Long-Range Ocean Acoustic Propagation, T-Phases, Earthquakes and Hydro-Acoustic Networks

Ralph A. Stephen

Woods Hole Oceanographic Institution

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Motivation

Active collaboration between the CTBTO-IMS and the broader worldwide scientific community has the potential to benefit all participants.

Benefits to the CTBTO-IMS

An improved understanding of the role of bottom interaction in long-range ocean acoustic propagation and of the coupling of seismic energy from the deep seafloor into the SOFAR channel will help the CTBTO to optimize the results from the IMS hydro-acoustic network.

- improved locations of events
- improved discrimination of explosions from earthquakes
- improved estimates of the magnitude of events

Benefits to the Broader Scientific Community

The IMS hydro-acoustic network provides an excellent worldwide database that will be a valuable resource for research in:

- marine geology
- marine biology
- weather and climate
- oceanography
- seismology
- cryo-seismology and glaciology
- tsunamis

The IMS hydro-acoustic database will complement data from other permanent and short-term oceanic seismo-acoustic networks.

History - Long-range Ocean Sound Propagation - 1960

• Underwater Sound Waves Recorded Through 12,000 Miles—Sound waves generated by depth charges fired by the Lamont Geological Laboratory's research vessel *Vema* at a point off the coast of Australia, were picked up at the Laboratory's Bermuda Station. This indicates a travel of 12,000 miles for recorded waves, or nearly halfway around the Earth. This is almost the maximum distance for such reception, inasmuch as the circumference of the Earth is less than 25,000. The travel time was reported to be approximately 144 minutes. The sound waves followed a great circle past the Cape of Good Hope, dropping to depths of about 4200 feet near the Equator; such waves could be picked up only in areas where a great circle path traverses deep water. The instruments at the Bermuda Station are at a depth of 4200 feet. Scientists believe that an underwater atomic blast fired near the sound channel could be picked up by the Station.

The first observation of ocean sound propagation half-way around the earth and the suggestion that underwater sound can be used to detect an underwater atomic blast.

The source was a 300lb depth charge.

In: "Notes and Personalia"- Transactions of the American Geophysical Union, v41, p670, 1960.

Long-range Ocean Sound Propagation - 1960 - cont'd

The principle of SOFAR (Sound Fixing and Ranging), demonstrated by Maurice Ewing, Director of Lamont Observatory, during World War II, has been considered by many to be the most important discovery in communications since radar. For instance, aircraft or ships in distress at sea might be able to signal their position by means of small depth charges. The method was perfected by Ewing in 1945, when sound had been transmitted from Dakar, West Africa, to Bermuda—a distance of 3000 miles—in 62 minutes. The recent recording of shots for a distance of 12,000 miles is considered particularly remarkable because there is no clear, direct path in the water between the firing and reception points. John I. Ewing, also a member of the Observatory staff, pointed out that the sound waves had to follow paths around islands and through shallow areas.

But the propagation mechanism around islands and through shallow water was not understood – and still isn't!

T-phase Excitation by Earthquakes - A Primer

T-phases are the third (tertiary) principal arrival after an earthquake that is observed on island and coastal seismic stations (that is, after the primary (P) and secondary (S) waves).

They have at least part of their propagation path in the ocean sound channel.

T-phases are readily observed on hydrophones moored in the ocean.

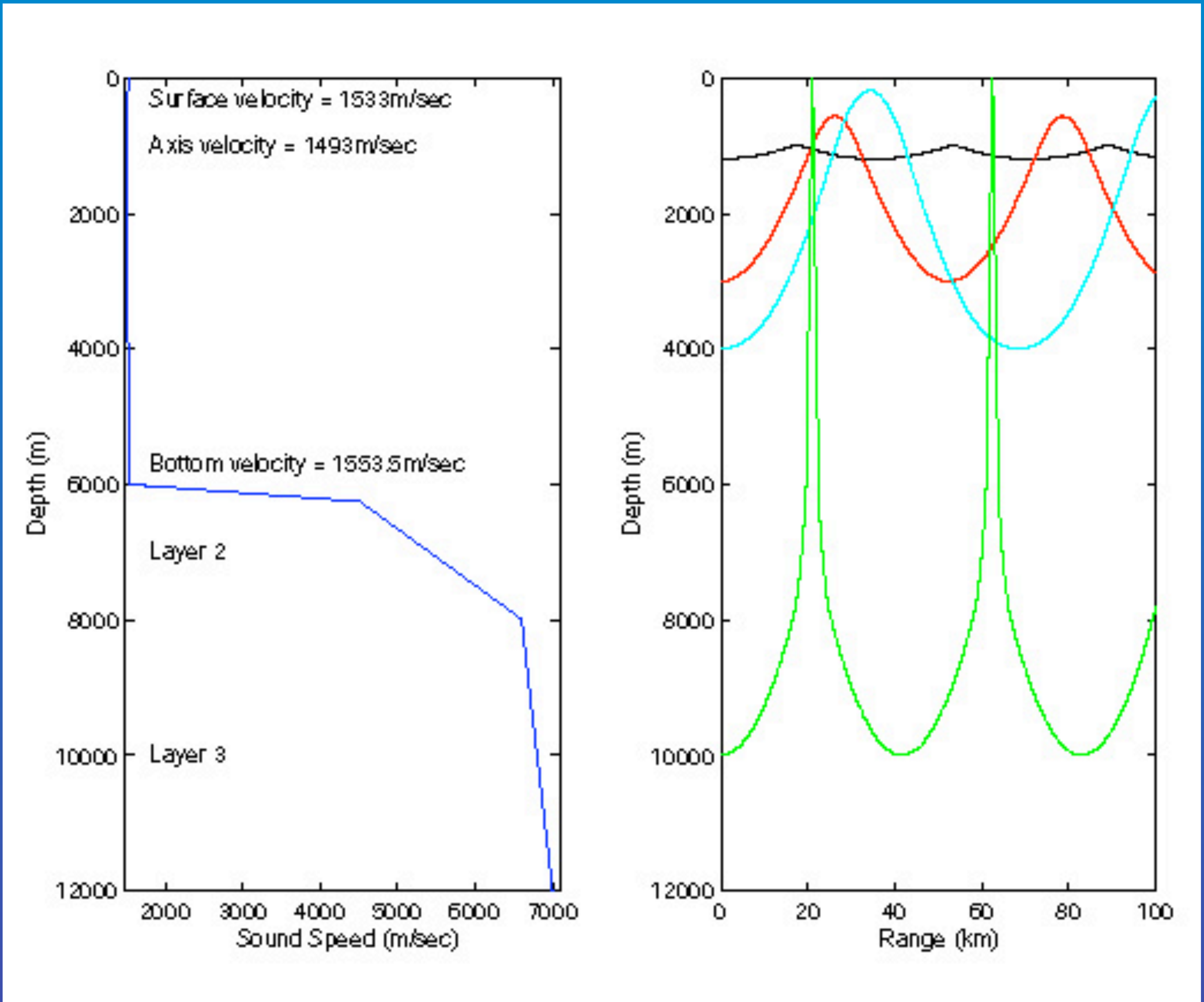
Hydrophone networks detect much smaller earthquakes over basin scales than land-based networks - events down to mb 3.0 compared to mb 4.5.

Hydrophone networks detect many more earthquakes than comparable regional scale seismic networks.

Since T-phases travel at lower velocities they result in much more precise locations of events.

An excellent review of T-phases is given by Okal (2008).

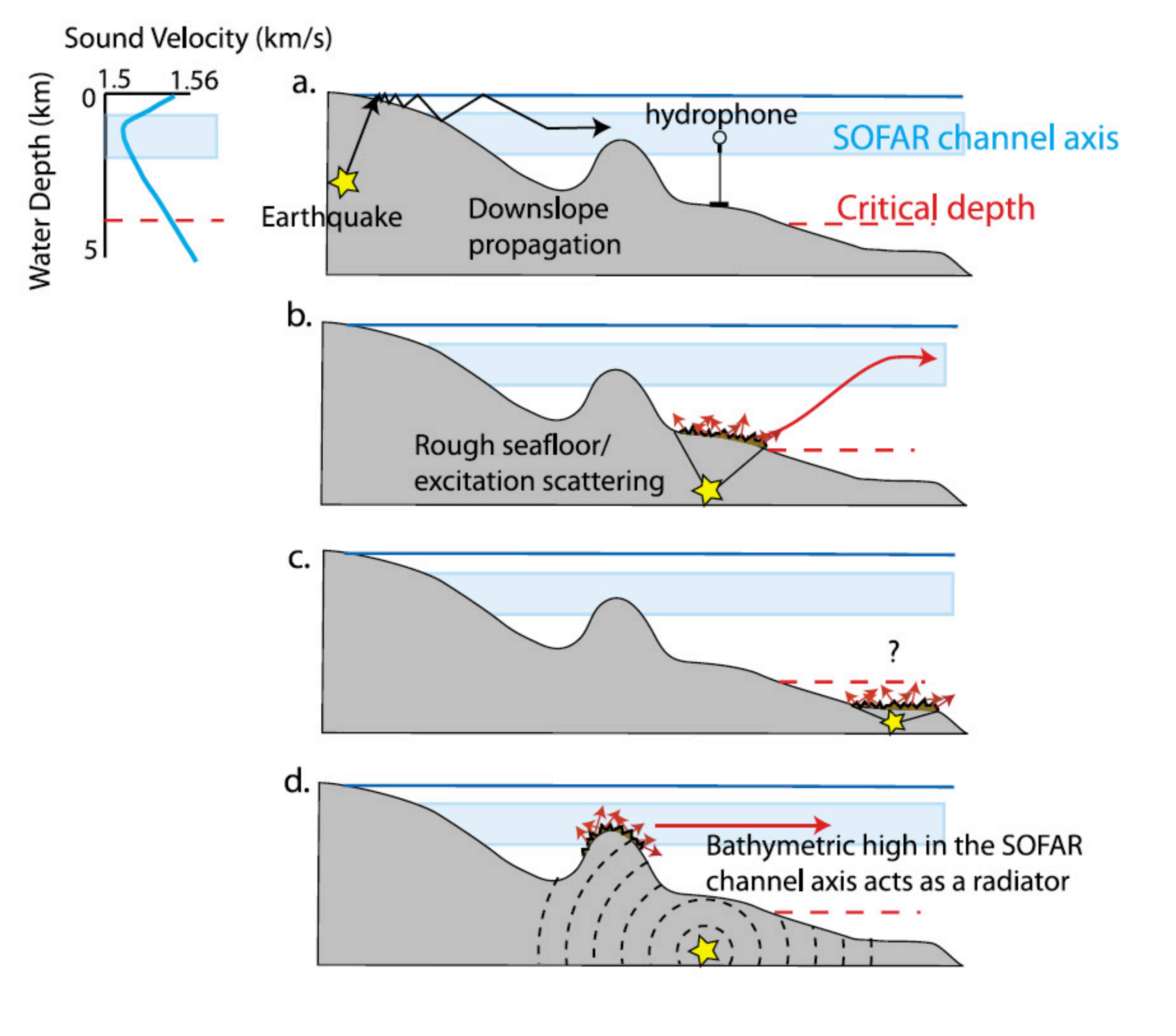
The "T-phase Problem" for Earthquakes



Ray paths from sources in the high velocity crust are too steep (low incident angles) to couple into the sound channel.

Sound channel propagation requires flatter (high incident angle) rays.

T-phase Excitation Mechanisms



a. Downslope propagation

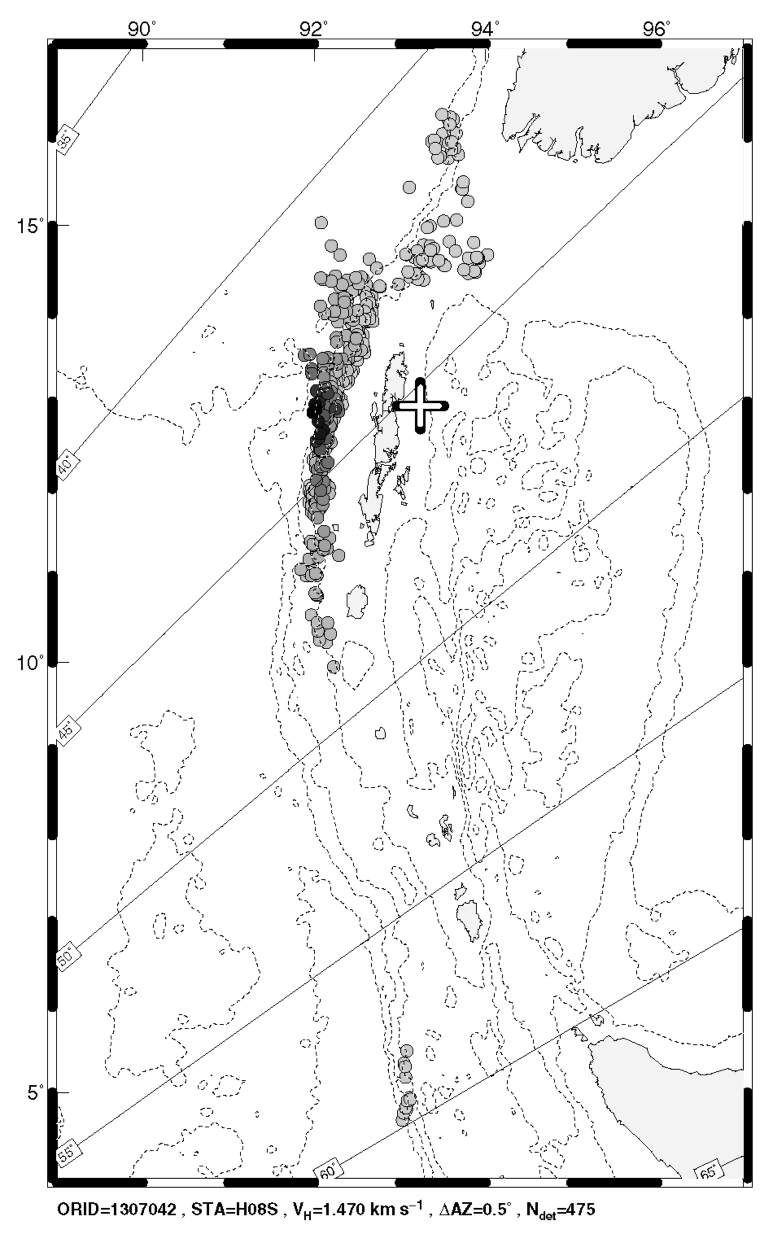
b. Rough seafloor scattering in the sound channel

c. Unexplained excitation for the seafloor below the sound channel

d. Bathymetric radiators

Figure from Williams et al (2006)

Bathymetric Steering



Points of T-wave excitation (circles) for an earthquake (Mb=5.7, cross) near the Andaman Islands as observed from the IMS hydro-acoustic station at Diego Garcia (South) in the Indian Ocean.

Zones of T-wave excitation are quite well constrained by the shape and strike of adjacent topographic and bathymetric features.

Figure from Graeber and Piserchia (2004)

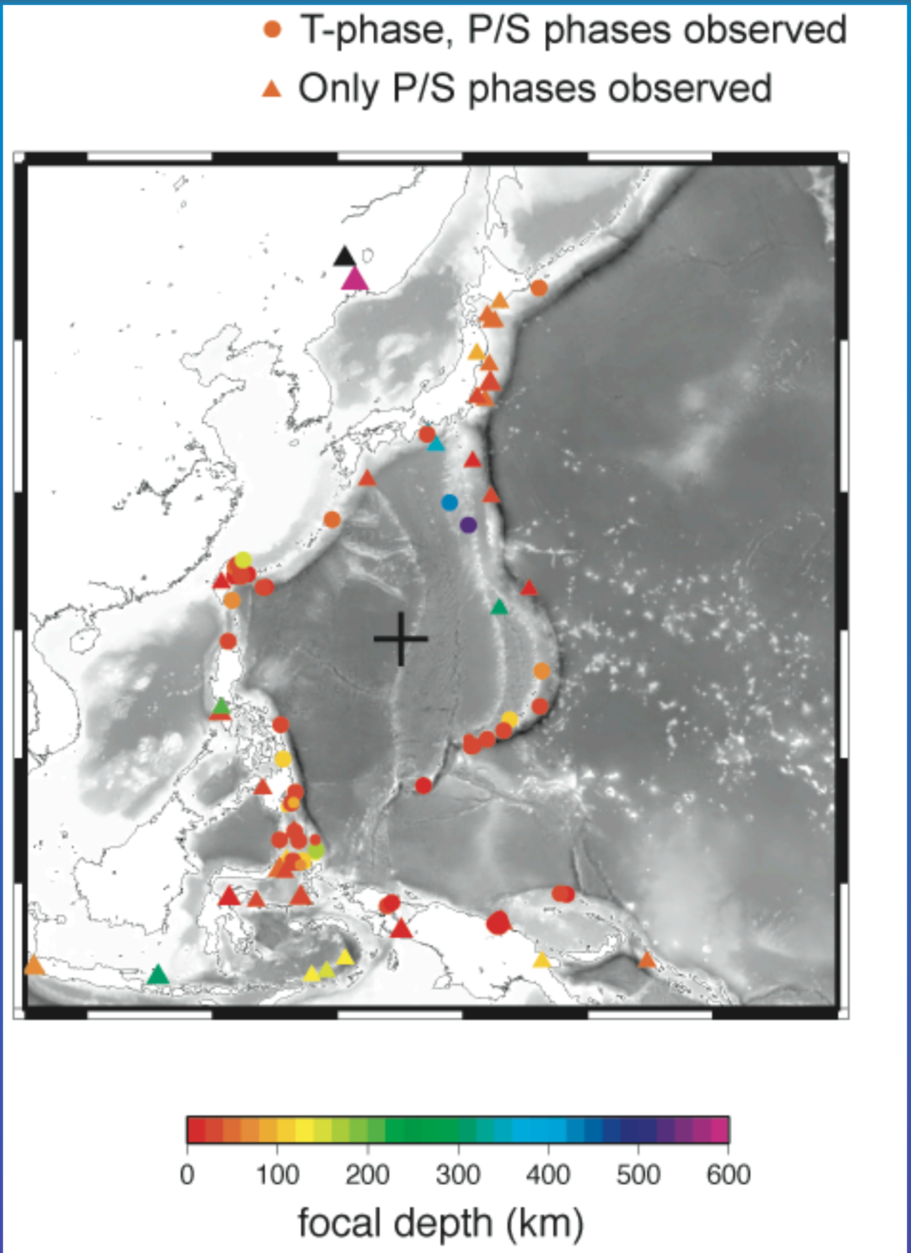
What do T-phases and ocean acoustics have in common?

T-phases from earthquakes beneath the seafloor propagate very efficiently in the sound channel. But we do not understand the physical mechanism that gets vertically propagating energy from below the seafloor into horizontally propagating energy in the ocean sound channel.

In long-range sound propagation experiments in ocean acoustics using point sources in the sound channel, we observe a different (unexplained) arrival structure in the deep shadow zone beneath the sound channel than we do in the sound channel (Stephen et al (2009) and poster at this meeting).

The two problems are reciprocals of one another.

T-phases Observed in Boreholes Beneath the Deep Seafloor - 1



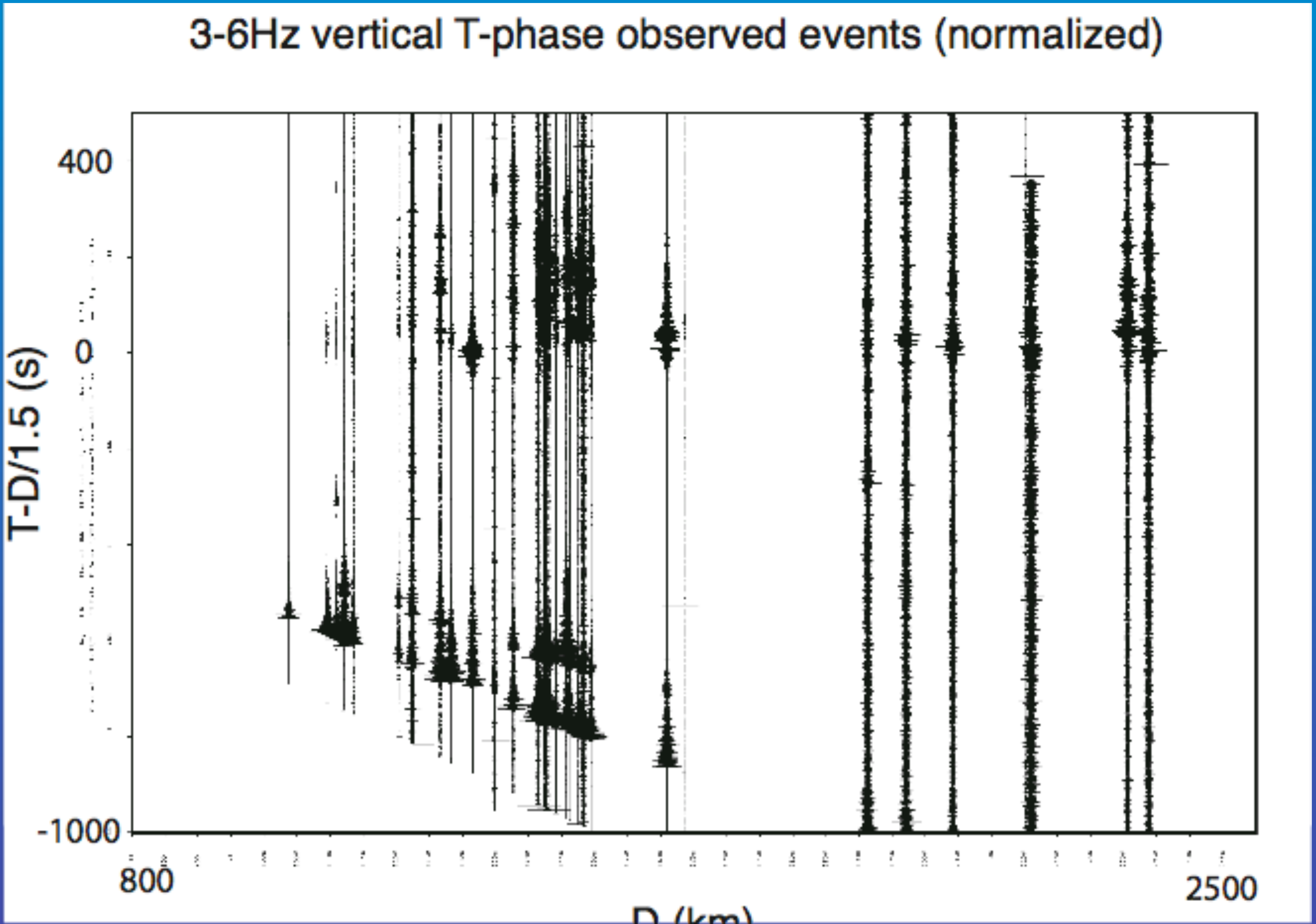
Philippine Sea (WP-1)

Borehole Seismic Installation

Water Depth (m)	5721
Sediment Thickness (m)	521
Sensor Depth (mbsf)	561
ODP Leg	195
ODP Site	1201

From Araki, 2004, T-phase observed at deep seafloor boreholes

T-phases Observed in Boreholes Beneath the Deep Seafloor - 2



Complementing Tsunami Warning Systems

A hydro-acoustic solution to the local tsunami warning problem

Salzberg, D. H.
American Geophysical Union, Fall Meeting 2008, abstract #OS43D-1325

We demonstrate the potential for using the spectral content of T-phases from earthquakes to identify events involves a component of splay faulting. There is significant evidence indicating that splay faulting explains extreme local tsunamis in events with more moderate distant tsunamis. For example, the distant tsunami from the Dec. 26, 2004 Megathrust is fully explained by the primary rupture. However, the local tsunami was significantly (3 to 4x larger) than predicted and 10 minutes early. The discrepancy can be explained by significant rupture along a splay fault approximately 90km west of Banda Aceh. The secondary rupture produces a high amplitude, short wavelength tsunami that is not resolvable seismically, as the softer sediments would produce significantly (1/40th to 1/100th) less seismic radiation than the primary rupture. However, the secondary rupture appears to generate observable hydroacoustic signals. The shallow rupture of the secondary source results in less anelastic attenuation, producing a shallower spectral slope of the T- phase than the much larger primary rupture. The observed signal is the combination of the weaker shallow secondary rupture and the much larger (and deeper) primary rupture. At low frequencies, the primary rupture dominates the spectral shape. At higher frequencies, the weaker shallow source predominates. We are able resolve the dual rupture in the case of Northern Sumatra. This is significant because, in the 378 earthquakes analyzed, only three events showed this pattern for more than 50 seconds; two of those events had anomalously large local Tsunamis: Northern Sumatra and Nias Island. The third event was an Mw 7.6 strike slip fault. It is thus likely that a significantly curved T-phase spectrum is indicative of secondary (possibly splay) sources, and increased likelihood of local tsunamis. A prototype system to identify the signatures of the secondary faulting has been developed and installed at the Pacific Tsunami Warning Center in Ewa Beach, HI.

From Salzberg (2008)

Ocean Thermography and Global Warming

"Acoustic thermometry" can be used to study climate change. Is the Pacific Ocean becoming warmer? Is the integrated sound speed on basin-wide scales increasing?

So far the inter-annual variability is too large to discern a trend.

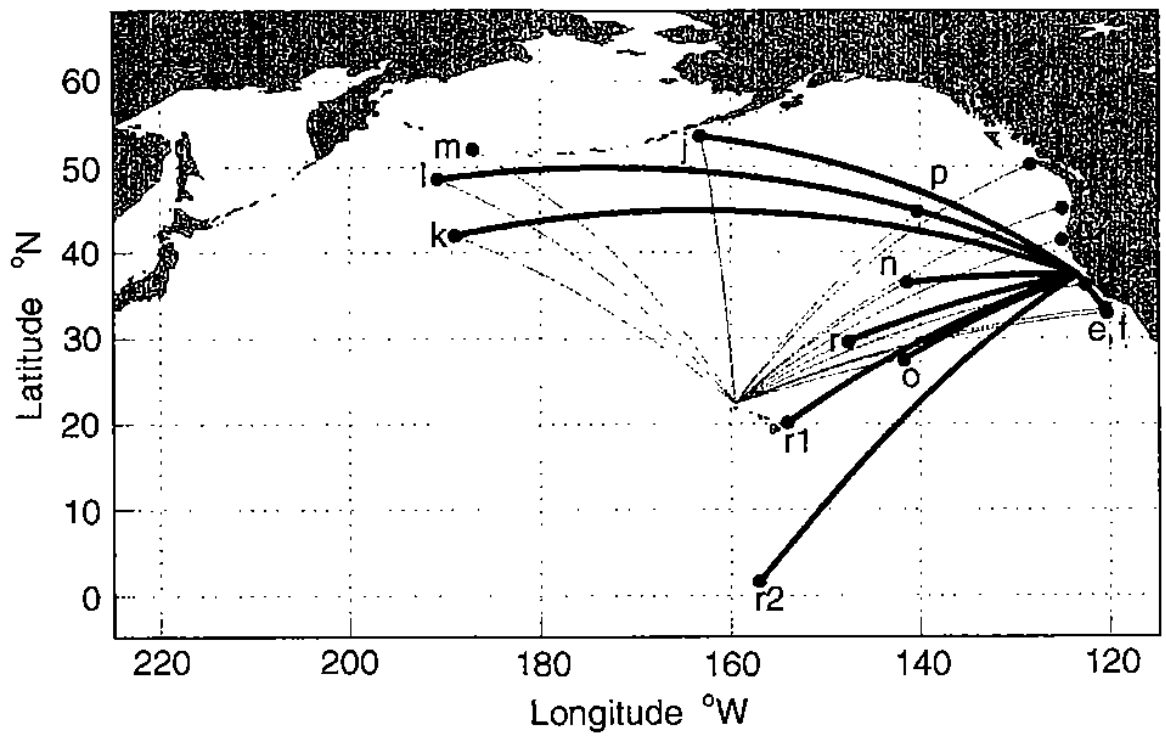
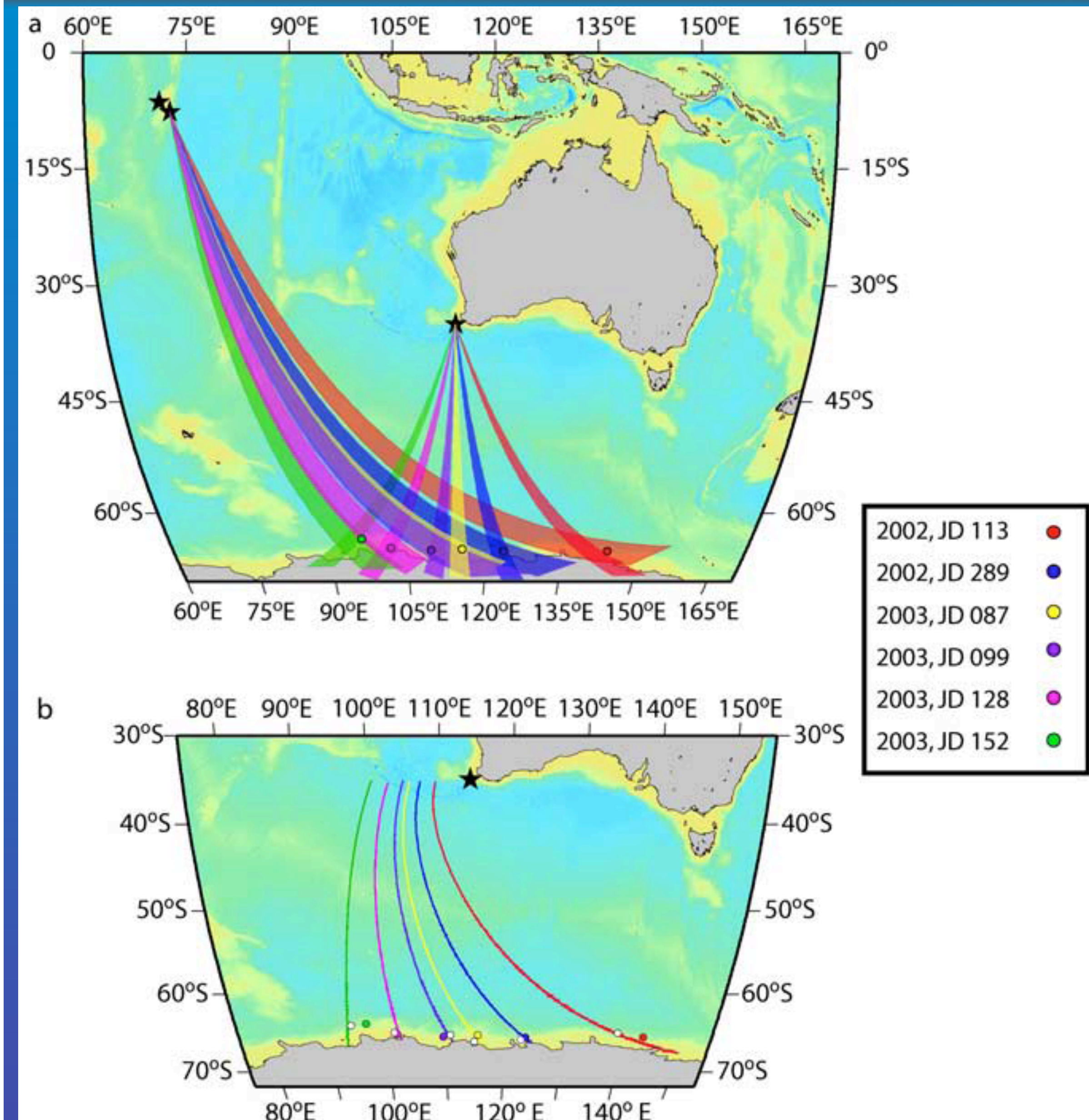


Fig. 1. The ATOC array. The array spans most of the North Pacific Ocean. Acoustic paths to the various receivers from the acoustic source mounted on Pioneer Seamount off the coast of California are shown by the heavy lines, and acoustic paths from the acoustic source off the north coast of the Hawaiian island of Kauai are shown by the light lines. This paper discusses the data obtained from the Pioneer Seamount transmissions; data from the Kauai transmissions are similar.

Figure from Dushaw et al (1999)

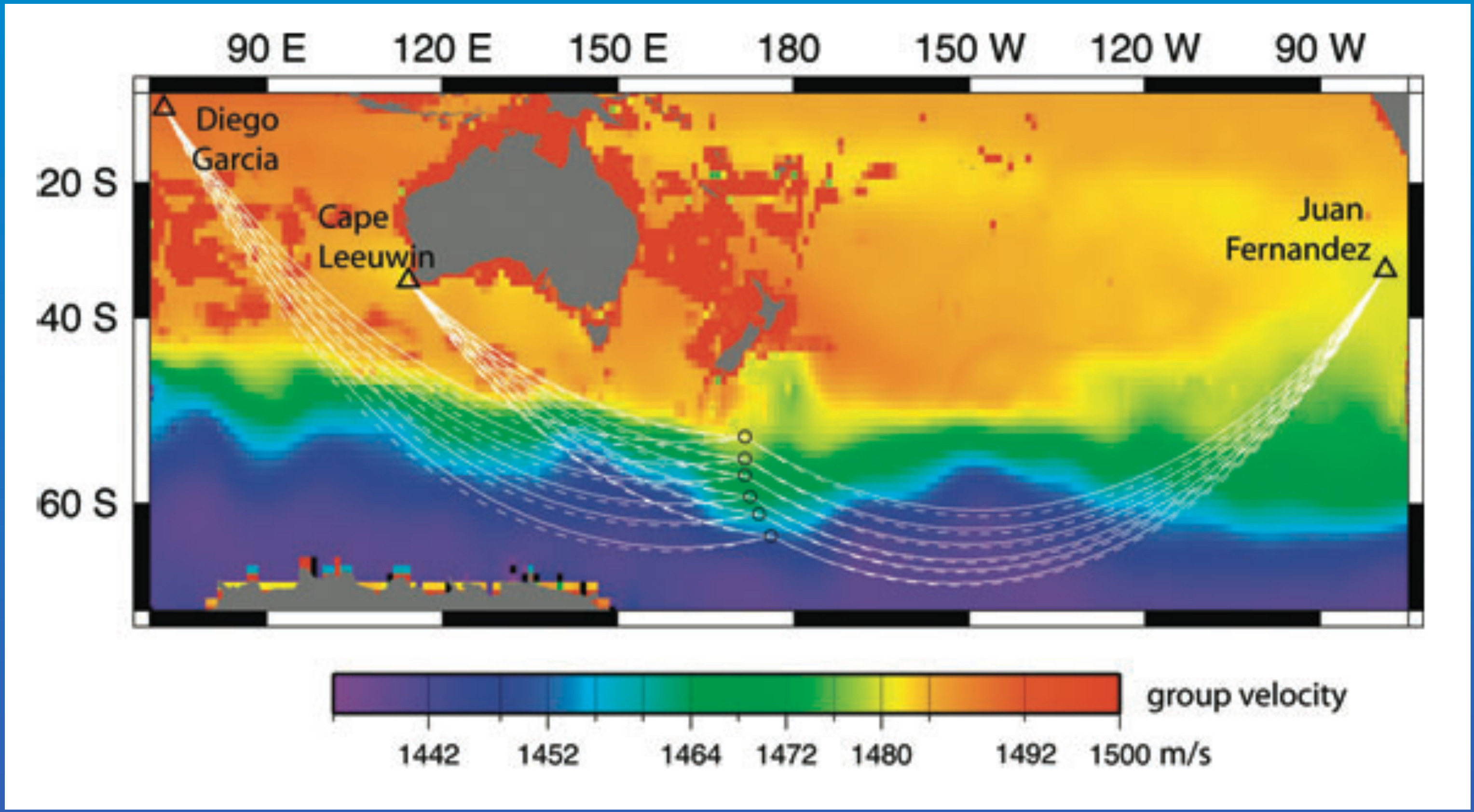
Cryo-seismology - Seismo-Acoustics of Ice Sheets



Harmonic tremor from ice-sheets in Antarctica has been observed at the IMS stations at Diego Garcia and Cape Leeuwin.

From Chapp et al (2005).

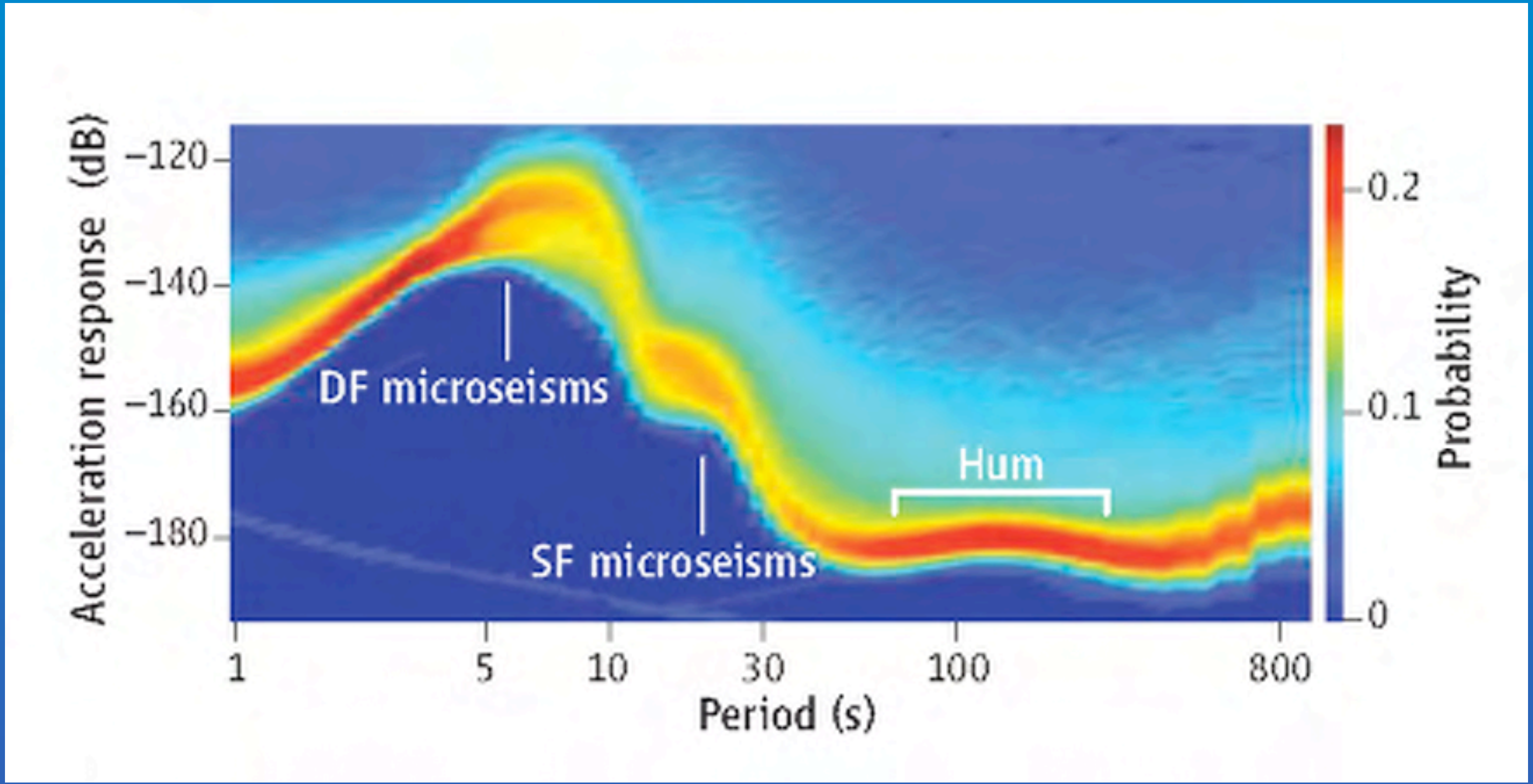
Hydro-acoustic Propagation at the Antarctic Circumpolar Current



Refracted paths at the Antarctic Circumpolar Current (solid lines) are deflected from the geodesic paths (dashed lines).

Figure from deGroot-Hedlin et al (2009)

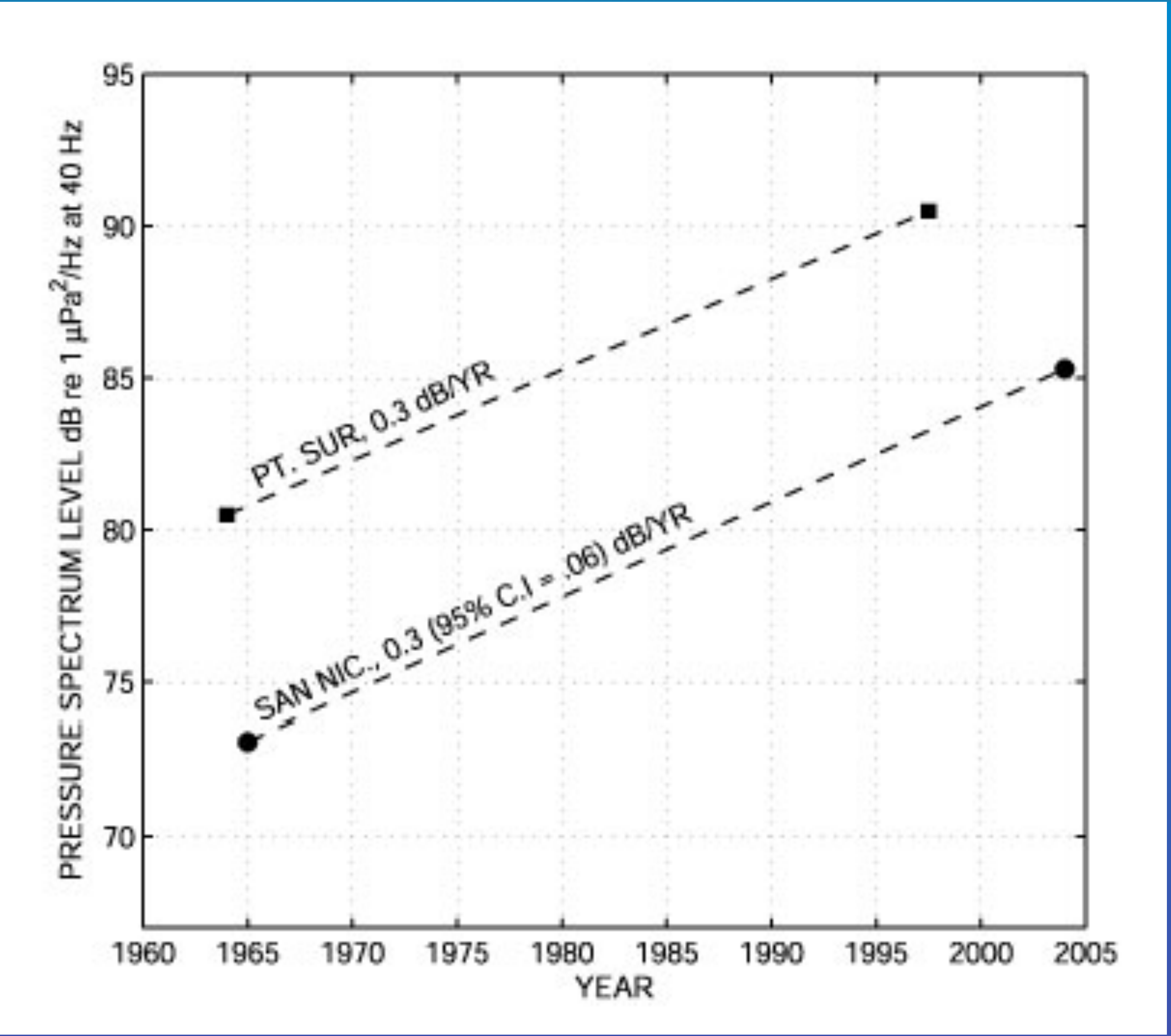
Storm Generated Noise in the Oceans



Oceanographic processes excite seismic waves in the earth. Three examples are double frequency (DF) microseisms, single frequency (SF) microseisms and the Earth's "hum".

Figure from Bromirski, 2009

Marine Mammals and Anthropogenic Noise



Sound pressure levels, here at 40Hz in the North Pacific are increasing at about 3dB per decade due to increased shipping.

How will this affect marine mammals? Will they be able to adapt quickly enough to the increased level of ambient noise?

From McDonald et al (2006)

Submarine Volcanoes and Internal Tides

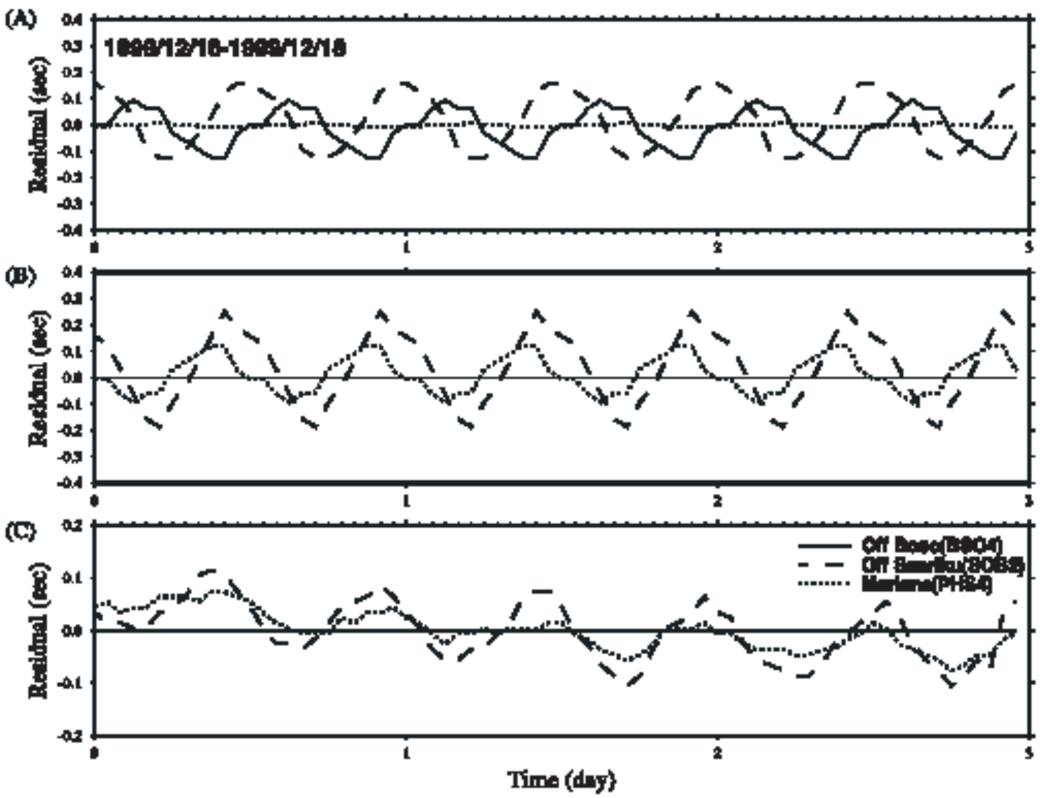
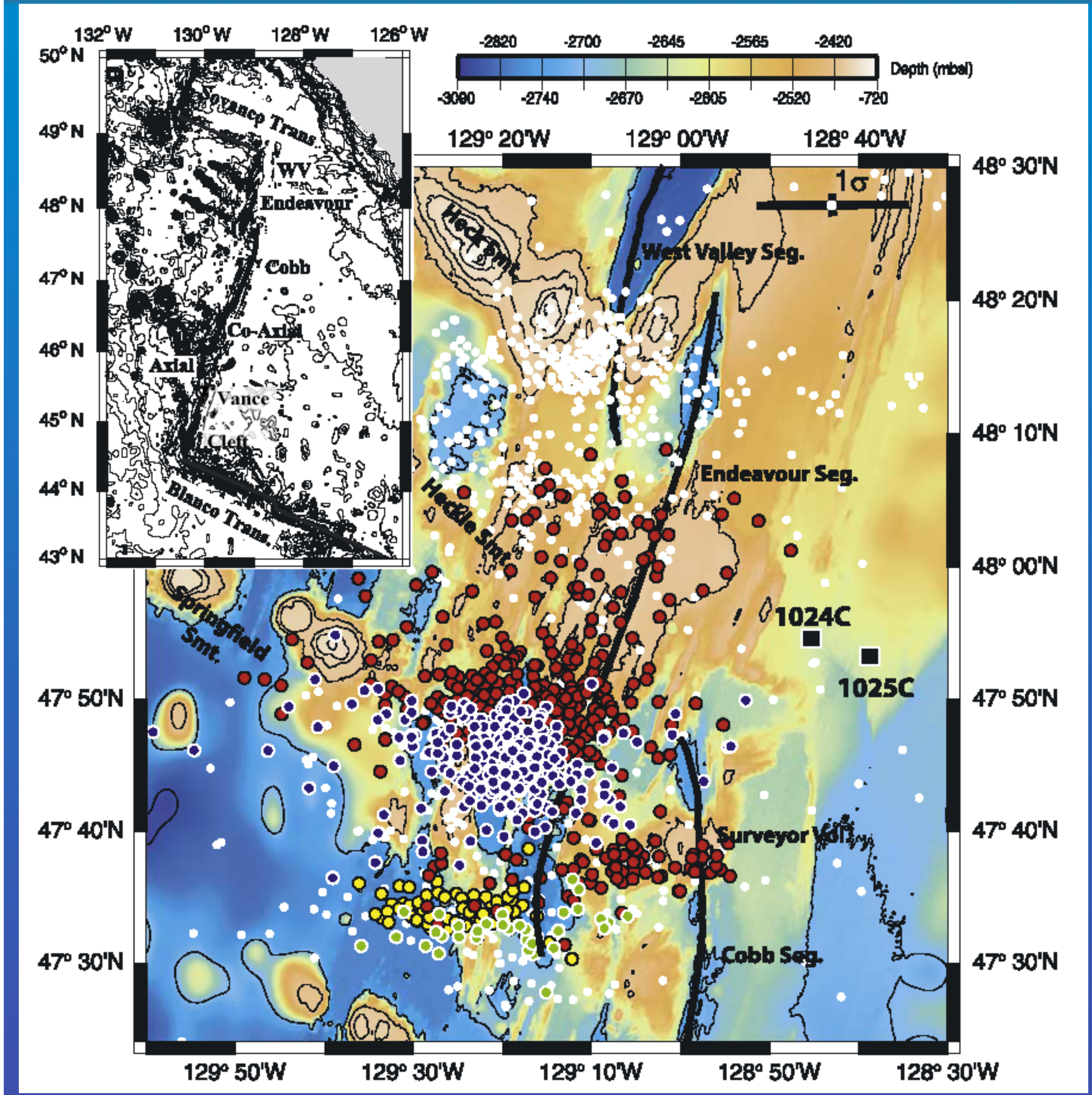


Figure 4. Comparison of the computed and observed travel time variations due to the M_2 internal tide. (a) Computed travel time variations at three stations BSO4, SOB2 and PHS4. (b) Computed differential travel time variations at SOB2 and PHS4 relative to BSO4. (c) Observed differential travel time variations at SOB2 and PHS4 relative to BSO4.

Observations of a three-day long T-wave swarm from an active volcano show the effect of the M2 internal tide on SOFAR channel propagation.

from Sugioka (2005)

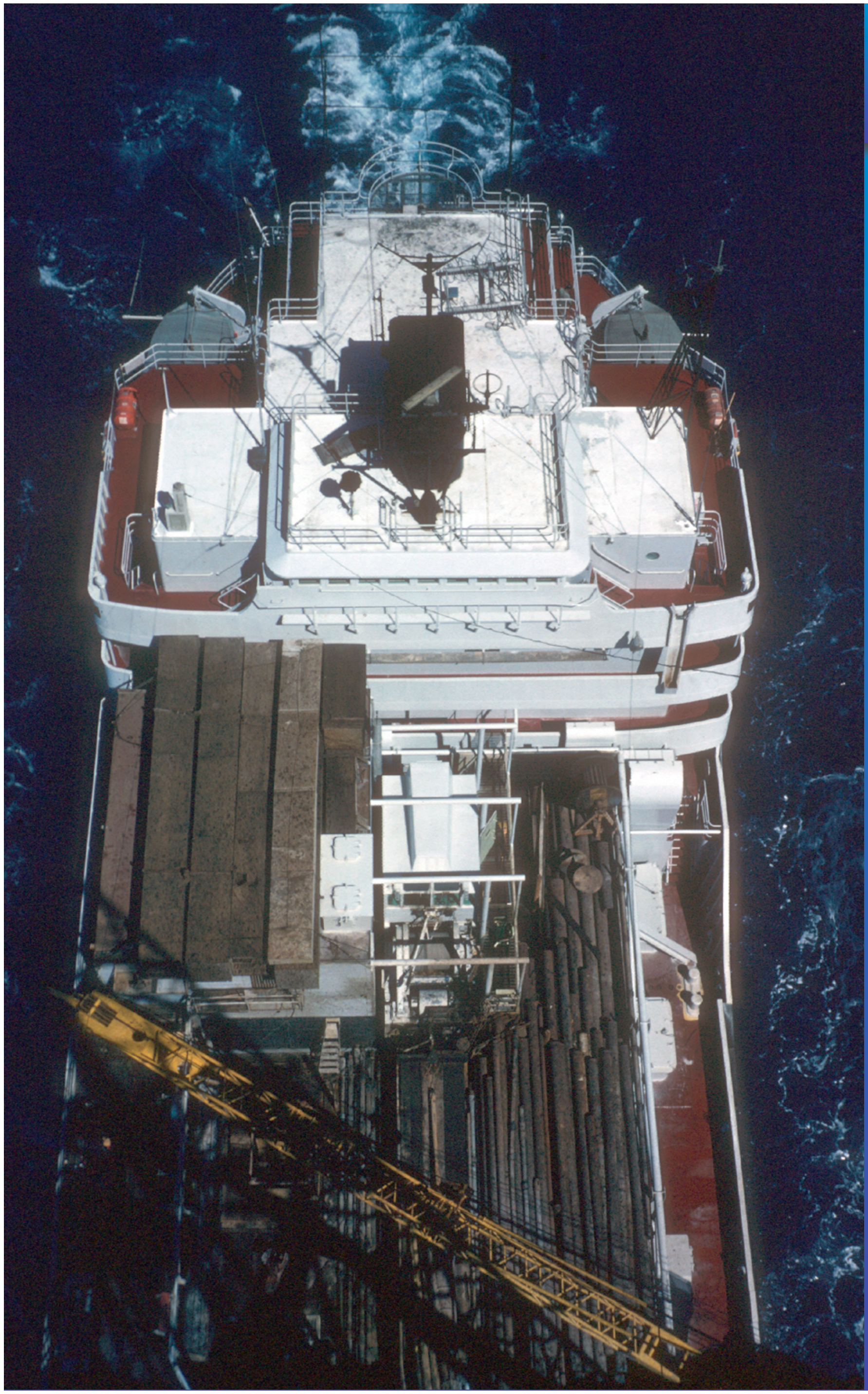
Mapping Submarine Micro-Earthquakes



Micro-earthquake swarms on the Juan de Fuca Ridge located from SOSUS stations.

These events correlate with the existence of an axial magma chamber, magma-induced stress changes, and hydrothermal activity.

Figure from Bohnenstiehl et al (2004)



Conclusions

The CTBTO-IMS hydro-acoustic data base is a valuable resource for studying a broad range of scientific problems in the oceans.

The physics of long-range sound propagation in the oceans is still not completely understood.

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