Macquarie Island's Finch-Langdon fault: A ridge-transform inside-corner structure

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ABSTRACT

Macquarie Island consists of uplifted oceanic crust, uniquely situated in the ocean basin where it formed, thus allowing onshore structures to be placed into their regional oceanic tectonic context. The Finch-Langdon fault, the most significant spreading-related structure on the island, juxtaposes upper-crust rocks against lower-crust and upper-mantle rocks. It consists of dominantly oblique strike-slip, northwest-, west-northwest–, and north-northeast–striking fault segments that bear hydrothermal mineralization indicative of faulting during seafloor spreading. Talus breccias and graywackes overlain by volcanic flows proximal to the fault indicate a long-lived submarine fault scarp that exposed diabase dikes and gabbros during volcanism. Swath reflectivity and bathymetry reveal ridge-parallel spreading fabric and perpendicular fracture zones, the closest ~7 km east of the island. On the basis of field and swath data, we propose that this fault zone formed near the inside corner of a ridge-transform intersection and that structures on the island are conformable with those in the surrounding seafloor.

Keywords: Macquarie Island, ophiolite, transform, spreading center, ocean crust.

INTRODUCTION

Macquarie Island is the sole complete subaerial section of oceanic crust found in the ocean basin in which it formed (Fig. 1; Varne et al., 1969, 2000), offering a unique window into the tectonic, magmatic, and hydrothermal processes associated with seafloor spreading and transform faulting. Its crust formed ca. 10 Ma (Duncan and Varne, 1988) at a spreading-ridge segment along the Australian-Pacific plate boundary (Varne et al., 2000). Regional marine geophysical data (Massell et al., 2000) show tectonic spreading fabric (faulted abyssal hills) and associated perpendicular fracture zones that formed parallel and perpendicular to spreading-ridge segments, respectively (Fig. 2). These fracture zones, the spreading fabric, and magnetic anomalies demonstrate that spreading, which started in Eocene time, progressively changed orientation until extension was nearly parallel to the present-day plate boundary and evolved into the transform plate boundary observed today (e.g., Lamarche et al., 1997; Cande et al., 2000; Massell et al., 2000) (Fig. 2). Transpression along the plate boundary deforms adjacent oceanic crust to produce the Macquarie Ridge Complex with Macquarie Island as its apex. Spreading fabric can be traced continuously onto the Macquarie Ridge Complex where it is cut by faults related to the current transform plate boundary (Massell et al., 2000). Therefore, oceanic crust exposed on Macquarie Island formed during late seafloor spreading along short ridge segments separated by transform faults before volcanism shut off; magnetic anomalies on both plates (Wood et al., 1996; C.G. Massell and W.R. Keller, 2002, personal

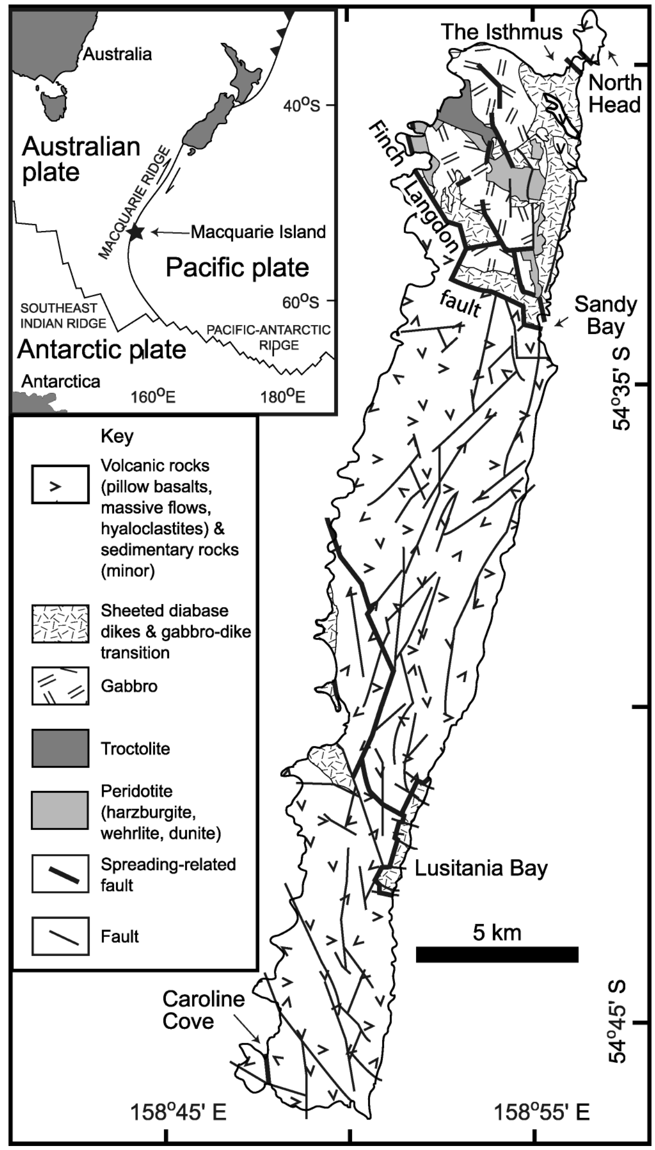

Figure 1. Generalized geologic map after Goscombe and Everard (2001). Finch-Langdon fault, seafloor spreading-related structure, juxtaposes serpentinized peridotite, gabbroic rocks, and sheeted diabase dikes (northern fourth of island) with volcanic rocks (southern part of island). Faults that formed during both seafloor spreading and uplift of island dissect terrain. Inset shows island location on Australian-Pacific plate boundary.

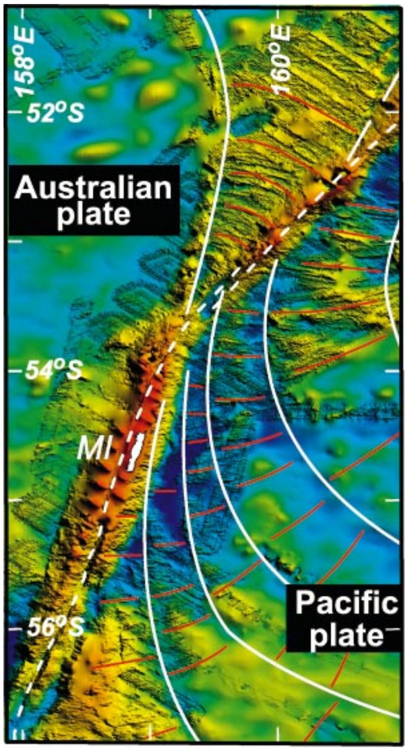

Figure 2. Bathymetry of Macquarie Ridge Complex near Macquarie Island (MI) (Bernardel and Symonds, 2001), showing modern-day transform plate boundary (white dashed line). Fracture zones that formed at Macquarie paleo–spreading center (white lines) become asymptotic approaching plate boundary; spreading fabric is orthogonal (red lines). Macquarie Island is proximal to both modern plate boundary (west) and two fracture zones (east). (Data are from 1994 *Rig Seismic*, 1996 *Maurice Ewing*, and 2000 *L'Atalante* swath mapping [rougher areas]; shipboard data gaps are filled with satellite-derived predicted bathymetry [smoother areas; Smith and Sandwell, 1997].)

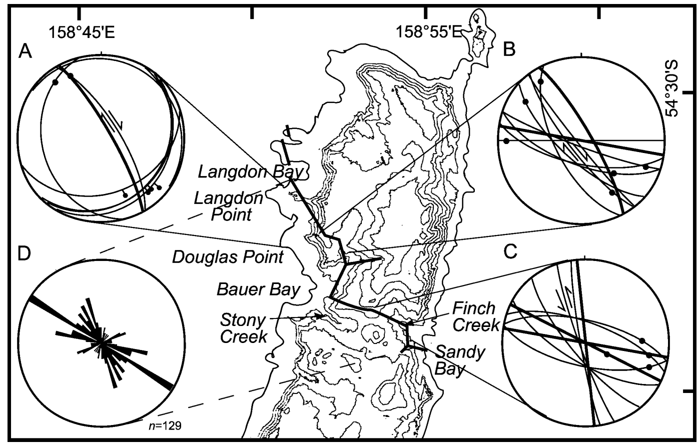

Figure 3. Finch-Langdon fault trace superimposed on topography. Note in Finch Creek, fault coincides with valley, whereas in Stony Creek, it does not. A–C: Stereonets (lower hemisphere, equal angle) show fault orientations, slickenlines (dot), and kinematics for three parts of Finch-Langdon fault zone. Trace of Finch-Langdon fault (Goscombe and Everard, 2001) in each region is plotted for comparison (bold lines; if no dip mapped, shown as 90°). D: Rose diagram showing that strikes of dikes adjacent to fault zone are subparallel to segments of Finch-Langdon fault, dominantly striking northwest (largest petal represents 16 values, 12% of all values; strike direction 5° all classes).

commun.) show both right- and left-stepping ridge segments, including those that project toward Macquarie Island.

The many faults that cut Macquarie Island (Fig. 1) are either (1) older, spreading-related faults or (2) younger transform or transpressional-related faults that postdate volcanism. The two groups differ markedly in faulting style and orientation, and we focus on the first. Our field and petrologic investigations of the Finch-Langdon fault zone, integrated with analyses of surrounding major submarine structures (Massell et al., 2000), indicate that it formed near the inside corner of a spreading-ridge–transform fault intersection. This interpretation explains the geology (Varne et al., 2000) and early structures (Goscombe and Everard, 2001) on the island in both local and regional tectonic contexts.

FINCH-LANGDON FAULT ZONE

The Finch-Langdon fault, the most significant spreading-related structure on the island, places lower-crust and mantle rocks in the north against upper-crust rocks in the south (Fig. 1). It consists of seven segments, ranging in length from 0.5 km to 2.25 km, that join at high angles (Fig. 3), and is the only fault exposed on the island with such significant displacement. The highest concentration of faults on the island is in an ~2 km adjacent zone. Although the fault is poorly exposed overall, subsidiary faults within the fault zone are plentiful and mimic the larger feature. No dramatic fault scarps are found within the zone (Fig. 3); two segments that parallel the modern-day plate boundary may have undergone minor reactivation, enhancing relief. We investigated previously mapped (Mawson and Blake, 1943; Goscombe and Everard, 2001) fault segments to determine the original (spreading vs. transform related) tectonic setting, orientation, crosscutting relationships, kinematics, and extent.

New Structural Data

The seven segments of the Finch-Langdon fault are oriented either 280°–295°, 330°–350°, or ~20°, forming high-angle intersections pointing southwest or northeast (Fig. 3). The faults forming this unusual pattern do not appear to truncate one another and were confirmed by lithologic changes and the presence of faults and fault rocks observed along their traces.

The subsidiary faults form three orientation regions along the Finch-Langdon fault zone (Fig. 3). In all cases, the outcrop-scale, mineralized faults within the zone are oriented similarly to nearby traces of the Finch-Langdon fault (Fig. 3), indicating that they are related to the larger system. Most outcrop-scale faults dip steeply and have moderately to shallowly plunging mineral-fiber slickenlines (Fig. 3) with rare steps indicating dextral oblique slip; we observed one sinistral oblique slip and one thrust fault. At Langdon Point, a 15-m-long listric normal fault within pillow basalts has four southeast-dipping splays that join in one subhorizontal plane containing epidote slickenlines. At Langdon Bay, the main fault is exposed as a highly fractured ~160 m^2 plane (330°/90°), but wave erosion has removed much of the mineralized surface.

Mineralization

Faults are common pathways for hydrothermal circulation associated with seafloor spreading, resulting in fault planes that are cemented with and/or have slickenlines composed of hydrothermal minerals, such as prehnite, epidote, actinolite, sulfides, and quartz (Alexander and Harper, 1992). Rock adjacent to the fault is usually hydrothermally altered and/or fractured and has veins filled with hydrothermal minerals. High-temperature hydrothermal circulation only affected Macquarie Island rocks during seafloor spreading; thus, the presence of these hydrothermal minerals indicates faulting associated with seafloor spreading.

Along the Finch-Langdon fault, small fault planes and fault rocks contain hydrothermal minerals. Slickenlines composed of epidote, prehnite, and/or retrograde chlorite occur as thin mineral fibers on fault planes. Hydrothermal minerals also cement fault breccia. For example, gabbros adjacent to the fault contain meter-scale faults characterized by 0.5–2-cm-thick cataclastic zones of angular clinopyroxene and plagioclase rock fragments cemented by undeformed prehnite. In addition, these fault surfaces are scored by mineral slickenlines indicating dextral oblique slip. The Finch-Langdon fault zone also contains foliated cataclasite with superimposed shear bands. Small nuggets of hydrothermal epidote are part of the cataclastic material in the brittlely sheared rock, and prehnite veins truncate the sheared material, indicating faulting prior to and/or during active hydrothermal activity on the seafloor. Two segments of the western half of the fault show sulfide-rich mineralization such that hydrothermally altered pillow lavas are indistinguishable from sheeted dikes.

Rocks adjacent to faults have extensive fractures filled with one or more generations of mineralization consisting of prehnite, epidote, zeolites, quartz, and/or carbonate. Multiple fracture sets crosscut each other at high angles. In places, small (1–4 cm wide) calcium-metasomatized shear zones (epidote, calcic clinopyroxene replacement) are associated with faults and with prehnite and epidote veins. Pervasive sulfide alteration is also common; abundant pyrite is associated with amphibole, chlorite, and epidote in gabbro, diabase, and basalt.

Rocks Adjacent to the Fault

North of the fault, sheeted dikes strike primarily northwest (Fig. 3) with dips of 20°–80°N and S. Although dike strikes vary, dikes are commonly subparallel to the adjacent segment of the Finch-Langdon fault, suggesting that sheeted-dike anisotropy may have controlled the initial orientation of some Finch-Langdon fault segments. Hydrothermal-mineral–filled fractures are numerous near the fault, and dikes immediately adjacent contain abundant meter-scale faults filled with cataclasite. Gabbros adjacent to the fault exhibit small (≤20 cm wide), ubiquitous mylonite zones in addition to the fractures and faults previously described; most dip steeply (70°–90°N and S), striking ~150° parallel to the adjacent northwest end of the Finch-Langdon fault. The subparallelism of mylonite zones to the fault suggests that they may be related to early fault motion.

The upper-crustal section south of the fault consists of pillow basalts, interbedded with massive basalt flows, hyaloclastites, and sedimentary rocks exposed in nearly continuous sections for more than 10 km in coastal outcrops. Directly adjacent to the fault on the west coast, pillow basalts are overturned, dipping steeply northward; farther from the fault, however, the units are generally upright, dipping moderately southward. Although outcrop-scale spreading-related faults are observed across Macquarie Island, hydrothermally mineralized outcrop-scale faults are most abundant within ~1 km of the Finch-Langdon fault.

Talus breccias and other sedimentary rocks are interbedded with the volcanic rocks on the west coast for more than 4 km south of the fault. Talus breccias are clast supported with mudstone matrices; clasts are basalt, diabase, and gabbro. Graywackes are poorly sorted and contain angular clasts of oxides, devitrified glass, clinopyroxene, plagioclase, chlorite, carbonate, epidote, prehnite, and lithic clasts of basalt, diabase, and gabbro. Rare pink and white limestone and thinly banded chert are exposed.

The island's largest talus breccia (~150 m wide and ~140 m thick) is at the southern end of Bauer Bay, 500 m from the Finch-Langdon fault. This breccia is cut by diabase dikes and is overlain by a repeating sequence of graywacke with rare chert interspersed with volcanic rocks that continues for ~2 km. Another significant sedimentary package ~700 m from the fault at Douglas Point consists of a clast-supported breccia (clasts are ≤40 cm, some red mudstone matrix) that fines upward to graywacke. The package is ~4 m thick, contains gabbro clasts, and is overlain by a basalt flow. These sequences confirm concurrent active volcanism and shedding of clastic material from a submarine fault scarp. Abundant talus breccia and sedimentary rocks on the west coast and their general lack along the east coast indicate that a topographic high existed to the northeast.

DISCUSSION

Macquarie Island is dissected by numerous faults that formed during seafloor spreading and by younger postspreading faults that formed during transform motion and uplift of the island. The Finch-Langdon fault is unique for its magnitude of uplift, the complicated fault segment geometry, and the extent and provenance of sedimentary rocks most likely shed off its fault scarp. The younger faults differ in that they have dramatic, fresh fault scarps and no hydrothermal mineralization. Only two Finch-Langdon fault segments have some topographic expression, suggesting some reactivation during uplift; most are not appropriately oriented for reactivation. Delicate mineral slickenlines preserved on discrete fault planes throughout the Finch-Langdon zone also argue against major reactivation.

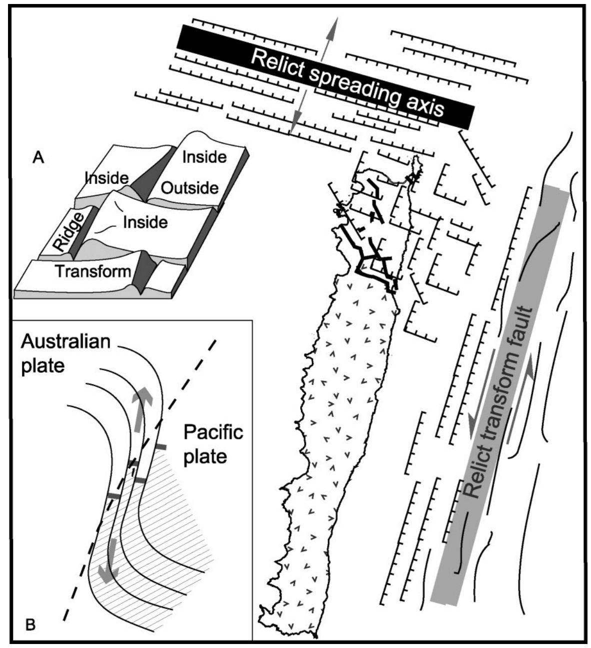

Figure 4. Proposed tectonic setting of Finch-Langdon fault: ridge-transform intersection (RTI). Finch-Langdon and related faults are shown. Inset A: Schematic geometry of RTI, after Tucholke and Lin (1994). Inside corners have higher elevation (400–2500 m higher) than outside corners (Severinghaus and Macdonald, 1988). Inset B: Geometry of Australian-Pacific plate boundary ca. 10 Ma when Macquarie Island crust formed (after Massell et al., 2000). Sigmoidal black lines—fracture zones; short, gray lines—spreading centers; dashed black line—present transform plate boundary; arrows—spreading direction.

Submarine ridge–transform fault intersections have (1) an outside-corner ridge and aseismic fracture zone intersection, and (2) an inside-corner active spreading-ridge–transform fault intersection (Collette, 1986; Severinghaus and Macdonald, 1988) (Fig. 4). On the outside corner, hot and thin new crust accretes adjacent to previously sheared crust; however, little or no further motion takes place along the fracture zone. The inside corner crust is thickened, and relief increases as new crust accretes to the edge of the active transform valley (Severinghaus and Macdonald, 1988). Extensive faulting (including detachment faults) exposes deeper rocks, whereas rocks in the outside corner are usually basaltic (Karson and Dick, 1983).

At spreading-ridge–transform fault intersections, structures form in response to interactions between spreading and transform motion. Complex structures form parallel to the spreading ridge, parallel to the transform fault, and oblique to both (Fox and Gallo, 1984), but in the orientation predicted for normal fault formation a simple-shear system along the transform fault (Fig. 4). A model for deformation at inside corners (Allerton and Vine, 1992), based on observations of the Troodos ophiolite where a fossil ridge–transform fault intersection has been described (Moores and Vine, 1971; MacLeod et al., 1990), proposes that the outside corner is dominated by normal faulting, whereas the inside corner undergoes both normal and strike-slip faulting.

We propose that the Finch-Langdon fault formed within an inside corner of a spreading-ridge–transform fault intersection (Fig. 4). Swath reflectivity and bathymetric data in the ocean basin directly east of the island indicate roughly east-west–oriented spreading fabric perpendicular to a fracture zone ~7 km from the island (Figs. 2 and 4; Massell et al., 2000). Sheeted dikes and spreading-related extensional faults on the island are consistent with spreading-fabric orientations in the swath data.

Interpretations of the swath data east of the island allow us to place the unusual geometry of the Finch-Langdon fault (many short faults at high angles and junctions that point to the southwest or northeast) into a larger oceanic tectonic context: some Finch-Langdon fault segments parallel the offshore relict transform fault (fracture zone; north-northeast), some parallel the relict spreading center (spreading fabric; west-northwest), and others are oblique to both (northwest). Pervasive hydrothermal mineralization on outcrop-scale faults and alteration along the fault zone are consistent with deformation at a mid-ocean ridge. The predominantly oblique normal and strike-slip faulting along the Finch-Langdon fault zone is most consistent with fault kinematics within the inside corner of a spreading-ridge–transform fault intersection (Allerton and Vine, 1992). We observed no detachment faults, and mylonite foliations and lineations in the adjacent gabbros also have steep dips and plunges, respectively, suggesting that the high-angle faults first had normal motion and were reactivated with the observed oblique slip motion during further shearing at the ridge–transform fault intersection. The predominantly dextral shear on faults at high angles or oblique to the relict transform fault suggests counterclockwise rotation of fault blocks in an overall sinistral transform zone; the one observed sinistral fault parallel to the relict transform fault supports this interpretation. Talus deposits and angular, unsorted graywackes most likely formed at the base of fault scarps, and their distribution indicates that there was a topographic high to the northeast, which is consistent with lower-crust and mantle exposures. Gabbro clasts in the talus breccias and graywackes indicate that gabbros were exposed on the seafloor, as commonly occurs in inside-corner environments. Furthermore, volcanic rocks overlying sediments indicate synchronous volcanism and sedimentation. With an inside-corner interpretation, orientations of oblique faults relative to spreading fabric and fracture zones, as well as the location of the paleo–topographic high, require that the island adjoin a sinistral transform fault. Such a configuration is reasonable on the basis of observed magnetic anomalies that predict right- and left-stepping ridge segments projecting toward the island. The present-day dextral transform fault formed later, after volcanism shut off, crosscutting the short ridge segments.

CONCLUSIONS

Macquarie Island provides an exceptional opportunity to observe seafloor processes and features on land where the tectonic context is preserved in the surrounding seafloor. The Finch-Langdon fault zone—on the basis of the fault pattern, mineralization, and associated sedimentary deposits, coupled with the tectonic setting documented by swath reflectivity and bathymetry data—is best explained as having formed in an inside corner of an active spreading-ridge–transform fault intersection near the end of seafloor spreading.

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