MARTIAN GEOLOGY

A surface gravity traverse on Mars indicates low bedrock density at Gale crater

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Gravimetry, the precise measurement of gravitational fields, can be used to probe the internal structure of Earth and other planets. The Curiosity rover on Mars carries accelerometers normally used for navigation and attitude determination. We have recalibrated them to isolate the signature of the changing gravitational acceleration as the rover climbs through Gale crater. The subsurface rock density is inferred from the measured decrease in gravitational field strength with elevation. The density of the sedimentary rocks in Gale crater is 1680 ± 180 kilograms per cubic meter. This value is lower than expected, indicating a high porosity and constraining maximum burial depths of the rocks over their history.

Aeolis Mons (informally known as Mount Sharp) on Mars, a 5-km-high mound located within Gale crater, is the primary science target of the Curiosity rover. The rover has so far explored only the lowermost exposed layers of Mount Sharp. It remains uncertain how the majority of Gale crater's sedimentary rocks were deposited and subsequently eroded. In particular, there is ongoing debate whether Gale crater was once filled completely with sediment, followed by intense erosion to the modern topography of Mount Sharp, or instead that only a fraction of the crater volume was ever filled in the past.

Gravity surveys have been used to understand the internal structure of Earth and other planetary bodies. Recent orbital studies have probed both deep stratification and shallow crustal density anomalies of planetary objects (*1*, *2*). Gravimetry, the precise measurement of gravitational fields, is used in terrestrial geophysics to detect and map density variations in Earth's subsurface at a variety of scales. A ground-based gravity survey on another Solar System body was made by the Traverse Gravimeter Experiment (TGE) carried to the Moon by Apollo 17, which was used to infer the thickness of a basaltic lava flow filling the Taurus-Littrow valley (*3*, *4*). In principle, gravimetric measurements from surface rovers could probe the subsurface to depths not possible with existing in situ analytical techniques, while also revealing finer-scale structure than is possible from orbital gravity surveys.

Since landing in 2012, Curiosity has driven more than 18 km across the plains of Aeolis Palus and reached the lower slopes of Mount Sharp on sol (martian day) 753 after landing (Fig. 1). Over this time, the rover has steadily gained elevation, covering more than 350 m vertically. The geologic units analyzed by Curiosity since landing consist of sedimentary rocks. These rocks include a minor fraction of pebble-sized conglomerates, but mostly have grains that are sand-sized or finer. The bulk of Curiosity's vertical traverse has been within the fine-grained Murray formation (*5*). These sediments are interpreted to have been deposited predominantly within an ancient lake, and they include minor intervals likely deposited by rivers and wind-blown sand dunes (*5*–*7*).

The Curiosity rover's science payload did not include an instrument designed to measure changes in gravitational acceleration, *g*. However, the rover engineering package includes primary and backup LN-200S Rover Inertial Measurement Units (RIMUs) used for navigation and fine-attitude determination. Each RIMU contains a set of three-axis gyroscopes and microelectromechanical system (MEMS) accelerometers for measuring changes in velocity and orientation, respectively. MEMS accelerometers are not typically used for gravimetry on Earth because their precision is low relative to modern scientific gravimeters. Recently, a MEMS device with a sensitivity of 40 μGal $Hz^{-1/2}$ (1 Gal = 1 cm s^{-2}) was used to detect Earth's tides (on the order of 100 μGal amplitude) (*8*).

The Curiosity RIMU is used while driving and for fine attitude determination while stationary. We use the latter measurements, which are only performed on sols when no drive or arm motion is planned for the rover. Fine attitude measurements consist of 2- or 5-min averages for each of the three accelerometer axes, originally sampled at 400 Hz. Each integration is preceded by a 3-min instrument warmup period before averaging begins, to ensure steady-state conditions. We used data from sols 60 to 1743 of the mission, encompassing more than 700 measurements (data S1). Figure 2 shows raw accelerometer data from these sequences.

To derive more precise measurements, we calibrated raw accelerations using rover engineering data acquired on Mars. We first adjusted the total acceleration at each location to account for the expected change in gravitational acceleration with latitude due to planetary rotation and flattening (*9*). We then evaluated potential effects on the data from both internal [bias and scale differences among accelerometer axes; e.g., (*10*)] and external [e.g., temperature (*8*), elevation, subsurface density] sources. We used a nonlinear regression model to jointly solve for these parameters (*9*). We found that the dominant external variable is temperature, which we modeled as a quadratic function. We also applied a thermal history term consisting of an exponential moving average of temperature over approximately two diurnal cycles (*9*). We estimated the effect of rover elevation and subsurface density on gravitational acceleration by subtracting the free-air correction for altitude, then solving for the best-fitting density to account for the attraction of surface topography (complete Bouguer correction) (*9*). Our final regression model contained temperature, elevation, and tilt-related terms that account for bias and scale factors among the three accelerometer axes. The resulting solution accounted for 98% of the variance in the raw acceleration data, with residual errors of 10 mGal, similar to the precision achieved by the Apollo 17 gravimeter (*3*).

From these calibrations, we determined the vertical gravity gradient along the rover traverse to be −0.152 ± 0.006 mGal m^{-1}. This value is smaller than the expected effect of increasing elevation on Mars (free air correction, −0.218 mGal m^{-1}) because of the additional gravitational attraction of the topography beneath the rover (*11*). We determined an average density of 1680 ± 180 kg m^{-3} from the best-fitting complete Bouguer correction for the nearly 300-m-thick wedge of rock beneath the rover traverse. Figure 3 shows both the elevation along the Curiosity traverse and the modeled component of the calibrated gravity measurements resulting from this elevation gain. The two signals show a strong correlation (r = 0.71), and the change in the ascent rate of the rover around sol 1400 is clearly visible in the acceleration record. The model without including the effect of subsurface density (free-air correction only) is also shown in Fig. 3 for comparison.

Our density estimate represents an average value for the topography over which Curiosity has driven, and thus includes likely intact bedrock to a depth of hundreds of meters (the elevation gain of the rover), rather than loose soil at the surface. However, our derived value of 1680 ± 180 kg m^{-3} is low relative to typical sedimentary rocks; this is likely due to high porosity, ϕ. To determine the mineral (pore-free) density of the sedimentary rocks of Mount Sharp, we used x-ray diffractometry of surface samples performed by Curiosity's CheMin instrument (*9*). We estimate a value of 2810 ± 133 kg m^{-3} using derived mineral abundances within the Murray formation, which constitutes most of the vertical section.

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The discrepancy between this estimate and the gravity-derived value indicates a high porosity, averaging $\phi = 40 \pm 6\%$ over the 300-m-thick section traversed by Curiosity. This is a typical value for soils and poorly lithified sediments, but porosity is typically reduced in sedimentary rocks that have experienced burial and compaction. We can constrain the maximum burial depth of the sedimentary rocks analyzed by Curiosity using Athy's law (*12*) for self-compaction and scaling for martian gravity (*5*, *13*). We assume an initial depositional porosity of $\phi_0 = 55$ to 70% for fine-grained silts or shale (*14*), consistent with observations of lower Mount Sharp (*5*). From these calculations (*9*), we estimate that the geological units observed by Curiosity never experienced burial to depths greater than 1600^{+1000}_{-800} m (silt) to 1800^{+600}_{-500} m (shale) (fig. S2). Because subsequent cementation of the sediments may further reduce porosity, we interpret this as an upper limit on the maximum burial depth.

The infilling history of Gale crater remains a matter of debate. The summit of Mount Sharp exceeds the height of much of the Gale crater rim, leading previous authors to propose that the crater was once filled completely with sediment, with the mound an erosional remnant of a once more extensive deposit (*15*, *16*). If the entire height of Mount Sharp represents formerly crater-filling sedimentary units, the rocks at the Curiosity landing site would have been buried to a depth of nearly 5 km. An alternative model invokes aeolian (wind-driven) deposition promoted by topographically driven slope winds, which naturally drive sediment to the center of the basin (*17*). This model proposes that Mount Sharp formed largely in its current form as a free-standing mound within Gale. In this scenario, much shallower burial depths are expected along Curiosity's traverse across the floor of Gale and the lower slopes of the mound, likely between 0 and 2 km (*18*). Our derived average density and modeled loss of porosity through compaction are consistent with shallow burial depths. We find it unlikely that sediments encountered by Curiosity were buried to a depth of 5 km while groundwater persisted, which would substantially reduce porosity [$\phi = 15\%$ (shale) to 21% (silt)] (*9*), although burial under dry conditions or after cementation may permit porosity retention to somewhat deeper depths (*9*). Aeolian deposition of the upper units of Mount Sharp and incomplete infilling of Gale crater provides a possible explanation for the observed high porosity. This allows accumulation of several kilometers of sediment within the center of the basin while leaving the margins of the mound relatively uncompacted (*18*). A major erosional surface exists within the Mount Sharp stratigraphy, ~800 m above Curiosity's current location (*19*); this could mark a transition between rocks interpreted as dominantly lacustrine within the Murray formation and overlying possible aeolian units, which constitute the upper several kilometers of Mount Sharp.

These findings are consistent with several lines of independent evidence. The layers of Mount Sharp above the rover traverse are inclined several degrees to the northwest (*17*, *20*). The projected layers are only slightly less steeply inclined than the modern topography of Mount Sharp and would intersect the crater floor before reaching the rim. This geometry is consistent with our prediction of shallow burial along the traverse. Although it is difficult to measure porosity directly in the fine-grained rocks encountered by the rover, the rover's drill provides a

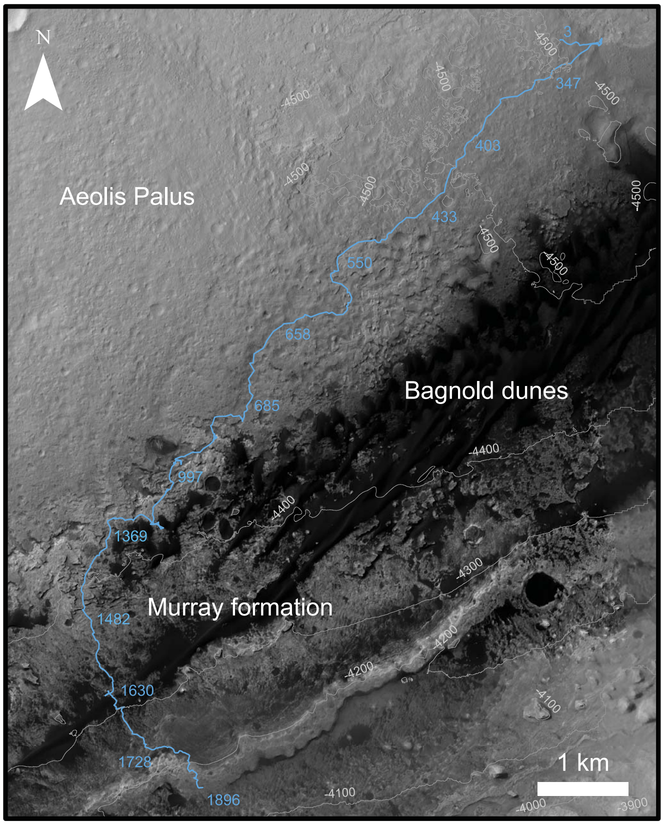

Fig. 1. Curiosity traverse from sol 0 to sol 1896. The background image (*30*) shows the transition from the Aeolis Palus on the floor of Gale crater to the Murray formation at the base of Mount Sharp. Contours show topographic elevation in meters (*31*). Curiosity's path is indicated by the solid blue line; adjacent numbers indicate time in sols since landing.

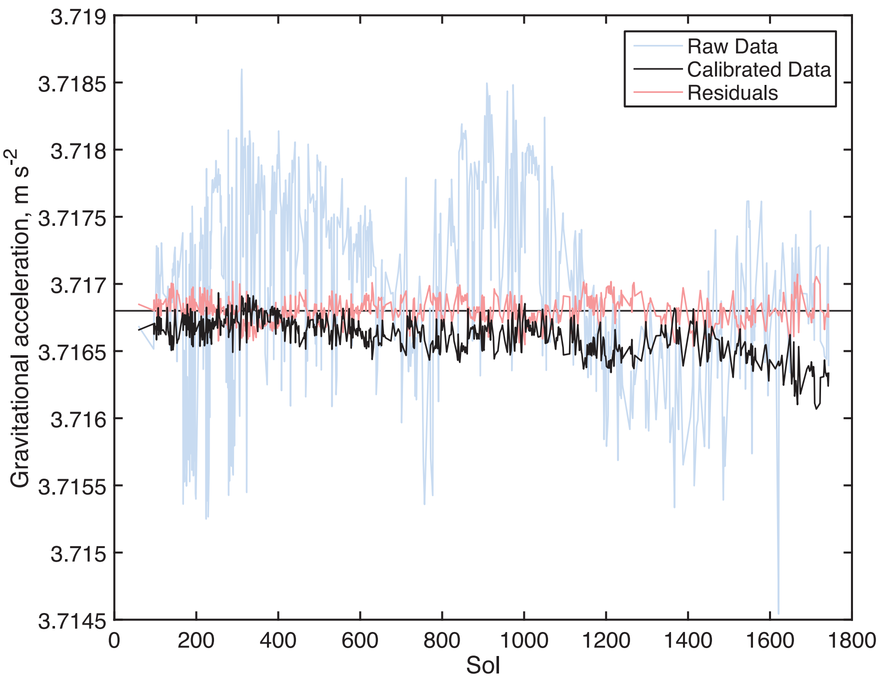

Fig. 2. Curiosity accelerometer data calibration. Raw (blue) and calibrated (black) accelerometer data are shown. The measured local gravitational acceleration falls off because of increasing elevation as Curiosity ascends Mount Sharp. The 1σ residuals of our model (red) are 10 mGal after accounting for elevation and other variables.

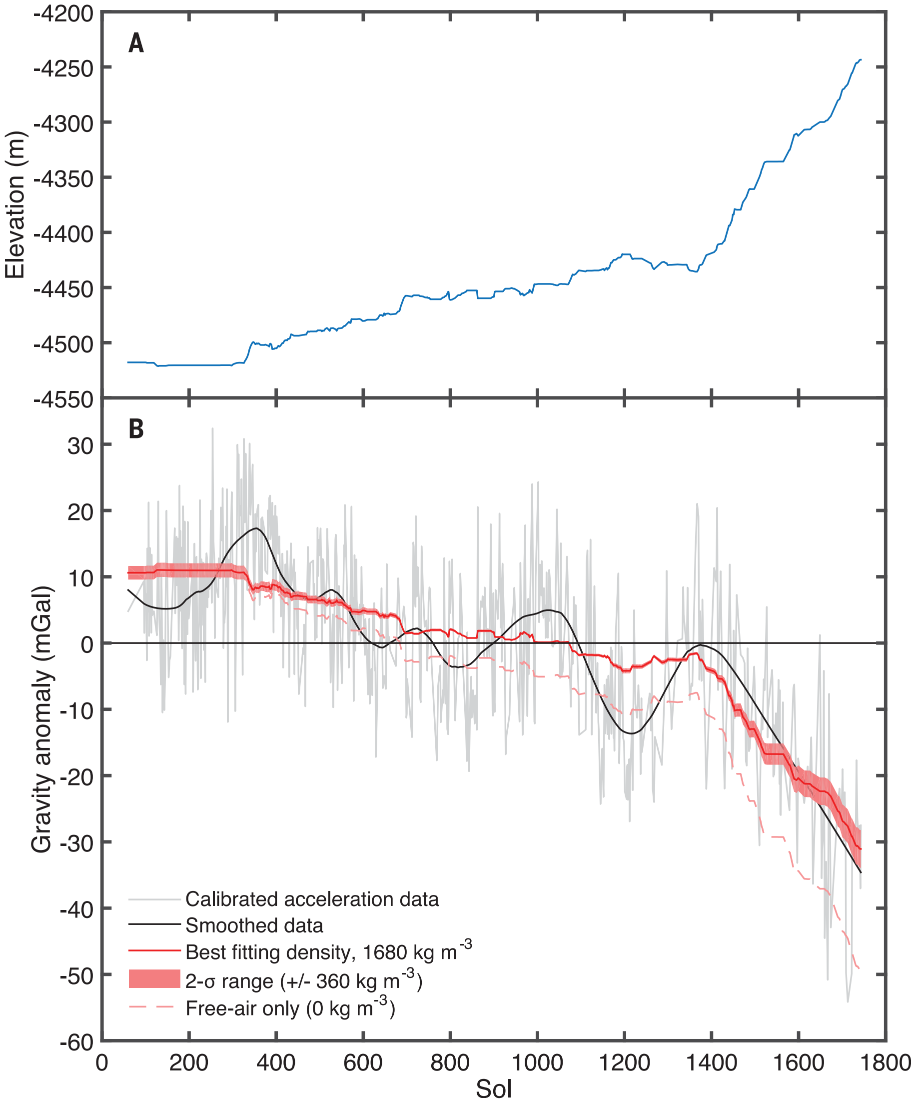

Fig. 3. Modeled effect of rover elevation on gravitational acceleration. (**A**) Rover elevation along the traverse, from the Bradbury landing site to the lower slopes of Mount Sharp (*30*). Elevation generally increases over time, with a sharp increase in the ascent rate occurring around sol 1400. (**B**) Modeled Bouguer correction to the calibrated gravity data (as shown in Fig. 2), assuming a constant subsurface density along the traverse, including 2σ density confidence interval.

measure of rock hardness. Data from drilled mudstones suggest a weak to medium compressive strength relative to typical geological materials, comparable to adobe bricks or concrete (5 to 30 MPa) (*21*). Although multiple factors affect compressive strength, porosity is a major determining factor and is strongly anticorrelated with mechanical strength in terrestrial analogs (*22–24*). Modeling of active neutron data (*25*) and thermal inertia (*26*) on outcrops along the traverse are also consistent with low bedrock density; our porosity estimates might help to explain observations of sedimentary rocks with low thermal inertia elsewhere on Mars (*27*). The likely high permeability of the Murray formation may have helped to promote subsequent chemical alteration by groundwater (*7*).

Our results provide information about the martian subsurface that is currently unattainable from analytical techniques (hundreds of meters in depth over distances of ~1 to 10 km in this case). Orbital gravity data have lower horizontal resolution, limited by the height of the martian atmosphere. Ground-penetrating radar instruments can provide some information about density, but no subsurface returns have been detected at Gale crater (*28*). In addition to gravimetry, we have evaluated the sensitivity of the Curiosity acceleration data to seismic signals (*9*). Our ability to detect most seismic activity is limited as a result of the intermittent temporal sampling provided by the RIMU and the expected rarity of a magnitude $M_w > 5.5$ marsquake in the vicinity of the rover (fig. S3).

The Curiosity data show the practicality of gravimetric experiments on landed planetary missions. On Mars, the density of sedimentary rock units may differ from that of igneous units by as much as a factor of 2 (*29*). Surface gravimetry probes a range of scales that are difficult to survey through other methods. Mobile rover measurements can complement orbital gravity surveys, particularly for planetary bodies with atmospheres such as Mars.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/363/6426/535/suppl/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S5
Tables S1 and S2
References (*32–59*)
Data S1

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Teaching Curiosity to do gravimetry

Gravimetry––the measurement of tiny changes in gravitational fields––can be used to weigh mountains. Large-scale gravimetric mapping can be done from orbit, but examining small details requires a vehicle on the ground. The Curiosity rover on Mars carries several accelerometers used for routine navigation. Lewis *et al.* recalibrated these accelerometers to allow them to be used for gravimetry. They measured how the local gravitational field changed as the rover moved through Gale crater and began to climb Aeolis Mons (Mount Sharp). The resulting density of material under Gale crater shows that it is relativity porous, disproving a theory that the crater floor was once buried under several kilometers of rock.

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