Splitting a continent: Insights from submarine high-resolution mapping of the Moresby Seamount detachment, offshore Papua New Guinea

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Splitting a continent: Insights from submarine high-resolution mapping of the Moresby Seamount detachment, offshore Papua New Guinea

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ABSTRACT

The Moresby Seamount detachment in the Woodlark Basin (east of Papua New Guinea) is arguably the best exposed active detachment fault in the world. We present the results of a high-resolution autonomous underwater vehicle survey of bathymetry, bottom water temperature, and turbidity. In combination with dredging and existing drillhole data, a synthesis of the tectonic geomorphology, kinematics, and mechanics of the detachment is provided. The detachment surface, which has a 30° northward dip and ~8 km post-Pliocene displacement, is well preserved. Two major smooth areas are tectonically created, and megascopic (kilometer scale) slickensides indicate downdip direction of movement. The detachment is transected by a major sinistral strike-slip fault, suggesting deformation partitioning in the detachment zone in response to the 500 k.y. change in plate kinematics. The mainly gabbroic protoliths and cataclasites from the fault show pervasive syntectonic alteration, leading to large increases in abundance of quartz and, more important, calcite. Resulting quartz-rich and calcite-rich mylonites play a crucial role, as weak fault rocks and ductile microstructures point to detachment operation at low differential stress. A kilometer-sized anomaly in bottom water temperature and turbidity is found at the downdip end of the detachment zone, indicating that it hosts an active hydrothermal system, probably fed by overpressured fluids from a deep crustal source.

INTRODUCTION

Few places on Earth show the ongoing transition from continental rifting to seafloor spreading as clearly as the Woodlark Basin (east of Papua New Guinea), where active tectonic structures are not covered by thick sedimentary successions. Separation of the Woodlark plate from Australia (Fig. 1A) produces an along-strike gradation from rapid continental extension to seafloor spreading over only a few hundred kilometers (e.g., Weisel et al., 1982; Taylor et al., 1995, 1999). Seafloor spreading began 6 m.y. ago in the east (Taylor et al., 1999), and propagated westward; extension started synchronously along the entire length of individual spreading segments (Goodliffe et al., 1997). Rifting at a rate of 20–40 mm yr⁻¹ has produced 100–200 km of extension along the modern spreading axis. Geodetic data suggest that recent rates are ~30% slower (Wallace et al., 2004), after reorganization in spreading kinematics 500 k.y. ago (Goodliffe et al., 1997).

Moresby Seamount (9°49′S, 155°35′E) is located east of the D’Entrecasteaux Islands (Fig. 1A), a series of physiographic highs reflecting Neogene metamorphic core complexes (e.g., Baldwin et al., 1993; Little et al., 2007). Multichannel seismic profiles across Moresby Seamount reveal a large northward-dipping normal fault that maintains a dip of ~30° to ~9 km depth (Mutter et al., 1996) and generates large earthquakes (Abers et al., 1997). Faulting and uplift at Moresby Seamount are younger than 3.5 Ma (Taylor et al., 1999). Moresby Seamount has been considered as a large fault-bounded horst in the hanging wall of a major subhorizontal detachment at depth (Little et al., 2007). However, the present tectonic activity, the large post-Pliocene displacement, and the low dip angle may justify the term Moresby Seamount detachment (MSD). Here we show the first-ever autonomous underwater vehicle (AUV) high-resolution map of an active extensional detachment exposed at the seafloor over 30 km². The AUV technique allows us to present submarine maps with a spatial resolution of 2 m (see the GSA Data Repository¹ for details on data acquisition). This is an improvement by approximately one order of magnitude over earlier maps of such structures (e.g., Smith et al., 2006; Tani et al., 2011). The absence of erosion at most parts of the fault surface and suppression of local sedimentation by strong bottom water currents provide a unique opportunity for AUV mapping and sampling.

The proximity to the spreading ridge tip (Fig. 1A) suggests that the MSD is the last continental fault to develop before crustal breakup and formation of oceanic crust. Any information regarding fault mechanics, geometry, and kinematics will therefore provide unique insights into the process of crustal breakup. We discuss interpretations regarding active tectonics, especially the evidence for strain partitioning and the role of the MSD as a potential location for crustal breakup. We also document the spatial link of the fault with a major fluid discharge system, and make some inferences concerning fault zone stresses and rheology.

Geological Map and Fault Rocks of Moresby Seamount

Dredging results, Ocean Drilling Program (ODP) drillhole information (Taylor and Huchon, 2002), and bathymetric surveys are integrated here to produce the first geological map of Moresby Seamount (Fig. 1C; Devey, 2009; see the Data Repository). Fault rocks of the MSD are cataclasites and mylonites. Protoliths are dominated by mafic basement rocks of Paleogene or older age (Taylor et al., 1999), and were found at various stages of deformation in dredges (DR) DR39–DR43, DR103, and DR105 (Fig. 1C). Subsidiary protolith types include metapelite and calc-silicate gneiss and schist; their occurrence is restricted to DR69. Hydrothermally altered cataclasites with intense fracturing and veining, mainly from the upper part of the MSD, are indicative of cohesive cataclastic flow (Fig. 2A). The cataclasites have greenschist-grade brittle deformation fabrics, with multistage extensional fractures filled with epidote, quartz, and calcite. Mylonites (Fig. 2B) display a significant content of fine-grained calcite and quartz as elongated aggregates, or disseminated in the matrix (Fig. 2C). Dredged protoliths of the MSD are exclusively mafic, and quartz and calcite were infiltrated syntectonically in veins and microcracks. Cataclasites are rich in multiple generations of quartz and calcite veins that, after formation, become incorporated into the ductile deformation of the rock matrix. While the protoliths, rich in plagioclase and clinopyroxene, likely show brittle behavior up to at least 450 °C, syntectonic infiltration of quartz and calcite brings about a major change in mineralogical composition. This enables the fault rocks to deform plastically above syntectonic temperatures of 220 °C (calcite; cf. Herwegh

¹GSA Data Repository item 2011204, data acquisition, appendix to rock types, and flow stress estimation, is available online at: online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
boundaries are indicative of bulging recrystallization. Qtz—quartz; Cal—calcite.

Large quartz grains (50–80 µm) formed by subgrain rotation recrystallization show mation microstructure of quartz vein infiltrated by calcite leading to further weakening (DR–2A). After 20 h, the AUV dive yielded a high-resolution bathymetric map of the detachment surface (Fig. 3). Approximately 5 km² in a depth range of 500–2800 m below sea level (mbsl) were surveyed (Fig. 1B). From top to bottom, we identified four topographic domains (Fig. 3).

The upper rugged area (Fig. 3; 500–950 mbsl) is made up of Pliocene–Pleistocene clastics (DR43, ODP Site 1114). Resolution is sufficient to trace individual beds tilted to the southwest, indicating that Moresby Seamount is a tilted fault block of a larger extensional system. In the lower portion (800–950 mbsl), the slope is gentler, with depositional fans at the exits of erosional channels. The upper smooth area (Fig. 3) is an extremely planar, north-dipping surface between 950 and 1100 mbsl. DR103 recovered only mafic basement with an intense cataclastic overprint. We interpret this surface as the exposed top of the MSD. The upper boundary of the lower rugged area (Fig. 3) is a steep erosional cliff, which cuts a few tens of meters into the cataclastic surface above. Between 1100 and ~2000 mbsl, rough topography is defined by erosional scarps. Structurally, this area is a window into the footwall of the cataclastic-covered surface described here. DR42 and DR105 obtained a mix of cataclasites, mylonites, and undeformed mafic intrusives. The lower smooth

**Tectonic Geomorphology and Structures of MSD**

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and Pfiffner, 2005) or 280 ± 30 °C (quartz, cf. Stipp et al., 2002). As we discuss here, the infiltration process leading to rheological changes may be crucial for the MSD to form and operate under low-stress conditions.
area (Fig. 3) is a planar and structurally smooth surface. The most spectacular features here are several north-south–oriented, extremely straight grooves, hundreds of meters long, which we interpret as megascopic slickensides. DR41 recovered mainly mylonites (and subordinate cataclasites), indicating that the surface forms the top of a ductile mylonite zone. The upper boundary is straight in map view and the tectonic geomorphology suggests a structural discontinuity. The northeast-southwest strike of this structure is subparallel to rift-related transform faults (Figs. 1A, 1B, and 3). Evidence for strike-slip faulting is provided by the fact that this structure sinistrally offsets an antithetic normal fault on the crest of Moresby Seamount (Fig. 1A). The two smooth areas, probably belonging to the MSD shear zone, are dominated by cataclastic deformation in the upper part and mylonitization in the lower part. The lower rugged area is an erosional window into the footwall of the fault plane, while sediments above the basement of the footwall form the upper rugged area.

**Water Temperature and Turbidity Anomaly**

Our AUV dive data show an anomaly in the records of bottom water temperature and turbidity above the lowermost part of the MSD (Fig. 4). Over an ~800-m-wide area, water turbidity is ~50% above the background value (Fig. 4C). This anomaly coincides with a bottom water temperature increase of 0.013 ± 0.002 °C (Fig. 4B), likely of the same origin as the turbidity anomaly. We interpret these anomalies to reflect active seeping of warm fluids from the detachment zone. As fossil fault–controlled mineralizations are known from the hanging-wall block of the detachment at depth (e.g., Kopf et al., 2003), we think that the detachment fault shows a long-term hydrothermal activity.

**DISCUSSION**

Detachments often show transitions from cataclastic deformation at the top to mylonitization at deeper levels (Davis, 1983). This stratification reflects progressive shear localization as rocks in the footwall undergo a plastic to brittle transition during exhumation and cooling. At the MSD, this vertical stratification is expressed as follows. We recovered cataclasites and mylonites everywhere except for the upper smooth area, which yielded only cataclasites. More than 3 km of young exhumation in the lower smooth area at a geothermal gradient of 100 °C/km (Taylor and Huchon, 2002) brings pristine mylonites to the Earth’s surface.

Genetic algorithm inversion of seismic reflection data parallel to the MSD shows a layer with seismic velocities of ~4.3 km/s at 4–5 km depth, including isolated zones with velocities as low as ~1.7 km/s (Floyd et al., 2001). This inversion suggests that high fluid pressures and hydrothermal flow may be actively weakening the MSD. Therefore the MSD must be weakly coupled, either due to low-friction fault-zone materials or fluid overpressure, or both. The bottom water anomalies identified above the lower smooth area (Fig. 4) indicate that the MSD is a conduit for fluids. High fluid pressure in the fault zone at depth probably drives intermittent hydraulic fracturing necessary to create quartz and calcite veins, as documented by foliation-parallel hydrofractures with crack–seal textures (Fig. DR2 in the Data Repository). Evidence for the source of focused fluid flow is given by low B, C, and O isotopic ratios in calcite veins, attesting to an upward circulation of hot fluids released by the devolatilization of metamorphic rocks at >8 km depth (Kopf et al., 2003).

Dredges from the lower rugged area and the lower smooth area yielded a mix of cataclastic and mylonitic structures. The fracturing and hydrothermal addition of quartz and calcite and the mutual overprinting with mylonitics fabric indicate multiple switches from brittle fracture to plastic deformation at depth, probably driven by changes in pore pressure. The addition of sufficient calcite and quartz allows the MSD mylonites to creep plastically at very low differential stress. The quartz microstructure (Fig. 2C) displays subgrain rotation recrystallization and lower stress (higher temperature) bulging recrystallization.
talization (BLG II; recrystallized grain size >10 µm). Any evidence for higher stress (lower temperature) bulging recrystallization (BLG I; recrystallized grain size <5 µm), the key indicator of the brittle-plastic transition at high stresses (Stipp et al., 2002), is lacking. The lower stress bulging recrystallization microstructure with a minimum grain size of 1.1 ± 3.3 µm corresponds to a maximum flow stress of 72 MPa for the MSD when applying the experimental piezometer of Stipp and Tullis (2003; for details, see the Data Repository). The low overburden precludes high differential stresses, a clear difference from the higher confining pressure situation common in greenschist facies mylonites. Hence, the MSD represents the case of a brittle-plastic transition at comparatively low differential stress controlled by Goetze’s criterion, where differential stress cannot be higher than confining pressure to assure plastic deformation (e.g., Kohlstedt et al., 1995). This allows for repeated switches from plastic to brittle behavior caused by episodic changes in the effective confining pressure, and explains why earthquake-generating instabilities (Scholz, 1998; microearthquakes described by Ferris et al., 2006) may occur above temperatures usually associated with the brittle-plastic transition of quartz and calcite mylonites.

The MSD is currently one of the major structures on which continental extension is localized. The tip of Woodlark Ridge, east of Moresby Seamount at 151°39’E (Fig. 1A), is spreading at a rate of 34 mm yr⁻¹ (Taylor et al., 1999), and is in a right-stepping offset configuration with respect to the MSD, placing Moresby Seamount in an inside-corner high position relative to ridge-transform intersection geometry (Mutter et al., 1996; Floyd et al., 2001). Moresby Seamount has structural features common to oceanic inside-corner highs, including an asymmetric rift axis, an ~30° dip, and a basin opposing the elevated footwall (e.g., Tucholke et al., 1998). Our AUV mapping shows that deformation on and below the MSD is apparently partitioned into dip-slip normal faulting (represented by the megascopic slickensides) and strike-slip faulting (Figs. 1B, 1C, and 3A). This partitioning mimics plate tectonic constraints, as strike-slip fault orientation is about equal to that of transform faults predicted for present-day relative plate motions (Fig. 1B) between the Australian and Woodlark plates (Wallace et al., 2004). Hence, the strike-slip fault traversing the MSD (Fig. 3) is suited to operate as a transform fault after crustal breakup. Therefore we suspect that the MSD will be the candidate structure to host continental breakup and the generation of new oceanic crust in the geological future.

CONCLUSIONS

The use of AUVs to image submerged fault surfaces allows assessment of tectonic geomorphology in unprecedented detail and resolution. The key conclusions that we draw from our observations are the following:

1. Active deformation at Moresby Seamount is partitioned into dip-slip normal and sinistral strike-slip faulting, directly reflecting plate kinematic constraints. The MSD may thus be the candidate structure for crustal breakup and oceanic crust generation.

2. The detachment zone appears to be a long-time active pathway for hydrothermal fluids from depth.

3. The coalescence of high fluid pressures and weakening processes in the MSD fault rocks allows intermittent plastic and brittle deformation and operation of the MSD at low differential stress.

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