Proceedings, Seismo-Acoustic Applications in Marine Geology and Geophysics Workshop, Woods Hole Oceanographic Institution, 24–26 March 2004

by Robert I. Odom[1] and Ralph A. Stephen[2]

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Technical Report
APL-UW TR 0406
July 2004

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1013 NE 40th Street Seattle, Washington 98105-6698

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Steering committee members:

- Rhett Butler, *Incorporated Research Institutions for Seismology*
- Catherine de Groot-Hedlin, *Scripps Institution of Oceanography*
- Bob Dziak, *Pacific Marine Environmental Laboratory*
- Bob Odom, *Applied Physics Laboratory, University of Washington*
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I. Executive Summary

The workshop, "Seismo-Acoustic Applications in Marine Geology and Geophysics," took place at Woods Hole Oceanographic Institution on March 24–26, 2004. The thirty-three attendees of the workshop represented a broad spectrum of researchers including experimentalists and modelers, and spanned the fields of marine geology and geophysics, long-range ocean acoustics, and continental crustal seismology. The following were the workshop's goals:

- Identify necessary, important, or promising research directions to further the application of seismo-acoustics (T-phases) in marine geology and geophysics. What are the limitations of our present knowledge? What potential is there for improving seismo-acoustics as a technique to study earth science in the oceans? What are the Navy-relevant aspects of T-phase research?
- Provide an opportunity for the marine geology and geophysics and ocean acoustics communities to organize their thoughts on this topic, and provide funding agencies and the community with clear guidelines for future research in this field. Workshop recommendations could be cited, for example, in proposals from individual (or groups of individual) investigators to ONR and NSF.

The workshop participants concluded that although T-phase studies have already contributed substantially to marine geology and geophysics, there is still considerable potential for further advances in T-phase research. Further research is required

- to improve our confidence in earthquake locations, depths, magnitudes, and source mechanisms from T-phase data
- to infer volcanic and tectonic processes from T-phase data
- to understand the role of bottom interaction in long-range, low-frequency acoustic propagation in the oceans
- to assess hazard potential from events such as tsunamis and landslides
- to apply T-phase technology to the study of ocean processes such as internal waves and ice floes

This potential can be realized through a combination of field experiments, which extend and complement existing T-phase and long-range propagation installations, and an improved understanding of the physical mechanisms of T-phase excitation and propagation.

The workshop participants made the following recommendations:

- ***Recommendation to IRIS*** to make available in real time adequate waveform windows at a handful of island stations allowing T-phase evaluation and research in real time. (At present BH* channels are available for a window not exceeding 10 min after P and LH* for 1 h after P. Increase BHZ to 2 h after P at critically located stations (RPN, RAR, JOHN, XMAS, WAKE).
- ***Recommendation to Navy*** to piggyback T-phase investigations onto Navy experiments, e.g., deploy some ocean bottom seismometers (OBSs) during controlled source

experiments. Use Navy deployed vertical arrays to study the modal structure of T-phases.

- ***Recommendation to extend T-phase networks*** to the Western Pacific, Indian, and Southern oceans.
- ***Recommendation that one node*** in each of the North Atlantic and North Pacific T-phase arrays be extended to include at least three hydrophones to provide azimuthal information.
- ***Recommendation that a hydrophone*** be installed above seafloor borehole seismic instruments so that both the in-water and ocean bottom interfacial signals can be recorded.
- ***Recommendation that modeling efforts be expanded*** beyond the small region of the parameter space for the excitation of T-phases that has been explored to date. The effects of sediment thickness and rigidity, roughness, slope, and source mechanism need to be more thoroughly investigated. An effort should be made to extend models to three dimensions.
- ***Recommendation to NEPTUNE and ORION*** that T-phase observatories including vertical hydrophone arrays and horizontal OBS/OBH arrays be added to the observatory nodes. T-phase stations will improve our knowledge of ocean basin seismicity. The vertical arrays are necessary to resolve modal structure of the T-phases. Horizontal OBS/OBH arrays are necessary to resolve interface wave propagation and seafloor characteristics.

II. Summary and Recommendations

The March 2004 workshop, "Seismo-Acoustic Applications in Marine Geology and Geophysics," at the Woods Hole Oceanographic Institution brought together thirty-three participants who represented a broad spectrum of researchers including experimentalists and modelers; their work spans fields ranging from marine geology and geophysics, to long-range ocean acoustics, and to continental crustal seismology. The workshop's goals were:

- Identify necessary, important, or promising research directions to further the application of seismo-acoustics (T-phases) in marine geology and geophysics. What are the limitations of our present knowledge? What potential is there for improving seismo-acoustics as a technique to study earth science in the oceans? What are the Navy-relevant aspects of T-phase research?
- Provide an opportunity for the marine geology and geophysics and ocean acoustics communities to organize their thoughts on this topic, and provide funding agencies and the community with clear guidelines for future research in this field. Workshop recommendations could be cited, for example, in proposals from individual (or groups of individual) investigators to ONR and NSF.

For the purposes of this workshop "seismo-acoustics" refers to the ocean acoustics of earthquakes. The majority of acoustic arrivals related to earthquakes in the ocean occur as "T-phases." This name is derived historically from land seismology: the third or tertiary phase occurs after primary (compressional) and secondary (shear) arrivals on coastal seismic stations. It was recognized over fifty years ago that this arrival propagated in the ocean sound channel. Here, we define "T-phases" as any phase that propagates mainly within the ocean basins, but spends at least part of its propagation path within the earth's crust. "Hydro-acoustics" is another common term used to distinguish ocean acoustics from atmospheric acoustics, "aero-acoustics."

Acquiring T-phase data in the ocean basins is a relatively inexpensive way to acquire a large amount of data from earthquakes below the seafloor that are too small to be observed on continental or island stations. There are many exciting problems in marine geology, marine geophysics, and earthquake dynamics that could potentially be addressed with these data. There are explanations for some of the observed characteristics of T-phases and these can be used to make some basic interpretations, such as event detection and location, but no single model for T-phase excitation and propagation (including blockage) explains all of the salient observations.

For example, a common procedure for T-phase event location is to pick the peak amplitude of the T-phase envelope or to pick the broadest spectral event in a spectrogram. Many T-phase arrivals (and in some data sets, most arrivals) either do not have any well defined peak, have multiple peaks, or have a very diffuse spectral character. Location methods that allow for topographic steering to explain multiple arrivals are just being developed. These are primarily based on only P-wave excitation of the seafloor even though there are some clear examples of distinct arrivals in some T-phases of both S and P excitation.

Another example is that common analysis techniques assume that all of the T-phase energy is coming directly from the event location. There are a number of clear instances where this is not the case. In some cases different segments of the T-phase arrival come from various bathymetric features in the vicinity of the event location. There are other examples, however, where T-phase energy arrives from bathymetric features that are in entirely different parts of the ocean basin than the event. If data is acquired on a sparse array of single hydrophones, the azimuthal information necessary to resolve these effects is not available.

Most of the "sound channel propagation" models do not consider interaction with the seafloor when the water depth is below the critical depth. T-phases are observed on seafloor hydrophones and seismometers in deep water and they are observed on borehole seismometers hundreds of meters into the seafloor when water depths are well below critical. This implies that the sound is coupled between the sound channel and the bottom (at least in the low shear velocity sediments). *Butler and Lomnitz* (2002) and *Park et al.* (2001) developed propagation models that could explain these observations, but neither model has been tested extensively. Although traditional acoustic modes all have tails that decay exponentially towards the seafloor, the amplitudes at the seafloor are quite low. To argue that sea bottom interaction is significant for traditional modes would require the simultaneous observation of absolute amplitudes at hydrophones on the seafloor and in the sound channel.

The reciprocal problem is an enigma for the generation of T-phases from epicenters in water depths well below the critical depth. T-phase arrivals in the North Atlantic, for example, show very little sensitivity to the water depth at the event location, which conflicts with the commonly accepted physical models.

To address these and other issues, the body of the workshop comprised five keynote addresses, two special addresses, and four breakout group discussions. The keynote addresses served to review the past history and current state-of-the-art in ocean seismo-acoustic observation and theory and provided focal points for the four breakout groups. The five keynote addresses were:

- "Background of T-phase Observations," Maya Tolstoy, *Lamont Dougherty Earth Observatory*
- "Proven and Potential Application of T-phases," Robert P. Dziak, *NOAA/Pacific Marine Environmental Laboratory*
- "Theory of T-phase Excitation," Emile Okal, *Northwestern University*
- "Theory of Long-Range Acoustic Propagation", John Colosi, *Woods Hole Oceanographic Institution*
- "Seismic Event Location: Fundamentals and Potential Problems in Event Locations Utilizing T-phases," Gary Pavlis, *Indiana University*

There were also two special addresses:

- "Observation of Seismo-Acoustic T-waves at and Beneath the Seafloor," Rhett Butler, *Incorporated Research Institutions for Seismology*
- "Wave-theory Modeling of Oceanic T-phase Coupling at Continental Margins and Seamounts," Henrik Schmidt, *Massachusetts Institute of Technology*

In addition there were 18 poster presentations (Table 1; Appendix 4). Ample time was allowed to view the posters and the poster room was an area of active discussions during the workshop.

Motivated by the keynote and special addresses, the attendees formed four breakout groups (Appendix 3):

- T-phase Measurements and Observations
- Application of T-phases in Marine Geology and Geophysics

- Theory of T-phase Excitation
- Theory of Long-range Acoustic Propagation

The broad charge to the breakout groups was to elucidate the state-of-the-art and to identify (and ideally prioritize) the key issues. In addition the group members were asked to identify the links between the theory and analysis groups.

Table 1: Workshop Poster Presentations

Author(s)	Title
Araki	T-phase observed at deep sea boreholes
Bohnenstiehl	Application of T-wave data: T-wave earthquake catalog used to study the time-clustering behavior of spreading center seismicity
Castor, Gerstoft, Roux, and Kuperman	Long-range propagation of finite amplitude acoustic waves in an ocean waveguide
Chi and Dreger	Finite fault inversion of the 1999 Chi-Chi, Taiwan, earthquake (Mw=7.6)
de Groot-Hedlin	Hypocentral location using T-phase waveform matching: Ridge events
Dziak	Long-term seismo-acoustic monitoring of the Pacific and Atlantic oceans
Matsumoto, Dziak, and Mellinger	Global T-phase monitoring: Past, present, and future
McCormack	T-phases observations from land-based arrays
McGuire, Collins, and Smith	Long-term, continuous, seismic, and seismo-acoustic monitoring of the Northern Atlantic Basin: An observing system for the scientific community
Pulli, Upton, and Bhattacharyya	T-wave Observations in the Indian Ocean
Park, Odom, Dziak, Jin, and Hong	T-wave excitation from seafloor tectonic and volcanic events
The SIRENA team: Goslin, Perrot, Royer, Martin, Fox, Dziak, Matsumoto, Fowler, Haxel, Luis, Lourenco, Matias, and Bazin	Interactions between the MAR and the Azores hotspot as imaged by the seismicity distribution using autonomous hydrophone arrays
Bazin	Attempt to improve the Caribbean seismic network array with autonomous hydrophones
Smith, Collins, and McGuire	Activity on the shallow top of the Atlantis massif: Is it seismically active of just a T-phase radiator?
Stephen, Smith, and Williams	The dynamics of abyssal T-phases
Sugioka	Semidiurnal variation of the ocean sound velocity associated with the M2 internal tide
Williams, Stephen, and Smith	Hydroacoustic events located near the Atlantis (30°N) and Kane (23°30'N) transform faults on the MAR

T-phase Measurements and Observations

The T-phase measurements and observations breakout group identified five main issues and questions. Understanding the correlation between actual source magnitude and the source levels recorded at the hydrophone is crucial if T-phases are to be used for studies of total energy release in tectonically or volcanically active areas (or for source strength estimates as part of Test Ban Verification). [Note: The planned scope of the workshop did not include Test Ban Treaty Verification; in some instances the application of hydroacoustics to marine geology and geophysics and treaty verification overlap. We have put text related to treaty verification in parentheses.] Understanding of the often emergent and extended T-wave arrival is tightly coupled with the spatial and temporal origins of the T-phases, and is important for identifying the common features, if any, of T-phase arrivals, and for classification of T-phases. As the amount of T-phase data increases and is entered into catalogues, understanding the relations among the various catalogues is important for quantitative inter-comparison. How do source location accuracy and detection limits vary from area to area? The bathymetry is clearly important for the generation and propagation of T-phases. Are the current bathymetric databases complete enough, accurate enough, and of high enough resolution to serve the needs of both the T-phase data interpretation and modeling communities? In most cases, the answer is probably not. Finally are current T-phase data of sufficient quantity, geographic coverage, and quality to be employed as a natural and cost free source for tomographic reconstructions of the ocean? Are the signal amplitudes high enough, and are the propagation paths free enough from blockage to be employed for tomographic purposes? Can reflections from bathymetric features be localized well enough to be used as additional paths for tomography?

T-phase Applications

T-phases have already proven their usefulness in a number of areas and have potential for extension to others. They have been used to detect volcanism with accuracy suitable for real-time location of volcanic events. Earthquakes much too small to be recorded by land-based seismometers produce T-phase signals easily recorded by hydrophones, permitting mapping of low-magnitude seismicity. This leads to a better understanding of ridge, transform, subduction, and intraplate processes. In addition the detection of small events associated with larger events allows investigation of stress triggering. T-phase signal content carries information about the earthquake focal mechanism, and the envelope can be used to estimate focal depth. In the Indian Ocean particularly, T-phases provide a substantial amount of information on earthquake locations as they are in many cases the only signals available. (Source mechanism effects have been documented in the T-phase data, which points to the value of T-phases for explosion discrimination. T-phases are the signals of interest for the hydroacoustics component of Comprehensive Test Ban Treaty compliance verification.)

Better understanding of the T-phase source mechanism shows potential for earthquake source tomography with consequent application to plate boundary processes. T-phases recorded from icebergs may be used to understand the nature of the triggering events (“icemology”), and as an adjunct to climatological studies. They may be useful for risk assessment of the danger from tsunamis generated from underwater slides. More work needs to be done on this issue. With suitably accurate locations T-phases show promise for forensic seismo-acoustics to locate airplane crashes, missile launches, meteor impacts, and maritime accidents.

Theory of T-phase Excitation

One of the key questions we need to address is how earthquakes generate T-phases, which are defined as any phase that propagates mainly within the ocean basins, but spends at least part of its propagation path within the earth's crust. Two mechanisms, either singly or in combination, have been used to describe T-phase excitation; these are:

- **Multiple reflections at a sloping boundary**. This mechanism is usually described using ray theory terminology. A seismic phase incident from below on a sloping seafloor generates an acoustic phase that propagates almost vertically due to the large impedance contrast between the seafloor and ocean column. Repeated reflections between the sea surface and sloping seafloor steer the acoustic phase from a vertical to a horizontal trajectory. T-phase excitation at continental margins and islands has been explained by this "slope T-phase" mechanism. The role of this mechanism at submerged bathymetric highs (seamounts and ridges, for example) has not been addressed.
- **Scattering of seismic energy at a rough boundary**. If the seafloor boundary is rough on a scale smaller than the wavelength of the incident seismic phase (about 150–500 m for 10-Hz compressional energy), the individual scatterers serve as point sources, that is, they re-radiate some portion of the incident seismic energy into nearly horizontally-propagating acoustic energy. Normal mode terminology has been used to model this phenomenon. T-phase excitation in the deep ocean has been explained by this "abyssal T-phase" mechanism. Long-range propagation in the ocean, however, is most efficient when the "source," the secondary scattering from the seafloor, is within the sound channel. Generating abyssal T-phases when the water depth is much deeper than the critical depth (the bottom of the sound channel) remains a problem.

Outstanding issues in the generation of T-phases include the relative contributions of various seismic phases (i.e., P-waves, S-waves, and interface waves) in seismic-to-acoustic coupling. This has bearing on the duration, amplitude, and probably spectral content of T-phases. It was emphasized several times that T-phase excitation is a **three-dimensional effect**; thus, while many two-dimensional forward modeling techniques exist that can give us insights into seismic to acoustic coupling, three-dimensional forward modeling is necessary to fully predict realistic T-phase characteristics.

Two-dimensional forward modeling studies can address several outstanding problems in T-phase research such as:

- The role of marine sediments in T-phase excitation. How does the thickness or rigidity of the sediments affect T-phase amplitudes and spectral content?
- Whether the scattering of acoustic energy into the sound channel occurs at the seafloor or at the base of the sediments
- The effect of seafloor depth at the epicenter on T-phase characteristics. It was noted that although the reciprocal depth (also known as the critical depth—the depth at which the sound velocity in the water is equal to the value at the surface) does not serve as a cutoff for T-phase generation, the efficiency of excitation decreases with increasing epicentral depth in some studies but not in others.

Accurate T-phase modeling also requires using a realistic earthquake focal mechanism (i.e., strike-slip vs. normal faulting) for the source. Ideally, we would like to model both the spectral and temporal content of T-phases, which would require three-dimensional forward modeling. It was noted that for sources near the center of a ridge, the observed shape and frequency content of the T-phase sometimes varies with azimuth of observation for a single event, with single peaks observed at some azimuths and double peaks at others. Several hypotheses were advanced to explain this phenomenon, such as multiple reflections at bathymetric promontories, or bathymetric steering, which involves the preferential excitation of acoustic energy at several high points on the seafloor in the vicinity of the epicenter. In either case, three-dimensional forward modeling is required to explain these azimuthal variations in the observed T-phase spectrograms, which may in future be useful for inferring source parameters for small and moderate-sized earthquakes. In several studies, progress has been made in understanding the effects of focal mechanism on T-phases, and of bathymetry and blockage on T-phases. However, work needs to be done on combining the results of these disparate studies to model realistic T-phase characteristics, using accurate environmental models, so that T-phases may be used to infer source parameters.

Theory of Long-range Acoustic Propagation

Ocean acoustic propagation at frequencies above about 50 Hz without bottom interaction is more or less a solved problem. Without bottom interaction elastic effects (rigidity or shear modulus) need not be considered. The primary environmental properties affecting propagation are variations in the sound speed along the propagation path due to basin-scale variations, e.g., the presence or absence of the SOFAR channel as the latitude increases from the equator to the poles, and internal waves that scatter the sound. Bathymetric highs can block sound, but it is usually not necessary to invoke the elastic properties of the bottom. Simple shadowing usually suffices to explain the data.

Propagation at frequencies of 5–10 Hz, corresponding to wavelengths of 15–300 m, is a shallow water acoustics problem, even in deep water. The bottom is inherently part of the system and elastic, i.e., shear effects are important. There are no three-dimensional elastic codes that can handle the complex bathymetry to propagate a 5–10-Hz signal over a range of 500–1000 km. Fully three-dimensional wave-theoretic elastic codes, even if they existed, might not be practical with current computer technology. It remains to be seen if extant or developing two-dimensional codes could handle the complex range dependence at typical T-phase frequencies in reasonable execution times. The effects of internal waves on T-phase signals in the 5–10-Hz band, while probably less than at higher frequencies, has not been investigated.

The long-range acoustics community could assist in the understanding of T-phases by placing a vertical line array (VLA) near a land based seismometer to improve our understanding of the conversion process from water to land. A VLA located in an active acoustic source region would improve our understanding of the conversion process from land to water.

There is existing VLA data that could be analyzed for T-phase arrivals. The North Pacific Acoustic Laboratory (NPAL) experiment had five VLAs in 1800 m of water off Sur Ridge recording for 20 min every 4 h from summer 1998 through summer 1999 within a 10–100-Hz band. Complementary seismic data is available from land-based seismometers. Funded by NOAA, data has been collected from a four-element vertical receiver array located on Pioneer Seamount and is available publicly.

The best near-term opportunity will occur in September 2004 during the intense recording period for the NPAL04 VLA, which will be deployed in June 2004. Deployment of one or two OBSs collocated with the VLA would be valuable both to the T-phase community and also to the long-range acoustics community. Our understanding of the below-critical-depth arrivals, which are in a classical shadow zone, would be improved by making simultaneous seismic and acoustic measurements.

A final issue is Navy interest in the 10–20-Hz band because of ship and submarine acoustic radiation. Bathymetric blockage within this frequency band is of potential interest to the U.S. Navy. A technology development goal would be to develop a controlled source in this band. It is expected that scattering from internal waves would be much less at 20 Hz than at higher frequencies.

Workshop Recommendations

- ***Recommendation to IRIS*** to make available in real time adequate waveform windows at a handful of island stations allowing T-phase evaluation and research in real time. At present BH* channels are available for a window not exceeding 10 min after P and LH* for 1 h after P. Increase BHZ to 2 h after P at critically located stations (RPN, RAR, JOHN, XMAS, WAKE).
- ***Recommendation to Navy*** to piggyback T-phase investigations onto Navy experiments, e.g., deploy some ocean bottom seismometers (OBSs) during controlled source experiments. Use Navy deployed vertical arrays to study the modal structure of T-phases.
- ***Recommendation to extend T-phase networks*** to the Western Pacific, Indian, and Southern oceans.
- ***Recommendation that one node*** in each of the North Atlantic and North Pacific T-phase arrays be extended to include at least three hydrophones to provide azimuthal information.
- ***Recommendation that a hydrophone*** be installed above seafloor borehole seismic instruments so that both the in-water and ocean bottom interfacial signals can be recorded.
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- ***Recommendation to NEPTUNE and ORION*** that T-phase observatories including vertical hydrophone arrays and horizontal OBS/OBH arrays be added to the observatory nodes. T-phase stations will improve our knowledge of ocean basin seismicity. The vertical arrays are necessary to resolve modal structure of the T-phases. Horizontal OBS/OBH arrays are necessary to resolve interface wave propagation and seafloor characteristics.

III. Keynote Address Abstracts

"Background of T-phase Observations"

Maya Tolstoy, *Lamont Dougherty Earth Observatory*

The primary motivations for using T-phases to study marine geology and geophysics problems are earthquake mechanics, eruption monitoring, and understanding impacts of earthquakes on hydrothermal and biological systems.

The velocity structure of the oceanic water column provides for the efficient propagation of sound, with relatively little energy loss compared to the solid earth. T-phase energy is generally trapped in the SOFAR channel either through scattering (e.g., in the abyssal setting) or through downslope propagation (e.g, islands, shelves, subduction zones). On occasion the energy will be trapped in the SOFAR channel because the source is located in it. Various studies have shown that energy trapped through scattering is trapped in the SOFAR channel much more efficiently where there is a rough seafloor, such as along a mid-ocean ridge.

Hydroacoustic monitoring of T-phases in the SOFAR channel provides a method of event localization that is complimentary to traditional seismic monitoring. This technology represents a critical intermediate scale of earthquake monitoring, able to capture more than an order of magnitude more events in many remote oceanic areas than land stations, with at least an order of magnitude less expenditure compared to an OBS experiment to monitor a similar spatial area. T-phase catalogs provide a critical insight into geological workings and eruption monitoring on the seafloor that could not be provided practically through OBSs, and is not possible with the resolution of land stations.

T-phase locations reflect the seafloor position from which most of the energy is being propagated into the water column. Therefore, they are commonly referred to as T-phase radiator locations rather than epicenters. Geological evidence gathered from numerous mid-ocean ridge studies suggest that T-phase locations are reliable to within a few km. This is based on locations of fresh lavas associated with eruptions, and association with specific geological features. T-phase locations are not observed to be preferentially occurring at topographic highs, and so do not appear to be routinely topographically steered. However, for deeper shelf or slab events radiator locations will generally appear at the closest point of entry into the SOFAR channel, and so, at these sites, the T-phase radiator location may differ significantly from the seismic epicenter.

Another important factor to remember when looking at earthquake locations from magmatic swarms is that a dike intrusion can trigger seismicity on nearby faults that fall within the extensional deformation zone above an intrusion, and so the seismic activity may not always track directly above a dike intrusion.

In summary, the geophysical and geological utility of T-phases is already well proven (see bibliography). However, this does not mean that there is not room for improvement, both in the area of location methods (e.g., automating utilization of T-phase envelopes, T-phase waveform synthesis), and a better understanding of the physics of T-phase propagation.

Seminal Problems

I think the seminal problem in terms of marine geology and geophysics applications is how to overcome the perception that T-phases are not useful for these problems. There is now a strong body of peer-reviewed literature that highlights useful findings, but there has been significant difficultly in translating this to funded proposals to continue these types of studies.

[Editor's note: This is not unique to T-phase research. By putting T-phases on a firmer, physical foundation, and by broadening the community to include ocean acousticians and other marine seismologists, we should be able to expand the credibility and funding for this type of research.]

“Proven and Potential Application of T-phases”

Robert P. Dziak, *NOAA/Pacific Marine Environmental Laboratory*

Proven and still developing T-phase applications:

- Detection of volcanism (low-magnitude seismicity, tremor, and related signals)
- Tectonic seismicity (transform and subduction related)
- Explosion detection and discrimination
- Shape of T-phase envelope used to estimate earthquake depth
- T-phase signal content to estimate earthquake focal mechanism
- Submarine slumps and tsunamigenesis
- Arctic Ocean earthquakes (under-ice scattering) and iceberg tremor
- Structure of subducting slabs

Potential T-phase applications:

- Earthquake source tomography (rupture length, subevents/aftershocks, estimate stress drop)
- Solid earth tomography (acoustic converted P-arrivals from mantle/core)
- Global climate change (sound velocity/ocean temperature changes)
- Others?

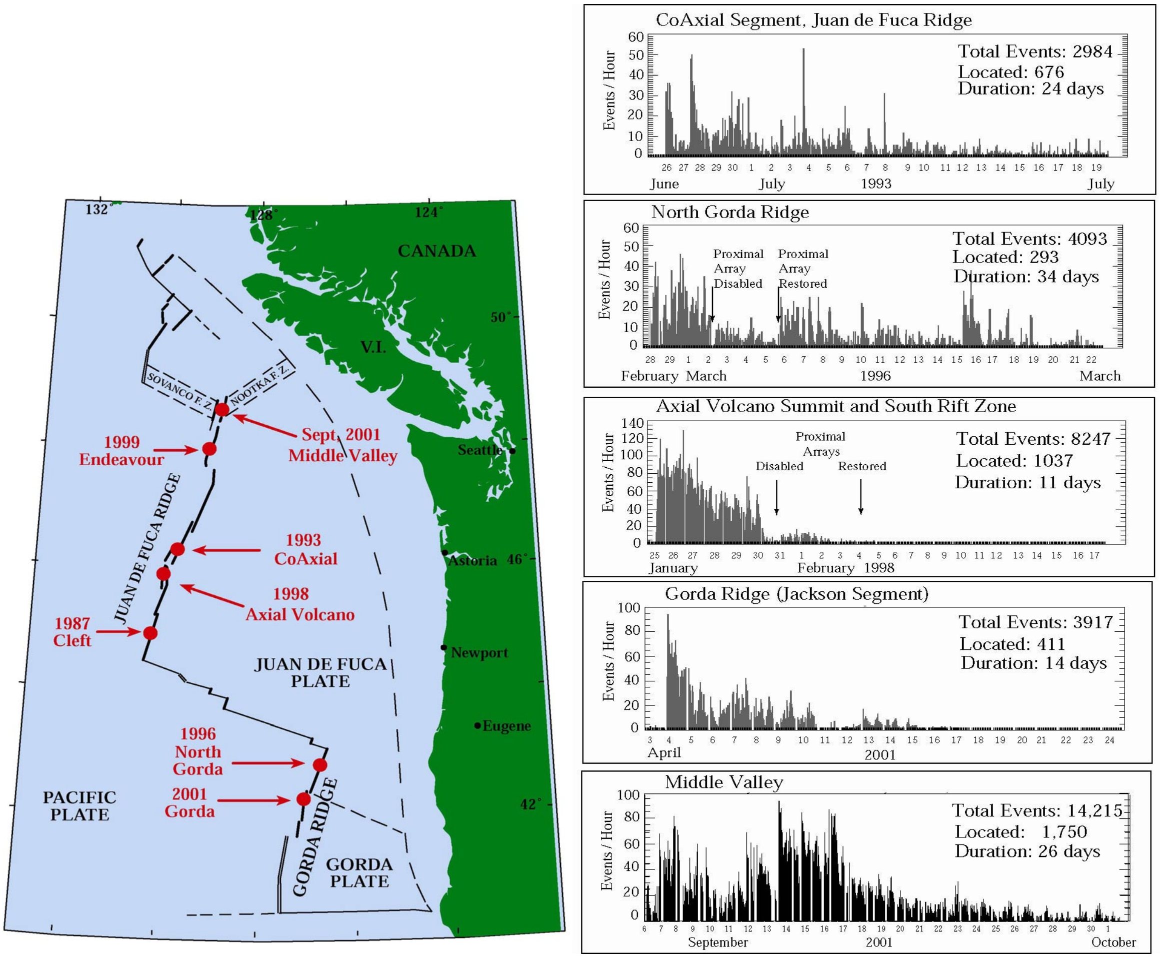
T-phase geophysical milestones:

- First comprehensive description of T-phases generated by distant earthquakes by *Tolstoy and Ewing* (1950)
- First published detection of underwater volcanism using hydroacoustic signals by *Dietz and Sheehy* (1954)—*1953 Eruption of Myojin (Izu Islands) recorded on Navy hydrophones off California*
- First use of hydrophone network to locate Pacific basin earthquakes and volcanic activity by *Johnson et al*. (1963)—*U. Hawai’i using Air Force Pacific Missile Impact Location System*
- Discovery of Macdonald Seamount, previously unknown end member of the Austral Island chain, by *Norris and Johnson* (1969)

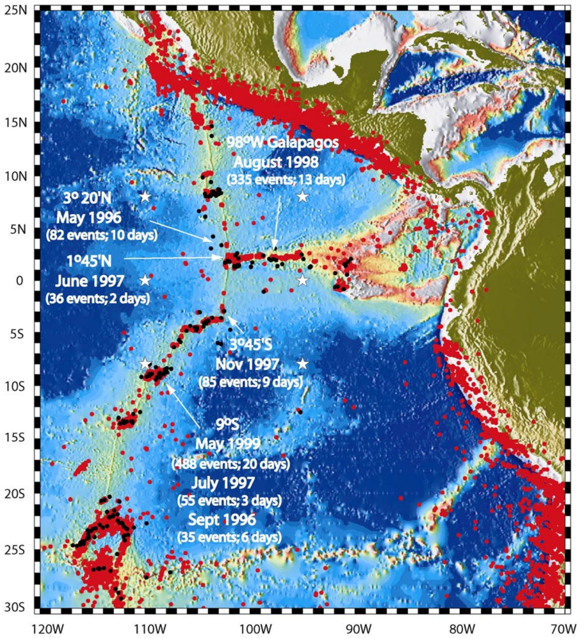
- Farthest in-land detection of T-waves, more than 1000 km from coast in Sweden, by *Bath and Shahidi* (1971)
- Detection of T-phases from Arctic Ocean Earthquakes via under-ice scattering by *Keenan and Merriam* (1991)
- First detection of a mid-ocean ridge spreading episode in real time by *Fox et al.* (1995)—*U.S. Navy SOSUS hydrophones in NE Pacific, lead to discovery of sub-seafloor microbial communities*
- Discovery of a massive volcanic structure at the Hollister Ridge—Eltanin F.Z. by *Talandier and Okal* (1996)
- First hydroacoustic record of submarine landslides at Kilauea Volcano by *Caplan-Auerbach et al*. (2001)
- Identification of T-phase signals caused by large icebergs in Antarctica by *Talandier et al*. (2002)
- First quantification of a high energy seismo-acoustic interface phase (*Ti*) on H2O seafloor seismometer by *Butler and Lomnitz* (2002)
- Identification of the T-phase from the New Guinea tsunamigenic submarine slide by *Okal* (2003)

Past and present T-phase networks (mainly for volcano-tectonic earthquake monitoring):

- Pre-1960—U.S. Navy hydrophones off California, Bermuda, as well as coastal/island seismic stations (e.g., *Linehan*, 1940; *Dietz and Sheehy*, 1952; *Tolstoy and Ewing*, 1950)
- 1960s—Pacific Missile Impact Location System, U. of Hawai'i (*Johnson et al*., 1963)
- 1970s to present –French Polynesian Seismic Network, RSP (*Talandier and Kuster*, 1978)
- 1990s to present—North Pacific SOSUS hydrophone array, dual use with U.S. Navy and NOAA/OSU (*Fox et al.*, 1994)
- 1990s—Atlantic SOSUS arrays (*Nishimura and Conlon*, 1994)
- 1990s to 2002, 2003—HUGO and H2O T-phase stations (*Duennebier et al*., 2001; *Butler et al*., 2000)
- Late 1990s to present—International Monitoring System, Comprehensive Nuclear Test Ban Treaty (UN), hydrophone and T-phase stations

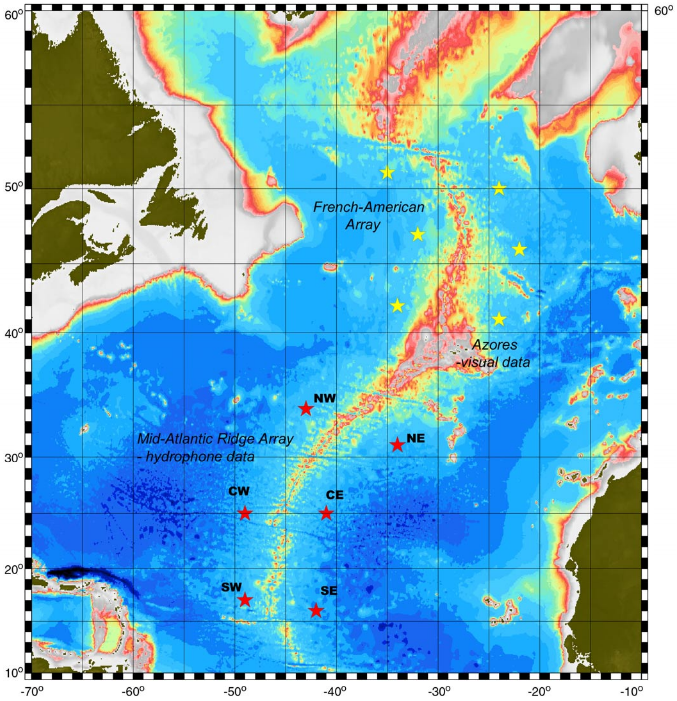


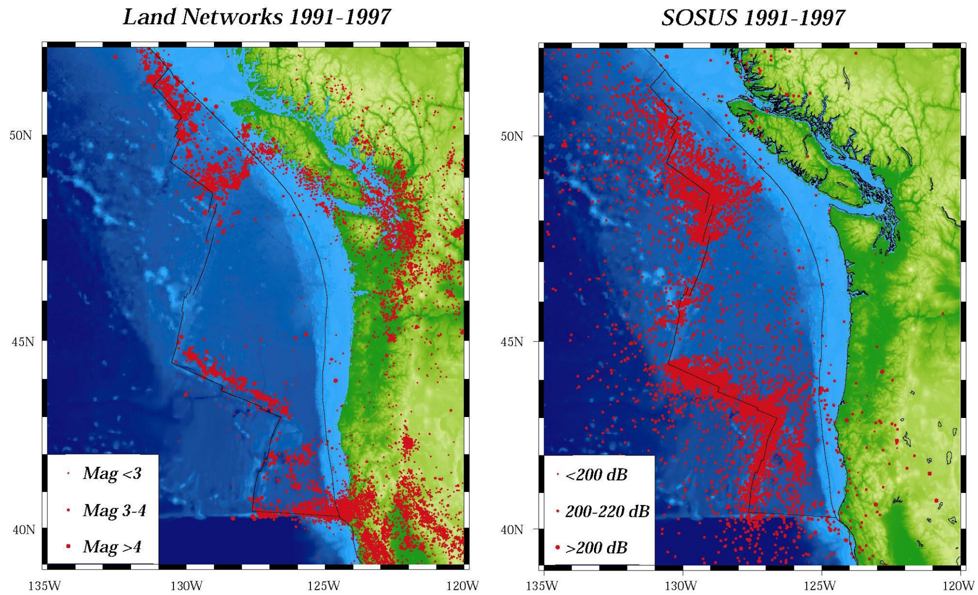
The U.S. Navy SOSUS hydrophone array in the northeast Pacific (NOAA/OSU) detected volcanic activity from seven major mid-ocean ridge seafloor spreading episodes.



East Pacific Rise hydrophones (first deployed May 1996) detected seven volcanic earthquake swarms in five years (*Tolstoy et al*., 1999, *Fox et al*., 2001).

Mid-Atlantic Ridge hydrophones (first deployed February 1999) detected one volcanic earthquake swarm in three years (*Smith et al*., 2002; *Dziak et al*., 2004)



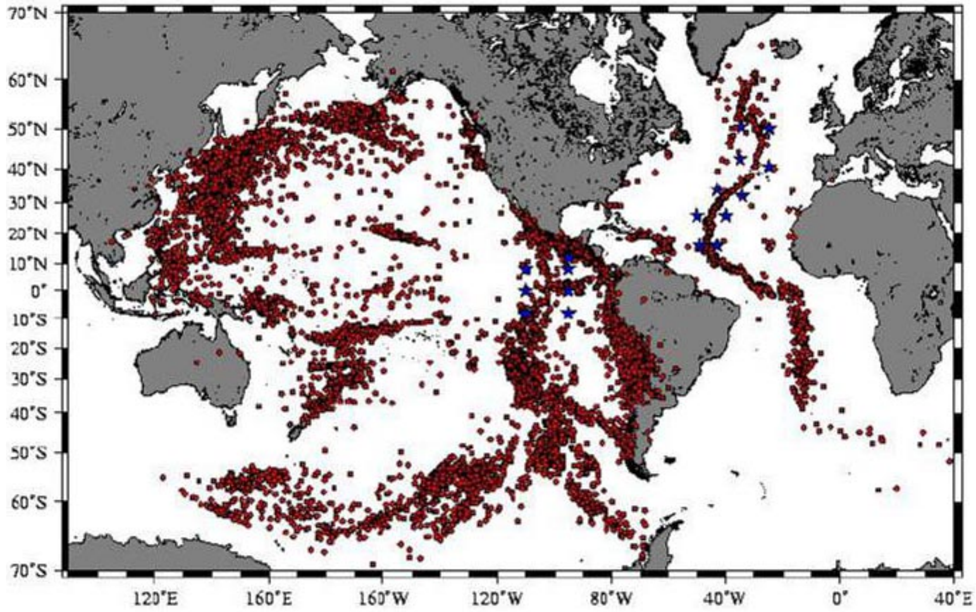


Land Networks 1991-1997

SOSUS 1991-1997

Tectonic seismicity recorded by SOSUS

USGS, PGC, UW, UC-B seismic networks	NOAA/OSU SOSUS hydrophone array
1,792 Juan de Fuca Plate events	21,958 Juan de Fuca Plate events



Hydrophone Array	Inception	Earthquakes Located
North Pacific (SOSUS)	August 1991	31,889
East Pacific Rise	May 1996	56,072
Mid-Atlantic Ridge	February 1999	11,452
	Total	99,413

T-phase Information Available Online (NOAA/OSU):

http://www.pmel.noaa.gov/vents/acoustics/seismicity/seismicity.html
Earthquake Locations (North Atlantic, North and East Pacific)
Digital Hydrophone Data
Real-time volcanic event detection information (North Pacific SOSUS)
T-phase Bibliography

“Theory of T-phase Excitation”

Emile Okal, *Northwest University*

We present a largely historical review of the concepts used to explain the generation of *T* phases, primarily by dislocation sources located in the solid earth. Following the description by Ewing in the 1950s of the generation of *T* phases by conversion from seismic body waves at continental margins, Johnson developed in the 1960s the model of “downslope conversion” to describe the alignment and subsequent trapping of a multiply reflected ray inside the SOFAR channel in the presence of a sloping interface. We discuss the influence of the slope angle on the efficiency of this process, and the contribution of both *P* and *S* waves to the generation of *T* phases. We discuss the limitations of this theory in the framework of the so-called abyssal *T* phase, generated in the absence of documented sloping features such as continental margins. We present a number of successful applications of the theory of scattering to the modeling of the abyssal *T* wave, notably in the framework of normal mode acoustics, introduced by Pekeris in 1948.

We then present several approaches to the question of quantifying a T-phase record in relation to earthquake sources. We review the limitations of the simple measurement of a T-phase amplitude due to the rapid saturation of the very high-frequency far field generated by a growing source, and discuss the early efforts at quantifying the duration of the T wavetrain. We propose to both combine and contrast the two measurements (amplitude and duration) to obtain more robust estimates of the seismic properties of the source. We first show that the T-phase energy flux (TPEF), integrating the energy recorded in the T wavetrain, can reveal any departure of the seismic source from scaling laws when compared to the seismic moment measured at much lower frequencies. The resulting parameter $\Gamma = TPEF/M0$ is characteristic of the slowness of the seismic source, and in particular shows a deficiency of 1 to 2 orders of magnitude for the so-called “tsunami earthquakes.” The second approach consists of comparing (on logarithmic scales) the amplitude of the maximum ground velocity of a *T*-phase wavetrain to its duration, defined as the integrated time window over which it sustains 1/3 of that maximum amplitude. We build a discriminant *D* that successfully differentiates most earthquakes from explosive sources in the water. This amplitude-duration discriminant is also capable of identifying anomalous trends in the behavior of seismic sources in relation to the mechanism (e.g., conversion at a steep slope, at a shallow slope, or abyssal scattering) by which it can generate acoustic energy. We discuss the correlation between the various parameters (G, *D*) introduced and the generally deficient behavior of such sources as underwater landslides.

“Seismic Event Location: Fundamentals and Potential Problems in Event Locations Utilizing T-phases”

Gary Pavlis, *Indiana University*

Location of seismic events using a mix of conventional seismic phases and T-phases presents some serious technical challenges. In order to understand the nature of these problems I first review the fundamentals of seismic event location methods universally used for land-based seismology networks. Most seismic event locations are estimated by nonlinear inversion of a set of seismic phase arrival times, although phased array (slowness vector) measurements are sometimes used (notably in the global nuclear monitoring system). Like most inversion problems people have tended to focus too much on the solution construction problem and not enough on the error analysis problem. Since the 1960s the workhorse algorithm for solution construction is nonlinear least squares. Recently grid search methods have become more common due to the increased speed of computers, but I argue that a grid search has little intrinsic value compared to the nonlinear least squares methods. The primary benefit of a grid search is that it can always produce a solution and is not subject to local minima artifacts. In reality most location problems are intrinsic geometry problems (e.g., trying to locate teleseismic events with a local network) that are independent of the algorithm used to construct the inverse solution. The issue about solution construction most important to T-phases is the data misfit norm that is minimized by the location algorithm. This is important for locations mixing T-phases and other seismic phases because the answer can depend strongly on the minimization norm. A first order concern is that the measurement precision of T-phases is commonly very different from seismic phases like P, S, or Pn. A minimization norm that accounts for these differences is probably essential.

Errors in location estimates should always be a fundamental concern. It is now well known that location errors should be viewed in two different contexts: (1) measurement errors and (2) model errors. Measurement errors are random. They can and should be appraised by statistical models. Progress on this issue in T-phases needs to focus on developing a more realistic error model for the measurement processes used to extract arrival time (parameter) estimates from measured time series data. The term I call “model errors” is different. Although some have tried to cast this in a statistical framework I would argue this is incorrect. Earth model errors are smoothly varying functions of position that result from inadequacies of all available earth models. Work done by myself and others in the 1980s demonstrated that model errors can induce random-looking errors due to interactions with variations in the constellation of stations that record different events. The error terms themselves, however, are not random and form smooth functions of space. A current trend in land-based location is to build empirical corrections surfaces (volumes) as an alternative to velocity models. For the T-phase model errors are a multifaceted problem. When T-phases are mixed with conventional seismic phases the model errors in “conventional” phases limit the accuracy of location estimates in the same way they do land-based estimates. The T-phase problem is complicated by the fact that the propagation path is subject to an additional modeling complication. That is, numerous authors have suggested that the coupling of seismic waves into the SOFAR channel is controlled by scattering processes. This complicates accurate estimation of theoretical travel times for T-phases because standard location estimation methods universally used ray-based travel time calculators. Scattering is, by definition, a wave phenomenon that is not necessarily amenable to a ray-based mathematical model.

A recent trend that has led to dramatic improvements in location precision is the use of waveform correlation methods. I argue that waveform correlation methods should be viewed as a reciprocal array processing problem. The concept is that an ensemble of data from a localized region of the earth observed at a single station (a common receiver gather in seismic reflection jargon) will have very similar waveforms. The reason is the fundamental fact that wave propagation in the earth is the primary factor that converts a relatively simple source pulse into the long string of pulses that make up real seismic data. Sources at nearly the same point in space will excite similar propagation modes and record similar time-series data. Land observations show that these correlation methods can be applied to events separated by distances of one to a few tens of km depending upon the dominant frequency of the data. Correlation methods have not yet been extensively utilized for T-phase measurements and I suggest this is likely to be an important frontier to use T-phase data more effectively. Correlation lengths for time-series cross correlation methods are likely to be small and may limit their use to analysis of special features like single active volcanic vents. What may be more promising for routine location estimation with hydrophone networks is the technique called “incoherent beams.” An incoherent beam is a stack of the envelope of an ensemble of time-series data. They have been used extensively to extend the capabilities of receiver arrays for analysis of regional phase seismograms. The use of incoherent beam methods applied to T-phases could improve the precision of T-phases in location estimation.

“Theory of Long-range Acoustic Propagation”
John Colosi, *Woods Hole Oceanographic Institution*

Observations and theory for ocean basin-scale acoustic propagation are presented based on nearly two decades of work in the North Pacific Ocean utilizing controlled sources and vertical and horizontal receiver arrays. Broadband sources are considered with center frequencies of 250, 75, and 28 Hz, which are somewhat higher frequency than the T-phase band (1–30 Hz). Many aspects of observed long-range acoustic fields are statistical in nature because of scattering due to ocean internal waves and density compensated finestructure. It is shown that there are two distinct scattering regimes observed in the broadband multipath arrival pattern; one in which scattering is relatively weak and clear time resolved wavefronts are evident; and one in which a complex interference pattern is seen. Associated with both regimes is significant in-filling of acoustic energy into deterministic shadow zones, especially when the receivers are near the seabed or when the sources are off the sound channel axis. Scattering effects are diminished at 28 Hz relative to 75 and 250 Hz but they are not absent. Ray theory and coupled normal mode theory are shown to give new insights into the long-range ocean acoustic scattering problem.

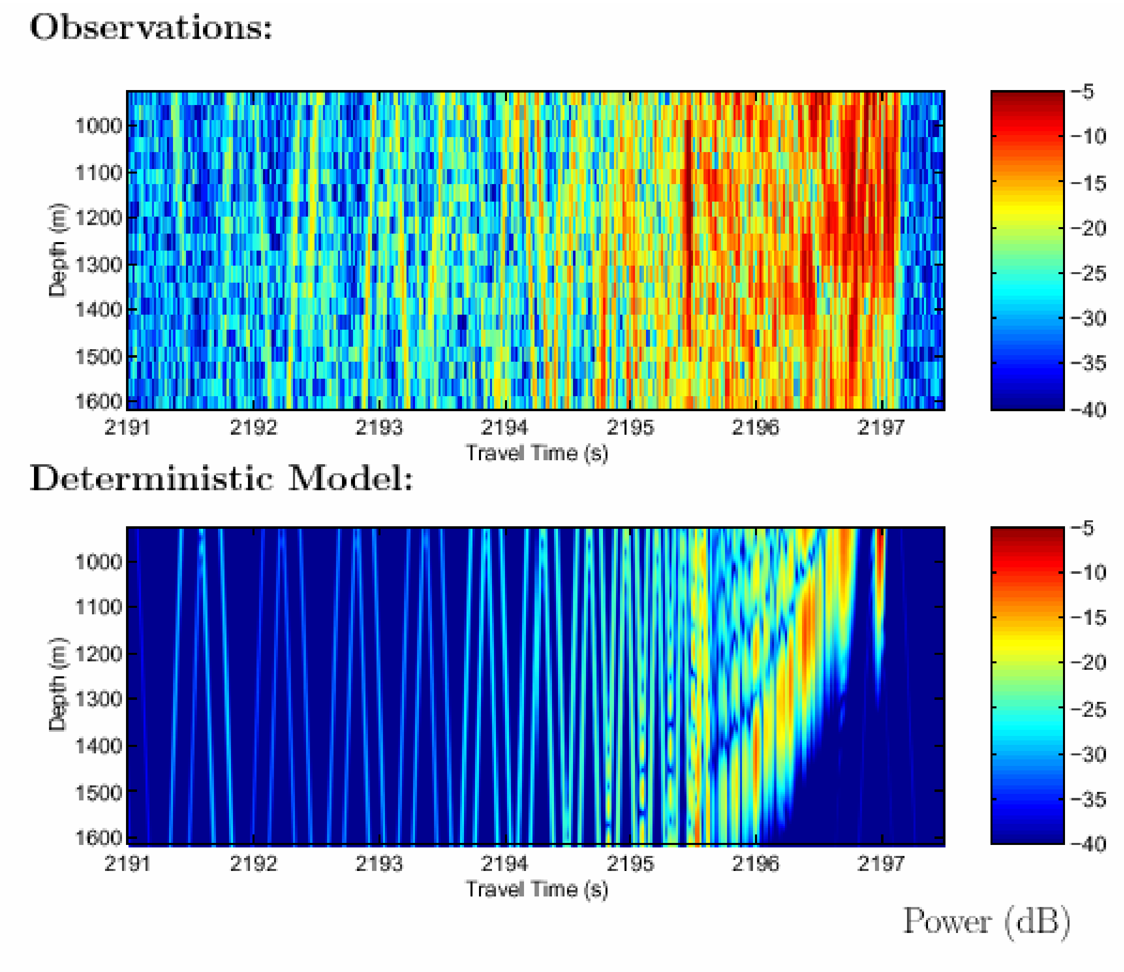
Seminal Problems

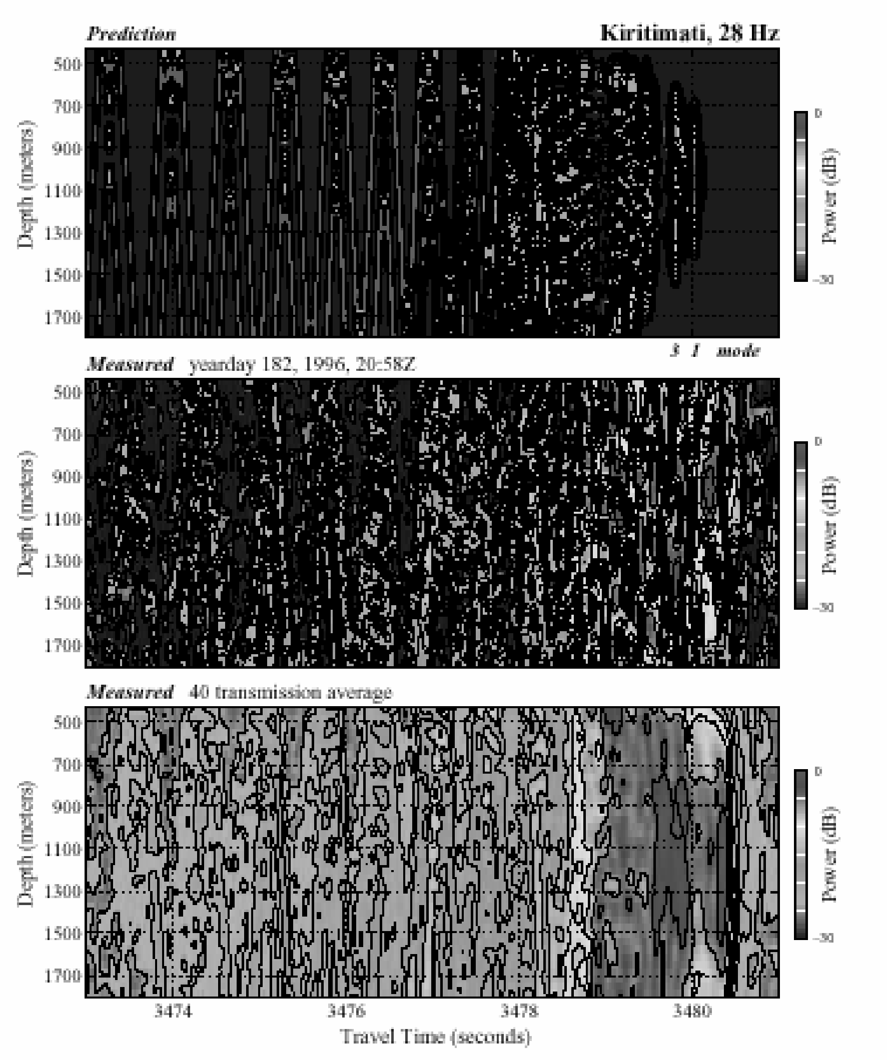
1) Low-frequency (1–30 Hz) basin-scale acoustic propagation is a “shallow water” problem as the waveguide only supports a few propagating normal modes. We do not understand the interplay between oceanographic mode coupling (internal waves, etc.), bathymetric mode coupling (abyssal hills, sea mounts, mid-ocean ridges, etc.), and bottom attenuation. This is the T-phase ocean forward problem.

2) We do not have observations of the vertical structure of T-phases to validate against forward models.

In a vertical array, range 3200 km, frequency 75 Hz, two co-existing and distinct regimes are observed:

- Early arriving wavefront region, travel time < 2195 (s), weak scattering *SI* < 1
- Late arriving wavefront region, 2195 < Travel Time < 2197 (s), stronger scattering *SI* ~1





Vertical array, range 5100 km, 28 Hz

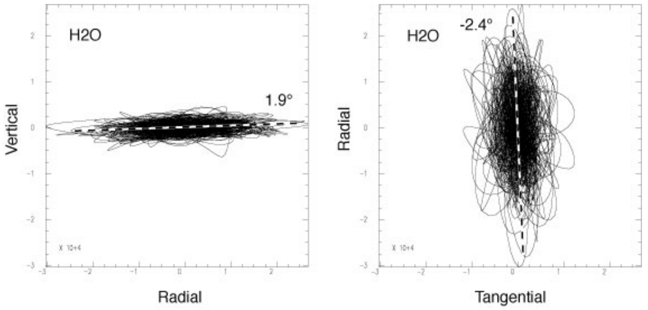
IV. Special Address Abstracts

"Observation of Seismo-Acoustic T-waves at and Beneath the Seafloor"

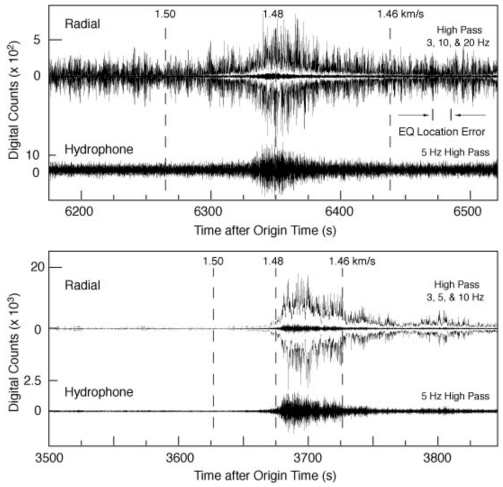
Rhett Butler, *Incorporated Research Institutions for Seismology*

The combined use of seismic and hydrophone observations show that the traditional *T* wave propagates as a seismo-acoustic, interface wave (*Ti*) coupled to the seafloor. Seismo-acoustic *Ti* waves propagating at the sound speed of water are routinely observed over megameter distances at the deep (4979 m) seafloor Hawaii-2 Observatory (H2O) between Hawaii and California, even though the seafloor site is within a shadow zone for acoustic wave propagation. *Ti* has also been observed 225 km SSW of Oahu at the OSN1 site at the seafloor and within its ODP borehole into the basalt basement. Analyses of timing, apparent velocity, energy, and polarization of these interface waves are presented. At low frequency (< ~5 Hz) *Ti* propagates dominantly in the sediments and is consistent with coupled higher-mode Rayleigh waves. At higher frequencies the observed *Ti* waves show characteristics consistent with acoustic scattering. Although no single scattering mechanism appears to be capable of generating the observed *Ti* waves, internal waves, spiciness, acoustic bio-scattering, and sea surface roughness may contribute to the observations. The observation of *Ti* from an earthquake in Guatemala at OSN1, whose path is blocked by the Island of Hawaii, suggests scattering from the vicinity of the Cross Seamount southwest of Hawaii.

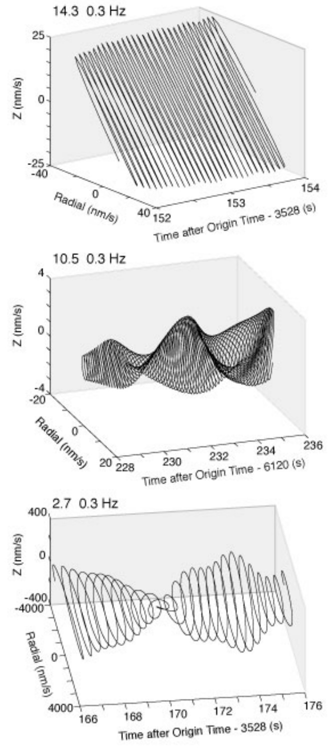
Polarization



Apparent Velocity



Particle Motion



Apparent Velocity

T waves recorded on the seismometer and hydrophone at H2O have an apparent velocity of about 1.48 km/s, corresponding with the velocity near the axis of the SOFAR channel 4 km above the seafloor site (top) for an earthquake (magnitude Mw=6.7) on the South Pacific Ridge at 9400 km on August 8, 2001. Uncertainty of apparent velocity is estimated from epicentral uncertainty (bottom). An earthquake (Mw=6.5) near the coast of Kamchatka at a distance of 5440 km on October 8, 2001, shows radial components successively high-pass filtered in three stages; the hydrophone is high-pass filtered at 5 Hz. The seismic wave field is polarized, and only the largest component, radial, is shown.

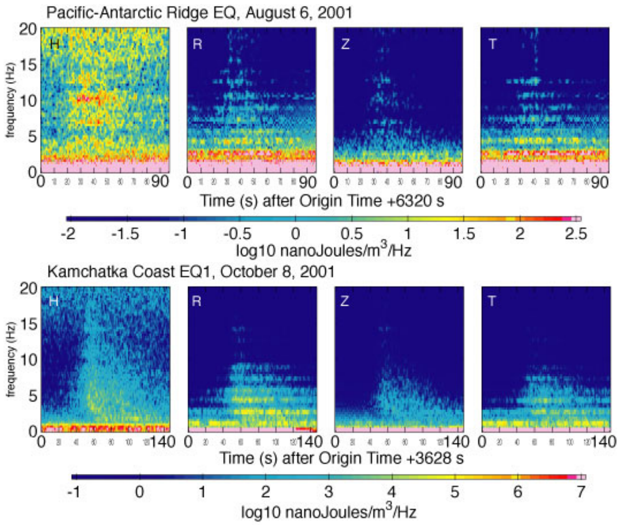
Polarization

Ti polarization of October 8, 2001, earthquake near Kamchatka from the Guralp seismometer buried in sediments. Acceleration records are normalized for instrument response, high-pass filtered at 5 Hz. Left is vertical and radial, right is radial and tangential. Both are at the same scale for direct comparison. Positive radial is toward the source, positive tangential is +90 degrees clockwise from the radial. Dotted lines show the least-squares fitting line, computed iteratively without assuming either axis as the dependent or independent variable.

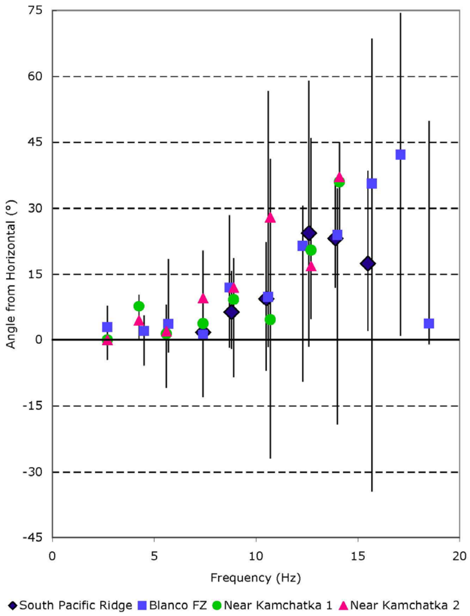
Particle Motion

Examples of *Ti* polarization observations in the sagittal plane are shown for three frequency bands from events shown in the apparent velocity panels. The upper and lower examples are from the earthquake near Kamchatka, whereas the middle example is from the southern East Pacific Rise earthquake. The lowest frequency is polarized within 1° of horizontal and displays elliptical particle motion characteristic of seismoacoustic coupled Rayleigh waves. Higher frequency bands display a wide range of steeper polarization angles, and both elliptical and rectilinear particle motions characteristic of acoustic energy from the upper ocean being scattered incident upon and coupling to the seafloor. The middle and upper observations show average polarizations at 9.5° and 40.9°, respectively, from horizontal.

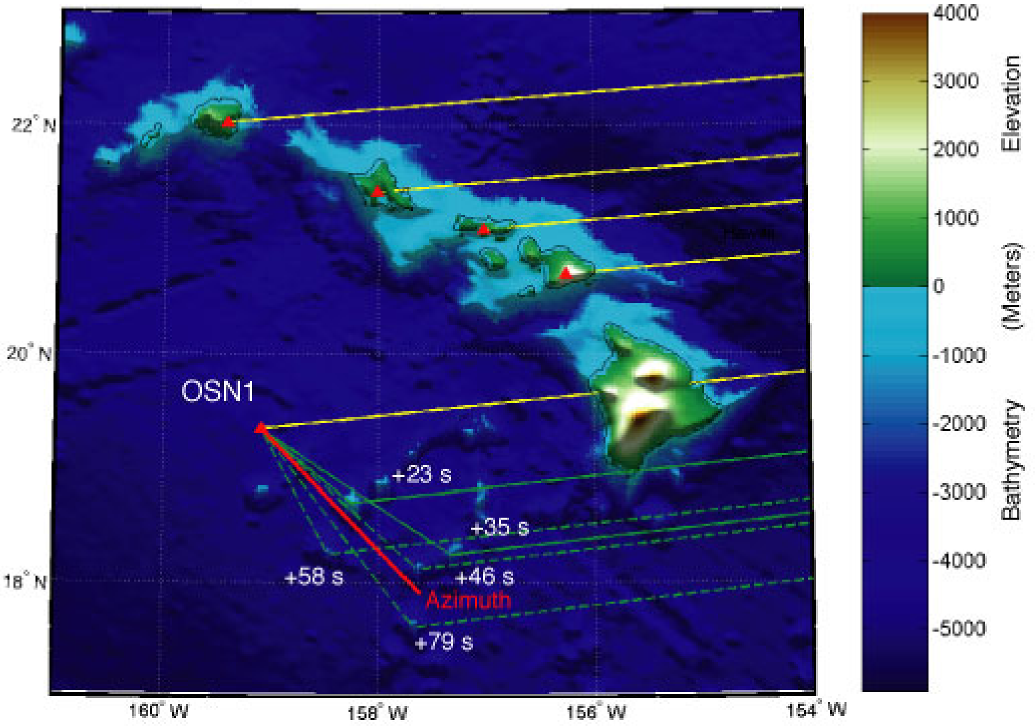
Energy: Hydrophone & Seismometer



Polarization Angle



T Wave Scattering at Seamounts Along Polarization Azimuth
Time Delay Relative to Great Circle Path to OSN1



Energy: Hydrophone and Seismometer

Spectrograms plot energy versus frequency and time corresponding to the two events. The four plots (left to right) show the hydrophone and seismic vertical, radial, and tangential components of motion, respectively, all at the same scale for a given event. At frequencies below about 5 Hz, the total energy on the seismic components in the seafloor sediment is greater than on the hydrophone located in the water only 0.5 m above the seafloor. However, at higher frequencies, the power in the hydrophone signal is greater. The banded structure in the seismic traces is indicative of modal coupling to the seafloor sediments. The hydrophone shows both modal structure and scattered energy.

Polarization Angle

The polarization (radial-vertical) angles of individual *Ti* modes are shown as a function of frequency for four earthquakes. Positive angle is down and radially away from the source. The second event near Kamchatka (Mw=6.4) occurred 6 minutes after the first and at the same location (distance and azimuth within 0.02% of first event from H2O). The Blanco Fracture Zone earthquake (Mw=6.2) on June 2, 2000, occurred at a distance of 2130 km northeast of H2O. Low-frequency modes (<5 Hz) have near radial orientation whereas higher frequencies (>5 Hz) show increasingly steeper angles and greater scatter. Symbols are plotted at the polarization of the maximum energy; lines indicate range of polarization of modal frequencies. Small variations in frequencies of individual modes are observed between events. Note polarization variation of *Ti* mode at 10.7 Hz between the first and second earthquakes near Kamchatka, which have almost identical paths.

Ti Wave Propagation and Seamount Scattering

The great circle paths (yellow) from the Guatemalan earthquake to the OSN1 site and Hawaiian Islands seismic stations are shown. The apparent great circle to OSN1 is blocked by the big Island of Hawaii. *Ti* is observed on both on the OSN1B seafloor-buried sensor as well as the OSN1 borehole seismometer 245 m below the seafloor. The apparent propagation direction of *Ti* derived from polarization analysis on the seafloor buried seismometer is shown as the red line. The green lines indicate propagation delays for paths scattered from seamounts to the southeast.

Seismoacoustic T

- < ~5 Hz
- Propagates dominantly in the sediments, observed in borehole in basalt
- Coupled higher-mode surface wave
- Propagation from earthquake source or regionally scattered?
- Seamount scattering

- > ~5 Hz
- Propagates dominantly in the water
- Scattered to seafloor, but no clear single mechanism: Internal waves, spice, bio-scatter (large marine animals), sea surface
- Multiple scattering?

"Wave-theory Modeling of Oceanic T-phase Coupling at Continental Margins and Seamounts"

Henrik Schmidt, ***Massachusetts Institute of Technology***

The role of seismo-acoustic seabed scattering as a mechanism for coupling of seismic energy into oceanic teleseismic waves or T-phases is investigated using a new versatile modeling capability for seismo-acoustic propagation in laterally inhomogeneous or range-dependent ocean waveguides. The Virtual Source Approach (VISA) uses a local Rayleigh-Kirchoff approximation to handle the transmission and reflection of plane waves at the vertical interfaces separating horizontally ocean stratified sectors. Combined with the wavenumber integration approach, which inherently computes the plane-wave decomposition of the seismo-acoustic field in stratified fluid-elastic waveguides, it provides a robust approximation to the seismo-acoustic coupling phenomena in shallow and deep ocean waveguides. The VISA approach has been implemented in the OASES seismo-acoustic modeling framework and used to investigate the role of seismo-acoustic conversion and scattering by seabed topography and roughness in generating oceanic T-phases at continental margins and seamounts. It is demonstrated that the excitation of the oceanic T-phases can be explained by the coupling of crustal shear body waves into seismic interface waves, or seabed Scholte waves, which then subsequently scatter into the waterborne modal spectrum. This wavenumber conversion mechanism implies that the excitation of the T-phases will be significantly stronger by earthquakes producing crustal SV-waves than those producing predominantly P-waves. This in turn suggests that earthquakes associated with dip-slip failure modes excite significantly stronger T-phases than buried explosive sources.

V. Working Group Summaries

T-wave Measurements and Observations—*Pulli and Bohnenstiehl*

Group Recommendations to ORION

- Each station be configured to receive T-phase signals
  - Small vertical and horizontal array (modal structure, horizontal azimuth)
  - Bandwidth ≥ 100 Hz.
- Collocated borehole, seafloor, vertical and horizontal array measurements (at some nodes); sites of continuously recording borehole instruments in Japan could be used now to compliment observations at OSN and H20.

What are the Observational Issues?

- Earthquake magnitude–source level correlation (source mechanism, path, blockage effects)
- Understand structure of T-wave arrival (moment vs. hypocenter location)
- Associate catalogs:
  - Location comparison and detection limits in different areas
  - Implications for localization (good or bad?)
- Do we need better bathymetry to understand generation and propagation?
- Tomography possible?
  - Amplitude, blockage, travel time (repeating events; reflections increase observations)

T-Phase Applications—*Dziak and Schmidt*

Scientific Issues

- Generating mechanisms
  - Earthquake source parameters (discrimination between volcanic and tectonic earthquakes)
  - Ocean waveguide coupling and propagation physics
  - Explosion discrimination
- Solid earth tomography
  - Complementary to seismic arrays
  - T-phase to better constrain earthquake location
- Plate boundary processes
  - Eruptions
  - Plate spreading
  - Fracture zone mechanics
  - Subduction

- “Passive” margin processes
  - Small earthquakes
  - Slumps
- Oceanic intraplate events
- “Icemology”
  - Nature and triggering of events
  - Climatology
- Risk assessment for undersea landslides
  - Population and distribution
  - Acoustics signatures
- Stress triggering of earthquakes (detection of small events associated with large events)
- T-phase hypocenter localization
  - Current accuracy is adequate for resolving science issues
  - Improvement possible
- Forensic seismo-acoustics
  - Airplane crashes
  - Missile launches
  - Meteor impact
  - Maritime accidents

Experiments

- Multitype arrays
  - OBS
  - Sub-seafloor seismometers
  - Vertical hydrophone arrays
  - Artificial sources
- Environmental assessment
  - Sound velocity profile
  - Seafloor bathymetry
- Component of ORION
  - Real-time, interactive infrastructure
  - “Infinite” bandwidth
  - “Infinite” power
  - Hydrophones are standard “system” sensors
  - Infrastructure for multitype arrays
- Array location
  - “Global” coverage
  - Dictated by scientific objectives
    - e.g., Ridge2000, Margins
    - Un-monitored or explored, e.g., Arctic and Antarctic
- Optimal array geometry
  - Scale dependent
  - Experiment dependent
- Data management strategy
  - Automated event detection, classification, and localization

  - Large database maintenance, quality control, metadata
  - Data processing and analysis resources
- Existing data and technology
  - Sonar signal processing technology (USN, ONR, CTBT)
  - Existing data (USN, ONR, CTBT, JAMSTEC)
  - Re-use of cables

Theory of T-Phase Excitation—*deGroot-Hedlin and Odom*

One of the key questions we need to address is how earthquakes generate T-phases, which are defined as any phase that propagates mainly within the ocean basins, but spends at least part of its propagation path within the earth's crust. Two mechanisms, either singly or in combination, have been used to describe T-phase excitation; these are:

- Multiple reflections at a sloping boundary. This mechanism is usually described using ray theory terminology. A seismic phase incident from below on a sloping seafloor generates an acoustic phase that propagates almost vertically due to the large impedance contrast between the seafloor and ocean column. Repeated reflections between the sea surface and sloping seafloor steer the acoustic phase from a vertical to a horizontal trajectory.
- Scattering of seismic energy at a rough boundary. If the seafloor boundary is rough on a scale smaller than the wavelength of the incident seismic phase, the individual scatterers serve as point sources, that is, they re-radiate some portion of the incident seismic energy into nearly horizontally-propagating acoustic energy. Normal mode terminology has been used to model this phenomenon.

Outstanding issues in the generation of T-phases include the relative contributions of various seismic phases (i.e., P-waves, S-waves, and interface waves) in seismic-to-acoustic coupling. This has bearing on the duration, amplitude, and probably spectral content of T-phases. It was emphasized several times that T-phase excitation is a **three-dimensional effect** thus, while many two-dimensional forward modeling techniques exist that can give us insights into seismic to acoustic coupling, three-dimensional forward modeling is necessary to fully predict realistic T-phase characteristics.

Two-dimensional forward modeling studies can answer several outstanding problems in T-phase such as:

- The role of marine sediments in T-phase excitation. How does the thickness or rigidity of the sediments affect T-phase amplitudes and spectral content?
- Whether the scattering of acoustic energy into the sound channel occurs at the seafloor or at the base of the sediments
- The effect of seafloor depth at the epicenter on T-phase characteristics. It was noted that although the reciprocal depth (also known as the critical depth, the depth at which the sound velocity in the water is equal to the value at the surface) does not serve as a cutoff

for T-phase generation, the efficiency of excitation decreases with increasing epicentral depth.

Accurate T-phase modeling also requires using a realistic earthquake focal mechanism (i.e., strike-slip vs. normal faulting) for the source. Ideally, we would like to model both the spectral and temporal content of T-phases, which would require three-dimensional forward modeling. It was noted that for sources near the center of a ridge, the observed shape and frequency content of the T-phase sometimes varies with azimuth of observation for a single event, with single peaks observed at some azimuths and double peaks at others. Several hypotheses were advanced to explain this phenomenon, such as multiple reflections at bathymetric promontories, or bathymetric steering, which involves the preferential excitation of acoustic energy at several high points on the seafloor in the vicinity of the epicenter. In either case, three-dimensional forward modeling is required to explain these azimuthal variations in the observed T-phase spectrograms, which may in future be useful for inferring source parameters for small and moderate-sized earthquakes. In several studies, progress has been made in understanding the effects of focal mechanism on T-phases, and of bathymetry and blockage on T-phases. However, work needs to be done on combining the results of these disparate studies to model realistic T-phase characteristics, using accurate environmental models, in order to use T-phases to infer source parameters.

It should be noted that T-phases have yielded many insights into global geophysical processes using existing analysis techniques. Our knowledge of ridge processes has advanced considerably over the past few years, thanks to long-term T-phase observations made at hydrophones in both the Atlantic and Pacific oceans. Some areas in which a better understanding of T-phase excitation may improve our understanding of ridge processes are in:

- inferring focal mechanisms from T-phases
- estimating focal depth; currently, we can detect only lateral migrations in event location over the course of an event swarm. T-phase modeling could be used to infer variations in source depth as well
- understanding rupture mechanics from T-phases. It was noted that existing location techniques identify the centroid of an event, not the locus of the initial rupture.

An unresolved issue is whether there is a bias toward identifying events in shallow bathymetry using existing event location methods, in which the T-phase source location is identified with the epicentral location. Both observational and forward modeling studies have shown that T-phases are preferentially excited in regions of shallow bathymetry. Although it was noted that many T-phase sources have been identified in both deep and shallow seafloor regions, the observation that event locations are weighted towards shallow regions is attributed to some combination of

- variations in detection limits with bathymetric depth in the epicentral region (since the efficiency of T-phase excitation decreases with increasing depth below the sound channel minimum)
- acoustic energy being preferentially excited through shallower bathymetric features in the near vicinity of the epicenter
- the fact that within the ocean basins, most events occur near ridges, where the bathymetry is shallow

An understanding of the details of near-source excitation could resolve the extent to which the bias in event location is attributable to the first two of these effects. This would require an examination of T-phase excitation in three dimensions.

Although most of the discussion revolved around excitation of T-phases by submarine earthquakes, it was noted that T-phase modeling could also yield insights into other source processes, like explosive volcanoes and landslides. Seafloor volcanoes can directly excite acoustic energy in the sound channel; in this case the acoustic energy has a pure water path only, which makes the T-phases appear more explosion-like than those excited by earthquakes. Modeling T-phase excitation by landslides would require a careful modeling of rupture mechanics.

The details of an ideal experiment to measure T-phases for the purpose of better understanding their excitation basically mirrored those listed the previous day in the breakout section on T-phase applications. Small horizontal arrays to measure azimuth to the source, and vertical line arrays to measure modal structure would ideally be located in both the near- and far-field. (Locating these arrays in both the near- and far-fields would shed light both on excitation and propagation processes). Several ocean bottom seismometers (OBS) should be located in the near-field to provide "ground-truth" estimates of source attributes like source depth and focal mechanism. Environmental characterization (e.g. detailed bathymetry, accurate estimation of seafloor velocity structure, and ocean sound speed profiles) would shed light on the coupling of seismic to acoustic energy.

Theory of Long-range Acoustic Propagation—*Worcester and McGuire*

Shallow Water Acoustics

- Propagation without bottom interaction is a more or less solved problem. (Note: This does not mean that T-phase propagation is a solved problem.)
- Propagation at frequencies of 5–10 Hz is a shallow water acoustics problem—even in deep water. The bottom is inherently part of the problem.
- We do not believe that we have elastic propagation codes adequate to make accurate predictions of 5–10-Hz propagation at ranges of 500–1000 km that take into account shear waves in the seafloor and complex bathymetry. Can we model low-frequency propagation across a mid-ocean ridge?
- Importance of internal wave induced fluctuations at 5–10 Hz should be assessed using Monte Carlo simulations
- Vertical array data would help identify modal structure of T-phase arrivals
    - A VLA located near a land-based seismometer would help improve our understanding of the conversion process from water to land

  - A VLA located in an active source region and collocated with an OBS array would help improve our understanding of the conversion process from land to water

Existing Vertical Array Data that Could be Analyzed for T-phase Arrivals

- NPAL (North Pacific Acoustic Laboratory) billboard array
  - Five vertical arrays in 1800 m of water off Sur Ridge
  - Recorded for 20 min every 4 h for 1 yr
  - Summer 1998–summer 1999
  - 10–100-Hz bandwidth (limited by cable strum)
  - Arthur Baggeroer has done a preliminary analysis of the data
  - Complementary seismic data available from land-based network
- Pioneer Seamount receiver
  - NOAA funded data collected from a 4-element vertical receiver array is available publicly
  - Complementary seismic data available from land-based network

Potential Future Experiments

- NPAL04 VLA
  - Deployed in central North Pacific June 2004–2005
  - Intense recording period during September 2004
  - Deployment of 1 or 2 collocated OBS would improve our understanding of the shadow-zone arrivals in deep water
  - NSF SGER proposal to fund OBS deployment? September 2004, high recording rate month of the vertical array.
- Floats
  - ARGO float receivers could return data every 10 days with GPS clock fixes to 1 ms (adds about $2K to the cost of a float)

Navy Issues

- U.S. Navy is interested in the 10–20-Hz band: ships and submarines
- Technology development goal would be to develop a controlled source that could operate in this band
- Scattering from internal waves should be much less at 20 Hz
- T-phase/acoustic blockage is of potential interest to the U.S. Navy

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VII. Appendix 1. Workshop Announcement

A Workshop on
Seismo-Acoustic Applications in Marine Geology and Geophysics

Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543
A workshop co-sponsored by the National Science Foundation and
the Office of Naval Research

MARCH 24–26, 2004

Registration Deadline: February 1, 2004

The goal is to identify necessary, important, or promising research directions to further the application of seismo-acoustics (T-phases) in marine geology and geophysics.

Topics will include (in each category what is the state-of-the-art, and what are the outstanding issues):

a) T-phase observations
b) Applications of T-phases in MG&G
c) Theory of T-phase excitation
d) Theory of long range acoustic propagation

Workshop format will include invited plenary talks, contributed research, posters, discussions and preparation of summary documents by working groups. A report from the workshop, including specific recommendations will be prepared.

Co-convenors:

Ralph A. Stephen
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For registration information, please call 508-289-3425, or register online at
http://www.whoi.edu/institutes/doei/activities/symposia_workshop.htm

VIII. Appendix 2. Workshop Participants

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IX. Appendix 3. Workshop Agenda and Notes for Breakout Groups

Workshop on Seismo-Acoustic Applications in Marine Geology and Geophysics

Co-sponsors: NSF and ONR

Co-convenors: Ralph Stephen (WHOI) and Bob Odom (UW)

Where: Woods Hole, MA

When: March 24-26, 2004

Duration: 2.5 days

Web Site: http://www.whoi.edu/institutes/doei/activities/symposia_seismo.htm

Steering Committee:

Rhett Butler, *Incorporated Research Institutions for Seismology*
Catherine de Groot-Hedlin, *Scripps Institution of Oceanography*
Bob Dziak, *Pacific Marine Environmental Laboratory*
Bob Odom, *Applied Physics Laboratory, University of Washington*
Henrik Schmidt, *Massachusetts Institute of Technology*
Debbie Smith, *Woods Hole Oceanographic Institution*
Ralph Stephen, *Woods Hole Oceanographic Institution*
Peter Worcester, *Scripps Institution of Oceanography*

Goals:

- Identify necessary, important, or promising research directions to further the application of seismo-acoustics (T-phases) in marine geology and geophysics. What are the limitations of our present knowledge? What potential is there for improving seismo-acoustics as a technique for studying earth science in the oceans? What are the Navy-relevant aspects of T-phase research?
- By providing an opportunity for the marine geology and geophysics and ocean acoustics communities to organize their thoughts on this topic, we hope to provide the funding agencies and community with clear guidelines for future research in this field. Workshop recommendations could be cited, for example, in proposals from individual (or groups of individual) investigators to ONR and NSF.

Acknowledgments: We would like to thank Dave Epp (NSF) and Nic Chotiros (ONR) for their support in planning this workshop.

Agenda

Wednesday, March 24

7:30 Projectionist available to help with downloading and testing electronic presentations. This morning's speakers, who did not send their files in advance, should download and test their presentations on the meeting laptop.

8:00–8:30 Continental breakfast and set up posters

8:30–8:40 Welcome and logistics—Ralph Stephen and Bob Odom

8:40–8:50 Remarks from NSF—Dave Epp

8:50–9:00 Remarks from ONR–Nick Chotiros

9:00–10:00 Keynote addresses and discussion, "Background of T-phase Observations," Maya Tolstoy, LDEO

10:00–10:30 Coffee break and poster session

10:30–11:30 Keynote address and discussion, "Proven and Potential Applications of T-phases," Bob Dziak, PMEL

11:30–12:00 Special address and discussion, "Observations of Seismo-acoustic T-waves at and Beneath the Seafloor," Rhett Butler, IRIS

12:00–1:00 Lunch

1:00–3:00 Breakout sessions on "T-phase Observations" and "Applications of T-phases in Marine Geology and Geophysics," see the attached "Notes for breakout groups"

3:00–3:30 Coffee break

3:30–5:00 Plenary session to review the progress of the breakout groups—working group leaders summarize the "key issues" identified by their groups; work on writing assignments

Thursday, March 25

8:00–9:00 Continental breakfast, view posters, and prepare electronic presentations

9:00–10:15 Keynote address and discussion, "Theory of T-phase Excitation," Emile Okal, Northwestern University

10:15–10:45 Coffee break and poster session

10:45–12:00 Keynote address and discussion, "Theory of Long-range Acoustic Propagation," John Colosi, WHOI

12:00–1:00 Lunch

1:00–3:00 Breakout sessions on "Theory of T-phase Excitation" and "Theory of Long-range Acoustic Propagation," see the attached "Notes for breakout groups"

3:00–3:30 Coffee break

3:30–5:00 Plenary session to review the progress of the breakout—working group leaders summarize the “key issues” identified by their groups; writing assignments

7:00–?:?? Dinner, Coonamesett Inn

Friday, March 26

8:00–9:00 Continental breakfast, view posters, and prepare electronic presentations

9:00–10:00 Keynote address and discussion, “Earthquake Locations Used to Address Geological Problems on Land,” Gary Pavlis, Indiana University

What resolution do they require? Are marine data sets better or worse than land data sets?

10:00–10:30 Coffee break and poster session

10:30–11:45 Bob Odom and Ralph Stephen—Summary of the results of the workshop, outline of the workshop report and writing assignments for the remaining sections of the report

11:45–12:00 Concluding remarks—Ralph Stephen and Bob Odom

Notes for Breakout Groups

Summary of T-phase Observations

Group Leader: Debbie Smith

Raporteur: Del Bohnenstiehl

What is the state-of-the-art and what are the outstanding issues? Using the questions as a guide and a starting point, identify (and ideally prioritize) the key issues.

How do T-phase location accuracies compare with the accuracy of land-based GSN arrays for MOR earthquakes? How do they compare with the accuracy of events inside and outside the small aperture of typical OBS arrays? How do they compare with the accuracy achievable by local land seismic networks for local earthquake activity on seismogenic structures ashore (say Southern California or Japan)?

Which part of the T-wave arrival coda should be used to estimate earthquake source locations? Is the onset, the peak amplitude, or the broadest band of the T-wave the best arrival to estimate the physical source of the signal? Can acoustic propagation and forward models help resolve this issue?

What is the relation, if any, between T-phase magnitudes and seismic source magnitudes? Several investigators have found strong correlations in source magnitude and T-phase amplitude over small source regions. What factors will influence the reliability of inferring source magnitude from T-phase amplitude?

In some cases, teleseismic P-waves are recorded on the same hydrophones used to observe T-phases. How can we use these to broaden our understanding of T-phases, microearthquakes, and volcanic activity?

Applications of T-phases in Marine Geology and Geophysics

Group Leader: Bob Dziak

Raporteur: Henrik Schmidt

What is the state-of-the-art and what are the outstanding issues? Using the questions as a guide and a starting point, identify (and ideally prioritize) the key issues.

What is the next step in "gleaning" as much geological information as possible from the T-phase data sets?

What geological problems would we like to address under the oceans and what epicenter accuracies are required to adequately address them? How do the required accuracies compare with common seismic practice on land and at-sea? Could some of the existing empirically based geologic results benefit from a more complete physical description of the T-phase process?

What experiments are required to test new applications?

What would the "ideal" T-phase experiment look like? For example, typical ocean basin T-phase arrays consist of single hydrophones moored in the SOFAR channel. Would we expect vertical arrays of hydrophones to help very much? What about horizontal arrays (linear or tripartite-triangular) to determine the azimuth of T-phase arrivals?

Theory of T-phase Excitation

Group Leader: Catherine deGroot-Hedlin

Raporteur: Bob Odom

How does energy get from the earthquake into the sound channel?

What is the state-of-the-art and what are the outstanding issues? Using the questions as a guide and a starting point, identify (and ideally prioritize) the key issues. What are the links between the theory and analysis groups (2nd day) and the measurement and marine geology groups (1st day)?

What existing forward modeling techniques could be used or combined to provide a predictive model for T-phase **excitation**? What are the important characteristics of T-phases that a model would need to predict? What level of accuracy do we need in our physical models to predict T-phase attributes?

How sensitive are the T-phase characteristics to the water depth above the epicenter? Can epicentral water depth be determined from T-phase observations and hence used to constrain event locations in regions of strong topography (such as the Mid-Atlantic Ridge)? Why do the spectral amplitudes, frequency content, and duration of T-phase arrivals appear in some instances to be independent of water depth at the epicenter?

What is the role of the earthquake source mechanism in T-phase excitation (for example, strike slip vs. normal faulting)? Are the excitation and blockage mechanisms sufficiently well known that we can use the azimuthal variations in T-phase characteristics to infer properties and/or source parameters of small and moderate size earthquakes?

What is the role of the sediment layer in T-phase excitation? Is the rigidity of the sediments an important factor? Can we predict T-phase characteristics (frequency content, amplitude levels, rise time, and coda duration) from a knowledge of bathymetry and sediment thickness (the rough basement surface may be more important than a rough sediment surface)?

Does earthquake energy only couple into the SOFAR channel through seamounts and other roughness elements on the seafloor? Is there a bias towards shallow bathymetry (seamounts and ridges) in the T-phase locations using existing techniques? Since T-phases do not locate many earthquakes in the deep transform fault valleys in the North Atlantic, does this mean that no earthquakes occur here or is the seafloor too deep to get energy into the SOFAR channel? Does the sound preferentially travel through the shallower bathymetric features such as the transform fault walls? If earthquakes are not observed on a section of fault or ridge is this because they did not occur or is it because the conditions for getting energy into the SOFAR channel are not satisfied?

Which is more important in detecting T-phases from shallow bathymetry, bathymetric steering or a lower attenuation rate because the earthquake source is closer to the sound channel? Since vertical propagation of acoustic body waves through the ocean water column undergoes spherical spreading, are detection thresholds reduced when the seafloor is closer to the sound channel? Perhaps more earthquakes are “detected” from shallow bathymetry, rather than locations being “steered” over to shallow bathymetry.

Theory of Long-range Acoustic Propagation

Group Leader: Peter Worcester

Raporteur: Jeff McGuire

What is the state-of-the-art and what are the outstanding issues? Using the questions as a guide and a starting point, identify (and ideally prioritize) the key issues. What are the links between the theory and analysis groups (2nd day) and the measurement and marine geology groups (1st day)?

What, if any, role do T-phases play in the performance of U.S. Navy systems? (For example, could earthquake sources be used to study long-range propagation, instead of controlled sources which may be difficult to deploy because of marine mammal issues? Could earthquakes be used to provide broader geographical coverage of the ocean basins for tomography studies? If T-phases involve the coupling of energy between the sound channel and the seafloor, what does this mean for models of ambient noise in the ocean in the frequency band 1–100 Hz?

What existing forward modeling techniques could be used or combined to provide a predictive model for T-phase **propagation**? What are the important characteristics of T-phases that a model would need to predict? What level of accuracy do we need in our physical models to predict T-phase attributes?

If T-phase propagation is trapped in the ocean sound channel, why do we observe T-phase events on seismic sensors on the seafloor and even sensors hundreds of meters into the seafloor in the deep ocean where the water depth exceeds the conjugate depth?

How important is bathymetric blocking in reducing the number of observed T-wave arrivals? Can simple ray models adequately explain blockage? For short-range observations (less than 500 km), do we need to consider convergence zone effects to understand blockage?

What is the role of the sediment layer in T-phase propagation? Is the rigidity of the sediments an important factor? Can we predict T-phase characteristics (frequency content, amplitude levels, rise time, and coda duration) from a knowledge of bathymetry and sediment thickness (the rough basement surface may be more important than a rough sediment surface)?

Further Background

Although T-phases were identified over 50 years ago, the application of T-phases to marine geology and geophysics was rejuvenated in the 1990s when the NOAA VENTS program used data from the northeast Pacific SOSUS arrays to monitor the seismic activity on the Juan de Fuca Ridge in real time. These observations taught us first that small and moderate size earthquake activity (>2.5 or 3 mb) in the ocean basins, particularly on active ridges, is more frequent than expected. Secondly, by monitoring small and moderate size earthquakes in real time it allowed investigators to respond to volcanic and/or magmatic events on the Juan de Fuca Ridge. The response to the Co-Axial event particularly provided convincing support for the existence of the deep hot biosphere. Subsequently the NOAA/VENTS program has deployed six hydrophones in the east central Pacific (near the TOGA/TAU buoys) to monitor the East Pacific Rise, and NSF has funded the deployment of six hydrophones in the North Atlantic to monitor the mid-Atlantic Ridge.

Funding is in place to continue to respond to events detected in the northeast Pacific. However, ideas for follow-on studies of the other hydrophone data have run into problems. There seem to be three main schools of thought:

1) We should be careful how we use T-phase locations until the physics of coupling energy from the earthquake in the crust into the sound channel is understood
2) The locations of small and moderate size earthquakes should be checked by deploying an array of OBSs on the ridge; events can be located by both the OBS array and the T-phase array
3) Before worrying about the physics of T-phase excitation and propagation, let us see if T-phases are providing information that can be used to solve a geologic problem

Some investigators use T-phase event locations to constrain models of geologic processes on the assumption that they are good proxies for epicentral locations. The success of T-phase locations to identify volcanic and/or magmatic events on the Juan de Fuca Ridge provides empirical evidence to support this case. Other investigators are concerned that there may be topographic or other biases in the T-phase locations. The T-phase locations are where the energy is entering the sound channel, which may not necessarily be directly above the epicenter.

X. Appendix 4. Poster Abstracts

E. Araki, R. A. Stephen, M. Shinohara, T. Kanazawa, and K. Suyehiro

T-phase observed at deep sea boreholes

We inspected seismic records from two seafloor borehole seismometers in the Philippine Sea and the NW Pacific. Long-term observation from the seafloor boreholes enabled us to cover the whole regional seismicity. Despite their station location at deep seafloor (> 5 km), we see many of the seismic events accompanied the T-phases below 10 Hz. The distribution of seismic events observed with the T-phases and their T-phase amplitude compared with those of P/S phases, are useful to infer characteristics of acoustic wave propagation in the sea.

Del Bohnenstiehl

Application of T-wave data: T-wave earthquake catalog used to study the time-clustering behavior of spreading center seismicity

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Kaelig Castor, Peter Gerstoft, Philippe Roux, and W.A. Kuperman

Long-range propagation of finite amplitude acoustic waves in an ocean waveguide

The Nonlinear Progressive Wave Equation (NPE) [McDonald and Kuperman, 1987] computer code was coupled with a linear normal mode code in order to study propagation from a high intensity source in either shallow or deep water. Simulations using the coupled NPE/linear code are used to study both harmonic (high frequency) and parametric (low frequency) generation and propagation in shallow or deep water with long-range propagation paths. Included in the modeling are both shock dissipation and linear attenuation in the bottom.

Wu-Cheng Chi and Doug Dreger

Finite fault inversion of the 1999 Chi-Chi, Taiwan, earthquake (Mw=7.6)

Catherine de Groot-Hedlin

Hypocentral location using T-phase waveform matching: Ridge events

A method of using a T-phase envelope matching technique to derive source hypocentral coordinates from T-phase data is presented for a single ridge event in the Indian Ocean. It is shown that for events like this, where the seafloor is below the SOFAR channel depth, the intensity of acoustic excitation decreases with depth below the SOFAR channel. Thus for abyssal events (those occurring below the SOFAR channel) T-wave excitation is strongest at bathymetric promontories. Synthetic T-wave envelopes may be computed and compared to the observed envelopes to derive a hypocentral location. For the event analyzed here, it is shown that the precision in the derived source location is approximately equal to the grid spacing. Synthetic back azimuths are also computed and compared to back azimuths computed from the T-waveforms for a series of short time windows within the T-phase coda. Both show that the back azimuth decreases as a function of time for this event. In future work, back azimuth information and fine-scale bathymetry will be used to refine hypocentral location.

Haru Matsumoto, Robert P. Dziak, and Dave K. Mellinger

Global T-phase monitoring: Past, present, and future

In 1991 NOAA (National Oceanic and Atmospheric Administration) and Oregon State University began continuous recording of digitized acoustic data from the Navy’s fixed hydrophone array (SOSUS) for the detection of T-phase sound waves in the northeast Pacific. Following the successful detection of an underwater eruption, NOAA/OSU developed autonomous hydrophone (AUH) arrays to monitor other tectonically active areas not covered by the fixed hydrophones. This strategy requires deployment of multiple hydrophones, each with its own battery powered self-recording package. The array is moored at SOFAR channel depth over extended deployment periods. In May of 1996, the first AUH array consisting of six autonomous hydrophones was deployed and began long-term monitoring of the East Pacific Rise between 20ºN and 20ºS. Each hydrophone package consisted of a pre-amp with a pre-whitening filter, a clock accurate to 1 s/yr, a data logger to digitize the hydrophone signal, and IDE hard disks for data storage. In 1999 monitoring of the central mid-Atlantic Ridge (MAR array supported by NSF) area began using the second generation of autonomous hydrophones. As of 2004, the current NOAA/OSU autonomous hydrophone is capable of data sampling at 2.5 kHz with 16-bit resolution with and storage capacity up to 400 GB. Evidence from the NSF supported mid-Atlantic and north Atlantic array (in cooperation with University of Brest, France) suggests that large teleseismic events propagating through the deep-mantle and core can enter the water column vertically and be detected by the hydrophone array. Compared to a cabled ocean observatory, the AUH approach allows deployment of an array in an area of importance for the scientific community for a relatively low cost. To achieve real-time monitoring capability by the battery operated hydrophone, a simple but reliable event detection algorithm is imperative.

David McCormack and Cathy Woodgold

T-phases observations from land-based arrays

This poster describes a series of T-phase observations carried out on the Queen Charlotte Islands, an archipelago off the west coast of Canada. Located at 53ºN and with elevations to 1123 m, the area has both extreme weather conditions and typical mid-latitude sound speed profiles.

Jeff McGuire, John A. Collins, and Deborah Smith

Long-term, continuous, seismic, and seismo-acoustic monitoring of the Northern Atlantic Basin: An observing system for the scientific community

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Jay J. Pulli, Zachary M. Upton, and Joydeep Bhattacharyya

T-wave Observations in the Indian Ocean

Minkyu Park, Robert I. Odom, Robert P. Dziak, Young Keun Jin, and Jong Kuk Hong

T-wave excitation from seafloor tectonic and volcanic events

A modal representation of the seismo-acoustic wave field provides a natural framework for modeling T-waves, and makes clear well known features of T-waves such as generally weak dispersion and the connection of the energy near the SOFAR channel axis. T-waves are numerically modeled using mode scattering theory (*Park and Odom*, 1999) and a T-wave excitation mechanism (*Park et al*., 2001). We also present preliminary results derived for seafloor volcanic and magmatic activities. Near-field and far-field excitation of T-waves are also discussed in this poster.

The SIRENA team

Interactions between the MAR and the Azores hotspot as imaged by the seismicity distribution using autonomous hydrophone arrays

An array of six autonomous hydrophones was deployed on the flanks of the mid-Atlantic Ridge, north of the Azores, between latitudes 40º20'N and 50º34'N. The deployment took place in the framework of the France-USA-Portugal cooperative "SIRENA" experiment.

R/V *Le Suroit* moored the six instruments during the SIRENA 2002 cruise. The ship sailed from Ponta Delgada (Azores) on May 17 and docked in Brest on June 3, 2002. The array recovery was achieved during the SIRENA 2/D274 cruise, sailed by the RRS *Discovery* between Govan (Scotland, September 12, 2003) and Ponta Delgada (October 1, 2003).

The interpretation of the hydroacoustic signals recorded by the SIRENA network begun in Brest in early November 2003 and in Newport by the end of 2003. This interpretation was conducted along two different lines:

- We first concentrated on some of the periods during which large earthquakes (i.e., with a typical magnitude over 4.5 to 5.0) had been detected by global seismic networks and listed in the NEIC catalog. This first approach allowed to assess the global performance of the SIRENA network and gave new results on the seismicity of the Reykjanes Ridge.
- Then a systematic event location was undertaken by picking from a composite data set including both the SIRENA and the South Azores PMEL/NSF networks, during the common period of operation of both networks (that is from June 1, 2002, start of the SIRENA data set to April 200 when the South Azores network was last serviced). This picking has hitherto been completed over a three-month period, from June 1 to August 31, 2002.

The results below should therefore be considered as very preliminary. They nevertheless provide exciting ideas on the processes that are active in a slow ridge/mantle plume interaction context. Finally, event picking on the SIRENA data over this three-month period and over shorter "test" periods confirms that the network succeeded in detecting and locating 20 to 30 times more events than the global seismic networks.

Sara Bazin

Attempt to improve the Caribbean seismic network array with autonomous hydrophones

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Deborah K. Smith, John A. Collins, and Jeffrey J. McGuire

Activity on the shallow top of the Atlantis massif: Is it seismically active of just a T-phase radiator?

Ralph A. Stephen, Deborah K. Smith, and Claire Williams

The dynamics of abyssal T-phases

Ocean seismic networks that exploit T-phase arrivals provide a popular, convenient, and inexpensive approach to monitoring earthquake activity in the ocean basins. The characteristics of earthquakes, as revealed by T-phase observations, have the potential to provide important constraints on physical models of crustal processes under the oceans. We do not know, however, how to infer earthquake source mechanisms, magnitudes, or depth from T-phase observations because we do not know the physical mechanisms responsible for getting T-phase energy from the earthquake epicenter into the ocean sound channel. The "T-phase problem" can be described as a disconnect between i) the steep grazing angles of sound propagation in the ocean from a source in the crust or upper mantle and ii) the shallow grazing angles required for sound traveling in the ocean sound channel. It has been postulated that some form of scattering at or near the seafloor is necessary to convert the compressional and shear body waves from earthquakes into the low grazing angle paths necessary for propagation in the ocean sound channel. Other mechanisms include "wave tunneling," interface waves (Stoneley, Scholte, and Rayleigh waves), and shear wave resonances (modes) in the sediments. We use the time domain finite difference method to demonstrate how these mechanisms work.

Hiroko Sugioka

Semidiurnal variation of the ocean sound velocity associated with the M2 internal tide

Swarms of hydroacoustic waves (T-waves) occur in the higher submarine volcanic activity. Many T-wave events associated with the activity in the Izu-Bonin-Mariana volcanic region are detected using several Japanese cabled ocean bottom seismometers (OBS). The epicenter was located at 20.3729 ± 0.49031ºN, 144.9508 ± 0.2755ºE) by solving the linearized observation equation. The ringing sounds from seamounts gave us knowledge not only about the feature of the volcanic activity but also about the nature of the internal tides. We found the T-wave travel times associated with the submarine volcanic events over long range have the semidiurnal variations.

Here, we show that the periodical variation of the sound velocity (~ 0.2 s) is associated with the M2 internal tide using the numerical model of the internal tides, which excited by flat-bump topography of the western Pacific Trench, to be consistent with the traveling length charge due to the vertical displacements (~ 300 m) in phase with ocean tidal forces.

Claire Williams, Ralph A. Stephen, and Deborah K. Smith

Hydroacoustic events located near the Atlantis (30°N) and Kane (23°30'N) transform faults on the MAR

The main goal of this project is to obtain a better understanding of the acoustic T-phases from oceanic crust earthquakes. We use data from an autonomous hydrophone array that has been monitoring the Mid-Atlantic Ridge (MAR) between 15ºN and 35ºN since February 1999. The T-phases chosen for the investigation are located at two study areas: the inside corner (IC) and ridge transform intersection at the eastern ends of the Kane (23º30'N) and Atlantis (30ºN) transform faults in the North Atlantic. Both regions of high relief (up to 5000 m from the transform valley to the top of the IC massif) and T-phase events are located on the top and flanks of the massif and in the transform valleys. In order to address our goals we make four assumptions: 1) the T-phase event locations are accurate, 2) the locations represent earthquake epicenters, 3) all the events have a similar magnitude and 4) that current models of T-phase generation and propagation are correct. We investigate the spatial distribution of the T-phase event locations as a function of water depth. We examine in detail the characteristics of the T-phases as a function of both distance from the event to each hydrophone and T-phase location water depth. Finally, we use a simple ray trace model to study the effects of known topography along the propagation path of the T-phase to test for bathymetric blockage.

The results of the study reveal several important observations. The acoustic magnitude of the T-phase shows no dependence on the water depth of the T-phase location. This is opposite to the predictions from current T-phase generation models which yield a water depth dependence. There may be a correlation between T-phase acoustic magnitude and propagation path topography but the results are sensitive to the sound velocity profile used in the mode. The results of the study underscore the complexity of T-phase generation and propagation and argue that current models describing the mechanics of T-phases are insufficient.

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13. ABSTRACT *(Maximum 200 words)*

The workshop, "Seismo-Acoustic Applications in Marine Geology and Geophysics," took place at Woods Hole Oceanographic Institution on March 24–26, 2004. The thirty-three attendees of the workshop represented a broad spectrum of researchers including experimentalists and modelers, and spanned the fields of marine geology and geophysics, long-range ocean acoustics, and continental crutal seismology. The following were the workshop's goals:

1. Identify necessary, important, or promising research directions to further the application of seismo-acoustics (T-phases) in marine geology and geophysics. What are the limitations of our present knowledge? What potential is there for improving seismo-acoustics as a technique to study earth science in the oceans? What are the aspects of T-phase research relevant to the U.S. Navy.
2. Provide an opportunity for the marine geology and geophysics and ocean acoustics communities to organize their thoughts on this topic, and provide funding agencies and community with clear guidelines for future research in this field. Workshop recommendations could be cited, for example, in proposals from individual (or groups of individual) investigators to ONR and NSF.

This report consists of a 58-page summary of the workshop and its recommendations and 13 poster presentations included on a multimedia CD-R available through the APL-UW Library (library@apl.washington.edu).

14. SUBJECT TERMS
T-phase, T-waves, ocean acoustics, seismo-acoustics, submarine volcanism, hydrophone arrays, marine crustal processes, T-phase excitation, marine geology and geophysics

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