Did the earth move for you? From great earthquakes to silent slip

Rebecca Bell

This presentation covered the most exciting discovery in seismology in the last 15 years, which has found that the earth moves in a new and completely unexpected way. It also illustrated how technology designed to help the military (global positioning satellites - GPS) has helped us to find out more about seismic hazard and risk.

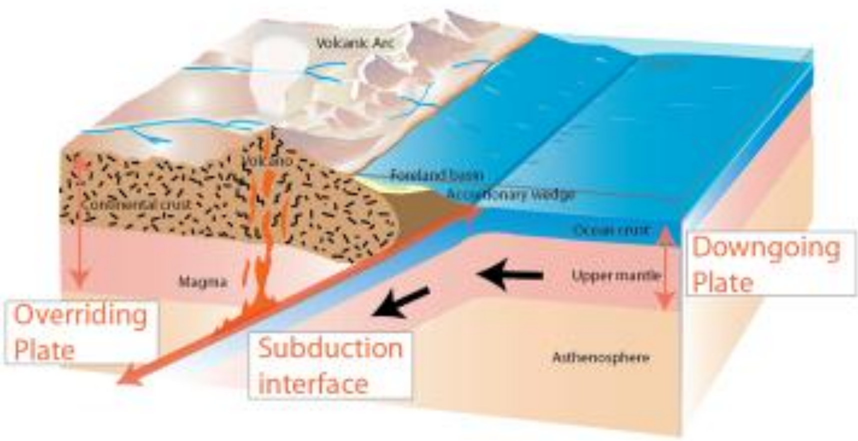
A magnitude 7.5 earthquake is big and devastating, the magnitude being on the Richter scale, which has been in use since the 1930s to measure the amplitude of seismic waves (ie the amount of shaking). The highest magnitude is about 9, with the 2004 Sumatra earthquake at M9.1 and the 2011 Japan earthquake at M9.0 in recent years. It is a logarithmic scale with the amount of shaking increasing tenfold with each unit increase while the energy increases 30-fold. The effects of an earthquake depend on its depth, the geology and how far away it is. Earthquakes happen when rocks stick along a fault line until the pressure exceeds the friction, when the rock ruptures suddenly at 2km/second – this is stick – slip motion.

Aftermath of the Tohaku earthquake and tsunami, Japan, March 2011

Seismic hazard analysis needs the location and size of faults. For example, the hazard in the recent Christchurch, New Zealand, earthquake was previously unknown because it occurred on a fault buried by sediments since the Ice Age 12,000 years ago. Faults can be seen and the Blue Anchor Fault near Minehead, Somerset, is one of the most obvious faults visible in the UK. Displacement on extensional faults like the Blue Anchor Fault is generally around 1m in each earthquake, with maximum earthquake magnitude around M6.5. At Tien Shan, China, faults can be identified with 5km displacement and in the South Island of New Zealand, the Alpine Fault extends along the entirety of South Island with a few hundred km displacement on a 600km-long fault capable of M8.

Seismologists today use the Moment magnitude rather than the Richter magnitude, which is based on the area of the fault that slips and gives a better measure of the amount of energy. The Moment magnitude is approximately equivalent to the Richter magnitude in most cases. The greatest movements take place at the boundaries of tectonic plates, where they are separating, as at mid-ocean ridges, sliding past each other, as at the San Andreas Fault, or colliding to generate mountain-building or subduction. Collision zones have the largest faults on earth. Britain is relatively aseismic, though it does have small earthquakes such as the M5.1 Lincolnshire earthquake on 2008, which caused some damage to church spires and chimneys. The Pacific ring of fire is the locus of deadly subduction zones and the edges of the Pacific plate are picked out by earthquakes in the last

30 years. Subduction zones are characterised by one plate sinking (the downgoing plate) and one over-riding it along megathrust faults up to thousands of km long, which can slip by tens of metres. The 2004 Sumatra earthquake had a 1,000km long rupture.



Subduction zone megathrust fault

Silent earthquakes

The audience were then asked what they would do if they had been in Gisborne, a coastal town in North Island, New Zealand, in 2010 when a M6.8 earthquake occurred along a shallow fault at 15km depth directly beneath them – Do nothing? Dive under the table? Head for high ground in case of a tsunami or run around screaming? In fact, nothing happened, no-one felt it and seismometers did not detect it. To put this in its context, North Island has the Pacific plate subducting westward beneath the Australian plate, South Island has the Australian plate subducting eastward beneath the Pacific plate and the Alpine Fault is taking up the deformation in strike – slip movement. However, there have been no large earthquakes recorded on the North Island megathrust fault in the last 200 years and seismologists have looked for evidence of prehistoric earthquakes (palaeoseismology) such as tsunami deposits, without success.

Up to 30 years ago, megathrust faults were considered to move by stick – slip movement or by aseismic creep at about 4cm/year. If the North Island megathrust fault were locked, it would push the over-riding Australian plate westwards and GPS technology, which was developed in the 1960s-1970s, has been used to assist in determining this. GPS stations on North Island do indeed show that it is moving to the west. In 2002, first analyses of the GPS data showed jumps in the data but no earthquake was detected and the events took place over about 4 weeks, not seconds as with an earthquake, at the rate of about 0.5-1.0 cm/day. These slow-slip events happen regularly every 2 years. Such slow-slip events, or silent earthquakes, have now been found around the world.

The North Island events are shallow at 15km, so they are amenable to seismic reflection imaging using an air gun at sea – standard oil industry technology. Analysis shows an accretionary wedge with flat-lying sediments on the sea floor, which rises offshore to the Gisborne Knolls, and the megathrust fault shows very high amplitude reflections indicating a massive change in rock properties, probably high fluid content in the sediments being subducted, which lubricate the fault and reduce friction. It is now planned to drill 6km beneath the seabed into the zone of slow-slip. International Ocean Drilling Proposal 781A in 2017-18 has riser drilling of a number of 1km holes, which will be instrumented to observe the slow-slip cycle. Proposal 781B is the flagship project to drill into the megathrust fault. Before this deep drilling can commence 3-D seismic reflection data will be collected to ensure there are no drilling hazards. This survey will likely take place in 2018..

It is possible that slow-slip on a megathrust fault increases stress elsewhere. Japanese workers in a paper in *Nature communications* in 2015 suggested that slow-slip triggered the Tohaku earthquake in 2011.

Tsunami earthquakes

The audience were then asked for their reactions when, if out for a walk in Gisborne in 1947, a Richter M5.8 earthquake were to occur on a shallow fault 15km deep, out to sea. Would they continue their walk, pick up items that had fallen off shelves, head inland or run for the hills? What happened was that there was not much shaking on land, just a gentle ground rolling, which went on for about 60 seconds but 30 minutes later the coast was hit by a 10m high tsunami, which would not have been expected from a M5.8 earthquake. It was what is now known as a tsunami earthquake as opposed to a tsunamigenic earthquake. Such earthquakes are very rare with only about 10 recorded in the literature. Prior to 1947, the tsunami advice in New Zealand was to go to high ground in the case of a strong earthquake. The one described occurred in March 1947 and there was another one in May 1947 and in, 1880, travellers found fish way inland. Tsunami earthquakes are really shallow (<5km). If the down-going plate is very rough, it increases friction in the very shallow zone. With sea mounts up to 1km high in the Gisborne Knolls, the high magnetic anomalies and seismic reflection results suggest that a sea mount was subducted off Gisborne. Shallow rupture is not enough to cause a tsunami unless the rupture velocity was very low (c 100m/second). As a result the tsunami advice was up-dated to recommend moving to high ground in the case of an earthquake lasting more than one minute or one too strong to stand in.

Conclusion

Plate movement was believed 30 years ago to be either by slow creep at 4cm/year or by stick-slip earthquakes moving at 2km/second. Two other types of movement have now been recognised – tsunami earthquakes moving at 100m/second and slow-slip earthquakes moving at 0.5-1.0cm/day. There are probably other types of movement as well.