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Comparison between Crustal Density and Velocity Variations in Southern California

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Abstract. We predict gravity from a three-dimensional V_p model of the upper crust and compare it to the observed isostatic residual gravity field. In general this comparison shows that the isostatic residual gravity field reflects the density variations in the upper to middle crust. Both data sets show similar density variations for the upper crust in areas such as the Peninsular Ranges and the Los Angeles basin. Both show similar variations across major faults, such as the San Andreas and Garlock faults in the Mojave Desert. The difference between the two data sets in regions such as the Salton Trough, the Eastern California Shear Zone, and the eastern Ventura basin (where depth to Moho is <30 km), however, suggests high-density middle to lower crust beneath these regions. Hence the joint interpretation of these data sets improves the depth constraints of crustal density variations.

Introduction

Spatial density variations generated by crustal geological processes in southern California (Fig. 1) can be modeled using a variety of data sets, including gravity and seismic velocities. To examine the ability of geophysical data to resolve the 3-dimensional (3-D) distribution of density variations, we analyzed two independent data sets, the isostatic residual gravity map and a 3-D crustal velocity (V_p) model [*Hauksson*, 2000]. The two data sets are complementary in that velocity data provide constraints on subhorizontal interfaces whereas gravity data image steep boundaries well.

To provide detailed understanding of the 3-D density distribution we compared predicted gravity from the 3-D velocity model for the uppermost 10 km of the crust with the observed isostatic residual gravity field. This comparison makes it possible to discern which anomalies reside in the upper crust and to infer that the long-wavelength differences are caused by density variations in the lower crust. Thus we are able to provide independent depth constraints for the crustal density anomalies beneath southern California.

We use the results of this joint interpretation of isostatic gravity, 3-D V_p model, and depth to Moho to suggest a general inverse relationship between lower crustal density and thickness. This relationship applies to most areas of Southern California except in active tectonic areas, such as the northern end of the Salton Trough and the eastern Ventura basin.

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Methods

Gravity data were corrected for earth-tide, instrument drift, elevation, latitude and terrain, and then reduced to Bouguer anomalies using a reduction density of 2670 kg/m^3. An additional isostatic correction using a sea-level crustal thickness of 25 km, a crustal density of 2670 kg/m^3, and a mantle-crust density contrast of 400 kg/m^3 was applied to the gravity data to remove long-wavelength gravitational effects of isostatic compensation of the crust due to topographic loading. The resulting field is termed the isostatic residual gravity anomaly and reflects, to first order, density variations within the middle and upper crust (Fig. 2a)[*Simpson and others*, 1986]. The uncertainty in the measurements used to create the isostatic residual gravity map is on the order of 0.1 mGal and can be as high 5 mGal in extreme cases.

Other methods, such as polynomial fitting or by wavelength filtering, are often used to calculate residual gravity anomalies but those methods eliminate all wavelengths longer than some threshold, whether or not they are related to topographic features. In particular, long-wavelength anomalies entirely caused by lateral variations in crustal density will be eliminated by these techniques. Even though base levels may change, short-wavelength residual anomalies (<100 km) produced by upper-crustal sources tend to be little changed by the use of different isostatic models in California [*Jachens and Griscom*, 1985] which vary only by 10 percent and are long wavelength in character.

The 3-D V_p model is determined from local earthquake data on a 15 by 15 km horizontal and 4 km depth grid, as described by *Hauksson* [2000]. We predicted the gravitational effect of this V_p model, assuming that density can be related to velocity in a straightforward way. For velocities <5.5 km/s, we used the density-velocity relationship of *Gardner and others* [1974] that was empirically derived from sedimentary rocks. The Gardner relationship is nearly identical to the density-velocity relationship obtained from a handful of wells in Los Angeles and San Fernando basins [*Langenheim and others*, 2000]. For velocities >6 km/s, the relationship of *Christensen and Mooney* [1995] developed for crystalline rocks at a depth of 10 km was utilized. To determine the predicted gravity, we calculated the gravitational effect of the volume between each layer of the 3-D V_p model, starting with the ground surface to a depth of 10 km (Fig. 2b).

The average standard error in the V_p model (about 0.1 km/s) corresponds to an uncertainty of ~100 kg/m^3 in density, simply based on the density-velocity relationships. An equivalent error in mGal depends on the geometry and depth of the source. For an infinite slab 1 km thick, an error of 100

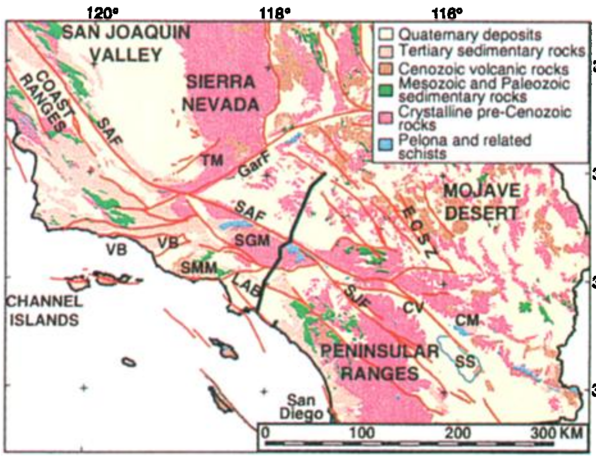

Figure 1. Simplified geologic map of southern California. Thick black line is the LARSE high-resolution seismic profile. Abbreviations: CM, Chocolate Mountains; CV, Coachella Valley; ECSZ, Eastern California Shear Zone; GarF, Garlock fault; LAB, Los Angeles basin; SAF, San Andreas fault; SGM, San Gabriel Mountains; SJF, San Jacinto fault; SMM, Santa Monica Mountains; SS, Salton Sea; TM, Tehachapi Mountains; VB, Ventura basin.

kg/m^3 would give rise to 4.2 mGal error (regardless of depth). For a cylinder 1 km thick with a radius of 1 km and located just beneath the topographic surface, an error of 100 kg/m^3 would give rise to 2.5 mGal error. This same cylinder buried at 6 km depth would give rise to 0.01 mGal error. Thus, assuming our velocity-density relations are correct, the fit between the predicted and isostatic residual gravity should be good, presuming we are mostly interested in anomalies larger than 5 mGal.

The predicted gravity field is generally smoother than the isostatic residual gravity field because the V_p model was created using a 15 km horizontal grid and incorporates damping of large velocity variations. In comparison, the gravity station coverage merits a finer grid of 2 km over the entire region of the isostatic residual gravity map. As discussed above, gravity data are more sensitive to shallow volumes whereas the uppermost layer of the V_p model represents an averaging of velocities from the surface to depths of 4 km. Thus, some of the smaller, shallower, or narrower features seen in the isostatic residual gravity data are not imaged by the V_p model.

Results

Our results confirm that the isostatic residual gravity field generally reflects sources in the upper and middle crust for

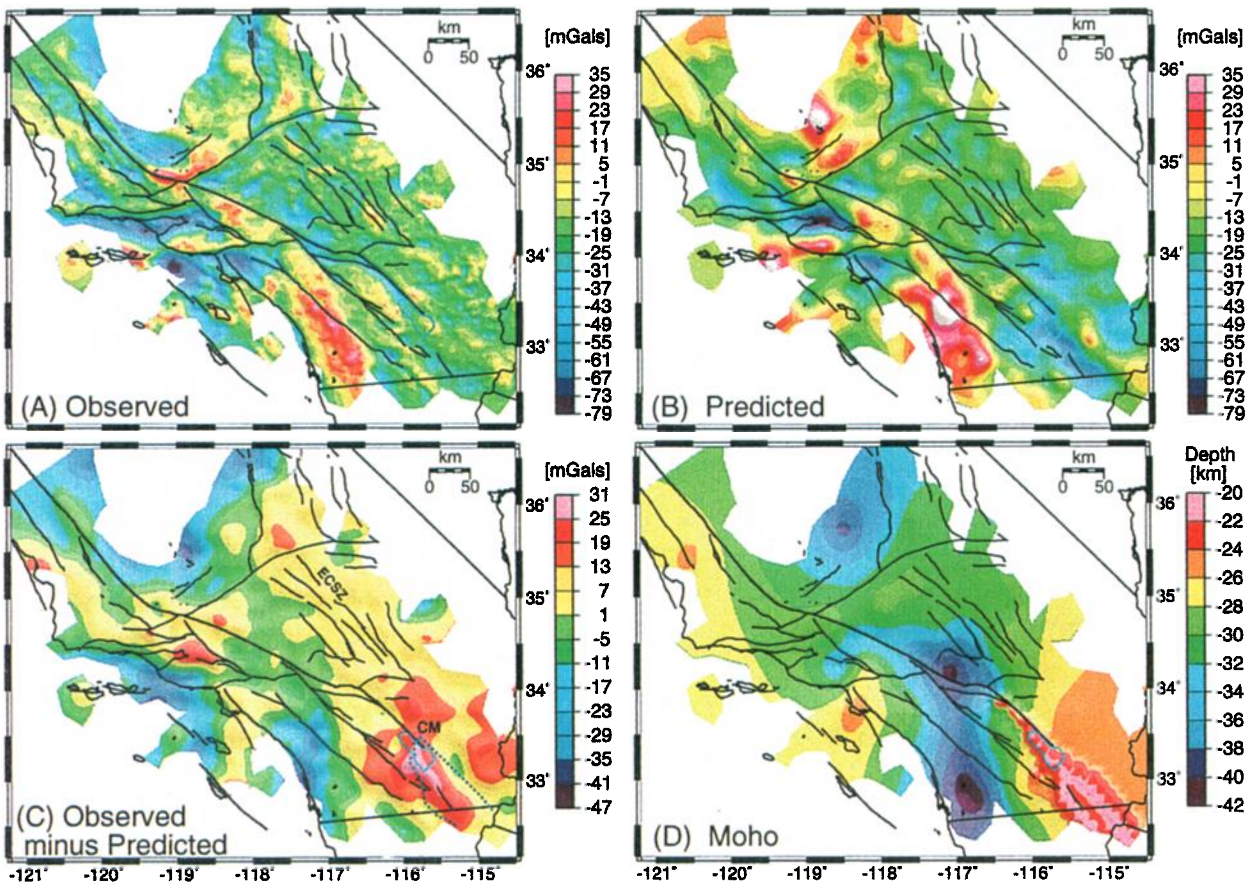

Figure 2. (A) Observed isostatic residual gravity field. (B) Predicted gravity field from 3-D V_p model. Both grids are trimmed to areas where ray density is sufficient for the V_p model. See *Hauksson* [2000] for details. (C) Difference between the isostatic residual gravity and predicted gravity fields, filtered to enhance longer-wavelength components caused by lower crustal density variations. Note the large positive anomaly centered over the Imperial Valley that coincides in part with the absence of crystalline basement based on seismic-refraction data [*Fuis and others*, 1984], shown by the dotted blue line. (D) Depth to Moho [*Magistrale et al.*, 2000].

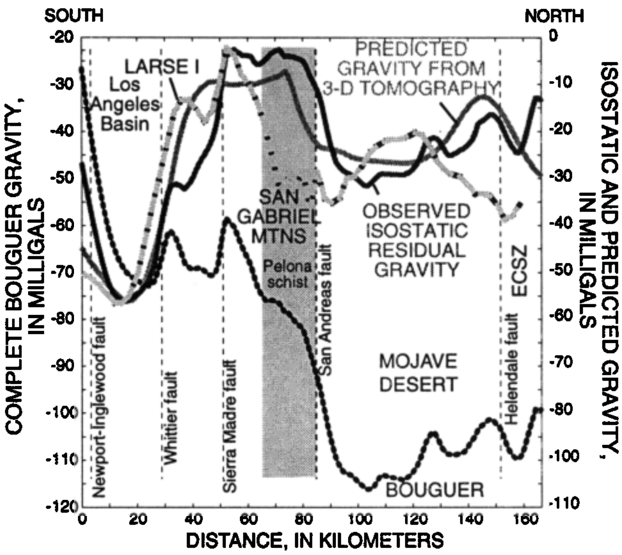

Figure 3. Isostatic residual gravity and predicted gravity from 2-D LARSE and 3-D V_p models across LARSE I line. The curve labeled "LARSE I" is calculated for the upper 10 km of the 2-D model from *Fuis et al.* [2000]. Bouguer gravity curve is included for reference.

much of southern California. The predicted gravity (Fig. 2b) agrees well with the observed isostatic gravity (Fig. 2a) except for the offshore regions and along the edges of the 3-D V_p model. Both the predicted and observed gravity fields are positive over the western Peninsular Ranges, the San Gabriel, Santa Monica, and the Tehachapi Mountains. The predicted gravity matches the strong isostatic gravity gradient between the western and eastern Peninsular Ranges.

Similarly, both isostatic and predicted gravity indicate large-amplitude gravity lows over the Los Angeles and Ventura basins. The Ventura basin has a somewhat stronger predicted gravity low than the isostatic low, suggesting high-density basement at greater depths and/or that the density-velocity relationships are not correct for this basin. For example, high pore pressure reduces seismic velocities but has a negligible effect on density (Eberhart-Phillips and Michael, 1993). High V_p/V_s for the upper 5-10 km of the Ventura basin (Hauksson, 2000) supports the presence of high pore pressure in the basin fill. Thus, comparing the observed and predicted gravity fields can give insight into the material properties of the crust.

Some of the larger basins in the Mojave Desert and along the eastern margin of the Sierra Nevada are also successfully identified in both data sets. Exceptions, such as the Coachella Valley, illustrate how higher-resolution gravity can be used to image basin shapes and augment the 3-D V_p model.

Onshore, the largest difference between the two data sets occurs in the Salton Trough, where the 3-D V_p model produces a pronounced linear gravity low that is not mirrored in the isostatic gravity data. Possible explanations for this discrepancy could be (1) inaccurate velocity-density relationships, (2) lower crustal density variations that are not properly removed by the isostatic correction, (3) variations in the density contrast across the crust-mantle boundary, or (4) poor resolution in the V_p model. We favor the presence of lower crustal density variations that require more detailed analysis.

Offshore, the two gravity fields do not agree as well. Predicted gravity values reflect highs along the Channel Islands. The pronounced isostatic gravity lows of the Santa Monica and offshore Ventura basins or the small offshore basins northwest of San Diego are not imaged because of poor seismographic station coverage and relatively few earthquakes offshore.

To quantify differences between the predicted and isostatic residual gravity, we subtracted the predicted gravity from the isostatic residual gravity. To determine the residual difference map, this difference was then upward continued 5 km to enhance the longer-wavelength differences that would be caused by sources in the middle and lower crust (Fig. 2c).

The residual difference map shows a negative anomaly extending from the Sierra Nevada in the north to the Peninsular Ranges in the south. This central density low is flanked by positive anomalies centered over the Salton Trough and the Eastern California Shear Zone (ECSZ) to the east, and beneath the Los Angeles basin and parts of the western Transverse Ranges to the west. The central density low corresponds to the regions where the depth to Moho is unusually deep (36 to 40 km) while to the east and west the lower crust is thinner [*Magistrale et al.*, 2000](Fig. 2d). This observation suggests that areas of active tectonism, excluding the San Andreas fault proper, may be characterized by thinner crust and by higher densities in the lower crust.

The residual difference map shows a large positive anomaly centered over the Salton Trough. This anomaly coincides in part with the absence of crystalline basement (and presumed presence of high-velocity, high-density mafic crust) as interpreted from seismic-refraction data [*Fuis et al.*, 1984] and thin crust (Fig. 2d). The residual gravity high spills onto crystalline basement both west and east of the Salton trough basin, and a residual high of lesser magnitude trends to the northwest, roughly coincident with the ECSZ and with Tertiary and Quaternary volcanism [*Miller et al.*, 2000].

Discussion

In general variations in gravity and velocity data from the upper and middle crust reflect the presence of major basins (except for the Salton Trough) and the surrounding major mountain ranges. The agreement between the isostatic residual and predicted gravity in these regions makes it possible to apply the higher resolution observed gravity to provide improved constraints on basin shapes, as suggested by *Lees and VanDecar* [1991].

In areas such as south of the Salton Sea, where the isostatic and predicted gravity differ, new insights about crustal density variations are gained from comparison of these two data sets. This region is characterized by high heat flow, Quaternary volcanism, frequent shallow seismicity, and vigorous geothermal activity [*Elders et al.*, 1972]. Well information and the 3-D V_p model indicate that the basin sediments extend to at least depths of 4 km. Seismic-refraction data suggest that the sediments may be as thick as 6 km and overlie greenschist-facies metasedimentary basement that extends to depths of 10-16 km [*Fuis et al.*, 1984]. Because there is no isostatic residual gravity low over the Salton Trough area, high-density mafic lower crust must mask the gravity low caused by low-density sediments.

The residual gravity high associated with the Salton Trough extends to the northeast over the Chocolate Mountains (Fig. 2c). Similarly, *Parsons and McCarthy* [1996], who analyzed data from a wide-angle seismic transect, found that the high velocity layer (V_p 6.8 km/s) between 15 and 22 km beneath the Salton Trough extends to the northeast, outside the Salton Trough, where it pinches out at the Moho. The residual gravity high also extends to the northwest, toward the San Jacinto fault and approximately coincides with a broad region of high heat flow [*Lachenbruch et al.*, 1985].

We have also compared the isostatic gravity with predicted gravity from a high resolution 2-D crustal velocity model along the Los Angeles Regional Seismic Experiment (LARSE) I line [*Fuis et al.*, 2001]. The predicted gravity from the 3-D V_p model matches well with the isostatic gravity along the transect (Fig. 2c; Fig. 3). In contrast, analysis of gravity data and 2-D seismic velocities along the LARSE I transect suggests that the velocities of the 2-D model are too slow for the upper crustal rocks of the San Gabriel Mountains relative to those in the Mojave Desert and thus do not successfully predict the observed gravity along that part of the transect (Fig. 3)[*Langenheim*, 1999]. The disagreement between the predicted gravity from the Fuis model and the isostatic gravity could be caused by the non-uniqueness in the LARSE I 2-D velocity model or by anisotropy in the Pelona schist, which would affect the LARSE results more than the 3-D V_p model or gravity data. The maximum anisotropic change in V_p of 0.8 km/s, caused by foliation of the Pelona schist [*McCaffree Pellerin and Christensen*, 1998], is sufficient to explain the difference in the gravity signature.

Zhu [2000] interpreted the gravity gradient centered over the San Andreas fault to reflect a deepening of the Moho north of the San Andreas fault. The predicted gravity from the 3-D V_p model indicates a gravity high of similar amplitude (within the resolution of the model) in the same position as the isostatic gravity high (Fig. 3). Most of the San Gabriel Mountains gravity high can therefore be explained by higher-density upper crustal rocks, and a density step at Moho depths [*Zhu*, 2000] is not required by the gravity data.

Conclusions

The results of this study demonstrate a close correlation between the isostatic residual and predicted gravity from a 3-D V_p model down to depths of 10 km. Jointly the models provide constraints on the depth of density anomalies in the crust of southern California. The overall agreement demonstrates that the sources of most isostatic residual anomalies are located in the upper and middle crust. At lower crustal depths, negative density anomalies are imaged over the Sierra Nevada and the western Peninsular Ranges and coincide with the region of deepest Moho in southern California. These areas are flanked by positive density anomalies that occur in the Salton Trough, ECSZ, western Transverse Ranges, and Los Angeles basin, suggesting high-density lower crust. In some regions, the higher-resolution isostatic residual gravity map can be used to map major geological features such as sedimentary basins and thus complement and improve available 3-D V_p crustal models.

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