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FREE-AIR GRAVITY ANOMALY MAP OF ARIZONA [1]

by

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Abstract

On a regional scale, the broad anomaly features on a free-air gravity map indicate the degree to which an area is isostatically compensated. The more local anomalies are related to subsurface mass excesses and deficiencies, such as bedrock or alluvium, and also to surface elevations, such as mountains or valleys. The free-air gravity map of Arizona has anomalies that can be interpreted as being due to these various factors.

Southeastern Arizona appears to be in isostatic equilibrium, and the free-air anomaly zero contour closely outlines the pediment edge of higher density bedrock. The regional free-air anomaly in southwestern Arizona is slightly negative, probably due to the nearby presence of the East Pacific Rise and the San Andreas fault system, and the minus 10 to 20 mgal contour more closely follows the pediment edge in this part of the state.

The free-air gravity anomaly map has practical importance in indicating areas of tectonic stress. Also, in the Basin and Range province of Arizona, the edges of pediments under shallow alluvial cover may be located with a reasonable degree of certainty.

The free-air gravity anomaly values of the stations in the Arizona Gravity Data Base have been mapped and contoured for the state of Arizona. The "Free-air Gravity Anomaly Map of Arizona" (Plate 2, in pocket) has a 10-mgal contour interval, a contour interval twice that of the "Bouguer Gravity Anomaly Map of Arizona" (West and Sumner, 1973). This larger contour interval was necessary because of the steep gradients and high amplitudes of the free-air gravity anomalies. These factors are related to the effect of local variations in the altitude of the gravity stations.

The geoid is the gravitational equipotential sea-level surface of the earth. The geoid is therefore the real, observable gravitational shape of the earth, and broad undulations of the geoid are related to the degree to which the earth is in isostatic equilibrium. Over large areas on an earth that is in isostatic equilibrium, free-air gravity values would tend to be zero. In mountainous areas, it is sometimes difficult to make a comparison of the geoid and free-air gravity anomalies. This report discusses the "Free-air Gravity Anomaly Map of Arizona."

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The map shows a unique correlation between the free-air gravity anomalies and the mountain ranges and valleys in southeastern Arizona. In areas of exposed bedrock, free-air gravity values are almost always positive. The zero contour on the free-air gravity anomaly map closely outlines mapped exposed bedrock as shown on the "Geologic Map of Arizona" (Wilson, Moore, and Cooper, 1969). Considering the variety of sources of gravity data and the broad assumptions made in the gravity corrections and theoretical earth models, the closeness of fit of this correlation was unexpected. The "Free-air Gravity Map of Arizona" shows that the relationship between zero contour and bedrock contact does not occur everywhere but is restricted to the Basin and Range province of southeastern Arizona, an area also known as the Mexican Highlands section of the Basin and Range province.

West of the San Pedro Valley this correlation does not hold; the zero free-air anomaly contour occurs not at the edge of bedrock but definitely on bedrock. The minus 10 to 20 mgal gravity contours provide a better correlation with the bedrock contact. Although some bedrock contacts do have zero free-air gravity values, the consistency of the zero free-air correlation with the bedrock contact seen in the southeast is not seen in other parts of Arizona. Ample gravity data exist in the Tucson and Altar valleys so that it is possible to trace the transition from zero free-air gravity to more negative values. The transitional zone trends approximately along long 110°30' W. south from the Mogollon Rim to Mexico.

The Basin and Range province of central and northwestern Arizona has the same free-air correlation with the bedrock contact as in southwestern Arizona. The White Tank Mountains west of Phoenix have negative values along the edges of bedrock. The lower altitude Gila Bend Mountains and Buckeye Hills have negative free-air values throughout, which is typical in central Arizona where exposed bedrock is generally at lower altitude.

Some areas of the Basin and Range province have thin alluvial cover, and in places there is the possibility of a considerable thickness of volcanic rocks interbedded with the alluvium. These factors could cause some alluvium-covered areas in Arizona to have positive free-air anomalies. Since the distribution of bedrock is known, a correlation of positive free-air values with bedrock is a reasonable indicator of the consistency of the zero free-air contour correlation with the bedrock contact. The distribution of silicic volcanics relative to free-air gravity anomalies is ignored because such rocks commonly have a very low density, often similar in density to alluvium (2.2 to 2.4 g/cm^3). However, there does not seem to be any inconsistency in the free air-outcrop pattern in the rhyolites of the Chiricahua Mountains. The area has a zero free-air gravity anomaly contour at the edge of the mountains.

The Colorado Plateau has a wide range of free-air gravity anomaly values. Areas with negative free-air gravity values correspond to the Holbrook basin, Painted Desert, and Chinle Valley. The strong negative anomaly around the Grand Canyon is due to stations observed along the bottom of the canyon and thus the pattern here is not tectonically significant. Prominent positive free-air anomalies occur over the Kaibab Plateau and Black Mesa. The average free-air value, however, is about zero over the Colorado Plateau.

Basis for Interpreting Free-air Gravity Anomalies

Observed gravity values can be compared with the gravity of a theoretical spheroidal model of the earth that has the same characteristics

of mass, angular momentum, etc. as the actual earth. The gravity on the ideal spheroid is defined by the International Gravity Formula, a mathematical model of sea-level gravity as a function of latitude. This model of the earth lacks the lateral density changes that occur in the real earth, and all the mass of the spheroidal model is below sea level. In order to compare the observed and model earths, a correction must be made upon the observed values of gravity to reduce the values to sea level. In 1924, the International Union of Geodesy and Geophysics agreed on precise dimensions of the earth to define the international ellipsoid, or spheroid. In 1930, this group adopted a corresponding formula for the earth's normal sea-level gravity, g, a relationship known as the International Gravity Formula and written

$$g = 978{,}049\ (1 + 0.0052884 \sin^2\phi - 0.0000059 \sin^2 2\phi)$$

where ϕ is latitude. Additional surface and satellite gravity data accumulated since 1930 is being used by geodesists to refine this formula.

The "free-air gravity effect" is, to a first approximation, the decrease in gravity with distance from the earth's sea-level surface. The mass of intervening material is ignored as if the reading were being made in the "free air." The free-air effect can be readily derived from Newton's law of gravitation

$$g = \frac{GM}{r^2}$$

by differentiation, such that

$$\frac{dg}{dr} = -\frac{2g}{r} \qquad (1)$$

where r is the earth's radius, G is the gravitational constant, and M is the mass of the earth. Equation (1) is used to correct gravity observations that are not made at sea-level elevation.

An observed gravity value (g_{obs}) that is corrected for the free-air effect (FA) may still differ from theoretical gravity (g_{theo}), and this difference, known as the free-air gravity anomaly (Δg_{FA}) can be written

$$\Delta g_{FA} = g_{obs} - g_{theo} + FA.$$

The free-air gravity anomaly map accompanying this report consists of contoured free-air gravity anomaly values.

The free-air reduction removes variations in gravity due to changes in the distance to the center of the earth normalized to sea level. The free-air gravity anomaly is therefore the comparison of the real earth to the model earth. If the earth is not in isostatic equilibrium, the difference between the model and observed earth would also imply deviations from isostatic equilibrium. Free-air gravity anomalies around the earth do vary around zero, supporting the contention that the earth, as a whole, is in equilibrium. The actual figure of the earth, the geoid, can be defined by the free-air gravity of the earth. Published satellite geoids of the Arizona area show a gradual increase in gravity to the north and a decrease to the west, but the ground anomaly patterns in Arizona vary far more abruptly than those on the satellite geoid.

The mapping of the free-air anomaly contour and its correlation with exposed bedrock is an indicator of the regional free-air anomaly in the Basin and Range province of Arizona. If the free-air gravity anomalies are Fourier analyzed (filtered) in order to determine regional gravity anomalies, the regional anomaly will be similar to that regional anomaly

derived by examining the values on the edges of bedrock outcrops over a wide area. The relationship between free-air gravity anomalies and bedrock is significant as shown by the consistency of the pattern over a large region. Local correlations in themselves may not be of importance.

There is a bias in the distribution of the gravity stations in the state. There are more stations in valleys than in mountains for obvious logistical reasons. Roads through mountains are usually placed along passes and through mountain valleys. Therefore, there would be a tendency for the data not to accurately sample the higher altitudes and therefore usually more positive free-air gravity values. The object is to determine the average change in gravity over large areas. Anomalies that occur over short distances (small wavelengths) would be filtered out of the data in favor of anomalies over large distances. The data in southwestern Arizona are generally spaced at intervals of 5 miles or more. Since the mountain ranges are relatively narrow in southwestern Arizona (short wavelength), the bias in the data due to stations in mountain passes and mountain valleys would be diminished.

Tectonic Implications

The form of the geoid and the pattern of free-air gravity anomalies have been used (Kaula, 1972) as evidence for convection, but the evidence is not entirely convincing. Lliboutry (1969) and others point out that it is not necessary to invoke convection to explain plate motion; the more dense lithosphere may simply be gravitationally rafted over the asthenosphere from a ridge crest into a subduction zone. Mantle convection may indeed be responsible for plate motion, but plate motions do not require that the lower density, ascending convecting column be under a ridge or that a higher density, descending column be associated with a trench.

The classic model of sea-floor spreading is seen at the Mid-Atlantic ridge. In the northern part of the ridge there are positive free-air gravity anomalies over the ridge crest and broader, negative anomalies over the flanks. This correlation of positive free-air anomalies with the ridge crest could be interpreted as being related to the spreading rate from the ridge. If material extruding along the crest is moving at a rate in equilibrium with the lateral spreading, the mass as measured by gravity over the ridge, including the higher topography, would be the same as the mass apart from the ridge crest. The East Pacific Rise displays zero average free-air values over the ridge crest and must therefore by this model be in equilibrium. However, at the crest of the slower spreading Mid-Atlantic ridge, excess mass must be accumulating. The flanking free-air lows would result from a balancing isostatic effect created by a depletion of mass in the asthenosphere and a sinking of the overlying surface topography. The negative free-air gravity anomalies over the flanks and the positive anomalies over the crest of the Mid-Atlantic ridge could reflect this phenomenon.

Gravity data over the spreading locations of the spreading East Pacific Rise in the Gulf of California are incomplete and therefore the interrelations of gravity anomalies over the ridge to anomalies in Arizona are not known. If the Basin and Range province of southeastern Arizona has an average zero free-air value and southwestern Arizona is negative, this may be due to the presence of the East Pacific Rise in the Gulf of California. Southwestern Arizona could be out of isostatic equilibrium because of three related factors: thinning of the lithosphere, a lack of sufficient time for the movement of lower density mantle material, and a rise in surface elevation of a sufficient degree to have a total vertical mass distribution equivalent to that required by the theoretical earth.

Southeastern Arizona may be tectonically older and have deeper structural basins than southwestern Arizona. The region may have reached equilibrium, having gone through a process now affecting southwestern Arizona.

The existence of gravity equilibrium does not require any dynamic process in the earth's interior, only that any processes that do exist are operating at a rate at which changes in elevation, mass movement at depth, and so forth are in mutual equilibrium. In this respect, free-air gravity anomalies cannot be used as proof of mantle convection.

Vening Meinesz (Heiskanen and Vening Meinesz, 1958) has studied free-air gravity anomalies in the Southwest Pacific and found very large negative values (-200 to -300 milligals) over relatively narrow zones over the deep ocean trenches associated with subduction zones. Broad, positive values (+100 to +150 milligals) adjoin the trenches, often over the island arcs of the region.

Conclusions

The basic assumption in this study is that the International Gravity Formula closely approximates the geoid in Arizona. Observations over the earth have indicated that this formula is reasonably valid. Recently other formulas based on satellite data have been advocated. Regardless of the formula applied, the relative patterns in free-air gravity discussed in this report from southeastern to southwestern to northern Arizona would remain. The location of the intermediate zones would not be altered. What could change is the trend in absolute values of free-air gravity from west to east and south to north.

There is good evidence that the lithosphere of southwestern, central, and northwestern Arizona is fundamentally different from the lithosphere in southeastern Arizona. The Colorado Plateau and southern Arizona east of long. 110°30' W. appears to be dominated by an average free-air value of zero, whereas other portions of the state appear to have a general negative character. The difference in average anomalous values is not large. It is uncertain as to whether areas characterized by negative free-air values are more tectonically unstable than areas of zero average free-air gravity. The Basin and Range province in Arizona is characterized by high heat flow and is underlain by a shallow, low-velocity, low-density upper mantle. Equilibrium could be actively sustained in areas of zero free-air gravity by dynamic processes at depth. It is also possible that active dynamic processes could be causing large areas to be out of equilibrium as indicated by the negative free-air gravity. These areas could also be undergoing passive tectonism reflecting the result of previous dynamic processes now quiescent.

The average elevation is higher in the Colorado Plateau and southeastern Arizona areas of zero free-air gravity. If passive forces are acting in the areas of negative free-air gravity, this could imply that those areas will undergo an increase in elevation accompanied by lateral flow in the asthenosphere until an equilibrium in mass is reached.

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