Reports

Borehole Measurement of the Newtonian Gravitational Constant

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It has been reported that the geophysically determined Newtonian gravitational constant is consistently larger than the laboratory value by 1 to 2% on the basis of gravity measurements in Australian mines. This discrepancy may have strong implications for the physics of gravitation. To test whether similar results can be observed in a different geological environment, gravity measurements in a Michigan borehole have been examined. Although these results cannot be taken as conclusive, owing to the large uncertainties involved in mass determination on a geophysical scale, these measurements are generally consistent with those of the Australian experiment.

PRECISE DETERMINATION OF THE Newtonian gravitational constant G has been attempted by many investigators, both in the field and in laboratories. Because of the deficiencies associated with the instruments in the past, the geophysically determined values did not have the accuracy to match that obtained in laboratories. Consequently, the accepted value for the gravitational constant up to the present is determined in laboratories. During the late 1970s and the early 1980s, Stacey and his colleagues revived the earlier Airy approach (*1*) and attempted to determine the Newtonian gravitational constant by means of geophysical measurements. They have carried out numerous measurements in Australian mines, and reported their research results in several articles (*2–7*). Generally, their results indicate that the geophysically determined gravitational constants are consistently higher by about 1 to 1.5% than the accepted laboratory value. On the basis of their observations, Stacey and his colleagues have proposed a possible correction to the inverse square law of gravitation and have speculated on the existence of an intermediate-range force (sometimes known as the "fifth" force) (*2*). Since both the defect of the inverse square law and the possible existence of a fifth force have been independently proposed (*8, 9*), and if the validity of the observations by Stacey and his colleagues can be confidently established, its implication for the laws of fundamental physics will be profound. To test if similar results can be observed in a different geological environment, a gravimetric measurement in a borehole within the Michigan Basin has been examined to determine an inferred value for the Newtonian gravitational constant.

During September 1983, a gravity survey was carried out in the State Burch #1-20 well in Manistee County, Michigan, by EDCON, Inc. The borehole is located about 300 km northwest of the center of the Michigan Basin (Fig. 1) and was drilled to a depth of approximately 2 km, mostly through Devonian and Silurian sediments. The well is about 100 m from a small reef formation which domes upward slightly at a depth of about 1.4 km. Other than this reef structure, stratigraphic boundaries of the area are generally parallel with very little dipping as revealed by a three-dimensional surface seismic survey and some offset vertical seismic profiling studies (*10*). Thus, within a radius of about 2 km of the borehole, strata above the reef can be approximated by flat layers for all practical purposes. The gravity meter used for the survey is a LaCoste-Romberg instrument of slimhole design. It is housed in a 213-cm-long tool with a diameter of about 10.5 cm. Precision of the gravity survey is reported to be within 10 microgal (*11*) (1 gal = 1 cm sec^{-2}). Positions of the stations downhole are determined by an optical encoder which is clamped onto the logging wireline and provides a resolution of about 0.3 cm. However, the borehole deviates from the true vertical. There is an offset of about 40 m at the bottom of the hole. Most of the deviation occurs beneath 1-km depth. Taking this effect into consideration, the maximum uncertainty in position determination is estimated to be less than 0.2%. Spacings between stations are variable since the survey was designed for a somewhat different purpose; there is a higher than average density of coverage between the depths of 1200 to 1500 m. Station spacings can be as small as 20 m within this interval, and the spacings gradually increase towards the surface. Near the surface, station spacings can be as large as 150 m. Gravity readings in many stations have been repeated, not only for the purpose of instrument drift corrections, but also to ensure data reliability.

A theory for the variation of gravity within the Earth has been formulated that incorporates the effects of Earth's rotation and that assumes a layered Earth near its surface [equation 7 of (*2*)]. In principle, given gravity measurements at two stations along the same vertical and knowing the total mass sandwiched between these two stations, we can compute the Newtonian gravitational constant. For the Michigan borehole, gravity has been measured at various depths. After the standard corrections for instrument drift, tidal, and terrain effects, data of gravity differences from the reference surface value are shown in Fig. 2. The reference surface value, however, does not coincide with the surface gravity value at the borehole site because the gravity tool was calibrated at a Gulf Coast location for economic reasons. As a result, the gravity difference at the surface in Fig. 2 will not vanish. Figure 2 shows that gravity increases with depth following an almost linear trend. At about 1.5-km depth, a small deviation from the linear trend is noticeable. This is due to the anomalous density associated with the nearby reef formation. It should be noted that both the gravity and the depth can be determined to such a high precision that the error bars of the data are within the data points themselves in this scale. Since gravity within the borehole has been surveyed at various depths, G can be calculated with different

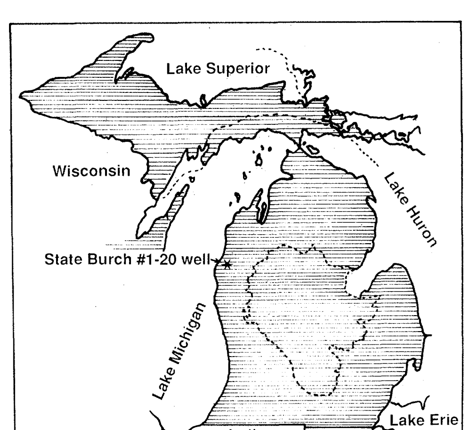

Fig. 1. Location of the State Burch #1-20 borehole in Michigan. Its position is at 44°10′N and 86°6′W.

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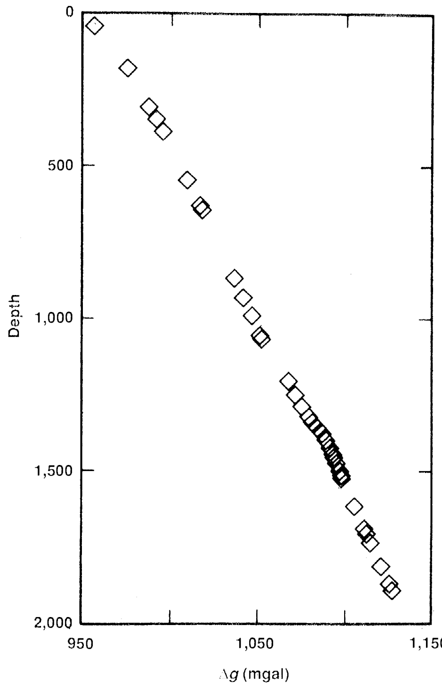

Fig. 2. Corrected gravity difference from the reference surface value (979.5609 gal) as a function of depth.

station separations. Choosing the uppermost station at about 43-m depth as the top station, the averaged gravity gradient results are tabulated in Table 1. All error bounds given in this table are estimated assuming the largest possible uncertainties for all variables. For the purpose of computing the gravitational constant, there should be as little lateral variation as possible in geological structures. Therefore, stations chosen for this study are those located above 1.3-km depth such that the effects of the reef are negligible. The effects of the reef on the gravity measurements can be estimated quantitatively. It produces a maximum vertical gravity anomaly of no more than 1 mgal. Consequently, the maximum uncertainty in gravity measurement is no more than one part in a thousand throughout the entire section of the borehole. For the stations above the reef, accuracy is expected to be much better.

Estimation of rock masses sandwiched between surveying stations is carried out based on the density information obtained from a gamma-gamma density log through the strata of interest. The gamma-gamma density instrument carries both a source and a detector of gamma rays. Rock elements interact with gamma rays mainly through Compton scattering and to a lesser degree through photoelectric absorption. Therefore, by measuring the intensity of gamma rays received by the detector after they have traveled through the formation, we can estimate the density of the rock formation. The instrument is quite insensitive to borehole fluids and the formation pore fluids. For most of sedimentary rocks, the detected gamma-ray intensity is directly proportional to the formation density (*12*). If carefully calibrated, it is a reliable instrument for the measurement of rock-formation density. Unfortunately, gamma rays are not able to penetrate very deeply into rock formations. Their maximum penetration depth is no more than 20 cm. As a result, densities determined by the gamma-gamma density log represent those of the rocks immediately adjacent to the borehole. The precision of this logging tool varies with borehole conditions. Density comparisons between a gamma-gamma log and a core sample analysis from another borehole (*12*) indicate that over 75% of the gamma-gamma density determinations are within 1% of those determined through core analyses. For the Michigan hole, core samples are unfortunately not available. In order to core a hole, the cost will be at least an order of magnitude higher. Since the tool has been carefully calibrated, the gamma-gamma log is expected to yield formation density to within 2%. In addition to density, the gamma-gamma log, together with other borehole data, provides detailed information about the lithology of the area. Thus, by integrating the gamma-gamma density together with the lithological thicknesses of individual stratum [see equation 7 of (*2*)], the mass integral between stations can be evaluated (Table 1).

Once these quantities are determined, the Newtonian gravitational constant can be calculated. The values associated with different station separations are listed in Table 1.

Table 1. Values for the averaged gravity gradient, the layer mass, and the calculated Newtonian gravitational constant.

Station separation (m)	Averaged dg/dz (mgal m^{-1})	Layer mass (10^6 kg m^{-2})	Gravitational constant (10^{-11} m^3 kg^{-1} sec^{-2})
264.5 ± 0.5	0.11640 ± 0.0080	0.69366 ± 0.014	6.6901 ± 0.0668
585.5 ± 0.5	0.10226 ± 0.0036	1.52710 ± 0.030	6.6837 ± 0.0650
886.5 ± 0.5	0.09509 ± 0.0024	2.34150 ± 0.050	6.6848 ± 0.0650
1163.5 ± 0.5	0.09456 ± 0.0018	3.04620 ± 0.060	6.7000 ± 0.0650

It is evident that the gravitational constant determined on the basis of this borehole measurement is higher than the laboratory value ($6.672 \pm 0.004 \times 10^{-11}$ m^3 kg^{-1} sec^{-2}) (*13*). These values are in general agreement with those reported by Stacey's group. Although station separations for this tabulation range from about 250 m to 1.2 km, all values calculated for the Newtonian gravitational constant are within 0.2% of each other. There appears no apparent length scale dependence in G over this range.

To establish the validity of this value for G, it is necessary to examine the error bounds of all the measurements involved. As discussed earlier, all gravity and position determinations can be estimated to better than 1%. Therefore, the observed small deviation in G cannot be accounted for by the errors associated with the gravity and the position determinations. However, the same thing cannot be said for the mass determinations. Although a carefully calibrated gamma-gamma density log is generally accepted with a high level of confidence by professionals, a quantitative accuracy has yet to be established. Even if such a density log can achieve a precision to within 1% as claimed (*12*), questions remain as to how representative the density surrounding a borehole is of the large-scale formation density. There exists no simple answer to this question. One way to prove or disprove whether a small variation in the Newtonian gravitational constant is real is to examine a large number of data sets to see if such a consistently small positive deviation can be statistically established. Although the G value reported here should not be considered conclusive, it is intriguing to note that the results derived from this study and that from the Australian experiments converge to a similar conclusion, despite the different geological environments where the experiments are carried out and despite the different instruments used for the experiments.

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Possible Tornado-Like Tracks on Mars

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Distinct atmospheric conditions suggest that dark, ephemeral, filamentary lineations on the martian surface may be formed during the passage of intense atmospheric vortices.

Viking Orbiter images reveal well-defined, dark filamentary lineations in numerous locations on the martian surface. Although similar markings were previously interpreted as linear seif dunes (*1*) or joint patterns (*2*), newly recognized characteristics, including a more complete recognition of their spatial and temporal distribution, make these interpretations unlikely. The occurrence of such lineations is controlled more strongly by seasonal atmospheric conditions than by surface or boundary layer processes. Consequently, formation by tornadic-intensity vortices may provide the closest analogy.

The filamentary lineations are from 2 km to at least 75 km long and less than 1 km wide. Most are straight to curvilinear, and some have obvious nontopographically initiated gaps in their path (Fig. 1, a and b). The lineations are sharply defined and do not have resolvable relief. Although some cross crater walls and other scarps, they are not initiated or terminated by such obstacles. Many crisscross at relatively low angles, and they generally have a similar average orientation: east to west in the southern hemisphere, and both northeast to southwest and east to west in the northern hemisphere. The lineations occur on smooth intercrater plains and the floors of some craters where the surfaces generally appear partially stripped of sediment cover.

Although the lineations are found at latitudes from about 65°S to 75°N and almost all longitudes (Fig. 2), most occur in several distinct locations in the southern hemisphere. Poorly defined lineations were detected only in isolated locations in the north with a general absence in equatorial latitudes. A high-resolution image of lineations between Argyre and Hellas Planitia (Fig. 1, a and b) reveals a density of 55 to 60 per thousand square kilometers, probably typical of the density in most areas.

The occurrence of both the lineations observed in this study and those observed during Mariner 9 (*2*) depends strongly on season: in the southern hemisphere they were visible only from midsummer into early fall. After formation they were rapidly modified and were no longer visible by midfall. In the northern hemisphere lineations appear from early to midsummer. By late summer these lineations also became smeared and faint; subsequently, they went undetected. The occurrence of lineations in the lower latitudes appears less seasonally dependent than those at higher latitudes.

Although groups of lineations recorded in 1972 by Mariner 9 (*2*) redeveloped in generally the same areas in 1976–1977, such as between Argyre and Hellas Planitia (Fig. 2), the specific location and orientation of individual lineations changed (Fig. 3). The high concentration of lineations near Elysium Mons in 1972 (*2*) contrasts with the paucity of lineations observed there in 1976–1977. The seemingly large fraction of lineations at low latitudes during Mariner 9 (*2*) reflects the existence of large gaps in high-resolution image coverage between 45°S and 55°S (*3*), where most of the lineations during the Viking mission were detected.

Dark filamentary lineations were first observed (*1*) in a large crater in Hellespontus (Fig. 3) and interpreted as linear seif dunes associated with an adjacent dune field. Veverka (*2*) concluded that such an analogy was unreasonable because the lineations (i) are highly variable in time, (ii) typically show a crisscross pattern, and (iii) cross crater walls. He suggested that the lineations were most consistent with an origin by preferred erosion of, or deposition within, joints. We believe that this suggestion is unlikely because the markings (i) cross features, local structural trends, and topographic obstacles without deflection (Fig. 1); (ii) vary in location from year to year (Fig. 3); (iii) are insensitive to regional structural grain; (iv) are larger than most terrestrial joints; (v) have grossly similar orientations on a hemispheric to global

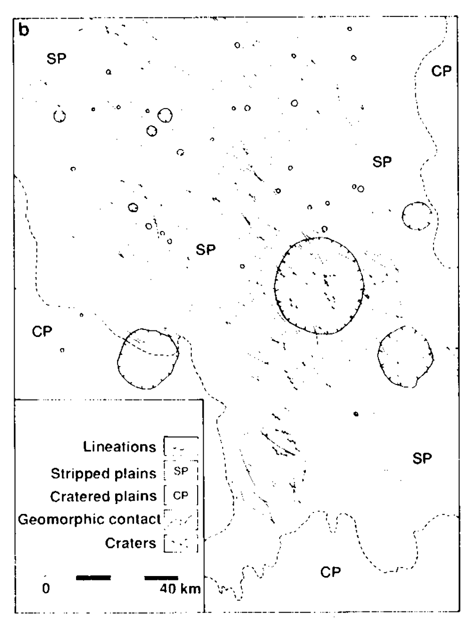

Fig. 1. (**a**) Filamentary lineations between Argyre and Hellas Planitia at 1°W, 49°S. (**b**) Terrain map of the area outlined in (a). Lineations cross crater walls in the right-center portion of the image. Note the stripped appearance of the plains (SP) surrounding the lineations. Viking image 541A76.

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