chlorite do exist between grains in different thin (0.5 mm thick) bedding laminae of the type rock, but these differences do not appear to be related to position relative to any garnet. Because of the low Mn counting rate, no systematic differences in biotite Mn content could be found. Each biotite had a Mn profile similar in magnitude to that of Fig. 1d. A gradient in Mn would affect the proposed model by affecting the fractionation factor.

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Level-Surface Profiles across the Puerto Rico Trench

Abstract. *Preliminary observations have been made from a ship of the warping of the geoid across the Puerto Rico Trench. Astrogeodetic and gravimetric measurements of the deflections of vertical and the corresponding level-surface profiles are compared for this site. The accuracies at which level-surface topography would provide a useful datum at sea are mentioned with reference to oceanographic requirements.*

Serial measurements of the deflections of vertical provide a means for tracing the posture of a level (equipotential) surface across reaches of ocean. Definition of an equipotential reference surface is fundamental to the study of ocean tides, changes of sea level, tilt of the sea surface due to wind stress, and if it is suitably refined, it serves as an origin for measuring the horizontal pressure gradients and geostrophic flow in ocean currents (*1*).

Deflections of the vertical were observed by direct (astrogeodetic) and verified by indirect (gravimetric) methods. The traverse was run from north to south along 66.3°W (Fig. 1) at a constant speed of 10 knots. The section started at 1000 (Q) on 31 March 1966 in 21.6°N over the ridge north of the Puerto Rico Trench, crossed the trench in a region where the free-air gravity anomaly is pronounced, and ended near San Juan, Puerto Rico at 0400 (Q) on 1 May 1966 as close to land as it was possible to bring the ship safely in darkness.

The site of this experiment enabled us to derive significant findings from relatively crude measurements. Where 66.5°W crosses the Puerto Rico Trench the free-air gravity anomaly approaches −385 milligal, and the anomaly isopleths are elongated in the east-west direction. Thus, meridional deflections vertical of 1 minute of arc or more are to be expected, a magnitude which places them within the range of astrogeodetic measurement with available methods of marine navigation. Moreover, the trade winds in the area are usually steady and the ocean currents are generally weak and predominantly zonal, that is, running from east to west. These factors allow a single component experiment to be conducted in which the differences between geodetic and astronomical latitude can be compared with reasonable assurance that the zonal components of the deflection of vertical are small and that the local gradients of free-air gravity anomaly are predominantly meridional.

Astrogeodetic measurements of the deflections of vertical were made as the ship traversed the Puerto Rico Trench at constant heading and speed. Astronomical position was measured by GEON (*2*). Geodetic position was found by LORAN-A from stations 2L2 and 2L3.

The GEON system can indicate gravity vertical at sea with an r.m.s. (root mean square) error of 15 arc-sec. LORAN-A provides geodetic position with a far larger peak-to-peak error than 15 arc-sec; but in favorable weather and under constant speed and heading conditions, peak errors can be reduced by the method of running averages. This method was used, and it is expected that the r.m.s. error of the ship's position on the spheroid was found to an accuracy commensurate with that of the astronomical reckoning; the error was approximately ± 0.2 arc-min in each case.

Deflections of vertical, ξ, were computed according to the convention (*3*),

$$\xi = \text{astronomical latitude} - \text{geodetic latitude}$$

and with the assumption that deflections in the plane of the prime vertical were zero.

The short vertical lines in Fig. 2 show the departures of astronomical latitude from simultaneous fixes of the ship's position on the spheroid. The length of the strokes (0.4 arc-min) indicates the error in each comparison. The abscissa of each stroke indicates the geodetic latitude, and the ordinate, the sign of magnitude of the astronomical latitude or deflection of vertical.

Calculation of deflections of vertical and shape of the geoid from gravity data is a more complicated process. Stokes' theorem is considered to provide a means for computing the shape of the geoid from observed gravity anomalies, with the sole restriction that all disturbing masses lie inside the geoid, a condition that is well satisfied at sea. The theorem gives N, the normal distance from the geoid to the spheroid at a point P, as an integral function of free-air gravity anomalies, Δg; namely,

$$N_P = \frac{a}{2\pi}\int_0^{2\pi} dA \int_0^{\pi} \Delta g\, f(\Psi)\sin\Psi\, d\Psi$$

where a and g are mean values of the radius of the spheroid and the gravity upon it, A is the azimuth, and ψ is the angular distance from P to the gravity anomaly for the element concerned. But there is a difficulty in evaluating Stokes' formula in that the weighting function, $f(\psi)\sin\psi$, converges only very slowly to zero. As Garland (*4*) has put it: "The calculation of N at any point is in fact dependent on a knowledge of Δg over the whole earth, and even today there are barely sufficient observations in some regions to permit accurate calculations anywhere."

In an effort to avoid this difficulty, Heiskanen and Vening Meinesz (*5*) have shown that in a series expansion of the weighting function for the deflection of vertical, the first term is dominant for short distances—out to some 30 km from P. They also suggest that where the gradient of gravity anomaly is smooth, the azimuth of the near-field deflection of vertical will coincide with the direction of the gravity anomaly gradient.

The near-field formulas (*5*) for the north, ξ, and east, η, components of the deflection of vertical in the left-handed coordinate system are simply,

$$\delta\xi'' \simeq 0.105'' (\delta\Delta g/\delta y)\, r_o$$

and

$$\delta\eta'' \simeq 0.105'' (\delta\Delta g/\delta x)\, r_o$$

where $\delta\Delta g/\delta y$ and $\delta\Delta g/\delta x$ are the average free-air gravity anomaly gradients in milligals per kilometer across the north-south and east-west diameters, respectively, of a circle of radius $0 < r_o < 30$ km around a point P, within which gravity anomalies are accumulated.

Rice (*6*) has shown that the effect of increasing radius can be appreciable out to and sometimes beyond 200 km if accuracy of 1 arc-sec is required, and for values of $r_o = 30$ km or less only a major fraction of the total deflection may be accumulated (*7*). Thus it is to be expected that the near-field formulas are applicable only where the gravity gradients are essentially monotonic within $r_0 = 200$ km and that even in that case the topography of the corresponding geoid may be subdued or otherwise at variance with that obtained by astrogeodetic measurements.

To verify the astrogeodetic measurements of the deflections of vertical across the Puerto Rico Trench, gravity data were accumulated with a LaCoste-Romberg gravimeter while the ship made the traverse. The free-air gravity anomaly was calculated (*8*) with reference to the International Gravity Formula for 1930 according to the convention $\Delta g = g - \gamma_o$ where g is the gravity observed and γ_o is the standard gravity for the same latitude. From these gravity measurements the deflections of vertical were then calculated with the near-field formula (Fig. 2).

The two sets of values for the deflections of vertical show good qualitative agreement, but the gravimetric values are quantitatively smaller by 20 to 30 percent. Alternative values of r_0 were tested from 10 to over 60 km in attempts to obtain a better fit, but there was no significant improvement.

In both sets of data the inflection point of the trend of vertical deflections fails to coincide with the latitude of maximum free-air anomaly at 19°23′N. The inflection points in both series of points lie to the north, at a distance of 5.5 nautical miles in the astrogeodetic case and 3.0 nautical miles in the gravimetric case. These departures may be due to the asymmetry in the meridional gradients of gravity anomaly.

Neither do the two sets of data conform with each other in detail. The effect of ocean currents and variations of shaft revolutions per minute might be responsible for this. Although the weather was almost uniformly favorable for star sights, the force 2 winds blowing from the east northeast held throughout the experiment and there may have been a variation of speed of ± 0.2 knot. To this effect may be added the set due to the meridional components of current near the coast of Puerto Rico. If these influences had persisted for an hour or two they would be reflected in the astronomical navigation. On the other hand, geodetic positions obtained by ± 3-hour running averages through a series of LORAN fixes would have suppressed these irregularities by smoothing the geodetic rate of change of latitude. The differences in the two reckonings would then appear as fine structure in the astrogeodetic deflections of vertical having half-wavelengths of some 20 nautical miles. This fine structure can be seen in the trend of strokes in the upper part of Fig. 2 and possibly should be discounted as an artifact.

In the center section of Fig. 2 are two curves representing the undulations of the geoid derived from the astrogeodetic and gravimetric deflections of vertical. The origin of integration in each case has been taken at the latitude where the free-air gravity anomaly is zero—namely, where observed gravity agrees with that given by the international gravity formula for that latitude. At that point the physical sea surface should intersect the spheroid—discounting tides, steric anomalies in the ocean, wind stress, barometric gradients, and barotropic effects. The two sets of measurements of deflections of vertical were integrated numerically in steps of 5 nautical miles both seaward and landward of the origin, and curves drawn through the calculated points.

Both curves regain the spheroid over the north wall of the Puerto Rico Trench, which attests to the internal consistency of the two sets of measurements. The gravimetric geoid sinks below the spheroid by −12.7 m at its deepest point, while the astrogeodetic geoid reaches its maximum depth at −16.8 m. The positions of these maximum departures are naturally identical

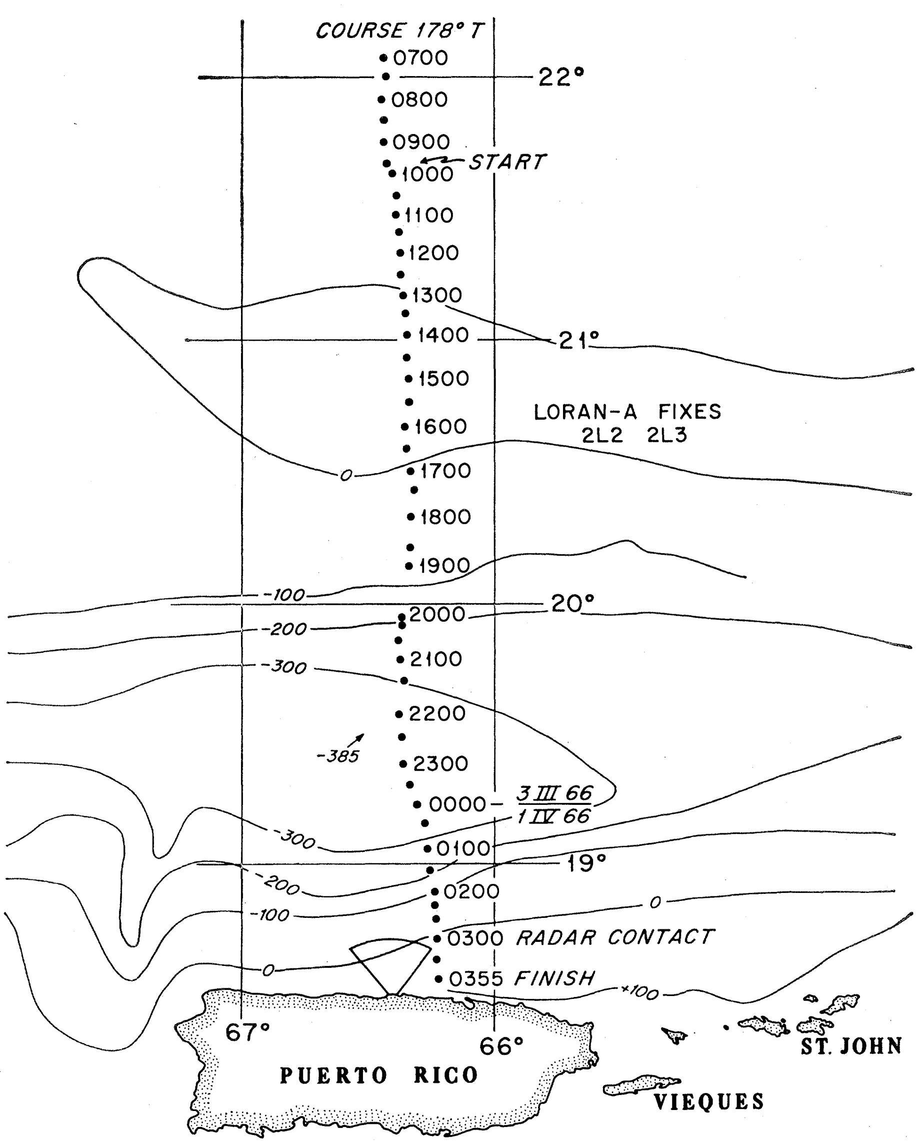

Fig. 1. Track of R.V. *Chain* across the field of gravity anomalies over the Puerto Rico Trench.

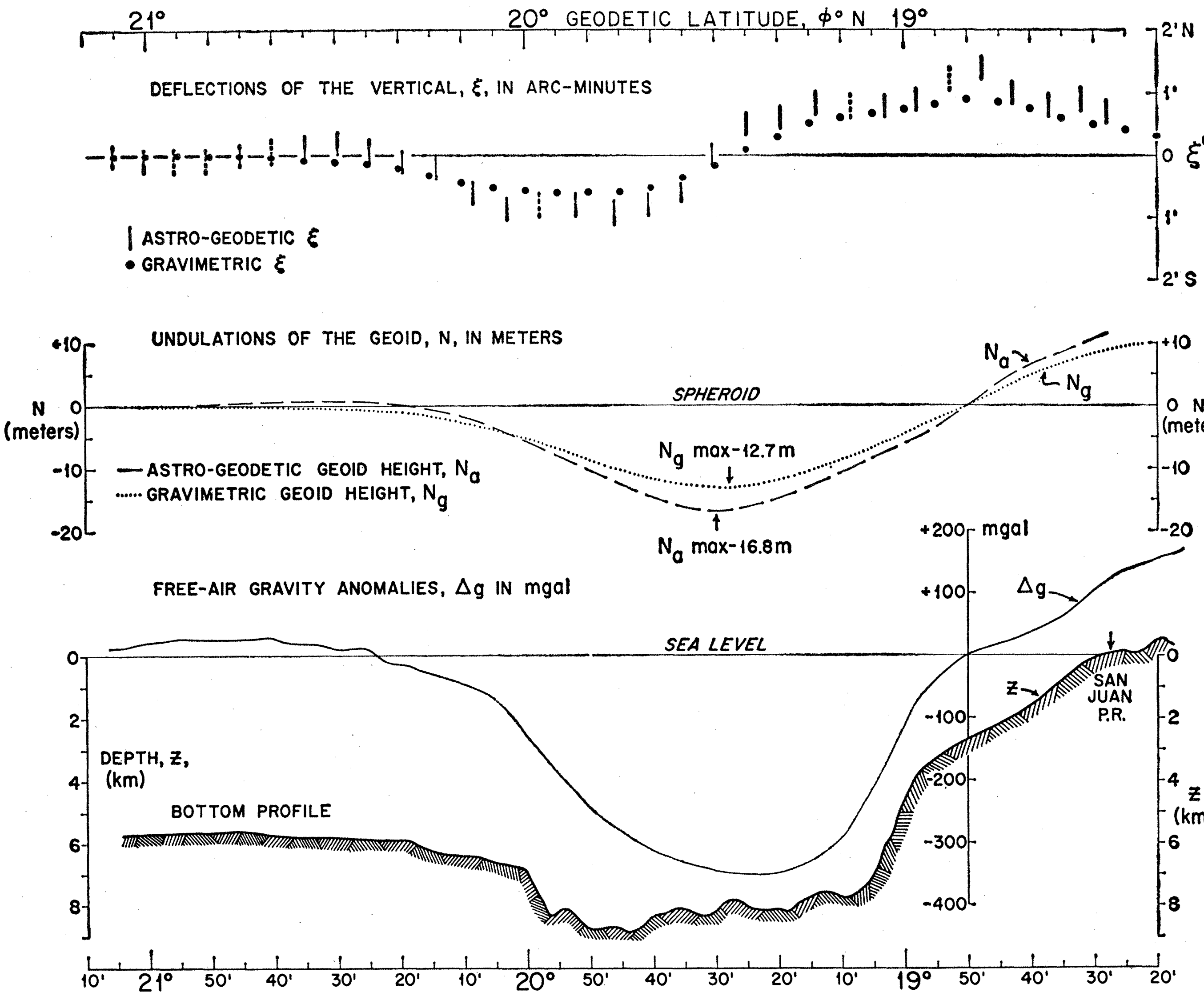

Fig. 2. (Top) Measurements of the deflection of vertical across the Puerto Rico Trench. Strokes, astrogeodetic observations; dots, gravimetric measurements. (Middle) Curvatures of the geoid relative to the spheroid derived from astrogeodetic and gravimetric measurements of the deflections of vertical. Dashed line, astrogeodetic measurements; dotted line, gravimetric measurements. (Bottom) Water depths and free-air gravity anomaly values observed along the ship's track (Fig. 1). Hachured line, water depths; solid line, free-air gravity anomaly values.

with the latitudes of the inflection points in the trends of the deflections of vertical by each method.

Both curves rise above the spheroid as they approach land. The difference in elevation of the geoid between San Juan harbor and the region of maximum free-air anomaly over the Puerto Rico Trench is 21.5 m in the gravimetric case and 28.6 m in the astrogeodetic case, revealing a spectacular "dent" in the level-surface topography.

The credibility of these numerical results is supported by "Level-Surface Contour Maps, Cape Canaveral to Puerto Rico" prepared with the use of Stokes' formula by the Geodesy Division of the U.S. Coast and Geodetic Survey (August 1957) for the U.S. Air Force Missile Test Center. The site of the present astrogeodetic traverse is a little east of the edge of the Coast Survey study, but by extrapolation it is found that the difference in elevation of their geoid between San Juan and the mid-trench region is close to 27 m, or nearly the same as that derived from shipboard astrogeodetic measurements presented here.

The astrogeodetic arc and profile described is an early, if not the first, attempt to make direct measurements of the figure of a portion of the earth at sea. The accuracy attained is barely comparable with that achieved by Eratosthenes two millennia ago when he estimated the circumference of the earth. The accuracies required for oceanographic purposes depend on the nature of the problem to be investigated (*9*). For example, a vertical uncertainty of 1 m would be useful in studies of global sea level, 10 cm would be valuable for tides and wind-driven tilt of the sea surface, but 1 cm or better is required for geostrophic calculations.

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Uplift of the Continental Margin and Possible Continental Accretion off Oregon

Abstract. *Sedimentary rocks collected from the continental shelf and slope off the central coast of Orgeon contain fossil benthic foraminifers of Pliocene and Miocene age. These fossils indicate water depths much greater than those from which the rocks were collected, implying that the rocks have been uplifted as much as 1000 meters since their deposition. Uplift of this magnitude near the edge of the continent is interpreted as representing an early stage of continental accretion, possibly as a result of compression normal to the continental margin. The average maximum horizontal component of this accretion would be about 16 kilometers.*

West of Oregon the continental margin has a generally convex surface 65 to 110 km wide. The continental shelf, which forms the upper part of the surface, slopes seaward less than 1 degree and ranges irregularly in width from 17 to 65 km. The lower part of the surface, the continental slope, is modified by numerous hills, benches, and valleys. The slope increases in average declivity from about 1 degree in the upper part to almost 10 degrees along the basal escarpment.

Off the central coast of Oregon, the margin has an average width of about 100 km (Fig. 1), while the continental shelf, with an outer edge at a depth of approximately 160 m, varies in width from 28 to 65 km. Rocks are exposed on several elongate banks on the shelf and slope. The geomorphology of the continental margin in this area has been described (*1*).

Closely spaced bottom gravity measurements have been made over the inner shelf north of Heceta Head and landward of Stonewall Bank (*2*). These and other measurements have been interpreted by Whitcomb, Erickson, and Berg (*3*) as indicating the presence of a synclinal basin containing sedimentary rocks approximately 6000 m thick between Stonewall Bank and Yaquina Bay. These workers suggested that the syncline terminates southward against a subsurface igneous rock mass extending seaward from Cape Perpetua. Subbottom profiles substantiate the presence of the synclinal basin and reveal a number of anticlines, synclines, and faults near the outer edge of the shelf

Table 1. Relative abundance of dominant and distinctive benthic foraminifers from Oregon offshore rocks. Depths at each station were as follows: No. 14, 137 m; No. 24, 90 m; No. 35, 113 m; No. 41, 90 m; No. 46, 86 m; No. 60, 119 m; No. 99, 54 m; No. 102, 45 m; No. 113, 81 m; No. 118, 540 m; No. 128, 1575 m; No. 137, 648 m. (A = abundant, C = common, R = rare).

Species	Relative abundances at various stations											
	14	24	35	41	46	60	99	102	113	118	128	137
Baggina cf. B. californica (Cushman)									C			
Bolivina advena striatella (Cushman)									C			
Bolivina argentea (Cushman)										A		
Bolivina brevior (Cushman)									C			
Bolivina seminuda foraminata (R. E. and K. C. Stewart)					R							
Bolivina seminuda seminuda (Cushman)										C		
Bolivina semiperforata (Martin)					C							
Bolivina spissa (Cushman)	C	C	C	C		C						
Bolivina subadvena sulphurensis (Cushman and Adams)					R					C		C
Bulimina striata mexicana (Cushman)												C
Bulimina subacuminata (Cushman and R. E. Stewart)		C					C					
Buliminella californica (Cushman)									A			
Buliminella exilis (H. B. Brady)	A				A	C				C		
Cassidulina delicata (Cushman)	A		R			A				C		
Cassidulina cf. C. modeloensis (Rankin)									C			
Cassidulina subglobosa (H. B. Brady)			A				C					
Cassidulina cf. C tumida (Natland)					C							
Cassidulinoides cornuta (Cushman)						A						
Cibicides mckannai (Galloway and Wissler)												C
Epistominella carinata pacifica (Cushman)			C	C		C		C				
Epistominella carinata parva (Cushman and Laiming)									R			
Epistominella carinata smithi (R. E. and K. C. Stewart)			A									
Loxostomum pseudobeyrichi (Cushman)	C				C							
Nonion pompilioides (Fichtel and Moll)											R	
Nonionella costifera (Cushman)									R			
Plectofrondicularia advena (Cushman)	C											
Stilostomella adolphina (d' Orbigny)						C						
Stilostomella advena (Cushman and Laiming)						C						
Uvigerina juncea (Cushman and Todd)								A				
Uvigerina peregrina hispidocostata (Cushman and Todd)				C			A					C
Uvigerina peregrina peregrina (Cushman)	C	C	C	A	C	C				A		A
Uvigerina cf. U. segundoensis (Cushman and Galliher)										R		R
Uvigerina senticosa (Cushman)											C	
Uvigerinella californica ornata (Cushman)									C			