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Origin of dipping structures in fast-spreading oceanic lower crust offshore Alaska imaged by multichannel seismic data

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ABSTRACT

Multi-channel seismic (MCS) reflection profiles across the Pacific Plate south of the Alaska Peninsula reveal the internal structure of mature oceanic crust (48–56 Ma) formed at fast to intermediate spreading rates during and after a major plate re-organization. Oceanic crust formed at fast spreading rates (half spreading rate ∼74 mm/yr) has smoother basement topography, thinner sediment cover with less faulting, and an igneous section that is at least 1 km thicker than crust formed at intermediate spreading rates (half spreading rate ∼28–34 mm/yr). MCS data across fast-spreading oceanic crust formed during plate re-organization contain abundant bright reflections, mostly confined to the lower crust above a highly reflective Moho transition zone, which has a reflection coefficient (RC) of ∼0.1. The lower crustal events dip predominantly toward the paleo-ridge axis at ∼10–30°. Reflections are also imaged in the uppermost mantle, which primarily dip away from the ridge at ∼10–25°, the opposite direction to those observed in the lower crust. Dipping events in both the lower crust and upper mantle are absent on profiles acquired across the oceanic crust formed at intermediate spreading rates emplaced after plate re-organization, where a Moho reflection is weak or absent. Our preferred interpretation is that the imaged lower crustal dipping reflections within the fast spread crust arise from shear zones that form near the spreading center in the region characterized by interstitial melt. The abundance and reflection amplitude strength of these events (RC ∼ 0.15) can be explained by a combination of solidified melt that was segregated within the shear structures, mylonitization of the shear zones, and crystal alignment, all of which can result in anisotropy and constructive signal interference. Formation of shear zones with this geometry requires differential motion between the crust and upper mantle, where the upper mantle moves away from the ridge faster than the crust. Active asthenospheric upwelling is one possible explanation for these conditions. The other possible interpretation is that lower crustal reflections are caused by magmatic (mafic/ultramafic) layering associated with accretion from a central mid-crustal magma chamber. Considering that the lower crustal dipping events have only been imaged in regions that have experienced plate re-organizations associated with ridge jumps or rift propagation, we speculate that locally enhanced mantle flow associated with these settings may lead to differential motion between the crust and the uppermost mantle, and therefore to shearing in the ductile lower crust or, alternatively, that plate reorganization could produce magmatic pulses which may lead to mafic/ultramafic banding.

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1. Introduction

Oceanic lithosphere produced at mid-ocean ridges covers 70% of Earth, yet fundamental questions remain about mantle flow and melt migration at mid-ocean ridges, and the mechanism(s) of crustal accretion. Is the crust accreted from a single mid-crustal axial magma lens with passive mantle flow (e.g., "gabbro glacier" model, Phipps Morgan and Chen, 1993; Quick and Denlinger, 1993) or in situ through the injection of a series of sills through-

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out the crust (e.g., "sheeted sill" model, Boudier et al., 1996; Kelemen et al., 1997)? How active is the mantle upwelling beneath mid-ocean ridges (e.g., Forsyth, 1992; Blackman and Kendall, 2002)? Magmatic and mantle flow processes exert control on the deformation style of the crust and upper mantle at and near the ridge axis and thus on the seismic structure of the crust.

Fast-spreading mid-ocean ridges have axial highs and a thin axial magma lens (AML) characterized by significant melt content that is underlain by the axial magma chamber (AMC). The AMC is a 5- to 10-km-wide partially molten zone with significant interstitial melt that extends to the base of the crust (Vera et al., 1990; Kent et al., 1993; Dunn et al., 2000; Zha et al., 2014). Off axis magma lenses have also been recently imaged as bright mid-crustal reflections beneath the flanks of the East Pacific Rise (EPR) and at the Moho transition zone here (Canales et al., 2012; Han et al., 2014) in apparent contradiction to the predictions of the gabbro glacier model. However, the contribution of off-axis magma bodies to the formation of lower oceanic crust remains unclear. After its formation, the oceanic lithosphere cools and sinks away from the ridge axis. Convective hydrothermal circulation at the ridge axis and on ridge flanks facilitates cooling of upper oceanic crust until it is shut off by sediment blanketing. Debate continues about the roles of conductive cooling and penetration of seawater derived fluids in lower crustal cooling (e.g., McCulloch et al., 1981; Bosch et al., 2004). Cooling of the oceanic lithosphere can eventually generate thermal stresses that lead to cracking and fissuring (e.g., Parmentier and Haxby, 1986), which can further modify the off-axis fluid flow and contribute to continued cooling (e.g., Fisher, 1998; von Herzen, 2004).

Little is known about the structure of and aging processes in old oceanic crust due to the lack of data; most studies have focused on the ridge axis, fracture zones and seamounts, or at convergent and rifted margins. Most of the few MCS profiles across old, mature oceanic crust reveal dipping reflections in the lower crust (e.g., Ranero et al., 1997), but their origin still remains enigmatic. In most data from old oceanic crust formed at the slow-spreading Mid-Atlantic Ridge, some crustal reflections appear to continue through the entire crust and directly correlate to rough topography, so they are mainly attributed to large-scale extensional faulting (Mutter et al., 1985; NAT Study Group, 1985; McCarthy et al., 1988; White et al., 1990; Mutter and Karson, 1992; Morris et al., 1993; McBride et al., 1994).

Lower crustal reflections are also observed in data collected across fast spread crust in the Pacific Ocean (Eittreim et al., 1994; Ranero et al., 1997; Reston et al., 1999) that differ from those observed in slow-spreading crust in that they are confined to the lower crust and are not clearly related to offsets at the top or base of the crust. Consequently, they were attributed to either compositional layering (mafic/ultramafic banding) (e.g., Ranero et al., 1997) that has been observed in ophiolites and modeled to form by ductile flow from the AML with a passive mantle upwelling (e.g., Henstock et al., 1993; Phipps Morgan and Chen, 1993) or secondary shear zones generated in the ductile lower crust in response to a basal shear applied at the Moho transition zone (MTZ) by active mantle upwelling (Nicolas et al., 1994; Kodaira et al., 2014). Some studies invoke both near-axis processes/deformation and off-axis crustal aging (Hallenborg et al., 2003).

The described studies provide fundamental constraints on the structure of fast-spreading oceanic crust and the processes involved in its formation and evolution, but they leave several core questions unanswered. Many authors interpret dipping reflections as shear zones (Ranero et al., 1997; Kodaira et al., 2014), which appear to require some form of active upwelling. However, modeling and other observations at fast-spreading ridges suggest that upwelling is passive in these settings (Parmentier and Phipps Morgan, 1990; Blackman and Forsyth, 1992; Forsyth, 1992) although the pattern of mantle upwelling is still debated (Carbotte et al., 2004).

In this paper, we present MCS reflection images from the ALEUT (Alaska Langseth Experiment to Understand the megaThrust) experiment of the North Pacific oceanic crust offshore Alaska Peninsula, which surveys crust formed at both fast and intermediate spreading rates. We focus on the origin of lower crustal reflections by combining constraints from MCS data on the geometry, internal structure, amplitude and distribution of these events. We estimate the absolute reflection coefficients for the brightest events, which we use to test explanations for their amplitude. Our results, combined with published work, illuminate possible controls on the dipping events imaged in the lower oceanic crust such as spreading rate, mantle flow, plate reorganizations, and aging.

2. Geological setting and seafloor spreading history

The Pacific oceanic crust examined in this study formed in the late Tertiary (48 to 56 Ma) at fast to intermediate spreading rates and is currently located near the present day boundary between the North American and the Pacific plates (Fig. 1). This oceanic crust records significant variations in the direction and rate of spreading due to major plate reorganizations (Lonsdale, 1988). At ∼56 Ma (chron 25), a major plate reorganization occurred involving a reorientation of the Kula ridge and a jump in the Kula–Pacific–Farallon triple junction (Lonsdale, 1988; Seton et al., 2012). Plate reorganization was accompanied by an increase of the spreading rate (74 mm/yr half rate, Engebretson et al., 1984; 54 mm/yr half rate, Lonsdale, 1988) at the Pacific–Kula ridge and is preserved in unsubducted oceanic crust off the Alaska Peninsula. The fossil triple junction left behind by the reorganization is located at the T-shaped Anomaly 24.2 (53 Ma) (Fig. 1). Anomalies to the east of 158°W, younger than chron 23 (52 Myr) appear to reflect the intermediate Pacific–Farallon spreading rate (∼28–34 mm/yr, half rate) accreted after plate reorganization (Engebretson et al., 1984).

Of the ALEUT data seaward of the trench, Lines 5, 6 and 23C are near perpendicular to the magnetic anomalies and thus approximately coincide with the flow lines and provide a record of the processes of crustal accretion at fast and intermediate spreading rates (Fig. 1). Line 4 crosses the fossil triple junction (Nedimović et al., 2011; Bécel et al., 2012), Line 2 crosses the Patton–Murray seamount chain, and Line 6 passes near the center of a small seamount. The profiles shown here were chosen to avoid areas affected by subduction (∼60 km from the trench) and triple junction processes. However, as described later, the triple junction might have played a role in the formation of the lower crustal dipping events at the time of the crustal accretion.

3. Data acquisition

Data used in this study were collected by the R/V *Marcus G. Langseth* in summer 2011 for the ALEUT program. The survey imaged the subduction zone system, including the incoming oceanic plate ∼60–130 km seaward of the trench, before it was modified by bending and subduction (Fig. 1). In total, we acquired 3700 km of MCS data with two 636-channel, 8-km-long streamers and a 6600 cu. in. tuned 36-element airgun array (Fig. 1). The source and one of the streamers were towed at 12 m to maximize low frequencies and deep imaging while the second streamer was towed at 9 m for better imaging of the sediments and upper crust. The shot interval for the MCS data acquisition was 62.5 m and the group spacing 12.5 m resulting in nominal common midpoint (CMP) bin spacing of 6.25 m, and CMP data trace fold of 64. The long record length (22 s) allows us to fully capture the seafloor multiple needed for calibration and estimation of true reflection