinely used in urban seismology (Ward and Crawford 1966; Bonnefoy-Claudet et al. 2006; Nakata et al. 2011). It is also the frequency range of fluvial seismology where the seismic noise induced by rivers is well correlated with meteorological and hydrological data (Govi et al. 1993; Burtin et al. 2008; Tsai et al. 2012; Gimbert et al. 2014) and can be used as well to investigate erosion processes and sediment transport dynamics (Roth et al. 2016), avalanches, or rockfall activity (Hibert et al. 2011; Dammeier et al. 2011). This rapidly developing field will not be detailed here. Many natural events (icequakes, landslides) can be investigated in the whole broadband frequency range. At longer periods (smaller frequency), noise is dominated by natural sources. It is the strongest between 4 s and 20 s, and this period range is named the microseismic band, with two prominent peaks at ~7 s (secondary peak) and ~14 s (primary peak) due to the complicated nonlinear interaction between oceanic waves and solid Earth (Longuet-Higgins 1950; Hasselmann 1963; Kedar et al. 2008; Ardhuin et al. 2011; Stutzmann et al. 2012). At longer period, in the absence of earthquakes, the interaction between the liquid/gas envelopes (ocean, atmosphere) and the solid earth continuously excites the free oscillations (Suda et al. 1998; Kobayashi and Nishida 1998; Ardhuin et al. 2015). This phenomenon is named seismic hum.

Continuous Monitoring of the Earth Environment

Microseisms have been investigated for many decades and are continuously excited, and it is not possible to treat them as individual events. However, for a homogenous distribution of noise sources, it is possible to derive the empirical Green's function by using stacking contributions of all microseismic sources to the cross-correlations of seismic records of two stations. Cross-correlation formula CC_{AB} between seismic signals $s_A(t)$, $s_B(t)$ of two stations A and B is given by:

$$CC_{AB}(\tau) = \int s_A(t)\, s_B(t+\tau)dt$$

and the time derivative of $CC_{AB}(\tau)$ is simply related to the Green's function. Seismic records associated with microseisms and hum are dominated by surface waves, but it is possible to also extract body-wave data from noise data. So far, the application of cross-correlation methods has been the local tomography (Shapiro et al. 2005) or global tomography (Nishida et al. 2009) and the monitoring of seismogenic zones, and volcanic zones (see Campillo et al. this issue and references therein). The multiplicity of sources (microseisms, hum) and their continuous excitation can also be used to investigate environmental challenges (Larose et al. 2015).

Usually considered as noise, microseisms (and more generally environmental events) can also be recognized as a meteorological signal (Gutenberg 1958) as they provide complementary information on ocean activity, for example, and can ultimately provide invaluable information on global warming.

Spatiotemporally Localized Events

It is also possible to extract some specific events from the seismic noise that we can consider as deterministic events. Three examples are presented here: the glacial earthquakes, cyclones, and landslides.

Glacial Earthquakes

Cryoseismology, the field investigating seismic signals associated with the dynamics of glaciers, has exploded during the last two decades, (see the review papers of Podolskiy and Walter 2016, and Aster and Winberry 2017). Glacial earthquakes are specific cases of icequakes but belong to this new class of seismic environmental events of large magnitude which can be as large as ~5. These events have been discovered since the 70s and detected automatically in Greenland on long-period seismograms recorded on the FDSN (Federation of Digital Seismograph Networks) (Ekström et al. 2003).

Most glacial earthquakes occur during the late summer in the northern hemisphere, showing a strong seasonality. Most of them have been detected in Greenland and Alaska. Glacial earthquakes in Antarctica are less well studied, but some of them exhibit several characteristics similar to glacial earthquakes in Greenland. Different mechanisms are in play, and the cumulative stickslip motion of ice stream in West Antarctica is equivalent to an earthquake of moment magnitude ~7 in spite of modest seismic amplitudes owing to the source duration of 20–30 min (Wiens et al. 2008). The origin of large glacial earthquakes has been first interpreted as resulting from stick-slip motion or sliding at the base of marine terminating glacials (Ekström et al. 2003). However, thanks to mechanical models and more precise visual observations, it has been shown that iceberg calving is the main cause for generating the large glacial earthquakes even though other processes can be invoked for different kinds of icequakes (Tsai et al. 2008; Amundson et al. 2008; Sergeant et al. 2019). Indeed, a strong temporal correlation is observed between the distinct seismic signals of glacial earthquakes and large ice-loss events in which icebergs of cubic-kilometer scalecapsize against glacier terminus. Figure 1(left) displays an example of seismogram for a glacial earthquake detected in Alaska. It is characterized by abnormal long-period spectral content compared with a classical tectonic earthquake. Since there are generally no clear identifiable P- or S-wave arrivals, innovative techniques have been used to locate and quantify the glacial earthquakes, such as the cross-correlation technique of Ekström et al. (2006) or the time-reversal method (Larmat et al. 2006, Fig. 1 middle).

The seismogenic process is related to the force exerted by these icebergs on the glacier and the underlying solid earth. Sometimes, a sudden change in glacier speed results from these glacial-earthquake calving events. Figure 1 (right) shows the time variations of the force for a large-scale multiple-iceberg calving episode at the terminus of the Jakobshavn Isbrae on 21 August 2009 (Sergeant-Boy et al. 2016). It was recorded by broadband seismic stations located in Greenland including the seismic records from four permanent stations of the GLISN network (Dahl-Jensen et al. 2010).

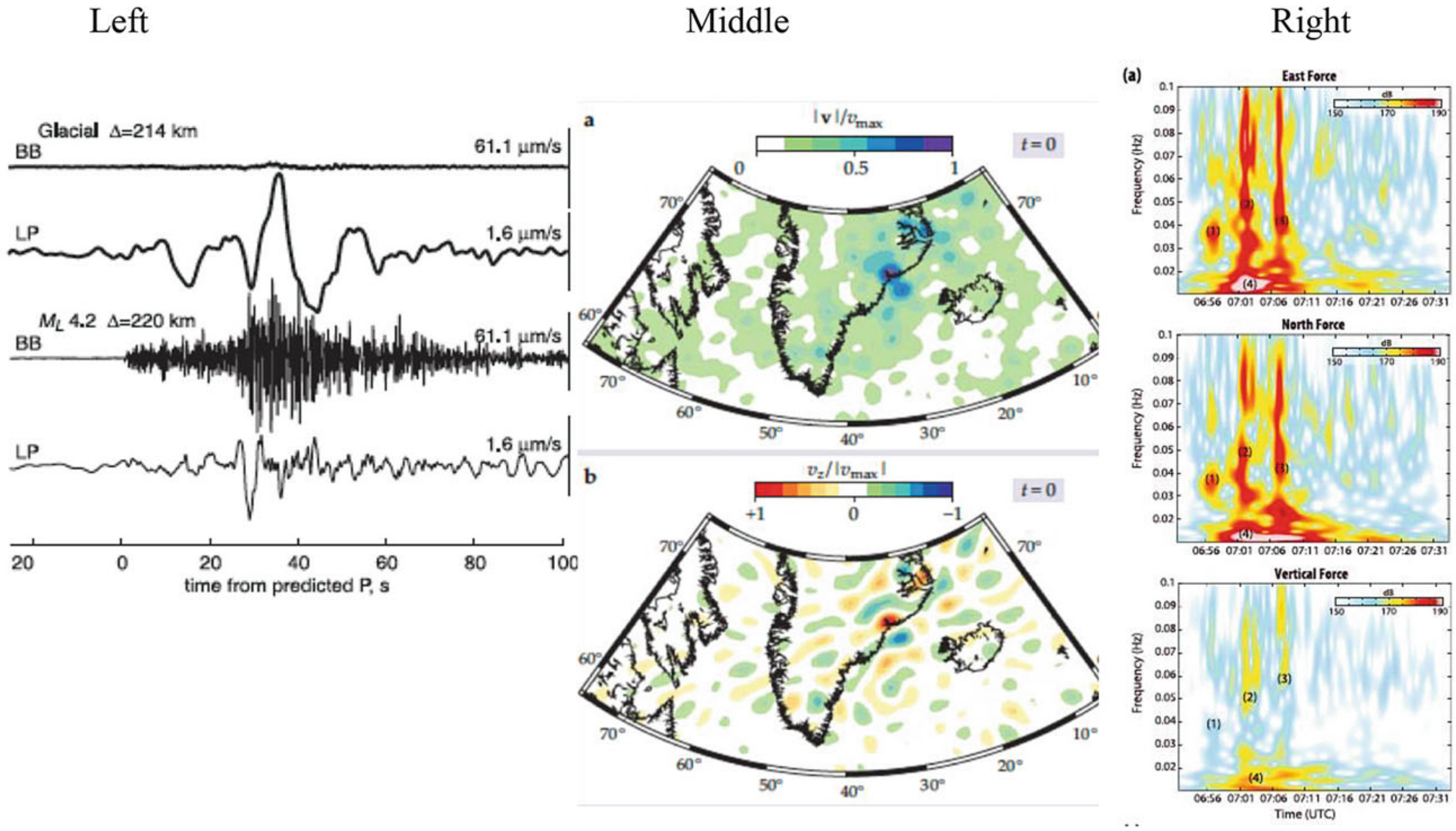
The rate of glacial earthquake occurrence varied during the last decades but tends to increase since the beginning of the century (Olsen and Nettles 2017; Sergeant et al. 2019). Seasonal and interannual variations in glacier-terminus position partly account for general characteristics of the temporal variation in earthquake occurrence. By coupling seismological analysis with numerical modeling of iceberg calving, Sergeant et al. (2019) quantified the spatiotemporal evolution of ice loss in Greenland from iceberg calving between 1993 and 2013. They showed that calving was responsible for the loss of 370 gigatonnes of ice, representing 8–21% of the mass lost on glacier termini, the rest attributed to ice melt.

Cyclones (Hurricanes–Typhoons)

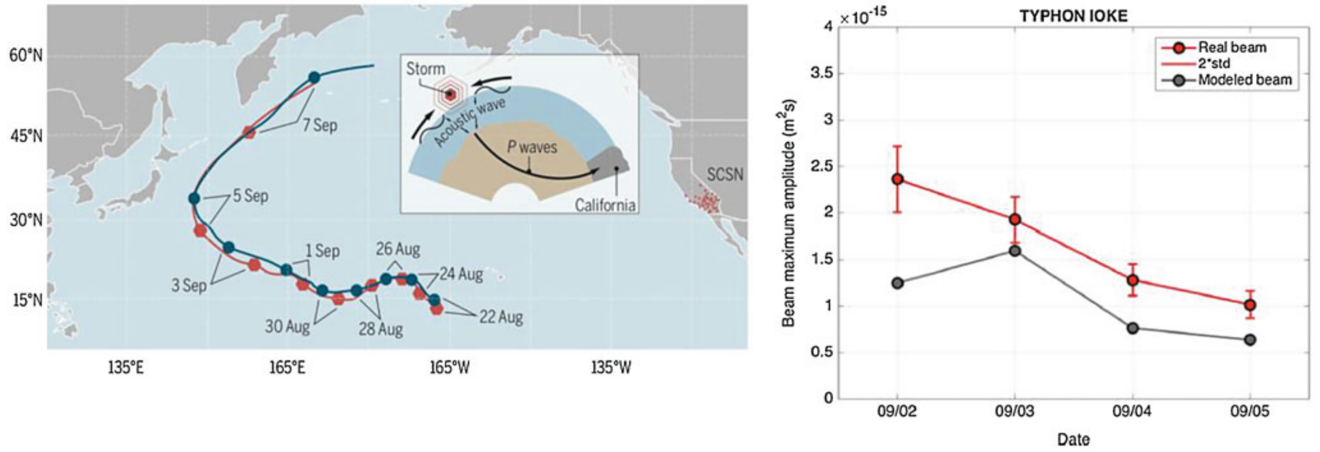
Tropical cyclones (hurricanes in the Atlantic Ocean and typhoons in the Pacific ocean) are also sources of seismic signal in the microseismic band. They participate to microseismic source distribution, as particular cases of the atmosphere-ocean system interacting with the solid Earth (Ebeling and Stein 2011). Storms are sensitive to topography and also carry information on the structure of the Earth and on meteorological processes.

Ocean wave-wave interactions are very large in the wake of cyclones. They generate P-waves just below the ocean surface that propagate in the ocean and reach the ocean bottom where they are reflected, transmitted, and converted, and the resulting body and surface waves propagate in the Earth (Gerstoft and Bromirski 2016). The *P* waves penetrate deep into the earth for the super Typhoon Ioke and have been recorded by the SCSN (Southern California Seismic Network) (Fig. 2a), allowing source localization with array processing. One application is the quantification of cyclones, by using the amplitude of seismic waves (Fig. 2b, Farra et al. 2016). The temporal discernible trends in the increase of the hurricane frequency or energy during the last decade can be monitored by their seismic signature.

Using machine learning algorithms such as blind source separation technique, it is also possible to measure travel times from individual strong sources in the diffuse seismic wavefield (Meschede et al. 2019). This method enables to



Seismology and Environment, Fig. 1 Left: example of Seismogram from a glacial earthquake in Alaska (4 September 1999, 15:15:20.0) (top two traces) compared to a nearby, tectonic, $M = 4.2$ earthquake (bottom two traces) recorded at comparable distances. For each trace pair, top shows broad-band (BB) (0.00833 to 20 Hz) velocity record, and bottom shows filtered long-period (LP) (0.01 to 0.2 Hz) velocity record. Vertical scale is shown by labeled height of line on right. The seismograms are aligned at the predicted *P*-wave arrival time (Ekström et al. 2003). Middle: localization of one glacial earthquake in Greenland by time-reversal method from broadband seismic records (Larmat et al. 2008). Right: source time function of glacial earthquake on the three-component derived from broadband seismic network in Greenland (Sergeant-Boy et al. 2016)



Seismology and Environment, Fig. 2 (**a**) The Super Typhoon Ioke in the Pacific ocean from 22 August to 7 September 2006 has been tracked by the National Hurricane Center(blue line), tracks Ioke-generated *P* wave sources (red) using the Southern California Seismic Network (SCSN). Locations of *P* wave sources (red hexagons) and storm centers (blue circles) are marked every second day (Gerstoft and Bromirski 2016). (**b**) Observed (red) and modeled (black) amplitude of the P-waves generated by the Super typhoon Ioke (Farra et al. 2016)

determine the mantle structure along paths usually not sampled by tectonic earthquakes and has promising application for ocean bottom networks (Fig. 3).

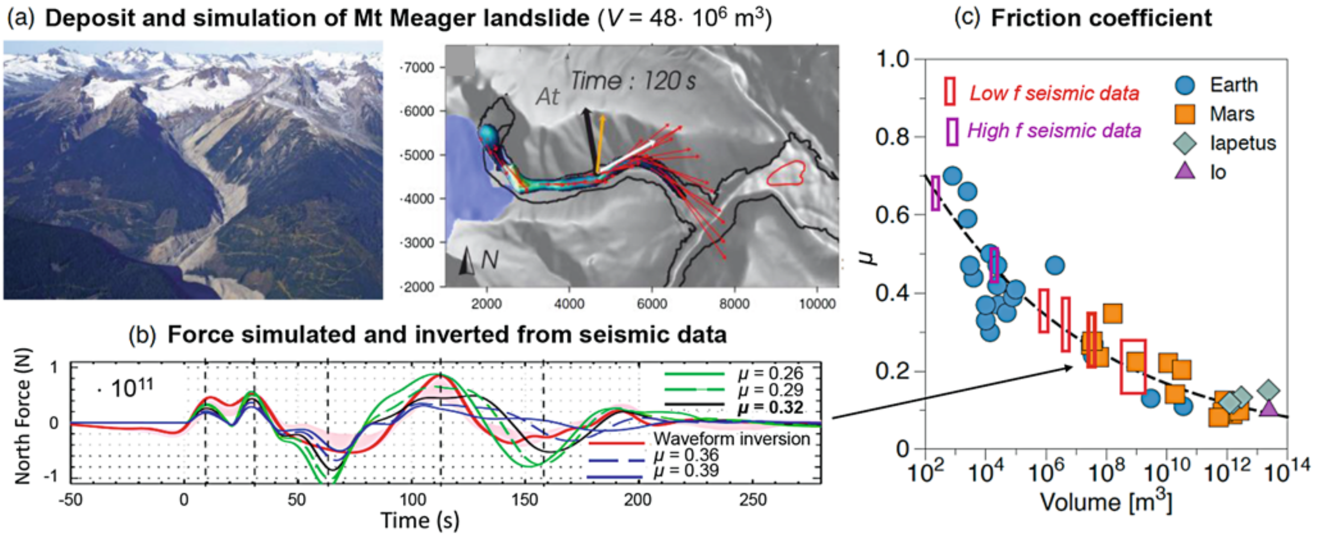
Landslides

Landslides are generally unpredictable and inaccessible processes, but their signature is available in the form of seismic waves (Kanamori and Given 1982; Kawakatsu 1989). The same seismic approach was also followed for avalanches (Lawrence and Williams 1976). Indeed, as landslides travel down the slope, the flowing mass apply a time varying force to the topography that generate waves in a broad frequency range (0.005–50 Hz). These waves are recorded at distances up to 1000 km from the source depending on the landslide volume (m^3 to km^3) and the frequency. Beyond mere detection and localization of landslides, exploitation of this amazing amount of high-accuracy wave data provides unprecedented clues to flow characteristics and dynamics (Hibert et al. 2011; Moretti et al. 2012). This is, however, a highly challenging issue because of the complexity of natural processes and of their subtle and intricate imprint on wave characteristics. The sources of the generated waves are highly sensitive to the dynamic history of landslides, which itself depends on landslide characteristics (volume, topography, fluid content, etc.) and on the physical processes involved (friction of the sliding material, collision of particles with the ground, erosion/deposition, etc.). As a result, detailed information on landslides dynamics can only be obtained by comparing the recorded waves with accurate modeling of the source processes and wave propagation.

The low frequency source of landslide-generated waves ($f < 1$ Hz) results from the mean acceleration/deceleration of the flowing mass (Brodsky et al. 2003), while the high frequencies are related to particle-scale force variations (Farin et al. 2018). Indeed, the huge energy released by a landslide at large scale breaks down into increasingly fragmented mass movements, generating different types of seismic waves. The energy is thus dissipated across a granular medium at intermediate scales down to the grain scale. Even if, during a landslide, the energy transmitted into seismic waves E_s is much smaller than the loss of potential energy of the granular mass ΔE_p ($E_s \approx (10^{-3}\text{-}10^{-6})*\Delta E_p$), it is high enough to be measured by seismometers (Deparis et al. 2008; Levy et al. 2015).

Extensive research has been carried out to extract detailed information on landslide characteristics from low frequency seismic waves because their inversion makes it possible to calculate the time history of the force exerted by the landslides to the ground (Kanamori and Given 1982). This is however not possible with high frequency seismic waves because of their high sensitivity to topography and Earth properties variations during their travel from the source to the station. However, empirical relations relating landslide characteristics (volume, friction coefficient, velocity, etc.) to high frequency seismic signals have been proposed (Hibert et al. 2011; Dammeier et al. 2011). Laboratory experiments on granular flows and generated waves have recently provided insight into the physical origin of these relations (Farin et al. 2019).

Unique strategies for landslide detection, quantification, and monitoring can be designed from seismic data analysis (Chao et al. 2017), making it possible to investigate the link between landslide activity and meteorological, climatic, seismic, or volcanic activity. As an example, based on these seismic approaches, Durand et al. (2018) showed the stability



Seismology and Environment, Fig. 3 (**a**) (left) Mt. Meager landslide deposit and (right) numerical simulation of the flowing mass at time 120 s (Moretti et al. 2015). The arrows represent the simulated velocities (in red), the velocity (around 40 m/s) of the center of mass (in white), and the horizontal force that the landslide applied to the ground, simulated and inverted from seismic data (in black and orange respectively). The color scale represents the thickness of the flowing mass, and the Capricorn glacier is shown in violet. (**b**) Sensitivity of the time evolution of the force to the friction coefficient used in the model. The red line corresponds to the best inverted force and the pink area is the confidence interval, while the black line corresponds to the best simulated force. (**c**) Friction coefficient that best fits observed deposits (symbols) of landslides on Earth and other planets and that best reproduces seismic data (rectangles with dimensions corresponding to the estimated error on this friction coefficient) (Lucas et al. 2014)

of volcanic craters can be inferred from rockfall activity and that rockfall characteristics may be an indicator of the location of future volcanic eruptions.

New Challenges

The new field of environmental seismology makes it possible to provide some key elements on the global change: For example, the increasing number of glacial earthquakes enables us the quantification of ice loss. The continuous monitoring of physical parameters of landslides and the analysis of tropical cyclone through microseisms can provide new insight in temperature, hydrology, and in processes of shallow subsurface and critical zone (thin outer layer of the Earth's surface). As these seismic signals are recorded continuously, their analysis in terms of physical processes involved, makes it possible to relate natural events' characteristics to external forcing such as meteorological (Stopa et al. 2019), climatic, volcanic, or seismic activity (e. g., Durand et al. 2018). This is particularly important nowadays as climate change strongly increases the risks associated with landslides, and glacier ice mass loss in mountainous, polar, and coastal regions (IPCC).

The distinction between anthropic seismology and environmental seismology is minor, since they are both rapidly growing fields addressing similar issues on the spatial and temporal evolution of our environment and using seismic signals previously considered as noise. Particularly challenging is the joint quantitative interpretation of high frequency and low frequency data. New efforts are made to develop methods making it possible to recover quantitative physical processes from the generated seismic waves. A key element of these efforts relies on the improvement of fluid and solid mechanical models used to interpret seismic data, providing unique opportunities to discriminate the intricated physical processes involved at the source of the waves.

Cross-References

- ▶ Body Waves
- ▶ Elastic Wave Propagation: Fundamentals
- ▶ Free Oscillations of the Earth
- ▶ Seismic Instrumentation
- ▶ Seismic Tomography
- ▶ Seismic, Ambient Noise Correlation
- ▶ Surface Waves
- ▶ Time-Reversal in Seismology
- ▶ Upper-Mantle Structure

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