



Morphotectonic and Gravimetric Analysis of the La Burra Valley, Central Precordillera, San Juan, Argentina

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Abstract. This work describes new evidence of Quaternary tectonic activity in the La Burra intermountain valley in the Central Precordillera, San Juan Province, Argentina. Quaternary structures are located in the eastern piedmont of the Sierra de la Crucecita, and western piedmont of the sierra de Talacasto (30° 54'–31° S and 68° 47'–68° 55' W), about 70 km northwest of the city of San Juan. By means of morphotectonic analysis, the main deformation features have been identified and located in both piedmonts, named from north to south: Las Crucecitas and Vertientes faults (in the eastern piedmont of the Sierra de La Crucecita) and the Western Talacasto fault system (in the western piedmont of the homonymous range). The faults affect alluvial deposits from Late Pleistocene to Holocene ages. They are defined by a series of features, typical of compressive environments such as: slope scarps (eastern piedmont of the Sierra de La Crucecita) and counter-slope scarps (western piedmont of the Sierra de Talacasto), fluvial strath terraces restricted to the hanging block of faults, sagponds, aligned springs, diverted and obstructed drainage, deeply incised and sinuous streams in the hanging blocks, alluvial fans with anomalous slopes, among other features that evidence their Quaternary activity. Six Quaternary alluvial levels were identified, from the most recent Q₁ to the oldest Q₆, according to their relative elevation, presence or absence of desert varnish and pavement and degree of incision. The faults affect Q₆ to Q₂ alluvial levels in coincidence with the east-verging thin-skinned structural style typical of the Central Precordillera. This deformation is related to the regional tectonics that have been active in the Precordillera area.

Besides, the main geological structures were identified by the analysis and interpretation of gravimetric anomalies, employing data obtained from WGM12 (World Gravity Map 2012), which includes earth and satellite gravity data derived from the EGM2008 model. The gravimetric response of the crustal blocks that compose the area under study, shows a correlation with the most superficial crustal structure and could be associated to the different morphotectonic domains recognized in the region.

Keywords: Morphotectonics · Faults · Gravimetry · Analytical signal · Precordillera · Andean ranges · San Juan · Argentina

1 Introduction

The Andean Precordillera of western Argentina is a first-order morphotectonic unit of the Pampean Segment of the flat subduction zone between 27° S and 33° S, being one of the most seismically active zones of thrust tectonics in the world. Nevertheless, up to now, papers describing Quaternary deformations in this portion of the Central Precordillera are scarce and isolated (Casa et al. 2011, 2014; Perucca and Vargas 2014).

The study area is located in a tectonic valley between the Sierras de La Crucecita and Talacasto, in the Central Precordillera geological province (30° 54' and 31° 00' S and 68° 55' and 68° 45' W), northwest of San Juan city, Argentina (Fig. 1). Sierra de La Crucecita is a mountain range that trends NNE, with a maximum elevation of 2,082 m a.s.l. Sierra de Talacasto has N-S to NW trend and a maximum altitude of 2,756 m a.s.l. The rivers located in the piedmonts of both mountain ranges drain by the de La Burra river, the main tributary of the Talacasto river, from north to south. Its headwaters are located to the east of the Pampa de Gualilán (Fig. 1). The Quaternary deformations identified in both foothills modify this drainage network, since small tributary streams are susceptible to variations, even subtle topographic modifications, depending on their erosion rate (Audemard 1999). There are very few previous papers in the area referring to neotectonic structures in this depression. Casa et al. (2011, 2014) mentioned some structures in the western foothills of the Talacasto mountain range, although they neither indicate their kinematics nor the alluvial levels affected. Perucca and Vargas (2014) described a natural exposure located in the northern portion of the eastern foothills of the La Crucecita mountain range, where they identified a reverse fault verging to the east that has been called the Las Crucecitas fault. Levina et al. (2014) evaluated the Cenozoic basin fill of the frontal sector of the Precordillera foreland basin in three valleys located along the San Juan river (one of them, the La Burra valley) concluding that the Neogene successions located in these depressions showed the internal construction of the Cordillera Frontal, the regional arc volcanism and the initial exhumation of the Precordillera. The changes of provenance recorded in the age of the detrital zircons, suggested an initial shortening in the Frontal Cordillera in coincidence with the change of aeolian to fluvial accumulation in the adjacent foreland basin, during the Early Miocene (24–17 Ma). They considered as the probable age of exhumation induced by the shortening and rise of the Precordillera to be between 12 and 9 Ma (Levina et al. 2014).

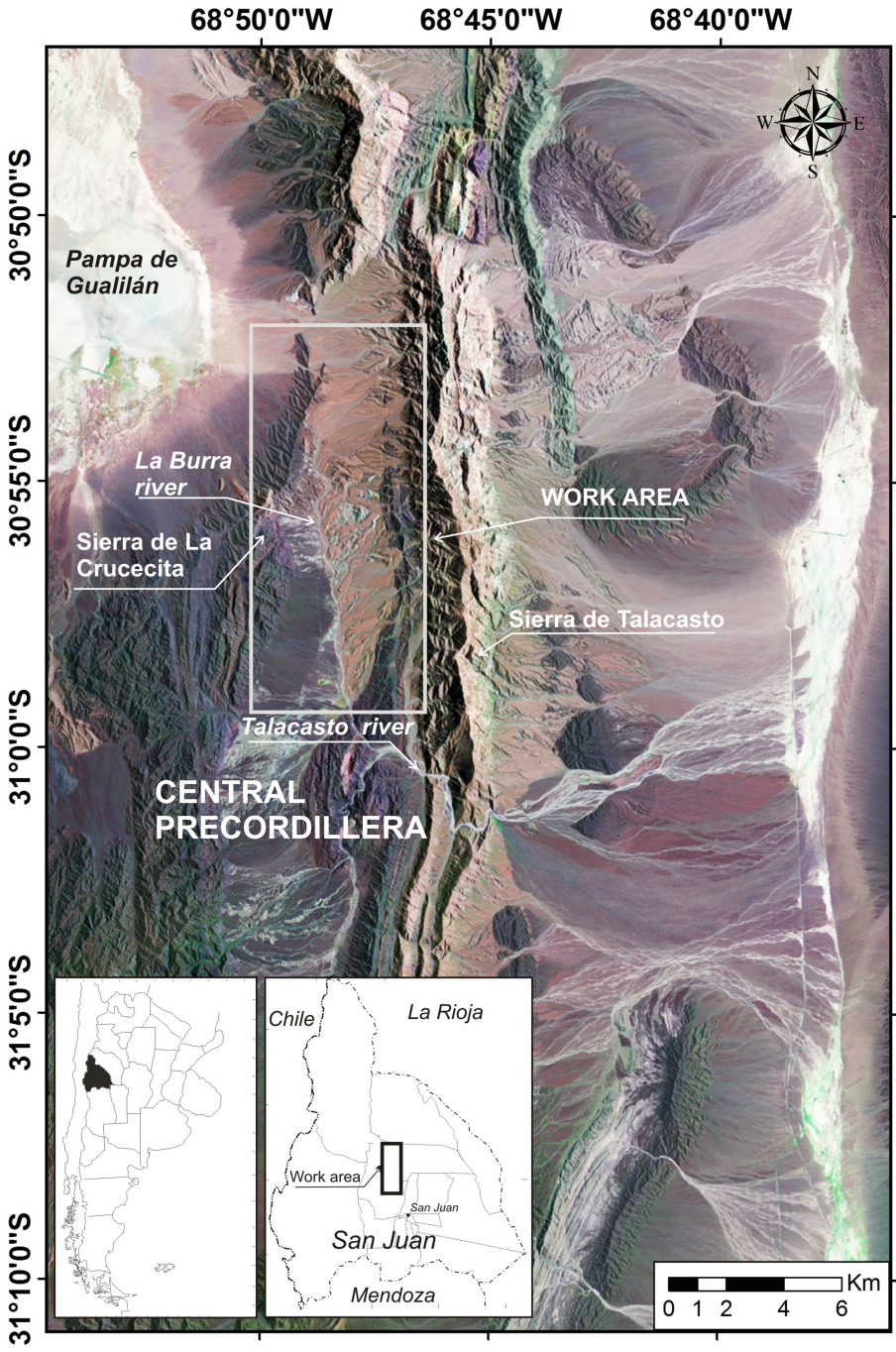


Fig. 1. Landsat satellite image with the location of the study area.

In this work, a morphotectonic analysis in the piedmonts located in the La Burra river valley is carried out, in which the main faults with Quaternary tectonic activity were identified. They were named from north to south: the Las Crucecitas and Vertientes (eastern piedmont of Sierra de La Crucecita) and the Western Talacasto fault system (western piedmont of Sierra de Talacasto). These faults disturbed deposits of Late Pleistocene to Holocene age and are defined by a series of typical landforms of compressive environments such as slope escarpments (western piedmont) and counter slope (eastern piedmont), strath terraces restricted to the hanging block, sag ponds, aligned slopes, diverted or disrupted streams, strongly incised and sinuous rivers in the hanging blocks of the faults, alluvial fans with anomalous slopes, among other features as evidence of Quaternary tectonic activity.

From the geomorphological analysis of the valley, the following morpho-structural units were recognized and described: Mountainous (high mountains and hills) and Transition (piedmonts). In addition, six Quaternary alluvial levels were identified (from the most recent to the oldest: Q₁, Q₂, Q₃, Q₄, Q₅) and a sixth level (Q₆) in the western piedmont of the Sierra de Talacasto. They were distinguished by their relative position, incision degree, presence (or not) of pavement and desert varnish. Quaternary faults affect almost all the alluvial levels (except the current channels) and they are consistent with structural style of the Central Precordillera, which are east-verging low-angle faults. This deformation is linked to the tectonism that disturbed the area of Precordillera at a regional scale.

On the other hand, our research tries to define the geological structures of the area based upon satellite gravimetric data processing and analysis. Gravimetric data obtained from the satellite missions have the advantage that allows viewing underground density variations within a high spatial stability and without disturbances by mathematical approximations.

This paper also tries to determine if there is a correspondence between the morphotectonic units recognized in the region and its spatial continuity based on satellite gravimetric data processing and analysis. In order to achieve a geophysical characterization, Free-air, Bouguer and Isostatic anomaly maps were calculated and analyzed.

Bouguer anomalies were filtered to separate shallow and deep gravity sources. Filters such as Upward Continuation and Band Pass can be used to separate a regional gravity anomaly resulting from deep sources from the observed gravity. When the estimated regional anomaly obtained from the Bouguer anomaly is subtracted, a residual anomaly may be obtained that clearly shows the location of the upper crustal structures.

Finally, it is intended to improve the knowledge about the active structures located in an intermountain depression located at scarcely 60 km northwest of the city of San Juan (>700,000 inhabitants) and near the main hydroelectric dams in the region.

2 Tectonic Setting

In the present geotectonic setting of convergence between the Nazca and South American plates (southern portion of the Central Andes), the Pampean flat-slab occurs between 27° and 34° S and had existed from 20 Ma ago (Jordan et al. 1983; Yáñez et al. 2001; Ramos et al. 2002). This is characterized by the absence of active volcanoes

and by an intense seismic activity (Cahill and Isacks 1992) attributed to the presence of relevant active faults that thrusts the Neogene sequences over the Quaternary alluvial deposits. In this way, evidence of Quaternary deformations has been described at these latitudes (Perucca et al. 1999; Costa et al. 2000; Perucca et al. 2012, 2014a, 2014b, 2015; Perucca and Vargas 2014, Audemard et al. 2016, among others).

The Precordillera is a Paleozoic orogenic unit that has been subdivided, according to its structural style in Western, Central and Eastern Precordillera (Ortiz and Zambrano 1981). The study area is located in the area of Central Precordillera, which constitutes a E-verging thin-skinned fold and thrust belt, and imbricated structures rooting down towards a 10–15 km deep main decollement (Zapata and Allmendinger 1996, Ramos 1988), with mountain ranges trending N–S.

Cenozoic rocks are preserved in the footwalls of major thrusts (Jordan et al. 1993; Alonso et al. 2005) and they were differentially eroded to form N-S trending inter-mountain valleys between the thrust-generated ranges (Levina et al. 2014).

3 Methodology

Structural and geomorphic analysis

Both analyses were made using topographic data, fieldwork and digital satellite imagery (Landsat 7-TM and SPOT 5). A geological sheet published by the Argentina Mining Geological Service (Furque et al. 1998) on a 1:250,000 scale was used to determine lithology that was mapped on screen in a GIS environment (in vector format) and later was verified by fieldwork.

Besides, three swath averaged topographic-profiles (north, center and south), were built across the valley to report the main landscape characteristics of the area, where the mean, maximum and minimum elevations of the DEM (SRTM 30) are projected into cross section planes and the strip width was set to 0.5 km with a length of ~ 10 km in order to examine trends in slope and local relief at this scale of work. These orthogonal (W-E) swath profiles crossing the La Burra Valley were selected to represent the asymmetry of the ranges, the main morpho-structural units, the differences in their heights, slopes and extension and the influence of the faults. In addition, a longitudinal swath profile trending N-S along the La Burra river was made. The elaboration of the geomorphological map allowed the integration of all these data, and the characterization of the geomorphology of the sector and the structures that disturb both piedmonts. The data processing of a Digital Terrain Elevation Model (DEM), (ASTER 30 m), was also carried out through the ArcGIS software, in order to highlight the main topographic characteristics of the La Burra valley. The fieldwork consisted in an analysis of the natural exposures identified in the channels that cross the Las Crucecitas and Western Talacasto faults, in order to determine the kinematics of these faults and the age of the disturbed deposits. From these exposures, two samples were taken and analyzed using Optically Stimulated Luminescence (OSL) Method carried out at the Laboratory of Datação, Comércio e Prestação de Serviços LTDA de Sao Paulo (Brazil).

Data and Gravity Anomalies

The area under study was covered with a gravity database obtained from the WGM12 (World Gravity Map 2012). The WGM is the first set of global gravity anomaly maps that take into account a realistic Earth model and that consider the contribution of most surface masses (atmosphere, land, oceans, inland seas, lakes, ice caps and ice shelves). The WGM denotes a set of high-resolution gravity anomaly maps and digital grids computed at global scale from available reference Earth's gravity and elevation models. The Release 1.0 (WGM12) includes a set of three anomaly maps (surface free-air, complete Bouguer and isostatic anomalies) derived from the EGM2008 Geopotential model and the ETOPO1 Global Relief Model.

Gravity information used is derived from the EGM2008 model, which was developed in spherical harmonics up to 2160 grade by the National Geospatial-Intelligence Agency (NGA). EGM2008 model includes surface gravity measurements (from terrestrial, marine or aerial studies), satellite altimetry and satellite gravimetry (GRACE Mission). Gravity anomalies are used to investigate the mass-density distribution of the Earth's interior to provide constraints on the geological structures from subsurface, crustal to upper mantle depths.

The surface free-air gravity anomaly was computed at the Earth's surface in the context of Molodensky theory (Heiskanen and Moritz 1967) and includes corrections for the mass of the atmosphere. The resulting complete Bouguer anomaly thus reflects the disturbance between the observed gravity and that computed for a given reference Earth model at a particular point P. It is also defined from the free-air anomaly (Δg_{FA}). The complete spherical Bouguer anomaly is determined over the whole Earth by computing in a single step the gravity contribution of all surface masses above or below the mean sea surface. The spherical Bouguer gravity anomaly at a given point P of the Earth's surface is given by:

$$\begin{aligned}\Delta g_B &= \Delta g_{\text{surface free-air}} - \Delta g_{\text{surface masses}} \\ &= g_{\text{obs}}(\mathbf{P}) - \gamma(\mathbf{Q}) + \delta g_{FC} - \delta g_{TOP} + \delta g_{Atm}\end{aligned}$$

In the same way, the contribution of their compensation at the crustal-mantle boundary is also computed in spherical geometry on the base of isostatic equilibrium (Airy-Heiskanen model) to determine the corresponding isostatic anomaly. A spherical harmonic approach has been used to provide homogeneous and accurate global computations of gravity corrections and anomalies up to degree 10800 ($1' \times 1'$ half-wavelength equivalent spatial resolution).

Free-air, Bouguer and Isostatic Anomaly charts were gridded according to the minimum curvature method with a 1.5 km grid pass, using Oasis Montaj software. A density of 2.67 g/cm^3 was considered for the upper crust rocks according to the proposal by Hinze. Gravity data covers the analyzed region and its boundary sectors. In order to eliminate edge effects a data expansion was performed.

Anomalies Filtering

It is well known that the Bouguer anomaly contains the sum of gravimetric effects of various sources and there are many techniques that allow for a proper separation of such. The Bouguer anomaly map contains two effects; one regional (attributed to the lower crust and mantle) and another residual (attributed to upper crust and intra-basement gravity sources). For separating regional gravity anomalies from residual ones, it is assumed that a regional anomaly is caused by sources that have wide horizontal extent, are deep in terms of the depth to the top of the sources, and have similar depth. Likewise, it is assumed that a residual anomaly is produced by sources that are limited in horizontal extent, are shallow, and have depths different from the deep anomalies but similar to one another.

Different frequency techniques as Upward Continuation, Band Pass filter, were applied. Nevertheless, due to the powerful influence of the Andean root, the filter that proved to be most efficient, was obtained by a Band Pass Filter.

In order to obtain the regional Bouguer anomaly map, grid data was filtered with a Band pass, rejecting all wavelength upper than 11 km and lower than 3 km. A residual anomaly chart was obtained subtracting the estimated regional anomaly acquired from the Complete Bouguer anomaly.

4 Geological Setting

Detailed mapping of the study area allowed the identification of several geological units (Fig. 2). From the oldest to the most recent, the stratigraphic units are: (1) Cambrian–Ordovician sedimentary rocks, mainly consisting of limestones, dolomites and shales; (2) Silurian–Devonian greywackes and shales, of marine origin; (3) Carboniferous continental sandstones and shales; (4) Neogene sedimentary rocks (conglomerates, sandstones and shales); (5) Quaternary colluvial–alluvial consolidated deposits and (6) unconsolidated modern deposits (gravel, sand, silt and clay), in the piedmont and in river channels.

The Neogene deposits are located in the central portion of the valley with an estimated thickness of 1000 m. Levina et al. (2014) described clastic depositional patterns in these intermountain exposures of Central Precordillera assigned to the Late Oligocene–Miocene retroarc foreland basin system. The oldest strata recorded a ~24 Ma transition from ephemeral playa lake/incipient dune field conditions to a regional eolian system. About 17 Ma ago, the eolian system replaced a fine-grained floodplain deposition. Upward coarsening fluvial and alluvial fan deposits reflect a 17–8 Ma shift from distal to proximal foreland basin facies, locally influenced by syn-orogenic volcanic activity. However, in the area of the La Burra valley, the majority of A–He ages fall between 12 and 10 Ma (Levina et al. 2014). These authors pointed out that this pattern is consistent with an eastward (cratonward) progression of thin-skinned thrusting and resultant structural fragmentation of the foreland basin into isolated intermountain segments.

In the eastern piedmont of the Sierra de La Crucecita and from east to west, Neogene rocks outcrop, trending N 50° E and dipping from 10° W that later increases to

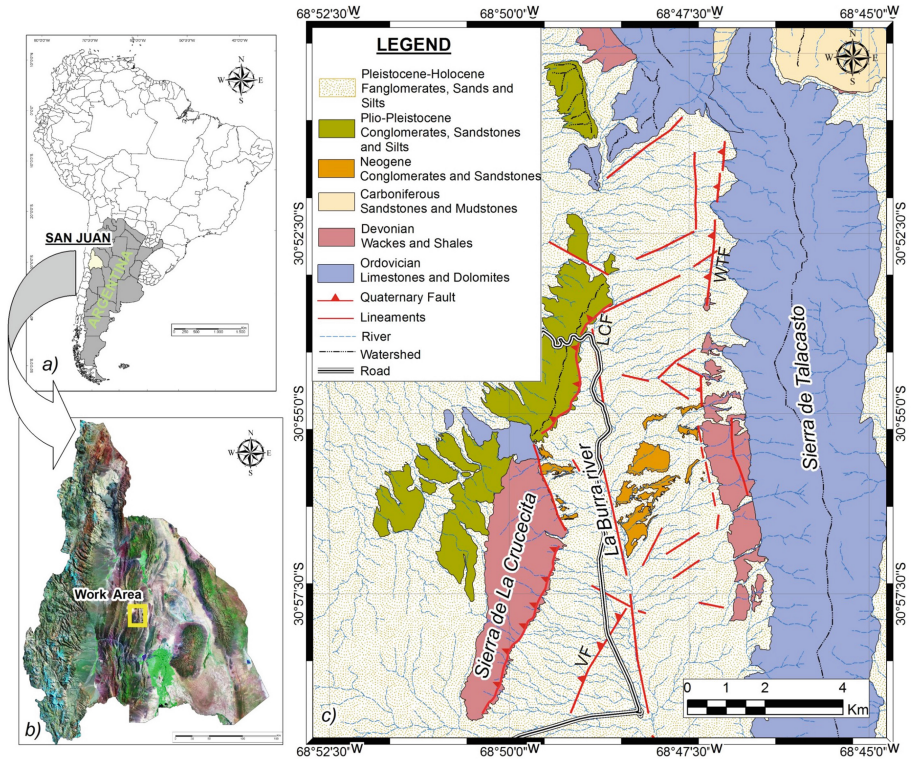


Fig. 2. Geological map of the La Burra river valley with Quaternary faults location, Las Crucecitas fault (LCF), Vertientes fault (VF) and Western Talacasto fault (WTF).

45° W westward. Near to the mountain front the strata dip 70° E, forming a synclinal that is faulted in its western flank. This reverse fault whose azimuth is 160° and dips from 47° to 67° W involves Devonian and Neogene rocks.

In the western piedmont of the Sierra de Talacasto, the Neogene strata have a trend of N 4° E, N 16° E and N-S and dip between 40° and 45° W. Towards the West, the trend of the Neogene strata is N 8° W and the dip increases to 70° W as far as the western flank of the Sierra de Talacasto, the Neogene deposits rest unconformably on rocks of Devonian age, with azimuth 355° and dip 60° W. This would suggest that the rise of the Sierra de Talacasto by a reverse fault verging to the east and located on its eastern flank, would have generated the tilt of the entire Neogene basin. The Pleistocene and Holocene alluvial deposits, consisting of poorly selected fanglomerates and conglomerates, with angular to subangular clasts of different sizes from the Paleozoic and Cenozoic sediments, are placed onto the Neogene outcrops by an erosion unconformity. Its matrix is a coarse-grained sand with frequent lenticular intercalations of coarse sandstones. Finally, modern deposits in the fluvial channels tributaries of the La Burra river and similar to those previously described, are mentioned.

5 Geomorphology

In the study area, the Mountainous and Transition morpho-structural units are identified as follows (Fig. 3):

The Mountain Unit is formed by the positive reliefs uplifted by faults. The Sierra de La Crucecita trends NNE with its highest elevations in the central sector (2,024 m a.s.l.), with a width ranging from 1 to 5 km. It is an important positive relief that provides detrital material towards the east. This mountain range is composed of Paleozoic sedimentary rocks and it is characterized by a gentle slope on its western flank, whereas the eastern one has an abrupt morphology due to the presence of the reverse fault that thrusts Devonian sequences over Neogene rocks.

The Sierra de Talacasto is a mountain range trending almost N-S with a width of about 3 km, and average altitude of 2,500 m a.s.l. Its W-E profile shows an abrupt eastern flank due to a reverse fault verging to the east that uplifts the calcareous unit.

The hill relief is represented by those positive units that contrast from the point of view of altitude with the high mountains, being less outstanding and forming a typical badland relief. They comprise sandstones, shales and conglomerates of Neogene and Pliocene-Pleistocene age, in some sectors with a thin Pleistocene to Holocene (?) cover. They show smooth and rounded slopes, with elevations between 1,650 and 1,700 m a.s.l.

The transition unit or piedmont establishes the morphological connection between the aforementioned mountain ranges and the local base level, which is the La Burra river. The piedmont located east of the Sierra de la Crucecita has an average slope of 18% in its northern area, with width that increases from north to south. In its central portion the average slope is 12.5%, and in the southern sector the slope reaches only 7% in average, with a greater extension than the northern and central portions. On the other hand, the western piedmont of the Sierra de Talacasto has an average width of 2 km, which is reduced to less than 500 m at its southern end, with a slope that varies between 10% in the northern part and 5% in the central and southern sector. Both piedmonts are covered by alluvial deposits that are formed by the accumulation of debris coming from the erosion of the structural highs (mountainous and hills units). Climate plays an essential role in its formation, since these deposits are rare in humid climates, whereas in areas of arid climate, scarcity of vegetation on the relief allows the disintegration of it into smaller fragments that accumulate and extend at the foot of the ranges. The alluvial levels overlie the erosion surface carved in Neogene outcrops, with the top surfaces of the oldest Quaternary units standing out.

Six alluvial levels (Q₆, the oldest, to Q₁ the present fluvial channels) were preliminary identified in both piedmonts according to their relative topographic position, grade of incision and presence or not of desert varnish (Fig. 3). However, these alluvial levels do not develop along the entire piedmonts and are only clearly identifiable where the Neogene rocks outcrop.

The drainage pattern is dendritic (divergent) in both piedmonts, typical of alluvial fans. However, several anomalies in the drainage occur when the streams cross the fault traces, increasing for example incision and sinuosity and showing diverted, obstructed, hanging and beheaded channels and showing aligned springs and unpaired terraces (Fig. 4a-d).

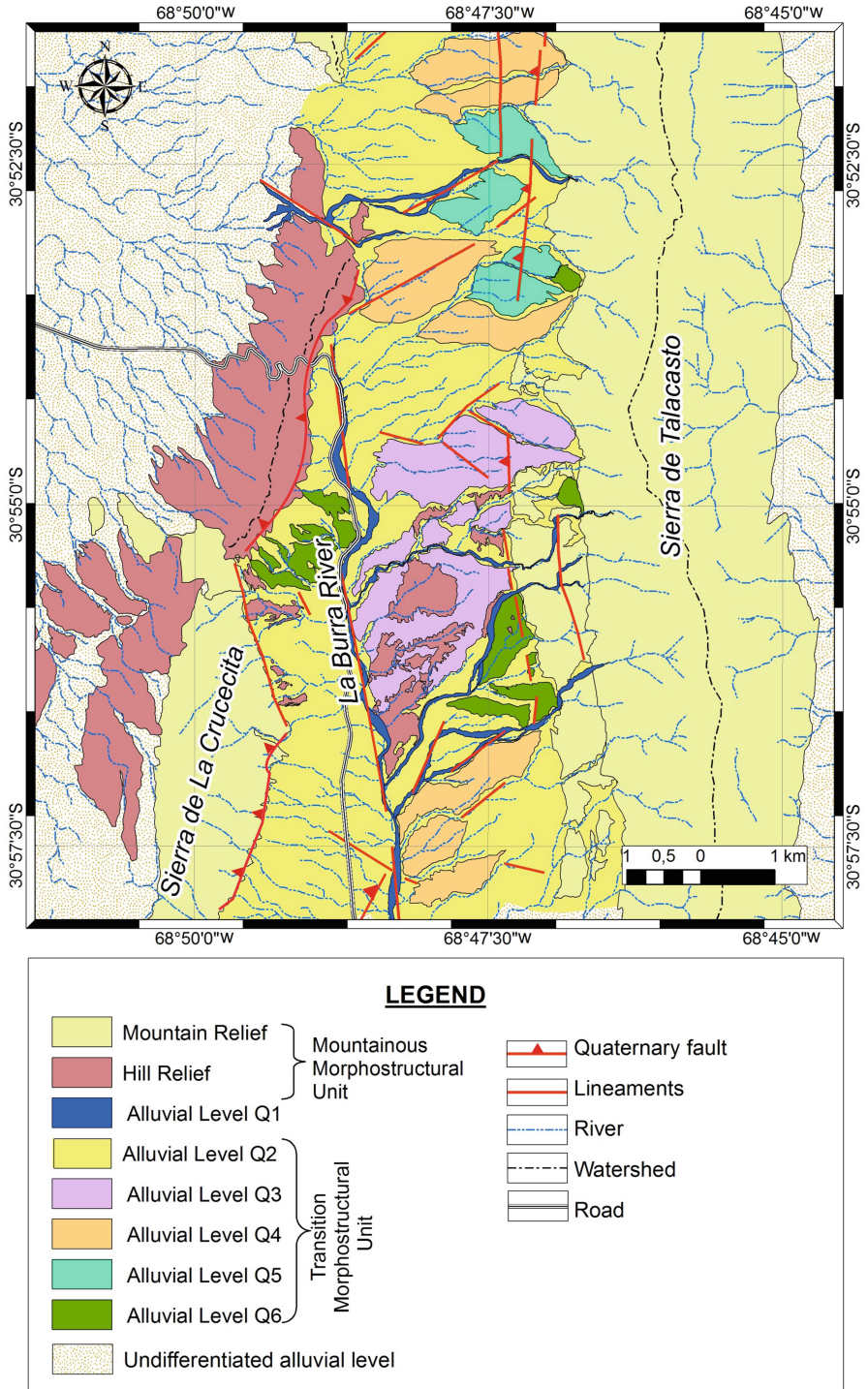


Fig. 3. Geomorphological map.

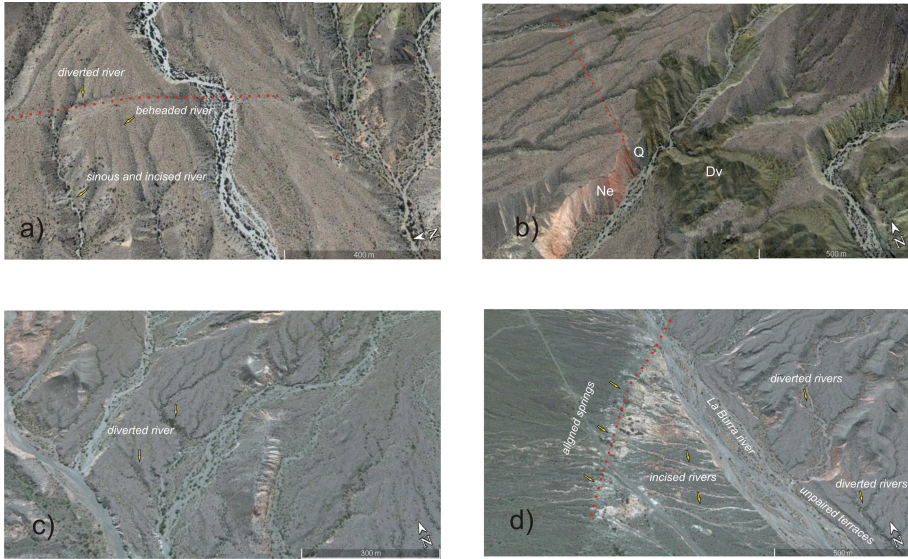


Fig. 4. Detailed Google Earth images showing (a) counter-slope fault scarp with river diversion and beheaded streams. Also the drainage pattern becomes more sinuous in the hanging block, (b) counter-slope scarp and natural exposure of Western Talacasto fault where Neogene rocks overlies Quaternary alluvial deposits, (c) shape-broom and diverted rivers, (d) aligned springs along the Vertientes fault trace and diverted rivers and unpaired terraces in the left margin of the La Burra river.

The La Burra river, which runs from north to south, becomes the main collector of tributaries from the mountain ranges. It has N-S trend and a length of 9.8 km. This river is tilted to the west in its upper river basin and to the south is located to the east of the valley showing a basin with a remarkable asymmetry. Besides, only at the left margin of this river there are three terraces (the two oldest are strath terraces being topographically higher and the youngest one, a fill-in terrace). That asymmetric distribution may be because of the variation of the local base level due to the tectonic uplift of the eastern portion of the valley.

6 Swath Profiles Analysis

As it was mentioned in the methodological section, three cross-sectional profiles were drawn up across the study area (North, Center and South) and one longitudinal profile along the La Burra river, in order to highlight the most distinctive topographic features of the valley, its piedmonts and the alluvial plain characteristics of the main river (Fig. 5a–e). With the standard deviation value between the extreme altitudes, slopes, relative heights, incision and the influence of the structures on the relief could be distinguished. The northern profile shows the most significant elevation difference between the Sierra de La Crucecita to the west ($\sim 1,850$ m a.s.l.) and the Sierra de

Talacasto to the east ($\sim 2,510$ m a.s.l.), the latter with an extensive piedmont (~ 3 km) showing low incision towards the distal portion and which increases towards the mountainous front of the calcareous range. On the other hand, the eastern piedmont of the Sierra de La Crucecita is very narrow (<300 m) and the alluvial levels are much incised (Fig. 5b). The alluvial plain of La Burra river lies to the western portion of the intermountain valley. In this upper section, the river has a gradient of 4.5%, and an average width of 87 m, with a dominant vertical incision. The central profile shows the decrease in elevation difference between both mountain ranges, even though the Sierra de La Crucecita does not exceed 2,000 m a.s.l. in this sector, whereas the Sierra de Talacasto has an elevation of 2,460 m a.s.l. Extensive piedmonts develop in both flanks of the valley, but the eastern one is strongly incised. The La Burra river is located symmetrically in the central portion of the valley (Fig. 5c). In this middle section, the river gradient diminishes, being 3%, whereas the river floodplain width decreases to 42 m. In the southern profile, the difference between the two mountain ranges is less than 200 m, with both piedmonts having a similar extension, although the western piedmont has a steeper slope, whereas the eastern one has a gentler slope, but it shows a greater incision. The La Burra river is located towards the east of the depression. The lower river section gradient diminishes to 1.5% and the river floodplain width increases to 114 m, where lateral erosion predominates showing a flat bottom (Fig. 5d).

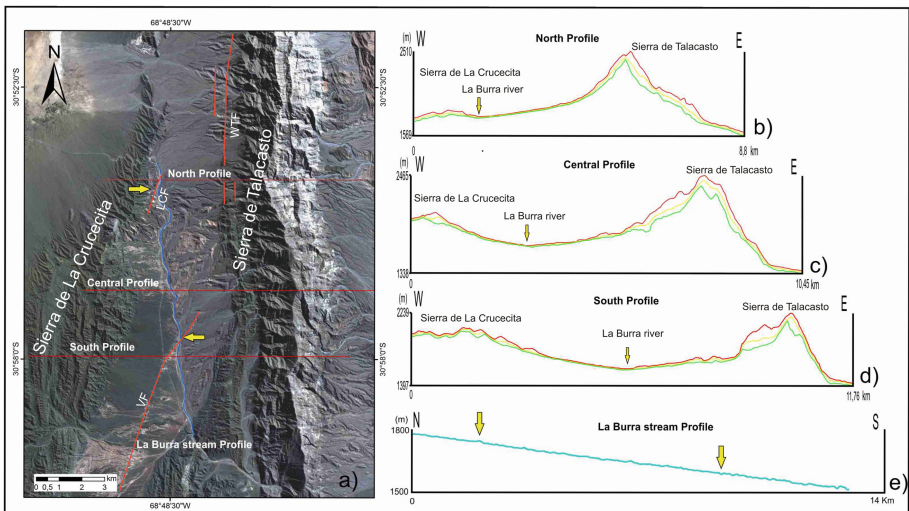


Fig. 5. (a) Satellite image showing main Quaternary faults: Las Crucecitas fault (LCF), Verientes fault (VF) and Western Talacasto fault (WTF) and topographic profiles location; (b) Northern, (c) Central and (d) Southern swath topography profiles (with 0.5 km window); performed across the river valley. Each profile shows focal statistics of the highest, mean and the lowest elevation, respectively, (e) Longitudinal profile of the La Burra River. Yellow arrows point knickpoints related to the Las Crucecitas and Verientes faults, suggesting a tectonic origin.

Finally, in the N-S La Burra river profile it is possible to appreciate that this profile is not in equilibrium and has two main slope breaks or knickpoints, located in its middle section. Both knickpoints would coincide with the location of the NNE Quaternary structures analyzed in this work; these are the Las Crucecitas and Vertientes faults (Fig. 5e).

7 Neotectonic Analysis

Faults with evidence of Quaternary tectonic activity were identified in both piedmonts of the La Burra river valley. They are reverse faults that trend N-S to NE, with eastern vergence, consistent with the structural style of the Central Precordillera (Fig. 6).

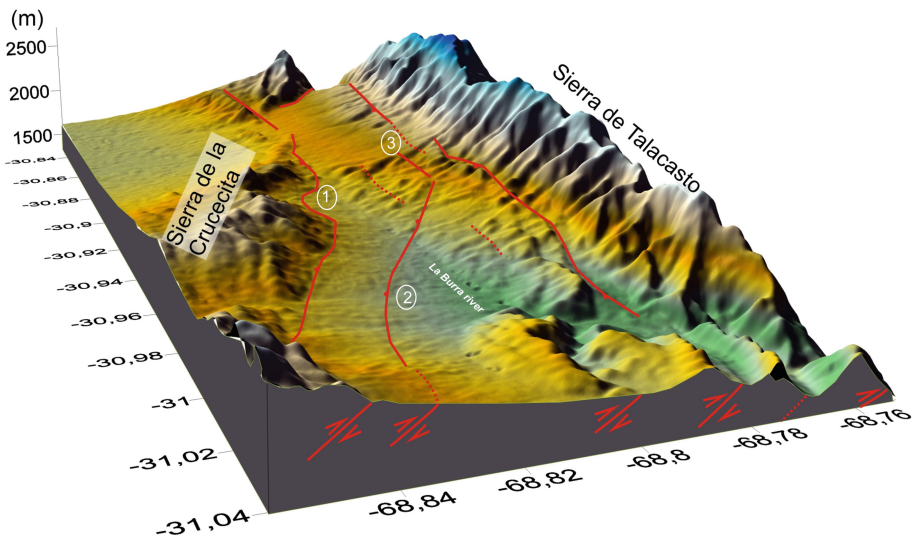


Fig. 6. Digital Elevation Model (DEM) map (ASTER GDEM) of the La Burra river valley showing its topographic features and location of the main Quaternary structures, Las Crucecitas (1), Vertientes (2) and Talacasto (3).

Eastern Piedmont of the Sierra de La Crucecita

From north to south, there are noticeable geomorphological differences along this piedmont. For example, four strongly incised alluvial levels (Q_4 to Q_2 and the present river channels Q_1) have been recognized in its northern portion. These Quaternary deposits cover Neogene rocks and have evidence of glacio-planation processes (Fig. 7a). However, to the south, only the present (Q_1) and Q_2 alluvial levels were identified, although Neogene rocks outcrop in the sectors where the Vertientes fault is recognized.

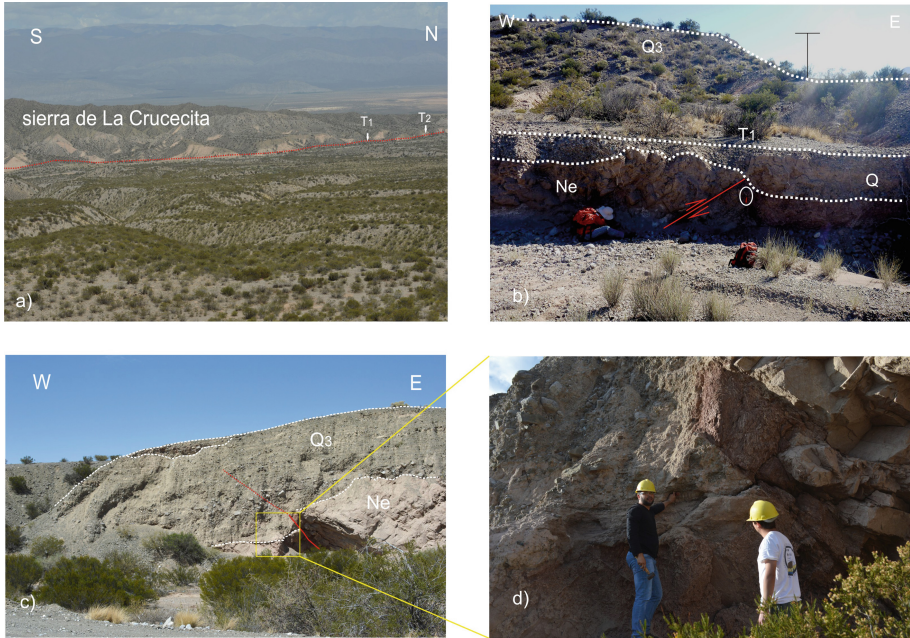


Fig. 7. (a) View to the northwest (northern end of the Sierra de La Crucecita) and location of natural exposures T1 and T2. (b) T1 trench in a strath terrace on the left margin of a small tributary of the La Burra river. The reverse fault that dips to the west places Neogene rocks over alluvial deposits assigned to the Holocene. Behind the terrace there is a favor-slope scarp corresponding to Q_3 alluvial level. The scarp is rounded and ~ 3 m height. (c) View to the south of the natural exposure T2 showing the Las Crucecitas fault, which dips to the west and disturbs the alluvial level Q_3 . (d) Fault detail in trench T2. The person in the photograph points the sample CRUZ 1 location.

On the northern end of the eastern piedmont of the Sierra de la Crucecita (Fig. 7b), Las Crucecitas reverse fault is located (Perucca and Vargas 2014). This fault, with a 210° azimuth and 40° W dip, was identified in a natural exposure (T1) as a strath terrace of a tributary of the La Burra river. The structure places Neogene rocks over alluvial deposits that have been assigned to the Holocene (Fig. 7b).

Further north, in the natural exposure T2, the fault affects the Q_4 alluvial level and shows a ~ 1.70 m high, slightly rounded, east-looking flexural scarp. The fanglomerates of level Q_4 present lenses of fine materials as well as clasts oriented and flexured as a result of deformation (Fig. 7c, d). Striae were measured on the fault plane, whose pitch is 57° NW, indicating thrust with a horizontal sinistral component. A yellowish, clayish lime deposit (Sample Cruz 1), located below the fault plane (Fig. 7d) was dated by OSL, yielding an age of 17 ± 1.75 kyr.

In the central and southern portion of the eastern piedmont of the Sierra de La Crucecita, there is another fault running $N 24^\circ$ in average with a soft inflection in its southern trace where it changes to $N 11^\circ$ (Fig. 8a), exhibiting an east-looking favor-slope scarp. This fault, named as the Vertientes Fault affects the Q_2 alluvial level and

even the present Q_1 alluvial level, modifying the drainage pattern, which presents hanging, diverted and obstructed channels with spring alignment (Figs. 4d and 8b, c). The fault length is ~ 6 km which crosses La Burra river course and crosses also the distal portion of the western piedmont of the Sierra de Talacasto. Here, this thrust trends $N 10^\circ$, dips 45° W, and uplifts Neogene rocks.

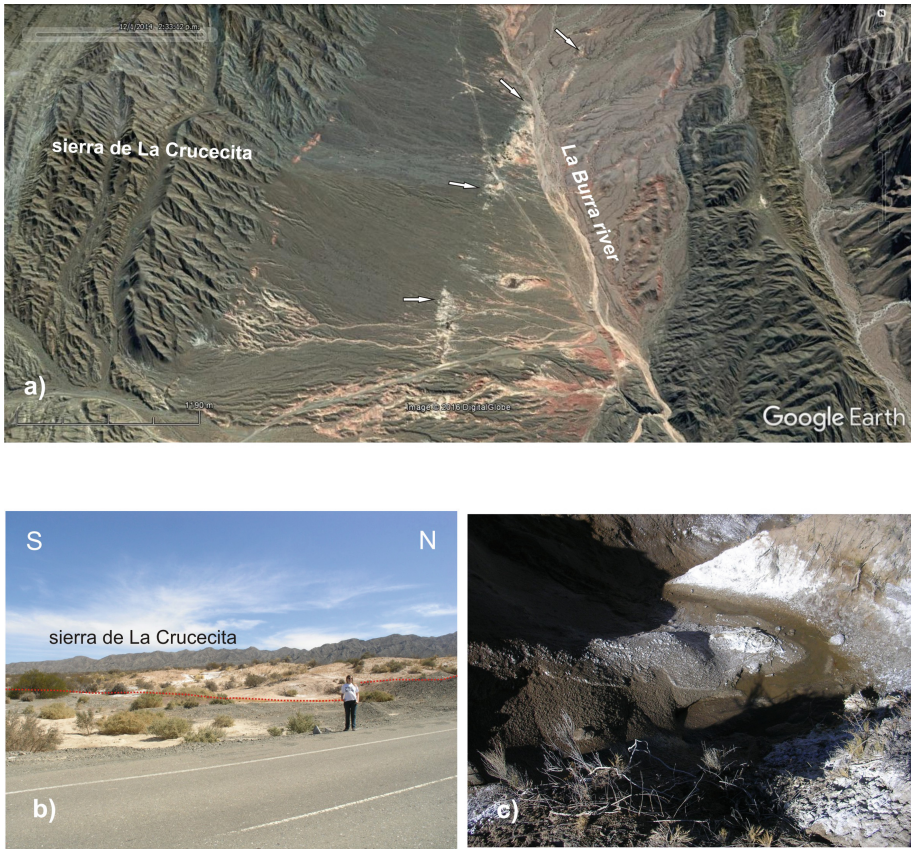


Fig. 8. (a) Google Earth image of the study area. White arrows point the location of the Vertientes fault. (b) View to the west of the silty deposits and aligned springs along the fault. (c) When the aquifer encounters the fault, it emerges as a surface spring.

Western Piedmont of Sierra de Talacasto

In the western piedmont of the Sierra de Talacasto, several discontinuous and sub-parallel fault sections and alignments were identified. These structures show simple and compound counter-slope and flexural scarps, strath terraces in the hanging blocks and stream anomalies like diverted, obstructed and shape-broom streams (Figs. 4a, b and 9a, b). In addition, an increase in the incision and sinuosity of the channels in the

hanging block of the fault is observed, where Neogene rocks outcrop (Fig. 4a, b, c). The scarp height ranges between 0.30 m and 10 m, being the most pronounced ones in the northern portion of the piedmont.

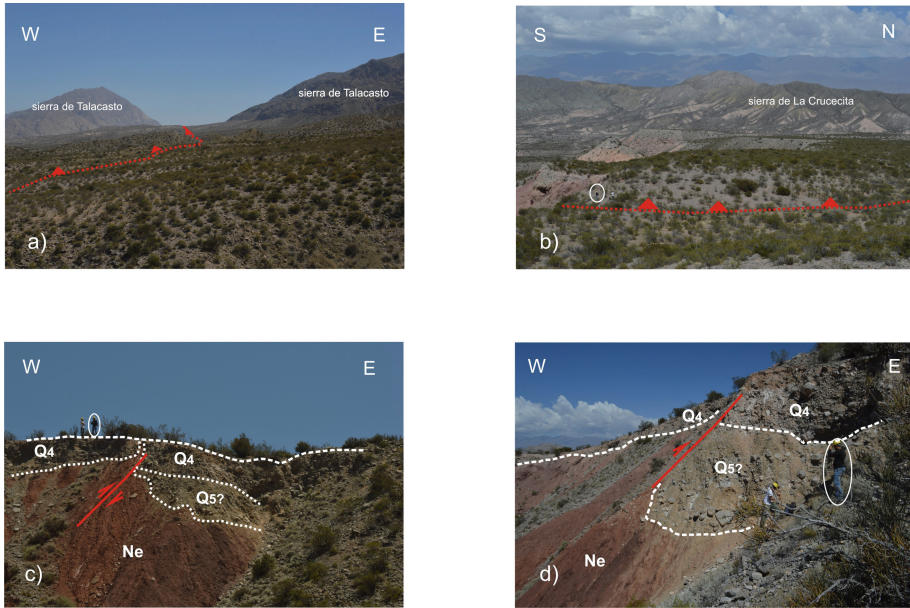


Fig. 9. (a) View to the north of the Western Talacasto fault. The counter-slope scarp affects Q_3 and Q_4 alluvial levels. (b) View to the west of the scarp. (c) Natural exposure showing a reverse fault that places Neogene rocks over alluvial deposits assigned to Q_4 level. (d) NW view showing the eastern vergence of the fault affecting Q_4 and Q_5 (?) alluvial levels. White circles point to a person for scale, where the sample CRUZ 2 was obtained.

In a natural exposure the fault thrusts Neogene rocks over alluvial deposits of level Q_4 and Q_5 . It dips 74° W and trends 25° (Fig. 9c and d). Deposits assigned to the Q_5 level, represented by the sample Cruz 2, yielded an age of 52.3 ± 4.5 kyr (Fig. 9d).

8 Gravimetric Analysis

The anomalies charts obtained for la Burra area reflect high-density contrasts to a crustal and lithospheric scale, where positive and negative values are apparently associated to the different units exposed in the study area. It is important to highlight the strong influence of the Andean root on the observed anomalies.

The Free-air anomaly map (Fig. 10) shows correspondence with the thrust fronts that uplift the mountain ranges of Central Precordillera, that is, the Sierra de Talacasto to the east and the Sierra of the Crucecita to the west. In addition, changes of gradient observed between the elevated morphotectonic units to the east (Sierra de Talacasto)

and to the west (Sierra de la Crucecita) would bound the depression corresponding to the La Burra valley.

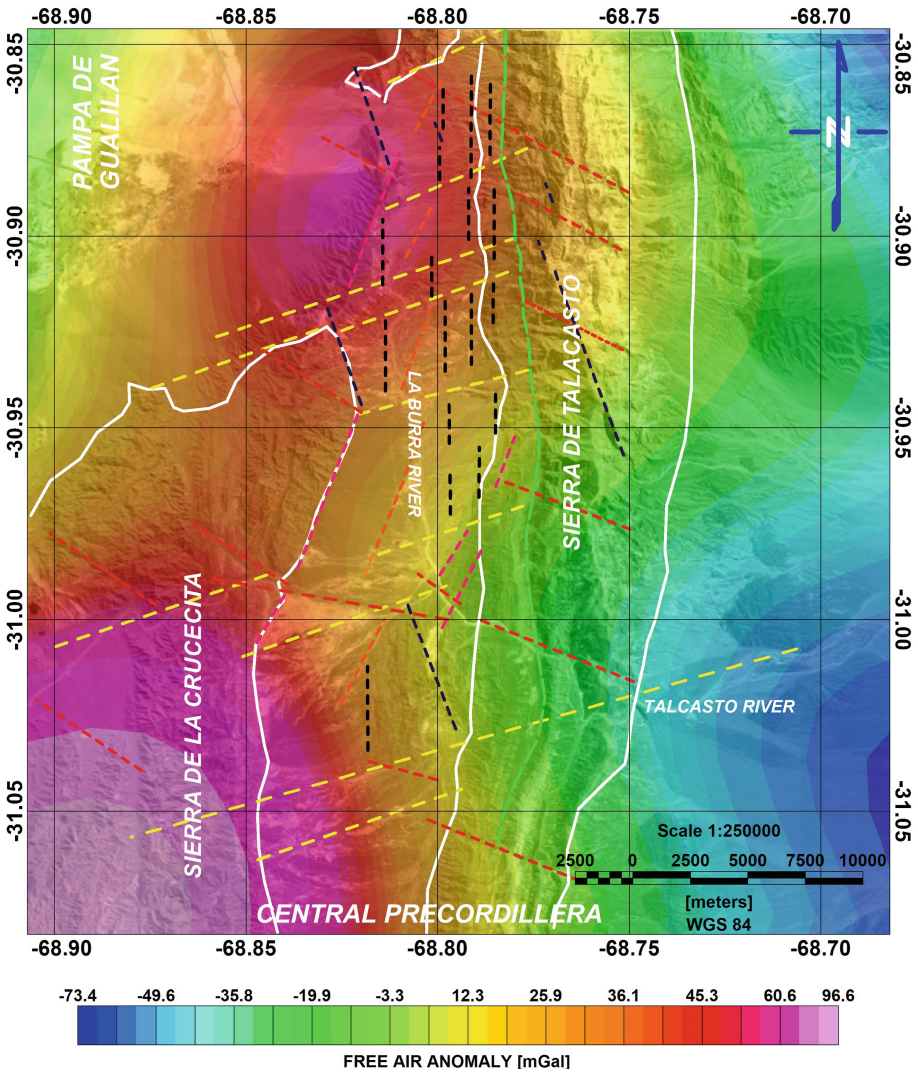


Fig. 10. Free-air gravity anomaly map.

In the complete Bouguer anomaly chart, negative values, associated with the mountain ranges that exhibit Paleozoic units and that were uplifted by N-S faults, were observed (Fig. 11). On the other hand, the positive values would seem to show the existence of intermountain depocenters (La Burra valley) where Neogene-Quaternary deposits predominate. These valleys seem to be controlled by NE and NW structures.

The isostatic anomaly chart preliminarily suggests a strong disequilibrium for the region under study, evidenced by negative values along the main mountain ranges as in Sierra de Talacasto to the east. On the other hand, the Cenozoic depocenters show positive values which also suggest an isostatic imbalance, so that tectonic adjustments would be expected for the region analyzed in order to reach the isostatic equilibrium (Fig. 12).

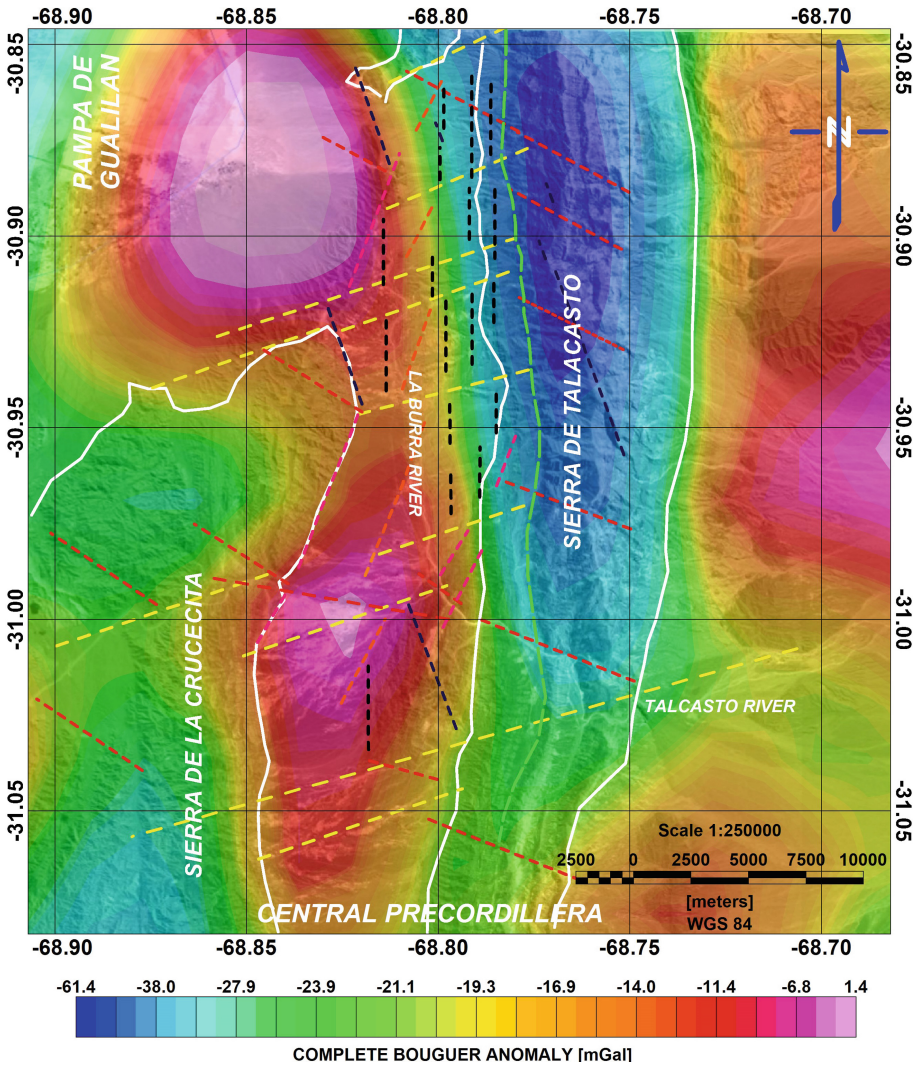


Fig. 11. Complete Bouguer anomaly map.

The analysis of the residual anomaly chart shows the existence of structural controls (thrust fronts), trending N-S, that exposed the Paleozoic units, reaching the highest topographical elevations. These structures bound both the east and west of the intermountain valleys filled by Neogene to Quaternary deposits. Besides, the residual anomaly chart reveals lateral density contrasts in a north-south direction associated with NE and NW structures that would segment the intermountain valleys (Fig. 12) (Fig. 13).

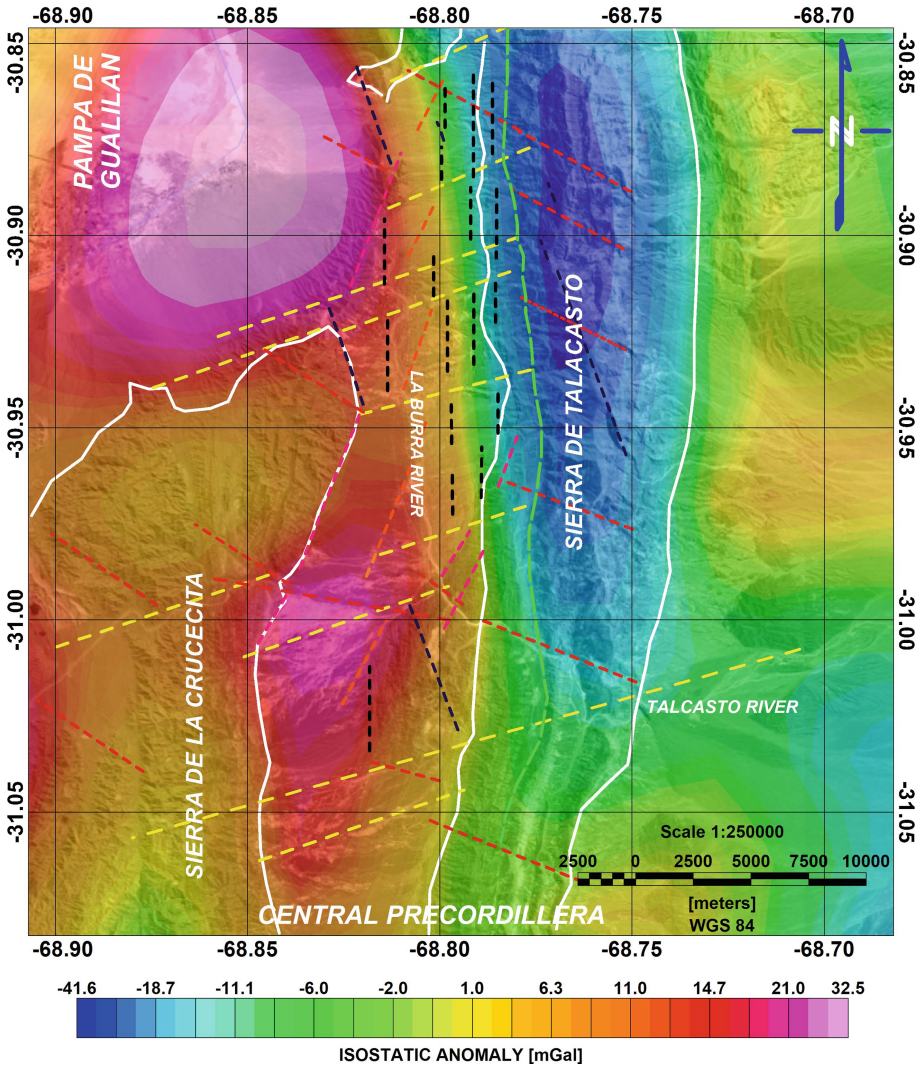


Fig. 12. Isostatic anomaly map. The isostatic anomaly chart shows the influence of the main superficial structures in the region under study.

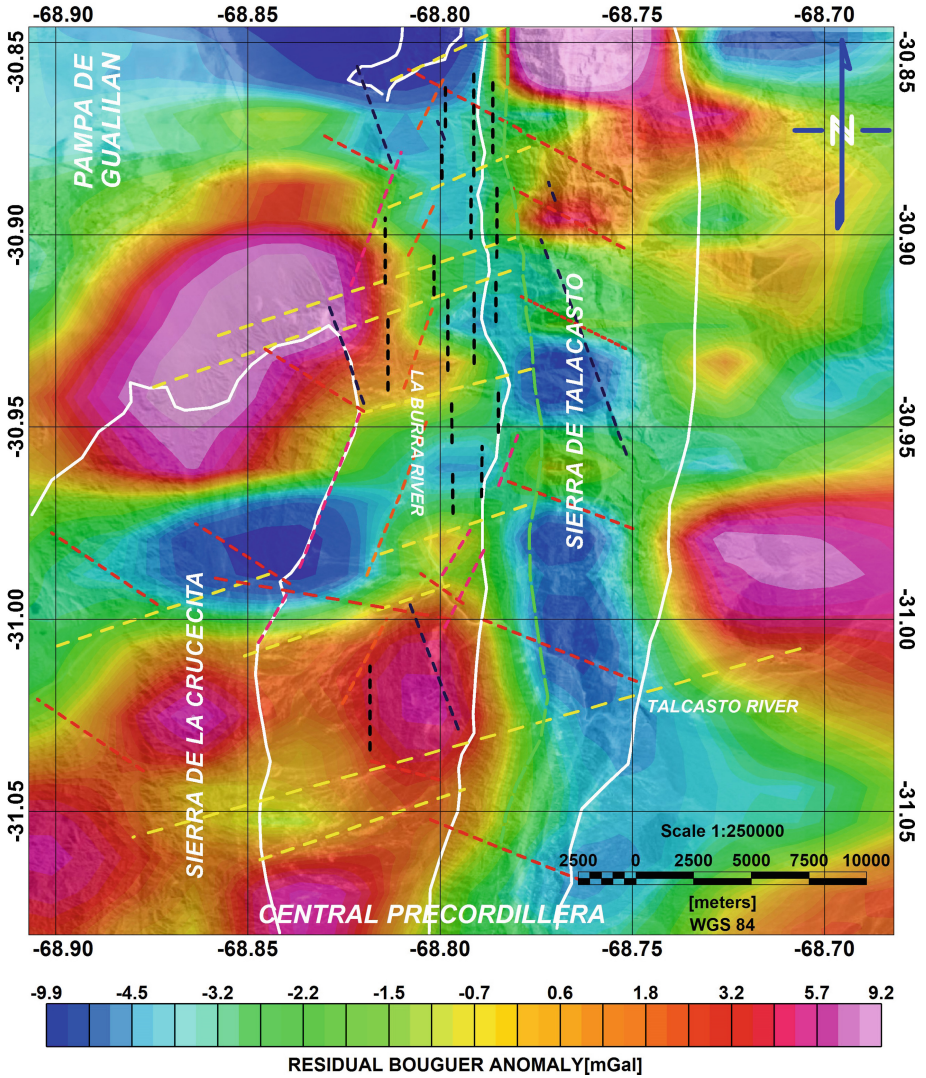


Fig. 13. Residual Bouguer anomaly map.

9 Conclusions

A neotectonic analysis in the longitudinal La Burra valley was performed between the Sierra de La Cruzecita at the west and the Sierra de Talacasto at the east. In this depression, evidence of Late Pleistocene to Holocene tectonic activity was identified, consistent with the fold-and-thrust belt area of the Central Precordillera.

Identification of several geomorphological markers showed the existence of active deformation along both piedmonts. These active structures have N-S preferential

orientation, with the exception of the Vertientes fault which trends N 30° E, affecting the Q₄ to Q₂ alluvial levels. Linear, sinuous, obstructed, diverted and incised streams, aligned springs, favor and counter-slope and flexural scarps, are common geomorphological anomalies, associated to all fault sections.

From the analysis of the two samples dated by OSL method, as well as the topographic position, pavement and varnish desert, it is suggested that the age of the alluvial levels would oscillate between the Late Pleistocene for the Q₆–Q₃ levels to the Holocene for the Q₁ and Q₂ level. From the analysis of those morphostructures identified in both piedmonts, it is possible to determine the structural control exerted by these structures and their Holocene tectonic activity. From the morphotectonic markers and natural exposures analyzed thrusts have been identified trending almost N-S, exhibiting average dips of 40° W.

The Bouguer anomalies recognized in the study area show high positive and negative values, reflecting high-density contrasts to a crustal and lithospheric scale, as well as possible isostatic disequilibrium. On the other hand, from the analysis and processing of the gravimetric data, a remarkable correlation with the most superficial crustal structure is noted. The gravimetric charts reveal lateral density contrasts in N-S direction in coincidence with main mountainous ranges, associated with NE and NW structures that cross the depression filled by Holocene deposits.

Finally, it is considered that these structures may act as potential seismogenic sources in the area of the Precordillera and that they should not be underestimated for seismological purposes, since these faults are close to four important dams located along the San Juan river and close to several of the main cities of central–western Argentina.

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