Earthquake T-phases and Long-Range Ocean Acoustic Propagation

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Seismic Waves in Laterally Inhomogeneous Media VII

Tepla, Czech Republic
June 21-25, 2010
Outline

Motivation
T-phase primer and the T-phase problem
Some T-phase examples:
  - Bathymetric steering in the Indian Ocean
  - Lack of water depth dependence in T-phases from the North Atlantic
  - T-phase arrivals on deep borehole seismometers in the Philippine Sea
Long-range ocean acoustic propagation in the North Pacific
TDFD models of Gaussian beams incident on a laterally inhomogeneous seafloor

Conclusions
Selected References
In spite of over 60 years of research and hundreds of research papers we still do not understand how earthquake energy gets into the sound channel in very deep water.

Until we have a better physical understanding of this process it will be very difficult to infer important earthquake characteristics (such as location, magnitude, source mechanism, and depth) from T-phase data.
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).
Intrinsic water depth dependence

(modified from Stephen et al., 2002)

(from Williams et al, 2004; 2006)
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)
With an array of only six hydrophones moored at the sound channel axis one can monitor earthquake activity on the mid-Atlantic Ridge in the North Atlantic. Most of these events would be undetected on land networks.
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
3-6Hz vertical T-phase observed events (normalized)
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).

The two problems are reciprocals of one another.
Water depth for the propagation paths on NPAL04 was deeper than 4400m.

(from Stephen et al, 2009a)
Three Classes of Arrivals

i) The earliest arrivals that appear on both OBS-S-GEO (vertical component) and DVLA-L20-Hyd (deepest hydrophone) and are modeled well by the PE. We call these “PE predicted”.

ii) Intermediate arrival time events that appear on DVLA-L20-Hyd but are either very weak or absent on OBS-S-GEO and are not modeled well by the PE. These correspond to “deep shadow zone” arrivals (occurring below shallower turning points). These are the arrivals that have been previously explained by “leakage” or the evanescent decay of the Airy phase.

iii) “Deep seafloor arrivals” appear on OBSs but they are not readily observed on the DVLA hydrophone just 750m above the seafloor. DSFA arrivals occur later than the first PE predicted arrival, their arrival time is not predicted by acoustic PE propagation models, and they do not correspond to decay from shallower turning points (as is the case for deep shadow zone arrivals). These are a new class of arrivals in ocean acoustics.
PE Predicted (P), Deep Shadow Zone (Z) and Deep Seafloor (S) Arrivals

(from Stephen et al, 2009a)
Seafloor OBS Arrival Structure is Very Different from DVLA Arrival Structure

(from Stephen et al, 2009a)
TDFD 1: This snapshot shows a Gaussian pulse-beam at 15 degrees grazing angle in a homogeneous medium with water properties. It was taken 40 Periods after the initiation of the beam. Only a single "ray" is represented by this beam.
TDFD 2: The same beam as in TDFD 1 insonifies the interface between water and a "high shear velocity" medium such as basalt. In this case the shear velocity of the bottom is faster than the compressional velocity of the water. The 15° grazing angle is sub-critical for both compressional and shear waves in the bottom and there is total internal reflection. Compressional and shear wave components of the evanescent wave below the interface (the direct wave root) can be observed.
TDFD 3: If a heterogeneity is introduced at the interface, in this case a facet that is one wavelength high, scattering into body and interface waves occurs. Even though the "ray" is incident on the facet at normal incidence there is no "reflected" or "transmitted" wave at the facet. Instead the facet acts as a secondary point source (Huygen's Principle). Since the secondary point source is near the interface, both forward and backward propagating Stoneley/Scholte waves are excited. There is also the complete family of compressional and shear body waves, including head waves, that would be expected for a point source on the interface.
Conclusions

The unexplained arrivals observed on the North Pacific Acoustic Experiment and the unexplained T-phase excitation mechanism are reciprocals of one another.

Both require mode conversion in the laterally inhomogeneous, ocean waveguide possibly involving
a) lateral inhomogeneity and
b) mode conversion from acoustic body waves to or from elastic seafloor interface waves.
Acknowledgements

Many thanks to the WHOI-DOEI and NSF for providing the seed money to OBSIP that made the OBS deployments possible and to ONR for funding NPAL04 and the OBS data analysis.

Colleagues and Collaborators

Jeff Babcock, SIO/OBSIP  
Mark Gibaud, SIO/OBSIP  
Patricia Cheng, SIO/OBSIP  
Jim Mercer, APL-UW  
Rex Andrew, APL-UW  
Linda Buck, APL/UW  
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Matt Dzieciuch, SIO  
Bob Odom, APL/UW  
Bruce Howe, SOEST/UH  

John Colosi, NPGS  
Debbie Smith, WHOI  
Clare Williams, WHOI/MIT  
Tom Bolmer, WHOI  
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Lora Van Uffelen, SIO  

Peter Bromirski, SIO  
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Eiichiro Araki, JAMSTEC  
Wayne Crawford, IPG Paris
