The Sendai earthquake of March 11, 2011: What does it mean to us?

Prof. Nick Eyles by the Chikyu ship

Japan is one of the most dangerous places to live anywhere on earth: 'earthquake central' with volcanoes thrown in for good measure. It lies where four plates come together; and they don't like each other. In a relatively small, densely urbanized island such as this, the effects of earthquakes, volcanic eruptions and tsunamis are magnified. Acceptance ofnatural disasters and the tough times that follow is hard-wired into the national psyche.

Japan is made up of some 3,900 islands and four large ones: Honshu; Hokkaido; Kyushu and Shikoku. Japan was not always surrounded by water but was joined to the Asian continent until just 15 million years ago. Subduction of the thick oceanic crust of the Pacific and Philippine plates down below Asia created an arc of volcanoes along the coast something like the modern day Andes in South America. Old heavy slabs of oceanic crust such as these descend very steeply under Japan (called a 'subduction zone') often curling under themselves (a process called 'subduction rollback'). This has had the effect of pulling off a sliver of continental crust from the outer edge of the Asian continent and opening up the Sea of Japan (which geologists call a 'backarc basin') between the coast and the modern day islands of Japan.

According to legend, Japan lies above a giant catfish pinned below a granite stone held in place by a god (Kashima) of the Earth. The thrashing of its tail is felt as an earthquake. The subducting Pacific plate sticks to the plate above bending its outer edge downward like a bent ruler. Every now and again, the bending plate (the ruler) springs back violently. Minor earthquakes are felt almost daily in different parts of the country with some estimates of as many as 1,200 earthquakes each year; any of these would be of major concern here in Ontario.

Japan is cut up by major fault zones that divide the country into crustal blocks that mark the boundaries of the four tectonic plates that make up this part of the Pacific Rim. The Median Tectonic Line (MTL) is the longest (1,000 km) and divides Japan into a northern zone made of old continental crust rifted from Eurasia ('basement rocks') and a southern much younger belt of highly deformed rocks scraped of the subducting Pacific Plate together with volcanic rocks belonging to several arcs. In the east, the Tanakura Tectonic Line (TTL) separates basement rocks belonging to northeastern Japan from those in the southwest. The Itoigawa-Shizuoka Tectonic Line (ISTL) cuts Japan completely in half in central Honshu marking the western side of a broad depression (the Fossa Magna) along the boundary between the Eurasian and the North American plates.

The Pacific coast of Japan is a long and very dangerous subduction zone. It is made up of two parts; the Nankai-Suruga Trough south of Tokyo and the Japan Trench to the north. The Nankai-Suruga Trough marks where low-angle thrust faults dip gently down below Japan as the Philippine oceanic plate slips under the Asian continental plate. To the north, the Japan Trench marks where the oceanic Pacific plate dives below North America. Along the Sagami Trough, the Philippine plate dives down below North America. As a consequence Tokyo lies at the intersection of the Nankai and Sagami troughs doubling its exposure to major earthquakes.

The pattern of past earthquakes reveals sectors each with its own clockwork frequency of tremors. On average, there is a disastrous earthquake every 90 to 150 years. These are named after the area in which they occur (e.g., the 'Tonankai Earthquakes' of 1498, 1605, 1707, 1854 and 1944). This behaviour reflects the 'stick-slip' motions of the faults. When plates are locked, strain builds up and there are no earthquakes (creating what is called a 'seismic gap'). With time, the strength of rocks is overcome and the fault abruptly ruptures (slip) creating a powerful tremor, extensive damage and uplift of the coastal margin as the overlying plate springs free.

In 2009, I met teary survivors of the 1944 Tonankai Earthquake (M7.9) spoke of their experiences as young school children. They had gone home for lunch only for the earthquake to strike leaving many friends dead under the rubble of their school. Today they are resigned to another large earthquake in the near future.

School kids practice emergency drills

The October 28, 1891 the Nobi Earthquake (M8; a along the boundary between Eurasian and North American plate (the Itoigawa-Shizuoka

Tectonic Line) had a profound psychological effect on Japanese society quite apart from the physical damage it caused. There was in effect, a crisis of faith. The Meiji Restoration in 1868 led to a rejection of the old Shogun warlord class and the adoption of a more outward looking approach that embraced western culture and technology. After 1870, foreign scientists such as British and American engineers were brought to Japan to modernize the country using steel, concrete and brick in favor of wood which was always susceptible to fire. The 1891 earthquake revealed the fatal weakness of this approach as steel railway bridges and western-designed buildings especially factories, collapsed wholesale while traditional wooden structures swayed but survived. The survival of old wood framed castles with their tiered structure was highlighted; did they not resemble that most sacred and most stable edifice Mount Fuji? The striking differences in the effects of the earthquake on different buildings was to eventually bring about a rejection of western learning, now seen as weak and vulnerable, in favor of traditional Japanese culture and workmanship. Henceforth Japan was increasingly wary of western culture, which it saw as inherently weak, and like its buildings, easily toppled. It's not a long stretch from the Nobi Earthquake of 1891 to the attack on Pearl Harbor in 1941 as we shall show below.

Prof. Nick Eyles at the Earthquake Observation Museum

A segment of the dangerous Neodani Fault which slipped during the 1891 earthquake is exposed to view today in the 'Earthquake Observation Museum' in Motosu City in Gifu Prefecture. The museum is a memorial to the 7000 people killed when the city of Gifu was completely leveled. A deep excavation below the museum's basement exposes the fault which cuts through Jurassic sedimentary rock and basalt. It is a left lateral fault and moved laterally by 8 m and vertically by 6 m producing a dramatic fault scarp still clearly visible outside in the surrounding valley. This earthquake was the subject of a novel report by John Milne and W.K. Burton ('*The Great Earthquake of Japan 1891*') in which it was clearly demonstrated (for the first time anywhere) that earthquakes were the product of slip along faults. They showed too, how the landscape could be read as a record of past earthquake activity in the form of scarps and offset rivers. It was truly ground shaking stuff; Milne and Burton later wrote (in 1898) '*Earthquakes and Other Earth*

Movements' where they established the science of seismology and a global monitoring system for measuring earthquakes. They also developed new instruments (seismographs) for measuring the size of earthquake waves and use the telegraph system to collect data from around the world.

Modern earthquakes in Japan are recorded and reported (somewhat strangely at first glance) by the Japanese *Meteorological* Association, a throwback to much earlier ideas of why earthquakes happen. Earth was seen a pan over a fire deep below. Wind, water and fire were the main earth elements; if the wind blew strongly, the fire would grow, the water would boil and its lid would bang up and down creating a tremor.

It was a common belief. Shakespeare wrote in King Henry IV;

'In strange eruptions, oft the teeming earth
Is with a kind of colick pinch'd and vex'd
By the imprisoning of unruly wind
Within her womb; which, for enlargement striving, Shakes the old beldame earth, and topples down steeples and moss-grown towers.'

Fusakichi Omori (1868-1923) was the first professional Japanese seismologist and completed a detailed statistical study of weather patterns and air pressure during earthquakes. He showed that many had occurred at times of little or no wind. In 1899, John Milne (the father of seismology) wrote a large review article in *Nature* making reference to meteorological explanations. In the late nineteenth century, it made perfect sense to place Japanese seismometers right next to meteorological recording stations.

As head of the Imperial Earthquake Investigation Committee, Omori oversaw the mapping of damage zones from which earthquake epicentres and the size of the tremors could be identified. He developed recording instruments (the 'Omori seismograph') and mapped epicentres around the world; his map of Pacific earthquakes identifying distinct 'zones' (what was later to be called the 'Pacific Rim of Fire') was later used as a key piece of evidence in the discovery of tectonic plates in the 1960's. He was the first foreign scientist to visit San Francisco after the earthquake in 1906, and Messina in Sicily, Italy which killed 120,000 people in 1908 (Europe's deadliest) and to make detailed reports of the damage. He showed one again, that masonry and brick buildings were unsuited to earthquake prone areas.

Omori is perhaps best remembered for his ‘gap theory.’ By mapping the location and timing of past events, the frequency of major earthquakes would be revealed, giving potentially life-saving clues as to future events. In this he was absolutely right. He identified ‘seismic gaps’ where earthquakes were overdue and could be expected shortly; the basis of most modern predictive capability albeit on timescales of decades not years. But there was a deadly limitation; Japan is an island and many faults lie offshore out of the reach of investigation. The great city of Tokyo lies at the head of Sagami Bay and a significant gap had already been identified as early as 1905 but evidence of past activity lay hidden under Tokyo Bay. Omori ironically read a series of ‘semi-destructive’ earthquakes in 1922 and early 1923 as evidence that the gap had been filled. In this opinion, he was catastrophically wrong. Near noon on September 1, 1923 disaster struck; the Great Kanto earthquake broke water pipes in Tokyo and 140,000 people died in the earthquake and fire that followed. Omori was in Australia at the time, returned ill and died in the turmoil just weeks after the earthquake. Not a fitting end to a fine earthquake scientist.

Frank Lloyd Wright made much of the fact that his Imperial Hotel survived the Great Kanto Earthquake but there was no escaping the wider message that Japanese-designed buildings had fared much better. Successive deadly earthquakes had important political consequences in Japan. Governments were judged by their ability to respond and manage. Central control was strengthened. Japan defeated a major European power (Russia) in battle in 1905. The rejection of foreign influences was to eventually push the country into isolation from the West down the road to military conflict with the West in WWII.

Such is the power of earthquakes.

Prior to this month’s cataclysmic events, the Great Hanshin earthquake of January 17, 1995 was the latest blow to Japan occurring near the city of Kobe. It was the largest ‘quake since 1923. Neither the city nor disaster preparedness managers were fully up to the task of fighting more than 160 fires. Some 5,000 people died and 300,000 were made homeless. The epicenter lay southwest of the city and the fault ruptured northwards hurling its force towards and not away from the city; a process called ‘directivity’ by geologists. Much of the port city was affected by severe ground shaking in which wet sediments suddenly liquefied and lost their strength. Infrastructure was not destroyed but rendered useless by tilting and flooding as the land suddenly sank. In this case, traditional Japanese wood frame houses with heavy tile roofs were especially at risk when they were shaken.

The lesson here is that every earthquake is different offering new challenges largely because of the vagaries of local geology below the city and the depth of the quake. At the time, it was the most expensive natural disaster in history ($100 billion). The Sendai quake of March 11 will be remembered for its effects on two nuclear plants in Fukushima, specifically the loss of coolant to keep the reactors cool. The reactors had been shut down but the backup power supply (diesel generators) failed. At this point (13 March) mildly radioactive steam has been vented and the status of the plants is uncertain. Japan generates 30% of its power from nuclear stations that are all at risk in future 'quakes.

The future is not pleasant

Tokyo prepares for disasters with pre-coordinated rescue drills

There is a deadly frequency to the timing of large earthquakes in the Tokyo area; 1633, 1703, 1872, 1853 and 1923, so the city is overdue for the next 'big one'. It got badly shaken in March 11 but the epicentre of that quake lay 240 km north and 80 km offshore. Today, some 23 million people live and work in the greater Tokyo-Yokohama area right above the convergence of the great four tectonic plates (Eurasian, North American, Philippine and Pacific). The last great earthquake of 1923 on September 1 (the Great Kantō earthquake; M 8.3) devastated Tokyo and the sister port city of Yokohama. Landslides and fires killed many. Rumors that Koreans were taking advantage of the earthquake to loot stores lead to a bloody pogrom. Ever since, the Japanese have emphasized the importance of communication; giving the public accurate information in the aftermath of an earthquake.

The next large earthquake in Tokyo is expected to create $380 billion of damage and will be the world's most expensive catastrophe. Much of Tokyo, like Kobe, is built on wet soft sediment which can be expected to turn to quicksand. Though new buildings are considered to be earthquake resistant their design is largely untested and much old housing remains. Even if the building remains intact, it may well sink into soft sediment below softened by liquefaction.' Local geological conditions always dictate the effects of earthquakes; a large tremor in one area underlain by hard rock can have very different consequences from another of the same magnitude where soft sediment predominates.

Thanks to the development of plate tectonic theory in the 1960's, geologists now have a clear understanding of the causes of earthquakes. But there are still a lot of unanswered questions surrounding large magnitude 'super quakes' triggered in subduction zones. The ability to predict them is no closer than it was in Omori's day. Scientists know why these earthquakes happen, they're less sure of the precise processes and still can't yet read the tell tale signs that precede them.

Scientists on board the Drill Ship '*Chikyu*' are drilling kilometres into the ocean bed to reveal the processes at work

Offshore, in the Nankai Trough just off Tokyo, one of the most earthquake prone regions around the entire Pacific Rim, scientists on board the Drill Ship '*Chikyu*' are drilling kilometres into the ocean bed to reveal the processes at work. They are looking for clues in the deep sea sediments being forced down into the subduction zone and the mechanisms that generate large earthquakes along these megathrust faults. The Chikyu (meaning '*the Earth'*) is a Japanese-built ship capable of drilling to 7,000m below the sea floor to collect rock samples and install sensors. It employs state-of-the-art 'riser' drilling technology which means that it pumps heavy mud down the hole to cool the drill bit and can safeguard against dangerous blowouts where rocks contain gases under very high pressure. An enormous 'blow-out preventer' sits on the sea floor. Formerly gas rich zones were extremely hazardous to earlier generations of drill ships such as the Canadian-built *Resolution.* The *Chikyu* is leased to the Integrated Ocean Drilling Program (IODP) supported by some 20 countries including Canada.

In late 2009, the *Chikyu* drilled 2 km deep into the floor of the Nankai Trough located off the southwest coast of Japan. It is one of the most active earthquake zones on the planet and the purpose of the drilling expedition is to establish what type of sediments are being dragged down into the Nankai Trough subduction zone. Previous work suggests the critical importance of fluids carried down within wet muddy sediments in lubricating slip between the descending plate and the overriding plate. Monitoring real time fluid pressures are a key objective because higher than usual fluid pressures might mean slippage is imminent thus foretelling a major, damaging earthquake. Here is a possible key to earthquake prediction.

The long term aims of the Chikyu are ambitious; the private company that owns it wants one day to be able to drill down through the entire thickness of the Earth's crust and reach the mantle; the implications for developing new energy sources and mineral deposits are far reaching to us all. Unfortunately, there is only one such vessel afloat today.

Currently, the Japanese Meteorological Association operates a national earthquake observation network collecting data from several thousand monitoring instruments operated by local governments and the National Research Institute for Earth Science and Disaster Prevention (NIED). These data are transferred to the headquarters of the Earthquake and Tsunami Observation System (ETOS) on a real-time basis. In the event of an earthquake, JMA releases information on its hypocenter, magnitude and shaking intensity to local disaster prevention authorities through dedicated lines, and to the public through local governments and the media. This information also plays a vital role as a trigger for rescue and relief operations.

National Disaster Prevention Day is held every year on September 1

Not surprisingly, Japan's budget for natural disaster management is huge; about 4.5 trillion yen equivalent to 5% of the entire national budget. National Disaster Prevention Day is held every year on September 1 (commemorating the 1923 Great Kantō Earthquake) when the military, various government agencies, schools and businesses practice co-ordinated rescue drills. The last great 'Tokai earthquake' occurred in 1853 so it is a safe bet that the port city of Hamamatsu will be badly damaged in the next few years. We visited Fukuroi Minami Junior High School to see preparations for an impending earthquake. At precisely 9 am a siren announced a major earthquake and was followed by frenetic activity as the school was evacuated and soup kitchens and shelters were quickly set up by the military. Children watched dramatic rescues of dummies trapped in cars and houses buried under debris.

Just how effective these drills are in helping real people is being tested now. The calm that Japan has experienced since 1995 ended abruptly on the March 11th.

Globally, as urban areas morph into supercities so the susceptibility to geologic hazards increases. Next up on the watch list is Istanbul.

What does it mean to us?

And what you might ask does all this mean for Canada? We are a Pacific Rim country just like Japan; the tectonic setting of Vancouver is no different from Tokyo but its geology is even more hazardous. Much of Vancouver, our only major west coast port, sprawls across soft wet sediment left by ancestral Fraser River. Large submarine landslides on the river's offshore delta tell of large pre historic tremors; 'ghost forests' of dead trees suddenly drowned by subsidence during major earthquakes, and sand layers preserved in coastal marshes keep a record of ancient Pacific tsunamis. Past is prelude; a foretaste of what is to come.

Southern Ontario on the other hand, occupies a so-called 'intraplate' setting, a safe place it was then thought when our nuclear plants were built decades ago in the absence of any fundamental knowledge of the faults that lie directly below Pickering or how Canada's geology had even been put together. Some geologists speculate that a large break (rift) in the crust lies below Lake Ontario connected to the dangerous St. Lawrence Rift which underlies the Ottawa Valley and St. Lawrence River extending as an arm down the Hudson valley to New York. Moderately large damaging earthquakes occurred in 1732 (Montreal; M5.8), in 1935 (Timiskaming; M6.2) and in 1944 (Cornwall, Ontario - Massena, New York; M5.6). The last was Canada's costliest with considerable impact on urban infrastructure. Large landslides in the Ottawa Valley and active faults below the floors of lakes in the northern reaches of the valley again indicate large prehistoric earthquakes. As geologic research moves forward, so the 'recurrence time' of such earthquakes steadily shrinks. A magnitude 7 earthquake every couple of thousand years is now suggested. But when was the last? Do we know the full population of faults below our towns and cities? Do we know enough about how local rocks and sediments behave when shaken?

The answer is that there is no safe place on the planet; we live on the surface of a mobile crust always on the move. Safeguarding the population from natural hazards is as important as preventing wars or disease; perhaps even more so since the last 12 months have been the deadliest yet for earthquakes.

Here then lie challenges to our universities to educate students and the public regarding the nature of the planet we live on and the tectonic threat. Here lie opportunities for programs in environmental geoscience to create those scientists on whom our future might depend; from pollution, depleting resources, to geologic hazards we need to know much more of our deadly neighbor.