the solid line shown in Fig. 1, this would be an indication that terrestrial atmospheric and solar-type xenon may be related to each other by a strong mass fractionating process (*11*). Trapped chondritic xenon, on the other hand, may possibly be related to solar-type xenon by the superposition on the latter of fission-xenon components with the required relative mass yields.

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References and Notes

1. K. Marti, paper presented at the 31st annual meeting of the Meteoritical Society, Cambridge, Massachusetts, 1968.
2. N. Grögler and K. Marti, in preparation.
3. K. Marti, *Earth Planet. Sci. Lett.* **3**, 243 (1967); O. Eugster, P. Eberhardt, J. Geiss, *ibid.*, p. 249.
4. A. O. Nier, *Phys. Rev.* **79**, 450 (1950).
5. K. Marti, P. Eberhardt, J. Geiss, *Z. Naturforsch.* **21a**, 398 (1966); M. W. Rowe, D. D. Bogard, P. K. Kuroda, *J. Geophys. Res.* **71**, 4679 (1966); C. M. Hohenberg, M. N. Munk, J. H. Reynolds, *ibid.* **72**, 3139 (1967).
6. P. Eberhardt, O. Eugster, J. Geiss, *J. Geophys. Res.* **70**, 4427 (1965).
7. M. N. Munk, *Earth Planet. Sci. Lett.* **3**, 457 (1968); O. Eugster, P. Eberhardt, J. Geiss, *J. Geophys. Res.* **74**, 3874 (1969).
8. O. K. Manuel, *Geochim. Cosmochim. Acta* **31**, 2413 (1967).
9. P. Signer and H. E. Suess, in *Earth Science and Meteoritics*, J. Geiss and E. E. Goldberg, Eds. (North-Holland, Amsterdam, 1963).
10. J. Zähringer, *Z. Naturforsch.* **17a**, 460 (1962).
11. D. Krummenacher, C. M. Merrihue, R. O. Pepin, J. H. Reynolds, *Geochim. Cosmochim. Acta* **26**, 231 (1962).
12. L. H. Aller, *The Abundance of the Elements* (Interscience, New York, 1961).
13. H. E. Suess and H. C. Urey, *Rev. Mod. Phys.* **28**, 53 (1956).
14. A. G. W. Cameron, in *Handbook of Geophysics and Space Environments* (U.S. Air Force Cambridge Research Laboratories, Washington, D.C., 1965).
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Late Cenozoic Underthrusting of the Continental Margin off Northernmost California

Abstract. *The presence of magnetic anomaly 3, age 5 million years, beneath the continental slope off northernmost California, is evidence for underthrusting of the continental margin during the late Cenozoic. Folded and faulted strata near the base of the slope attest to deformation of the eastern edge of the turbidite sediments in the Gorda Basin; the deformation observed is exactly that expected from underthrusting. The relative motions of three crustal plates also suggest underthrusting, possibly with a major component of right-lateral slip.*

Sea-floor spreading (*1*) and plate tectonics (*2, 3*) have provided a working model of global tectonic activity. A major problem, with important implications for continental geology, is the nature of deformation of continental margins that form the boundary between two crustal plates (*4*). The continental margin off northernmost California (Fig. 1) is such a boundary, and the structure of the margin, the magnetic anomalies of the sea floor, and the interpreted relative motions of crustal plates all suggest late Cenozoic underthrusting of the margin.

The structure of the continental margin was studied by reflection profiling, magnetic profiling, and bottom sampling. A series of north- to northwest-trending anticlines crops out on the continental slope (*5*) and dams turbidites that form the surface of a marginal plateau (Fig. 2). The folds are cut by faults with dip separations predominantly west side down. The anticlinal ridges yield fossiliferous fine-grained dolomite and limestone. The foraminifera in the rocks represent a maximum age of Miocene (*6*), but none of the species present are extinct.

Magnetic anomalies, associated with the Mason-Raff anomaly pattern of the northeastern Pacific (*7*), are mapped over the continental slope off the California-Oregon border (Fig. 1). The easternmost positive anomaly is correlated with anomaly number 3

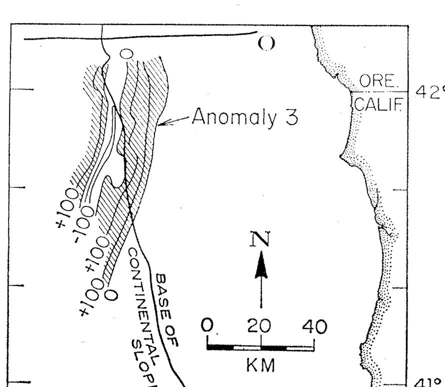

Fig. 1. Magnetic anomalies mapped on the continental slope off northernmost California. Shaded anomalies are positive. Contour interval is 100 gammas. The location of profile *O* is indicated.

(*8*). The estimated age of 5 million years for this anomaly (*1*) is probably very close because Cox and others (*9*) have dated the reversals radiometrically back to 4.5 million years. The presence of anomaly 3 beneath the continental slope suggests differential movement of the oceanic crust beneath the continental margin.

West of the slope (Fig. 2) is a thick section of horizontal strata, probably turbidites, filling a structural depression or trench at the base of the slope. Underlying the turbidite section are several hundred meters of poorly reflecting pelagic sediment draping the irregular basement topography. The superposition of turbidites on pelagic material suggests either a sudden change in depositional regime or a continuous process of conveying oceanic crust toward, and thrusting it under, the continental margin. The ridge at 52 km (Fig. 2) consists of folded strata acoustically similar to, and essentially as thick as, the layered basin deposits. This observation suggests deformation and uplift of the eastern edge of the Gorda Basin deposits. Compression of a tabular body of mechanically weak sediments against a continental margin in the process of underthrusting should produce deformation only on the leading or landward edge of the sediment body. The deformation observed at the base of the slope is compatible with underthrusting.

In order to determine the direction and rate of differential motion between the Gorda Basin and the continental margin, the relative velocities of three major crustal plates must be considered—the American, Pacific, and Gorda Plates (Fig. 3). While the Gorda may be considered as a single plate (*2*), account must be taken of the deformation of magnetic anomalies within the Gorda Basin (*1, 7*). Bending of the anomalies indicates more rapid spreading from the northern part of the Gorda Rise than from the southern part. Retardation in the southern part may be caused by impingement of the Gorda-Mendocino Escarpment on the southern edge of the Gorda Plate.

The relative velocity of the Gorda Plate with respect to the continental margin (G_a) is found by adding the motion of the Pacific Plate relative to North America (P_a) to that of the Gorda Plate relative to the Pacific (G_p) (Fig. 3). Both deformation within the Gorda Plate (*10*) and possible overthrusting of the Pacific Plate along the

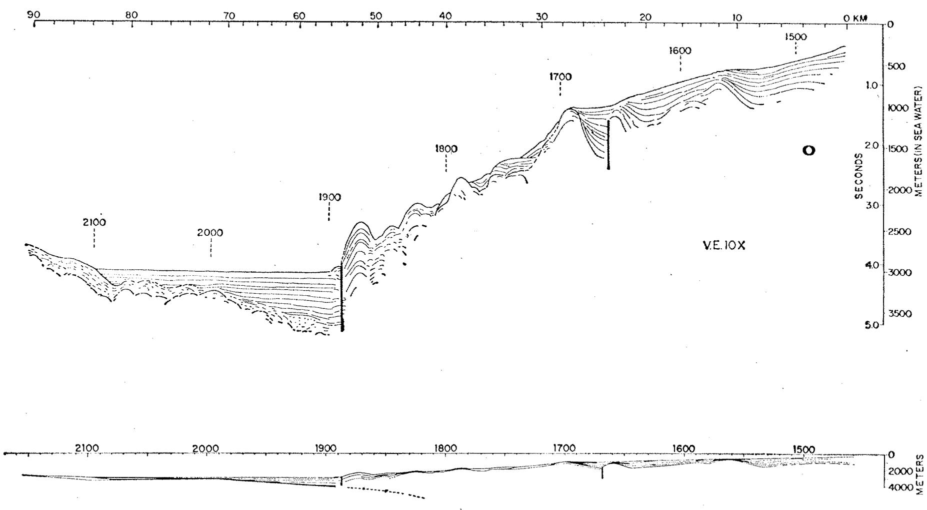

Fig. 2 (left). Profile *O*. Assumed sound velocity in sea water is 1463 m/sec. The lower profile is plotted to true scale. Vertical lines represent the locations but not the true dip of faults, as the attitude of the fault planes cannot be seen on this profile.

Gorda-Mendocino Escarpment would tend to decrease the effective magnitude of P_a used in the calculation. The direction of P_a is taken parallel to the San Andreas fault system. Published values for the rate of slip along the San Andreas fault range from 1 to 3 cm/year (*11*) to 6 cm/year (*12*). For each location within the Gorda Basin, G_p must be determined, because rates of spreading in this region are not constant in space or time (*1*). The direction of G_p is uncertain, because the Blanco Fracture Zone is not exactly perpendicular to the Gorda and Juan de Fuca Rise crests. Therefore, G_p was taken both perpendicular to the Gorda Rise and parallel to the Blanco Fracture Zone at four points in space and time. Calculations were made separately for the time of anomaly 3 (5 million years) and for the time of anomaly 1 (0 to 0.7 million years), both in the northern and southern parts of the Gorda Basin. The calculations were carried out both for $P_a =$ 2 cm/year and for $P_a = 6$ cm/year. Velocity G_a may have been directed from the west, southwest, or south (Fig. 3). Underthrusting is implied, as well as possible oblique right-lateral slip along the continental margin. Right-lateral first motions for earthquakes centered on northwest-trending faults near the coast have been reported (*10*). Application of the concepts of plate tectonics and use of the magnetic reversal time scale thus produce a consistent explanation for the relatively complex structure observed on the continental margin off northernmost California.

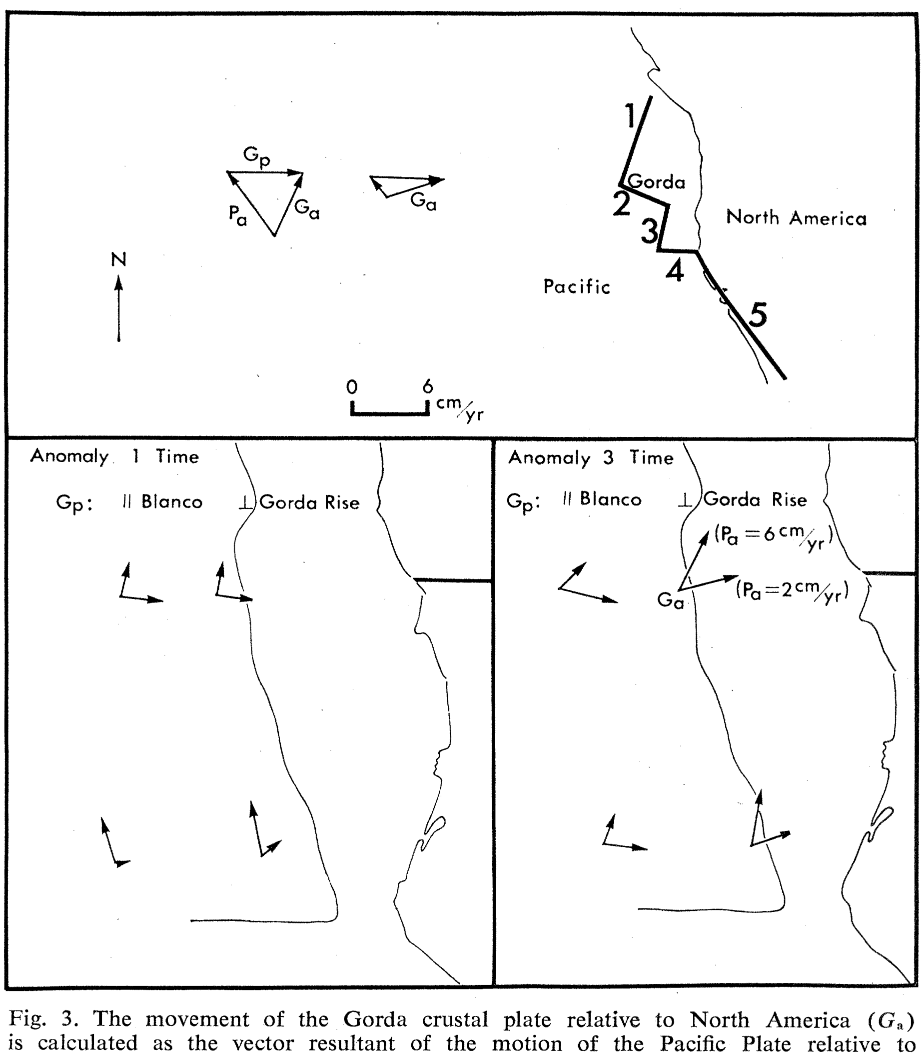

Fig. 3. The movement of the Gorda crustal plate relative to North America (G_a) is calculated as the vector resultant of the motion of the Pacific Plate relative to North America (P_a) plus that of the Gorda Plate relative to the Pacific (G_p). The upper diagram shows G_a calculated for anomaly 3 time, with G_p perpendicular to the Gorda Rise (at anomaly 3 time) and $P_a = 6$ cm/year and 2 cm/year. Only the resultants G_a are shown in the lower diagrams. Interpretation is given in text. 1, Juan de Fuca Rise; 2, Blanco Fracture Zone; 3, Gorda Rise; 4, Gorda-Mendocino Escarpment; 5, San Andreas Fault.

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References and Notes

1. F. J. Vine, *Science* **154**, 1405 (1966).
2. D. P. McKenzie and R. L. Parker, *Nature* **216**, 1276 (1967); W. J. Morgan, *J. Geophys. Res.* **73**, 1959 (1968); B. Isaacks, J. Oliver, L. R. Sykes, *ibid.*, p. 5855.
3. X. LePichon, *J. Geophys. Res.* **73**, 3661 (1968).
4. D. W. Scholl, R. von Huene, J. B. Ridlon, *Science* **159**, 869 (1967).
5. E. A. Silver, thesis, Univ. of California, San Diego (1969).
6. R. L. Pierce, personal communication (1969).
7. A. D. Raff and R. G. Mason, *Bull. Geol. Soc. Amer.* **72**, 1267 (1961).
8. W. C. Pitman, III, E. M. Herron, J. R. Heirtzler, *J. Geophys. Res.* **73**, 2069 (1968).
9. A. Cox, *Science* **163**, 237 (1969).
10. T. V. McEvilly, *Nature* **220**, 901 (1968).
11. R. O. Burford, *Ann. Acad. Sci. Fenn. Ser. A III Geol.-Geogr.* **90**, 99 (1966).
12. W. Hamilton and W. B. Myers, *Rev. Geophys.* **4**, 2137 (1966); R. L. Larson, H. W. Menard, S. M. Smith, *Science* **161**, 781 (1968).
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