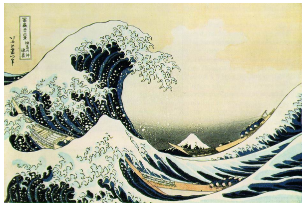
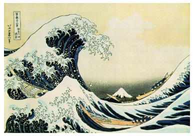


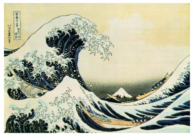
Tsunami generation, propagation, and devastation

John Fenton



Tsunami

- Tsunami is a Japanese term that means "harbour wave". It is used worldwide to describe a large sea wave generated by sea-floor disturbance.
- Oxford English Dictionary: A brief series of long, high undulations on the surface of the sea caused by an earthquake or similar underwater disturbance. These travel at great speed and often with sufficient force to inundate the land; freq. misnamed a tidal wave.
- Some spectacular tsunamis such as the 1883 Krakatoa and 1998 Aitape tsunamis were generated by sea-floor disturbances associated with volcanic eruptions or landslides. Subduction zone earthquakes, though, are the most common source of destructive tsunamis.
- The height of a tsunami in the open ocean might be of the order of 0.5m, but its wavelength might be several tens of kilometres: any change of water surface elevation can hardly be recognised.
- Period of waves – 5 min to 40 min, corresponding to a length of 70-500 km
- Approaching land, the period remains the same, the wave speed decreases (speed ~ depth)
  so that its length is less, and to conserve energy, its height increases (height ~ depth).



Tsunami source areas in the Pacific Ocean

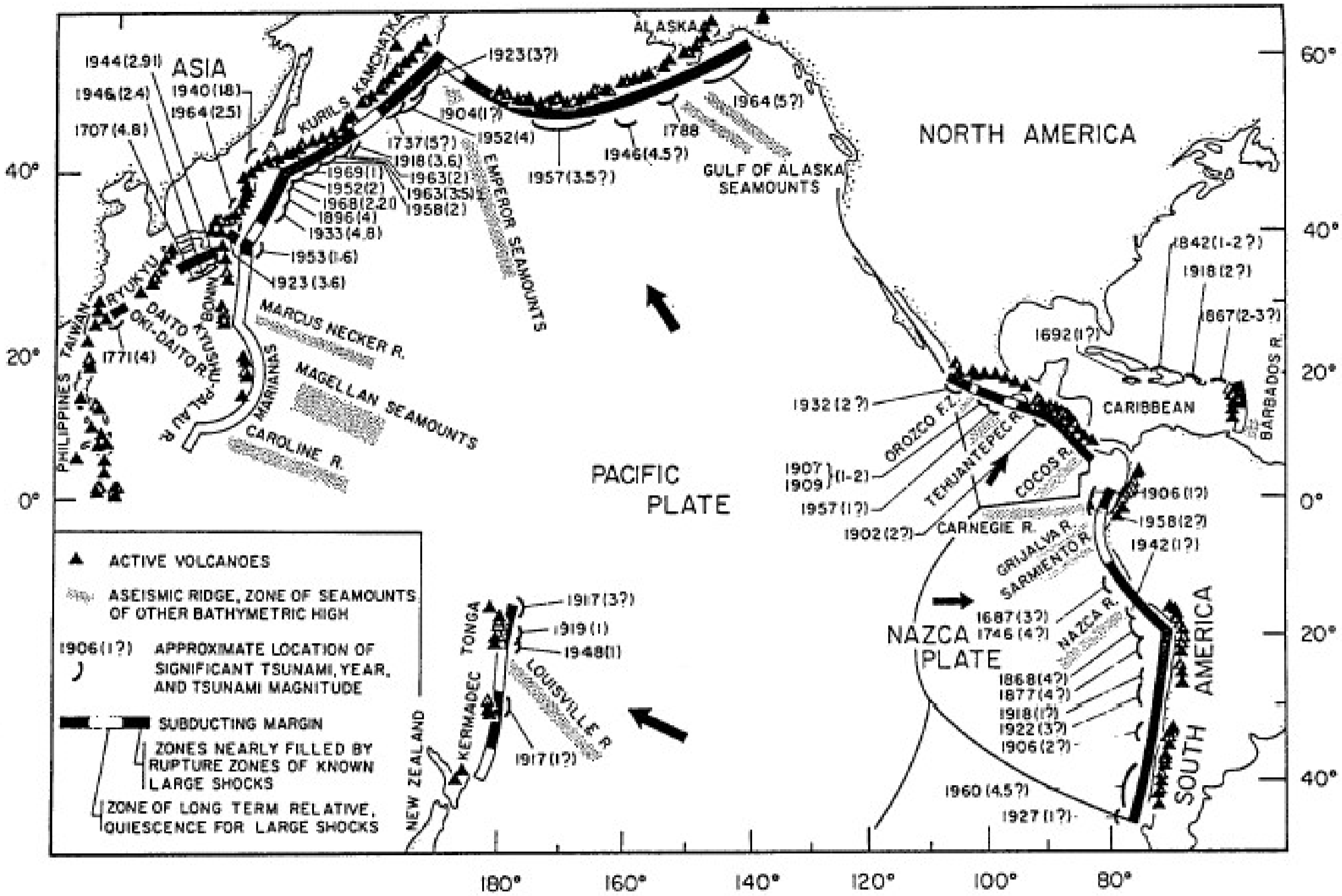
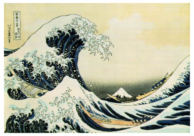


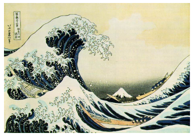
Fig. 1. Location of tsunami source areas in the Pacific Ocean (Kelleher, 1979).



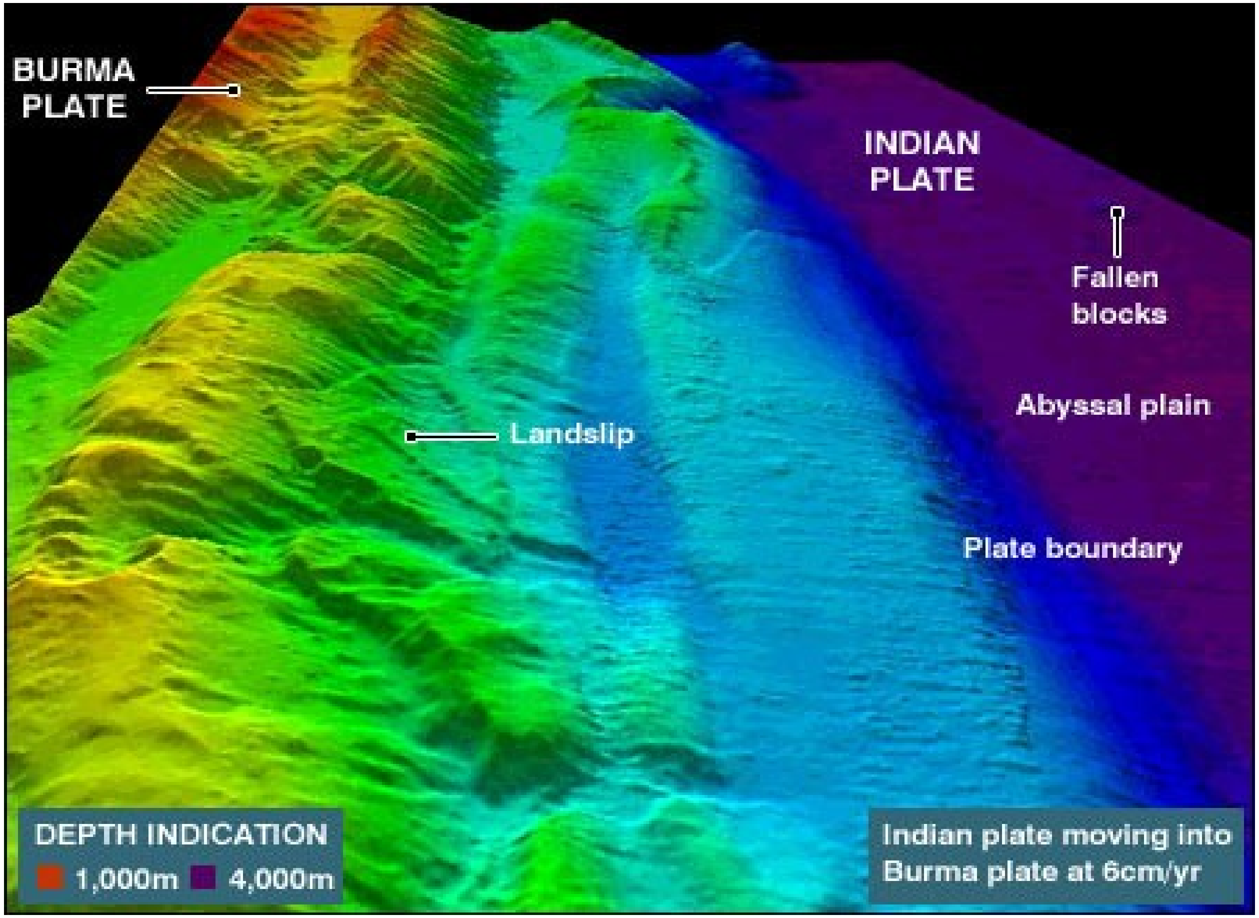
The 26th December 2004 Tsunami

To simulate the 26th December 2004, Sumatra earthquake of magnitude 9.0 the following logical assumptions were made:

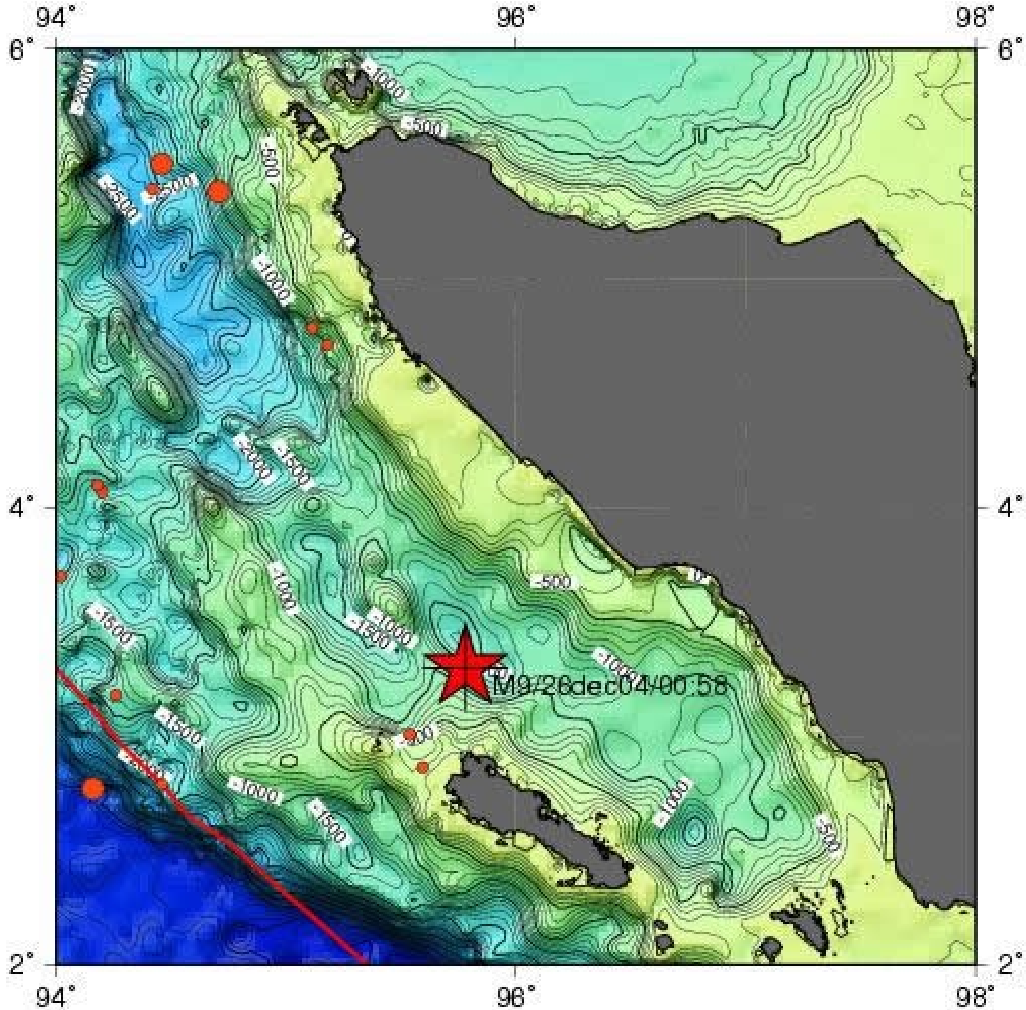
1. Length of the fault rupture is 1000 km (from the spatial distribution of aftershocks)
2. Width of the fault rupture is 100 km (from the focus up to the bathymetric trench along the megathrust)
3. Average displacement or slip along fault rupture is 15m
4. Thickness of the fault shear zone across the megathrust is 500m

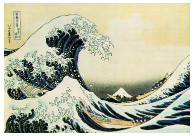


Some evidence for the role of undersea landslides

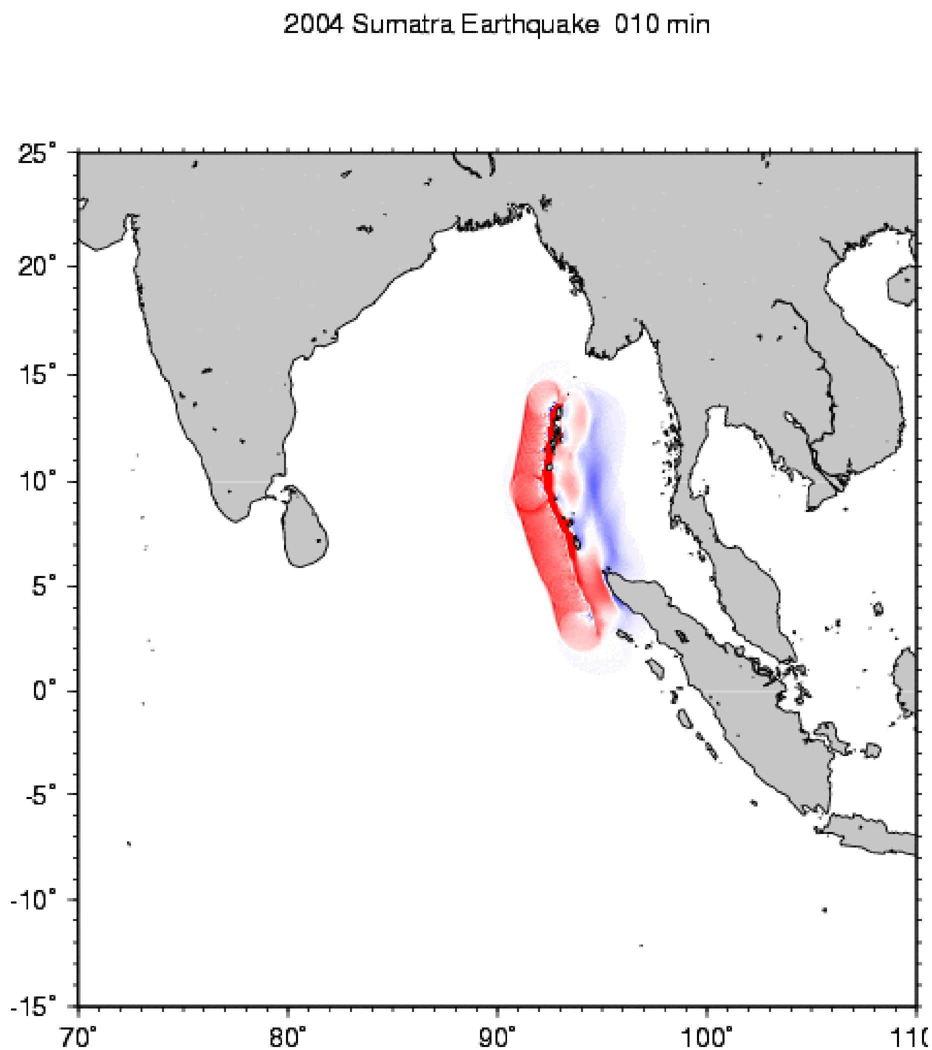


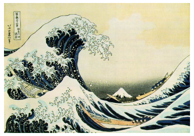
The 26th December 2004 Tsunami - Underwater topography near epicentre





Simulation from Japan

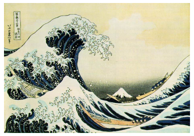




Animation from NOAA, USA

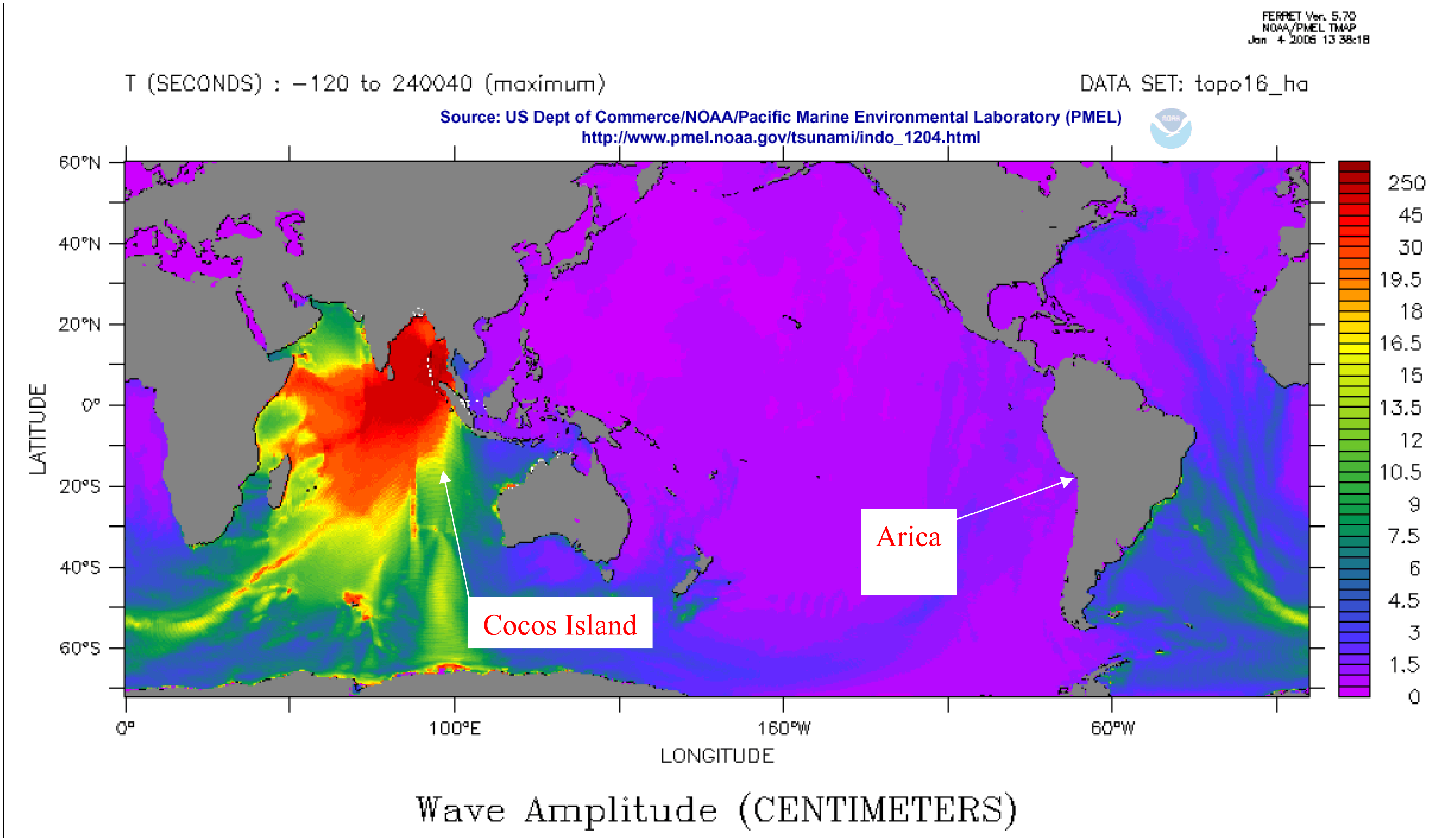
Not active on Internet site

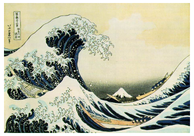
Banda Aceh – before and after



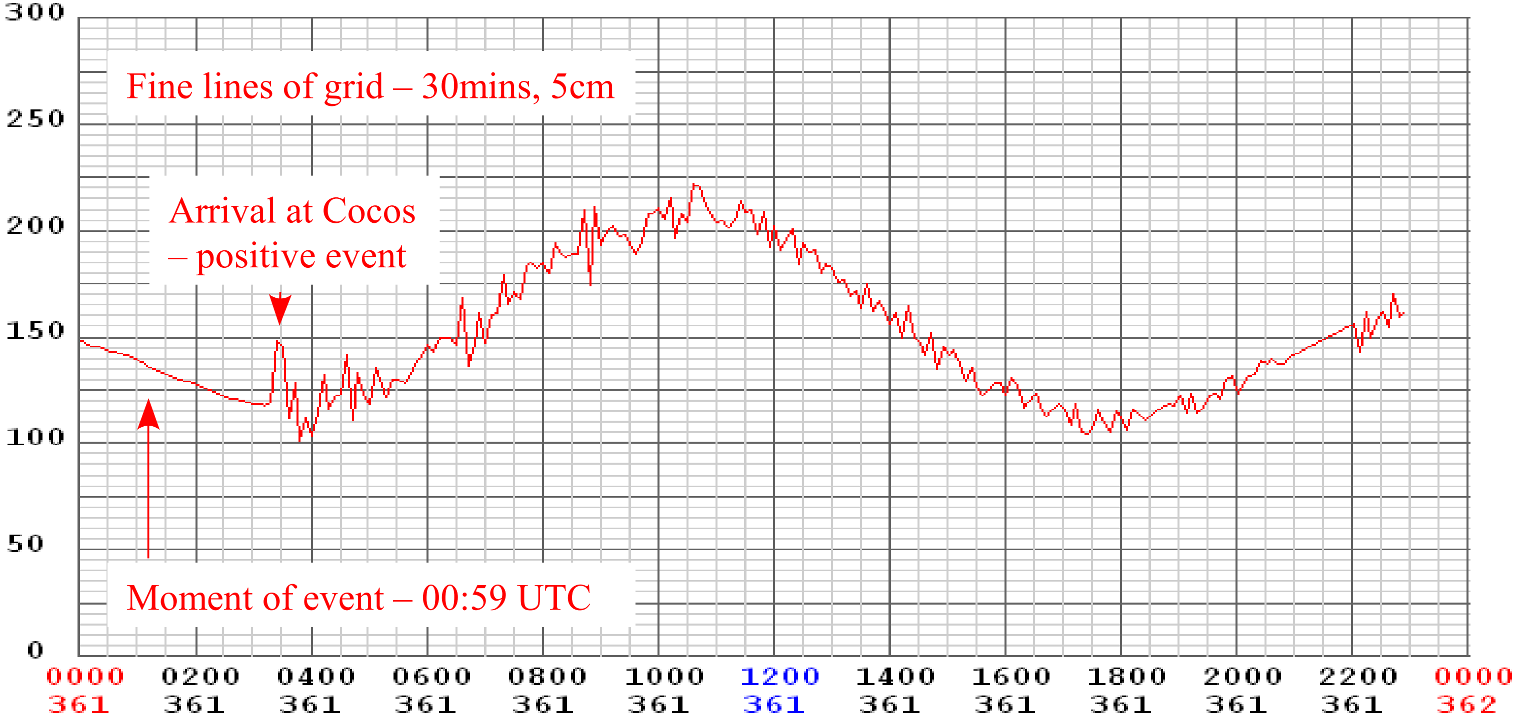
Sri Lanka – Kalutara Beach

Maximum wave height



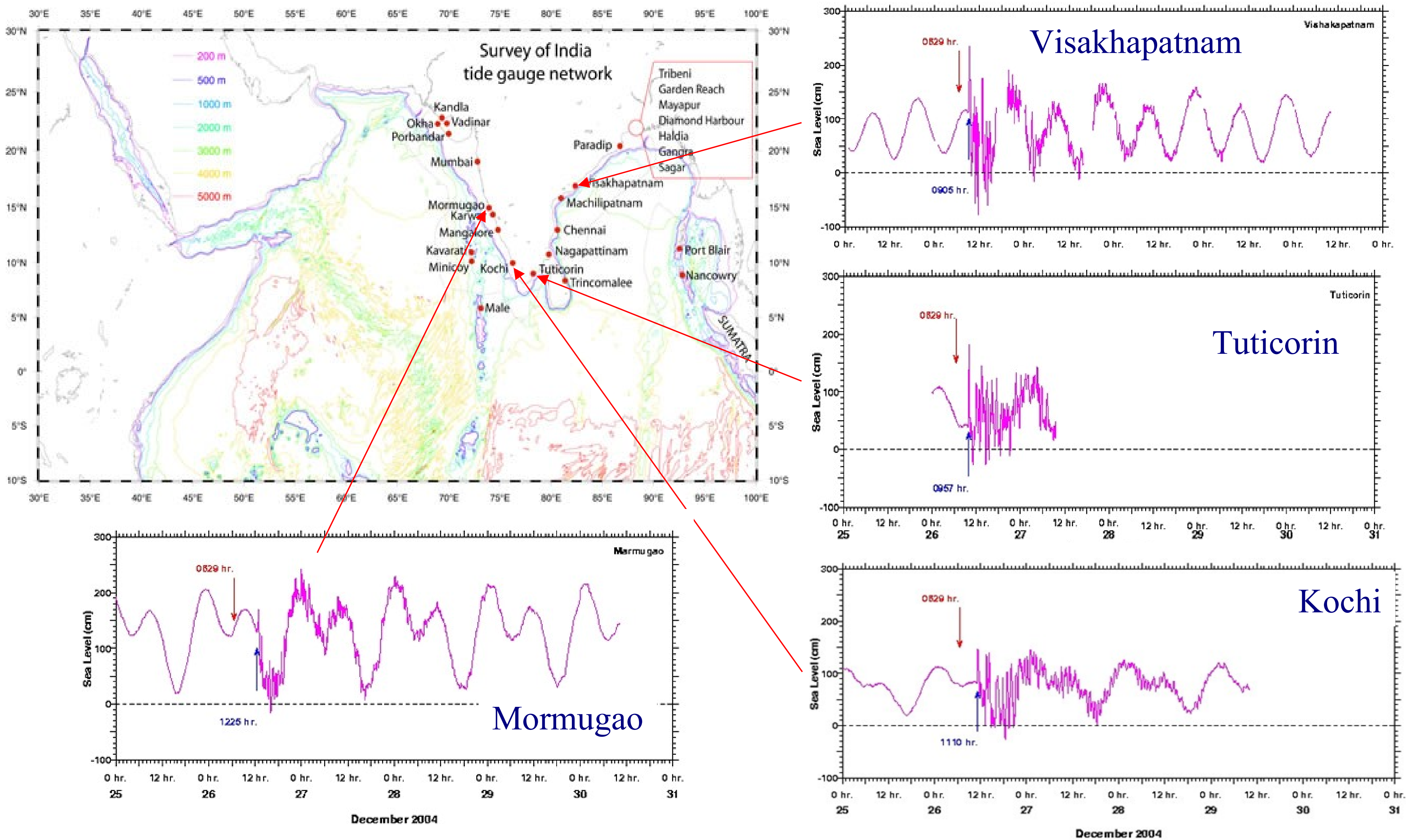


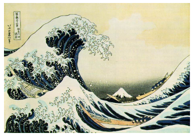
At Cocos Island – isolated island due south of the epicentre



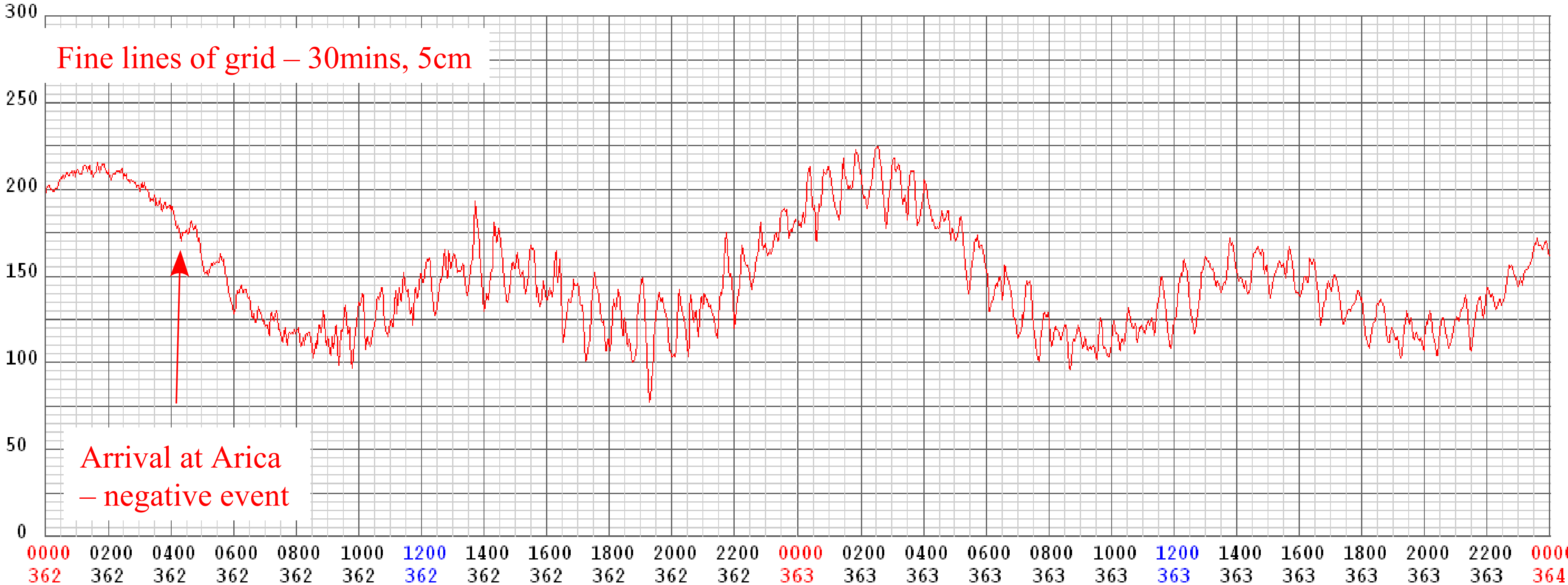
- Height of rise 30cm
- 2 hours after the initial shock
- The Indian Ocean seems to have rung like a bell for days
- No evidence of an initial recession of the water here
- Notice purity of semi-diurnal tide

National Institute of Oceanography, India – Port Tide Gauge Records

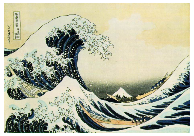




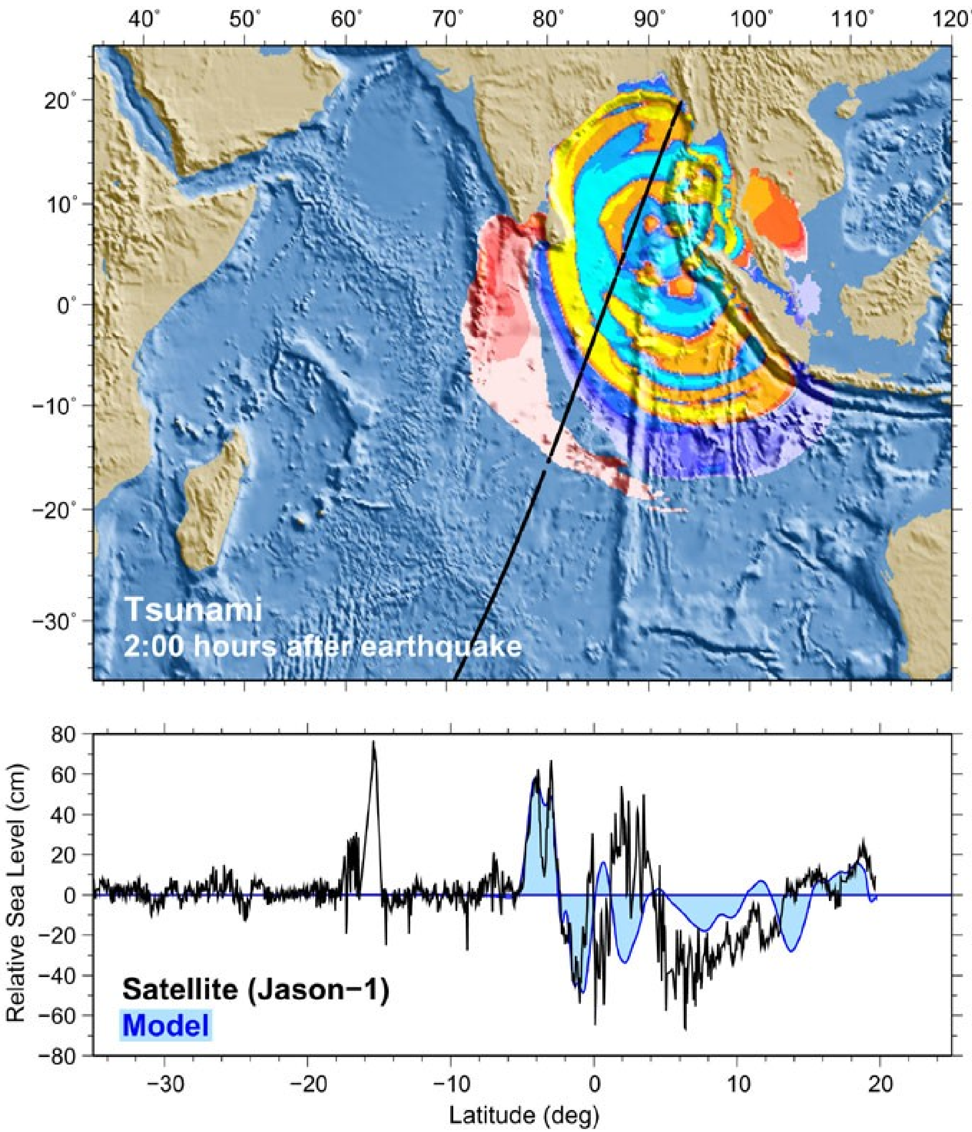
Arica – on the border between Chile and Peru, in a corner

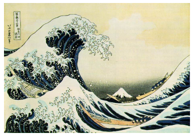


- Wave heights (crest-to-trough) of 70cm
- 26 hours after the initial shock
- The Pacific Ocean seems to have rung like a bell for days
- Notice that the first wave seems to have been one of depression
- Notice greater complexity of semi-diurnal tide



Satellite observations and comparison with numerical simulation





Some phenomena that have not been explained …

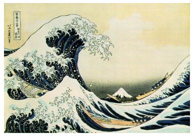
Why has it often been reported in Japan that a fierce wind blew just before a tsunami arrived?

????????

Why are there so many reports that often the first obvious warning of a tsunami is when the sea recedes dramatically, leaving fish flapping on the former seabed, and people go down to investigate and profit, and then the REAL tsunami comes in ...?

Evidence:

- Classical Greek and Roman writings
- the second photo we saw of Kalutara beach in Sri Lanka
- Numerous other reports of the recent tsunami
- The tide gauge recording of Arica in Chile



Possible explanations for negative first wave (1)

Does the wave speed depend on wavelength such that the tsunami waves actually travel as a *group* such that individual waves travel through the group and in 50% of cases the trough arrives first?

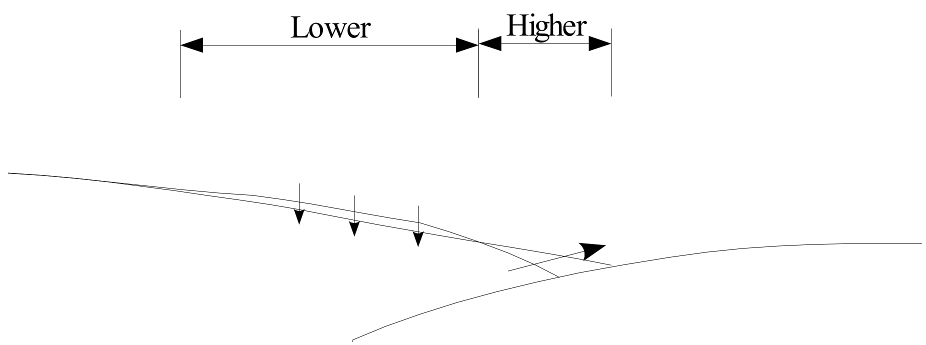
Conventional thinking (all tsunami waves are long such that their velocity is independent of wavelength and all waves will travel at the same speed) suggests this is not the answer.

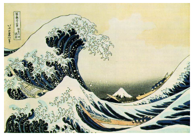
Does the subduction mechanism mean that in one direction the first wave generated is one of depression, and in the other one of elevation?

Confusing – remember the trough at Sri Lanka but the positive wave at Cocos Island.

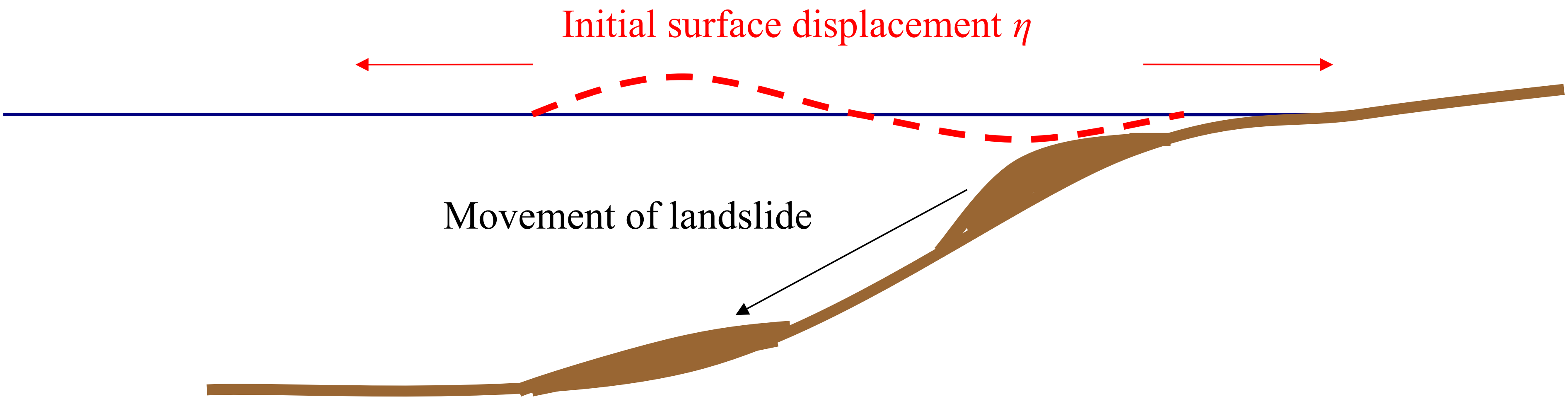
Can we appeal to mass-conservation and energy arguments?

Large lateral movement at toe ~10m; Typical slope ~1%; Increase in elevation at toe 0.1m; Decrease in elevation behind toe to provide the mass that has moved forward rather than up, and hence a general decrease in the water level?

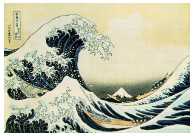




Generation by submarine landslide – after Baines

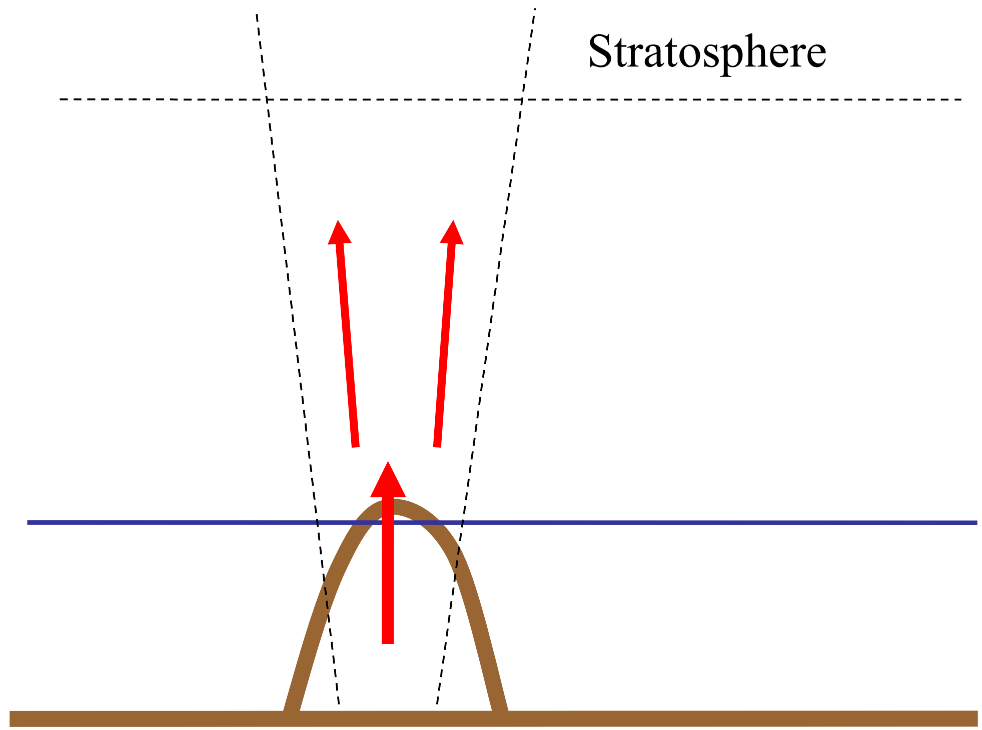


- Submarine landslides may be rapid events, but are not instantaneous.
- We would expect an initial displacement resembling that shown, which will result in a wave of depression propagating onshore, followed by a wave of elevation.
- This would explain the long period of tsunami

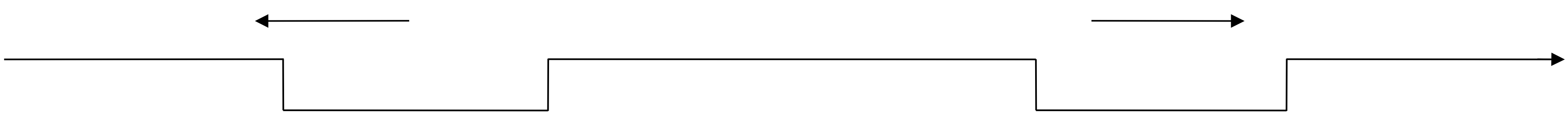


Generation by volcanic eruption – after Baines

For example, the Krakatoa eruption on 26 August 1883, in which an island (with most of the mass below the surface) was blown into the stratosphere.



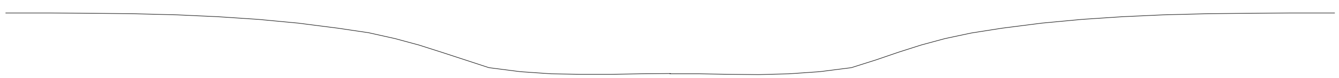
Net effect (shown in 1-D) :



Possible explanations for negative first wave (2)

Energy – rather than being so prescriptive, can we just say that after all the movement of the rock, it is likely, while strain energy might have provided some of that necessary for the motion, that the potential energy of the rock mass will provide some? The potential energy will be less afterwards than before, it will generally have slumped, and hence the water surface too will have dropped.

Instantaneous profile at tsunamigenesis



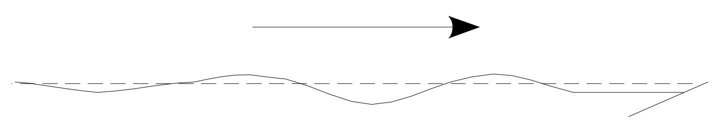
But, the initial conditions can not satisfy those precisely needed for a uni-directional travelling wave solution

Depression wave starting out

Part of wave travelling in the other direction

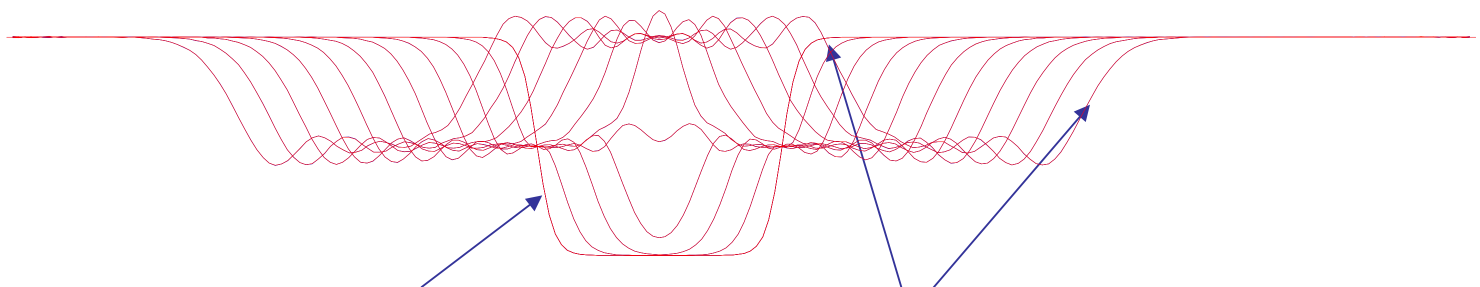
The original site has filled with water from surrounds. Now two waves of depression travelling in opposite directions

Now, after a long journey, the harmless depression wave has reached the shore, but at the rear, the elevation part has split into a train of higher waves because of the effects of finite depth, and they are now about to wreak havoc



Generation of a negative wave

The generation of an initial negative wave (simulated by numerical solution of the exact irrotational incompressible equations)



Initial "square wave"

Subsequent wave of half the amplitude travelling to right (as well as one to the left), including oscillatory waves due to finite length effects

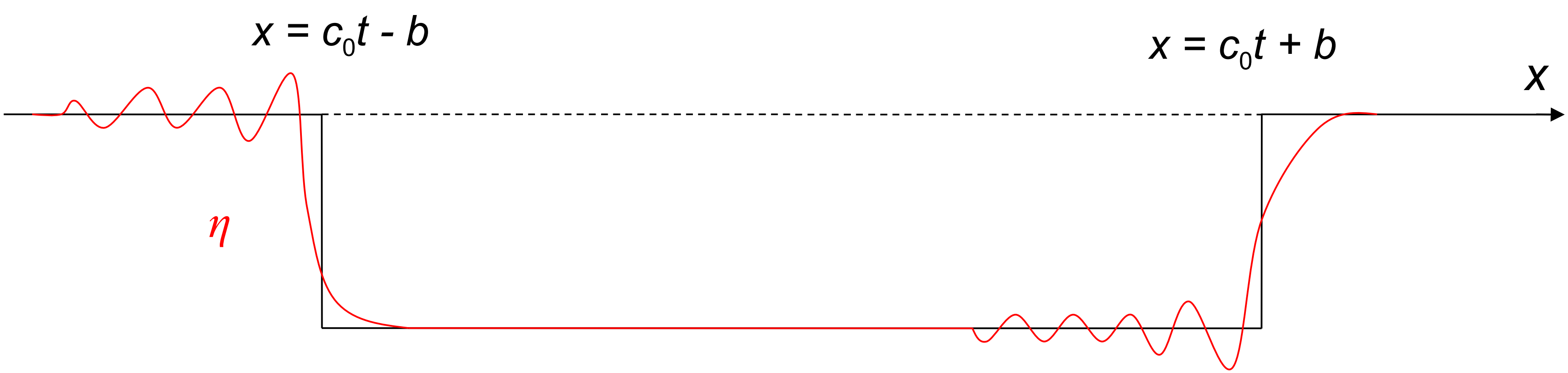
Baines' analytical solution for the propagation of a weakly dispersive trough

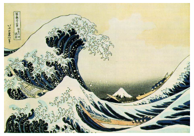
If we solve the KdV equation omitting the small nonlinear term for an initial square wave, namely Generation of a negative wave

$$\eta_t + c_0 \eta_x + \frac{1}{6} c_0 d_0^2 \eta_{xxx} = 0$$

the solution is obtained in terms of Airy functions

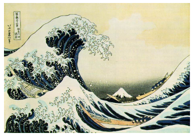
$$\eta_x = -\frac{a(\pi/2)^{1/2}}{(c_0 t d_0^2/2)^{1/3}} \left[A_i\left(\frac{x+b-c_0 t}{(c_0 t d_0^2/2)^{1/3}} \right) - A_i\left(\frac{x-b-c_0 t}{(c_0 t d_0^2/2)^{1/3}} \right) \right]$$





To summarise:

Hence in cases where the source is not too small, the propagating disturbance initially reflects the shape of the source. However, as the wave progresses the longest components of the disturbance begin to lead, and arrive first. If the overall effect of the source is to create a net depression of the sea floor, a wave of depression will dominate the initial disturbance arriving at distant locations.

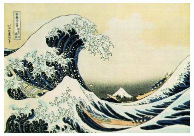


Propagation

Characteristics of tsunami approaching a shore

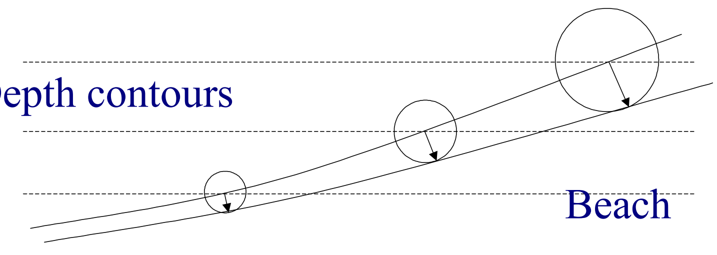
Characteristics of a wave of period 30 minutes

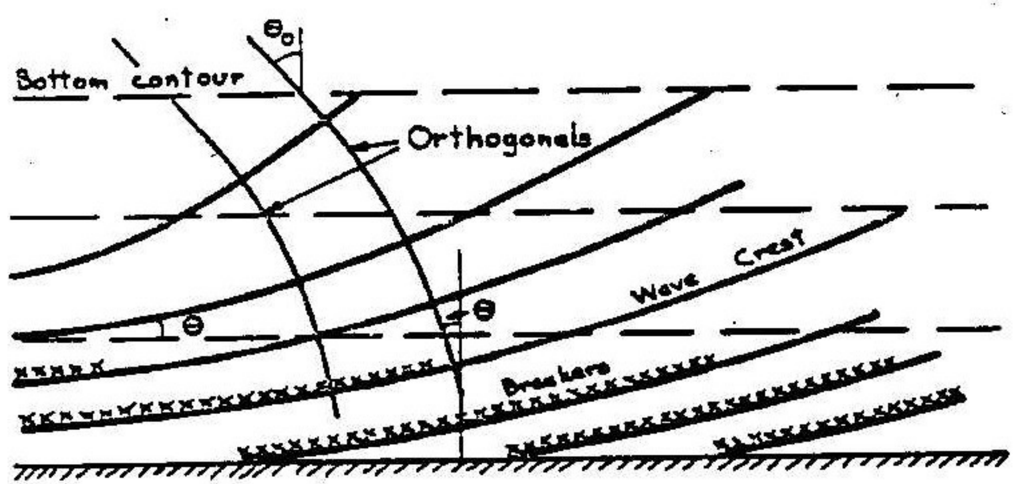
Water Depth	Length of wave	Height of wave
5 km	400 km	0.5 m
10 m	20 km	2.5 m
The wave will break in this interval		
1 m	6 km	4.2 m



Tsunami propagation – refraction of waves

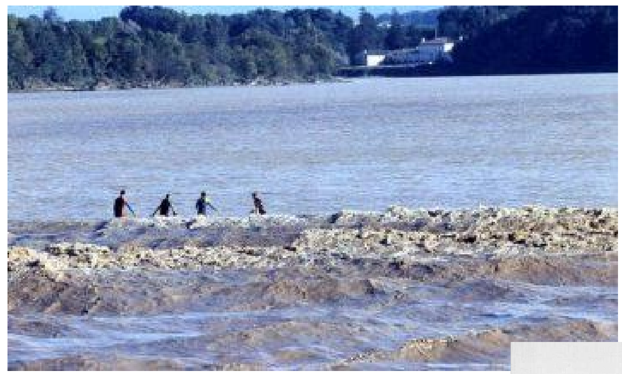
- The basic rule for long waves is that $c = \sqrt{gh}$
- Waves are faster in deeper water and slower in shallower water
- Leads to refraction, or the bending of waves as they enter shallow water
- Often they are still not exactly parallel to the coast
- Leads to littoral drift – sand moving along the beach





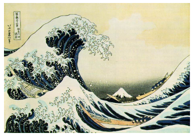
Models of a tsunami in shallower water – Tidal bores

The River Severn



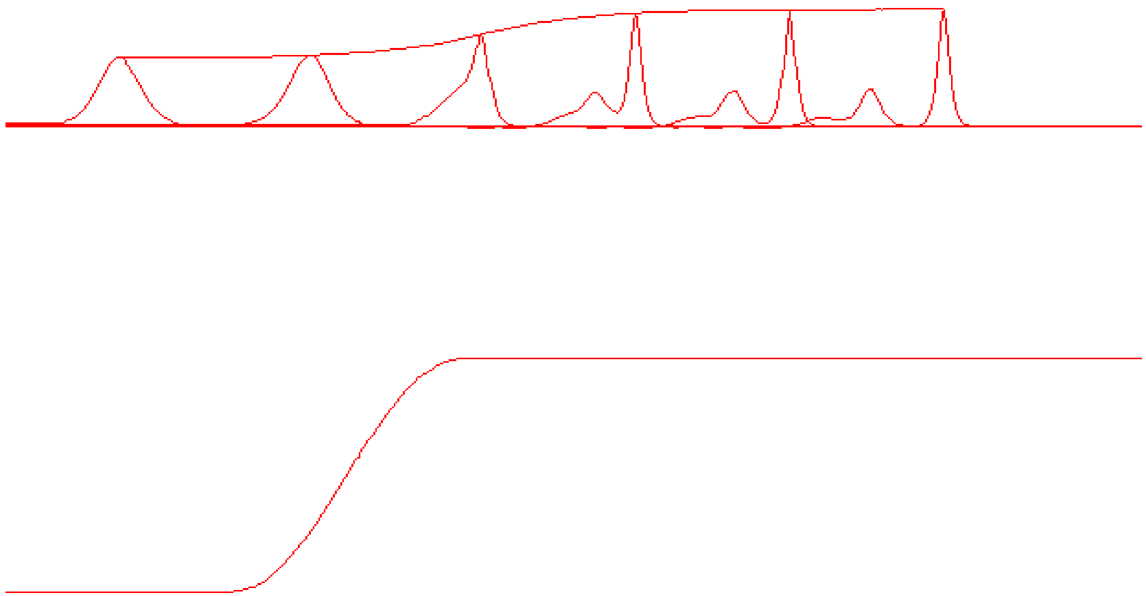
The Dordogne

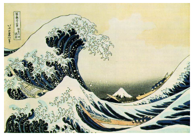
The Seine



Types of wave behaviour in shallow water (1)

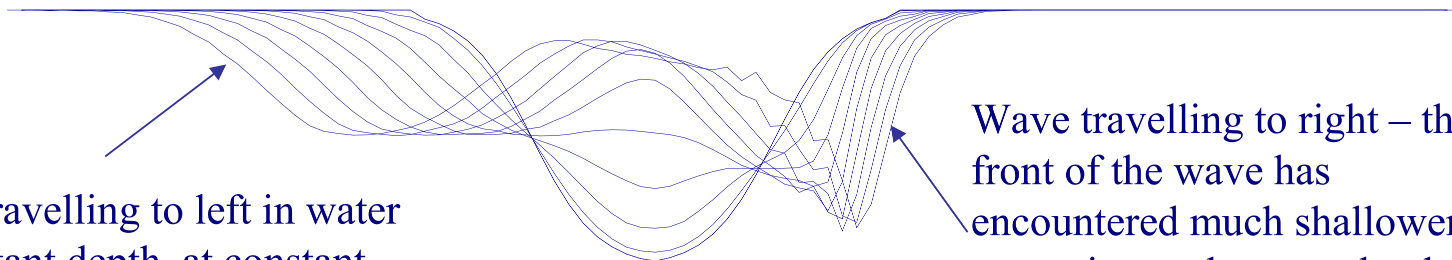
Splitting of the tsunami into several solitons as it crosses a shelf – from numerical solution of the full equations, but this phenomena can be explained by weakly nonlinear-dispersive scattering theory.





Steepening of wave of depression on shelf

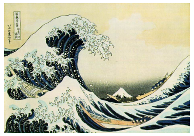
Previously our numerical solution of the exact equations for the wave of depression was for a flat bed. Now the rightwards-travelling wave is passing over a shelf – note the steepening, because the front of the wave is travelling slower than the rear. In real situations there will always be a tendency to this effect: the downrush on the beach could be very sudden



Wave travelling to left in water of constant depth, at constant speed

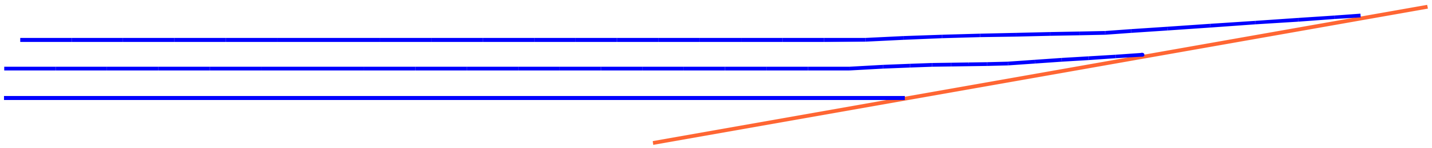
Initial wave

Wave travelling to right – the front of the wave has encountered much shallower water, it travels more slowly than the rear, which has lead to a shock here

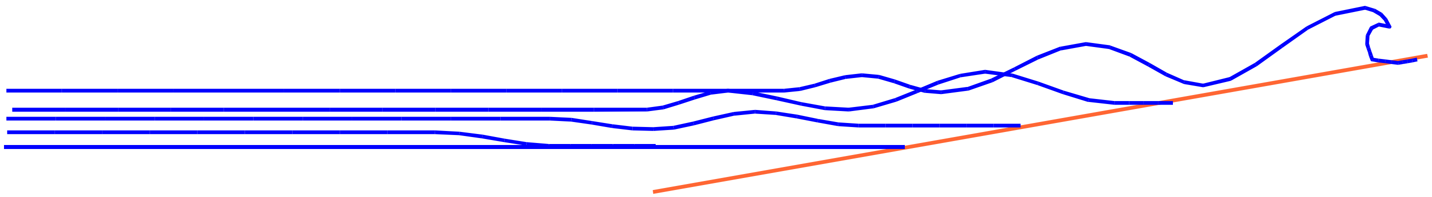


Types of tsunami behaviour in shallow water (2)

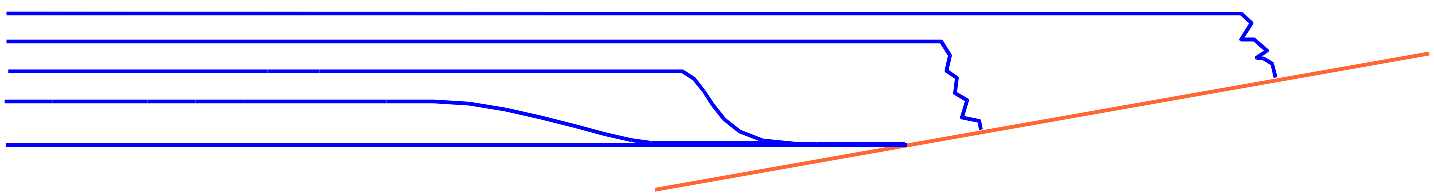
Height < 2 m, wave does not steepen appreciably, more like a gradual rise and fall of the water on the beach

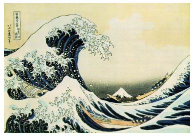


Height 2-5 m, wave steepens, then splits into a number of waves like an undular bore



Height > 5 m, wave steepens near the shoreline, sudden breaking and formation of a bore





A combined picture – the process as a whole

From numerical solution of the full equations, again