Some Notes on Subduction Earthquakes, Tsunami and LNG Terminals

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Introduction – It is essential that engineers, corporate and public officials and people living on the Oregon coast understand the risks entailed in siting liquid-natural-gas (LNG) terminals in the zones demonstrated by the Oregon Department of Geology and Mineral Industries to be subject to maximum inundation by "local" tsunami. Those great waves will follow the massive earthquake certain to occur when the North American tectonic plate again slips over the offshore Juan de Fuca plate. A summary of the understanding of that geology is offered here, starting with the siting plans. Then the nature and dangers of subduction earthquakes and tsunami will be reviewed. The goal is understanding that siting LNG terminals in locations near shore is unwise and might well be characterized as madness.

LNG Export Terminals Planned for Oregon's Officially Designated Tsunami Zones

In 1995 Oregon's government had become aware of the potential in the state for powerful subduction earthquakes and the resulting tsunami waves. The state legislature passed a law (1995 Senate Bill 379) forbidding the construction of critical facilities in low lying coastal areas likely to be inundated by tsunami: hospitals, schools, civic centers and facilities using or storing large amounts of toxic, flammable or explosive commodities. That law remains in effect. It also provided funds to the Department of Geology and Mineral Industries (DOGAMI) to evaluate and map coastal zones according to the degree of risk. A geologist named George Priest led the initial effort and generated a set of maps, basically contour maps. A revised set of maps in the form of tsunami evacuation posters was developed in the late 1990s based on the best tsunami modeling available. They colored the zone most likely to be swept by distant tsunami in orange, colored a second, higher range of altitude likely to be covered by local tsunami in yellow (keep climbing) and levels less likely to be affected in green. Suitable escape routes are indicated with black arrows.

It may well prove unfortunate that Bill 379 (1995) also included the possibility for variances to be issued under compelling circumstances. Part of the variance approval process involves DOGAMI, but like all government agencies, it is subject to political pressure. Some very disturbing variances have indeed been granted. The NOAA ship facility in Newport is entirely in an orange zone subject to distant tsunami and to maximum damage from larger local tsunami. In a local tsunami, those lovely white NOAA ships could come aground upstream someplace, maybe at Toledo. The new port facilities will be ruined. Stupid, but not so dangerous as locating LNG plants in low-lying areas given the "orange" rating or mooring LNG ships well away from shore in the Columbia estuary.

One developing plan is to site an LNG terminal, called the Jordan Cove Energy Project (JCEP), at the north end of Coos Bay in southern Oregon. The DOGAMI tsunami map for Coos Bay (Figure 1A) shows that the plant location (at the arrow) will be in the zone (yellow) expected to be inundated by a local tsunami. However, at least the ship docking will be in the orange zone subject to distant tsunami and maximum danger in local tsunami. Keep in mind that even if compressors and tanks are elevated above tsunami level (at significant expense), when the tsunami arrives the LNG ships will, essentially by definition, be at sea level and subjected to the maximum impact. Unfortunately, the map (Figure 1A) barely includes Jordan Cove. There are at present no homes or businesses north of the map, so there must not have seemed sufficient reason to map there. The road access to the spit, north of the map, is just above sea level. After subsidence from a great earthquake it is likely there will be no vehicle access to Jordan Cove. The zone colored in green just west of the plant site is in fact low lying. Walking the ground will demonstrate the obvious potential for a sequence of locally generated tsunami to sweep directly over the low dunes of the spit, rearranging the landscape and laying waste to everything in the vicinity. If you have a role in deciding whether an LNG plant should be built, make the trip, walk around the north end of Coos Bay.

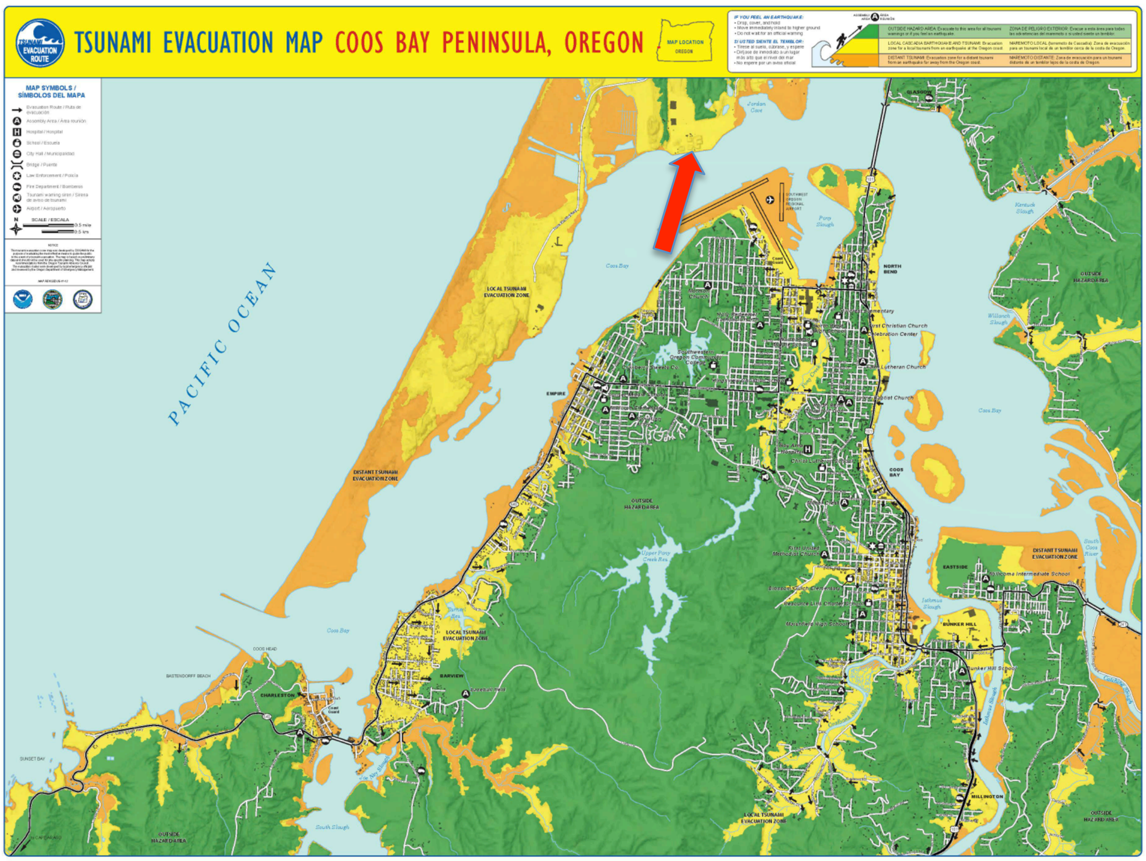


Figure 1A. DOGAMI tsunami zone classification for Coos Bay. The red arrow represents the proposed location of the Jordan Cove Energy Project LNG liquefaction and ship-loading facility. The site is subject to inundation by even distantly generated tsunami and to large overwash after Cascadia subduction zone earthquakes.

The DOGAMI tsunami risk and evacuation map for Warrenton, Oregon (Figure 1B) indicates that the site (at the arrow) is in the orange zone, which faces tsunami risk even for distant subduction earthquakes, and can be expected to suffer the most damage from locally generated tsunami. A 3-foot diameter pipeline with natural gas at very high pressure will come directly through the center of town, much of which is also in the orange and yellow zones. The ships loading at Warrenton are planned to moor well offshore at a long dock to be built on pilings. The LNG will be piped over a long trestle from the storage tanks near the end of the peninsula to the dock. The proposed ships would be superpanamax LNG carriers

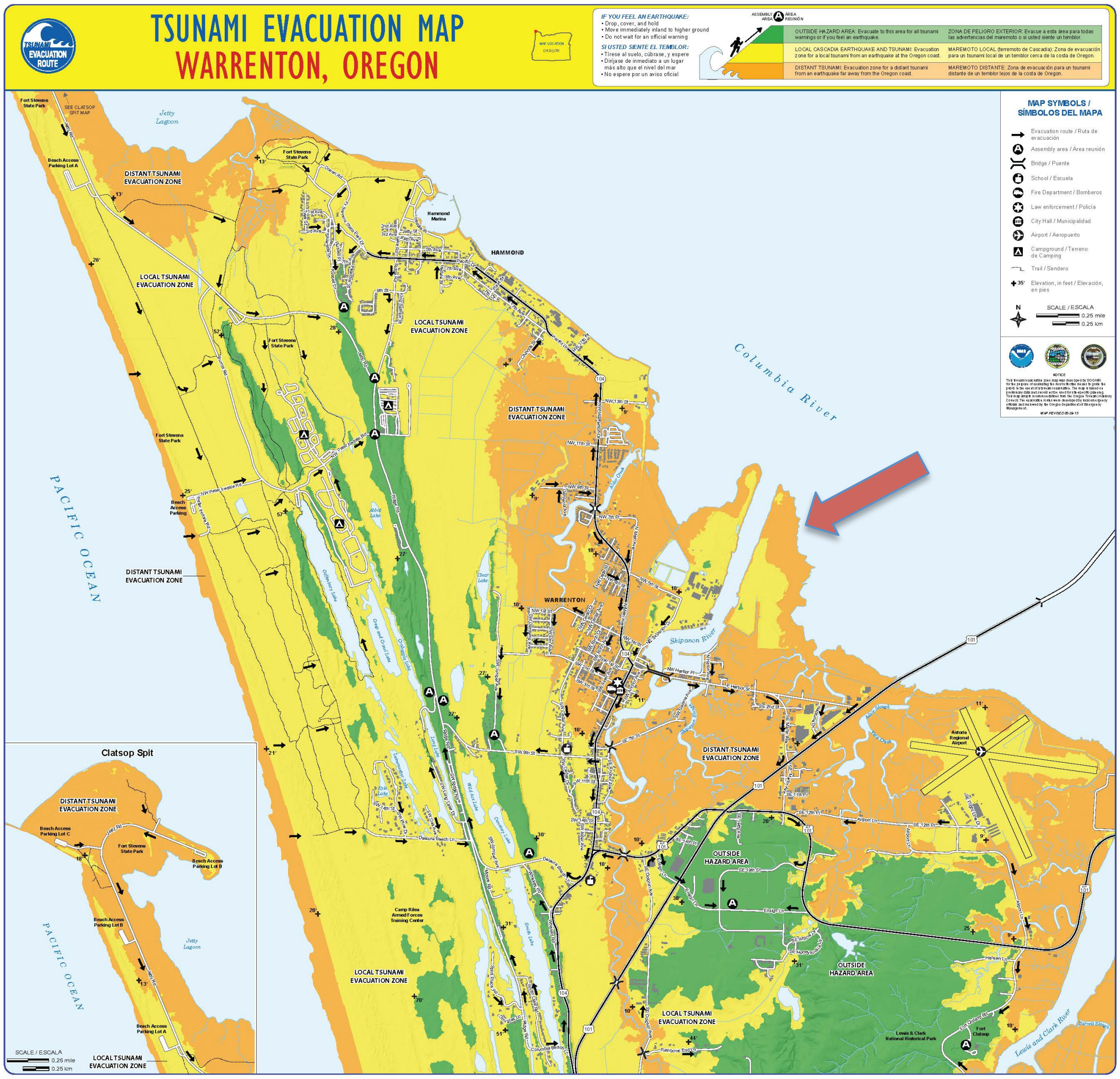


Figure 1B. DOGAMI tsunami zone classification for the Warrenton area just inside the Columbia River ocean entrance (inset lower left). The red arrow represents the location proposed for the Oregon LNG liquefaction and ship-loading facility adjacent to the channelized Skipanon River. Much of the site is fill over very deep soft soil (drilling to 350 feet has found no bed rock). Like Jordan Cove, the site is subject to inundation by even distantly generated tsunami and to large overwash after Cascadia subduction-zone earthquakes. Note how weakly protected the whole east side of the peninsula is from local tsunami approaching from the Pacific.

(up to 266 meters long) that haul on the order of 62,000 tons of LNG in a row of gigantic tanks. It would be interesting to know how they would respond to the buoyant force of a Tohoku-scale tsunami while tied up at this dock. After that great earthquake in Japan, the wave arriving at Ofunato was 23 meters (75 feet) above initial sea level. Interesting, yes, but we do not want to invite a demonstration by building this facility.

So, what exactly are tsunami and what is their connection to subduction earthquakes? Let's begin with tsunami:

Tsunami

The Japanese word tsunami translates literally as "harbor wave", and it refers to waves large enough to rise out of the ocean and move inland. They push into bays and into rivers emptying at the coast. The word, the same in Japanese for both singular and plural, has been adopted by practically all modern languages to designate the special sorts of ocean wave usually generated by undersea earthquakes, but sometimes also by submarine landslides and volcano eruptions, even by large meteor crashes into the sea.

The most common tsunami result from sudden formation of depressions or ridges in the seabed as a geotectonic plate on the ocean side of a subduction zone advances under the plate on the continental side. These events are consistently accompanied by earthquakes, and in not particularly unusual cases by quakes of magnitude (M_W) 8 to 9.4. Subduction zones around the Pacific rim are all close offshore, within 200 km or less from the coasts. Quake epicenters are thus beneath the sea. In the few minutes during the quake, the water above the depression or ridge drops or rises, and surface waters rush off in response to the resulting horizontal pressure gradients, forming a wave train headed away from the epicenter. Far at sea, tsunami waves typically have amplitudes (H), their height from trough to crest, of 0.5 meters or less (Figure 1), but they have extremely long wavelengths (crest to crest, L), on the order of 20 km or more. Thus, the slope of such a wave is not discernible by ships at sea.

Long, low ocean waves travel faster than short, steep-sided ones. In fact, a wave with $H = 0.5$ m and $L = 20$ km will move across the sea at 666 km/hour or 416 mph, with some variation depending upon bottom depth. That is the lower end of the range, which runs up to 900 kph, a typical speed for a jet airliner. Tsunami can cross the entire Pacific in a half day, and they only lose part of their energy along the way. The Tohoku earthquake in the Japanese subduction zone in March 2011 generated tsunami (Figure 2) that did significant damage in the Galapagos and washed a curiosity seeker off a jetty in southern Oregon. Because they are generated by a vertical shift in the seafloor, tsunami motion extends through the entire water column, and they actually move over the 3000 to 4000 meters-deep seafloor as "shallow water" waves. Their velocity (or for a wave "celerity," C) depends primarily upon the ocean depth: $C = \sqrt{gd}$, where g is gravitational acceleration (9.8 meters/second^2) and d is water depth in meters. The celerity is greater in deeper water.

Thus, as the seafloor slopes upward under a tsunami arriving at a continent, its leading edge is slowed sooner than its trailing edge, and the water piles up. As the celerity formula suggests, tsunami cross a continental shelf more slowly, about 100-200 km/hour, than they travel far at sea. For the shore near an earthquake epicenter, the quake itself is a warning to those on the coast that a tsunami will likely arrive in an hour or less, but still time to get to high ground. Earthquakes far across the basin give much more warning, and in recent decades we have learned to move uphill to avoid even these smaller, but still very dangerous "distant" tsunami. The warning time can be enough hours for everyone to reach safety and bring the dog. In Oregon, these "distant" tsunami waves can do damage coming from Alaska, the Aleutians and Japan. Earthquakes in Chile usually project their waves to the west and we are unaffected. The most dangerous tsunami originate from local subduction quakes, waves more dangerous because they can be much larger and they arrive so fast.

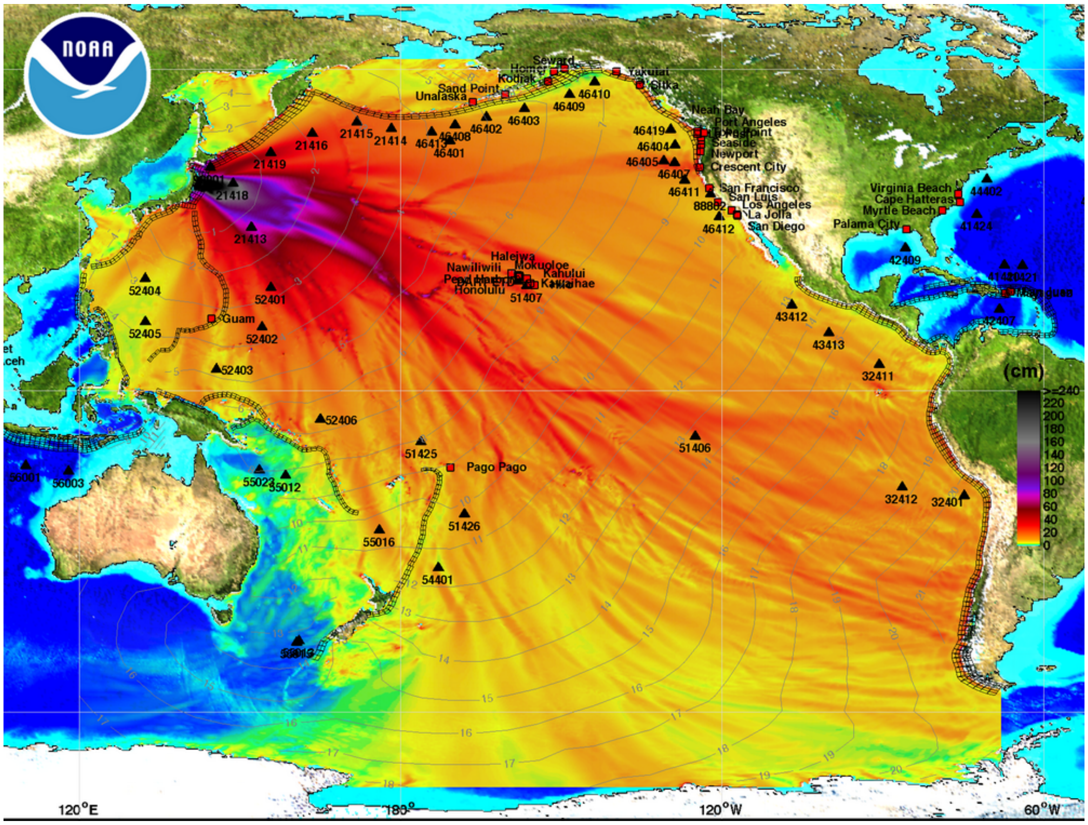


Figure 2. Calculated tsunami trajectories across the Pacific from the March 2011 subduction-zone earthquake with its epicenter to the east of the Tohoku region of Honshu Island, Japan. The color scale is in cm above background sea level (yellow least, black highest; red 30-40 cm).

Again, the warning of a local tsunami is the quake itself, but there is only time to put on good shoes and run for the hills. Oregon and Washington coastal residents living in the likely tsunami inundation zone have heard the suggestion to keep a “go bag” handy with a light load of survival essentials, because the sequence of tsunami can last many hours, and home may be gone after the wave.

Arriving against a beach on a low shore, a locally generated tsunami can slide water up and inland several kilometers. Striking at an angle against hills or cliffs, they can wash up to great heights, even to 100 meters. The mass of water can be very great, breaking essentially everything standing above the ground, both swashing in and washing back out: trees, houses, factories, peoples’ lives and livelihood. Valleys and other gaps between hills can focus the water motion, accelerating it forward and upward to amazing distances.

Tsunami in Estuaries and Inlets

Tsunami entering estuaries move as wave fronts similar to tidal bores (Figure 3), but they do not look like great surf waves curling over. The greatest tsunami bores rise several meters above the surface in front of them, and the sudden impacts are enormous. Objects like ships and floating docks are buoyed up powerfully, often breaking their moorings. When the wave’s crest passes, it is followed by the wave’s trough. So, floating objects just lifted but not torn away are then dropped far below their original level. The violence is devastating. Once a tsunami is moving inside a bay, it can reflect back downstream when it encounters shoaling upstream. If the entrance is narrow it can travel back and forth numerous times, primarily dissipating its energy by smashing into objects along the shores – hills, structures, trees. The fluid impact of the waves becomes much more damaging, because dislodged buildings, cars, tree trunks and boulders add to the mass impacts, but without water's fluid forgivingness.

Figure 3. Tsunami bore cresting a 6 meter sea wall adjacent to an inlet in northeast Japan after the March 2011 Tohoku earthquake offshore. The waves wrought similar damage all along the coast of Honshu near Sendai, killing more than 20,000 people and leaving hundreds of thousands homeless.

The sequences of tsunami waves passing along estuaries and inlets can be recorded by tide gauges, although those, or the docks they attach to, may be washed away by the wave impacts. Also, tide gauges are just floats inside a vertical tube attached to a piling, that move a cable over a vertically fixed pulley attached to a pen recorder (or equivalent). Usually there is a damping mechanism, so that only the general stand of the tide is recorded, not high frequency wind waves. For example, water might enter and leave the tube through small openings to slow its movement in and out. Thus the arrival of a tsunami bore can be more sudden than indicated by the record. Nevertheless, tide gauge records, "marigrams," give a strong impression of the powerful, sudden rises in water level caused by tsunami. Examples (Figure 4) come from the 1964 Alaskan earthquake ($M_W = 9.4$) recorded at Kodiak Island and the 2011 Tohoku ($M_W = 9.0$) earthquake off Japan.

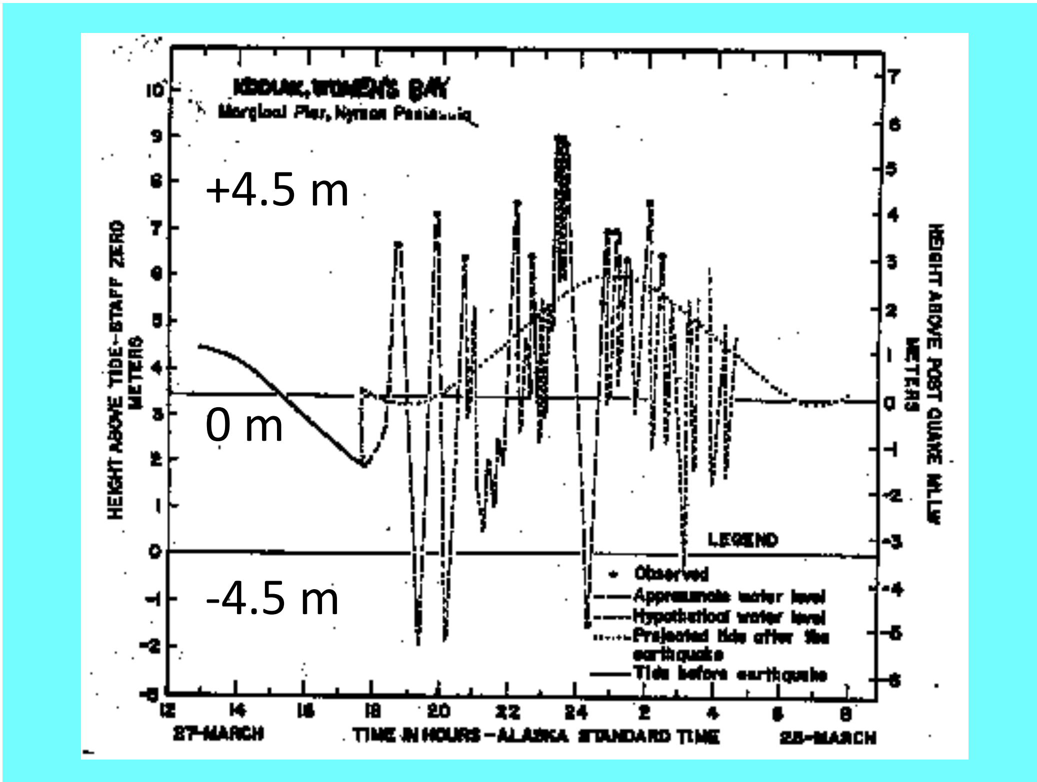
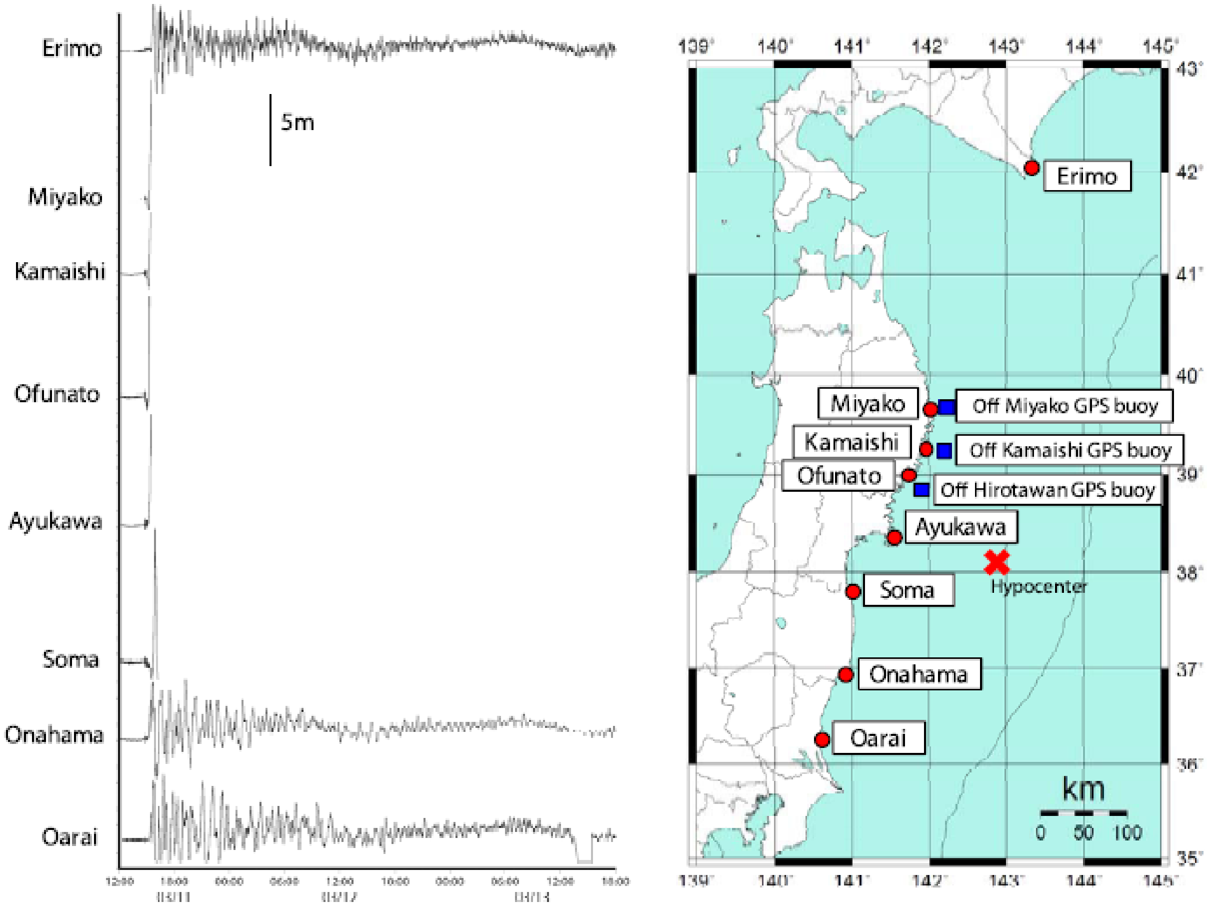


Figure 4A. Water level from the tide guage at the Coast Guard dock near the town of Kodiak on Kodiak Island, Alaska, on 27-28 March 1964. The initial event was land subsidence of 3.5 m, followed by arrival of a first tsunami wave 4.5 m above the new mean lower-low water level. A deep trough followed closely, dropping sea level by more than 8 meters. Great sloshing of second, third and later tsunami waves continued *for over 10 hours*. The greatest water level shift was 5 hours after the initial wave.

Figure 4B (next page). Tide gauge data ("marigrams") from stations along the Sanriku or Tohoku Coast of Japan (map at the right) during the tsunami sequence after the 2011 Tohoku earthquake of M_W=9.0. The initial waves arriving between Miyako and Soma were all at least 9 m above predicted tide level, so large that they (or smashing debris) disabled the tide gauges. Gauges at Erimo, Hokkaido, Onahama and Oarai, with lesser initial tsunami, continued to operate. The earthquake was at 14:46 hours. The initial tsunami arrived at Ofunato, Fukushima prefecture, at 15:18, 32 minutes later. Surveys after things settled down showed damage to heights of 23 m (75 feet). Some run-ups along the Sanriku coast reached 40 m above sea level.



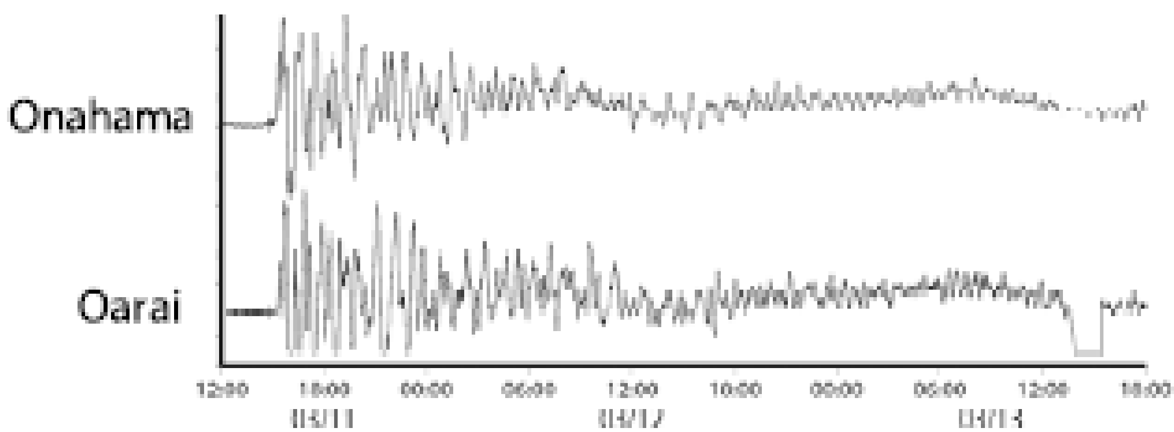


Figure 4C. Onahama and Oarai marigrams of Figure 4B enlarged. Tsunami come as wave *sequences* lasting hours, at Oarai 10 hours at full initial amplitude and ~20 hours before the sequence ended. Wave sequences where gauges were destroyed were also reported to have been similarly prolonged. Figs. 4B and 4C are from Ozaki (2011).

Models of tsunami entering a specific bay can be generated numerically or by physical simulations in wave tanks, but model prediction quality is likely to be uncertain, since the exact points of seismic origin of the initiating wave are only generally known. Moreover, waves can originate along a very extended offshore fault and are reinforced as they converge shoreward. Thus, it is not possible to predict for a given quake-prone area the exact height and impact of tsunami that will occur there. It is wise to assume the earthquakes certain to come in Oregon can be greater and generate bigger tsunami than locally experienced or as yet imagined. However, the dramatic and deadly 2011 Tohoku quake and tsunami in Japan are approximately what we must base our preparations upon for a subduction-zone quake and tsunami along the Oregon and Washington coasts. If the graphs in Figure 4 are not sufficiently sobering to make you reconsider siting LNG facilities in "orange" or "yellow" zones, more help follows here.

Subduction-Zone Earthquakes

Major tsunami are generated by major earthquakes along tectonic plate subduction zones. The damage a coastal population is already suffering from an earthquake of $M_W \geq 8$ can make appropriate response to the ensuing tsunami difficult or impossible. As a single telling example, consider the impact on the Fukushima Daiichi nuclear reactor during the March 2011 Tohoku earthquake 72 km offshore of northern Honshu's Oshika Peninsula. Here is a description from Gretel Ehrlich's book *Facing the Wave, a Journey in the Wake of the Tsunami*:

> "Not all waves are made of water. The workers described the earthquake as coming in two intense waves, and by the time the second one started, the pipes inside the Daiichi nuclear power plant that regulate the heat of the reactor and carry coolant to it were bursting open…. Oxygen tanks exploded, and the wall of the turbine building in reactor 1 cracked. A tangle of overhead pipes buckled. Others jerked away from the walls. Minutes later, but before the tsunami wave hit, the walls of reactor 1 began to collapse. A radiation alarm sounded and white smoke was seen coming from the top of the reactor."

Those earthquake impacts were then amplified by the tsunami, which radically exceeded the extremes predicted by models thought to be sophisticated. The tsunami wave at Fukushima crested at 15 m (49 feet) above sea level. Again from Ehrlich's book:

> "After the first tsunami wave hit the power plant, all the electrical and cooling systems failed…. The wave bashed the side of reactors 1 and 2 and flooded the basement of the turbine buildings, cutting off all power, including the emergency diesel generators. Though additional backup generators had been installed in watertight hillside buildings, the switching stations that connected backup power to the cooling systems were not watertight, and they failed. Temperatures rose. Reactors 1, 2, 3, and 4 experienced meltdowns."

Ehrlich's 2013 book is a testament to the levels of horror (Figure 5) that a major earthquake and tsunami can inflict. For those with the courage to face up to the potential for a similar disaster in the western U.S., it is essential reading.

Figure 5. Tsunami devastation in 2011 along the northeast coast of Honshu near Sendai, Japan. Picture from the worldwide web. Somewhat surprisingly, fires like those in the background are frequent in the aftermath of tsunami devastation.

The radiation contamination from the impact of the Tohoku quake extends to a wide expanse of Japanese coast and is an ongoing nightmare for now former residents. There is no end in sight as of April 2014. This failure of engineering design (actually an American design adopted in Japan) tells us what is the sane approach to the dangers of major earthquakes and tsunami on coasts adjacent to subduction zones: Nobody should build anything like nuclear reactors, liquid natural gas terminals, major oil pipelines or high pressure natural gas pipelines in the region. Placing such facilities in the tsunami zones of Oregon or Washington must be forbidden. No level of hoped for profit and no number of potential jobs should tempt us to add to the risks that the lives and well-being of our coastal populations already face. The notion that constructions can be engineered to withstand such devastating natural forces is an unforgiveable sin of hubris.

Oregon Subduction-Zone Earthquakes

The geology telling us that the Oregon and Washington coasts are adjacent to a nearshore subduction zone that generates earthquakes of magnitude M_W=8 to 9 at long intervals is moderately complex, but it is understandable to anyone who takes the time to read the analyses by geologists of tsunami deposits (called turbidites) along our continental slopes and in our coastal marshes. This science is a step-by-step argument from massively repeated observations and the conclusions are stronger, if that is possible, than those supporting the anthropogenic causes of ongoing global warming.

Geologists Brian Atwater in Washington State and Curt Peterson in Oregon began in the 1970s to study cores of soils and sediments from coastal marshes. They found an alternation downward through layer after layer between mud mixed with plant debris and sand of the sort found on coastal beaches and on the seafloor near to shore. After careful elimination of other hypotheses, it became clear that the coast had repeatedly dropped on the order of a meter relative to sea level, followed by delivery by tsunami of the sand layers from the nearby sea. Between the earthquakes that had lowered the land, there was time for silt and clay to accumulate above the sand layers and for salt marsh plants to grow in that sediment. Carbon-14 dating of the plant debris gave a rough chronology. For the recent events, counts of tree rings in still-standing cedars that had been killed by the salt water intrusions around their roots (and comparisons to tree-ring thickness variations in old growth above the tsunami zone) showed that the most recent quake, at least in northern Oregon, had happened about 300 years ago. Then, well-dated Japanese records in diaries and monastery archives from the Genroku era (the Japanese have a very old, very precise calendar system) showed that a distant earthquake not felt in Japan had generated a significant tsunami there in late January of 1700. Calculating the tsunami travel time from Oregon suggests that the last of these extremely big earthquakes occurred about 9 PM on the 26th of January. That agrees with Native American story histories from Cape Flattery to Northern California of a great and sudden nighttime in-flooding of the sea that drowned whole coastal villages. Many were killed, but some survived to pass down the stories.

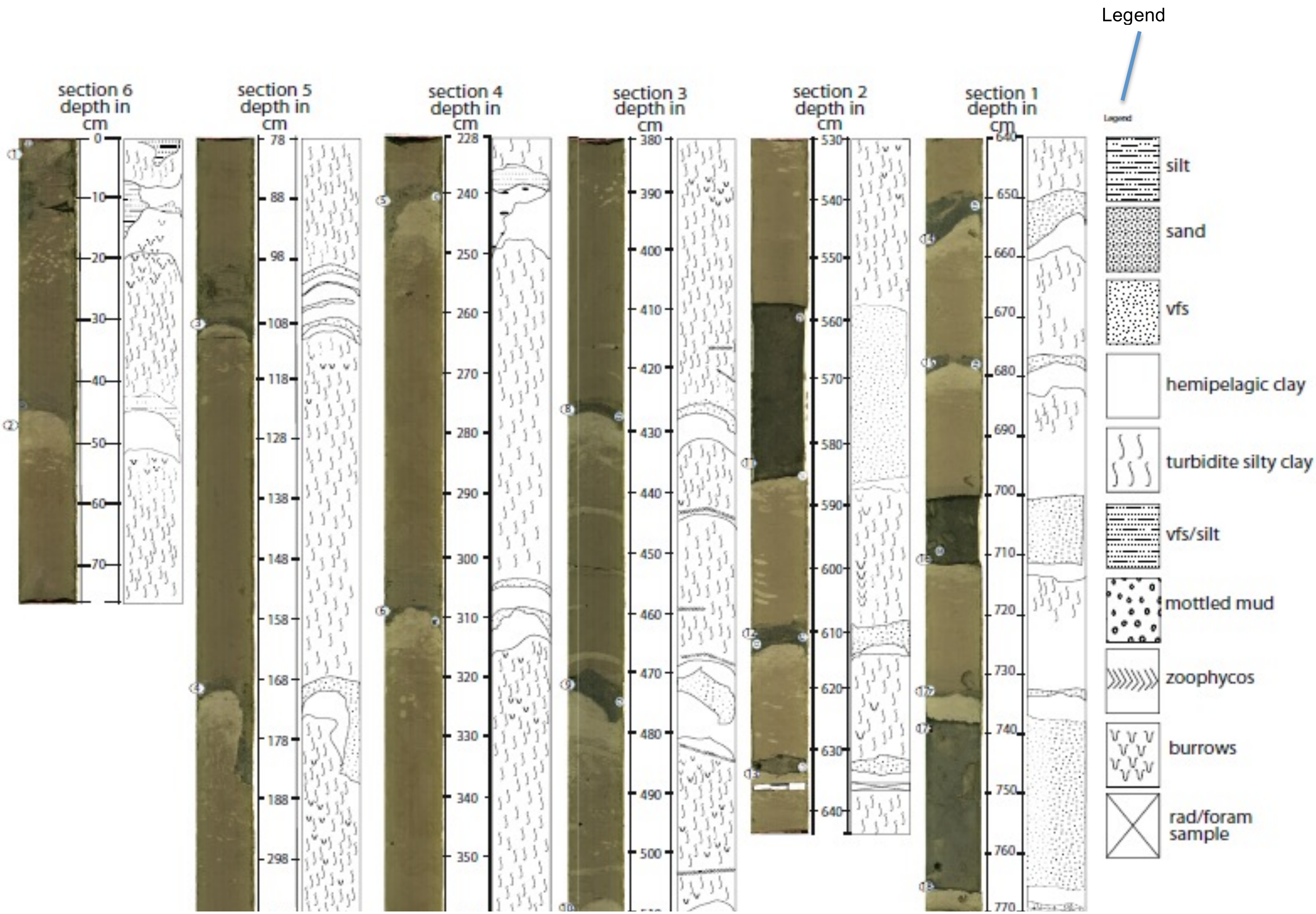
Part of the evidence that these truly were megaquakes, $M_W > 8$, is that the subsequent tsunami went far, far inland along coastal creeks, leaving sand deposits as records of their visits. Other evidence is that such quakes elsewhere (Japan, Alaska, Chile, Indonesia) are associated with similarly large drops of continental height relative to the average sea level of the time.

Some of the most convincing data regarding the intervals between these Pacific Northwest megaquakes has been developed by geologists Christopher Goldfinger, Hans Nelson and others from cores of sediment collected from ships positioned over the seafloor channels that run rather like deep irrigation ditches across the continental slope and adjacent deep bottom. When sea level was about 120 m lower during the ice ages, rivers flowing across what is now the continental shelf cut canyons that remain in the shelf. The rivers carried sand and mud and deposited it near their mouths. Eventually the slopes of the undersea piles got high enough to slump, and the resulting slurry of sediment and seawater, much more dense that just the water, would accelerate down the slope as a "turbidity current," eroding channels in the slope and seafloor beyond, depositing banks above the surrounding sea bottom to either side. After the great continental glaciers receded, and the melt water raised the sea to near its present level, the canyons in the shelf remained, and sediment accumulating in the submarine canyons can still slump and becomes deposited along the channels. The biggest turbidity currents happen after subduction-zone earthquakes, so the sediments in the channels alternate between layers of very fine clays and biological detritus sedimenting from the water column and layers of "turbidite" sand released in bulk from the canyons above. The arrivals of the turbidite layers can be dated from the carbon-14 ages of tiny carbonate shells of planktonic protozoa deposited just beneath them. To an impressive extent, the turbidity flow dates from sampling of all of the channels agree to within the modest variations of the method. Turbidite layers all along major sections of the Washington, Oregon, and in some cases the northern California coasts were laid down at the same times. Those dates are beyond reasonable doubt the times of subduction megaquakes to which this region is subjected. Dates determined by Curt Peterson, Brian Atwater and others for coastal marsh sediments just below tsunami deposits of ocean sands agree with the ocean turbidite dating.

The intervals differ between the section of the subduction zone from central Oregon northward and the section to the south. Subduction earthquakes have been more frequent in the Coos Bay section, 41 of them in the last 10,000 years, an average interval of about 240 years. Breaks have been less frequent along the northern stretch at intervals closer to 500 years, but some intervals were as short as 300 years. Quakes and tsunami generated by quakes at either end can be experienced, probably at variable intensity along the whole coast.

Goldfinger et al. detail all of the available data in a 2014 U.S. Geological Survey report, and one of their vast stock of turbidite vs. mud (termed “hemipelagic clay”) alternation diagrams (Figure 6) is shown here. They summarize by putting the chance in the next 50 years of a quake of $M_W > 8$ at ~40% off southern Oregon and at ~10% off northern Oregon and Washington. Barring a death wish, you would *not* play Russian roulette with two bullets in a five-shell revolver. Would you build an LNG export facility in the southern Oregon tsunami zone? The Jordan Cove Energy Project plans to do that. The Warrenton site proposed by Oregon LNG for a compression and shipping plant for LNG is now in “the early window” in which a megaquake and tsunami become likely. Three of 19 northern quakes occurred after intervals of 350 years or less.

Figure 6 (Next Page). Taken from Figure 25 in Goldfinger et al. (2014). Photos and interpretive diagrams for six sections (1 oldest, right, to 6 youngest, i.e., closest to the seafloor surface) of an 8 meter core taken in the Cascadia Channel. That is the confluence of outlets from several submarine canyons from Juan de Fuca Canyon on the north to the Columbia (River) Canyon on the south. After those channels merge, the Cascadia Channel runs north to south parallel to the coast along the base of the continental slope. On echograms it is an obvious groove in the seabed. Numbers in small white circles on the left sides of the core photos represent the bottoms of 19 turbidite layers deposited by turbidity currents set off by northern Cascadia subduction-zone earthquakes. The 19 quakes occurred at varying datable intervals since very close to 9700 years ago. vfs = very fine sand. Hemipelagic clay is a mixture of very fine mineral particles (clay), diatom shells and similarly sized biological particles. “rad/foram sample” means that shells of planktonic protozoa were extracted from a sample of the sediment for microscopic evaluation or elemental dating, e.g. at 240 cm.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LNG in the Warrenton and Coos Bay tsunami zones?

As stated above, it is possible to model the height of possible tsunami in various locations. However, to trust those models and think it possible to engineer a dangerous industrial facility to withstand a massive tsunami is simply stupid. Figure 7 shows the m marigram taken by Oregon LNG's design contractor to represent the "design tsunami" f their transfer facility proposed for construction on landfill over deep soft soils between t Columbia River estuary and the town of Warrenton, Oregon. Compare that diagram to a tide gauge records (Figure 4) from real and recent subduction-zone earthquake and tsuna events. Notice that the scale on Figure 7 is in feet, while the Alaska and Tohoku marigr are scaled in meters. Notice, too, that no trough follows the one wave considered. The tsunami evacuation route maps (Figure 1) for Coos Bay and Warrenton show that both proposed plant sites are in a zone for which the Oregon Department of Geology and Mir Industries rates the tsunami risk (by T-shirt sizes) as XXL, the orange shading on the ma

Moreover, to think that tsunami are all that matters is to forget the destructive po of the great earthquakes that precede them. Nevertheless, the recognized tsunami zones be forbidden to these dangerous installations. It has to be suggested that the leaders of tl Jordan Cove Energy Project and Oregon LNG consider human lives and the property of others as of very small consequence. We, The People, must not allow these plants to be

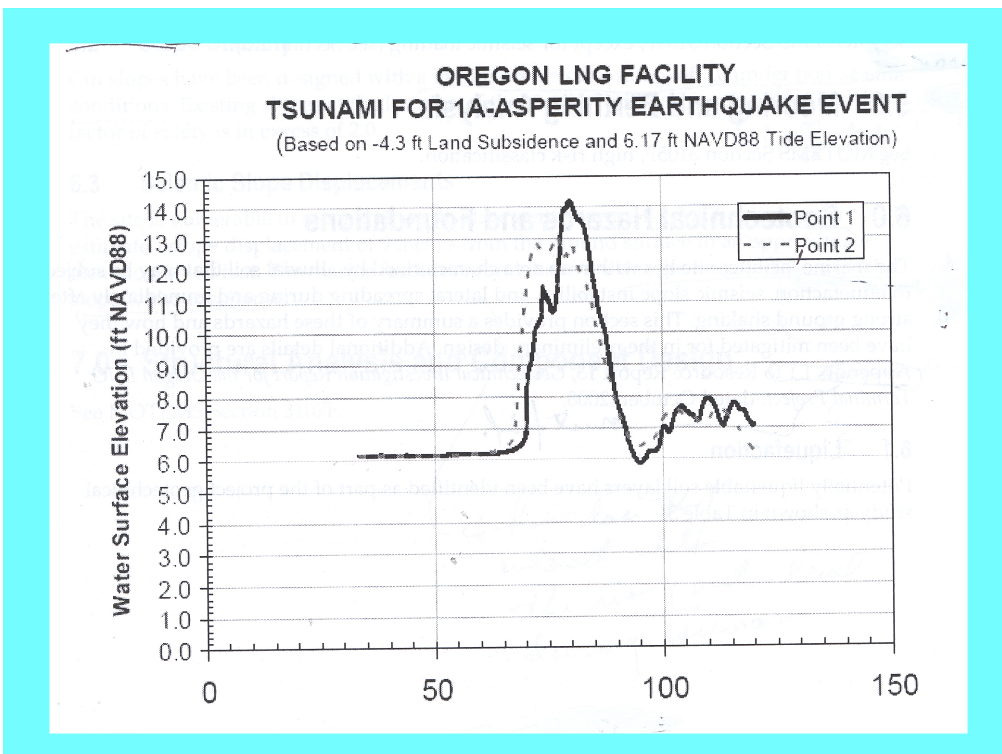

Figure 7. The model tsunami against which CH2M-Hill is designing the Warren LNG compression and storage facility, LNG transfer trestle and offshore ship loa dock for LNG tankers. Note the scale is in feet and that there is only *one* 8-foot wave. The engineers did not label the lower axis; presumably the numbers are sc units of time.

Figure 7 may not be the latest "design tsunami" being used by CH2M-Hill, but the most recent design papers submitted by Oregon LNG to the Federal Energy Regulatory Commission (FERC) are not available to the public. They apparently are rated CEII, Critical Energy Infrastructure Information, a designation clearly intended to keep terrorists from exploiting weaknesses in the design of power plants and the like. However, this rating is not applied only on its own initiative by FERC. Oregon LNG, through the lawyers who submit all of their documentation to FERC, urgently requests this rating. That can also be used to keep concerned citizens from knowing the details of their intentions. Let it be noted that susceptibility to terrorist activity is just one more reason that a facility as dangerous as an LNG production and transfer plant should not be cited within a mile of Warrenton. No "design tsunami" model marigram has been obtained for Jordan Cove.

Conclusion

Any thought of exporting LNG from massive compression and storage facilities in Oregon's tsunami zones should be abandoned. The savings to the corporations promoting construction of these facilities will be substantial *if* that wisdom is realized soon rather than eventually.

Authorship

This essay was written by Charles Miller, an oceanographer but neither a marine geologist nor an expert on tsunami. He is concerned that LNG terminals on the Oregon coast are an invitation to enhanced catastrophe. Aren't the near certainty of an earthquake of MW >8 and a major tsunami enough for Oregon's coastal residents to suffer? Potential for methane suffocation and natural gas fires should not be added to those threats.

Availability – You can obtain a PDF of this document from www.350corvallis.org. Click on the "Resources" tab and download the file.

References:

Ehrlich, Gretel (2013) *Facing the Wave, A Journey in the Wake of the Tsunami.* Pantheon Books, New York. 214 pages. (An emotional and poetic description of the impact of a great earthquake and tsunami in the recent industrialized past – object lessons for Cascadians.)

Goldfinger, Christopher and 12 coauthors (2014) Turbidite Event History—Methods and Implications for Holocene Paleoseismicity of the Cascadia Subduction Zone. In Robert Kayan, Editor, Earthquake Hazards of the Pacific Northwest Coastal and Marine Regions, U.S. Geological Survey Professional Paper 1661-F. 170 pages (only available on the Web: http://pubs.usgs.gov/pp/pp1661f/)
(Much is here of what you might want to know about our trenchless subduction zone.)

Henderson, Bonnie (2014) *The Next Tsunami, Living on a Restless Coast*. Oregon State University Press, Corvallis, Oregon. 322 pages. (A very good, lay-level review of subduction zone science and the potential impact of tsunami on coasts of the Pacific Northwest. The science is accompanied by profiles of many scientists whose lives are intensely engaged with these issues.)

Oregon Department of Geology and Mining Industries Tsunami Evacuation Brochures (maps and poster pages with evacuation instructions and precautions) are available for most of the Oregon coast at:
http://www.oregongeology.org/tsuclearinghouse/pubs-evacbro.htm

Oregon Coastal Zone Management Program (April 2014) *Tsunami Guide*, 69 pages. (Somewhat similar to this essay, it includes advice to coastal communities and residents regarding subduction zone earthquakes and tsunami. Find it at
http://www.oregon.gov/LCD/OCMP/docs/Publications/TsunamiGuide20140108.pdf

Oregon Revised Statutes §455.447 summarizes legislation relevant to citing of large, critical and hazardous facilities and structures in the seismic hazard and tsunami zones of Oregon.

Ozaki, T. (2011) Outline of the 2011 off the Pacific coast of Tohoku Earthquake (*M*w 9.0) - Tsunami warnings/advisories and observations. *Earth Planets Space*, 63 (no.8): 827–830. (Ozaki works for the Japan Meteorological Agency that operates tide gauges all along the Japanese coasts.)