Reprinted from Nature, Vol. 329, No. 6139, pp. 534-537, 8 October 1987

Evidence from en-echelon cross-grain ridges for tensional cracks in the Pacific plate

E. L. Winterer* & D. T. Sandwell†

* Scripps Institution of Oceanography, La Jolla, California 92093, USA
† Institute for Geophysics, University of Texas, Austin, Texas 78712, USA

Sea-floor topography in the Pacific is mainly aligned with original spreading directions[1], but is overprinted by alignments created by mid-plate processes. Spreading produces abyssal hills and fracture zones, and mid-plate volcanism generates seamounts, isolated or in chains. A different category of topography, the 'Cross-grain', discovered in geoid-height data collected by the Seasat radar altimeter[2], comprises linear troughs and swells spaced ~200 km apart, oblique to fracture zones and abyssal hills but parallel to the Hawaiian chain. Three models have been proposed for the Cross-grain: small-scale convection, organized into longitudinal rolls by the shear of the Pacific Plate[2]; compressive buckling[3]; and lithospheric boudinage resulting from plate-wide tensile stresses[4,5]. None of the previously available data ruled out any of these models. Here we report multi-beam bathymetric data revealing long, narrow en-echelon ridges along the Cross-grain, interpreted as evidence of tension cracks in the Pacific plate.

In the equatorial Pacific, cross-grain lineations extend for more than 4,000 km, crossing from young (5 Myr) sea floor near the East Pacific Rise to Cretaceous (100 Myr) sea floor near the Line Islands. The topographic relief associated with the cross-grain geoid undulations is typically only ~200 m and, although difficult to detect in available bathymetric profiles, has been confirmed by shipboard measurements of gravity and bathymetry on crust of age 6-35 Myr (ref. 6). Another manifestation of the cross-grain pattern appears in the Line Islands region as Cross Trend[7] ridges trending ESE, oblique to the main SSE trend of the Line Islands.

To study the Cross-grain, we explored an area in the equatorial Pacific (see Fig. 1) from RV *Thomas Washington* in February and March 1987. This region is especially suitable for study of the Cross-grain because it shows strongly here on the Seasat maps and profiles, and appears to continue westward as the Line Islands Cross Trend. The region is blanketed by a thick (300-1,000 m) cover of pelagic sediments, with basal ages from late Cretaceous at the west end of the area to Eocene at the east end, and with an internal stratigraphy to constrain the age of formation of the Cross-grain. Neogene seismic stratigraphy in the region is tied through drill holes to the biostratigraphic timescale[8]. Strong, discontinuous amplitude anomalies in the seismic reflection records[9,10] are spatially associated with one of the prominent cross-grain highs and resemble the seismic signature of mid-plate volcanic sills and flows in Deep Sea Drilling Project holes[11,12].

Bathymetry was surveyed using the Seabeam multi-beam sonar[13]. Seismic reflection profiling, using an 80-in^3 water-gun source, digital recording and processing to deconvolve the source signal, was used to detect volcanic units within the pelagic sediments, to fix their stratigraphic level[8] and to map the basement relief. To confirm and refine the Seasat observations, gravity was measured with a Bell BGM-3 gravimeter. Navigation was from transit and available Global Positioning Service satellite fixes.

Data collected along a zig-zag pattern during the first part of the expedition (Fig. 1) confirmed the existence of the cross-grain swells seen in the Seasat data. Beneath the sediments, broad (~200 km) undulations in the basement topography correlate with highs and lows in the Seasat-derived gravity[2], and with our shipboard gravity measurements. Exploration along the axis of the most prominent cross-grain high in the area, which extends south-east from Christmas Island (Fig. 1), revealed an unexpected series of narrow (7-15 km) ridges, en-echelon to the trend of the swell, which could be traced for ~1,000 km.

Individual ridges range in length from ~50 to 400 km and trend 10-20° more easterly than the summit line of the cross-grain swell. The en-echelon pattern steps southward in increments of ~35 km to stay mainly within ~100 km of the summit line. The known length of overlap of adjacent ridges is at least 90 km, but our survey is incomplete on this point. The ridges are continuous but not perfectly straight; short segments deviate from the main direction (095°) to follow the trend of fracture zones (077°).

The relief of the ridge system gradually decreases eastward. Beginning in the Line Islands, the ridges are high (2-3 km) and massive. The shallowest ridges form the Line Island Cross Trend[7]. Between 154 and 145° W, the ridges are generally ~1-2 km high and continuous, and east of 145° W they decrease further in height, length and continuity. Detailed surveys of two small areas at 136 and 138° W revealed only short ridges or

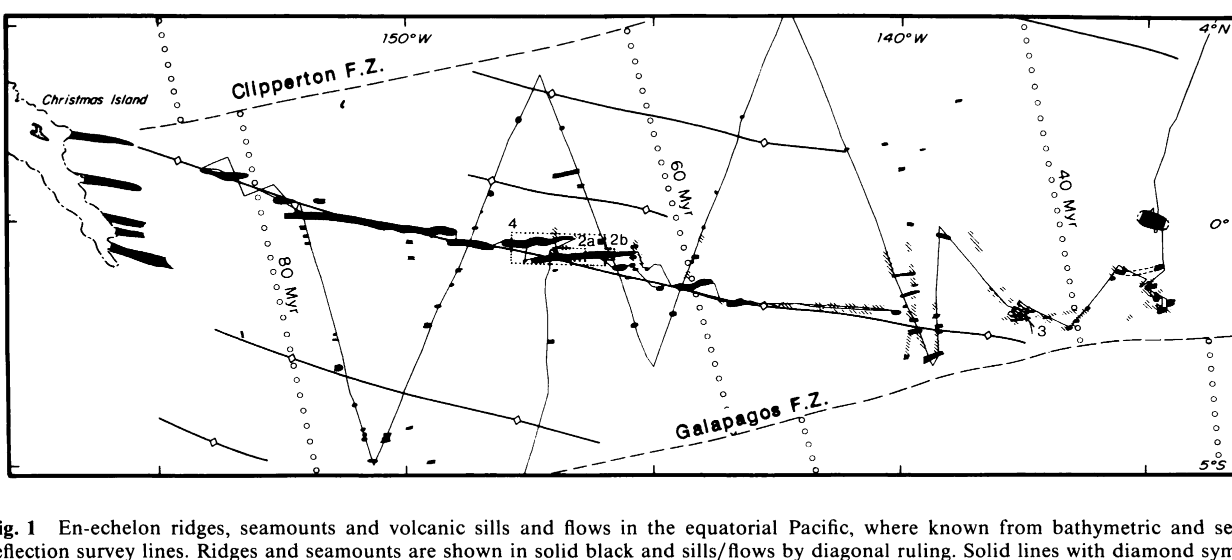

Fig. 1 En-echelon ridges, seamounts and volcanic sills and flows in the equatorial Pacific, where known from bathymetric and seismic reflection survey lines. Ridges and seamounts are shown in solid black and sills/flows by diagonal ruling. Solid lines with diamond symbols, axes of cross-grain swells seen on Seasat geoidal-height map[2]; dashed lines, fracture zones; dotted line, 4,000-m isobath on Line Islands ridge; thin line, track of RV *Thomas Washington*; open-circle lines, approximate positions of crustal isochrons. Locations of Figs 2-4 are shown by dotted rectangles (Figs 2, 4) and arrow (Fig. 3).

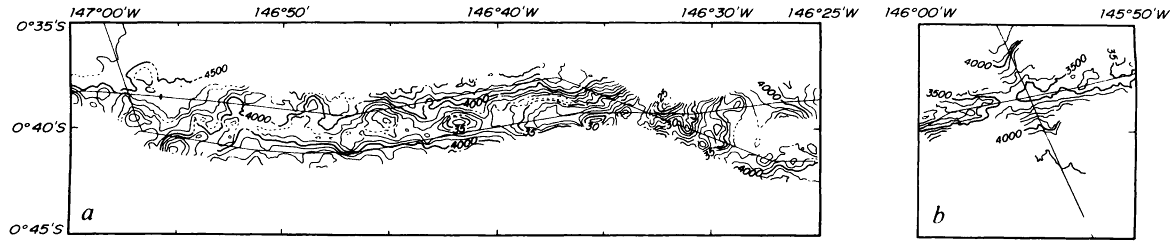

Fig. 2 Two segments of a typical en-echelon ridge, surveyed with a multi-beam swath-mapping system. The western segment (*a*) is mainly in the overlap zone of two adjacent ridges (Fig. 1), and descends westward from the beginning of the overlap, at 146.5° W (see Fig. 4). Summit peaks are staggered along a zone 2-3 km wide. Ship tracks are shown by thin lines; contour interval, 100 m.

chains of small, separated seamounts.

The ridges change morphology with size. The tallest ridges are 10-15 km wide and rise 2-3 km above the basement. They have steep flanks and relatively flat summit areas from 1 to 2 km wide. Intermediate-size ridges (1-2 km high) are narrower (7-10 km) and are topped by volcanic cones (see Fig. 2). The cones are mainly spaced at intervals of 3-7 km along the ridge, and in some places alternate from one side of the ridge to the other, like large stepping stones. The smallest ridges comprise volcanoes connected beneath the sediment cover. At wide intervals, large seamounts occur along even the smaller ridges. Where ridges turn to follow the fracture zone direction, the morphology commonly changes from 'stepping stones' to a razor-back ridge.

As the ridge system decays eastward, the expression of volcanism changes from volcanic edifices to a mixture of small volcanoes and flanking sills (and perhaps flows) intercalated within the sediments between volcanoes. Several lines of evidence support the identification of the strong reflectors as sills: (1) they are intercalated within the normal sequence of sedimentary reflectors[9,10] (Fig. 3); (2) they cut across sedimentary layers in some places (Fig. 3); (3) they occur at many stratigraphic levels, but not above a certain regional reflector known to be ~14 Myr old[8]. The highest units may be flows rather than sills. (4) They closely resemble discontinuous strong reflectors identified elsewhere as intrusive volcanic sills by drilling[11,12].

Sills and/or flows strongly tend to occur close to the en-echelon ridges and lines of small seamounts, and we suppose these to be their sources. A detailed survey, near 138° W, showed sills/flows in sedimentary troughs between aligned seamounts, either level-ponded or slightly sloping. The distribution of sills (Fig. 1) is complementary to that of the ridges. Going eastward, sills first appear at about 147 °W, between ridges, and increase in areal coverage farther east. They are most concentrated in a band within 100 km of the summit line of the swell, but occur as far away as 200 km.

The morphology and distribution of the en-echelon ridges suggest that they result from filling of tensional cracks in the lithosphere. We speculate that the widths of the cracks are about equal to the width of the relatively flat summits with volcanic peaks (1-2 km). The cracks are segmented such that they always lie on the cross-grain swell. This suggests that either this cross-grain swell is a broad zone of tensional deformation of the

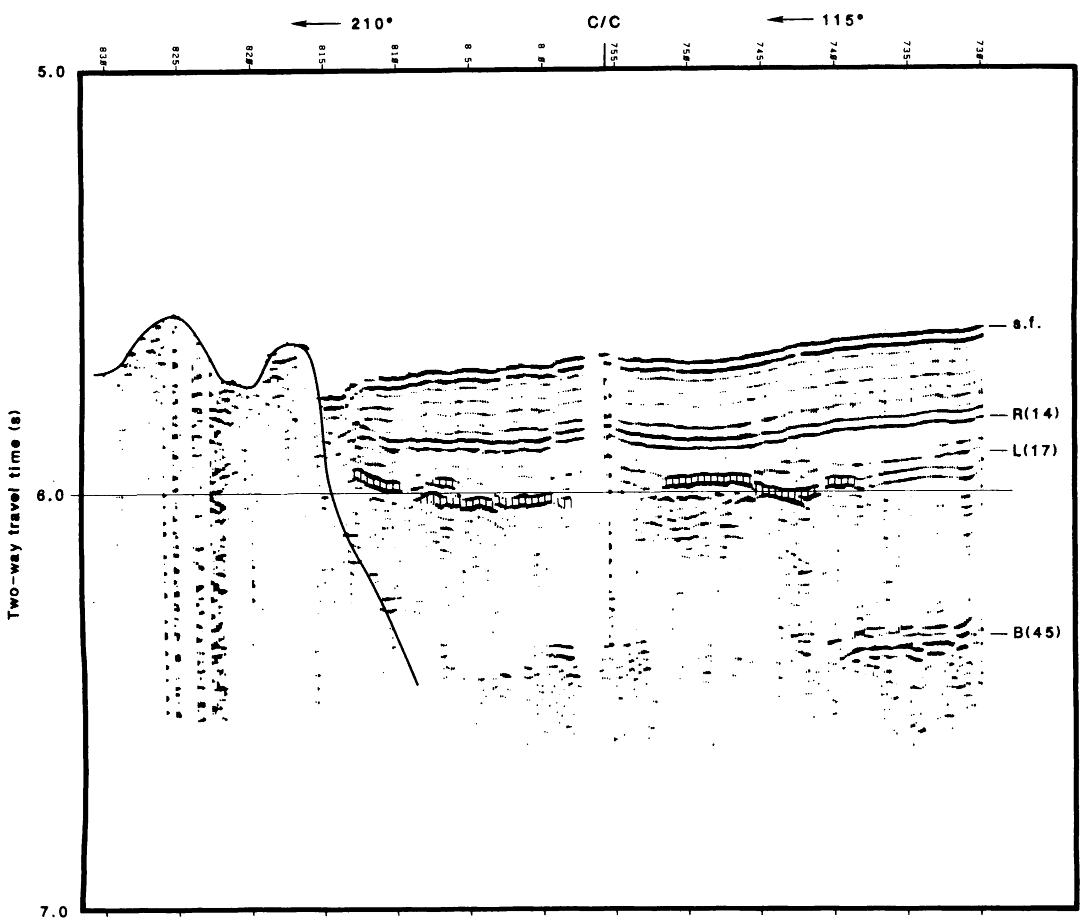

Fig. 3 Seismic reflection profile of volcanic sills intercalated in the sedimentary section. Note that the sills cut across sedimentary reflectors. The sills are identified by vertical ruling, and the volcanic ridge at left is outlined; otherwise, nothing on the original seismic record has been changed. Reflectors: s.f., sea floor; R, red reflector; L, lavender reflector; B, oceanic basement. Numbers in parentheses give the age of each reflector in Myr. At 1.8° S, 137.5° W (ref. 9). C/C denotes course change. 115° and 210° are the courses of the ship along the direction given by the arrows.

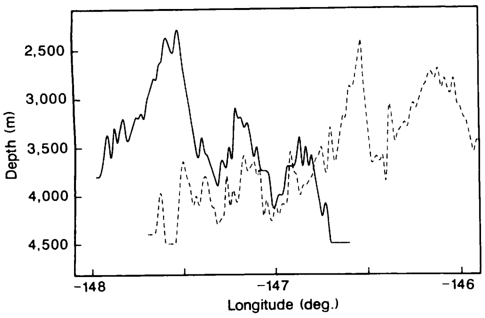

Fig. 4 Depth along the summits of two overlapping en-echelon ridges. In the overlap region, the northern ridge (solid curve) diminishes as the southern ridge grows. At depths of ⩾4,500 m the ridges are buried by pelagic sediments.

ductile lower lithosphere or the cracks develop on the weakest lithosphere, on the summit of the swell. We favour the first hypothesis because it also explains the en-echelon pattern of surface cracks. Experimental and theoretical studies of thin ductile sheets under tension show that plastic yielding occurs along diffuse flow layers (Luders' line) oriented 55–60° from the direction of tensile stress; both extensional and shear deformation occur within the flow layers[14]. If the cross-grain swell is due to ductile flow in the lower lithosphere, then the en-echelon ridges are the response of the upper brittle lithosphere to extension and shear deformation: extension opens the cracks and shear produces the en-echelon pattern. If this model is correct, then the central Pacific is being subjected to a large tensional stress oriented roughly north-south. This orientation is consistent with local intraplate earthquakes, which show plate-wide tension oriented NNE, approximately perpendicular to the direction of absolute plate motion[15].

Assuming that the tensional cracks are related to the formation of the Cross-grain, we can reject the lithospheric buckling model of cross-grain formation. We favour boudinage over the small-scale convection model because it requires tension and explains the opening of the cracks as well as their en-echelon pattern. On the other hand, our observations do not rule out the convection model, as small-scale convection beneath the lithosphere can also produce tensional stresses leading to cracking, as well as provide the excess temperatures required to produce melting and hence volcanism (B. Parsons, personal communication). Further work is needed to discriminate between the two models.

Our data do not indicate the source of the tensile stress, but possibilities include:(1) non-uniform cooling and contraction of the lithosphere[5]. Although most of this thermoelastic stress develops in the first 10 Myr and may be partially relieved along transform faults, this stress relief mechanism is less efficient when the spreading rate is high and transform faults are widely spaced[16]. (2) Plate-boundary forces such as slab pull[17]. (3) Drag at the base of the plate in the direction of absolute plate motion. This may produce compression in that direction and extension perpendicular to the cross-grain direction.

Given the angle between the Cross-grain and the individual ridges (10–20°), the ridge length and spacing are geometrically related. The crack spacing is relatively uniform (~35 km) and may be controlled by the thickness of the elastic part of the lithosphere. Ridge length therefore depends only on the angle between the cross-grain swell and the crack. This explains why ridges are shorter toward the north-west, as the angle between ridges and cross-grain swell increases (see Fig. 1).

Our simple analysis of en-echelon cracks indicates that the shear stress between two cracks decreases as the overlap increases. In the one place where we surveyed the overlap of adjacent ridges, the overlap is at least 90 km, or about three times the crack spacing. The overlapping-crack model predicts that the sum of the two crack widths in the overlap region is equal to the width of the single crack in the non-overlap region. Assuming that ridge height is related to crack width, each ridge should gradually diminish as the crack width decreases in the overlap region. A plot of ridge-crest elevations (Fig. 4) confirms this prediction.

We suggest that the progression of volcanic features, from high ridges in the west to discontinuous short alignments of small seamounts and ridges, interspersed with sills in the east, reflects an eastward change of some combination of tensional crack distribution and the volume rate of magma generation: either the thermal anomaly beneath the tension cracks diminished or the cracks themselves narrowed. The two effects may be combined.

The eastward sequence may also represent a time sequence, formed progressively as the Pacific plate moved northwestward. We have as yet only two indications of age along the Cross-grain: middle Miocene (14 Myr) sills/flows at 138° W, and possible late Eocene (36–40 Myr) for certain Line Islands Cross Trend features[18–20]. This age difference along the cross-grain is ~25 Myr and the distance is ~2,000 km, giving an average rate, assuming progression, of ~8 cm yr^{-1}, a figure close to the progression rate of the Hawaiian chain. Several ridges in the Line Islands Cross Trend appear to end westward in an elbow, congruent with the elbow junction between the Emperor and Hawaiian chains, also late Eocene in age[21].

This work was supported by the US Office of Naval Research. We thank Barry Parsons for a critical review of the manuscript.

Received 14 May; accepted 12 August 1987.

1. Mammerickx, J. & Smith, S. M. *Geol. Soc. Am. Map and Chart* Ser. **26**, (1978); **43**, (1980). (1980).
2. Haxby, W. F. & Weissel, J. K. *J. geophys. Res.* **91**, 3507–3900 (1986).
3. McAdoo, D. C. & Sandwell, D. T. *J. geophys. Res.* **90**, 8563–8569 (1985).
4. Turcotte, D. L. & Oxburgh, E. R. *Nature* **244**, 337–339 (1973).
5. Ricard, Y. & Froidevaux, C. *J. geophys. Res.* **91**, 8314–8324 (1986).
6. Parsons, B., Weissel, J. K., Daly, S., Buck, R. & Haxby, W. F. *Eos* **67**, 356 (1986).
7. Winterer, E. L. *Init. Rep. DSDP* **33**, 731–747 (1976).
8. Mayer, L. A., Shipley, T. H. & Winterer, E. L. *Science* **233**, 761–764 (1986).
9. Shipley, T. H. *et al. Init. Rep. DSDP* **85**, 825–837 (1985).
10. Winterer, E. L. & Shipley, T. H. *Eos* **65**, 977 (1984).
11. Winterer, E. L. *et al. Init. Rep. DSDP* **17**, 247–262 (1973).
12. Lancelot, Y. *et al. Init. Rep. DSDP* **41**, 233–326 (1977).
13. Renard, V. & Allenou, J.-P. *Int. hydrogr. Rev.* **56**, 35–67 (1979).
14. Nadai, A. *Theory of Flow and Fracture of Solids*, 320–326 (McGraw-Hill, New York, 1950).
15. Okal, E. A., Talandier, J., Sverdrup, K. A. & Jordan, T. H. *J. geophys. Res.* **85**, 6479–6495 (1980).
16. Sandwell, D. T. *J. geophys. Res.* **91**, 6405–6417 (1986).
17. Wortel, R. & Cloetingh, S. *Geology* **9**, 425–430 (1981).
18. Schlanger, S. O. *et al. J. geophys. Res.* **89**, 11261–11272 (1984).
19. Winterer, E. L. *et al. Init. Rep. DSDP* **17**, 47–102 (1973).
20. Premoli-Silva, I. & Brusa, C. *Init. Rep. DSDP* **61**, 439–473 (1981).
21. Jackson, E. D. *et al. Init. Rep. DSDP* **55**, 5–31 (1980).