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Non-coaxial horizontal shortening strains preserved in twinned amygdule calcite, DSDP Hole 433, Suiko seamount, northwest Pacific plate

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Abstract—Core sections from the lower, basaltic portions of DSDP Hole 433 (total depth: 550.5 m) in Suiko seamount contain amygdule and vein fillings of calcite which contain mechanical twins. Analysis of the calcite twins reveals the presence of two horizontal shortening strains that are nearly orthogonal to one another; the azimuthal orientation of these strains is only known with respect to stratigraphic top and bottom as the cores are not oriented in any other manner. Maximum shortening strain magnitudes for the best-developed, positive expected value (PEV) twin lamellae set is −1.7%. For the lesser-developed, negative expected value (NEV) split, the preserved horizontal strain magnitude is −4.3%. Inferred compressive paleostress magnitudes were on the order of 26 MPa. Horizontal differential stresses of this magnitude could be: (1) associated with hotspot plumes; and/or (2) are transmitted to the central portions of thin oceanic plates from distant plate boundaries.

Suiko seamount is composed of Paleocene basalts overlain by lithified middle Paleocene limestones, and is part of the Emperor seamount chain on the Pacific plate. The absence of secondary vein calcite in the overlying sediments suggests that the underlying amygdule calcite is Paleocene in age which indicates that the twinned calcite preserves a stress field reorganization (the NEV split) after the middle Paleocene that is oriented 64° from the earlier Paleocene stress field (the PEV split).

INTRODUCTION

CRUSTAL plates, especially those of oceanic composition and thickness, have limited flexural rigidity but infinite torsional rigidity and are proposed to transmit stresses over great distances between plate margins. Such stress trajectories were modelled by Richardson *et al.* (1979) and Richardson & Reding (1991) and these results have been partially confirmed by studies of contemporary *in situ* fields (Zoback & Zoback 1980, 1987) toward the goal of producing a contemporaneous world stress map (Zoback 1987, World Stress Map Workshop 1989).

Stress trajectories and magnitudes are becoming better known for some continental regions (e.g. Mount & Supper 1987, Zoback *et al.* 1987) but the *in situ* stress fields within oceanic plates are poorly known. Intraplate earthquake focal mechanisms (Richardson *et al.* 1979; sites 92–94) indicate a principal horizontal compressive stress that is ENE–WSW within the Pacific plate. *In situ* borehole stress measurements from wells (504B and 765D) near active spreading centers (Newmark *et al.* 1984; Castillo *et al.* 1991) indicate that the maximum horizontal stress is compressive and oriented normal to the spreading ridge (e.g. ridge-push). Our study uses the presence of mechanically twinned calcite within the basaltic section of DSDP Hole 433 to interpret the stress and strain field (orientation and magnitude) responsible for twinning the calcite. The calcite twinning strains in these basalts preserve two unique deformational events, but their use is limited due to the lack of azimuthal orientation data for the samples. An ideal study would have the following components: (1) oriented core, or core reoriented paleomagnetically; (2) isotopically dated calcite (Sr–Sr method); and (3) *in situ* stress measurements from the same borehole to correlate with the twinning strain measurements. Borehole stress measurements are ongoing at DSDP/ODP Hole 504B, and twinned calcite is present (Honnoreg *et al.* 1979), but the core is not oriented or available.

RESULTS

Six samples were obtained from DSDP Hole 433 (Figs. 1 and 2) from a variety of depths within the basaltic portion of the core. The basalts have been dated as 62.5 Ma (Paleocene) using the Rb–Sr technique, and the Suiko seamount has intruded Pacific plate basalts that range in age from 120 Ma (west) to 70 Ma (east). The secondary calcite fills both vesicles and fractures

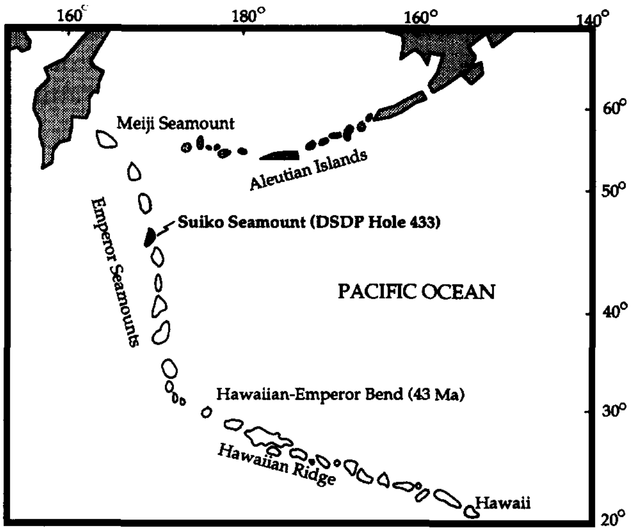

Fig. 1. Location map of DSDP Hole 433 and the Suiko seamount within the Emperor seamount chain in the northern Pacific Ocean.

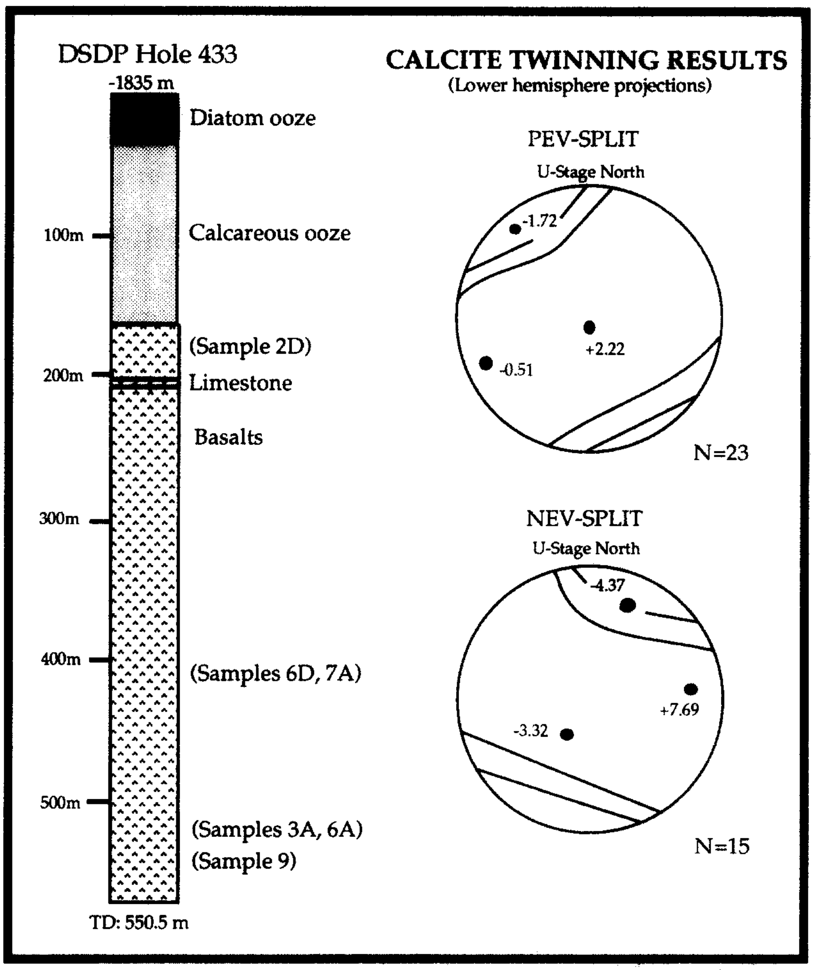

Fig. 2. Generalized stratigraphy of DSDP Holes 433a–c from the Suiko seamount, including the locations of our twinned calcite samples (see Table 1). Calcite twinning results are presented as lower-hemisphere projections for the positive (PEV) and negative (NEV) data splits. Universal stage north is noted, as all sample orientations are only with reference to a stratigraphic up direction. Turner (1953) compression axes are contoured, and principal strain axes are plotted (e_1 = greatest shortening strain, e_2 = intermediate strain axis, e_3 = greatest extensional strain axis).

and appears to be of one generation. In thin section the vein and amygdule calcite is in optical continuity and presumably of one filling phase. The overlying lithified Paleocene sediments do not contain cross-cutting calcite veins, so we presume that the calcite in the basaltic portion of the core is Paleocene in age. Dating of secondary calcite (Sr–Sr method) in oceanic ridge basalts has shown that multiple phases of calcite, of varying ages, may be present in a single core (Burns *et al.* 1992).

Calcite twin analysis method

Calcite mechanically twins at low stresses (10 MPa) independent of temperature and normal stresses. Twinning is possible along three glide planes and calcite strain-hardens once twinned; additional twinning is possible only at higher stress levels if that stress is oriented >45° from the initial stress orientation (Teufel 1980). The structural application of twinned calcite has been primarily restricted to studies of limestones (e.g. Engelder 1979, Wiltschko *et al.* 1985; Craddock *et al.* 1993), calcite veins (e.g. Kilsdonk & Wiltschko 1988) or, more rarely, marbles (e.g. Craddock *et al.* 1991). This is the first application of calcite twin analysis to secondary minerals in an igneous rock suite.

Paleostresses responsible for twinning can be calculated in terms of their compressional (or tensile) orientation (Turner 1953) and magnitude (Jamison & Spang 1976). Strain ellipsoids are computed using the Groshong method (1972, 1974) which is quite accurate (Groshong *et al.* 1984) for strains ranging from 1 to 17%.

The Groshong method also computes negative and positive expected values for all the twins in a given thin section. A negative expected value (NEV) for a twinned grain indicates that this grain was unfavorably oriented relative to the stress field that caused the majority of the grains in a given thin section to twin. A high percentage of negative expected values (>40%) indicates that a second, non-coaxial twinning event occurred and these two twinning strains (PEV and NEV groups, respectively) can be analyzed separately.

Twinning strains

We obtained six samples which were oriented with respect to stratigraphic up (top). Sample orientation throughout the core was a concern; within the middle

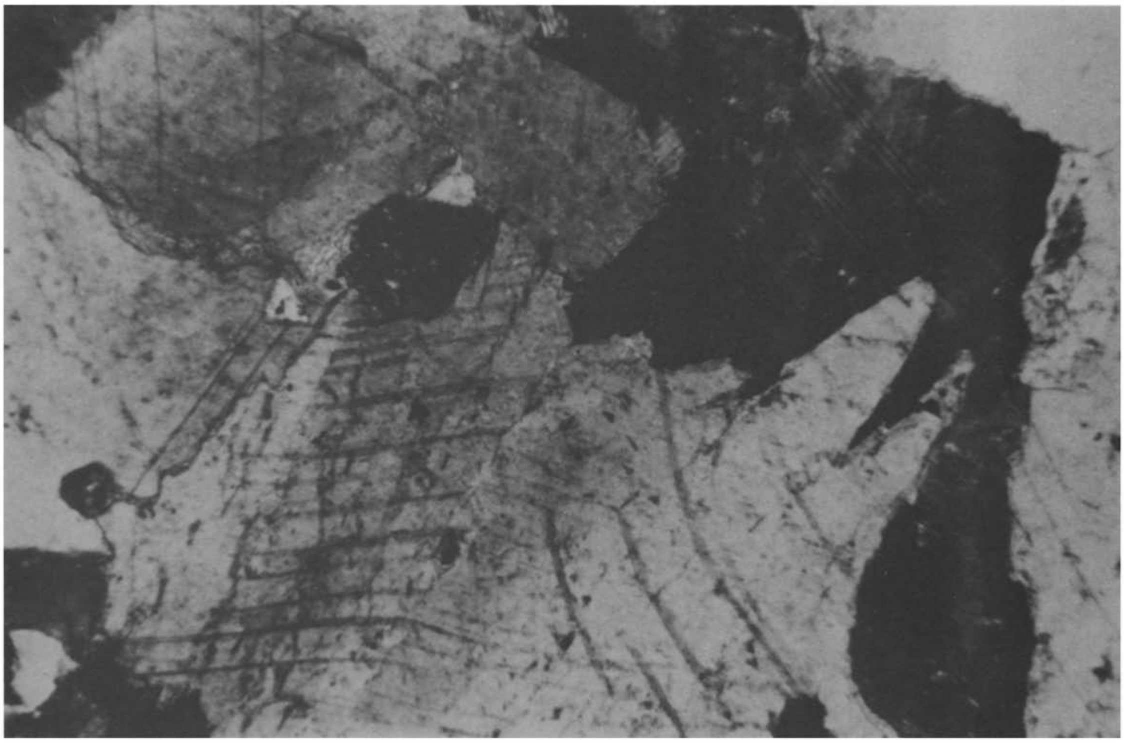

Fig. 3. Photomicrograph of twinned calcite from sample 9 (depth 533 m). Photograph width is ~2 mm.

Table 1. Results of calcite twin analysis

Sample	No. of grains	e_1 (%)	e_1 orientation	NEVs (%)	Error (%)
PEV	23	−1.7	300,10	0	0.73
NEV	15	−4.3	34,19	100	0.65

Sample piece	Depth (m)	e_1 (%)	Twinned grains (%)	Differential stress (MPa)
2D	165	0	0	0
6D	408	−2.16	15	23.8
7A	408	−1.59	18	24.3
3A	532	−1.39	26	26.3
3A	532	−3.41	26	26.3
6A	532	0	0	0
9	533	−14.4	40	30.7

(408 m) and lower (532 m) thin sections were cut in the same orientation for local continuity. In the end, we observed consistency in the PEV and NEV strains in each thin section throughout the core, relative to stratigraphic up. Two of these samples (2D and 6A) contained calcite that was not twinned, and from Sample 3A we cut two thin sections (Table 1). From the five thin sections analyzed we measured 38 twin sets and found that none of the twinned grains contained more than one twin lamellae set (Fig. 3). The high percentage of NEVs indicate that two non-coaxial shortening strains occurred (Teufel 1980). Consequently, we separated the PEV and NEV sets for each of the five thin sections and discovered two sub-horizontal, but nearly orthogonal, shortening strains. The combined result is shown in Fig. 2. The PEV split plunges 10° toward 330 (maximum shortening strain: −1.7%), and the NEV split plunges 19° toward 34 (maximum shortening strain: −4.3%). A notable difference between the PEV and NEV splits is that in the former the maximum extensional strain is vertical whereas in the NEV split the maximum extensional strain in sub-horizontal.

Using the method of Jamison & Spang (1976) we have determined that the differential stresses responsible for the calcite twinning were sub-horizontal and approximately 26 MPa in magnitude (Table 1). The magnitude of both the inferred differential stresses and shortening strain magnitudes do increase with depth for our small sample array (see also Friedman & Heard 1974).

DISCUSSION

Crucial to any tectonic interpretation we could derive from our twinning strains is the age of the calcite filling. The absence of vein calcite in the sediments overlying the basalts constrains the secondary calcite age to the Paleocene. Many of the amygdules are spheroidal suggesting that the vesicles filled shortly after the basalts crystallized. If we assume that the calcite is Paleocene in age, then the twinned calcite preserves two sub-horizontal shortening strain events that are 64° from one another. By convention, the PEV split is the best developed twinning strain fabric, whereas the NEV split represents a secondary, less developed strain fabric (Groshong *et al.* 1984). Unfortunately, the azimuthal orientations of the samples is unknown so we cannot attempt to correlate these strain results with more grandiose, distal plate reorganizations. We can, however, attempt to interpret the calcite strain results in terms of the location of these rocks during and since the Paleocene.

Bending and thermal stresses

The DSDP 433 samples are from a relatively shallow depth (<550 m) in a now submerged seamount. At the time of their extrusion and secondary calcite mineralization, these basalts were proximal to the Hawaiian hotspot thermal bulge and the calcite twinning strains may represent sub-horizontal shortening within a hotspot setting where lithospheric flexure can result in sub-horizontal bending stresses of approximately 100 MPa (Walcott 1970, Watts & Cochran 1974). Focal mechanism studies on the island of Hawaii (Thurber 1987) and *in situ* stress measurements in Iceland (Haimson & Voight 1977) also document sub-horizontal compressional stresses in a hotspot tectonic setting. Modelling of thermoelastic stresses associated with the Hawaiian hotspot by Zhu & Wiens (1991) suggests that horizontal compressive stresses parallel to the hotspot track (e.g. E–W) would be dominant at a depth of 25 km. Sub-horizontal tensile stresses (normal to the hotspot track) become more prevalent at shallower depths and around the margin of the hotspot, but horizontal compressive stresses are also present.

The interpretation of our two horizontal twinning strains needs to incorporate sub-horizontal compression as the Suiko basalts passed over the hotspot track (bending and thermal stresses), then were submerged as these rocks passed westward from the Hawaii hotspot bulge (unbending and thermal stresses) to their present position. The change in the orientation of the maximum extensional strain axis (e_3), from vertical to sub-horizontal between the PEV and NEV splits (Fig. 2), could record this stress field change.

Oceanic intraplate stresses

An alternative interpretation of the calcite strain results, in the absence of an absolute date of the calcite, would be that the sub-horizontal shortening strains are not associated with the hotspot setting, where bending and thermal stresses may negate each other, but rather with sub-horizontal stresses (magnitude >20 MPa) transmitted across the Pacific plate. Craddock *et al.* (1993) have documented the transmission of Appalachian compressive orogenic stresses and strains across ~2200 km of continental, cratonic North America. Perhaps the two sub-horizontal shortening strains represent stress (and strain) fields associated with tectonic events before and after the bend in the Emperor chain at 43 Ma. Curiously, the angle between the young and old portions of the Emperor chain is ~64°.

A recent re-evaluation of Pacific intra-plate seismicity by Lay (1991) suggests that coseismic stresses are not transmitted more than 2° oceanward of any active subduction margin. Some large intraplate earthquakes (M_s >6.0) do occur but the apparent stress minimum is in the range of 0.2–1.5 MPa (Bergman & Solomon 1980, Bergman 1986), well below the stress level needed to twin calcite. Dahlen (1981) has suggested that stress magnitudes of 10–20 MPa may be expected in old, thick oceanic lithosphere like the western Pacific. Govers *et al.* (1992), after Cloetingh & Wortel (1985, 1986), suggest that intraplate differential stress magnitudes are 100–200 MPa in the Pacific plate although it seems most intraplate seismic events are often within only a few hundred kilometers of an active plate margin.

Until *in situ* stress measurements are made within abyssal oceanic lithosphere, not adjacent to active spreading ridges (e.g. Holes 504B and 597C), or until oriented, calcite-bearing abyssal cores are available, the state of stress in oceanic plates will continue to be poorly understood.

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