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Celebration of Earth Day 2011

Recent large earthquakes from a geophysical perspective*

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Resum. En els darrers temps la nostra societat ha estat trasbalsada per l'efecte de diversos terratrèmols (Haití, Xile, Nova Zelanda i Japó). No es tracta de fenòmens nous, la Terra ha estat i estarà sotmesa a la seva acció, però els grans terratrèmols no són freqüents ni es produeixen arreu. Hi ha regions de la Terra més propenses que d'altres a ser sotmeses al seu efecte. D'altra banda, una societat adequadament preparada en pot mitigar el risc. Conèixer la perillositat de cada zona és imprescindible per a poder disminuir l'efecte dels terratrèmols, fet que implica l'estudi profund de les seves característiques i de les zones en què succeeixen. Aquest article repassa els últims grans terratrèmols des d'una òptica geofísica i n'analitzarem les característiques i el context geològic específic en què es produeixen. Per a dur a terme aquesta anàlisi s'ha fet servir els registres dels terratrèmols obtinguts a les estacions del LEGEF, que es poden trobar al nostre web, http://sismic2.iec.cat.

Paraules clau: terratrèmols · plaques tectòniques · sismologia · geofísica · registres sísmics

Abstract. In recent times our society has been disturbed by the effect of various earthquakes (Haiti, Chile, New Zealand, and Japan). These are not new phenomena, the Earth has been and will be subjected to their action, but large earthquakes are not frequent or occur elsewhere. There are regions of the Earth more likely than others to be affected by them. In addition, an adequately society can be prepared to mitigate the risk. Knowing the hazard of each area is essential in order to reduce the effect of earthquakes, which implies the thorough study of their features and of areas in which they occur. This article reviews the recent major earthquakes from a geophysical perspective and analyzes the characteristics and the specific geological context in which they occur. For this analysis, the records of earthquakes obtained at LEGEF stations, which can be found on our website (http://sismic2.iec.cat) have been used.

Keywords: earthquakes · tectonic plates · seismology · geophysics · seismic records

Introduction

On the year 2011 the world community took note of the recent large earthquakes in Haiti (7.1 Mw), Chile (8.8 Mw), and Japan (9.0 Mw) (Fig 1) (Mw is the momentum magnitude that is related to the energy released by the earthquake at the focus; see [10]). While the attention of the mass media is usually on the damage caused by earthquakes, the public is provided with very little information about the underlying science. This paper addresses several aspects of these studies. In addition to the aforementioned earthquakes, two others (Mw 7.1 and Mw 6.3), in the vicinity of Canterbury, New Zealand (Fig. 1), are considered here as well.

Seismologists study earthquakes from different perspectives: from the *near field*, taking into account the damage to both ground and buildings caused by the earthquake, to the *far field*, analyzing the information contained in the seismograms. The energy released by an earthquake travels through the Earth's interior in the form of seismic waves, which are recorded at seismic stations. Seismograms are the records of the seismic waves generated by an earthquake. They are a temporal series reflecting the ground motion (velocity/acceleration) during the passage of seismic waves. Seismologists, in collaboration with other scientists in related specialties, seek to better understand earthquake phenomena so that we may be better able to coexist with them.

Figure 1 shows the aforementioned earthquakes on a map of the world seismicity (M > 5.9) since 1990 [12]. Earthquakes occur in specific areas, mainly along the boundaries of the tectonic plates into which the surface of the Earth is divided, and their occurrence can be explained in accordance with the theory of plate tectonics, which was accepted in the 1960s [11]. These plates involve the entire lithosphere, which is more than 300 km thick. The thickness of the crust, i.e., the rigid part of

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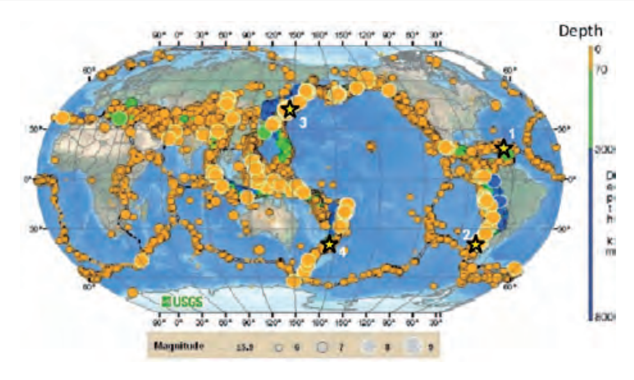

Fig. 1. Earthquakes considered on a world seismicity map since 1990 (M ≥ 5.9). 1: Haiti (Mw 7.1), 12 January 2010; 2: Chile (Mw 8.8), 27 February 2010; 3: Japan (Mw 9.0), 11 March 2011; 4: New Zealand (Mw 7.1), 3 September 2010 and (Mw 6.3), 21 February 2011. Source: U. S. Geological Survey (USGS).

the plates, depends on whether the plate is continental or oceanic (up to ~80 km depth) [2,9]. Earthquakes occur in the crust and result from the friction between moving plates.

Mechanical model

At the end of 19th century—after the earthquakes of Naples (1857), Japan (1891), and Assam (1897)—an attempt was made to relate tectonic processes with earthquakes. However, the first convincing attempt was in 1906, following the San Francisco earthquake, when Reid (1910) presented his mechanical model based on the gradual accumulation and subsequent release of stress and strain known as the 'elastic rebound theory' [6,13,14]. Figure 2 is a photo of the 2.5-m lateral displacement of a fence along the trace of the fault caused by San Francisco earthquake. This image inspired the model.

The theory can be explained by imagining a piece of stretched string that is cut, causing the sudden release of the energy accumulated within the strain. Likewise, the Earth's crust can gradually store elastic stress that is released suddenly during an earthquake. A piece of jelly candy provides us with another example. Imagine that we laterally pull its two ends. The jelly will accumulate strain until it snaps into two parts, each of which will then vibrate. This vibration represents the propagation of seismic waves in the Earth while the break in the jelly is the fault. In our example, the release of the accumulated energy was total. However, in general, this is not what happens to the Earth. The relative motion between the plates produces an accumulation of stresses in the crust that are not released totally.

Fig. 2. A 2.5-m displacement of a fence, near Point Reyes, California, produced along the fault during the 1906 San Francisco earthquake. Photo: by G.K. Gilbert.

The recurrence of earthquakes is common and depends on the tectonic conditions of the area. The following example allows us to visualize the situation. Imagine a piece of wood being pushed across a rough surface of a table. The piece of wood will move when the force applied exceeds the resistance due to the roughness of the table. A drop in stress will occur as the wood slips off the table. The same situation will occur again if the force continues to push the piece of wood, and the time between the slips will depend on the force applied and the roughness of the table. In our example, the piece of wood and the table are the plates, the force applied is the friction between the plates, and the slip and stress drop are the earthquake. The force is the tectonic force associated with the plates' motion. The time between slips is the recurrence period.

Seismograms: Tool of the seismologist

Seismograms of the earthquakes in Chile and Japan recorded at the seismic station installed by the *Laboratori d'Estudis Geofísics Eduard Fontseré* (Eduard Fontserè Laboratory of Geophysical Studies, LEGEF- IEC) [15] at the Fabra Observatory, in a collaboration with the *Reial Acadèmia de Ciències i Arts de Barcelona* (Royal Academy of Sciences and Arts of Barcelona, RACAB) [16], are presented in Fig 3. The seismograms correspond to the velocity of the ground (vertical axis) as depicted in three axes (E, N, Z). The horizontal axis is time and it tells us the duration of the seismic wave packets of the earthquake.

At present, more than 8000 seismic stations have been installed to monitor earthquakes worldwide. In addition, there are also permanent and temporary local seismic networks that are owned and operated by research groups. Yearly, 20,000 earthquakes of different magnitudes are localized and studied with this seismic infrastructure [17].

The source of information about earthquakes is the seismograms obtained at the seismic stations. The seismograms record the different wave packets generated by the earthquake itself plus the different wave packets created by refraction and reflection at the discontinuities of the Earth. Several types of analyses can be performed, depending on the characteristics of the available equipment. The seismological community is made up of diverse groups of specialists who are able to analyze and interpret the information contained in the seismograms. Integration of this information yields insights into the earthquake. Basic information about each earthquake is pre-

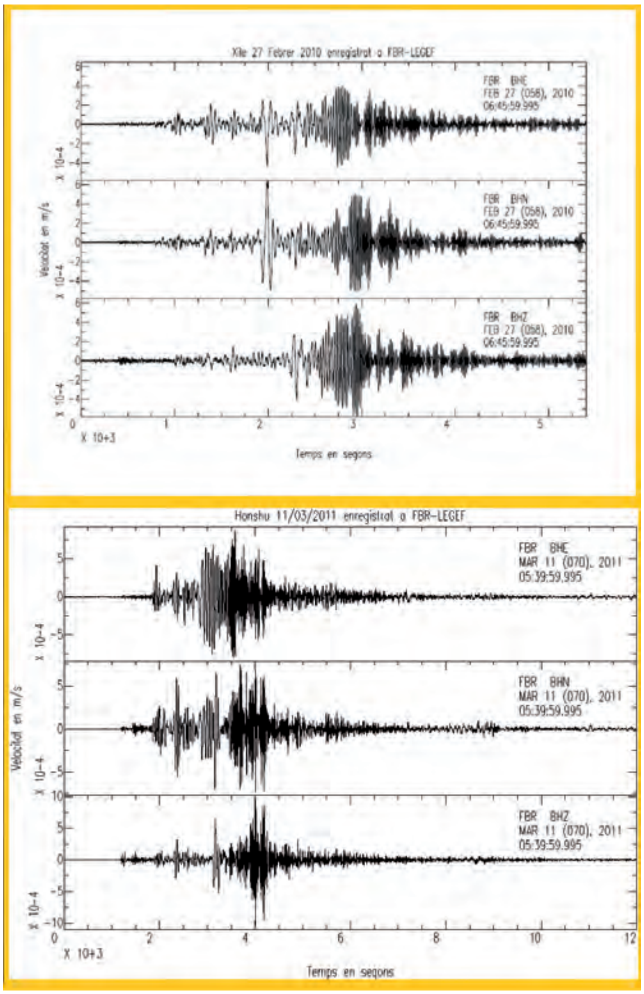

Fig. 3. Seismogram of the [top] Chile (27 February 2010) and [bottom] Honshu (11 March 2011) earthquakes, recorded at the FBR (LEGEF-RACAB) seismic station [15].

sented on the Web pages of seismological institutions [12,18–20] and is included herein. Specific studies in seismological journals have also been considered.

Understanding earthquakes

An earthquake is basically described by its focal parameters: location of the focus (latitude, longitude, and depth), time of origin, its size, the fault parameters, and the source mechanism [8,10]. This information is furnished by seismograms after a complex process of analysis that depends on the use of seismological algorithms, based on physical concepts, developed by the seismological community. With regard of size, seismograms provide the magnitudes of the earthquakes. The magnitude is related to the seismic energy released by the earthquake's focus [10]. The mechanism is independent of the size, dimensions, and orientation of the fault plane and the movement of the material involved in the slip. Information that provides the rupture model and indicates stress transmissions/release is obtained by numerical seismic waveform modeling [21].

Figure 4 shows the equivalent energy released (in kg of TNT) by an earthquake of a certain magnitude. This equivalence is based on empirical relationships in the absence of physic-mathematical relationships [8,10]. These relationships indicate that the ratio of energy between two consecutive magnitudes is approximately 32.

Regarding the seismicity of the Earth, the annual average number of earthquakes of magnitude 8.0–9.9 in the last decade (2000–2011) was one, with the exception of the four earthquakes in 2007 [1,22]. This rate increases for earthquakes of lower magnitudes, so that, for example, the annual average number of earthquakes of magnitude 7.0–7.9 is 17. We should mention the two in Sumatra in 2004 and 2007 (Mw 9.1 and 8.5, respectively), the 2001 earthquake in southern Peru (Mw 8.4), the one in 2009 in Samoa (Mw 8.1), the earthquake in Chile in 2010 (Mw 8.8), and the major one in Honshu in 2011 (Mw 9.0). In 2012, an earthquake of Mw 8.6 occurred on the west coast of northern Sumatra. Since 1900, the highest-magnitude earthquakes have been in Valdivia, Chile (M 9.5) in 1960, in Alaska (M 9.2) in 1964, in Sumatra (Mw 9.1) in 2004, in Kamchatka (M 9.0) in 1952, in Honshu (Mw 9.0) in 2011, in Colombia (M 8.8 [23]) in 1906, and in Chile (Mw 8.8) in 2010 [24].

The Haiti earthquake

On 12 January 2010, an earthquake of Mw 7.1 [25,26] struck Haiti. The epicenter was 25 km WSW of Port au Prince, at 13 km depth. Although the magnitude was not extraordinarily large, scientists regarded this earthquake as a major one because of the considerable destruction it caused. Even today, the humanitarian situation remains desperate. As stated above, earthquakes occur along plate boundaries. In this case, the Caribbean and the North American plates were involved. These plates move laterally in relation to each other through a transform fault. The relative movement of the plates is absorbed by the Septentrional Fault to the north and the Enriquillo Fault to the south. The latter fault, with an estimated slip rate of 7 mm/year, was implicated in the earthquake. The first 50–80 s of the seismograms recorded at 16 stations located 1000–2000 km from the epicenter were used to obtain the source mechanism by modeling. The fault length was 70 km, with a slip of 2 m and a speed of rupture of 2900 m/s. The duration of the slip was 12 s. The geometrical parameters of the fault obtained are coincident with the regional tectonics [27–29].

The affected area had been struck by earthquakes in the past [30], three of them occurring in the Enriquillo Fault area: two of M 8.0 in November and October of 1751 and one of M 7.5 in 1770. A number of earthquakes involved the Septentrional Fault (1887, 1842, 1953, and 2003) but the one with the greatest magnitude was that of 1946 (M 8.0). Although the 2010 earthquake did not produce a tsunami, other earthquakes in the area were tsunamigenic.

Despite the intense seismicity of the area, witnesses of the 2010 earthquake did not realize the source of the shaking, mistaking the earthquake for a tornado or other such phenomenon. This suggests a loss of 'seismic memory,' which is a very

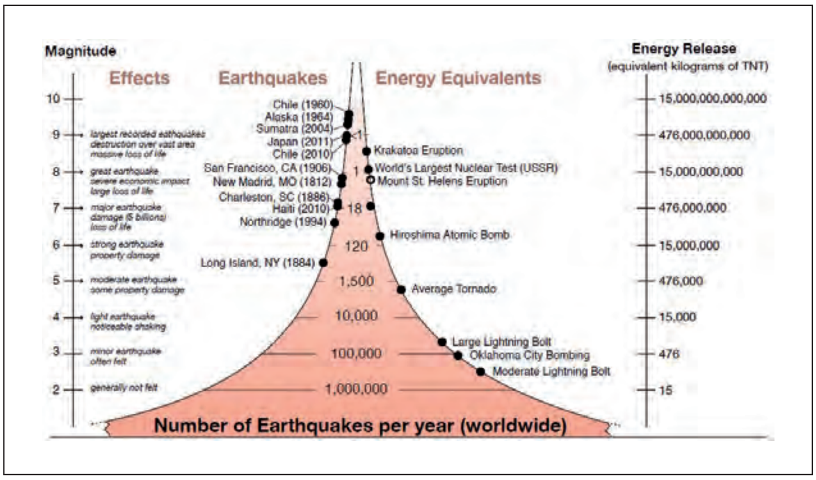

Fig. 4. Worldwide number of earthquakes per year, and energy equivalences. © The Iris Consortium. Education and outreach series, nº. 3.

important factor in adopting measures to mitigate the damage caused by earthquakes and in educating citizens in earthquake preparedness. Indeed, some of the damaged areas have since been re-occupied by the locals, who thus run a serious risk of injury from falling masonry.

The Chile earthquake

Approximately one month after the Haiti earthquake, on 27 February 2010, an earthquake of magnitude Mw 8.8 [31,32] and a depth of 35 km occurred near the site of the 1960 Valdivia (Mw 9.5) earthquake [33,34]. Kinematic inversion of the data revealed that the rupture was 550–650 km long and the slip was 4 m. The rupture speed was 3800 m/s, with a duration of 139.5 s [35]. Like the earlier earthquake, a tsunami was induced, with comparable amounts of damage and water invasion [36].

The area in which the later earthquake occurred is the subduction front of the Nazca Plate, under the South American Plate, with a rate of convergence of 7 cm/year. Due to the existing gap (in time and space) of earthquakes in the region, the area was under study using GPS equipment, temporary seismic stations, and geophysical measurements [37]. Consequently, this earthquake was expected [4].

The Japan earthquake

On 11 March 2011, an earthquake of magnitude Mw 9.0 and a depth of 20–30 km occurred on the eastern coast of Honshu Island, Japan [38,39]. This earthquake was the largest to strike Japan and among the five biggest in the world thus far. The rupture length was 400 km and the displacement was 30 m. These data were obtained from inversion modeling [40]. Several studies were undertaken immediately after the earthquake, such that this earthquake has been the most well-studied within the shortest time in history—due in large measure to the numerous broadband seismic stations worldwide that monitored the Earth in real time. Consequently, the findings were disseminated immediately. The results were posted on the Web pages of seismological services and research groups [40–45].

The Eurasian, Philippine, and Pacific plates were involved as were local microplates that subduct in a complicated geometry of convergence. The convergence rate of 79 mm/year produces earthquakes at different depths and magnitudes [41,42]. The seismic activity of the area is high, with two previous earthquakes, in 1896 and 1933, of magnitude ~8 that produced a tsunami with maximum wave heights of 25–28 m [43]. Historical documents in Japan mention an earthquake in 869 AD (called the Jogan earthquake), which created a tsunami that killed thousands of people. Studies of the deposits of this tsunami and of older ones yield a recurrence interval of 450–800 years for an event of such magnitude [5].

Two days before the well-known Mw 9.0 earthquake, there was an earthquake of Mw 7.2 (similar to that of the Haiti earthquake) followed by two more earthquakes, with magnitudes between 7 and 8 [38,39]. After the 9.0 earthquake, a series of aftershocks of relatively high magnitude, including one of Mw 7.1 (April 08), affected an area of 510 × 210 km^2 [45]. The aftershocks continued for months (1073 earthquakes Mw > 4.5 in ~1 month). These data give rise to two considerations. The first is a reflection on the different concepts of foreshock, main shock, and aftershock even though the definition seems to be clear. Only after the sequence of the earthquakes can these differences be determined. Thus, the earthquake of Mw 7.2 on 9 March was a foreshock. The second consideration is the large amount of energy accumulated in the area that was released by the different earthquakes. The rupture of the main shock lasted 25 min but calculations of the energy released in the whole process show that if the energy had been released at once the magnitude of the earthquake would have been 9.4 [40,45].

Detailed information about the superficial ground deformation in this earthquake was provided by measurements obtained from the very dense GPS network installed in the Japanese islands [43]. Networks of high-precision and high-resolution GPS stations have been set up in earthquake-prone areas. Interseismic, co-seismic, and post-seismic deformations associated with an earthquake can be determined from GPS measurements, after a complex processes of analysis. In the Japanese earthquake (Mw 9.0), horizontal displacements were as much as 4 m while the vertical displacements were mainly negative, up to –0.8 m [43]. The vertical acceleration of the ground due to the earthquake was also measured by the network of accelerometers installed in Honshu. The maximum value of acceleration was 2.7 g (ca. three times the acceleration due to gravity), as recorded by the Miyagi accelerometer [47]. Ground acceleration is an important factor in damage to buildings and must be considered in their seismic design. Geographic areas are classified according to the likelihood of undergoing a specific acceleration due to an earthquake. In Japan, liquefaction of the terrain was also present because of the ground acceleration [48]. This effect is associated with the vibration, the ground type, and the content of water in the ground.

Japan is one of the most highly monitored areas given that it is extremely sensitive to earthquake phenomena. Japan's Early Warning System, developed in 2007 by the Japan Meteorological Agency, detected the earthquake [49]. The city of Tokyo was alerted 80 s before the arrival of the earthquake waves. Citizens were warned via mobile telephones, TV, etc. Authorities in charge of the trains and other forms of infrastructure were alerted and all such means of transportation stopped, either automatically or manually. The Early Warning System is based on an efficient detection of the first ~8 s of the earthquake waves. The time between the warning and the arrival of the destructive waves depends on the speed of these waves on the ground and on the distance traveled. The farther the epicentral distance, the longer the time. Accurate knowledge of earthquake behavior in the area is essential for the smooth functioning of this system. It is worth noting that, from the standpoint of seismicity, the damage caused by vibrations was low, considering the very large magnitude of the earthquake. This is a direct consequence of the resistance of Japanese buildings and infrastructure to vibrations. Thus, instead, most of the damage was produced by the tsunami generated by the earthquake.

The New Zealand earthquakes

On 3 September 2010 and again on 21 February 2011, two earthquakes took place in the region of Canterbury in South Island, New Zealand [50,51]. While the earthquake of Japan monopolized the interest of seismologists because of its magnitude and circumstances, these two earthquakes attracted attention because of their unexpected behavior [3,7]. Both were located on the boundary of the Australia–Pacific plates, which move 35 mm/year (GPS measurements [52]).

The first earthquake (Mw 7.0 [50,51]) occurred near Darfield. The second one (Mw 6.1/6.3, depending on the source of information [52,53]) occurred 43 km east of the first and 5 km from Christchurch, as part of the aftershock sequence of that previous earthquake. The second earthquake was located at the easternmost limit of earlier aftershocks and revealed a new fault. Both earthquakes occurred at 5 km depth. For a long time afterwards, aftershocks continued to propagate to the east, delimiting new faults [55]. Because of the proximity of Christchurch to the epicenter, ground shaking in the city was much more severe in the case of the second earthquake than during the September 2011 event, which had had a larger magnitude (Mw 7.0). The accelerations recorded were six times higher and liquefaction occurred [53,54]. These extreme ground accelerations were greater than those expected from the predicted model, which assumed an earthquake of up to Mw 7.2 for the area. The reason for this behavior is that these events radiated anomalously high levels of energy relative to their magnitudes [7].

In summary, this article has examined earthquakes of different magnitudes, some of which have produced tsunamis. Throughout history, earthquakes and tsunamis have occurred repeatedly in the same areas. The earthquakes reviewed here testify to the fact that the resulting damage is not solely dependent on the magnitude of the earthquake but also involves the response of the Earth's crust. Today, seismologists are equipped with tools to help us to coexist with earthquakes. Their analyses provide further insights into the Earth's behavior, yielding information that can be applied in attempts to mitigate the damage caused by future earthquakes.

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