GRAVITY SURVEY AND INTERPRETATION OF BOUGUER ANOMALIES IN THE CAMPIDANO GEOTHERMAL AREA (SARDINIA, ITALY)*

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Abstract—A gravity survey of the Campidano geothermal fields and surrounding region was conducted in 1981. It covered an area of 1900 km² and included 952 uniformly distributed stations. The Bouguer anomaly is generally negative within the Campidano graben, reaching -10 mgal in the central zone, whereas a positive Bouguer anomaly prevails outside the graben, exceeding 20 mgal in several areas. The gravity data were interpreted using spectral analysis and two-dimensional models, to determine the thickness of sediments and andesitic volcanics within the graben. The total thickness of these formations reaches 3000 m in the centre, but is reduced elsewhere, especially towards the sides of the graben. The thermal springs on both the eastern and western sides of the graben are associated with residual positive anomalies and are near very steep gradients in the Bouguer anomaly.

INTRODUCTION

The geological and structural features, the presence of a large number of surface hydrogeothermal manifestations and their geochemical characteristics indicate that the island of Sardinia (Fig. 1) is one of the most promising regions in Italy for exploitation of geothermal resources. The increasing need to find new and renewable energy sources has stimulated interest in this island, especially in the Campidano graben (in the south) and Logudoro area (in the north).

Research is at an advanced stage and the first results can be synthesized as follows:
(i) maximum heat flow in the Campidano graben is 4.0 H.F.U. (Loddo et al., 1982),
(ii) the distribution of deep temperatures suggests values near 100°C at depths between 1.0 and 1.5 km (Panichi and Squarci, 1982).

Unfortunately there are not enough thermal and heat flow data at present to compile a reliable geothermal map for assessing the potential of the geothermal resources.

A gravity survey was carried out in the Campidano graben prior to drilling a new series of geothermal boreholes. The gravity anomaly maps are shown in this paper (Figs 2–4). The main structural features are analysed qualitatively; the maps are also interpreted quantitatively by the spectral analysis technique and by means of two-dimensional models, along sections across the Campidano graben. This survey has improved the knowledge of the regional geologic framework and the underground structure and revealed a close relationship between the local gravity anomalies, structural trends and several geothermal areas.

GEOLOGIC SETTING

Sardinia has a Paleozoic basement, consisting mainly of granitic metamorphic rocks; its western sector is intersected by a roughly N–S trending Tertiary Rift (Sardinian Rift) containing the Campidano graben (Fig. 1).

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The Rift is a deep, wide depression lying between the Paleozoic blocks of Nurra, Iglesiente-Sulcis and the eastern half of the Island; it is filled by volcanics (mainly andesite, ignimbrite and rhyodacite) and Oligo-Miocenic marine and continental deposits (Pala et al., 1982a).

The volcanic units of the Rift, reaching a maximum thickness of at least 1000 m, belong to the back-arc volcanism, that evolved during the drift and subsequent rotation (Middle–Upper
Gravity Survey of Campidano Area, Sardinia

Oligocene–Burdigalian) of Sardinia from the Gulf of Leone up to its present position. The volcanic rocks generally overlie the Paleozoic basement and Mesozoic limestones (Nurra), or Eocene sediments (Sulcis, Campidano, Trexenta). Upper Oligocene–Messinian marine and fluvial–lacustrine deposits (conglomerates, sandstones, tuffites, marls, limestones and clays), about 1000 m thick, are interbedded with, or overlie, the volcanic rocks.

The Campidano graben, whose limits are the Gulfs of Oristano and Cagliari, extends in the southern part of the island (Figs 1 and 2). The boundary faults in the graben have maximum throws up to 3000–4000 m. The depression is filled by a Pliocene–Quaternary sequence (800–1000 m thick) mainly composed of continental sediments interbedded with basaltic lavas. All these units lie in discordance on the Oligocene–Miocene volcanic–sedimentary deposits of the Rift. Four boreholes drilled by SAIS and AGIP within the Campidano area did not reach the Paleozoic basement; three of them (OR 1, 1800 m; OR 2, 1700 m; AGIP, 2400 m) ended in the Oligocene–Lower Miocene sediments or volcanics; borehole CI reached a depth of 1700 m, ending in Eocene continental deposits (clays and sandstones). The depth of the basement is consequently still unknown and the occurrence of Mesozoic limestones above the Paleozoic crystalline rocks has still to be proved. From a structural point of view, the geophysical and
geological data lead us to distinguish three main basins in the Campidano graben; from north to south these are: Oristano, S. Gavino and Cagliari basins. They are bounded by sills or structural highs, whose overall features were identified in Trudu (1963).

The main hydrothermal manifestations of Sardinia occur for the most part on the margins of the Tertiary Rift, along the major faults. They are prevalently chlorinated waters with temperatures of 45–78°C and up to 50 l/s of discharge. Sodium bicarbonate (rich in CO$_2$) springs occur along the post-Miocene boundary faults in the Campidano graben. CO$_2$ is connected with a limestone thermal metamorphism; on the contrary, the watershed area and the deep hydrological circulation seem to be represented by the Paleozoic basement (Bertorino et al., 1982; Caboi et al., 1982; Caboi and Noto, 1982; Dettori et al., 1982; Pala et al., 1982b). The hydrological role of the volcano-sedimentary sequences of the rift and graben, up to now considered only as an impermeable cover, has still to be clarified.

The main problems in the Campidano area are: (i) the depth of the Paleozoic basement, (ii) the structural relationship between each of the three above-mentioned basins, (iii) the distribution and subsurface morphology of the andesitic volcanics and (iv) the trend of the major faults that border and intersect the graben area, with special reference to hydrothermal circulation.
GRAVITY SURVEY

Several geophysical surveys, including gravity and magnetic (Trudu, 1953, 1961, 1962, 1963), geo-electrical (Marchisio et al., 1982), magnetotelluric (Finzi Contini, 1982) and seismic prospectings (Martinis, 1969; Guerra, 1981), have been concerned directly or indirectly with the Campidano graben. There are not enough data, however, to make a quantitative analysis of the graben structure, although the information available on the southernmost part is sufficient.

The gravity survey recently carried out in the Campidano covers all the area from Latitude 39°17′ N to 39°45′ N (Fig. 2). The measurements were made in 952 stations, with a density of 1 station every 2 km, using a LaCoste & Romberg model G gravimeter (No. 351) with a scale constant $K = 1.06 \text{ mgal/} \text{div}$ and instrumental drift of less than 0.05 mgal/day. The reference network consists of 12 stations of the gravity survey of Sardinia (Trudu, 1962). Elevation of our stations was determined by trigonometric levelling using a AGA model 14 geodimeter and a Wild model 12 theodolite. The Italian Military Geographic Institute bench-marks were also utilized.

The mean estimated error is about 0.03 mgal for the gravity measurements and 0.2 m for the elevation.

To obtain the Bouguer anomaly, all the usual corrections were applied to the observed gravity. In order to obtain more reliable results and highlight the pattern of the structure, the densities used for these corrections were obtained on the basis of a lithological evaluation and
of measurements made on rock samples. The gravitational effect of the terrain was assessed up to Hayford zone L. This distance is sufficient for the limited area surveyed and for the moderate topographic relief. The mean estimated total error for the Bouguer anomaly is about 0.1 mgal. Absolute, residual and regional Bouguer anomaly maps were drawn by a computer program on the basis of the methods outlined by Hessing et al. (1972) and Bolondi et al. (1977). The resulting Bouguer anomaly map is shown in Fig. 2.

BOUGUER MAP: DESCRIPTION AND INTERPRETATION

The Bouguer anomaly map (Fig. 2) is characterized by:

1. A large negative anomaly, which trends approximately NW - SE (similar to the graben axis and the main structural features of the island) and consists of a sequence of lows separated by small gravity highs. From the structural point of view, the gravity lows are related to the thickest sectors of the graben Tertiary fill, prevalently Miocene - Pliocene sediments. The lows coincide with the areas in which the top of the Paleozoic basement is deeper. The maximum depth of the top of the basement is probably near S. Gavino. On the other hand, near Serramanna, in correspondence to a small gravity high, the basement seems to be uplifted with respect to the structural low of the Gulf of Cagliari.

2. The contour lines on the western border are oriented parallel to the graben axis for the entire region. The horizontal gravity gradients show significant variations that can be related to the gradual stepwise morphology dipping towards the central part of the depression.

3. The isoanomalies on the eastern border are, also, generally oriented parallel to the graben and are regularly spaced; in the Monastir and Sanluri areas, on the contrary, the gravity gradients are unusually high and in the southwestern boundaries of Sardara the gradient reaches a maximum.

4. A gravity low marks the wide Miocene sedimentary basin of Trexenta. The southern boundary of this low shows a gentle slope and, consequently, small gradients only. A fault and/or a flexure directed SW - NE and perpendicular to the main structural framework may exist in this area, forming the lateral contact between the andesitic volcanics and the Miocene marly formation.

REGIONAL AND LOCAL GRAVITY ANOMALIES

The distinction between regional anomalies, related to the deep events, and local anomalies of shallow origin, is a useful means of defining the structural features outlined in the Bouguer map. This procedure also facilitates the qualitative analysis of the depth range of the different anomalies and simplifies their quantitative interpretation.

The distinction between local and regional anomalies is a very delicate procedure in gravity studies; there are several mathematical and empirical methods available for this purpose and the choice is essentially subjective. We chose a two-dimensional filtering method which, according to several authors (Fuller, 1967; Bozzi Zadro and Caputo, 1968; Bath, 1974) seems to offer a reasonable degree of objectivity and is also very effective for anomaly resolution.

On the basis of the general shape and wavelengths of the anomaly shown in the Bouguer map, several filtering tests were made using the following cut-off frequencies: $\omega = \frac{2\pi}{5}; \frac{2\pi}{10}; \frac{2\pi}{15}; \frac{2\pi}{20}$ km$^{-1}$. Analysis and comparison of the various residual and regional gravity contour maps led to a qualitative evaluation. In the $2\pi/5$ km$^{-1}$ gravity residual map, the anomalies have no great structural significance because they refer to shallow sources and/or to the superficial part of the deeper geological structures. The $2\pi/10, 2\pi/15$ and $2\pi/20$ km$^{-1}$ residual maps are rather similar as regards shape and size of the anomalies. The $2\pi/15$ km$^{-1}$ residual map was thus chosen for the qualitative interpretation in order to analyse the characteristics and structural lines of the graben. The contour lines of the regional map (Fig. 3)
was assessed up for the anomaly is about 1.06 km by a computer method (Baldi et al., 1977).

The lows separated related to the graben can be uplifted by an axis for the northern and southern area of the graben. The positive gravity trend from the graben centre towards the SE and NW is probably due to very deep structures.

The residual map (Fig. 4) also shows the wide low which characterizes the original Bouguer map, forming an elongated NW – SE structure in the central part of the graben with a clear N – S distortion of the axis approximately between Villacidro and Samassi. Campidano area can, therefore, be divided into two seemingly different parts, the southern region having a more complex gravity pattern. There is a sequence of lows and highs in the southern region that cannot be observed in the northern region of the graben: this different pattern seems to be caused by tectonic discontinuities running north – south, dividing the depression into a series of blocks which lower or raise the basement, with consequent thickening or thinning of the Tertiary volcanic – sedimentary sequence. This hypothesis is supported by the magnetic discontinuities shown in the aeromagnetic map (Cassano et al., 1979) and, in part, by the surficial geological evidence. The low in the eastern region, in particular, coincides with the elongated basin of the Serrenti – Nuraminis marshes, whose Miocene formations, mainly represented by recent stratigraphic sequences, have very steep slopes, forming a syncline, lowered by a series of faults.

The gravity high between Villasor, Serramanna and Samassi could, on the basis of the above-mentioned block model, be interpreted as a structural high. There is little geologic evidence, however, except for some wide terraces on the Samassi Formation (this unit, here in Pliocene continental facies, has a maximum thickness of 200 m and overlies the Miocene sediments). We could ascribe this gravity high to the absence of the Pliocene – Miocene sequence in some layers. Borehole Cl, drilled on the southern border of the high, encountered no Lower Pliocene or Upper Miocene deposits within the stratigraphic sequence of Villasor. Assuming that the Miocene sequence north of Villasor was subjected to an intense erosion before the deposition of the Samassi Formation, then the high could indicate an uplift of Lower Miocene deposits only. The block sequence between S’Acquacotta and Villasor presents a large low corresponding to a wide alluvional plain. Steep westward gravity gradients clearly reveal the S’Acquacotta fault. Two gravity highs north and south of Vallermosa correspond to the Paleozoic schistose outcrops, associated subordinately to andesites. The highest gradient value corresponds to the fault related to the hydrothermal manifestation of S’Acquacotta (48°C; rich in CO₂).

The steep gravity gradient between the Serrenti – Nuraminis low and the above-described high clearly reveals the eastern main fault of the graben and the local structure. The main feature of northern Campidano graben is the large NW – SE gravity low of S. Gavino (25 km in length), which can be correlated with the general geologic framework of the graben. Further north, the main structural lines of the graben are directed N – S, as in the southernmost zone.

The gravity highs in the Guspini area (west of the graben) are clearly related to the granitic-
schistose basement. In addition, the small gravity gradients indicate a gradual lowering of the basement towards the centre of the graben.

A steep horizontal gradient near Sardara corresponds to the eastern main fault and the gravity high coincides with the outcrops of the schistose basement. The perfect alignment of the isopanomalies and of the E-W faults limiting the basement north and southwards has already been mentioned. Near the intersection between the main fault and the W-E fault, located north of S. Maria de Is Acquas, are some hydrothermal manifestations (55°C; rich in CO₂). Finally, the gravity low near Mogoro may provide new data on the thickness of the Oligocene–Miocene and Pliocene sediments (Samassi formation) and on basement depth beneath the thin basaltic cover.

QUANTITATIVE INTERPRETATION

The elongated structure of the graben and the regular and parallel trend of the contour lines has suggested an interpretation in terms of two-dimensional masses. Due to the paucity of geophysical and structural data, particularly with regard to the depth of the basement (never met by drilling) it is impossible to construct models that totally reflect the deep geological situation.

We have therefore tried to make a direct interpretation using the spectral analysis technique, before constructing a model for defining depth and thickness of the various units. The spectral technique is very effective for studying the potential fields and estimating the average depth of the deep structure and large-scale discontinuities, such as the Moho, or the Curie isotherm, and for solving complex structures such as volcanoes (Spector and Grant, 1970; Curtis and Jain, 1975; Shuey et al., 1977; Mishra and Pedersen, 1982; Negi et al., 1983).

Assuming that the deep discontinuity interface has a statistical behaviour, i.e. random geometrical parameters, then the amplitude spectrum of the magnetic or gravity fields along a profile will decrease linearly, in a well-defined longwave band, with respect to the corresponding wave number on a log–linear representation. The slope of this straight line provides an estimate of the average discontinuity depth. The basement can be referred to these parametric or statistical models. The various problems arising from this method are related, in particular, to estimates of amplitude spectrum and to the method itself. Pedersen (1978) debated in detail the different problems associated with the reliability of the discontinuity–depth estimate; Mishra and Pedersen (1982), analysing the method, established the spectral bandwidth within which we can accept the linear trend of the fit between the amplitude spectra and the wave numbers, and the influence of high frequencies on the estimate.

After constructing several theoretical models, the authors suggest the precautions and the expedients which must be used in various situations.

In our case, the amplitude spectra were computed along 24 parallel profiles (at a distance of 1250 m), approximately normal to the graben axis and 32 km in length. The first profile (1) is shown in Fig. 5. The gravity values were deduced from the Bouguer map, preliminarily filtered by a high-pass filter to remove the regional long-wavelength field connected to the deep crustal structure and the mantle. To obtain stable spectra a running averages procedure on the amplitudes was used for five frequencies (two for each side of the selected frequency). Figure 6 shows the amplitude spectra versus the wave number for all the selected profiles. The amplitudes at low frequencies are closely fitted by a straight line, but at high frequencies the large departure from linearity impedes estimate of the depth of the shallow discontinuities. Spectral analysis has enabled us to define only one density discontinuity. The variation in the slope of the straight lines, which fits the values, indicates a change in the average depth of the discontinuity extending from profile 1 to 24, or from SE to NW along the Campidano axis. The
trend of the depth of discontinuity along a SE–NW direction, reported in Fig. 7 (AA curve), shows some undulation. The maximum (about 3000 m) is reached in the neighbourhood of S. Gavino, while the minimum (1400 m) is on the above-mentioned structural high, near Serramanna. The results of spectral analysis were interpreted by means of a two-dimensional model (Talwani et al., 1959) whose constraints are:

1. discontinuity depth, as determined by the spectral analysis, is assumed as the interface between the Miocene andesites and the schistose crystalline basement,

2. the stratigraphic structure of the graben is assumed as follows: (i) sedimentary Oligo–Miocene–Pliocene sequence formation, (ii) andesitic tuffaceous Oligo–Miocene formation and (iii) granitic–metamorphic basement,

3. the densities in the Bouguer anomalies computation are obtained from rock samples coming from cores of sedimentary and andesitic formations (well C1) and from samples of the basement outcrops.

The average density values are:

- 2.65 g/cm³ for basement,
- 2.45 g/cm³ for andesites and tuffs,
- 2.10 g/cm³ for sediments.
Fig. 6. Amplitude spectra versus wavenumber for the 24 selected profiles in Campidano graben. Profile 1 is shown in Fig. 5.

Fig. 7. Section along Campidano axis, obtained by spectral analysis (AA curve) and two-dimensional models (BB and CC curves).
Gravity Survey of Campidano Area, Sardinia

As a consequence, the density differences (with respect to that of the basement) considered in the computation procedure are:

-0.20 g/cm³ for andesites,
-0.55 g/cm³ for sediments.

The quantitative interpretation was carried out along five selected profiles (AA', BB', CC', DD', EE' of Fig. 5) across the graben axis, using the Bouguer anomaly values, filtered by the regional long-wavelength field. These results are shown in Figs 8–12. The best fit interpretation models of the gravity profiles show a change in size and morphology of the depression along the five graben sections, particularly as regards the thickness of the sediments and of the andesites in the underlying basement. There also appears to be a correlation between the change in gravity gradients and the rather steep dip of the boundary faults. In any case, the gravity gradient over the western margin of the depression is less than that over the eastern margin, indicating that the eastern main fault is more steeply sloping than the western one.

Figure 7 shows the discontinuity trend along the graben axis, which was clearly revealed by spectral analysis (AA curve), and also the andesites–basement interface (BB curve), and the sediments–andesites interface (CC curve), as obtained from the two-dimensional models. The agreement between curves AA and BB is as good as the fit in the two-dimensional profiles. Thus, the results from the two different interpretation methods can be deemed reliable and, as a consequence, both the models of Figs 8–12 and the trends of Fig. 7 probably correspond roughly to the structure of the depression. The models used for the gravity interpretation are simplified and do not consider some details (i.e., the very thin andesitic volcanics present along or near the borders of the graben). A more detailed interpretation is presented in Fig. 13.

Fig. 8. Observed and computed Bouguer anomalies and section across the Campidano graben along profile AA' (see Fig. 5). The solid line in the upper part of the figure is computed gravity and dots are the observed gravity values. The section shows the Paleozoic basement density and the density anomalies of sediments and underlying volcanics with respect to the basement (in g/cm³).
CONCLUSIONS

The gravity study of the Campidano graben has confirmed the presence of a wide negative anomaly, in the long-wavelength, near S. Gavino, where the Tertiary volcanic – sedimentary filling, overlying the Paleozoic basement, is probably about 3000 m thick. The study has also defined the main structural lineaments of the graben more precisely, confirming those already
Gravity Survey of Campidano Area, Sardinia

Fig. 11. Observed and computed Bouguer anomalies and section across the Campidano graben, along profile DD' (for other details see Fig. 8).

Fig. 12. Observed and computed Bouguer anomalies and section across the Campidano graben, along profile EE' (for other details see Fig. 8).

known or supposed and clarified some other features. The study has also shown that the eastern border is steeper than the western one, in close relationship with the gravity gradients. Particularly interesting is the residual positive anomaly between Villasor and Samassi, previously unknown, which has been interpreted as a rise of the basement. The most important geothermal manifestations in the Campidano are associated with the residual positive anomalies, along the border of the graben, where the Paleozoic granitic metamorphic basement outcrops. This can be observed both at S’Acquacotta, where the steep gravity gradients mark
the western main fault, and at S. Maria de Is Acquas, where the eastern fault crosses the fault associated with the hot spring of the same name.

The lack of other surface geothermal manifestations along the southern part of the eastern main fault (where there are Paleozoic outcrops related to steep gradients) does not exclude the possibility that geothermal fluids are kept at depth by the impermeability of the cover.

REFERENCES


Gravity Survey of Campidano Area, Sardinia


