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T WAVES

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Definition and introduction

T phases are defined as seismic recordings of signals having traveled an extended path as acoustic waves in the water body of the oceans. This is made possible by the "Sound Fixing and Ranging" (SOFAR) channel, a layer of minimum sound velocity acting as a wave guide at average depths of 1,000 m (Okal, 2007). It allows the efficient propagation of extremely small signals over extremely long distances, in practice limited only by the finite size of the ocean basins. The existence of the SOFAR channel results from the dependence of the velocity of sound in water on temperature, pressure and salinity. As a result, the detailed structure of the channel (including the value of the minimum velocity) varies both geographically (mainly with latitude) and seasonally, but at first order, the SOFAR channel can be regarded as a quasi-universal feature of the world's oceans.

At the shoreline of a continent or island, the acoustic wave is converted into a seismic wave which can be recorded by a seismometer or, occasionally, felt by humans. Efficient propagation inside the waveguide requires short wavelengths, in practice frequencies above 3 Hz, and thus T phases generally attenuate fast once converted, although in exceptional geometries they have been detected up to 1,000 km inside stable continental shields. Even though records of T waves were reported as early as 1927, they were not identified as hydroacoustic signals until the late 1940s, when results from antisubmarine warfare during World War II were declassified.

Sources of T waves

T waves can be generated by a diversity of underwater sources, as long as their energy becomes trapped in the SOFAR channel. Most earthquakes in oceanic margins generate strong T phases, since in the presence of a sloping ocean floor, multiple downslope reflections can lead to efficient penetration of the SOFAR (Johnson et al., 1963). However, their generation by earthquakes in abyssal plains deprived of large-scale bathymetry defies the laws of geometrical optics, and remains to this day a major theoretical challenge; it is generally thought that abyssal T phases result from scattering along small random heterogeneities of the ocean floor (Yang and Forsyth, 2003). Also, T waves are occasionally generated by non-shallow earthquakes, even the deepest ones, even though their source is de facto distant from the ocean column. This excitation is made possible by travel through the subducting oceanic slabs which, being cold, propagate high frequencies with limited attenuation and can deliver them to the water interface for conversion to acoustic waves (Okal, 2001a).

Underwater landslides are also T-wave generators. As compared with earthquakes, such sources, which move generally smaller segments of ocean floor over much larger distances, have a considerably longer duration, a lower-frequency spectrum, and thus result in T waves of longer duration but smaller amplitudes (Okal, 2003).

By contrast, explosions at sea, which are intrinsically high-frequency, are particularly efficient sources of T waves; in most instances, they involve a shallow source located inside the SOFAR channel, thus providing optimal feeding of acoustic energy into the channel. In particular, seismic reflection experiments are routinely recorded thousands of kilometers away.

Underwater volcanic eruptions are also regular generators of T waves. Because of the diversity of processes involved during a volcanic sequence, these signals may

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feature a wide variety of characteristics. The opening of cracks during the formation of magmatic plumbing systems is essentially in the nature of an earthquake, while magmatophreatic explosions at the contact between a lava conduit and the oceanic column are reminiscent of chemical explosions. The steady output of lava into the ocean takes the form of a prolonged noise of low amplitude which may be compared to underwater slumping (Caplan-Auerbach et al., 2001). Finally, the oscillation of magma inside the plumbing system, known to cause volcanic tremor long recorded seismically on subaerial volcanoes, generates harmonic T-wave signals. Supercritical hydrothermal venting during volcanic events has also been documented as the source of monochromatic hydroacoustic signals (Talandier and Okal, 1996).

Among the most remarkable T waves ever reported, signals from the eruption of Macdonald Volcano (29°S; 140°W) on 29 May 1967 led to the eventual discovery of this unchartered underwater seamount, and its interpretation as the active member of the Cook-Austral hotspot chain (Johnson, 1970).

The collision of large icebergs, during which their masses can rub against each other, has also been documented as a source of T waves, which can exhibit a harmonic character during episodes of stick-and-slip friction between tabular icebergs (MacAyeal et al., 2008). Hydroacoustic waves are also generated during the disintegration of large icebergs, and thus could be used to monitor and assess any possible change in climatic conditions (Li and Gavrilov, 2006).

Finally, marine mammals can talk into the SOFAR channel and correspond across hundreds of kilometers, using signals in the range of a few tens of hertz, but specific to each species.

Human perception

T waves of sufficient amplitude can be felt by shoreline populations. For example, the underwater nuclear test WIGWAM on 14 May 1955 off the coast of Southern California was felt in Hawaii and even in Japan, 8,000 km away. Large events such as the Alaskan earthquake of 10 July 1958 and the deep Bolivian shock of 9 June 1994 were felt in Hawaii, and T waves from the 2004 Sumatra earthquake were felt in the Maldives and possibly on Zanzibar; they could have provided a warning of the impending tsunami in these otherwise aseismic areas, but their populations were unprepared.

Use in comprehensive nuclear-test ban treaty monitoring

Because hydroacoustic waves can detect small sources (especially intra-oceanic ones) at great distances, they have been included as one of the four technologies used by the International Monitoring System (IMS) of the Comprehensive Nuclear-Test Ban Treaty. Their spectacular efficiency in propagation allows a full coverage of the all the Earth's oceans using only 11 receiver sites, six of which are hydrophones deployed within the SOFAR channels, and five special seismic stations close to shorelines ("T-phase stations"), instrumented for high-frequency seismic recording in the 50–100 Hz range (Okal, 2001b).

Acoustic thermometry of ocean climate

This project consisted of using acoustic sources in the 57 Hz range fired in the vicinity of Heard Island, South Indian Ocean, a location allowing the illumination of all three major oceans (Munk et al., 1994). Detection at extreme ranges of up to 17,000 km allowed precise measurement of acoustic velocities, and it was envisioned to repeat these experiments over several decades, to monitor any evolution of sound velocities, as a proxy to changes in temperature, possibly in the context of global warming. Unfortunately, the project had to be halted in the late 1990s under pressure from the environmental lobby.

Quantification

Like other seismic phases, quantitative measurements of T waves can provide information on source parameters. However, absolute measurements (especially of amplitudes) at seismic receivers are difficult to interpret due to the complexity and site specificity of the conversion processes. In addition, the high-frequency nature of the phase results in amplitude saturation at relatively low magnitudes. In this context, quantification of T waves has emphasized duration of wavetrains over amplitude, and relative measurements under common or comparable receiver conditions. *Okal et al.* (2003) have introduced the concept of *T*–phase energy flux, *TPEF*, reminiscent of the evaluation of seismic energy from body waves, and which should scale with seismic moment M_0 for regular seismic sources. Any deviation in the ratio $\Gamma = \text{TPEF}/M_0$ identifies anomalous source properties; in particular, slow earthquakes exhibit deficient Γ, a property with some potential in tsunami warning.

The comparison of duration and amplitude of T wavetrains can efficiently discriminate between earthquakes and explosions at sea, based on the strong differences in the scaling of their source processes (Talandier and Okal, 2001), although small earthquakes located inside steep volcanic edifices remain a challenge in this respect.

A few geophysical applications

As most of their path is hydroacoustic, T phases propagate at a velocity close to that of sound in water, 1.5 km/s; that gives them late arrivals on seismic records, hence their name "T" for "third". Such slow velocities allow a remarkable resolving power for source locations, after accounting for small geographic and seasonal variations in SOFAR velocities, and for the contribution of the converted [seismic] segments of the phase.

In this context, the superior detection capabilities of T phases have been used to improve considerably our coverage of low-magnitude seismicity in the oceanic environment, and especially our understanding of small-scale processes at mid-oceanic ridges, notably in conjunction with swarms of volcanic activity (Dziak et al., 1995).

The slowness of T waves also allows to very precisely beam a receiving array (e.g., triangles of hydrophones at sites of the International Monitoring System [IMS]) to back-track the source of T phases, or even of individual fragments of their wavetrains; this procedure was used to obtain a detailed source tomography of the great 2004 Sumatra-Andaman event (e.g., Tolstoy and Bohnenstiehl, 2005).

Conclusion

Because of their high-frequency character, T waves provide a valuable complement to more traditional phases in the field of body-wave seismology. Their incorporation into the IMS allows their more systematic recording and opens up a number of new research opportunities.

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Cross-references

Seismic Monitoring of Nuclear Explosions
Seismology, Monitoring of CTBT