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Late Miocene to recent morphotectonic evolution and potential seismic hazard of the northern Lerma valley: Clues from Lomas de Medeiros, Cordillera Oriental, NW Argentina

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ABSTRACT

The Lomas de Medeiros are low relief hills located at the northern extreme of the Lerma valley, where new structural, morphological and topographic key data have been collected and integrated with the available stratigraphic and geochronological data in order to elucidate the morphotectonic evolution of the region during the last ~10 Ma. In this area, Pliocene to Lower Pleistocene conglomerates and siltstones (Piquete Formation) are deformed delineating an asymmetrical anticline with eastward vergence, axial plane trending N10°E, and progressive unconformities at the backlimb. Syntectonic sedimentation has been documented as related to N–S trending normal faulting near the fold axis as well. Middle Pleistocene to Holocene thick fluvial conglomerates cover unconformably the Piquete Formation as strath terraces with a few meters of thickness. The higher and oldest terrace has been uplifted more than 160 m respect to the top of Calvimonte Formation conglomerates (~0.33 Ma), its stratigraphic correlate at the undeformed Lerma valley. Detailed topographic profiles of the terraces show evidences of progressive uplifting by folding and the presence of scarps related with reverse faulting. The anticline has been modeled using the fault propagation folding mechanism with a blind ramp dipping 32° to the west and a decollement level located 2.7 km below the surface, at the contact between the Cenozoic cover and the Paleozoic basement. The integration of these observations with previously published data allowed to establish the morphotectonic evolution of this region during the last 10 Ma. Folded and faulted Middle Pleistocene to Holocene terraces at Lomas de Medeiros and Upper Pleistocene deposits uplifted at Mojotoro range are strong evidences of the seismogenic potential of the faults related with these morphostructures. Applying relationships with the subsurface rupture length, earthquakes with maximum moment magnitudes (M_w) of 6.5, 7.0 and 7.1 have been estimated for Medeiros, Lesser and Mojotoro faults respectively.

1. Introduction

The Cordillera Oriental of NW Argentina is a thick skinned fault and thrust belt characterized mainly by N–S to NNE trending basement-cored thrust sheets whose eastern part has been uplifted since late Miocene synchronously with deposition of fluvial–alluvial sediments (Carrapa et al., 2011; Carrera and Muñoz, 2008; Díaz and Malizia, 1984; Galli et al., 2011; Mon and Salfity, 1995; Monaldi et al., 1996). The Lerma valley is an intermontane basin located between 24°30′ and 25°35′ S and tectonically limited by uplifted basement ranges (Fig. 1). The infill of the basin is comprised by Upper Miocene to Pleistocene–Holocene synorogenic fluvial and alluvial siltstones, sandstones and conglomerates (Gebhard et al., 1974; Hain et al., 2011; Russo and Serraiotto, 1978; Starck and Vergani, 1996; Vergani and Starck, 1989). Middle Pleistocene to Holocene thick alluvial conglomerates of proximal provenance and minor siltstones and mudstones are filling the valley and exhibit gentle deformation at several Quaternary morphostructures (Gallardo and Georgieff, 1999; Gallardo et al., 1996; García et al., 2011a; Georgieff and González Bonorino, 2005; González Bonorino and del Valle Abascal, 2012a, 2012b; Hain et al., 2011).

In a recent review volume about the Quaternary tectonics of South America there are no reports of important neotectonic structures in the eastern part of the Cordillera Oriental (Costa et al., 2006), whereas only a few faults have been catalogued mainly in the western sector of the Cordillera Oriental but without structural nor kinematic specifications (Casa et al., 2011; Costa et al., 2000). Recently, growth strata and progressive unconformities have been documented for Pleistocene to Holocene conglomerates (Carrera and Muñoz, 2008; Hain et al., 2011) and Plio-Pleistocene thermochronological exhumation ages have been published (Carrapa et al., 2011). The strong crustal seismicity recorded in the region (Araujo et al., 1999; INPRES, 2012), suggests that the neotectonics of the eastern part of the Cordillera Oriental and surrounding areas remains poorly known and that more detailed studied

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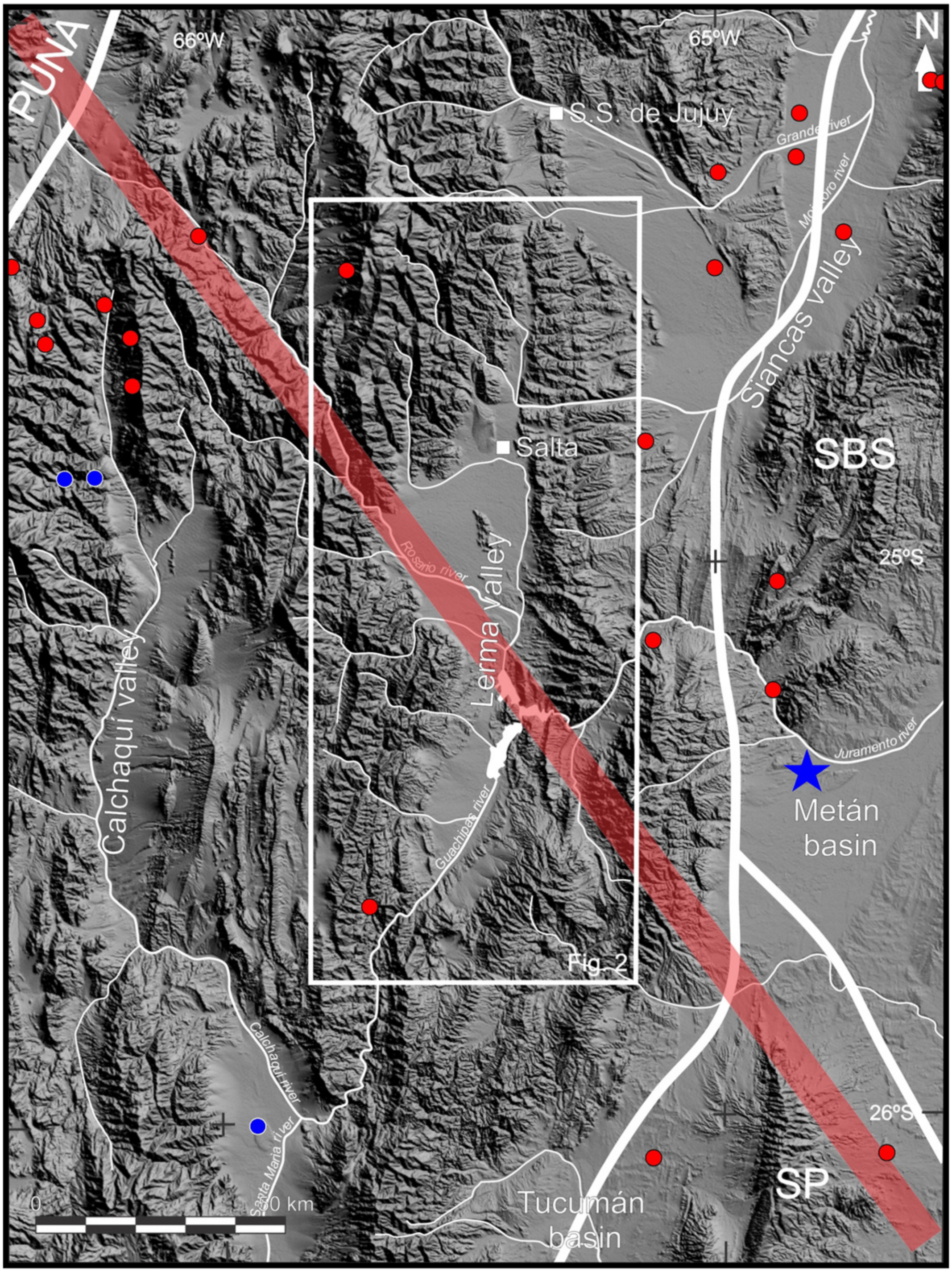
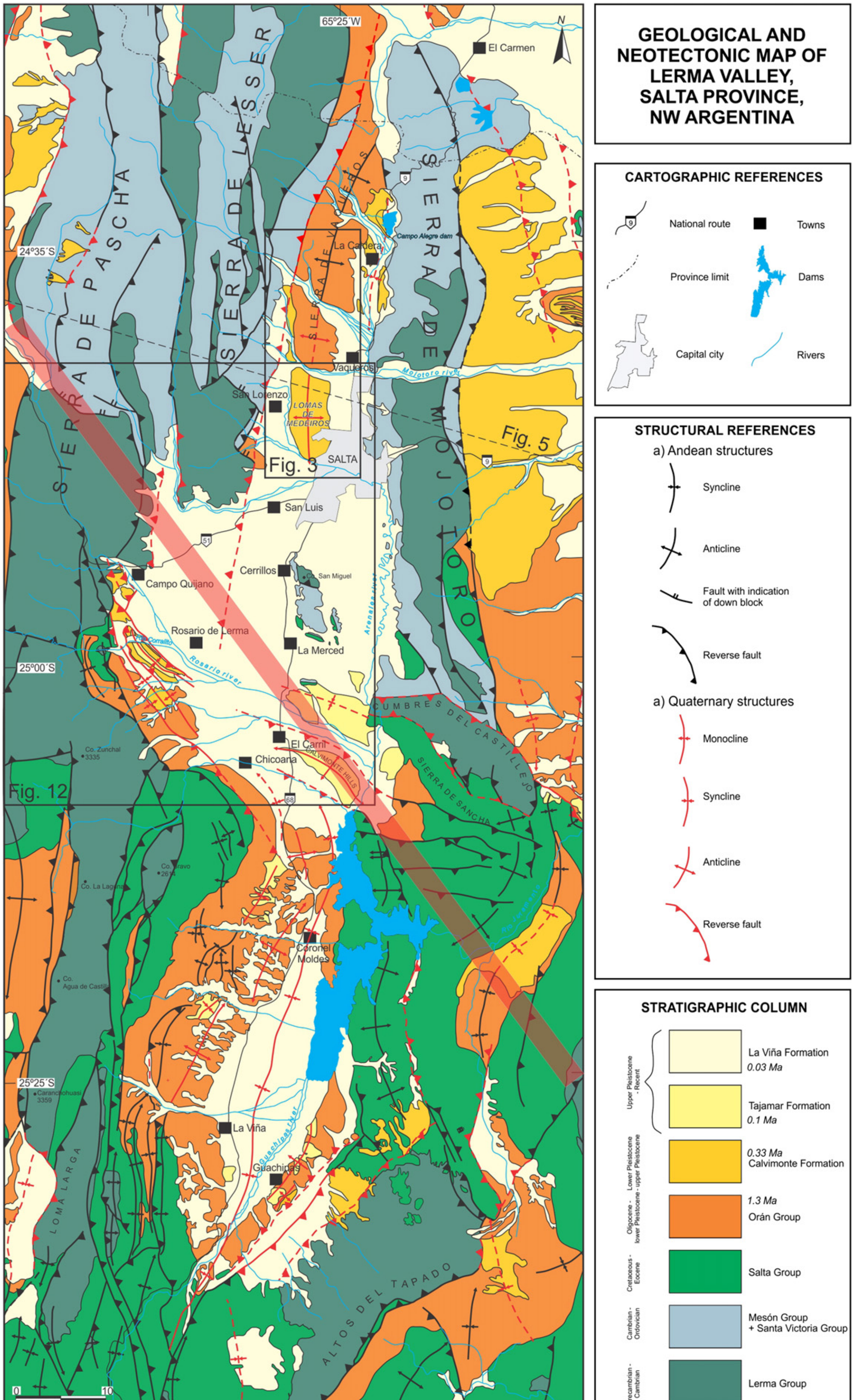


Fig. 1. Shaded relief image based on a 30 m DEM showing the location of the Lerma valley in the southern Cordillera Oriental of NW Argentina. The thick white lines indicate the boundaries between the main geological provinces (SBS: Santa Bárbara System; SP: Sierras Pampeanas). The trend of the Calama–Olacapato–Toro lineament is highlighted with the red stripe. Blue star: location of the September 13th of 1692 Talavera de Esteco historical earthquake. Blue and red dots: historical and instrumental shallow seismic activity ($M_w > 4.5$, depth < 40 km) respectively, recorded in the region prior to the $M_w = 6.1$ Salta earthquake of February, 27th 2010 (INPRES, 2012; NEIC, 2013).

are needed. Dense vegetal cover and high erosion rates harm the preservation and exposition of good outcrops and morphogenic structures, limiting the exposures to rivers and route cuts.

The Lomas de Medeiros are low relief hills located at the northernmost part of the Lerma valley (Fig. 2), just to the northwest of Salta city (536 K inhabitants). They are the geomorphic expression of the southward propagation of the Vaqueros anticline (Baudino, 1996; García, 2010, 2011; García et al., 2012). Structural data measurements and topographic surveying collected during fieldwork, have been combined with interpretation of satellite images and aerial photographs to describe the geometry of the Vaqueros–Medeiros anticline and its related fault. The integration of these new data with previously published geochronological (Carrapa et al., 2011; Hain et al., 2011; Malamud et al., 1996) and stratigraphic (Gallardo and Georgieff, 1999; González Bonorino et al., 2003; Hain et al., 2011; Russo and Serraiotto, 1978; Starck and Vergani, 1996) data has allowed to determined six stages of morphotectonic evolution of this region for the last 10 Ma, as well as to obtain shortening and uplift rates for each morphostructure.


GEOLOGICAL AND NEOTECTONIC MAP OF LERMA VALLEY, SALTA PROVINCE, NW ARGENTINA
CARTOGRAPHIC REFERENCES
National route
Towns
Province limit
Dams
Capital city
Rivers
STRUCTURAL REFERENCES
a) Andean structures
Syncline
Anticline
Fault with indication of down block
Reverse fault
a) Quaternary structures
Monocline
Syncline
Anticline
Reverse fault
STRATIGRAPHIC COLUMN
Upper Pleistocene - Recent
La Viña Formation 0.03 Ma
Tajamar Formation 0.1 Ma
Lower Pleistocene - upper Pleistocene
0.33 Ma Calvimonte Formation
Oligocene - lower Pleistocene
1.3 Ma Orán Group
Cretaceous - Eocene
Salta Group
Cambrian - Ordovician
Mesón Group + Santa Victoria Group
Precambrian - Cambrian
Lerma Group
65°25´W
N
El Carmen
SIERRA DE PASCHA
SIERRA DE LESSER
SIERRA DE MOJOTORO
24°35´S
La Caldera
Campo Alegre dam
Vaqueros
Mojotoro river
San Lorenzo
LOMAS DE MEDEIROS
Fig. 3
SALTA
Fig. 5
San Luis
Campo Quijano
Cerrillos
Co. San Miguel
Rosario de Lerma
La Merced
Rosario river
Arenales river
25°00´S
CUMBRES DEL CASTILLEJO
SIERRA DE SANCHA
El Carril
Chicoana
CALVIMONTE HILLS
Co. Zunchal 3335
Fig. 12
Co. La Laguna
Coronel Moldes
Co. Agua de Castilla
25°25´S
LOMA LARGA
La Viña
Guachipas
ALTOS DEL TAPADO
0 10 km

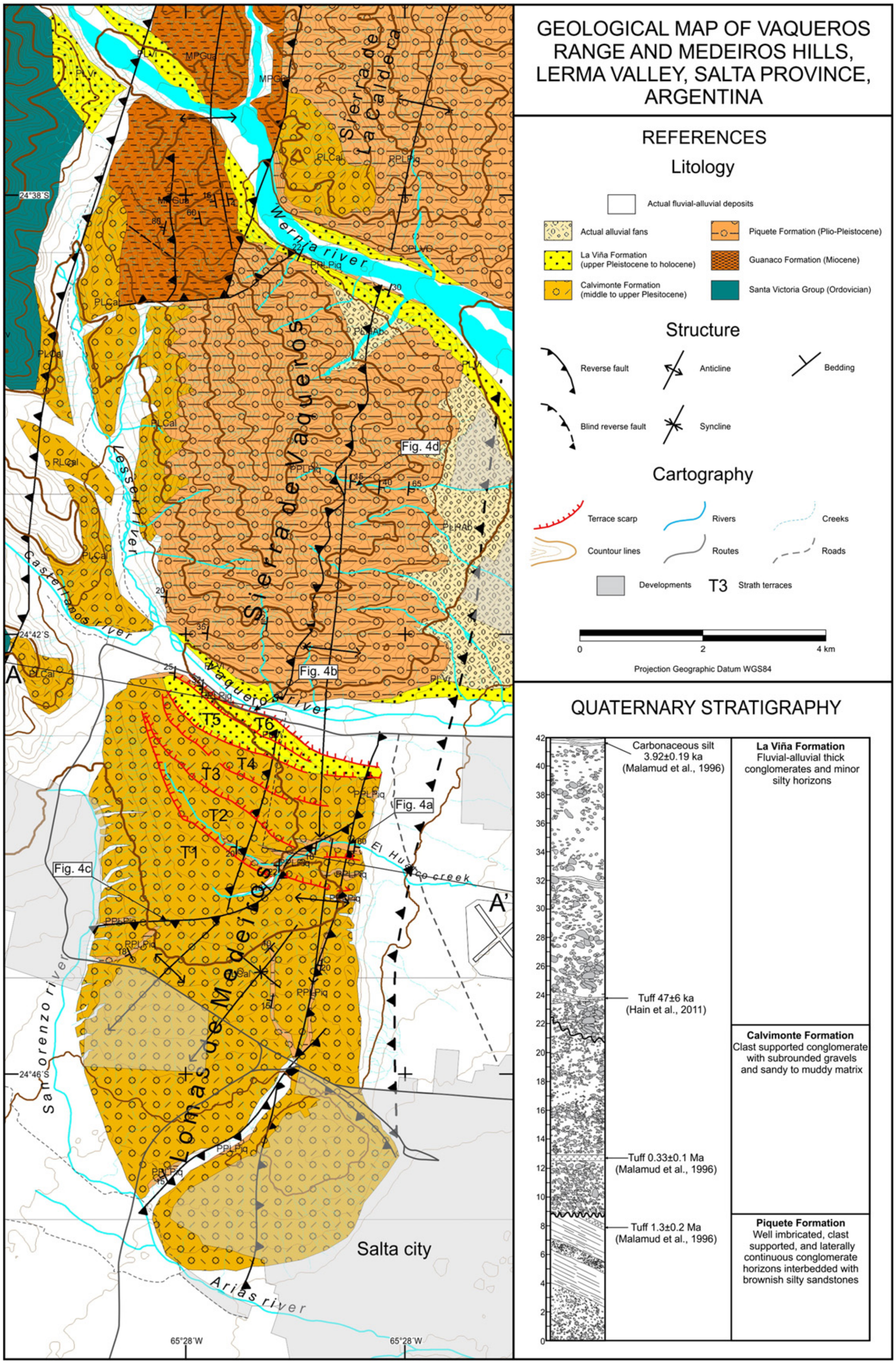


Fig. 3. Detailed geological and structural map of Lomas de Medeiros and Sierra de Vaqueros region. A — A′) Trace of the balanced structural cross section shown in Fig. 6.

Fig. 2. Geological and neotectonic map of the Lerma valley and surrounding areas. The main structures and stratigraphic units are shown. The structures with evidences of Quaternary activity have been mapped in red (dashed lines for the interpreted neotectonic structures). The trend of the Calama–Olacapato–Toro lineament is highlighted with the red stripe. Modified after Fuertes et al. (1997) and Salfity and Monaldi (2006).

Folded terraces of probable Holocene age at Medeiros hills and uplifted Upper Pleistocene deposits at Sierra de Mojotoro are the strongest evidences of the tectonically active character of these morphostructures. Estimations of the maximum expected earthquake size associated with these potential seismogenic sources have been calculated using the regressions of Wells and Coppersmith (1994). These potential seisms would be useful to improve the evaluation of the seismic hazard in the region.

2. Geological setting

The Cordillera Oriental of NW Argentina lies E of the Puna, W of the Santa Bárbara System, and N of the Sierras Pampeanas (Fig. 1). The Lerma valley is the easternmost intermontane basin in this geological province. The stratigraphy exposed at the surrounding ranges of the Lerma valley includes in sucession: deformed metasedimentary rocks of Early to Middle Cambrian age (Puncoviscana Formation); Cambro–Ordovician marine sandstones and mudstones (Mesón and Santa Victoria Groups); Cretaceous–Paleogene continental clastics, limestones, and evaporites (Salta Group); and thick (2–3 km) Mio-Pleistocene continental conglomerates and sandstones (Orán Group). These synorogenic continental strata overlie unconformably the Paleozoic units and paraconformably the Salta Group deposits (Moya, 1998; Ruiz Huidobro, 1968).

The NW–SE Calama–Olacapato–Toro lineament (Fig. 1; Salfity, 1985) divides the Lerma valley in northern and southern sectors with outstanding geological and morphostructural differences. Northward of the lineament there are scarce outcrops of Salta Group, while southward there are no records of Paleozoic sequences, evidencing a strong and long-lived morphotectonic control (Figs. 1 and 2).

2.1. Stratigraphic framework

2.1.1. Early to Middle Cambrian basement (Puncoviscana Formation)

The basement mainly consists of a monotonous succession of thin bedded sandstones and shales from Early to Middle Cambrian age (Puncoviscana Formation; Aceñolaza, 1979; Turner and Mon, 1979). These rocks were slowly metamorphosed and intruded by granites during the Cambrian (Aparicio González et al., 2010; Escayola et al., 2011).

2.1.2. Early Paleozoic strata (Mesón and Santa Victoria Groups)

The Middle to Upper Cambrian Mesón Group (Sánchez and Salfity, 1999; Turner, 1970) is represented by light gray and pink quartzite sandstones with some interbedded greenish shales. These rocks unconformably overlie the Puncoviscana Formation.

Light colored quartzite sandstones and green-yellowish sandy mudstones of the Uppermost Cambrian–Lower Ordovician Santa Victoria Group (Moya, 1998) conformably or slightly unconformably cover the Mesón Group or directly unconformably overlap the basement in some places.

The Ordovician episodes of metamorphism, magmatism and deformation, well represented in the northern Sierras Pampeanas, western Cordillera Oriental and Puna, did not affect the oldest units of the Lerma valley (Hongn and Mon, 1999; Willner, 1990).

2.1.3. Cretaceous to Paleogene rift deposits (Salta Group)

The Salta Group is divided in three subunits. The Pirgua Subgroup is composed by sandstones, conglomerates and siltstones with abrupt lateral thickness variations from thousands to some hundreds of meters in few kilometers that reveal its syn-extensional character (Marquillas et al., 2005).

The Balbuena Subgroup was accumulated during the Maastrichtian to Early Paleocene and represents the early postrift stage. The typical section is 400–500 m thick. The lower part is formed of white sandstones (Lecho Formation), and the upper part contains gray limestones (Yacoraite Formation) and dark pelites (Olmedo/Tunal Formations). These deposits cover the Pirgua Subgroup and underlie the Santa Bárbara Subgroup (Marquillas et al., 2005).

Since the Middle Paleocene, the sub-basins remained active with a very low subsidence rate, which caused the accumulation of three units of regional continuity, the Mealla, Maíz Gordo and Lumbrera Formations grouped into the Santa Bárbara Subgroup. The succession is dominated by red fine-grained sandstones and siltstones and green mudstones. This deposit represents the late postrift stage of the Salta basin (Marquillas et al., 2005).

2.1.4. Miocene to Lower Pleistocene synorogenic strata (Orán Group)

In NW Argentina the Orán Group is divided in Metán and Jujuy Subgroups (Gebhard et al., 1974). In the studied region only the younger Jujuy Subgroup crops out. The lower part of this unit is composed by reddish sandstones and mudstones with interbedded ashes grouped into the Upper Miocene Guanaco Formation (Russo and Serraiotto, 1978; Viramonte et al., 1984, 1994). This succession reaches 700 m of thickness in the Medeiros area. The uppermost part of the Jujuy Subgroup is characterized by conglomerates interbedded with brownish siltstones whose top has been dated in 1.3 ± 0.2 Ma (Malamud et al., 1996). These beds compose the Piquete Formation deposited between the Pliocene and the Lower Pleistocene synchronously with the uplift of the basement ranges that surround the Lerma valley (Monaldi et al., 1996; Reynolds et al., 1994). Growth strata geometries and great lateral thickness variations have been documented for this unit (Hain et al., 2011; Starck and Vergani, 1996). The thickness of a partial section of this unit at the backlimb of the Vaqueros–Medeiros anticline reaches 1200 m. From structural reconstructions these unit measures more than 2000 m at the northern Lerma valley.

2.1.5. Quaternary alluvial sediments

These sediments unconformably cover the older units. Gallardo et al. (1996) defined three units: Calvimonte, Tajamar and La Viña Formations.

The Calvimonte Formation covers all the extension of Lerma valley. The best outcrops of this unit expose no more than 10 m with its base covered. The succession can be described as clast-supported conglomerates with subrounded gravels and sandy to muddy matrix. In the subsurface, it shows high lateral compositional variability, with gravels and blocks at the western edge of the valley and thick to medium sands at the eastern one. The matrix varies as well from sandy to silty-muddy in a west to east transect (Baudino, 1996; Gallardo et al., 1996; González Bonorino et al., 2003).

The thickness of Calvimonte Formation in the basin is difficult to calculate because its transitional contact with the Piquete Formation. A maximum thickness of 240 m has been inferred from water wells located some kilometers southward from Medeiros hills, between the Cerrillos de San Miguel and the western edge of the basin (Baudino, 1996) and from seismic records (González Bonorino et al., 2003; Hain et al., 2011). Malamud et al. (1996) have reported a Zircon FT age of 0.33 ± 0.10 Ma from a tuff layer interbedded in terraces that correlated with Calvimonte Formation near the Campo Alegre dam (Fig. 2). The depositional time span estimated for this unit would be between ~1.05 and ~0.10 Ma in the Lerma valley (Malamud et al., 1996).

In the studied area, the Calvimonte Formation is represented by a thin deposit of conglomerates (less than 10 m) that covers the four older strath terraces (T1 to T4) of Lomas de Medeiros (Fig. 3). The contact with the Piquete Formation in this sector is represented by an angular unconformity (Fig. 4a).

The Tajamar Formation (Gallardo and Georgieff, 1999; Gallardo et al., 1996) is composed by laminated clay rhythmites of millimetric to centimetric white and pink layers alternating with millimetric darker layers (Malamud et al., 1996). This unit is ~0.1 Ma and has been interpreted as the relict of a paleo-lake that covered almost completely the surface of Lerma valley (Malamud et al., 1996). Nevertheless, in the northernmost Lerma valley there are not outcrops of these sediments.

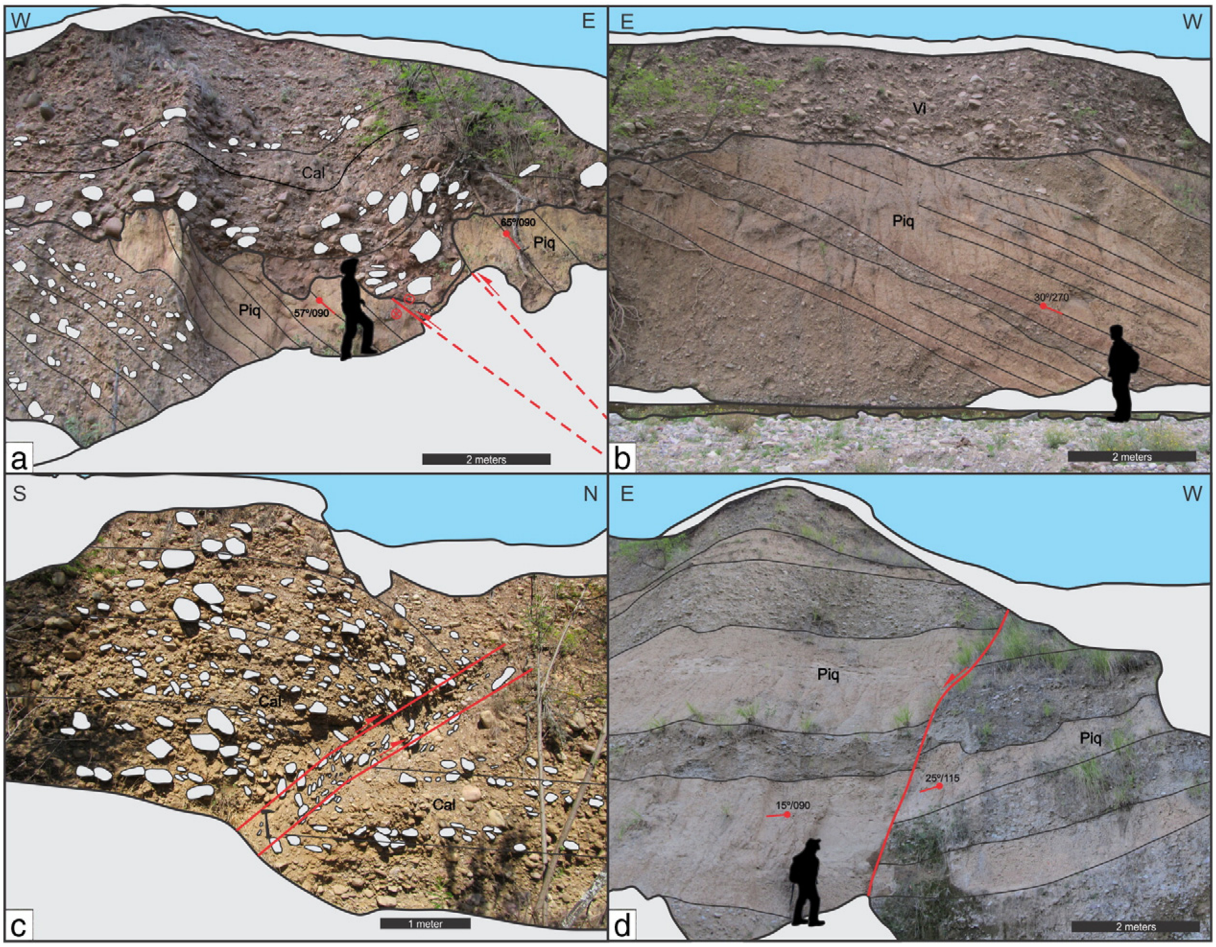


Fig. 4. a) Subhorizontal thick conglomerates unconformably covering conglomerates and siltstones dipping between 57° and 65° to the east at El Huaico creek. A interstratal reverse fault is displacing the unconformity and the upper conglomerates. b) Conglomerates and siltstones dipping 30°/W to the west covered unconformably by subhorizontal thick conglomerates at the right margin of the Vaqueros river. c) Thick conglomerates dragged by a reverse fault dipping 30°/SSE to the SSE at a small creek in the backlimb of the Medeiros anticline. d) Conglomerates and siltstones gently dipping to the east and affected by a high angle normal fault with evidences of syntectonic sedimentation. Piq: Piquete Formation; Cal: Calvimonte Formation; Vi: La Viña Formation. See location of the photographs in Fig. 3.

The La Viña Formation (Gallardo and Georgieff, 1999; Gallardo et al., 1996) is found throughout the Lerma valley and consists of fluvial–alluvial conglomerates and minor siltstones with thickness up to 30 m (Malamud et al., 1996). In the studied area this unit has been correlated with the cover of the two younger strath terraces (T5 and T6) at the northern extreme of Lomas de Medeiros.

Hain et al. (2011) introduced La Troja Formation to describe all the post-Piquete Formation sediments that fill the Lerma valley and Metán area. Tuffs interbedded in fluvial conglomerates gave zircon U/Pb ages of around ~0.05 Ma (Hain et al., 2011). Although the use of this new name is avoided in the present contribution because of the simplification that supposes for the Quaternary stratigraphy, its age can be applied for La Viña Formation.

Recently, González Bonorino and del Valle Abascal (2012a, 2012b) grouped the fluvial–alluvial Quaternary deposits of Lerma valley into the Lerma Valley Group. Due to possible naming confusions with the Lerma Group of Early to Middle Cambrian age (Escayola et al., 2011; Salfity et al., 1975), the classical subdivision of Gallardo et al. (1996) is preferred in this study.

2.2. Tectonic setting

The studied area is located in the southern extreme of the Cordillera Oriental near its eastern boundary with the Santa Bárbara System (Fig. 1). The Andean structure at these latitudes is characterized by a thick skinned fold and thrust belt with an estimated decollement level at a depth of ~15–20 km (Carrapa et al., 2011; Carrera and Muñoz, 2008; Cristallini et al., 1997; Hongn et al., 2010; Mon, 1976; Mon and Salfity, 1995; Monaldi et al., 1996). The main thrusts and faults are N–S trending with some important oblique structures (NW–SE) like the Calama–Olacapato–Toro lineament (Salfity, 1985). The Andean structures show the typical double-vergence of the Cordillera Oriental (e.g. Mon and Salfity, 1995). Albeit the west-vergent structures seem to be dominant, the more prominent thrusts are east verging. This arrangement is the combined result of the reactivation of Cretaceous normal faults and pre-Andean basement structural grain, and the eastward transport of basement wedges at depth (Carrera and Muñoz, 2008; Cristallini et al., 1997; Mon and Hongn, 1991). Two west-dipping subparallel thrusts uplift the Sierra de Pascha–Sierra de Lesser and Sierra de Mojotoro while minor backthrusts split the Sierra de Pascha and Sierra de Lesser (Fig. 5). The northern Lerma valley is a piggy-back basin lying between these ranges. The Sierra de la Caldera and Sierra de Vaqueros are composed by Piquete Formation whose structure delineates an assymmetrical anticline with east vergence. The low relief hills of Lomas de Medeiros are the topographic expression of the southward propagation of this anticline (Figs. 2 and 3). The shallower decollement levels that control the folding at Vaqueros–Medeiros and proto-Sierra de Mojotoro structures were derived from their respective wavelengths (Fig. 5).

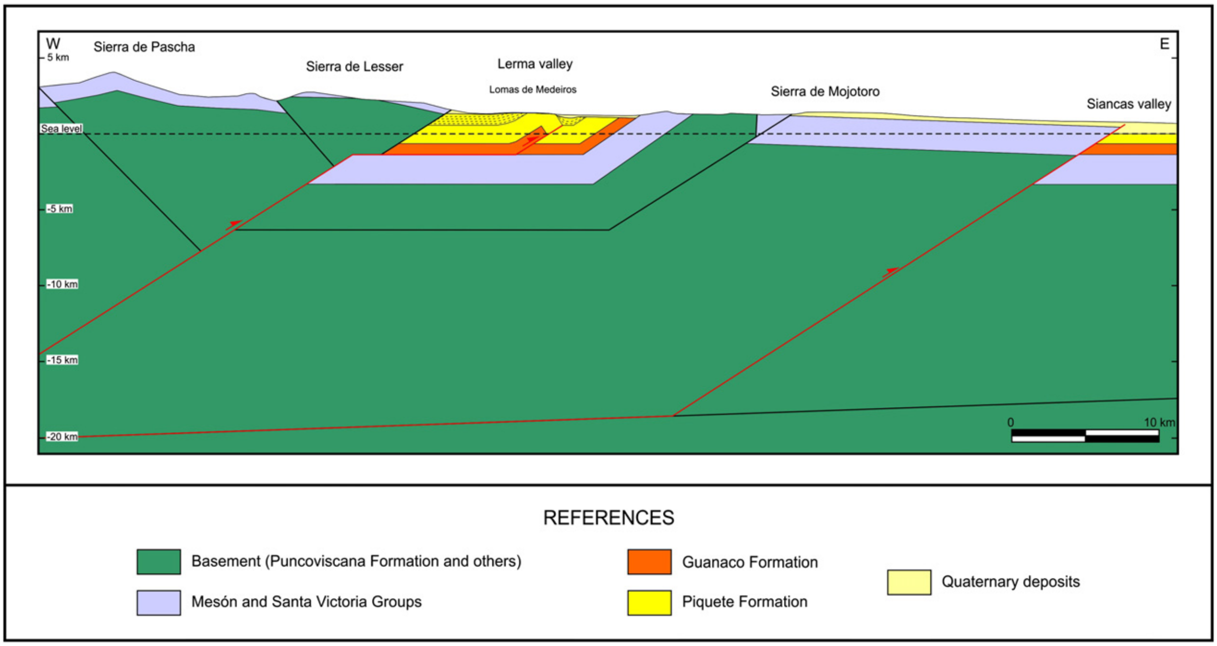


Fig. 5. Regional structural cross section of the northern Lerma valley (compilation of data from Baudino, 1996; Fuertes et al., 1997; González Bonorino et al., 2003; García et al., 2011a; this study). See location of the section in Fig. 2.

3. Structure

Detailed structural and geological mapping have been done in the Lomas de Medeiros and Sierra de Vaqueros, paying special attention to the relationship between the Piquete Formation and the Middle Pleistocene to Holocene alluvial sediments, and to the presence of growth strata geometries and synsedimentary faults. A geological and neotectonic map of the area (Fig. 3) and a balanced structural cross section have been constructed with the collected data (Fig. 6).

3.1. Lomas de Medeiros

The outcrops of the Piquete Formation along the Lomas de Medeiros are restricted to small creeks and to the right margin of the Vaqueros river at the northernmost part of these hills. At the headwaters of the El Huaico creek (Fig. 3), this unit dips around 20°/W. Nearly one kilometer and a half to the east, the same unit is subhorizontal and just a couple hundred meters eastward these strata dips 60°/E. The unconformable relationship between the Piquete and Calvimonte Formations can be observed near the outlet of this creek. At this site, an interstratal reverse fault developed along muddy layers of the Piquete Formation displaces almost 2 m the Calvimonte conglomerates (Fig. 4a). Near the fold axis, several N–S trending high-angle normal faults have been recognized with evidences of syn-sedimentary displacement during the deposition of the Piquete Formation.

The northernmost part of the hills has been incised by the Vaqueros river, exposing at its right margin the most continuous section of Piquete Formation. The dips measured at this site range between 32° and 15°/W, decreasing progressively from east to west. The angular unconformity with La Viña Formation is well developed in this sector as well (Fig. 4b).

At some small creeks in the westernmost part of the hills, the Piquete Formation dips between 10° and 18°/WSW, being covered subhorizontally by the Calvimonte Formation. A reverse fault dipping 30°/SSE dislocates this unit at least 2 m (Fig. 4c). In the southernmost part of the hills the outcrops of the Piquete Formation are scarce and almost completely covered by the Calvimonte Formation. In some places it is possible to measure dips up to 10°/S in the Piquete Formation showing the southward plunging of the fold axis.

3.2. Sierra de Vaqueros

The Sierra de Vaqueros is mainly composed by conglomerates and siltstones from the Piquete Formation. At the southwestern sector, this unit dips between 15° and 40°/W, decreasing progressively from east to west. To the northwest, dips vary between 20° and 30°/W showing the same decreasing pattern (Fig. 3).

In the central E–W creek of the range Piquete Formation dips 10°–15°/E near the fold axis and 68°/E in the outlet. High-angle N–S normal faults can be observed just to the east of the fold axis with evidences of synsedimentary activity during the deposition of the Piquete Formation (Fig. 4d). This kind of faults were not mapped due scale reasons.

Reddish sandstones and siltstones correlated with the Guanaco Formation crop out towards the northwest of the Sierra de Vaqueros (Fig. 3). The contact between this unit and the Piquete Formation is a thrust dipping around 45°/W. In this sector the Guanaco Formation is dipping between 45° and 60°/W and intensely deformed showing repeated sheets of overturned folds limited by reverse faults. The N–S striking main thrust merges with a secondary oblique one in its southern end.

3.3. Structural cross section

The Vaqueros–Medeiros anticline has been modeled as a fault propagation fold (Suppe and Medwedeff, 1990) with the software Pliegues 2D (Cristallini, 2002–2008). The fold was modeled as developed over a ramp dipping around 32° to the west with a decollement level located at 1400 m b.s.l. along the contact between the Cenozoic and the Paleozoic basement (Fig. 6). The frontal limb dips 60° to the east while the backlimb dips around 32° to the west. The accumulated slip of the fault is 1700 m and the propagation reaches 3700 m giving a P/S relation of 2.15. The maximum structural relief at the fold axis attains 1300 m.

The progressive decreasing of dips measured for the upper section of Piquete Formation at the westernmost part of the Vaqueros–Medeiros

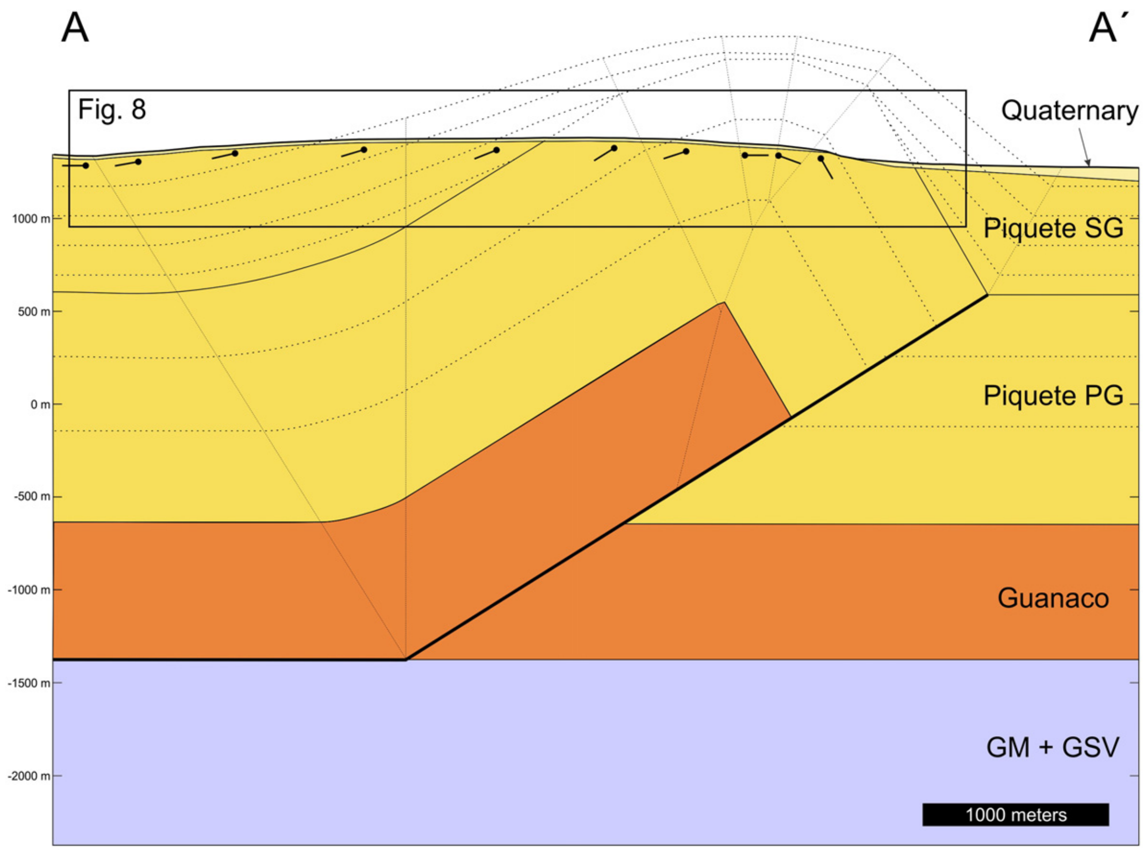


Fig. 6. Balanced structural cross section of the Lomas de Medeiros (see location in Fig. 3). The ramp is dipping 32°/W and the decollement level is located at the contact between the Paleozoic rocks and the Cenozoic cover. SG: syn-growth strata; PG: pre-growth strata; GM + GSZ: Mesón and Santa Victoia Groups. Jujuy Subgroup thickness from: Hain et al. (2011); Iaffa et al. (2011); this study.

backlimb has been modeled applying the backlimb trishear algorithm (Cristallini and Allmendinger, 2002) using an apical angle of 30° (Fig. 6).

4. Tectonic geomorphology

The strath terraces preserved in the northern part of the Lomas de Medeiros are the most outstanding geomorphic markers in the studied area. In order to determine the geometry of these surfaces, detailed topographic profiles were surveyed using a GPS receiver with barometric altimeter and then corrected with ground control points from a SRTM-X DEM of 30 m of spatial resolution (Fig. 7a).

4.1. Uppermost surface of Lomas de Medeiros

The oldest strath terrace level (T1) shaves the folded Piquete Formation and composes the broader uppermost surface of Lomas de Medeiros (Fig. 3). The gravels composition and the textural appearance allow to correlate the conglomerates covering T1 with the Calvimonte Formation. This surface can be topographically correlated with remnants of strath terraces at the headwaters of the Lesser river preserved more than 100 m above the actual river course (Fig. 3). Both features (T1 surface and Lesser river terraces) should have been created by the erosive action of a river with a drainage area much more extensive than the Vaqueros river catchment. In the following section a possible explanation for this observation is discussed.

Two subparallel reverse fault scarps running NE–SW uplift the southern blocks of the hills to the NW (Fig. 3). The northern one has been correlated with the fault deforming the Calvimonte Formation showed in the Fig. 4c and a maximum scarp height of 5 m was measured. The southernmost fault has accumulated more throw with 15–25 m of scarp height (Fig. 3).

Another reverse fault scarp was identified affecting T1 surface. This scarp has a N10°E trend and is developed at the frontal limb of the fold running subparallel to its topographic break with the piedmont (Fig. 3). This scarp is related with interstratal slip in Piquete Formation mudstones (Fig. 4a) and its height ranges between 5 and 20 m.

4.2. Strath terraces of Paleo-Vaqueros river

The surveyed topographic profiles (Fig. 7a) have been re-projected along an E–W line, perpendicular to the axis of the anticline, in order to evaluate if the terraces are folded. The Vaqueros river has a convex down profile showing a tendency to balance the stream power and the transported sediments. The terraces' profiles, instead, are convex up indicating that they were affected by successive folding events (Fig. 7b).

The altitude difference between the terraces and the Vaqueros river was calculated to quantify the amount of deformation accumulated by each one (Fig. 7d). The profiles of the older terraces (T1, T2 and T3) show an irregular design in the eastern half of the fold reflecting degradation by erosional processes. The younger T4, T5 and T6 terrace profiles are more symmetrical. The amplitude of the folding is maximum for T1 (80 m) and minimum for T6 (10 m).

The resulting geometry of the terraces at the backlimb has been successfully modeled by means of the trishear algorithm (Cristallini and Allmendinger, 2002) using the profile of the actual Vaqueros river as undeformed feature (Fig. 8).

The erosional behavior of the Vaqueros river at Lomas de Medeiros during the last ~1.3 Ma is shown by the strath terraces studied. Nonetheless, continuous alluvial sedimentation has been documented in the adjacent basin roughly for the same period (Gallardo and Georgieff, 1999; Gallardo et al., 1996; González Bonorino and del Valle

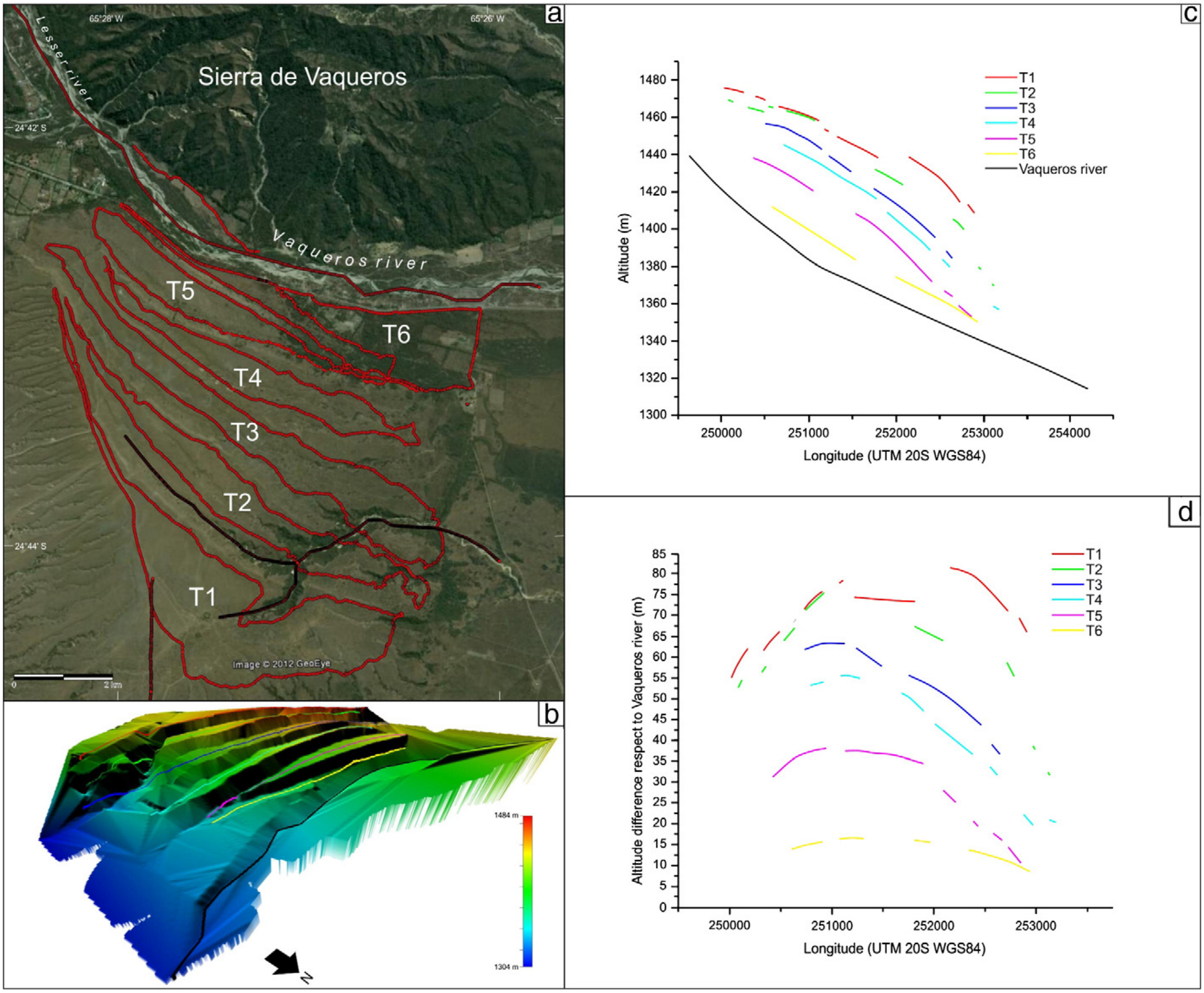


Fig. 7. a) Topographic profiles surveyed on the northern terraces of the Lomas de Medeiros and Vaqueros river (Geoeye image from GoogleEarth(R)). b) Digital elevation model constructed with the surveyed profiles with the traces of the topographic profiles used to determine the deformation of each terrace (vertical exageration = 5x). c) Topographic profiles of the terraces and the Vaqueros river projected over a line perpendicular to the fold axis (vertical exageration = 21x). d) Altitude difference between the terraces and the Vaqueros river (vertical exageration = 41x).

Abascal, 2012a, 2012b; González Bonorino et al., 2003; Malamud et al., 1996). At the undeformed Lerma valley, 2 km to the southeast of Lomas de Medeiros, the top of the Calvimonte Formation is located at least 80 m below the surface (Baudino, 1996). This fact indicates that the total structural uplift for each terrace should be, at least, twice of the measured with respect of Vaqueros river.

5. Morphotectonic evolution

Field observations, structural measurements and available stratigraphic and geochronological data have been integrated in order to establish the late Miocene to Recent morphotectonic evolution of the northern Lerma valley. Six stages have been recognized, obtaining the mean uplift and shortening rates for each morphostructure involved.

5.1. Stage 1 (~10 Ma to ~5 Ma)

Prior to the Pliocene, the Lerma and Siancas valleys were broader and divided by the proto-Sierra de Mojotoro, a regional N–S anticline with basement outcrops at its core that represents the Andean orogenic front for those times at these latitudes (Fig. 9a; Moya, 1998). The asymmetry of the fold indicates its eastern vergence related with a west dipping thrust, while its wave-lenght is in agreement with a detachment located at around 5 km of depth into the basement (Fig. 10a). Hain et al. (2011) have demonstrated the activity of this structure between ~10 Ma and ~5 Ma from provenance analysis on sandstones from the Guanaco Formation. The incipient uplifting of the Sierra de Pascha composes the western border of Lerma valley at this stage (Fig. 10a).

The continuity of the Guanaco Formation outcrops on both sides of the proto-Sierra de Mojotoro indicates a balance between uplift, erosion and flexural subsidence rates at this point. The uplift rate calculated for the proto-Sierra de Mojotoro and Sierra de Pascha derived from structural reconstructions (Fig. 10a) gave ~0.6 mm/year and 0.25 mm/year respectively (Fig. 11a).

The shortening accumulated by the Mesón and Santa Victoria Groups during this period is around 4.6 km at a rate of ~0.92 mm/year (Fig. 11b).

5.2. Stage 2 (~5 Ma to ~2 Ma)

Between ~5 Ma and ~2 Ma, prior to the start of growth of the Vaqueros–Medeiros anticline, the uplift of the Sierra de Lesser controlled the deposition of the lower to middle sections of Piquete Formation

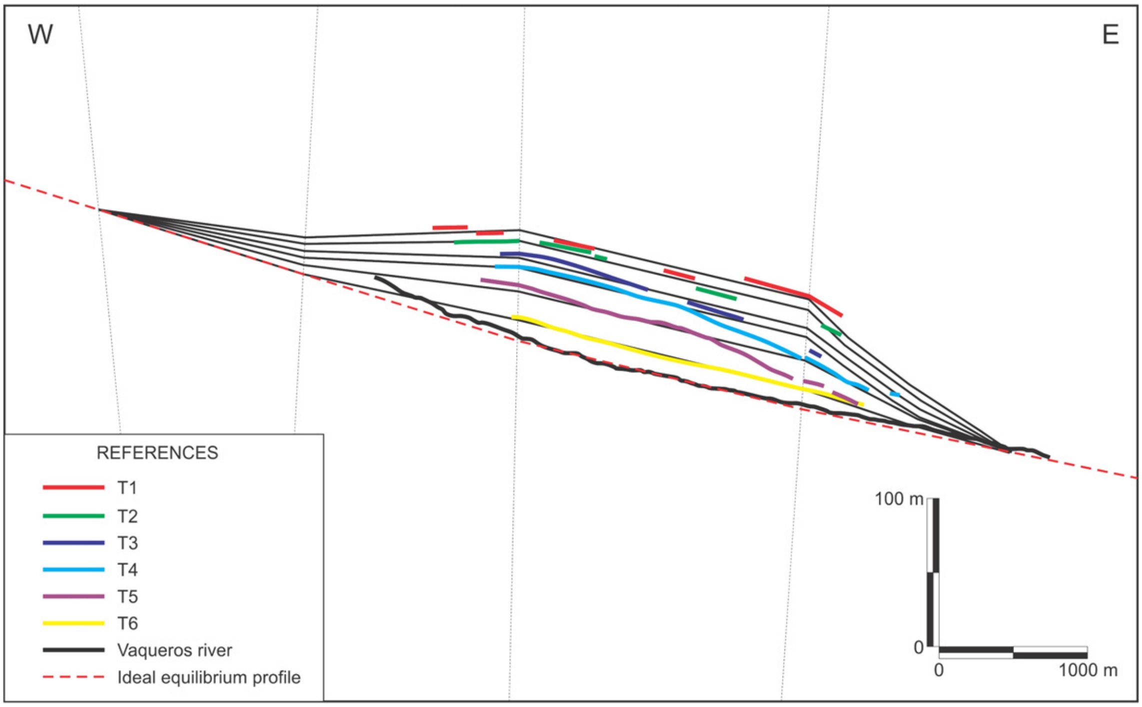


Fig. 8. Comparison between the folded terraces measured and the geometries obtained from an ideal equilibrium profile applying the same backlimb trishear algorithm than in the Fig. 6 (vertical exageration = 10x).

(Fig. 10b). The piedmont river network during this time span was characterized by subparallel E–W streams with the majority of headwaters at Sierra de Lesser and some antecedent rivers flowing from the Sierra de Pascha (Fig. 9b). The Sierra de Mojotoro did not exerted a major control on river networks as evidenced by the deposition of Piquete strata of finer grain in the Siancas valley and almost without proximal provenance (Figs. 9b and 10b; Hain et al., 2011).

From Fig. 10b, the minimum structural relief generated by the Sierra de Lesser with respect to its piedmont is around 2850 m giving an uplift rate of ~0.95 mm/year during this stage.

The mean sedimentation rate of the basal to middle section of Piquete Formation is ~0.43 mm/year. Due the lack of Piquete Formation outcrops at the Sierra de Mojotoro, it must started to grow at this stage by the inception of a new and deeper thrust, but at slightly slower rate than subsidence, being a by-pass sector for sediment transport (Fig. 10b). Supposing that the accomodation space generated by flexural subsidence is overcome by sedimentation then the uplift rate of Sierra de Mojotoro must be just below or close to ~0.43 mm/year (Fig. 11a).

The shortening accumulated by the Paleozoic units at Pascha–Lesser and Mojotoro structures during this period is around of 6.2 km at a rate of ~2 mm/year (Fig. 11b).

5.3. Stage 3 (~2 Ma to ~1.3 Ma)

The synsedimentary normal faults at the fold axis (Fig. 4d) and the progressive unconformities in the upper section of Piquete Formation at the backlimb (Fig. 6), are both evidences of the beginning of folding at the Vaqueros–Medeiros anticline since ~2 Ma (Fig. 9c). During this period the southern Sierra de Lesser was exposed causing the detour of the Arenales river to the south (Fig. 9c), while the Sierra de Mojotoro should have had the same behavior than in the previous stages, allowing the sedimentation of the Piquete Formation to the east (Fig. 10c; González Bonorino and del Valle Abascal, 2012a, 2012b; Hain et al., 2011).

During this period the Sierra de Lesser was uplifted another 700 m (Fig. 10c) at an uplift rate of ~1 mm/year. The vertical component of the folding process at Vaqueros–Medeiros anticline for this time span is around 600 m, giving a mean uplift rate of ~0.85 mm/year (Fig. 11a). The mean sedimentation rate of the upper section of Piquete Formation was 1 mm/year.

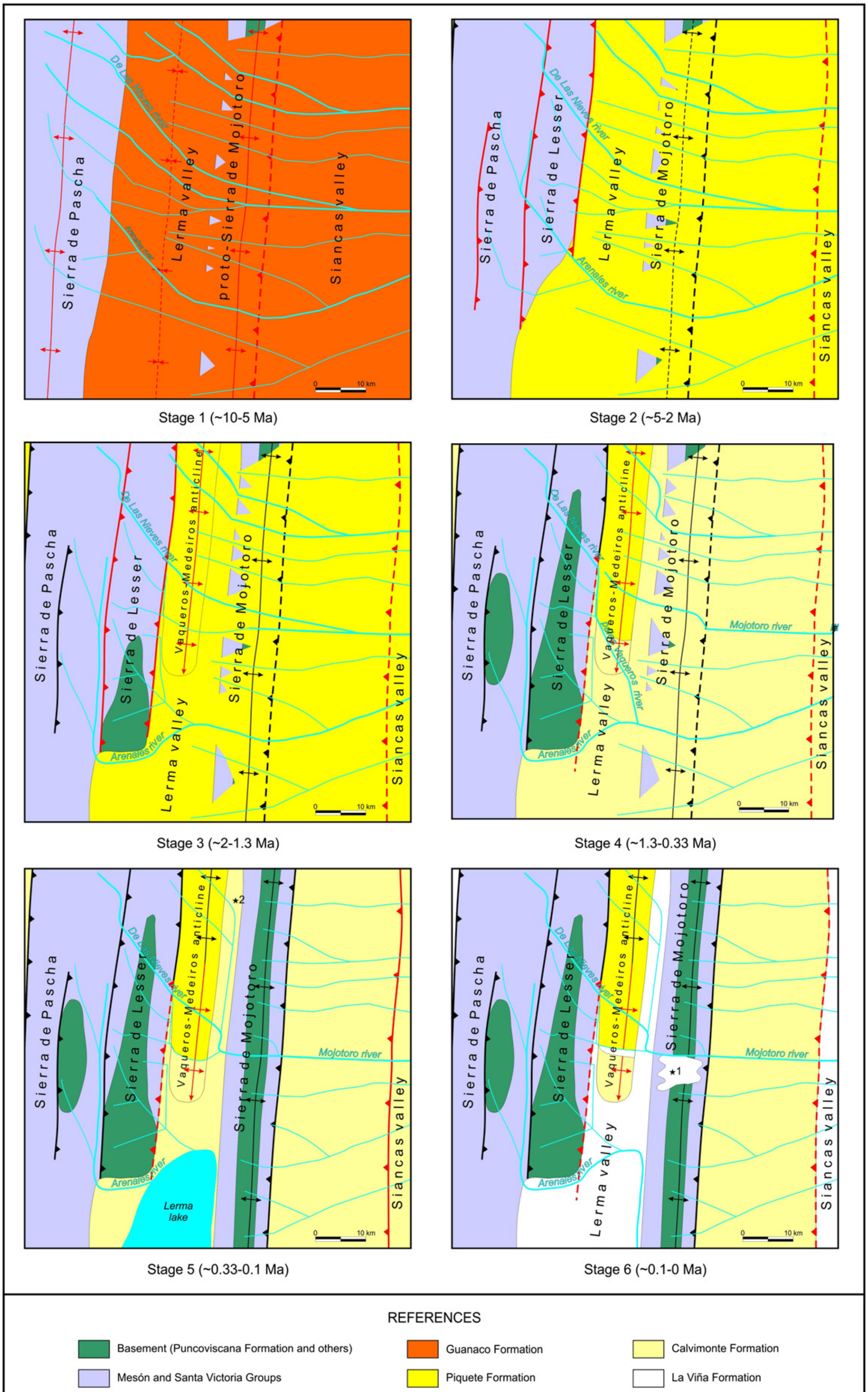
The shortening accumulated by Paleozoic deposits at Pascha–Lesser and Mojotoro structures during this period is around of 2.1 km giving a rate of ~3 mm/year (Fig. 11b).

5.4. Stage 4 (~1.3 Ma to ~0.33 Ma)

The angular unconformity that separates Piquete and Calvimonte Formations at the Lomas de Medeiros encompasses a depositional hiatus between ~1.3 Ma and ~0.33 Ma (Malamud et al., 1996). In the Lesser river headwaters there is an extended strath terrace more than 100 m above the actual course (Fig. 3), suggesting that a bigger paleo-river was the responsible for its formation. This terrace can be topographically correlated with the oldest terraced surface (T1) in Lomas de Medeiros. The incremental uplift of the Vaqueros–Medeiros anticline and the progressive exhumation of less erodable deposits could explain the southward detour of De Las Nieves river and its capture by the Lesser river, that reached a stream power enough to shave the Lomas de Medeiros while it was growing. At the same time the Sierra de Mojotoro continues its gradual uplift without significant exhumation (Figs. 9d and 10d).

The amount of material eroded from the Lomas de Medeiros during this stage has been measured using the maximum uplift of the younger growth strata from the balanced structural cross section (Fig. 6) and subtracting 160 m of post ~0.33 Ma uplift giving around 540 m. Thereby, the mean uplift rate for Vaqueros–Medeiros anticline is ~0.54 mm/year for this period.

The piedmont deposits at the eastern flank of Sierra de Mojotoro can be correlated with the Calvimonte Formation. In this area the uppermost surface of this deposits is around 480 m above the top of the Calvimonte Formation at the Lerma valley. By subtracting 200 m of uplift undergone in the last ~0.33 Ma, the altitude difference of 280 m gives a mean uplift rate of ~0.28 mm/year of the Sierra de Mojotoro for the stage 4 (Fig. 11a).


Sierra de Pascha
De Las Nieves river
Lerma valley
proto-Sierra de Mojotoro
Siancas valley
0 10 km
Stage 1 (~10-5 Ma)
Sierra de Pascha
Sierra de Lesser
De Las Nieves river
Lerma valley
Sierra de Mojotoro
Arenales river
Siancas valley
0 10 km
Stage 2 (~5-2 Ma)
Sierra de Pascha
Sierra de Lesser
De Las Nieves river
Vaqueros-Medeiros anticline
Sierra de Mojotoro
Arenales river
Lerma valley
Siancas valley
0 10 km
Stage 3 (~2-1.3 Ma)
Sierra de Pascha
Sierra de Lesser
De Las Nieves river
Vaqueros-Medeiros anticline
Sierra de Mojotoro
Mojotoro river
Arenales river
Lerma valley
Siancas valley
0 10 km
Stage 4 (~1.3-0.33 Ma)
Sierra de Pascha
Sierra de Lesser
De Las Nieves river
Vaqueros-Medeiros anticline
★2
Sierra de Mojotoro
Mojotoro river
Arenales river
Lerma lake
Siancas valley
0 10 km
Stage 5 (~0.33-0.1 Ma)
Sierra de Pascha
Sierra de Lesser
De Las Nieves river
Vaqueros-Medeiros anticline
Sierra de Mojotoro
Mojotoro river
★1
Arenales river
Lerma valley
Siancas valley
0 10 km
Stage 6 (~0.1-0 Ma)
REFERENCES
Basement (Puncoviscana Formation and others)
Mesón and Santa Victoria Groups
Guanaco Formation
Piquete Formation
Calvimonte Formation
La Viña Formation

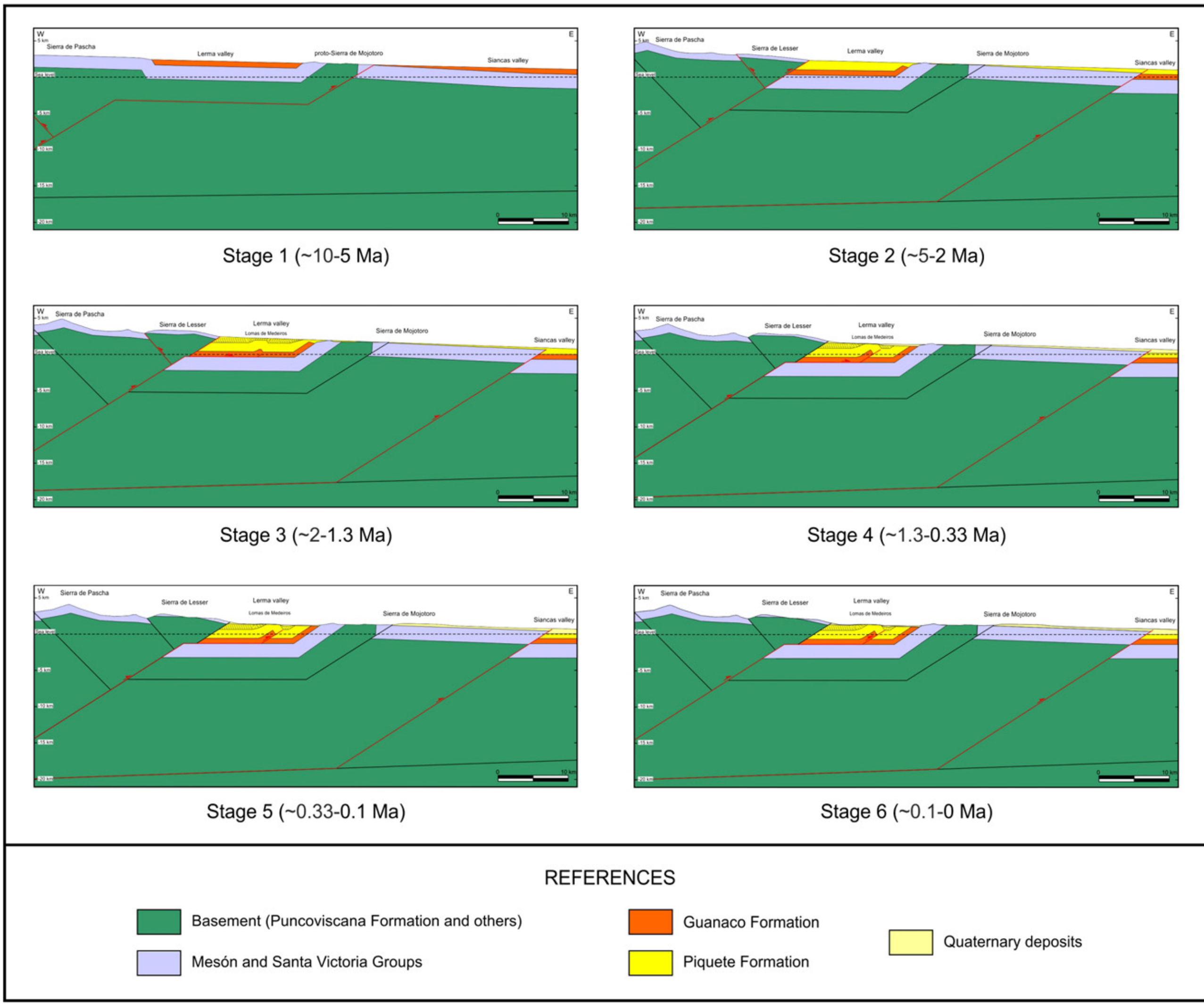


Fig. 10. Regional squematic structural cross sections showing the evolution and the faulting sequence of the northern Lerma valley and the surrounding ranges.

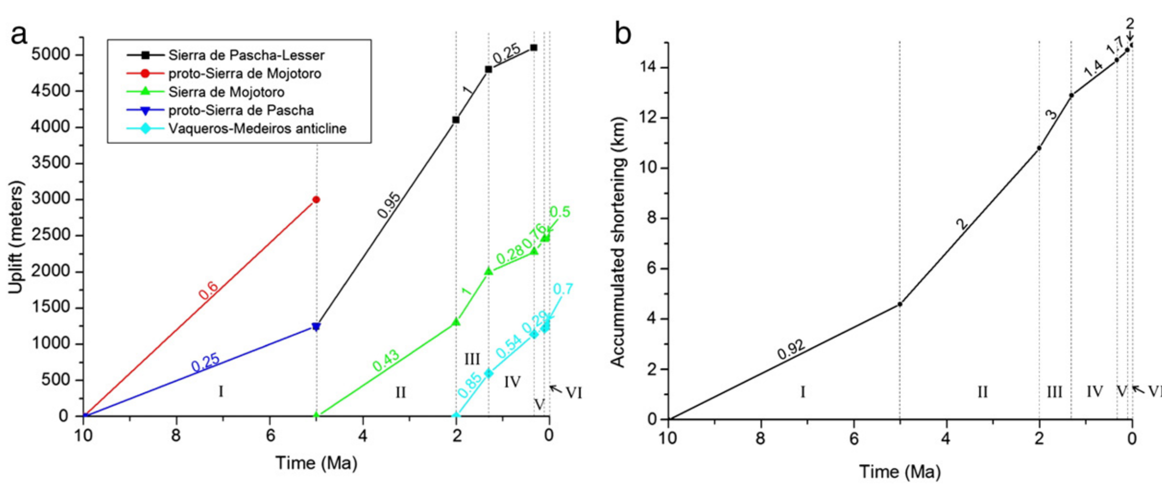


Fig. 11. a) Late Miocene to recent evolution of the mean uplift rate (mm/year) of the Sierra de Pascha–Lesser, Sierra de Mojotoro and Vaqueros–Medeiros anticline. b) Late Miocene to recent evolution of the mean shortening rate (mm/year) of the Cambro–Ordovician rocks with respect to the regional structural section.

Fig. 9. Late Miocene to recent morphostructural evolution of northern Lerma valley showing drainage networks, active morphostructures and depositional units. 1: Tuff dated at 47 ± 6 Ka ($^{238}U-^{230}Th$ zircon model ages, Hain et al., 2011); 2: Zircon FT age of 0.33 ± 0.10 Ma from a tuff layer interbedded in terraces correlated with Calvimonte Formation (Malamud et al., 1996).

The shortening accumulated by the Mesón and Santa Victoria Groups during this period is around 1.4 km at a rate of ~1.4 mm/year (Fig. 11b).

5.5. Stage 5 (~0.33 Ma to ~0.1 Ma)

Between ~0.33 Ma and ~0.1 Ma the T2–T4 strath terraces were sculpted at the northern Lomas de Medeiros. The changes in the erosional capacity and base level could be related with the re-capture of the De Las Nieves river by retrograde erosion of the Wierna river (Fig. 9e). The growing of Lomas de Medeiros continues during this period as evidenced by the folded terraces (Figs. 7 and 10e). The fault scarps affecting T1–T3 terraces (Fig. 3) were probably formed during this stage. Assuming an age of ~0.275 Ma for T2 strath terrace and 80 m of uplift by folding a mean uplift rate of ~0.29 mm/year is obtained for the Vaqueros–Medeiros anticline (Fig. 7c).

Taking into account the water gaps generated at Sierra de Mojotoro along this period an uplift rate of ~0.76 mm/year was estimated (Fig. 11a). This acceleration of the uplift at Sierra de Mojotoro would have generated the main changes in drainage network deflecting main rivers to the south and controlling the establishment of the lacustrine environment related with the deposits of Tajamar Formation (Fig. 9e; Malamud et al., 1996; González Bonorino and del Valle Abascal, 2012a, 2012b).

The shortening accummulated by Paleozoic rocks at Pascha–Lesser and Mojotoro structures during this period is around of 0.4 km at a rate of ~1.7 mm/year (Fig. 11b).

5.6. Stage 6 (~0.1 Ma to recent times)

During the last ~0.1 Ma the northward migration of Vaqueros river was controlled mainly by folding at the Lomas de Medeiros (Figs. 7 and 9f). T5 strath terrace, assumed to be ~0.1 Ma in age, is ~35 m above the actual Vaqueros river course, whilst its undeformed correlate at the Lerma valley could be ~35 m below the actual surface. The difference of ~70 m gives an uplift rate of ~0.7 mm/year for the last ~0.1 Ma (Fig. 7c). The same values can be estimated for the Sierra de Lesser due the structural connection between those morphostructures (Fig. 10f).

Ash levels dated as 47 ± 6 Ka ($^{238}U-^{230}Th$ zircon model ages, Hain et al., 2011) are interbedded in conglomerates correlated with La Viña Formation at the western flank of Sierra de Mojotoro. They are uplifted at least ~25 m with respect of Lerma valley deposits evidencing neotectonic activity of this structure as well at a rate of ~0.5 mm/year (Fig. 11a).

The shortening accumulated by the Mesón and Santa Victoria Groups during this period is around 0.2 km at a rate of ~2 mm/year (Fig. 11b).

5.7. Discussion

The mean shortening rates obtained for the last ~1.3 Ma oscillate between ~1.4 and ~2 mm/year (Fig. 11b). These values account for less than a half of the permanent shortening rates modeled, based on GPS geodetical data, by Kendrick et al. (2006) for the Andean backarc at this latitude. This fact implies that the remaining shortening must be absorved by some other active structures, probably along the Santa Bárbara System (Fig. 1). The shortening rate for this morphostructure should be between ~2 and ~2.6 mm/year.

In the transition zone between the Subandean and Santa Bárbara systems (Fig. 1), Ramos et al. (2006) determined Holocene shortening rates of 2.34 mm/year for the Lomas de Olmedo morphostructure. This value is in agreement with the shortening rate for the Santa Bárbara System predicted in the present contribution.

6. Potential seismic hazard

It has been previously noted that for intraplate single structures, recurrence intervals of 10^3–10^4 years are the most common, leading to underestimate the seismic hazard in many regions (e.g. Costa, 2005; Costa et al., 2001; Sagripanti et al., 2011). Taking this fact into account, the probable maximum magnitude of earthquakes related with Vaqueros–Medeiros, Pascha–Lesser and Mojotoro morphostructures has been calculated applying the uplift rates obtained and the relationships of Wells and Coppersmith (1994).

6.1. Vaqueros–Medeiros anticline

Although the Siancas and Calchaquí valleys and the Metán and Tucumán basins register important seismic activity (Araujo et al., 1999; INPRES, 2012; NEIC, 2013), there are only a few events located at the Lerma valley and no records of historical nor instrumental seismicity that can be related to the Vaqueros–Medeiros morphostructure (Fig. 1). One possible explanation for this could be that the growth of the fold is controlled by aseismic creeping mechanisms (Colombi et al., 2002). On the other hand, a long term recurrence interval for fault reactivation could be invoked. If the last option is correct, a minimum recurrence interval of 500 years could be applied to establish, taking into account the mean uplift rate of ~0.7 mm/year obtained for the last ~0.1 Ma, a maximum displacement of ~0.66 m along the fault plane and a maximum uplift of ~0.35 m during earthquake events. Thereby, the maximum moment magnitude (M_w) obtained using the relationship with the maximum surface uplift is $M_w = 6.4$ (Wells and Coppersmith, 1994).

Considering the whole Vaqueros–Medeiros morphostructure, the length of the potential active fault is ~16 km. Applying the relationship between the subsurface rupture length and moment magnitude of Wells and Coppersmith (1994) a maximum earthquake of $M_w = 6.5$ is obtained. The maximum surface uplift calculated with the regression published by the same authors gives ~0.55 m for such events, 1.6 times more than the established for the 500 years recurrence interval. Such earthquake would require a minimum recurrence interval of 785 years to happen.

6.2. Sierra de Pascha–Lesser

As described in the regional structural section (Fig. 5), the active fault that controls the folding of the Vaqueros–Medeiros anticline is a splay of the major thrust that uplifts the Sierra de Pascha and Sierra de Lesser. Using the maximum surface uplift of Wells and Coppersmith (1994) similar maximum moment magnitude of $M_w = 6.4$ is obtained, meaning that the Lesser fault could be reactivated in discrete segments of ~22 km length.

Taking into account the total extension of the Lesser fault (~60 km, Fig. 2) and applying the subsurface rupture length vs. moment magnitude relationship (Wells and Coppersmith, 1994), potential earthquakes of $M_w = 7$ are obtained for Pascha–Lesser morphostructure. Such an earthquake could produce a maximum surface displacement of around 2.87 m (Wells and Coppersmith, 1994). Using the uplift rate of 0.7 mm/year for the last ~0.1 Ma a recurrence interval of 4100 years is deduced for an event of that magnitude.

6.3. Sierra de Mojotoro

Few instrumental shallow earthquakes where registered at this big morphostructure (Fig. 1). As well as in Lomas de Medeiros, creeping mechanisms has been invoked to explain the lack of seismicity in this region (Colombi et al., 2002). Taking into account the other end member explanation, that is a long recurrence interval for ruptures at this structure, some considerations on the seismogenic potential can be done.

Assuming 500 years of recurrence interval and applying the uplift rate of ~0.5 mm/year established for the last ~0.1 Ma, the maximum surface displacement obtained is of ~0.25 m. Using the relation between the maximum surface displacement vs. moment magnitude an earthquake of $M_w = 6.3$ is obtained for Sierra de Mojotoro (Wells and Coppersmith, 1994). Such event would not be able to re-activate the entire Mojotoro fault suggesting that, for these recurrence interval, it would be reactivated in discrete segments shorter than 20 km.

The maximum length of the Mojotoro ramp is around 70 km. Applying the subsurface rupture length vs. moment magnitude relationship (Wells and Coppersmith, 1994) an earthquake of $M_w = 7.1$ is estimated for this morphostructure. The maximum surface uplift computed for such event reaches 3.58 m, requiring a recurrence interval of at least 7100 years to it occur.

6.4. Discussion

The shallow (14 km) earthquake $M_w = 6.1$ (García et al., 2011b) occurred on February 27th of 2010 and located 17 km southwest of Salta city was the first of such magnitude registered in the Lerma valley since the beginning of instrumental and historical recording (Figs. 1 and 12). The focal mechanism published by García et al. (2011b) for this event allows to relate it with N–S reverse faulting located just south of the southeastern end of Sierra de Pascha. Due the depth and magnitude of this earthquake, no superficial effects were documented. The most probable seismogenic sources could be the Lesser fault or some related backthrust responsibles of the southward propagation of this morphostructure (Fig. 5).

The Talavera de Esteco earthquake that occurred on September 13th of 1692 close to Metán city (Fig. 1) has a reconstructed moment magnitude of $M_w = 7.3$ (Castano and Zamarbide, 1978). It caused the total destruction of the small town of Esteco and severe damage in

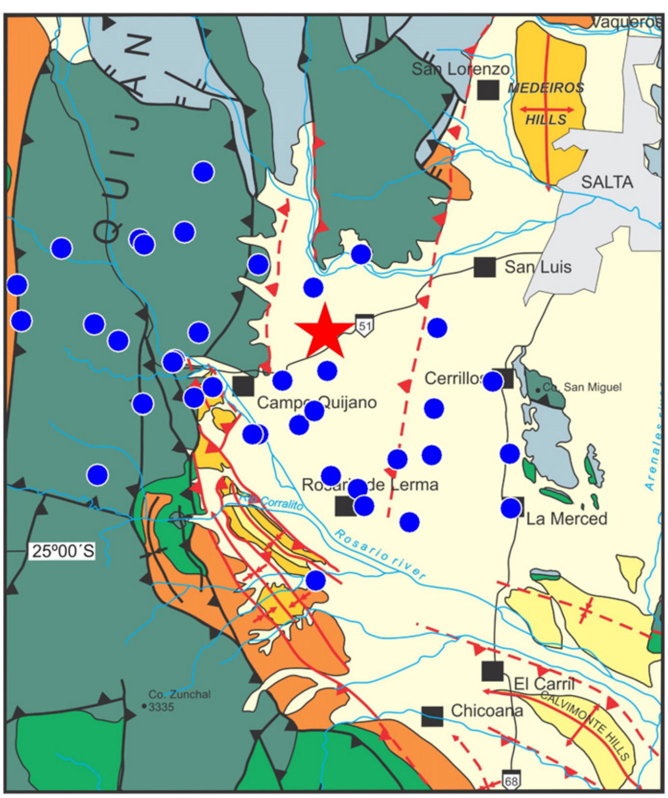


Fig. 12. Detail of the geological map of the Fig. 2 showing the spatial distribution of the $M_w = 6.1$ Salta earthquake of February 27th, 2010 (red star, depth 14 km) and the related aftershocks (blue dots, magnitude between 2.5 and 4.5, depth between 10 and 30 km) (data from INPRES, 2012).

Salta city with an intensity of IX–X in the Mercalli scale at the epicenter (Castano and Zamarbide, 1978). Since Cornell (1968) destructive earthquakes of such intensity are related to return periods of between 1200 and 4000 years. The seismogenic source of this event has not been identified yet, allowing us to note that the Mojotoro fault could be one of the suspects for this earthquake.

The tectonically active character of the Santa Bárbara System deduced from the cited mismatch between geodetical rates and long-term velocities obtained in this work (see Section 5.7) and confirmed by seismic activity (Jujuy earthquake of October 6th of 2011, $M_w = 6.2$; depth = 10 km) points to another important seismogenic source for the region. This morphostructure should be object of further investigations on this topic following the pioneer studies of Ramos et al. (2006) in related tectonic settings.

7. Conclusions

In the present contribution new structural, stratigraphic and geomorphological data was analysed in order to establish the geometry, kinematics and morphotectonic evolution of the Vaqueros–Medeiros anticline. The integration of these observations with previously published data let us to pose six stages of evolution for the northern Lerma valley: (1) From ~10 to ~5 Ma the proto-Sierra de Mojotoro and Sierra de Pascha were formed at low uplift rates establishing the compartmentalization of the foreland into the Lerma and Siancas valleys. (2) Since ~5 Ma the Sierra de Pascha–Lesser was uplifted and exhumed controlling the deposition of the lower and middle sections of the Piquete Formation. The main thrust of Sierra de Mojotoro was developed at this time uplifting this range but at a lower rate that prevented its exhumation. (3) Between ~2 and ~1.3 Ma the Sierra de Pascha–Lesser and Sierra de Mojotoro were uplifted at ~1 mm/year whilst the Vaqueros–Medeiros anticline started to growth at ~0.85 mm/year being covered by the upper section of the Piquete Formation. (4) Local drainage network reorganization at the Lomas de Medeiros took place between ~1.3 and ~0.33 Ma triggering the syncronous erosion with uplift that controlled the formation of T1 surface. The Sierra de Mojotoro reduced its uplift rate to ~0.28 mm/year allowing the deposition of the Calvimonte conglomerates at its eastern flank. (5) The final exhumation of the Sierra de Mojotoro took place at ~0.33 Ma as documented by the main drainage networks reorganization and the establishment of a lacustrine environment at the Lerma valley. The uplift of Lomas de Medeiros continued at a rate of ~0.29 mm/year as registered by folded strath terraces. (6) During the last ~0.1 Ma the Lomas de Medeiros grew at a rate of ~0.7 mm/year as deduced from the geometry of the youngest strath terraces folded. The Sierra de Mojotoro has been uplifted at ~0.5 mm/year during this stage.

The lack of significant seismicity on this area could be more related with the short registration time span rather than to a real aseismic behavior, as was evidenced by the Salta earthquake of 2010. Using a recurrence interval of 500 years and the obtained uplift rates for the Vaqueros–Medeiros anticline and the Sierra de Pascha–Lesser and Sierra de Mojotoro, maximum earthquakes of moment magnitude $M_w = 6.4$, $M_w = 6.4$ and $M_w = 6.3$ were respectively established. Taking into account the potential subsurface rupture length of each related fault, $M_w = 6.5$, $M_w = 7.0$ and $M_w = 7.1$ earthquakes were also obtained. The recurrence intervals for such earthquakes are of 785, 4100 and 7100 years respectively. The historical earthquakes of intensity IX–X in the Mercalli scale occurred in the region must be alerts to improve the neotectonic and paleoseismological knowledge of northwestern Argentina.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.tecto.2013.06.021. These data include Google map of the most important areas described in this article.

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