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Tectonic analysis and paleo-stress determination of the upper lava section at ODP/IODP site 1256 (East Pacific Ocean)

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ABSTRACT

Research on the deep sea is of great importance for a better understanding of the mechanism of magma emplacement and the tectonic evolution of oceanic crust. However, details of the internal structure in the upper levels of the oceanic crust are much less complete than that of the more fully studied sub-aerial areas. For the first time, this study proposes a dynamic analysis using the inversion method on core data derived from the drilled basement of the present-day intact oceanic crust at ODP/IODP Site 1256 in the Cocos plate. The research is based on an innovative core reorientation process and combines different stress hypothesis approaches for the analysis of heterogeneous failure-slip data via exploitation of two distinct techniques. From the analysis of the failure-slip data, both techniques produce 5 distinct subsystem datasets. All calculated subsystems are mechanically and geometrically admissible. Interpretation of the results allows the researchers to note a complex local and regional tectonic evolution deriving from the interplay of (1) the ridge push and rotation of both the East Pacific Rise and the Cocos-Nazca Spreading Center, (2) the effect of the slab pull of the Middle America Trench, (3) the influence of lava emplacement mechanisms, and (4) intra-plate deformation.

1. Introduction

Research on the deep sea is of great importance to a better understanding of the eruption, transport mechanisms, and related tectonic evolution either at the ridge axis or off-axis. However, details of the internal structures of the upper levels of the oceanic crust are much less complete than those of the more fully studied sub-aerial areas because of the inaccessibility in deep water and a paucity of direct observations. The brittle deformation of the sub-aerial environment is generally quantified using fault kinematic analysis methods, and such methods are based on measurements of mesoscale faults and associated striae (i.e., failure-slip datum). Since Anderson (1942), several methodologies have been proposed for dynamic analysis of brittle structure systems for the reconstruction of paleo-stress axes orientation. After Carey and Brunier (1974) and Angelier (1979), kinematic indicators (e.g., slickensides) were considered as the key to reconstruction of the geological paleo-stress tensor in analysis of the failure population (see, e.g., Etchecopar et al., 1981; Armijo et al., 1982; Angelier, 1984, 1990; Huang, 1988; Twiss and Gefell, 1990; Marrett and Allmendinger, 1990; Nemcok and Lisle, 1995; Twiss and Unruh, 1998; Fry, 1999; Nemcok et al., 1999; Yamaji, 2000; Shan, 2003; Shan and Fry, 2005; Žalohar and Vrabec, 2007). Such approaches are commonly referred to as the “inversion method” or “inverse problem”. They primarily use a minimization or maximization criterion given by objective equations to obtain the best fitted average deviatoric stress tensor (stress hypothesis; see, e.g., Twiss and Unruh, 1998) that corresponds to a given failure-slip dataset. The minimization/maximization procedure provides determination of the three principal stress directions of the stress tensor (where σ_1 is the greatest principal stress, σ_3 is the least principal stress, and σ_2 is the intermediate principal stress) as well as of the stress ratio (stress shape ratio Φ):

$$\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3) \tag{1}$$

The inversion methods in most of the proposed stress hypothesis studies can be addressed under a few important assumptions: (1) the direction of movement on the failure plane is reflected by the striation on the failure surface; (2) the shear stress is parallel to the direction of movement; (3) no rotation of the failure plane occurs during deformation; (4) the failures do not interact with each other during deformation, and the displacements on the fault planes are small with respect to their lengths; (5) the rocks

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bounded by failure planes are rigid and behave as a rheologically linear material (linear elasticity is commonly considered a requirement) that is physically homogeneous and isotropic; and (6) the stress field is spatially homogeneous and temporally constant. These assumptions are simplifications that are not always satisfied in the deformation of natural rocks (see, e.g., Pollard, 2000; Lacombe, 2012).

Another approach to interpreting kinematic indicators is the so-called kinematic hypothesis (see Twiss and Unruh, 1998 and references therein), which assumes that, in a symmetrical case, the slip directions are parallel to the direction of maximum resolved shear rate (Twiss et al., 1991, 1993). The mathematics for the calculations of the direction of the strain rate tensor (kinematic hypothesis) instead of the stress tensor (stress hypothesis) are identical, and thus, the inversion method for a fault population would give the correct solution for both the stress and strain rates. Generally, either the difference between the two methods is considered irrelevant or one hypothesis is merely preferred over the other (see Twiss and Unruh, 1998; Žalohar and Vrabec, 2010; Lacombe, 2012; Žalohar, 2012, 2014 for a formal review of the two interpretations).

Certain inversion problem techniques propose the “geometrical constraint” using Coulomb's failure criterion (Coulomb, 1776) and stress orientation (Anderson, 1942). These methods are based on the relationships between shear stress direction and slip direction (e.g., Wallace, 1951; Bott, 1959; McKenzie, 1969; Célérier, 1988; Célérier et al., 2012 and references therein). Others propose the “mechanical constraint” using Amonton's law (Bowden and Tabor, 1950) based on the possibility of activating slip on a pre-existing discontinuity plane. Eventually, certain other techniques combined both geometrical and mechanical approaches (e.g., Célérier, 1988; Angelier, 1990; Žalohar and Vrabec, 2007). Because a technique based solely on the geometrical constraint might allow mechanically unacceptable solutions (notably small shear stress combined with a notably large normal stress), a technique that combines both approaches is generally preferable (Célérier, 1988; Federico et al., 2010). Reviews of different techniques are provided by Angelier (1994), Ramsay and Lisle (2000), Liesa and Lisle (2004), Hippolyte et al. (2012) and Célérier et al. (2012), among others.

The inversion method is performed using data from field measurements collected on accessible study areas, mineral twinning, microboudinage and other materials-science-based approaches or starting from seismic focal mechanisms; hence, this approach represents a multi-scalar and feasible method (see, e.g., Blenkinsop et al., 2006 and references therein; Lacombe, 2012). However, difficulties in operating on the deep seafloor make similar studies on cores collected from the deep-sea basement of the oceanic crust usable with difficulty.

Craddock and Pearson (1994) used the presence of mechanically twinned calcite to interpret the stress and strain field in the Suiko Seamount (a component of the Hawaiian-Emperor Chain, Pacific Ocean, DSDP Site 503, Leg 55), but the azimuthal orientation of these strains is only known with respect to the stratigraphic top and bottom because the cores are not oriented in any other manner. Craddock et al. (2004) proposed a paleo-stress determination on oceanic domain using calcite twinning indication on samples recovered from Iceland.

Stress and paleo-stress studies on ocean sediments were performed to analyze the anisotropy of magnetic susceptibility (AMS) as a strain indicator (Owens, 1993; Housen et al., 1996; Housen and Kanamatsu, 2003; Ujiie et al., 2003; Kitamura et al., 2010; Kanamatsu et al., 2012).

Since Bell and Gough (1979), the crustal stress in drilled holes has been generally studied using borehole breakouts and drilling-induced fractures, which are well-bore failures that form at the azimuth of the minimum horizontal compressive stress (and perpendicular to the maximum horizontal stress σ_h) due to either compressive or tensile stress concentrations that exceed the in situ rock strength (see, e.g., Bell and Gough, 1979; Zoback and Zoback, 1980; Gough and Bell, 1981; Newmark et al., 1984). For a summary review of breakout formation, see, e.g., Moos and Zoback (1990), Goldberg and Janik (2006), and Zoback (2010) and references therein. Breakouts might have certain limits when used to inspect the stress evolution of a certain area because: (1) they give an indication for the current stress field, and hence, no paleo-stress determination can be performed with them; and (2) breakouts allow the reconstruction of the sole horizontal component of the stress field. Therefore, inversion methods might represent a better choice and a more complete source of information for a better understanding of the evolution of the stress field.

This study proposes a dynamic analysis using the inversion method for the first time on core data derived from the drilled basement of the present-day intact oceanic crust. After depth corrections and re-orientation of core measurements with respect to magnetic North using the technique described by Fontana et al. (2010), a significant amount of core structural analyses can be used for more accurate interpretations of the local and regional stress fields in the present-day oceanic crust.

2. Geological setting

During the ODP leg 206 four holes were drilled at Site 1256 (6°44.2′ N, 91°56.1′ W; Fig. 1) on the seafloor of the Cocos plate in the Pacific Ocean. The oceanic crust at ODP-IODP Site 1256 is 15 Ma old and formed from the East Pacific Rise (EPR) during a superfast spreading rate episode (Wilson, 1996; Müller et al., 2008).

Holes 1256A and 1256B cored the sedimentary layers only, whereas holes 1256C and 1256D include basement penetrations. Hole 1256C was drilled down to approximately 340 m below the seafloor (mbsf), and Hole 1256D was drilled but not cored down to 276 mbsf and deepened during the ODP leg 206, IODP Expedition 309, 312, and 335 reaching the current total depth of ~1520 mbsf (Wilson et al., 2003; Teagle et al., 2006; Expedition 335 Scientists, 2011). The cored interval of Hole 1256D was preliminarily subdivided into the following sections: a single massive lava flow (276–350 mbsf), inflated flows (350.3–533.9 mbsf), sheet and massive flows (533.9–1004.2 mbsf), a transition zone (1004.2–1060.9 mbsf), sheeted dike complex (>1060 mbsf) and plutonic complex (>1407 mbsf; Teagle et al., 2006; Wilson et al., 2006, Fig. 2). A new igneous stratigraphy (from 312 mbsf to 1425 mbsf) was proposed by Tominaga et al. (2009) based on electrofacies analysis. These authors suggest 10 units, i.e., massive flows, massive off-axis ponded lava, fractured massive flows, thin flows-thick pillows, pillows, fragmented flows, breccias, isolated dikes, dikes in sheeted dike complex, and gabbros (see Fig. 2).

This study focuses on the shallowest massive flow commonly referred to as the “Lava Pond” (see Fig. 2) or “Lava Field” (Panseri et al., 2010; Zucali et al., 2014) that occurs in both holes 1256C (280.27–312.8 mbsf) and 1256D (276.1–348.02 mbsf), representing the thickest massive basalt igneous unit of the entire Site 1256 (~30 m at Hole 1256C and ~70 m at Hole 1256D). Several authors (Teagle et al., 2006; Tartarotti et al., 2009; Fontana and Tartarotti, 2013; Zucali et al., 2014) interpreted the Lava Pond as an off-axis lava flow based on (1) a seismic structure related to typical Pacific off-axis seafloor; (2) distinctive high electric resistivity and weakly fracturization compared with deeper portions of the drilled basement; (3) more evolved N-MORB than deeper basalts; (4) the occurrence of dominant subhorizontal structures and hence positioning of the Lava Pond sufficiently far from the axis region where