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Recent Advances in Multichannel Seismic Imaging for Academic Research in Deep Oceanic Environments

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Academic research using marine multichannel seismic (MCS) methods to investigate processes related to Earth's oceanic crust has made substantial advances in the last decade. These advances were made possible by access to state-of-the-art MCS acquisition systems, and by development of data processing and modeling techniques that specifically deal with the particularities of oceanic crustal structure and the challenges of subseafloor imaging in the deep ocean. Among these methods, we highlight multistreamer three-dimensional (3D) imaging, streamer refraction tomography, synthetic ocean bottom experiments (SOBE), and time-lapse (4D) studies.

A strength of 3D MCS reflection imaging lies in the ability to migrate the seismic wavefield in three dimensions, resulting in improved accuracy and resolution of structure, particularly in rugged terrains such as at mid-ocean ridges (MORs) where energy scattered by rough seafloor contaminates and degrades the recorded signal.

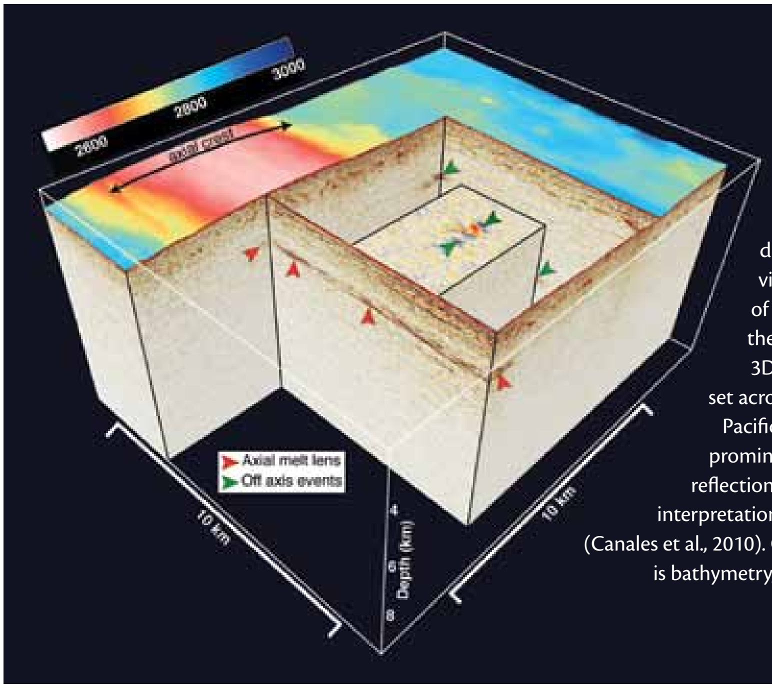

Figure 1. Three-dimensional visualization of a subset of the MGL0812 3D MCS data set across the East Pacific Rise, with prominent crustal reflections and their interpretation indicated (Canales et al., 2010). Color scale is bathymetry, in meters.

Magmatic systems along MORs drive and link fundamental physical and chemical processes such as volcanic construction, hydrothermal circulation, seafloor mineralization, and biological colonization. The fine-scale structure of these systems was explored earlier by single-streamer 3D MCS imaging across a ridge discontinuity at the East Pacific Rise (EPR; Kent et al., 2000) and beneath a Mid-Atlantic Ridge (MAR) volcano (Singh et al., 2006), and more recently by multistreamer 3D MCS imaging at the Ridge 2000 Integrated Study Site at the EPR (Mutter et al., 2010; Carbotte et al., 2012, in this issue; Figure 1). Advanced 3D MCS methods can also contribute to imaging the complex geometry of oceanic detachment faults, whose dips presumably vary in depth and with azimuth, and which have been recently recognized as a fundamental component of a distinct mode of seafloor spreading (Escartín and Canales, 2011).

Long-offset streamers make it possible to record wide-angle MCS data that can be used to infer subseafloor velocity structure via streamer refraction tomography (Zelt et al., 2004) with high resolution thanks to a densely sampled (in space) wavefield. Streamer refraction traveltime tomography was recently

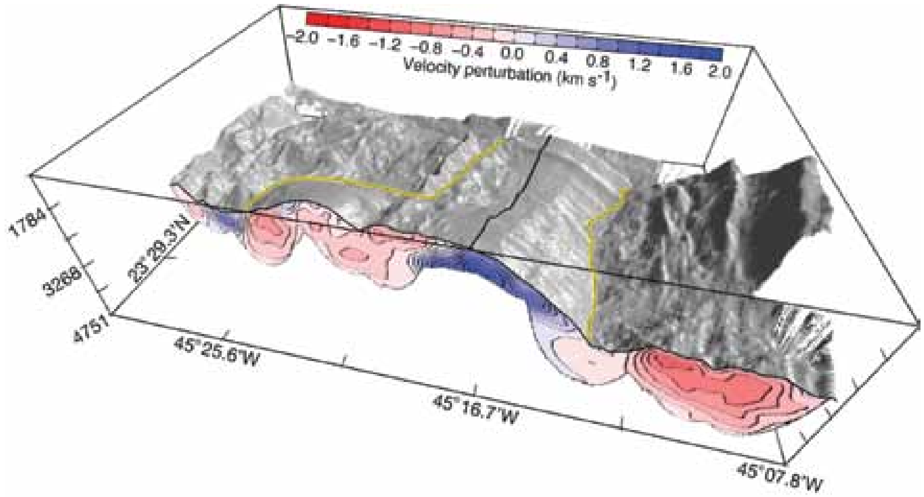

Figure 2. Example of subseafloor variations in shallow seismic velocity (red-blue image) derived from streamer refraction traveltime tomography across the Kane oceanic core complex. Velocity perturbation, contoured every $0.2\ \mathrm{km\ s^{-1}}$, is shown relative to a one-dimensional structure with constant vertical gradient of $1.75\ \mathrm{s^{-1}}$ and $V_p = 3.7\ \mathrm{km\ s^{-1}}$ at the seafloor. Gray shaded relief is bathymetry, and dashed yellow lines delineate the smooth, corrugated detachment surface. Horizontal axes are latitude and longitude, and vertical axes show depth in meters. *From Canales et al. (2008)*

applied in a few deep-ocean settings to investigate problems such as seismic Layer 2A structure beneath an MAR high-temperature hydrothermal field (Arnulf et al., 2011), the heterogeneity of slow-spread lithosphere exposed on oceanic core complexes (Canales et al., 2008; Henig et al., 2009; Xu et al., 2009; Figure 2), or the evolution of seismic Layer 2B across the flanks of the Juan de Fuca Ridge in the Northeast Pacific Ocean (Newman et al., 2011). The densely sampled wavefield also allows applying more advanced techniques such as 2D refraction waveform tomography for obtaining seismic velocity information at scales close to the seismic wavelength (Canales, 2010; Delescluse et al., 2011).

The effectiveness of both traveltime and waveform tomography can be enhanced by downward continuation of data originally recorded at the sea surface to a datum at, or just above, the seafloor, creating a SOBE (Berryhill, 1979; Harding et al., 2007). In surface data, refractions from Layer 2A arrive after the seafloor reflection and are often obscured by pervasive high-amplitude seafloor scattering (Figure 3a). Downward continuation transforms these refractions into first arrivals (Figure 3b), making it possible to pick larger numbers of near-offset traveltimes to reduce uncertainty in determining the shallowmost velocity structure. The implicit 2D filtering of the downward continuation process reduces noise and enhances refraction continuity, making the transformed data a better starting point for waveform tomography.

MOR processes are spatially and temporally variable. The axial magma lens is a dynamic structure that must at least partially drain during eruptions and replenish with magma, perhaps on a cycle of fewer than 20 years (Perfit and Chadwick, 1998). Time-lapse techniques using repeat 3D surveys ("4D seismics") are well established in the hydrocarbon industry (e.g., for tracking depletion of oil fields or for monitoring CO_2 injections; Lumley, 2001), and can be readily applied to MOR settings. Accurate comparisons of two generations of data require equalizing the source signal, geometry, and amplitudes. Preliminary comparison between 1985 2D data and 2008 3D MCS data suggest that changes in magma lens properties along the EPR can be recognized despite considerable acquisition differences (Mutter et al., 2010).

In summary, steady access to and employment of advanced MCS methods by the academic community in the near future will be a key factor in expanding our understanding of oceanic crustal processes. Three-dimensional MCS data acquisition, processing, and

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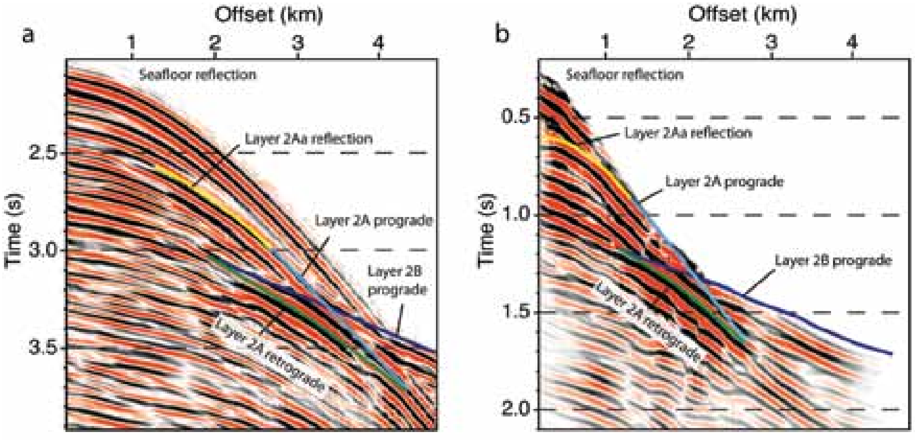

Figure 3. Example illustrating the synthetic ocean bottom experiments, or SOBE, procedure. (a) Common midpoint gather recorded on the sea surface. (b) Same gather downward continued to 1,365 m below the sea surface. Corresponding seismic arrivals are indicated in both panels. Note that in (a), Layer 2A prograde and most of Layer 2B prograde arrivals are secondary (i.e., arrive after the seafloor reflection), while in (b), collapsing of the seafloor reflection makes Layer 2A and 2B prograde branches become first arrivals and thus easier to interpret and to use in standard traveltime tomographic inversions. *From Arnulf et al. (2011)*

modeling, including 3D pre-stack migration, 3D waveform inversion (e.g., Ben-Hadj-Ali et al., 2008), and 3D time-lapse monitoring offer tremendous opportunities to improve understanding of the dynamics and fine-scale structure of complex deep-sea geological systems such as axial magma chambers and oceanic detachment faults.

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REFERENCES

Arnulf, A.F., S.C. Singh, A.J. Harding, G.M. Kent, and W.C. Crawford. 2011. Strong seismic heterogeneity in Layer 2A near hydrothermal vents at the Mid-Atlantic Ridge. *Geophysical Research Letters* 38, L13320, http://dx.doi.org/10.1029/2011GL047753.

Ben-Hadj-Ali, H., S. Operto, and J. Virieux. 2008. Velocity model building by 3D frequency-domain, full-waveform inversion of wide-aperture seismic data. *Geophysics* 73(5):VE101–VE117, http://dx.doi.org/10.1190/1.2957948.

Berryhill, J.R. 1979. Wave-equation datuming. *Geophysics* 44(8):1,329–1,344, http://dx.doi.org/10.1190/1.1441010.

Canales, J.P. 2010. Small-scale structure of the Kane Oceanic Core Complex, Mid-Atlantic Ridge 23°30'N, from waveform tomography of multichannel seismic data. *Geophysical Research Letters* 37: L21305, http://dx.doi.org/21310.21029/22010GL044412.

Canales, J.P., B.E. Tucholke, M. Xu, J.A. Collins, and D.L. Dubois. 2008. Seismic evidence for large-scale compositional heterogeneity of oceanic core complexes. *Geochemistry, Geophysics, Geosystems* 9(8), Q08002, http://dx.doi.org/08010.01029/02008GC002009.

Canales, J.P., H. Carton, M. Xu, M.R. Nedimović, S. Carbotte, and J.C. Mutter. 2010. Evidence from three-dimensional seismic reflection images for crustal magma bodies off the East Pacific Rise. Abstract OS13G-02 presented at the 2010 Fall Meeting, American Geophysical Union, San Francisco, California, December 13–17, 2010.

Carbotte, S.M., J.P. Canales, M.R. Nedimović, H. Carton, and J.C. Mutter. 2012. Recent seismic studies at the East Pacific Rise 8°20'–10°10'N and Endeavour Segment: Insights into mid-ocean ridge hydrothermal and magmatic processes. *Oceanography* 25(1):100–112, http://dx.doi.org/10.5670/oceanog.2012.08.

Delescluse, M., M.R. Nedimović, and K.E. Louden. 2011. 2D Waveform tomography applied to long streamer MCS data from the Scotian slope. *Geophysics* 76(4):B151-B163, http://dx.doi.org/10.1190/1.3587219.

Escartín, J., and J.P. Canales. 2011. Detachments in oceanic lithosphere: Deformation, magmatism, fluid flow and ecosystems. *Eos, Transactions, American Geophysical Union* 92(4):31, http://dx.doi.org/10.1029/2011EO040003.

Harding, A.J., G.M. Kent, D.K. Blackman, S. Singh, and J.P. Canales. 2007. A new method for MCS refraction data analysis of the uppermost section at a Mid-Atlantic Ridge core complex. *Eos, Transactions, American Geophysical Union* 88(52): Fall Meeting Supplement, Abstract S12A-03.

Henig, A.S., D.K. Blackman, A.J. Harding, G.M. Kent, and J.P. Canales. 2009. Seismic velocity variation within the footwall of an oceanic core complex: Atlantis Massif, Mid-Atlantic Ridge, 30°N. *InterRidge Newsletter* 18:9–12.

Kent, G.M., S.C. Singh, A.J. Harding, M.C. Sinha, J.A. Orcutt, P.J. Barton, R.S. White, S. Bazin, R.W. Hobbs, C.H. Tong, and J.W. Pye. 2000. Evidence from three-dimensional seismic reflectivity images for enhanced melt supply beneath mid-ocean-ridge discontinuities. *Nature* 406:614–618, http://dx.doi.org/10.1038/35020543.

Lumley, D. 2001. Time-lapse seismic reservoir monitoring. *Geophysics* 66(1):50–53, http://dx.doi.org/10.1190/1.1444921.

Mutter, J.C., H. Carton, M. Marjanovic, S. Carbotte, J.P. Canales, and M.R. Nedimović. 2010. Eruption-related changes in magma chamber structure at 9°50'N on the EPR from coincident reflection images, 1985 and 2008. *Eos, Transactions, American Geophysical Union*, Abstract OS24A-01.

Newman, K.R., M.R. Nedimović, J.P. Canales, and S.M. Carbotte. 2011. Evolution of seismic Layer 2B across the Juan de Fuca Ridge from hydrophone streamer 2-D traveltime tomography. *Geochemistry, Geophysics, Geosystems* 12, Q05009, http://dx.doi.org/10.1029/2010GC003462.

Perfit, M.R., and W.W. Chadwick. 1998. Magmatism at mid-ocean ridges: Constraints from volcanological and geochemical investigations. Pp. 59–115 in *Faulting and Magmatism at Mid-Ocean Ridges*. W.R. Buck, P.T. Delaney, J.A. Karson, and Y. Lagabrielle, eds, American Geophysical Union, Washington, DC.

Singh, S.C., W.C. Crawford, H. Carton, T. Seher, V. Combier, M. Cannat, J.P. Canales, D. Dusunur, J. Escartín, and M.J. Miranda. 2006. Discovery of a magma chamber and faults beneath a Mid-Atlantic Ridge hydrothermal field. *Nature* 442:1,029-1,032, http://dx.doi.org/10.1038/nature05105.

Xu, M., J.P. Canales, B.E. Tucholke, and D.L. Dubois. 2009. Heterogeneous seismic velocity structure of the upper lithosphere at Kane oceanic core complex, Mid-Atlantic Ridge. *Geochemistry, Geophysics, Geosystems* 10, Q10001, http://dx.doi.org/10010.11029/12009GC002586.

Zelt, B.C., B. Taylor, J.R. Weiss, A.M. Goodliffe, M. Sachpazi, and A. Hirn. 2004. Streamer tomography velocity models for the Gulf of Corinth and Gulf of Itea, Greece. *Geophysical Journal International* 159:333–346, http://dx.doi.org/10.1111/j.1365-246X.2004.02388.x.