



Surface and Subsurface Microgravity Data in the Vicinity of Sanford Underground Research Facility, Lead, South Dakota



Open-File Report 2015–1043

U.S. Department of the Interior
U.S. Geological Survey

COVER

Photograph showing the Ross and Yates Headframes at the Sanford Underground Research Facility, Lead, South Dakota. U.S. Geological Survey photograph by Jeffrey Kennedy.



Surface and Subsurface Microgravity Data in the Vicinity of Sanford Underground Research Facility, Lead, South Dakota

By Jeffrey R. Kennedy, Karl R. Koth, and Robert L. Carruth

Open-File Report 2015–1043

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2015

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit <http://www.usgs.gov> or call 1-888-ASK-USGS (1-888-275-8747)

For an overview of USGS information products, including maps, imagery, and publications, visit <http://www.usgs.gov/pubprod>

To order this and other USGS information products, visit <http://store.usgs.gov>

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this information product, for the most part, is in the public domain, it also may contain copyrighted materials as noted in the text. Permission to reproduce copyrighted items must be secured from the copyright owner.

Suggested citation:

Kennedy, J.R., Koth, K.R., and Carruth, R.L., 2015, Surface and subsurface microgravity data in the vicinity of Sanford Underground Research Facility, Lead, South Dakota: U.S. Geological Survey Open-File Report 2015-1043, 32 p., <http://dx.doi.org/10.3133/ofr20151043>.

Acknowledgments

We thank the staff at the Sanford Underground Research Facility, including Jaret Heise, Tom Trancynger, and Tom Regan, for ensuring that field work proceeded safely and efficiently. Planning support from Mark Anderson, Andrew Long, and Donald Pool is gratefully acknowledged. This project has been supported by the USGS Groundwater Research Program.

Contents

Abstract	1
Introduction	1
Hydrogeologic Setting	6
Microgravity Monitoring of Groundwater Storage Changes.....	6
Purpose and Scope.....	7
Methods.....	7
Absolute Gravity Measurements	7
Determination of Station Position	9
Results.....	10
Observed Gravity Values	10
Status of the Gravity Network.....	26
Local Hydrologic Data	26
Conclusion	30
References Cited	31

Figures

1. Map showing simplified geology in the vicinity of the Sanford Underground Research Facility, Lead, South Dakota.....	2
2. Map showing surface gravity stations at the Sanford Underground Research Facility and surrounding area, South Dakota.....	4
3. Three-dimensional view of the former Homestake Mine, South Dakota, showing selected subsurface and surface gravity stations.....	5
4. Photographs of selected gravity stations located in the vicinity of the Sanford Underground Research Facility, Lead, South Dakota. <i>A</i> , USGS hydrologist Robert Carruth checking the verticality of the A-10 absolute gravimeter at the Ross-4850 station. <i>B</i> , Station Yates-4800 at the entrance to the Large Underground Xenon experiment.....	8
4. Photographs of selected gravity stations located in the vicinity of the Sanford Underground Research Facility, Lead, South Dakota. <i>C</i> , Gravity station Ross-300. <i>D</i> , Loading the A-10 absolute gravimeter onto the Yates shaft on the 4850 level.—Continued.....	9
5. Scatter plots showing temporal trends in gravity at each station, 2007–2017.....	19
6. Line plot showing gravity change at all stations.....	23
7. Map showing the spatial variation of gravity change from 2010 to 2014.....	25
8. Graph showing Homestake Mine, South Dakota, water levels in the Ross shaft measured by the Sanford Underground Research Facility.....	26
9. Graphs showing streamflow at stations Deadwood Creek at Central City, South Dakota (06436165) and Bear Butte Creek near Deadwood, South Dakota (06437020) during the period of microgravity measurements, 2007 to 2014.....	28
10. Graph showing streamflow at station Bear Butte Creek near Deadwood, South Dakota (06437020) from 1990 to 2014.....	29
11. Graph showing monthly precipitation data from the Lead, South Dakota, station (394834) of the National Weather Service (NWS) Cooperative Network. Interpolated data are from the Parameter-elevation Relationships on Independent Slopes Model.....	30

Tables

1.	Position coordinates, gravity values, and error statistics for absolute gravity stations in the vicinity of the Sanford Underground Research Facility, Lead, South Dakota. Reported values are at 100 cm above the station mark, calculated using the vertical gradient -3 microGal/cm.	11
2.	Absolute-gravity values from 2007, 2010, 2011, 2012, 2013, and 2014, arranged by year. Reported values are at 100 cm above the station mark, calculated using the vertical gradient -3 microGal/cm.....	16
3.	Surficial absolute-gravity station position coordinates from Global Positioning System (GPS) measurements made in 2007, 2012, 2013, and 2014.....	18

Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Flow rate		
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
Pressure		
bar	100	kilopascal (kPa)
Acceleration		
microGal (μGal)	10	nanometer/second ² (nm/s ²)
microGal (μGal)	0.328 x 10 ⁻⁹	ft/second ² (ft/s ²)

Except where noted, vertical coordinates are ellipsoid heights referenced to the GRS80 ellipsoid.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83[2011] epoch 2010.00).

Surface and Subsurface Microgravity Data in the Vicinity of Sanford Underground Research Facility, Lead, South Dakota

By Jeffrey R. Kennedy, Karl R. Koth, and Robert L. Carruth

Abstract

Absolute gravity data were collected at 32 stations in the vicinity of the Sanford Underground Research Facility from 2007 through 2014 for the purpose of monitoring groundwater storage change during dewatering of the former Homestake gold mine in the Black Hills of South Dakota, the largest and deepest underground mine in North America. Eight underground stations are at depths from 300 feet below land surface to 4,850 feet below land surface. Surface stations were located using Global Positioning System observations, and subsurface stations were located on the basis of maps constructed from survey measurements made while the mine was in operation. Gravity varies widely at many stations; however, no consistent temporal trends are present across all stations during the 7-year period of data collection.

Introduction

In 2007, the US. Geological Survey (USGS) established a time-lapse microgravity study to monitor dewatering of the Homestake Mine in the Black Hills of South Dakota. The mine, which began operation in the late 1800s and closed permanently in 2002, was the largest and deepest gold mine in North America and encompassed both underground workings and an 800-foot-deep open cut (Mitchell, 2009). In 2003, pumping to dewater the mine stopped, and water levels rose from more than 8,000 feet (ft) below land surface (BLS) to about 4,500 ft BLS. During the 2000s, the mine became the preferred site for a Deep Underground Science and Engineering Laboratory (DUSEL), with plans to resume pumping to lower water levels back to over 8,000 ft BLS. In 2007, the planned DUSEL facility was scaled back and renamed to the Sanford Underground Research Facility (SURF). As of summer 2014, water levels in the facility are maintained at approximately 5,750 ft BLS. Several geoscience and physics experiments are installed, the deepest of which are on the 4850 level (approximately 4,850 ft BLS). Current (2014) plans are for static water levels to be maintained at approximately 5,750 ft BLS (Heise, 2014).

The Homestake Mine was developed in Precambrian metamorphic rocks and Tertiary rhyolitic dikes (fig. 1; Caddey and others, 1991; Strobel and others, 1999). Groundwater in the regional groundwater system is stored primarily in secondary porosity from fractures, and inflow rates into the mine workings are generally low (Rahn and Roggenthen, 2002; Murdoch and others, 2011). Despite the low inflow rates, continuous pumping was required to maintain dewatered conditions while the mine was operational. During operations, water levels in the mine declined at a nearly uniform rate of 85 ft/year from about 1900 until 1975 (Murdoch and others, 2011) due to mine excavations at progressively greater depths. The total average annual inflow rate occurring on all levels of the mine during the latter

part of mine operations was estimated as 733 gallons per minute (gpm), of which 109 gpm came directly from precipitation on the drainage area of the open cut (Zhan and Deux, 2010). Dewatering pumps were turned off in 2003, and pumping resumed in 2008 in preparation for the SURF facility.

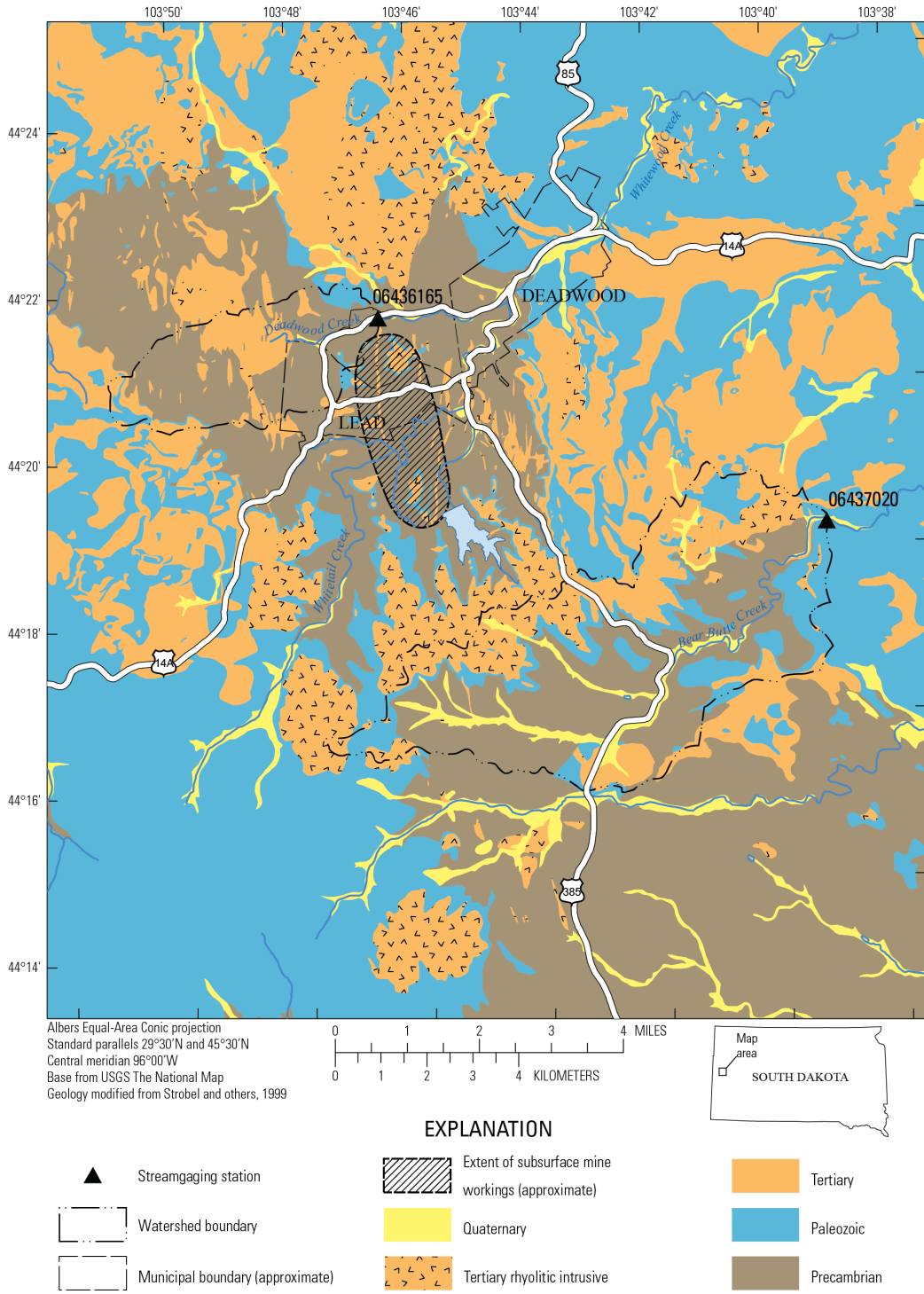
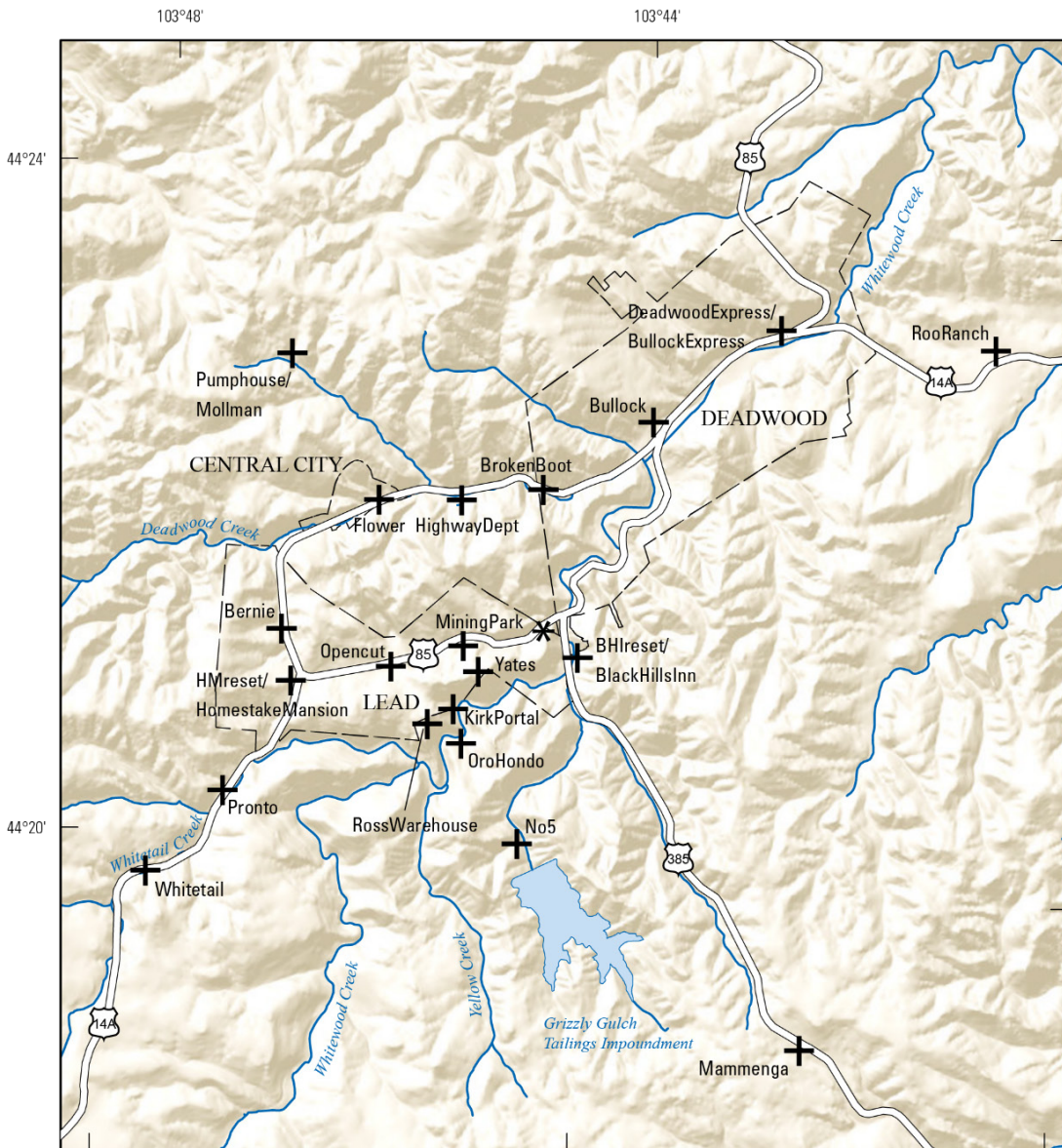


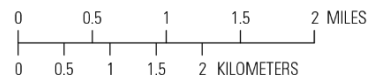
Figure 1. Map showing simplified geology in the vicinity of the Sanford Underground Research Facility, Lead, South Dakota.

Few historic groundwater-level data are available that are representative of the regional groundwater-flow system (that is, from deep monitoring wells) other than the water level measured within the mine workings. The lack of data makes it difficult to evaluate the effect that dewatering has on surface water and, in particular, whether streamflow is being captured by the pumping to dewater the mine. Furthermore, the lack of groundwater-level data means little to no calibration data exist from which to develop a groundwater-flow model. Water pumped from the mine by the dewatering process is ultimately released to Whitewood Creek (fig. 2). Consequently, net infiltration of surface water to the groundwater-flow system over a large area may be minimal. Locally, however, groundwater pumping may dewater fractures in the aquifer and cause increased capture of surface water.

A network of absolute gravity stations was established throughout the mine's vicinity to provide information about change in groundwater storage (figs. 2 and 3). If groundwater pumping removes a significant amount of water from fractures in the region around the mine, and this water is replaced by air, then a measureable decrease in gravity may occur because of the overall density change of the subsurface. This change will be larger and occur over a longer time period than the relatively rapid density changes expected from dewatering of the mine excavations alone. Conversely, if fracture dewatering is insignificant, then little or no overall density change will occur in the aquifer, and the gravity data will indicate change caused only by dewatering of the mine excavations rather than long-term changes correlated with pumping. Gravity data are also sensitive to near-surface water-storage change in the unsaturated zone and perched or alluvial aquifers.



Base from USGS The National Map
 Albers Equal-Area Conic projection
 Standard parallels 29°30'N and 45°30'N
 Central meridian 96°00'W



EXPLANATION

- +** Active gravity station/
Destroyed gravity station
- *** Location where water
pumped from underground is
discharged as surface water
- Municipal boundary (approximate)



Figure 2. Map showing surface gravity stations at the Sanford Underground Research Facility and surrounding area, South Dakota.

Twenty-one surface gravity stations were established in 2007. Absolute gravity was measured at each station in 2007 and annually from 2010 through 2014. During this period, some stations were destroyed, and other stations were established as replacements or to augment the network (fig. 2). In 2011, an underground profile was established along the Ross shaft of the Homestake Mine (fig. 3). The Ross and the Yates shafts provide the primary access from the surface to the 4850 level of the mine. The Ross profile includes stations on the 300 level, 800 level, 2000 level, 4100 level, and 4860 level (level numbers refer to approximate depth below land surface). Refurbishment activities on the Ross shaft began in 2012, and except for the 300 and 4850 level stations, these stations have not been revisited. In 2012, three new underground stations were established: (1) near the Yates shaft on the 4100 level, (2) near the Yates shaft on the 4850 level, and (3) at the 4 Winze Wye on the 4850 level, midway between the Ross shaft and Yates shaft (fig. 3). As of 2014, the absolute gravity network includes 16 surface stations and 9 underground stations.

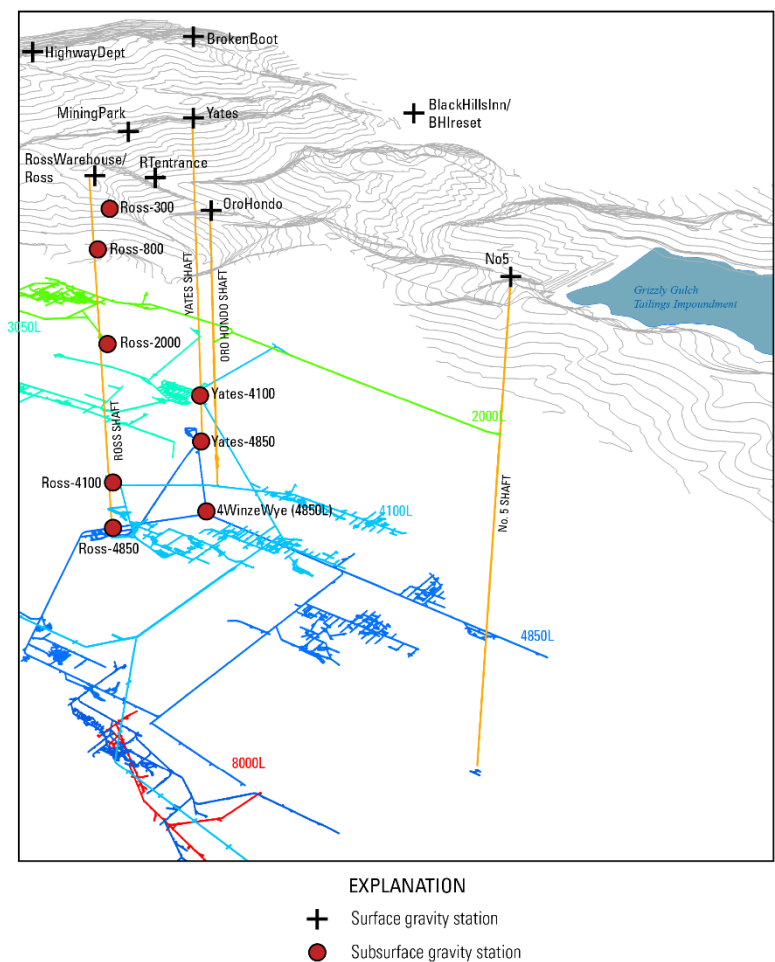


Figure 3. Three-dimensional view of the former Homestake Mine, South Dakota, showing selected subsurface and surface gravity stations. Major mine levels are shown in color. Scale varies in this perspective.

Hydrogeologic Setting

The Black Hills are a structural dome with a core of Precambrian rocks and Paleozoic sedimentary formations dipping radially outward on the flanks of the dome. Tertiary igneous rocks intruded Precambrian rocks and deformed Paleozoic sedimentary rocks in the northern Black Hills between 58 and 50 million years ago (Lisenbee and DeWitt, 1993). Detailed geologic and hydrogeologic descriptions of the region can be found in DeWitt and others (1986), Strobel and others (1999), and Redden and DeWitt (2008). The primary focus of this study is the Precambrian metamorphic and igneous rocks and Tertiary igneous rocks in the region of the SURF. Precambrian units, primarily phyllite and schist, have very low primary porosity and are typically considered the lower confining unit for the overlying Paleozoic aquifer units (Carter and others, 2003). Nonetheless, localized aquifers occur in the enhanced secondary porosity that is a result of fracturing from the Laramide orogeny and weathering. These aquifers are usually unconfined, and groundwater flow is often heavily influenced by land-surface topography (Driscoll and Carter, 1998).

Paleozoic rocks in the SURF vicinity are dominantly limestone and constitute the majority of the total thickness of the units in the regional groundwater-flow system. The Madison and Minnelusa aquifers can be well over 1,000 ft in thickness (Carter and others, 2003). The underlying interbedded sedimentary Deadwood and Winnipeg Formations and Whitewood Limestone, all relatively thin with respect to the overlying limestone aquifers, contain locally important aquifers. Tertiary igneous rocks also occur in the SURF vicinity (Caddey and others, 1991). These rocks are not considered aquifers and likely have hydrogeologic characteristics similar to the Precambrian rocks (secondary porosity from fracturing after emplacement).

A detailed description of the hydrogeology of the mine and a numerical groundwater-flow model were presented by Murdoch and others (2011). The conceptual hydrologic model included a shallow groundwater-flow system from the surface to a depth of 330–460 ft that received recharge and supported base flow in streams, and a deeper regional groundwater-flow system which is hydrologically connected to the shallow system. The numerical model suggested the existence of a recharge capture zone extending up to 5 miles (8 km) horizontally from the mine and at depths up to 5,900 ft (1,800 m). Water below these depths was assumed to be derived from storage through upward flow of older water.

Microgravity Monitoring of Groundwater Storage Changes

Microgravity refers to repeat measurements of small changes in Earth's gravity field. The method has been demonstrated for a wide range of applications, including mapping aquifer storage change (Pool and Anderson, 2008), studying near-surface terrestrial water storage (Creutzfeldt and others, 2010), and tracking the movement of a wetting front through a thick unsaturated zone (Kennedy and others, 2014). As the amount of water stored in both the unsaturated and saturated zone changes, through processes such as recharge, base flow to streams, and pumping, the average density changes along with the water-mass change. In unconfined aquifers and the unsaturated zone, this change in density occurs when water is replaced by air. In confined aquifers, density change occurs when water is released from storage through the decompression of water and compaction of the aquifer; generally, the density and gravity change is much smaller than in unconfined aquifers.

Typically, the addition of mass in the subsurface causes an increase in the measured gravity value, and conversely, the subtraction of mass causes a decrease in the measured gravity. However, in areas with substantial topographic relief, such as the area around SURF, water-storage change at elevations above a station has the opposite effect of storage change below a station. That is, if a station is located in the bottom of a valley and water is added to the hillslopes above it (through rainfall, for example), this mass “pulls up” on the gravimeter and the measured gravity value decreases. Therefore, it

is important to consider the local topography when interpreting results. The primary use of the gravity data presented here is to evaluate and calibrate a groundwater-flow model. To do so, predictions of the expected change in gravity are made using the model and are then compared to measured gravity change.

Purpose and Scope

This report describes absolute gravity data measured at 32 stations in the vicinity of the SURF from 2007 to 2014. Gravity data were collected for the purpose of monitoring subsurface water storage. Global Positioning System (GPS) locations are presented for each surface station where credible results were obtained. Additional relevant hydrologic data are also presented: precipitation at Lead, S. Dak.; streamflow at Deadwood Creek at Central City, S. Dak., and Bear Butte Creek near Deadwood, S. Dak.; and water levels within the mine workings.

Methods

Absolute Gravity Measurements

Absolute gravity data were collected at a total of 32 stations (figs. 2–4) using an A-10 absolute gravimeter (Micro-g LaCoste, Inc.). The A-10 absolute gravimeter measures the acceleration of a free-falling mass using a distance measurement obtained from a laser interferometer and a time scale determined by a rubidium oscillator. A spring mechanism isolates the interferometer from long-period seismic noise. Each measurement consists of between 720 and 1,200 drops of the free-falling mass, collected in sets of 120 drops, over a 15 to 30 minute time period. Measurement sets may be removed from final processing by visual inspection if they are not consistent with other sets. Although nominal accuracy for the A-10 absolute gravimeter reported by the manufacturer is ± 10 microGal ($1 \text{ microGal} = 1 \times 10^{-8} \text{ m/s}^2$), after several years of operation, the observational standard deviation for measurements using a single gravimeter at stable sites is estimated to be ± 5 microGal, and this value is used in data processing (Schmerge and Francis, 2006; Kennedy and Winester, 2011). To ensure this accuracy is met, the instrument undergoes periodic calibration, maintenance, and comparison with other absolute gravimeters (Schmerge and Francis, 2006; Schmerge and others, 2012). Earth tide corrections for absolute gravity measurements are determined using the ETGTAB model with the default wave groups in the Micro-g LaCoste, Inc. software (<http://www.microgacoste.com/>). Ocean-loading corrections are determined using the finite element solution tide model FES2004, produced by Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (<http://www.legos.obs-mip.fr/>) and Collecte Localisation Satellites' Space Oceanography Division and distributed by AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic Data), with support from Centre National d'Etudes Spatiales (<http://www.avis.altimetry.fr/>). Polar motion corrections were determined using coordinates provided by the United States Naval Observatory. The barometric pressure correction is calculated using measured barometric pressure and an admittance factor of 0.3 microGal/mBar.

A



B

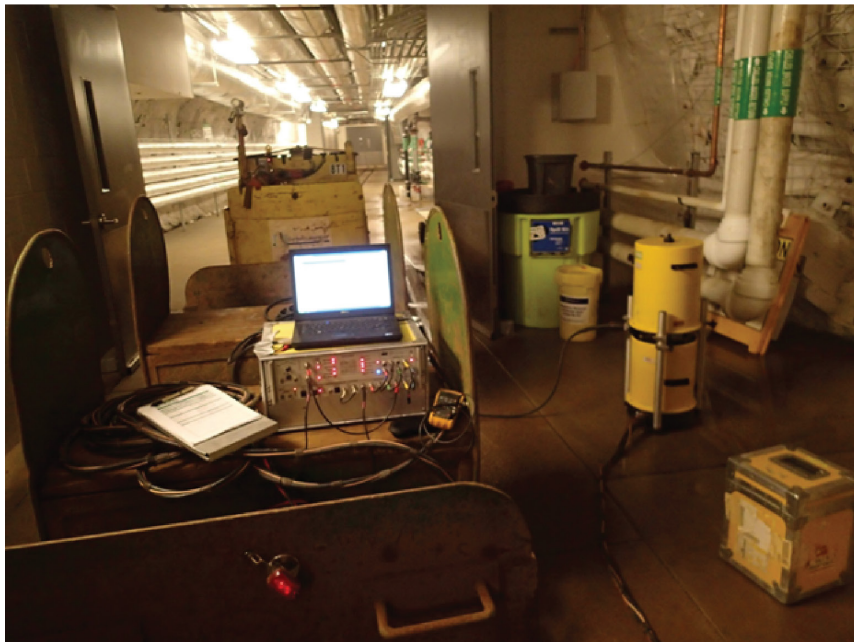


Figure 4. Photographs of selected gravity stations located in the vicinity of the Sanford Underground Research Facility, Lead, South Dakota. *A*, USGS hydrologist Robert Carruth checking the verticality of the A-10 absolute gravimeter at the Ross-4850 station. *B*, Station Yates-4800 at the entrance to the Large Underground Xenon experiment.

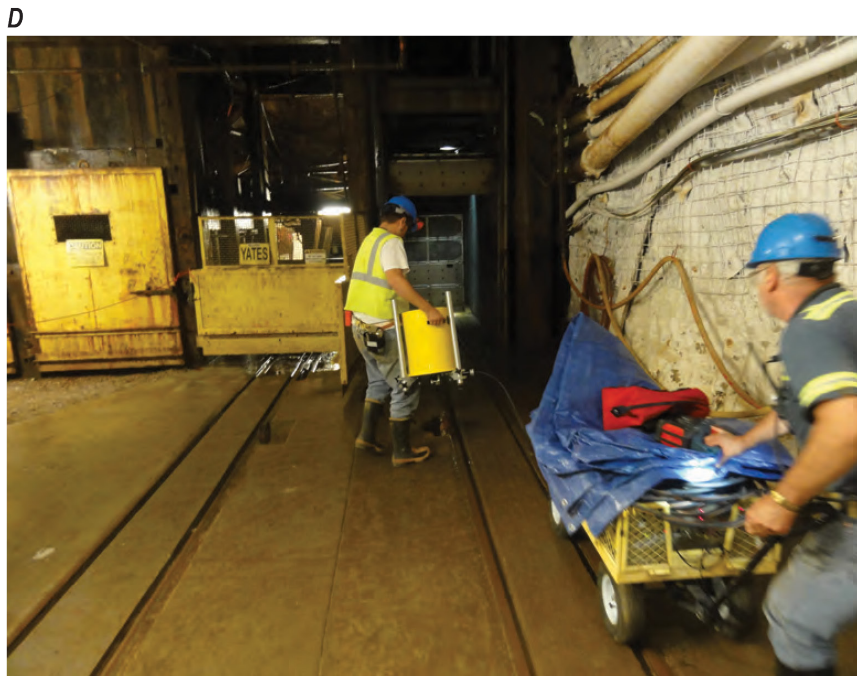


Figure 4. Photographs of selected gravity stations located in the vicinity of the Sanford Underground Research Facility, Lead, South Dakota. C, Gravity station Ross-300. D, Loading the A-10 absolute gravimeter onto the Yates shaft on the 4850 level.—Continued

Determination of Station Position

Global Positioning System (GPS) data provide point longitude, latitude, and elevation, and where repeat data are available, an indication of elevation change at a station. In 2007 and 2011, GPS

data were collected using standalone receivers. Data from 2007, collected at stand-alone receivers mounted on tripods, were post-processed using the Online Positioning User System (OPUS; National Geodetic Survey, 2014). At station HomestakeMansion, OPUS processing failed; consequently, baselines were manually post-processed using UNAVCO stations P043 and P054 and the National Oceanic and Atmospheric Administration's Earth System Research Laboratory station MRRN. The 2011 GPS data, collected from a receiver mounted on top of the A-10 absolute gravimeter, could not be processed, owing to the relatively short occupation times (30–45 minutes) and long distances to the nearest reference stations. In order to improve the quality of GPS solutions, in 2012, 2013, and 2014, a GPS base station was deployed at station Opencut-GPS, and a second GPS antenna/receiver was deployed using the mount permanently installed on the top of the A-10 absolute gravimeter. Data were post-processed using OPUS to determine a position for Opencut-GPS, which in turn was used as a starting position for the post-processed GPS vectors between Opencut-GPS and each gravity station. The change in position at station Opencut-GPS was less than measurement error of about 0.8 in. (2 cm) in the horizontal and 1.2 in. (3 cm) in the vertical; therefore, a single average position was used for all years. As a result, published coordinates for most stations are tied to a single coordinate for Opencut-GPS. Where observations were available in multiple years, an average position was calculated.

Many of the gravity stations are located in areas that are relatively poor for GPS reception because of nearby buildings, overhanging roofs, trees, and (or) topography. At five stations (Bullock, Mollman, RossWarehouse, RTentrance, and Yates; fig. 2), a precise location via GPS was not possible; instead, a position was digitized from aerial imagery retrieved from The National Map (<http://thenationalmap.com/>). In these instances, the imprecise position makes the gravity data unsuitable for modeling density heterogeneity in the subsurface (that is, traditional Bouguer gravity studies). However, the precision of the measured change in gravity over time is only affected by the ability to consistently set up the meter in the same location for each measurement. This was aided by permanent survey marks, photographs, and detailed site descriptions. Because GPS observations are impossible underground, subsurface stations were located using computer-aided design (CAD) files created when the Homestake Mine was in operation. As with surface stations without GPS positions, the precision of the measured change in gravity is minimal as long as the gravity meter is accurately repositioned for each measurement.

Results

Observed Gravity Values

The observed absolute gravity values, their position coordinates, and measurement uncertainty are presented in table 1. Uncertainty includes instrument accuracy (± 5 microGal), setup error, and error associated with unmodeled environmental effects such as Earth tides, ocean loading, and barometric pressure changes. The same gravity values, rearranged to facilitate time-series analysis, are presented in table 2. GPS coordinates and processing results for those stations where acceptable GPS data were collected are presented in table 3. Gravity values for 2007–2014 vary considerably at most stations, and at many, two or more measurements have minimal or no overlap in their error bars (fig. 5). This indicates the differences in gravity values are likely due to change in groundwater storage or other mass and unlikely due to measurement error. A notable feature at most of the stations is the relatively low observed gravity in 2013 (fig. 6); these low gravity measurements may be related to relatively low precipitation in 2012 and 2013.

Table 1. Position coordinates, gravity values, and error statistics for absolute gravity stations in the vicinity of the Sanford Underground Research Facility, Lead, South Dakota. Reported values are at 100 cm above the station mark, calculated using the vertical gradient -3 microGal/cm. [cm, centimeters; μ Gal, microGal; NAD83, North American Datum of 1983(2011) epoch 2010.0]

Station name	Latitude (NAD83)	Longitude (NAD83)	Height (meters above GRS80 ellipsoid) ¹	Setup height (cm)	Gradient (μ Gal/cm)	Gravity measurement date	Gravity (μ Gal)	Set scatter (μ Gal)	Precision (μ Gal)	Uncertainty (μ Gal)	Sets collected	Sets processed
4winzewye	44.3463	-103.7533	115	0	-3	8/27/12	980,267,820.1	2.10	0.67	6.04	10	10
4winzewye	--	--	115	0	-3	8/21/13	980,267,814.2	1.37	0.48	6.02	8	8
4winzewye	--	--	115	0	-3	8/27/14	980,267,816.8	2.14	0.68	6.04	10	10
Bernie	44.35502	-103.77912	1,584.65	0	-3	12/11/07	980,154,460.9	2.90	0.92	6.07	10	10
Bernie	--	--	1,584.65	0	-3	7/25/10	980,154,477.5	1.58	0.56	6.03	8	8
Bernie	--	--	1,584.65	0	-3	6/25/11	980,154,491.1	1.28	0.45	6.02	9	8
Bernie	--	--	1,584.65	0	-3	8/18/12	980,154,493.6	1.72	0.54	6.02	10	10
Bernie	--	--	1,584.65	0	-3	8/18/13	980,154,469.5	0.85	0.30	6.01	8	8
Bernie	--	--	1,584.65	0	-3	8/23/14	980,154,495.6	1.45	0.51	6.02	8	8
BHireset	44.35451	-103.73794	1,436.17	0	-3	8/19/12	980,186,275.4	1.85	0.66	6.04	8	8
BHireset	--	--	1,436.17	0	-3	8/18/13	980,186,254.0	2.04	0.83	6.06	8	6
BHireset	--	--	1,436.17	0	-3	8/23/14	980,186,278.2	0.35	0.14	6.00	6	6
BlackHillsInn	44.35443	-103.73739	1,436.82	0	-3	12/13/07	980,185,497.4	3.34	1.06	6.09	10	10
BlackHillsInn	--	--	1,436.82	0	-3	7/25/10	980,185,473.9	2.48	0.88	6.07	8	8
BlackHillsInn	--	--	1,436.82	0	-3	6/24/11	980,185,498.0	0.66	0.27	6.00	8	6
BlackHillsInn	--	--	1,436.82	0	-3	8/19/12	980,185,508.0	1.13	0.40	6.01	8	8
BrokenBoot	44.37105	-103.74413	1,405.76	0	-3	12/11/07	980,195,104.1	0.46	0.16	6.00	9	8
BrokenBoot	--	--	1,405.76	0	-3	7/25/10	980,195,097.7	1.61	0.51	6.02	10	10
BrokenBoot	--	--	1,405.76	0	-3	6/25/11	980,195,094.4	1.11	0.39	6.01	8	8
BrokenBoot	--	--	1,405.76	0	-3	8/18/12	980,195,112.9	1.56	0.49	6.02	10	10
BrokenBoot	--	--	1,405.76	0	-3	8/17/13	980,195,076.1	0.71	0.25	6.01	8	8
BrokenBoot	--	--	1,405.76	0	-3	8/24/14	980,195,106.2	0.34	0.14	6.00	6	6
Bullock	44.3784	-103.7293	1,375	0	-3	12/12/07	980,205,800.7	1.30	0.41	6.01	10	10
Bullock	--	--	1,375	0	-3	7/25/10	980,205,808.1	1.12	0.40	6.02	8	8
Bullock	--	--	1,375	0	-3	6/25/11	980,205,798.5	1.42	0.50	6.02	8	8
Bullock	--	--	1,375	0	-3	8/19/12	980,205,811.0	1.05	0.33	6.01	10	10

Station name	Latitude (NAD83)	Longitude (NAD83)	Height (meters above GRS80 ellipsoid) ¹	Setup height (cm)	Gradient (μGal/cm)	Gravity measurement date	Gravity (μGal)	Set scatter (μGal)	Precision (μGal)	Uncertainty (μGal)	Sets collected	Sets processed
Bullock	--	--	1,375	0	-3	8/17/13	980,205,784.3	2.92	0.92	6.07	10	10
Bullock	--	--	1,375	0	-3	8/28/14	980,205,812.3	1.54	0.63	6.03	6	6
BullockExpress	44.38864	-103.71269	1,372.51	0	-3	12/12/07	980,205,117.6	2.15	0.68	6.04	10	10
BullockExpress	--	--	1,372.51	0	-3	7/25/10	980,205,104.0	2.88	1.02	6.09	10	8
BullockExpress	--	--	1,372.51	0	-3	6/24/11	980,205,101.6	4.71	1.49	6.18	10	10
DeadwoodExpress	44.38803	-103.71323	1,367.90	0	-3	8/19/12	980,206,104.9	1.56	0.49	6.02	10	10
DeadwoodExpress	--	--	1,367.90	0	-3	8/17/13	980,206,076.3	2.37	0.75	6.05	10	10
DeadwoodExpress	--	--	1,367.90	0	-3	8/26/14	980,206,097.8	1.68	0.53	6.02	10	10
Flower	44.36871	-103.76676	1,467.38	0	-3	12/11/07	980,180,886.0	6.35	2.59	6.54	10	6
Flower	--	--	1,467.38	0	-3	7/24/10	980,180,874.2	2.94	0.93	6.08	10	10
Flower	--	--	1,467.38	0	-3	6/25/11	980,180,871.9	1.57	0.55	6.02	8	8
Flower	--	--	1,467.38	0	-3	8/18/12	980,180,884.1	1.08	0.34	6.01	10	10
Flower	--	--	1,467.38	0	-3	8/18/13	980,180,856.7	1.04	0.43	6.02	8	6
Flower	--	--	1,467.38	0	-3	8/23/14	980,180,882.8	0.27	0.11	6.00	6	6
Highwaydept	44.36913	-103.75538	1,433.35	0	-3	12/13/07	980,187,923.1	2.51	0.79	6.05	10	10
Highwaydept	--	--	1,433.35	0	-3	7/24/10	980,187,911.1	4.13	1.25	6.13	16	11
Highwaydept	--	--	1,433.35	0	-3	6/25/11	980,187,920.2	1.00	0.35	6.01	8	8
Highwaydept	--	--	1,433.35	0	-3	8/18/12	980,187,926.6	1.48	0.47	6.02	10	10
Highwaydept	--	--	1,433.35	0	-3	8/17/13	980,187,903.6	0.73	0.26	6.01	8	8
Highwaydept	--	--	1,433.35	0	-3	8/24/14	980,187,924.0	2.09	0.66	6.04	10	10
HMreset	44.34948	-103.77663	1,633.80	8.95	-3	8/23/12	980,144,511.2	3.41	1.08	6.06	10	10
HMreset	--	--	1,633.80	9.6	-3	8/18/13	980,144,500.3	2.17	0.69	6.01	10	10
HMreset	--	--	1,633.80	8.85	-3	8/24/14	980,144,515.4	3.01	0.95	6.04	10	10
HomestakeMansion	44.34971	-103.77718	1,637.10	0	-3	12/12/07	980,143,910.5	1.59	0.50	6.02	10	10
HomestakeMansion	--	--	1,637.10	3	-3	7/25/10	980,143,910.1	3.01	1.06	6.08	8	8
HomestakeMansion	--	--	1,637.10	3	-3	6/26/11	980,143,922.9	2.69	0.95	6.06	10	8
Mammenga	44.31704	-103.70199	1,707.39	0	-3	12/13/07	980,134,441.7	1.95	0.62	6.03	10	10
Mammenga	--	--	1,707.39	0	-3	7/25/10	980,134,418.7	2.85	0.90	6.07	10	10
Mammenga	--	--	1,707.39	0	-3	6/24/11	980,134,447.8	1.15	0.41	6.01	8	8
Mammenga	--	--	1,707.39	0	-3	8/19/12	980,134,437.2	0.66	0.23	6.00	8	8
Mammenga	--	--	1,707.39	0	-3	8/23/14	980,134,459.3	0.75	0.30	6.01	6	6

Station name	Latitude (NAD83)	Longitude (NAD83)	Height (meters above GRS80 ellipsoid) ¹	Setup height (cm)	Gradient ($\mu\text{Gal}/\text{cm}$)	Gravity measurement date	Gravity (μGal)	Set scatter (μGal)	Precision (μGal)	Uncertainty (μGal)	Sets collected	Sets processed
MiningPark	44.35460	-103.75520	1,520.54	0	-3	8/23/12	980,170,479.3	0.82	0.33	6.01	6	6
MiningPark	--	--	1,520.54	0	-3	8/18/13	980,170,457.7	1.55	0.55	6.02	8	8
MiningPark	--	--	1,520.54	0	-3	8/23/14	980,170,493.3	0.78	0.28	6.01	8	8
Mollman	44.3825	-103.7807	1,545	0	-3	12/13/07	980,166,967.3	1.67	0.53	6.02	10	10
Mollman	--	--	1,545	0	-3	7/24/10	980,166,937.6	0.88	0.36	6.01	6	6
Mollman	--	--	1,545	0	-3	6/25/11	980,166,955.1	1.21	0.43	6.01	8	8
No5	44.33538	-103.74378	1,553.25	0	-3	7/27/10	980,161,951.2	5.00	1.77	6.25	10	8
No5	--	--	1,553.25	0	-3	6/27/11	980,161,946.4	1.41	0.45	6.02	10	10
No5	--	--	1,553.25	0	-3	8/20/12	980,161,963.6	0.28	0.11	6.00	6	6
No5	--	--	1,553.25	0	-3	8/20/13	980,161,936.1	1.08	0.38	6.01	8	8
No5	--	--	1,553.25	0	-3	8/26/14	980,161,959.0	0.87	0.31	6.01	8	8
Opencut	44.35204	-103.76338	1,567.12	0	-3	12/14/07	980,157,898.8	1.02	0.32	6.01	10	10
Opencut	--	--	1,567.12	0	-3	7/24/10	980,157,902.7	1.53	0.54	6.03	10	8
Opencut	--	--	1,567.12	0	-3	6/25/11	980,157,908.1	1.64	0.52	6.02	10	10
Opencut	--	--	1,567.12	0	-3	6/28/11	980,157,907.9	1.63	0.58	6.03	10	8
Opencut	--	--	1,567.12	0	-3	8/18/12	980,157,908.4	1.58	0.50	6.02	10	10
Opencut	--	--	1,567.12	0	-3	8/17/13	980,157,888.1	1.51	0.53	6.02	8	8
OroHondo	44.34502	-103.75257	1,492.11	0	-3	7/27/10	980,173,549.2	3.09	1.09	6.10	8	8
OroHondo	--	--	1,492.11	0	-3	6/27/11	980,173,556.4	1.02	0.32	6.01	10	10
OroHondo	--	--	1,492.11	0	-3	8/20/12	980,173,553.8	0.46	0.19	6.00	6	6
OroHondo	--	--	1,492.11	0	-3	8/20/13	980,173,526.7	1.53	0.54	6.02	8	8
OroHondo	--	--	1,492.11	0	-3	8/26/14	980,173,555.0	1.02	0.36	6.01	8	8
Pronto	44.33830	-103.78558	1,595.81	0	-3	12/11/07	980,147,685.6	2.81	0.94	6.07	9	9
Pronto	--	--	1,595.81	0	-3	7/24/10	980,147,691.7	3.08	0.97	6.08	10	10
Pronto	--	--	1,595.81	0	-3	6/27/11	980,147,682.5	2.36	0.75	6.05	10	10
Pronto	--	--	1,595.81	0	-3	8/18/13	980,147,676.5	1.03	0.37	6.01	8	8
Pronto	--	--	1,595.81	0	-3	8/23/14	980,147,692.3	0.52	0.21	6.00	6	6
Pumphouse	44.37908	-103.77575	1,516.42	0	-3	8/19/12	980,172,346.3	4.19	1.32	6.14	10	10
Pumphouse	--	--	1,516.42	0	-3	8/18/13	980,172,321.0	1.67	0.59	6.03	8	8
Pumphouse	--	--	1,516.42	0	-3	8/24/14	980,172,336.4	1.69	0.53	6.02	10	10
RooRanch	44.38834	-103.68242	1,416.85	0	-3	12/14/07	980,192,913.0	0.56	0.23	6.00	10	6

Station name	Latitude (NAD83)	Longitude (NAD83)	Height (meters above GRS80 ellipsoid) ¹	Setup height (cm)	Gradient (μGal/cm)	Gravity measurement date	Gravity (μGal)	Set scatter (μGal)	Precision (μGal)	Uncertainty (μGal)	Sets collected	Sets processed
RooRanch	--	--	1,416.85	0	-3	7/25/10	980,192,920.7	2.93	0.93	6.07	10	10
RooRanch	--	--	1,416.85	0	-3	6/24/11	980,192,925.7	1.16	0.41	6.01	8	8
RooRanch	--	--	1,416.85	0	-3	8/19/12	980,192,923.8	0.85	0.30	6.01	8	8
Ross-300	44.3464	-103.7574	1,500	0	-3	6/29/11	980,164,401.7	1.18	0.37	6.01	10	10
Ross-300	--	--	1,500	0	-3	8/20/12	980,164,419.3	1.12	0.35	6.01	10	10
Ross-300	--	--	1,500	0	-3	8/20/13	980,164,408.4	0.83	0.29	6.01	8	8
Ross-300	--	--	1,500	0	-3	8/28/14	980,164,412.6	1.14	0.40	6.01	8	8
Ross-800	44.3463	-103.7582	1,350	0	-3	6/28/11	980,176,846.4	1.27	0.40	6.01	10	10
Ross-2000	44.3458	-103.7581	984	0	-3	6/28/11	980,203,973.4	1.20	0.35	6.01	12	12
Ross-4100	44.3461	-103.7581	343	0	-3	6/28/11	980,249,726.8	1.29	0.49	6.02	9	7
Ross-4850	44.3458	-103.7583	114	0	-3	6/28/11	980,265,522.8	0.67	0.27	6.00	10	6
Ross-4850	--	--	114	0	-3	8/27/12	980,265,523.1	0.72	0.23	6.00	10	10
Ross-4850	--	--	114	0	-3	8/21/13	980,265,510.4	0.99	0.35	6.01	8	8
Ross-4850	--	--	114	0	-3	8/27/14	980,265,499.3	1.76	0.56	6.02	10	10
RT_entrance	44.3483	-103.7542	1,499	2.2	-3	6/29/11	980,172,691.6	1.00	0.35	6.00	8	8
RT_entrance	--	--	1,499	3.2	-3	8/20/12	980,172,679.2	2.43	0.86	6.05	8	8
RT_entrance	--	--	1,499	1.1	-3	8/20/13	980,172,654.0	1.97	0.70	6.03	8	8
RossWarehouse	44.3455	-103.7578	1,620	0	-3	7/27/10	980,147,375.0	1.37	0.49	6.02	8	8
RossWarehouse	--	--	1,620	0	-3	6/27/11	980,147,376.7	0.77	0.27	6.01	8	8
RossWarehouse	--	--	1,620	0	-3	8/20/12	980,147,378.5	1.49	0.53	6.02	8	8
RossWarehouse	--	--	1,620	0	-3	8/20/13	980,147,359.9	1.05	0.37	6.01	8	8
RossWarehouse	--	--	1,620	0	-3	8/26/14	980,147,388.2	1.97	0.62	6.03	10	10
Whitetail	44.32967	-103.79529	1,650.67	0	-3	12/12/07	980,137,169.8	1.23	0.43	6.01	9	8
Whitetail	--	--	1,650.67	0	-3	7/24/10	980,137,161.0	4.72	1.67	6.23	14	8
Whitetail	--	--	1,650.67	0	-3	6/26/11	980,137,166.9	0.92	0.33	6.01	8	8
Whitetail	--	--	1,650.67	0	-3	8/18/12	980,137,177.0	1.00	0.32	6.01	10	10
Whitetail	--	--	1,650.67	0	-3	8/18/13	980,137,153.6	2.04	0.64	6.03	10	10
Whitetail	--	--	1,650.67	0	-3	8/24/14	980,137,174.0	1.91	0.60	6.03	10	10
Yates	44.3522	-103.7511	1,606	0	-3	12/11/07	980,152,913.3	1.35	0.43	6.01	10	10
Yates	--	--	1,606	0	-3	7/23/10	980,152,914.0	1.78	0.56	6.03	10	10
Yates	--	--	1,606	0	-3	6/27/11	980,152,914.5	1.17	0.41	6.01	8	8

Station name	Latitude (NAD83)	Longitude (NAD83)	Height (meters above GRS80 ellipsoid) ¹	Setup height (cm)	Gradient ($\mu\text{Gal}/\text{cm}$)	Gravity measurement date	Gravity (μGal)	Set scatter (μGal)	Precision (μGal)	Uncertainty (μGal)	Sets collected	Sets processed
Yates	--	--	1,606	0	-3	8/20/12	980,152,900.7	1.15	0.43	6.02	8	7
Yates	--	--	1,606	0	-3	8/20/13	980,152,901.0	0.72	0.26	6.01	8	8
Yates	--	--	1,606	0	-3	8/26/14	980,152,921.9	1.28	0.45	6.02	8	8
Yates-4100	44.3520	-103.7513	343	5	-3	8/21/12	980,255,356.7	0.76	0.27	5.99	8	8
Yates-4100	--	--	343	0	-3	8/21/13	980,255,342.4	0.68	0.21	6.00	10	10
Yates-4100	--	--	343	0	-3	8/27/14	980,255,349.2	1.60	0.51	6.02	10	10
Yates-4850	44.3519	-103.7516	112	0	-3	8/21/12	980,270,595.1	1.16	0.41	6.01	8	8
Yates-4850	--	--	112	0	-3	8/21/13	980,270,581.7	0.63	0.22	6.01	8	8
Yates-4850	--	--	112	0	-3	8/27/14	980,270,592.6	1.61	0.51	6.02	10	10

¹Value for surface stations is from GPS data (table 3) or digitized from The National Map. Value for subsurface stations (4winzewye, Ross-300, Ross-2000, Ross-4100, Ross-4850, Yates-4100, Yates-4850) is elevation from the Homestake Coordinate System.

Table 2. Absolute-gravity values from 2007, 2010, 2011, 2012, 2013, and 2014, arranged by year. Reported values are at 100 cm above the station mark, calculated using the vertical gradient -3 microGal/cm.
[cm, centimeters; NAD83, North American Datum of 1983(2011) epoch 2010.0]

Station name	Latitude (NAD83)	Longitude (NAD83)	Height (meters above GRS80 ellipsoid) ¹	Observed gravity, in microGal					
				Dec. 2007	Jul. 2010	Jun. 2011	Aug. 2012	Aug. 2013	Aug. 2014
4winzewye	44.3463	-103.7533	115	--	--	--	980,267,820.1	980,267,814.2	980,267,816.8
Bernie	44.35502	-103.77912	1,584.65	980,154,460.9	980,154,477.5	980,154,491.1	980,154,493.6	980,154,469.5	980,154,495.6
BHireset	44.35451	-103.73794	1,436.17	--	--	--	980,186,275.4	980,186,254.0	980,186,278.2
BlackHillsInn	44.35443	-103.73739	1,436.82	980,185,497.4	980,185,473.9	980,185,498.0	980,185,508.0	--	--
BrokenBoot	44.37105	-103.74413	1,405.76	980,195,104.1	980,195,097.7	980,195,094.4	980,195,112.9	980,195,076.1	980,195,106.2
Bullock	44.3784	-103.7293	1,375	980,205,800.7	980,205,808.1	980,205,798.5	980,205,811.0	980,205,784.3	980,205,812.3
BullockExpress	44.38864	-103.71269	1,372.51	980,205,117.6	980,205,104.0	980,205,101.6	--	--	--
DeadwoodExpress	44.38803	-103.71323	1,367.90	--	--	--	980,206,104.9	980,206,076.3	980,206,097.8
Flower	44.36871	-103.76676	1,467.38	980,180,886.0	980,180,874.2	980,180,871.9	980,180,884.1	980,180,856.7	980,180,882.8
Highwaydept	44.36913	-103.75538	1,433.35	980,187,923.1	980,187,911.1	980,187,920.2	980,187,926.6	980,187,903.6	980,187,924.0
HMreset	44.34948	-103.77663	1,633.80	--	--	--	980,144,511.2	980,144,500.3	980,144,515.4
HomestakeMansion	44.34971	-103.77718	1,637.10	980,143,910.5	980,143,910.1	980,143,922.9	--	--	--
Mammenga	44.31704	-103.70199	1,707.39	980,134,441.7	980,134,418.7	980,134,447.8	980,134,437.2	--	980,134,459.3
MiningPark	44.35460	-103.75520	1,520.54	--	--	--	980,170,479.3	980,170,457.7	980,170,493.3
Mollman	44.3825	-103.7807	1,545	980,166,967.3	980,166,937.6	980,166,955.1	--	--	--
No5	44.33538	-103.74378	1,553.25	--	980,161,951.2	980,161,946.4	980,161,963.6	980,161,936.1	980,161,959.0
Opencut	44.35204	-103.76338	1,567.12	980,157,898.8	980,157,902.7	980,157,908.1	980,157,908.4	980,157,888.1	--
OroHondo	44.34502	-103.75257	1,492.11	--	980,173,549.2	980,173,556.4	980,173,553.8	980,173,526.7	980,173,555.0
Pronto	44.33830	-103.78558	1,595.81	980,147,685.6	980,147,691.7	980,147,682.5	--	980,147,676.5	980,147,692.3
Pumphouse	44.37908	-103.77575	1,516.42	--	--	--	980,172,346.3	980,172,321.0	980,172,336.4
RooRanch	44.38834	-103.68242	1,416.85	980,192,913.0	980,192,920.7	980,192,925.7	980,192,923.8	--	--
Ross-300	44.3464	-103.7574	1,500	--	--	980,164,401.7	980,164,419.3	980,164,408.4	980,164,412.6
Ross-800	44.3463	-103.7582	1,350	--	--	980,176,846.4	--	--	--
Ross-2000	44.3458	-103.7581	984	--	--	980,203,973.4	--	--	--

Station name	Latitude (NAD83)	Longitude (NAD83)	Height (meters above GRS80 ellipsoid) ¹	Observed gravity, in microGal					
				Dec. 2007	Jul. 2010	Jun. 2011	Aug. 2012	Aug. 2013	Aug. 2014
Ross-4100	44.3461	-103.7581	343	--	--	980,249,726.8	--	--	--
Ross-4850	44.3458	-103.7583	114	--	--	980,265,522.8	980,265,523.1	980,265,510.4	980,265,499.3
RTentrance	44.3483	-103.7542	1,499	--	--	980,172,691.6	980,172,679.2	980,172,654.0	--
RossWarehouse	44.3455	-103.7578	1,620	--	980,147,375.0	980,147,376.7	980,147,378.5	980,147,359.9	980,147,388.2
Whitetail	44.32967	-103.79529	1,650.67	980,137,169.8	980,137,161.0	980,137,166.9	980,137,177.0	980,137,153.6	980,137,174.0
Yates	44.3522	-103.7511	1,606	980,152,913.3	980,152,914.0	980,152,914.5	980,152,900.7	980,152,901.0	980,152,921.9
Yates-4100	44.3520	-103.7513	343	--	--	--	980,255,356.7	980,255,342.4	980,255,349.2
Yates-4850	44.3519	-103.7516	112	--	--	--	980,270,595.1	980,270,581.7	980,270,592.6

¹Value for surface stations is from GPS data (table 3) or digitized from The National Map. Value for subsurface stations (4winzewye, Ross-300, Ross-2000, Ross-4100, Ross-4850, Yates-4100, Yates-4850) is elevation from the Homestake Coordinate System.

Table 3. Surficial absolute-gravity station position coordinates from Global Positioning System (GPS) measurements made in 2007, 2012, 2013, and 2014.

[--, no GPS observation collected; Method: A, average of 2 or more differential GPS observations; S, single-baseline differential GPS observation; NAD83, North American Datum of 1983(2011) epoch 2010.0]

Station name	Method	Latitude (NAD83)	Longitude (NAD83)	2007–2014 Average height (meters above GRS80 ellipsoid)	Difference between observed height and average height (meters) ¹			
					2007	2012	2013	2014
Bernie ²	A	44.3550151	-103.7791195	1,584.652	0.051	-0.075	0.023	--
BlackHillsInn ²	A	44.3544342	-103.7373870	1,436.817	0.079	-0.080	--	--
BHlreset ²	A	44.3545085	-103.7379404	1,436.173	--	0.087	--	-0.087
BrokenBoot	A	44.3710507	-103.7441287	1,405.759	-0.013	-0.002	0.000	0.015
BullockExpress	S	44.388642	-103.712686	1,372.51	0	--	--	--
DeadwoodExpress	A	44.3880312	-103.7132274	1,367.903	--	-0.005	0.011	-0.005
Flower ²	S	44.368709	-103.766759	1,467.38	0	--	--	--
HighwayDept	A	44.3691293	-103.7553760	1,433.352	-0.004	0.022	-0.006	-0.011
Hmreset	A	44.3494782	-103.7766349	1,633.804	--	--	0.007	-0.007
HomestakeMansion	S	44.349711	-103.777180	1,637.10	0	--	--	--
Mammenga ²	A	44.3170411	-103.7019871	1,707.393	-0.099	-0.145	--	0.245
MiningPark	A	44.3545950	-103.7551999	1,520.535	--	--	0.006	-0.006
No5	A	44.3353787	-103.7437806	1,553.252	--	--	0.006	-0.007
Opencut	A	44.3520422	-103.7633779	1,567.119	-0.018	-0.002	0.021	--
Opencut-GPS	A	44.3523297	-103.7625595	1,565.414	--	-0.007	-0.005	0.005
OroHondo	A	44.3450197	-103.7525716	1,492.113	--	--	0.009	-0.009
Pronto ²	S	44.338304	-103.785580	1,595.81	--	--	0	--
Pumphouse ²	A	44.3790771	-103.7757547	1,516.416	--	0.023	0.014	-0.037
RooRanch	S	44.388344	-103.682419	1,416.85	--	--	0	--
Ross	S	44.345654	-103.758144	1,619.54	0	--	--	--
Whitetail	A	44.3296700	-103.7952907	1,650.668	0.282 ³	0.016	0.003	-0.019

¹Table entry "0" indicates the solution that was used for single-baseline solutions.

²Sky-view at the station is partly or completely obstructed.

³Observation not used in the average station position.

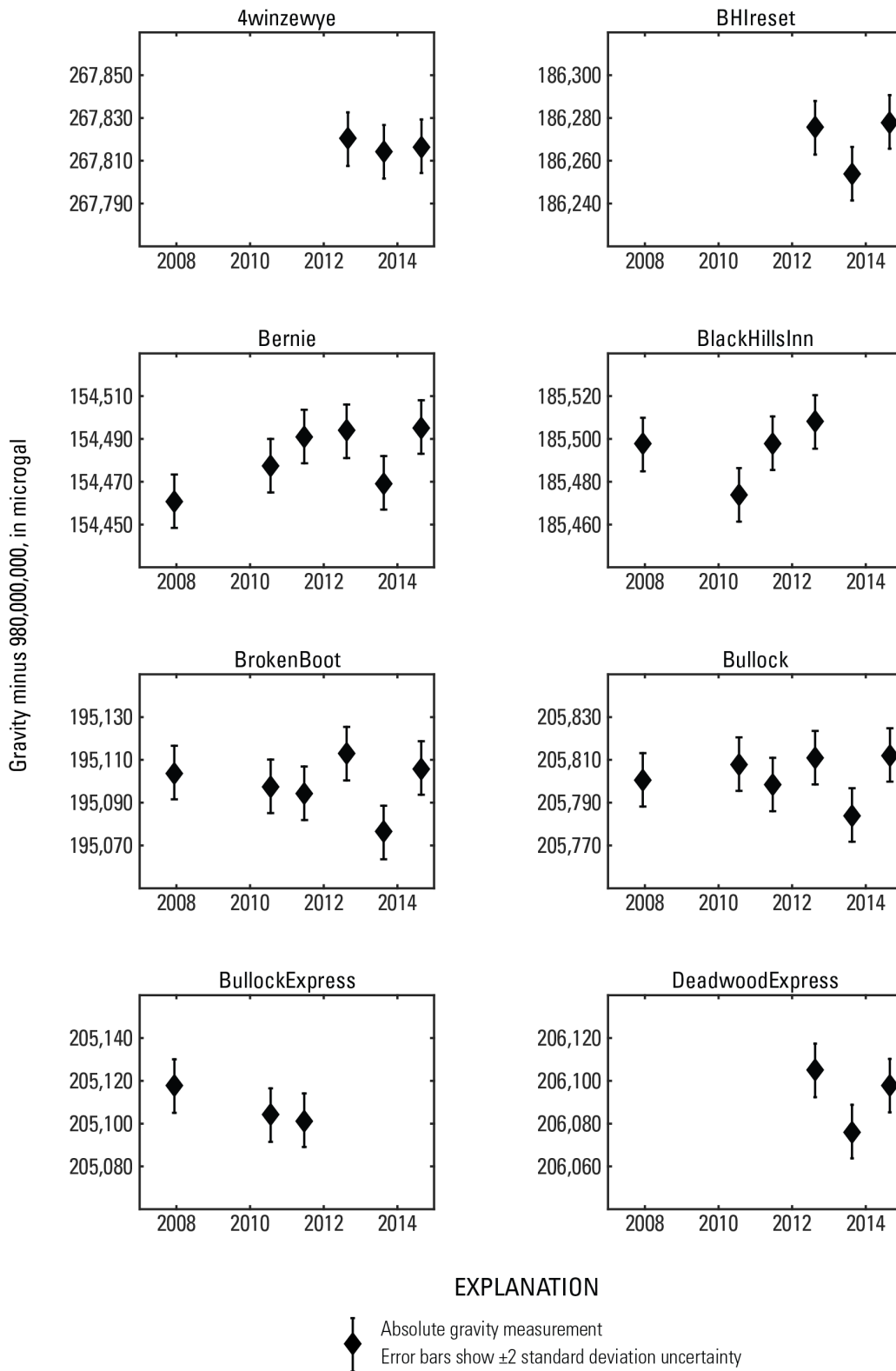


Figure 5. Scatter plots showing temporal trends in gravity at each station, 2007–2017.

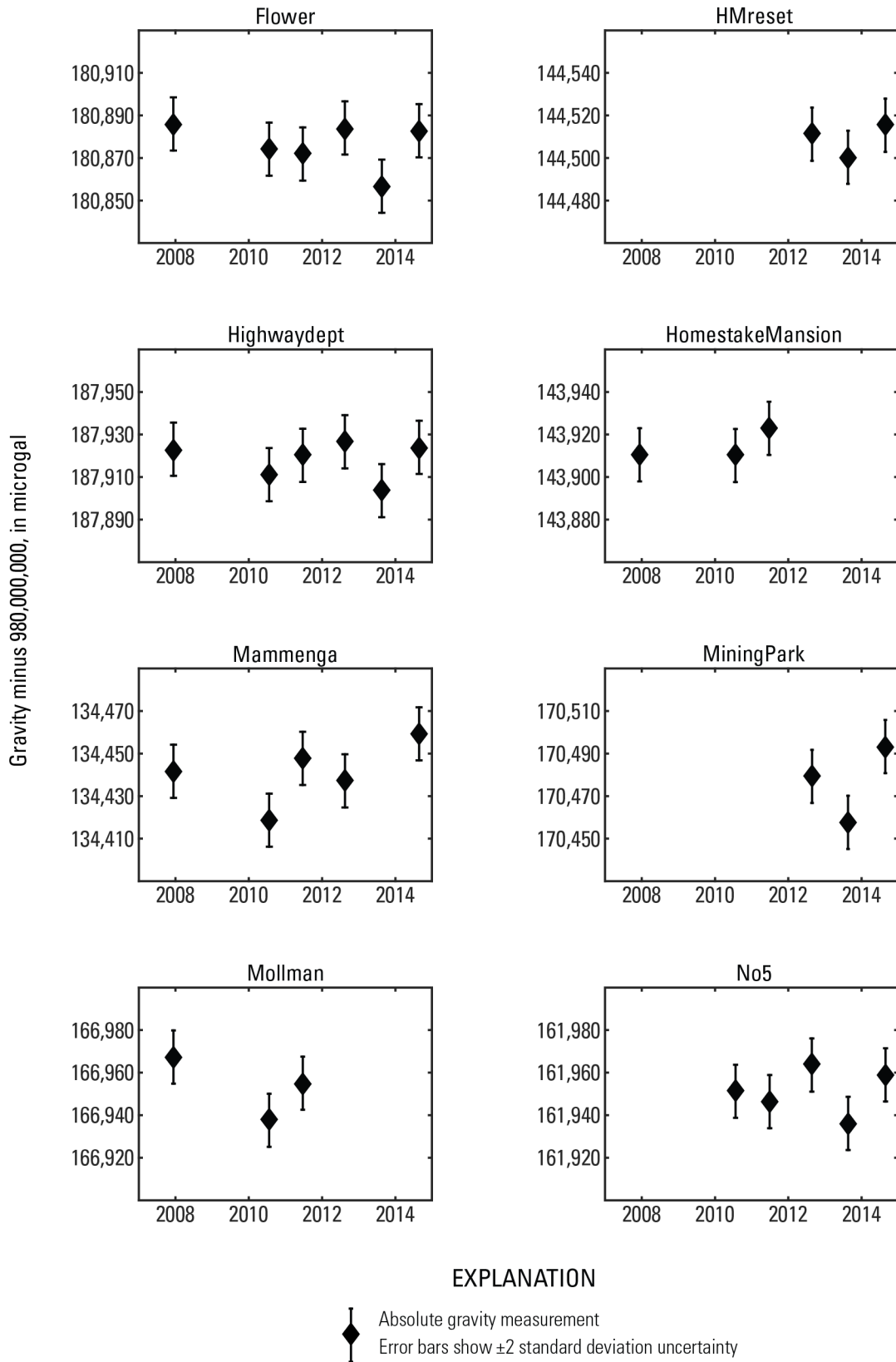


Figure 5. Scatter plots showing temporal trends in gravity at each station, 2007–2017.—Continued

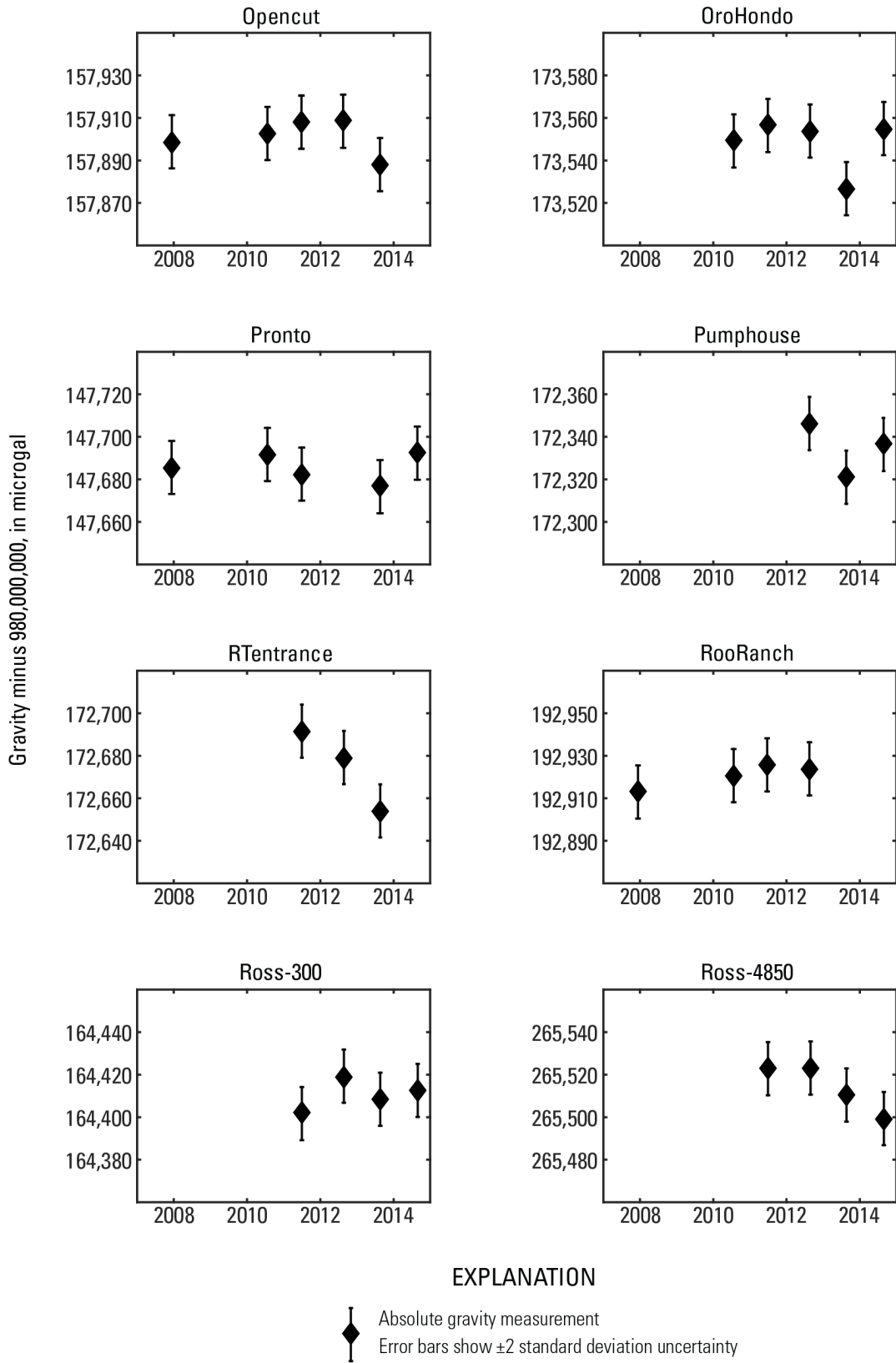


Figure 5. Scatter plots showing temporal trends in gravity at each station, 2007–2017.—Continued

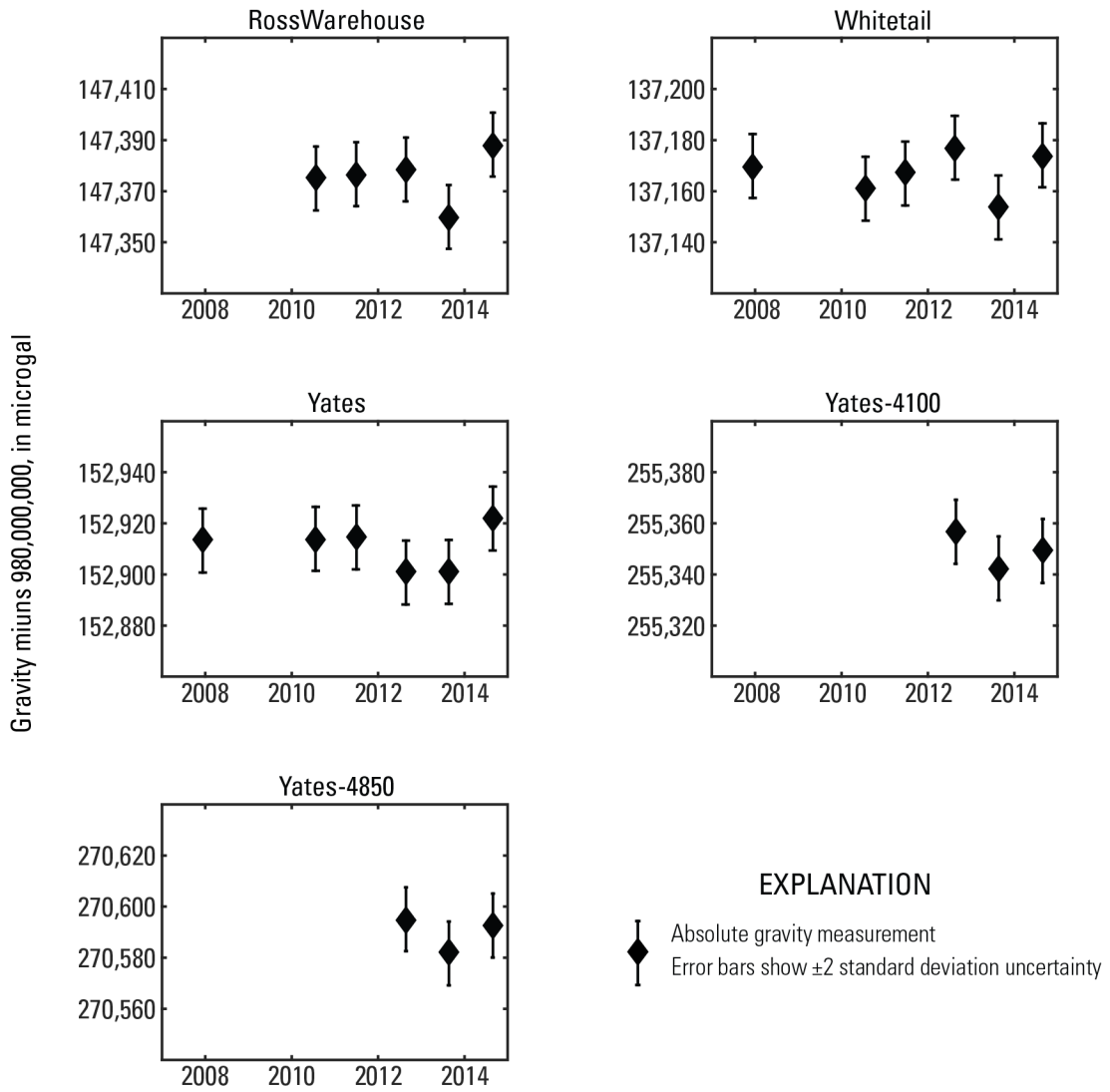


Figure 5. Scatter plots showing temporal trends in gravity at each station, 2007–2017.—Continued

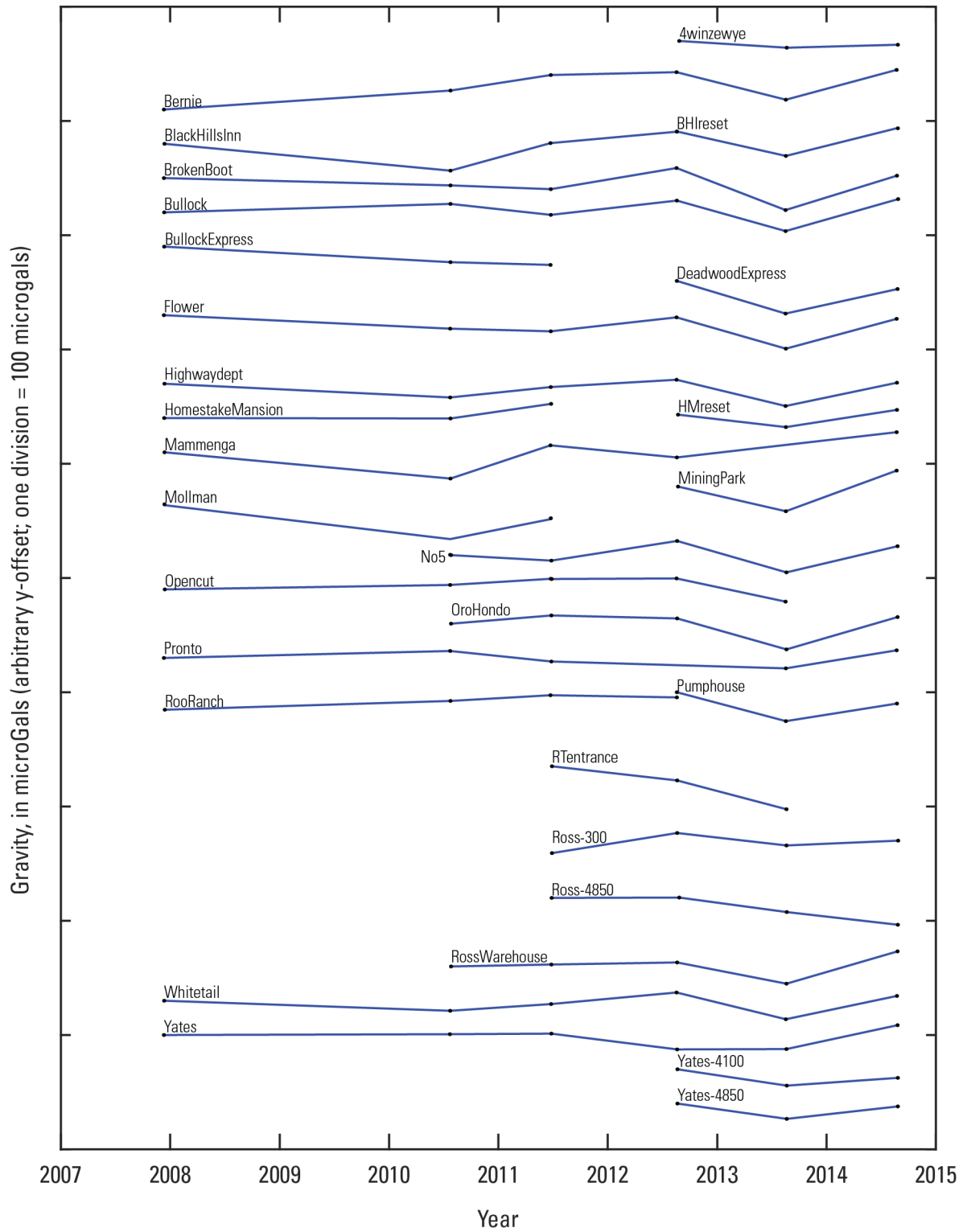
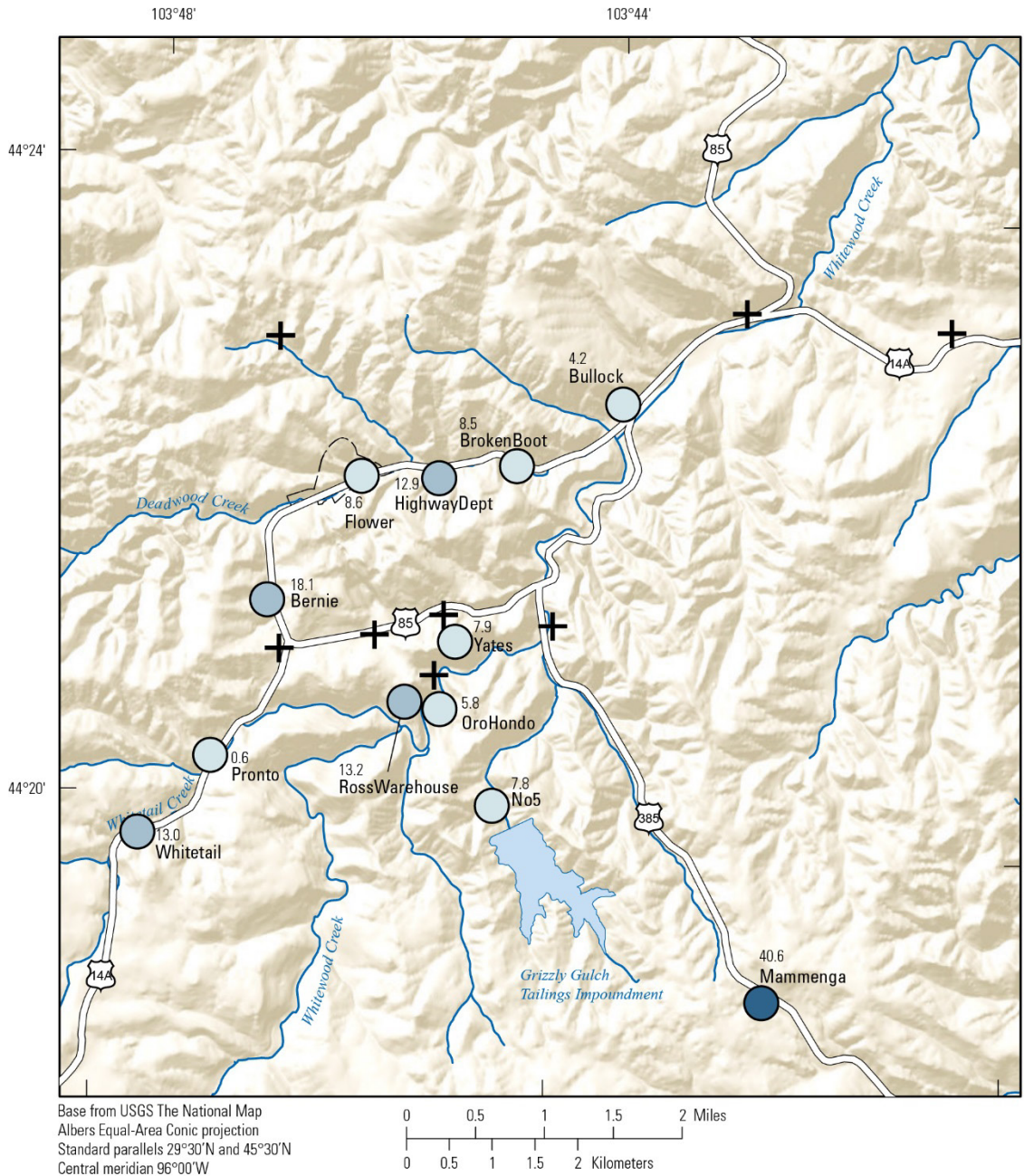


Figure 6. Line plot showing gravity change at all stations.

An important influence on the measured change in gravity is water stored in the near-surface as soil moisture and in perched aquifers. At the annual time scale, this reservoir of terrestrial water storage is largely independent of water stored in the regional groundwater-flow system, such that the long-term gravity change caused by changes in groundwater storage induced by dewatering could be obscured by higher-frequency gravity changes caused by changes in near-surface storage. As a result, the near-surface water-storage change must be carefully modeled, considering the detailed local topography at each station, and removed prior to evaluating the signal caused by dewatering. Another source of gravity change is changes in the gravity effect owing to water stored in the Grizzly Gulch Tailings Impoundment (fig. 2) as a result of water level changes; this has a potentially large influence at nearby stations, in particular station No5. Subsurface excavations made to house experiments may also have caused measurable gravity change. As with near-surface water storage, the gravitational effect of this variation can be modeled and removed. Such modeling is outside the scope of this report but will be required for future interpretation.

The variation of gravity change from 2010 to 2014 does not appear to be spatially correlated with dewatering of the deeper mine levels (fig. 7). Gravity at all stations increases over the 4 years, from 0.6 microGal at Pronto to 40.6 microGal at Mammenga. The latter is at the highest elevation and is therefore more sensitive to a larger area than stations at lower elevations. Most of the remaining stations exhibit gravity increases between 6 and 18 microGal, with no distinct spatial pattern associated with the mine, local topography, or other factors.



EXPLANATION

- + Gravity station missing 2010 or 2014 data
- 0.6 Pronto Change in gravity, 2010 to 2014
- Change in gravity, 2010 to 2014, in microGals
- 0 - 10

 11 - 20

 41 - 50

Figure 7. Map showing the spatial variation of gravity change from 2010 to 2014.

Status of the Gravity Network

As of 2014, five stations in the original 2007 network have been destroyed (BullockExpress, HomestakeMansion, Mollman, Opencut, and RooRanch). The first three of these were replaced by nearby stations in subsequent years (fig. 2). One station established in 2011 (RTentrance) that was destroyed has not been replaced. The vertical profile established along the Ross shaft in 2011 has not been revisited because the shaft is being refurbished and access is restricted. Expected completion is 2017, at which time stations Ross-800, Ross-2000, and Ross-4100 should be able to be reoccupied. All other subsurface gravity stations (Ross-300, Yates-4100, Yates-4850, and 4winzewye) are permanently marked and should be able to be reoccupied in future years.

Local Hydrologic Data

The water level within the mine excavations has been monitored since pumps on the 8000 level were turned off on June 10, 2003. Water levels rose continuously until mid-June 2008, at which time sustained pumping to dewater the mine resumed (fig. 8, data provided by the SURF). Between 2008 and 2012, water levels dropped from about 4,530 ft BLS to 5,900 ft BLS and have remained steady at between 5,900 and 5,700 ft BLS since then. Water levels are expected to be maintained at about this level unless future experiments are established at deeper mine levels.

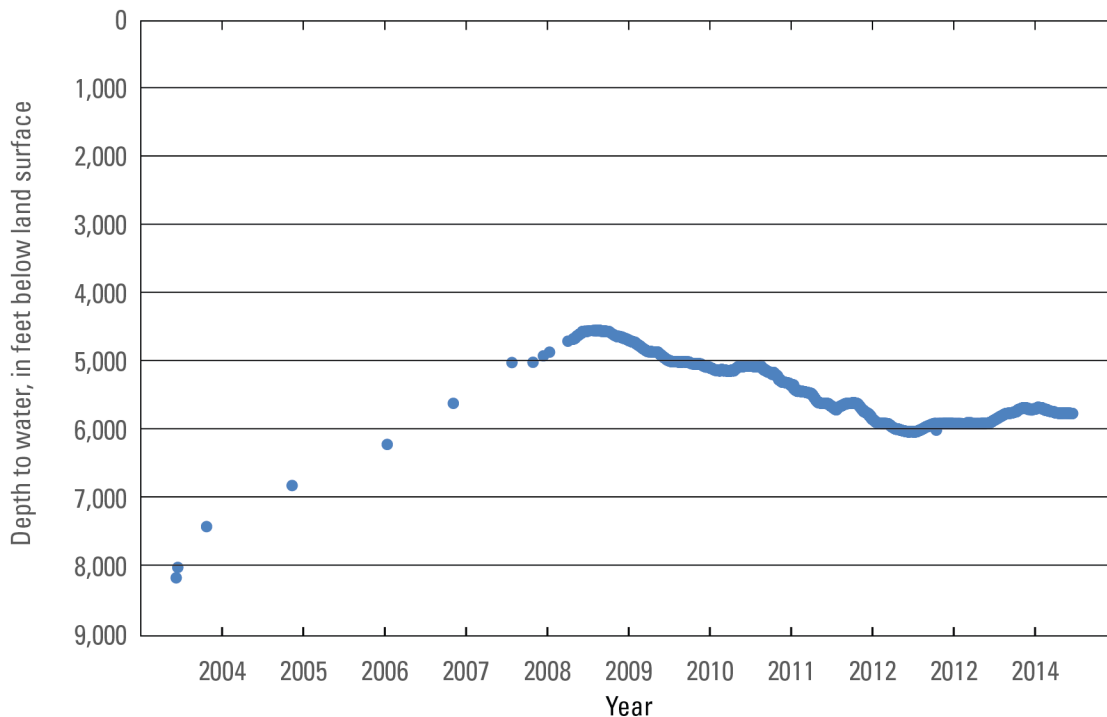


Figure 8. Graph showing Homestake Mine, South Dakota, water levels in the Ross shaft measured by the Sanford Underground Research Facility.

Variation in streamflow provides an indication of terrestrial water stored in the near-surface; when storage is greater, base flow is generally higher. Although two streamgaging stations are located near the SURF, no stations with periods of record concurrent with the gravity measurements are located directly along Whitewood Creek or its tributaries Whitetail Creek and

Yellow Creek, which pass directly over the deeper levels of the Homestake Mine. The two nearest stations with concurrent records are Deadwood Creek at Central City, SD (USGS station 06436165) and Bear Butte Creek near Deadwood, SD (USGS station 06437020); their watersheds are to the north and southeast, respectively, of the subsurface mine excavations (fig. 1). During the period of microgravity measurements from 2007 until 2014, a notable feature of the streamflow record at these two stations is a low-streamflow period between the middle of 2011 and early 2013 relative to other years; both the volume of discharge and the annual peak discharge are relatively low in 2012, and the volume of discharge is relatively low in 2013 (fig. 9). Relatively wet winters and larger volumes of spring runoff are observed in 2010 and 2014.

A longer record at station Bear Butte Creek near Deadwood, SD exhibits a notable downward trend in streamflow between about 2000 and 2005 (fig. 10; discussion of trends is in a qualitative sense only, and formal trend analysis has not been performed). There is an increasing trend in streamflow before and after this period. Although this period of decreasing streamflow generally corresponds with the period when pumping in the Homestake Mine stopped, a nearly identical trend is seen in streamflow records throughout the region, including those from much larger watersheds and at distances of hundreds of miles (for example, station Little Missouri River at Camp Crook, SD, USGS station 06334500; data available at http://waterdata.usgs.gov/sd/nwis/dv?site_no=06334500).

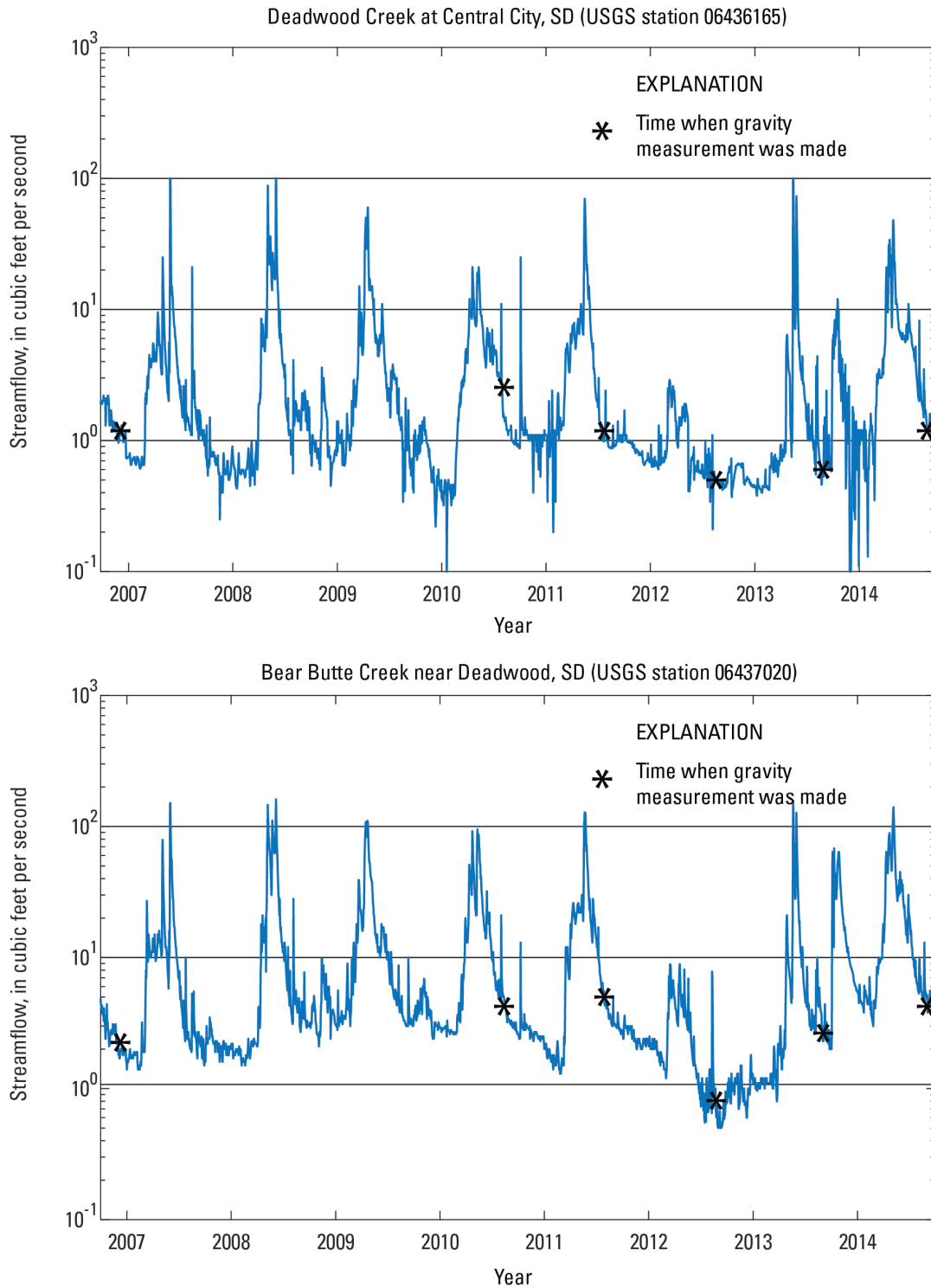


Figure 9. Graphs showing streamflow at stations Deadwood Creek at Central City, South Dakota (06436165) and Bear Butte Creek near Deadwood, South Dakota (06437020) during the period of microgravity measurements, 2007 to 2014.

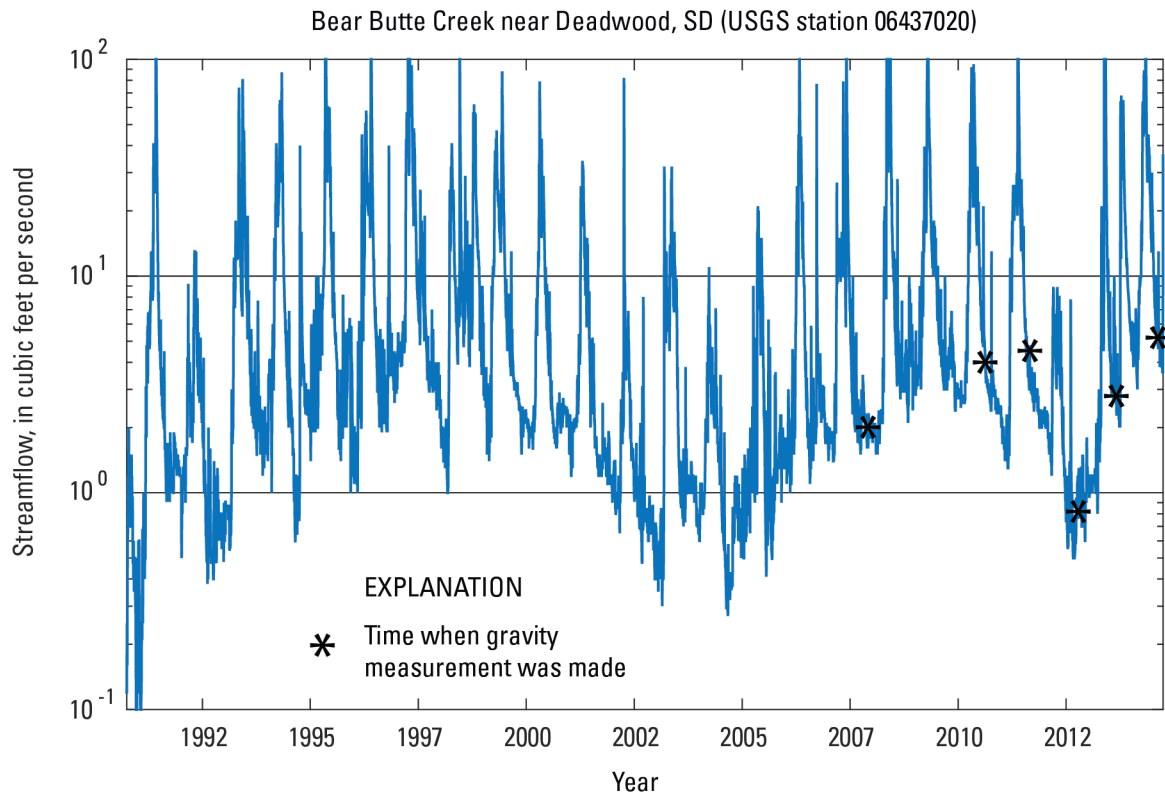


Figure 10. Graph showing streamflow at station Bear Butte Creek near Deadwood, South Dakota (06437020) from 1990 to 2014.

Precipitation data from the Lead, S. Dak., station (394834) of the National Weather Service Cooperative Network (Western Regional Climate Center, 2014) show little in the way of significant trends between 2000 and 2014 (fig. 11). Three months of missing data were interpolated from precipitation rasters provided by the Parameter-elevation Relationships on Independent Slopes Model (PRISM Climate Group, 2014). The period of relatively low precipitation in 2012 and 2013 evident in the streamflow records (fig. 9) is also present in the precipitation record, although similarly dry periods are also present in the early part of the 2000s; this earlier period corresponds with the decrease in streamflow observed between 2000 and 2005 (fig. 11). The period of highest sustained rainfall occurred in 2008 and 2009, when monthly rainfall was 1.5 inches or greater for 23 consecutive months.

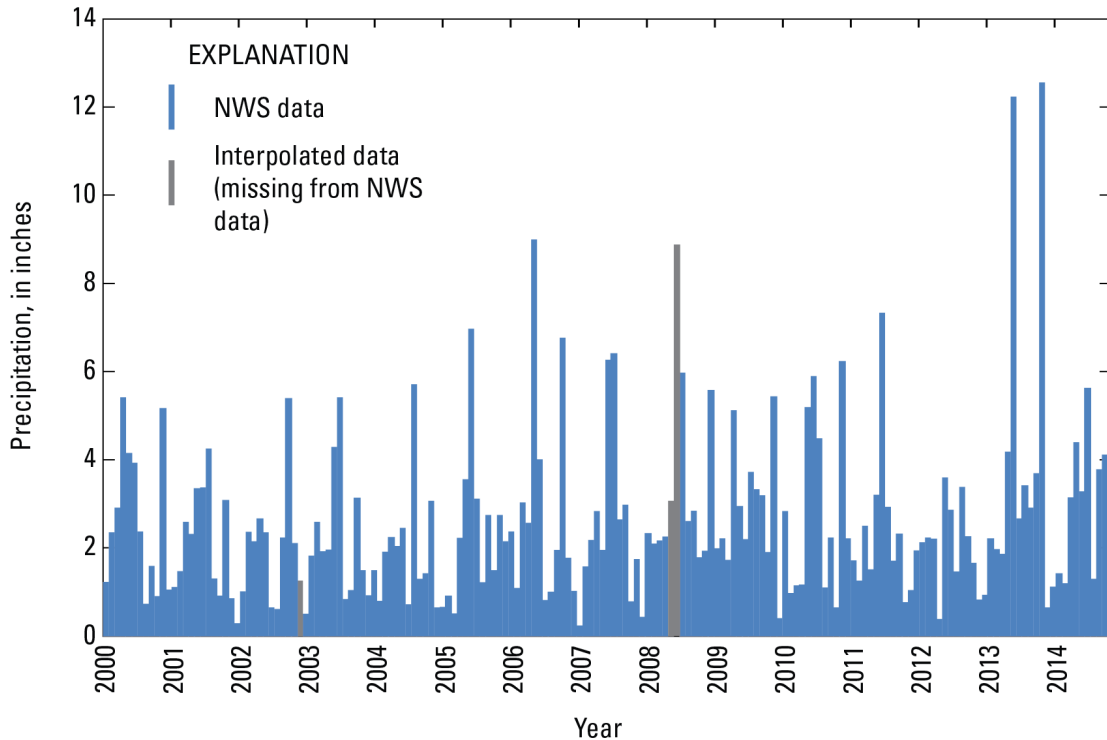


Figure 11. Graph showing monthly precipitation data from the Lead, South Dakota, station (394834) of the National Weather Service (NWS) Cooperative Network. Interpolated data are from the Parameter-elevation Relationships on Independent Slopes Model (PRISM Climate Group, 2014).

Conclusion

Absolute gravity data were collected at 32 stations at and in the vicinity of the Sanford Underground Research Facility in Lead, South Dakota, from 2007 through 2014. Eight stations are located underground at depths from 300 to 4,850 ft BLS; the deepest are 112 to 115 meters above mean sea level. GPS data were used to position each surface station where reliable data could be collected. Subsurface stations were positioned using CAD files provided by the SURF. Each station has a permanent mark and should be able to be reoccupied in the future. During the period of data collection, the water-table elevation in the facility decreased about 1,200 ft, but a corresponding change in gravity was not clearly evident. Although streamflow trends mirror the changes in pumping—streamflow declined when dewatering stopped in 2002 and increased after the mid to late 2000s, around when dewatering resumed—similar trends occur across the region and are probably unrelated to, or a secondary effect of, dewatering. Because gravity is an integrated measurement of all subsurface storage change, including soil moisture, perched and (or) alluvial aquifers, and the regional groundwater-flow system, unwanted signals must be removed from the data. Therefore, in order to evaluate the change in gravity owing to dewatering of the regional groundwater-flow system, near-surface storage change at each station must be estimated.

Data collected from gravity surveys such as these can be used for a variety of purposes. Most relevant to the Sanford Underground Research Facility might be the evaluation and calibration of storage parameters in a groundwater-flow model for the region. Specifically, the change in gravity from dewatering can be predicted by the model and then compared to actual gravity measurements, followed by recalibration of the model as necessary.

References Cited

- Caddey, S.W., Bachman, R.L., Campbell, T.J., Ried, R.R., and Otto, R.P., 1991, The Homestake Gold Mine, an early Proterozoic iron-formation-hosted gold deposit, Lawrence County, South Dakota: U.S. Geological Survey Bulletin 1857–J, 68 p. [Also available at <http://pubs.er.usgs.gov/publication/b1857J/>.]
- Carter, J.M., Driscoll, D.G., and Sawyer, J.F., 2003, Ground-water resources in the Black Hills area, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 03–4049, 36 p. [Also available at <http://pubs.usgs.gov/wri/wri034049/>.]
- Creutzfeldt, B., Güntner, A., Vorogushyn, S., and Merz, B., 2010, The benefits of gravimeter observations for modelling water storage changes at the field scale: *Hydrology and Earth System Sciences*, v. 14, no. 9, p. 1715–1730. [Also available at <http://www.hydrol-earth-syst-sci.net/14/1715/2010/>.]
- DeWitt, E., Redden, J.A., Wilson, A.B., and Buscher, D., 1986, Mineral resource potential and geology of the Black Hills National Forest, South Dakota and Wyoming: U.S. Geological Survey Bulletin 1580, 135 p.
- Driscoll, D.G., and Carter, J.M., 1998, Hydrologic conditions and budgets for the Black Hills of South Dakota, through water year 1998: U.S. Geological Survey Water-Resources Investigations Report 01–4226, 143 p. [Also available at <http://pubs.usgs.gov/wri/wri014226/>.]
- Heise, J., 2014, The Sanford Underground Research Facility at Homestake: *American Institute of Physics Conference Proceedings*, v. 1604, p. 331–344. [Also available at <http://arxiv.org/abs/1401.0861>.]
- Kennedy, J., and Winester, D., 2011, Gravity data from the San Pedro River Basin, Cochise County, Arizona: U.S. Geological Survey Open-File Report 2011–1287, 11 p. [Also available at <http://pubs.usgs.gov/of/2011/1287/>.]
- Kennedy, J., Ferré, T.P.A., Güntner, A., Abe, M., and Creutzfeldt, B., 2014, Direct measurement of subsurface mass change using the variable baseline gravity gradient method: *Geophysical Research Letters*, v. 41, no. 8, p. 2827–2834, doi: 10.1002/2014GL059673.
- Lisenbee, A.L., and DeWitt, E., 1993, Laramide evolution of the Black Hills uplift, *in* Snoke, A.W., Steidtmann, J.R. and Roberts, S.M., eds., *Geology of Wyoming: Geological Survey of Wyoming Memoirs*, v. 5, p. 374–412.
- Mitchell, S.T., 2009, *Nuggets to neutrinos—The Homestake story*: Bloomington, Ind., Xlibris Corporation, 738 p.
- Murdoch, L.C., Germanovich, L.N., Wang, H., Onstott, T.C., Elsworth, D., Stetler, L., and Boutt, D., 2011, Hydrogeology of the vicinity of the Homestake mine, South Dakota, USA: *Hydrogeology Journal*, v. 20, no. 1, p. 27–43, doi: 10.1007/s10040-011-0773-7.
- Pool, D.R., and Anderson, M.T., 2008, Ground-water storage change and land subsidence in Tucson Basin and Avra Valley, southeastern Arizona, 1998–2002: U.S. Geological Survey Scientific Investigations Report 2007–5275, 34 p. [Also available at <http://pubs.usgs.gov/sir/2007/5275/>.]
- PRISM Climate Group, [2014], PRISM Climate Data: Oregon State University Web page, accessed October 10, 2014 at <http://prism.oregonstate.edu>.
- Rahn, P., and Roggenthen, W., 2002, Hydrogeology of the Homestake Mine: *Proceedings of the South Dakota Academy of Science*, v. 81, p. 19–25.
- Redden, J.A., and DeWitt, Ed, 2008, Maps showing geology, structure, and geophysics of the central Black Hills, South Dakota: U.S. Geological Survey Scientific Investigations Map 2777,

- 44 p. pamphlet, 2 sheets, 8 maps, scale 1:100,000 to 1:500,000. [Also available at <http://pubs.usgs.gov/sim/2777>.]
- Schmerge, D., and Francis, O., 2006, Set standard deviation, repeatability, and offset of absolute gravimeter A10-008: *Metrologia*, v. 43, no. 5, p. 414–418.
- Schmerge, D., Francis, O., Henton, J., Ingles, D., Jones, D., Kennedy, J., Krauterbluth, K., Liard, J., Newell, D., Sands, R., Schiel, A., Silliker, J., and van Westrum, D., 2012, Results of the first North American comparison of absolute gravimeters, NACAG-2010: *Journal of Geodesy*, v. 86, no. 8, p. 591–596, doi: 10.1007/s00190-011-0539-y.
- Strobel, M.L., Jarrell, G.J., Sawyer, J.F., Schleicher, J.R., and Fahrenbach, M.D., 1999, Distribution of hydrogeologic units in the Black Hills area, South Dakota: U.S. Geological Survey Hydrologic Investigations Atlas HA-743, 3 sheets. [Also available at <http://pubs.usgs.gov/ha/ha743>.]
- Western Regional Climate Center, [2014], Cooperative climatological data summaries: Western Regional Climate Center Web page, accessed October 10, 2014, at <http://www.wrcc.dri.edu>.
- Zhan G., and Deux, T., 2010, Hydrologic evaluation of post-closure flooding and dewatering of the Homestake Mine: *Mining Engineering*, v. 62, no. 4, p. 64–68.