Available online at www.sciencedirect.com

SCIENCE DIRECT®

Tectonophysics 399 (2005) 155–172

TECTONOPHYSICS

www.elsevier.com/locate/tecto

Seismic and field evidence for selective inversion of Cretaceous normal faults, Salta rift, northwest Argentina

Jonas Kley[a,*], Eduardo A. Rossello[b], César R. Monaldi[c], Björn Habighorst[d]

[a]*Institut für Geowissenschaften, Universität Jena, Burgweg 11, D-07749 Jena, Germany*
[b]*CONICET-Depto. Cs. Geológicas, Universidad de Buenos Aires, Pabellón II, Ciudad Universitaria. 1428 Buenos Aires, Argentina*
[c]*Universidad Nacional de Salta-CONICET, Buenos Aires 177, 4400 Salta, Argentina*
[d]*Geologisches Institut, Universität Karlsruhe, Kaiserstr. 12, D-76131 Karlsruhe, Germany*

Received 22 November 2002; received in revised form 3 June 2003; accepted 23 December 2004
Available online 5 February 2005

Abstract

Northwestern Argentina was the site of the continental Salta rift in Cretaceous to Paleogene time. The Salta rift had a complex geometry with several subbasins of different trends and subsidence patterns surrounding a central high. Fault trends in the rift were extremely variable. There is evidence of normal and/or transfer faults trending N, NE, E and SE. It is not clear if all these faults were active at the same time, indicating a poorly defined extension direction, or if they formed in different, non-coaxial extension phases. In either case, their trends were very likely influenced by preexisting fault systems. Beginning in early Eocene time, the rift basins were superseded by Andean foreland basins and later became caught in the Andean thrust deformation propagating eastward, resulting in the inversion of rift faults. Due to their different orientations, not all faults were equally prone to reactivation as thrusts. N to NNE trending faults were apparently most strongly inverted, probably often to a degree where the traces of their normal fault origin have become obliterated. We present seismic evidence of moderately inverted N trending faults in the Tres Cruces basin and field examples of preserved E trending normal faults. However, reactivation sometimes also affects faults trending approximately parallel to the main Neogene shortening direction, indicating short-term deviations from the general pattern of Neogene thrust deformation. These pulses of orogen-parallel contraction may be linked to the intermittent activity of oblique transfer zones.

Keywords: Central Andes; Eastern Cordillera; Tres Cruces basin; Seismic lines; Inversion structures; Transfer zones

1. Introduction

Beginning in late Jurassic or early Cretaceous time, the continental Salta rift developed in northern Argentina (Galliski and Viramonte, 1988; Salfity, 1982; Salfity and Marquillas, 1994). This rift was

* Corresponding author. Tel.: +49 3641 948623; fax: +49 3641 948622.
E-mail addresses: jonas.kley@uni-jena.de (J. Kley), rossello@gl.fcen.uba.ar (E.A. Rossello).

0040-1951/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2004.12.020

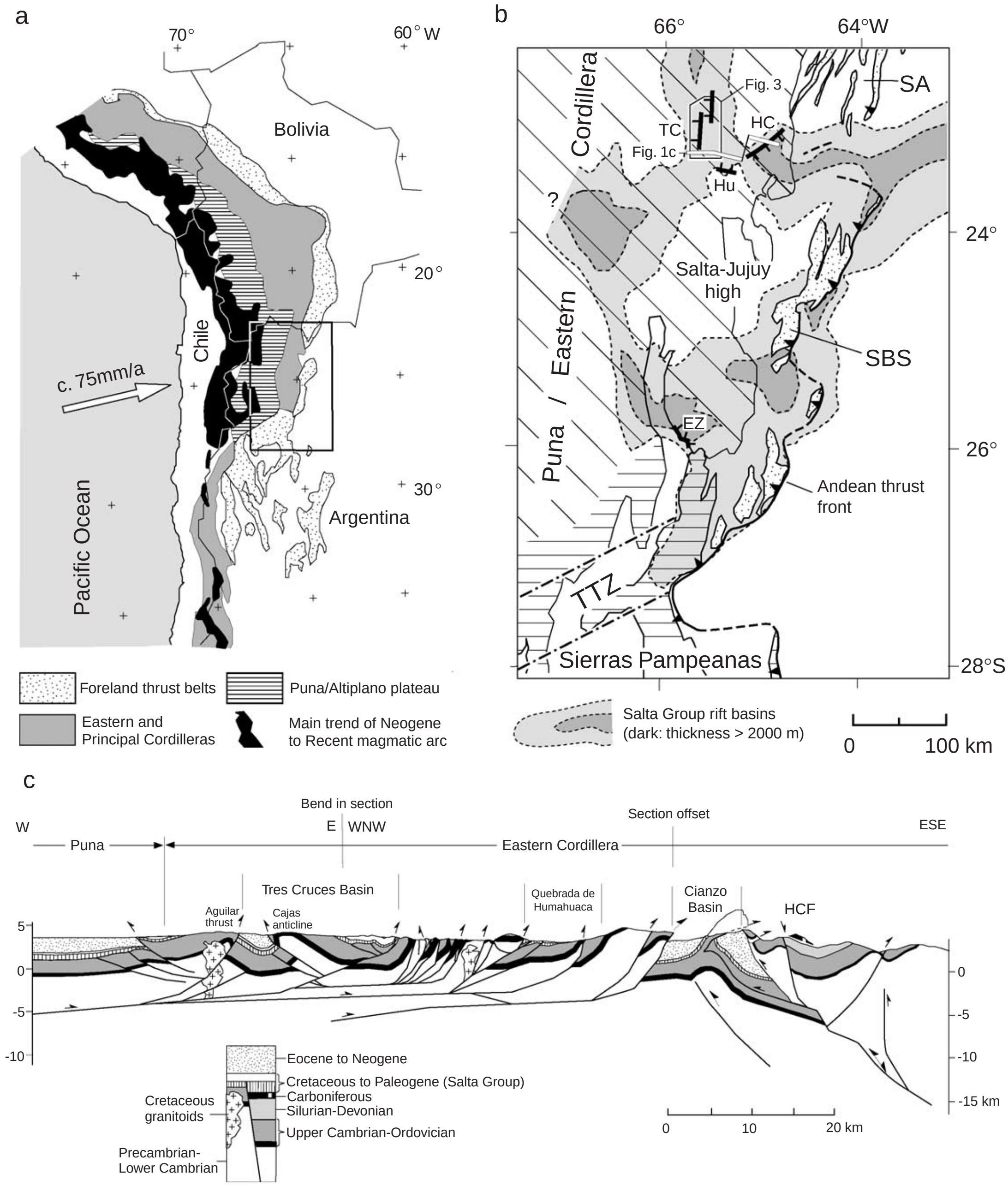


Fig. 1. (a) Main structural units of the Central Andes and location of the study area. Arrow indicates present-day Nazca/South America convergence direction and rate (after DeMets et al., 1994; Norabuena et al., 1998). (b) Outline and depocenters of the Cretaceous to Paleogene Salta rift system in northwestern Argentina (after Salfity and Marquillas, 1994) and its relation with the present-day Andean thrust front. Subandean (SA) and Santa Bárbara System (SBS) foreland thrust belts are stippled. Normal faults discussed in the text are indicated with general trend and sense of displacement. Abbreviations are HC, Hornocal fault; TC, Tres Cruces Area; Hu, Quebrada de Humahuaca near Huacalera; EZ, El Zorrito fault. TTZ is Tucumán transfer zone after De Urreiztieta et al. (1996). (c) Cross-section of the Eastern Cordillera and easternmost Puna in northwestern Argentina, mostly after own field data. Structure in Puna part is adopted from an interpreted seismic line in Gangui (1998), easternmost part is modified from Kocks (1999). HCF is Hornocal fault. Location in (b).

part of a large rift and basin system that probably extended southeastward to the nascent South Atlantic (Uliana and Biddle, 1988), but also to the E and W into what is now Paraguay and northern Chile. To the N, it was temporarily linked to other basins that provided the pathway for a marine ingression (Pindell and Tabbutt, 1995; Sempere, 1995). The onset of strong Andean contraction in Neogene time has reactivated and inverted many parts of this rift system (Bianucci et al., 1982; Cristallini et al., 1997; Grier et al., 1991; Kress, 1995). The Salta rift has a complex overall shape with basins of different trends that surround and radiate from a central positive area, the Salta-Jujuy high (Salfity and Marquillas, 1994) (Fig. 1). The present NNE trending thrust front of the Andes cuts obliquely across the Salta rift, leaving part of it in the Cordillera and on the Puna high plateau, and part in the low-lying foreland. The intricate geometry of the rift implies that its different segments lay at quite different angles with respect to the relatively uniform E to ESE Andean contraction. Reactivation of normal faults as thrusts has been described from both the foreland and the high Andes (Bianucci et al., 1982; Cristallini et al., 1997; Grier et al., 1991; Kley and Monaldi, 2002; Kress, 1995; Salfity et al., 1993; Uliana et al., 1995), and a strong influence of the rift structure on the regional pattern and style of Tertiary Andean deformation appears evident (Belotti et al., 1995; Grier et al., 1991; Kley et al., 1999). Still, there are not too many examples where inversion is unequivocally documented from stratigraphic relationships. Here we present evidence of inverted normal faults from industrial reflection seismic lines in the Tres Cruces basin. We compare these to exposed examples of reactivated and preserved normal faults in the Eastern Cordillera of northern Argentina. We then discuss the prerequisites for the reactivation of normal faults in terms of initial fault orientation and geometry and of changing Neogene deformation patterns.

2. Geologic setting

The Eastern Cordillera is the chain of high mountains forming the east flank of the Andes from Peru to northern Argentina. In the region considered here, it separates the Puna plateau in the west from the Subandean Ranges and Chaco lowlands in the east. The geologic history of the area is reviewed in Mon and Salfity (1995). The oldest rocks exposed in the Eastern Cordillera (Fig. 2) are slates and sandstones of late Proterozoic to early Cambrian age that were strongly folded, slightly metamorphosed and intruded by granites in a middle Cambrian event (Willner et al., 1987). They are unconformably covered by upper Cambrian to Ordovician quartzites and shales (Kumpa and Sánchez, 1988; Moya, 1988, 1999; Sánchez, 1999; Turner, 1960). Younger rocks of Silurian to Carboniferous age are only preserved locally (Starck, 1995). Typically, the basal redbeds of the Salta rift disconformably overlie Ordovician rocks. The strata laid down in the active and thermal subsidence stages of the Salta rift form the Salta Group (reviewed in Salfity and Marquillas, 1994), subdivided into the Pirgua, Balbuena and Santa Bárbara Subgroups. These subgroups can be identified and correlated across the entire basin, whereas individual formations are often restricted to subbasins. The Pirgua Subgroup consists of coarse to fine grained red continental clastics, with basalts intercalated in some areas (Galliski and Viramonte, 1988). It is generally interpreted to represent the late Jurassic or early Cretaceous to late Cretaceous synrift stage (see references below). The Maastrichtian to Paleocene Balbuena Subgroup comprises mature sandstones, lacustrine to restricted marine carbonates and evaporites in some subbasins. It contains the Yacoraite Fm. whose resistant limestones form an important marker both in seismic lines where they often stand out as a prominent reflector package and in the field where they appear as conspicuous light coloured cliffs. The Santa Bárbara Subgroup is mostly red and purple shales, with minor intercalations of limestone and sandstone. The Balbuena and Santa Bárbara Subgroups of latest Cretaceous to Eocene age are widely considered to represent the postrift thermal subsidence stage (Bianucci et al., 1982; Bianucci, 1999; Cominguez and Ramos, 1995; Gomez Omil and Albarino, 1996; Salfity and Marquillas, 1994; Welsink et al., 1995), although a much earlier switch from an extensional to a foreland basin setting has been claimed for correlative units in Bolivia (Sempere, 1995). However, in northern Argentina, minor normal faulting and basalt effusion still occur during Balbuena and

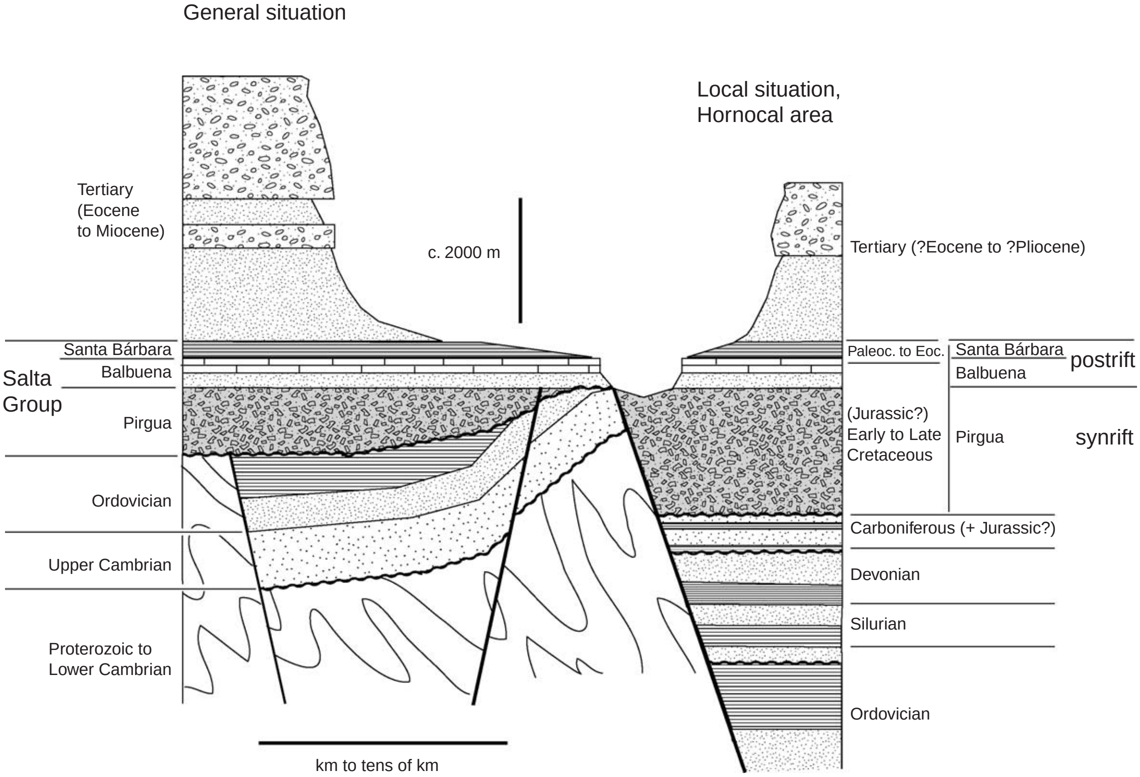


Fig. 2. Generalized stratigraphic relations in the Eastern Cordillera of northwestern Argentina, after sources cited in the text and own observations.

even early Santa Bárbara deposition (Bianucci et al., 1982; Viramonte and Escayola, 1999). Thick Tertiary continental clastics overlie the Salta Group or older strata on the Puna and in the eastern foreland (Hernández et al., 1996; Jordan and Alonso, 1987; Reynolds et al., 2001; Salfity et al., 1996), but only some remnants are preserved in the strongly uplifted and eroded Eastern Cordillera. The Tertiary succession of the Tres Cruces basin, located in the westernmost Eastern Cordillera, is Eocene to probably middle Miocene in age (Boll and Hernández, 1986). Other occurrences, as in the Humahuaca valley and in the Cianzo area, are not yet or not completely dated.

The Puna and Eastern Cordillera are Andean thrust belts of different age and structural style. Andean contraction set in earlier in the west than in the east. In the Puna, it apparently began in Eocene or Oligocene time (Coutand et al., 2001; Kraemer et al., 1999) and had largely terminated in the late middle Miocene at the latitude considered here (Boll and Hernández, 1986). The onset of thrusting and folding in the Eastern Cordillera is still poorly constrained in Argentina. The main contraction phase is bracketed between about 25 and 10 Ma in southern Bolivia (Gubbels et al., 1993; Müller et al., 2002), but thrust faults affecting Quaternary strata (Marrett et al., 1994) and seismicity beneath the eastern foot of the Eastern Cordillera (Cahill et al., 1992) show that shortening is still active in northern Argentina. The Puna has spaced, E and W vergent thrusts that emplace Ordovician over Tertiary rocks and produce a topography of isolated ridges and broad intervening flats (Allmendinger et al., 1997; Coutand et al., 2001; Mon and Salfity, 1995). The Eastern Cordillera is a high-standing, strongly imbricated stack of thrust slivers and thrust-bounded folds that expose the Proterozoic to early Cambrian basement (Mon and Salfity, 1995; Servicio Geológico Argentino, 1996).

3. Inverted normal faults

3.1. Tres Cruces basin

The Tres Cruces basin ("TC" in Figs. 1b and 3) is located in the westernmost part of the Eastern Cordillera where it borders the Puna plateau. The basin originated in Eocene time, very probably as part of a much larger foreland basin (Jordan and Alonso, 1987) and further developed into a thrust-bounded syntectonic depression (ramp basin) that was filled by up to 5 km of locally derived clastic sediments. Deposition and deformation in the Tres Cruces basin apparently ceased in the middle Miocene. Its Eocene to Miocene infill disconformably overlies Eocene shales of the Santa Bárbara Subgroup. It exhibits an overall upward coarsening trend from interbedded sandstone and shale to dominantly conglomeratic strata. Several unconformities have been described from this succession and correlated with regional tectonic phases (Boll and Hernández, 1986) but the contacts between different units are always conformable on the outcrop scale. Today, the Tres Cruces basin is overthrust by the regional El Aguilar thrust sheet from the west. At least one footwall splay of the Aguilar thrust is evident in the basin (Barro Negro thrust, Fig. 3). The eastern border is structurally more complex and marked by a monocline or west-verging thrust faults. In the northernmost and southernmost parts of the basin, two synclinal zones to the west and east are separated by a central anticlinal high (Tres Cruces and Cajas anticlines). In the central part, the anticlinal high is split into two anticline/thrust trends by an intervening syncline. The structures within the basin are extremely variable along strike. Sigmoidal structure contours are common. Fold axes often plunge steeply, producing abrupt, box-shaped fold terminations. None of the internal structures can be traced right along the basin without lateral offset or change in structural style. For example, the Cerro Colorado trend switches rapidly from a simple east verging thrust sheet to a broad, short, doubly plunging anticline. The most pronounced structural changes are aligned on three NW trending oblique zones, whose continuity suggests an influence of basement faults on the higher level structures (shaded bands in Fig. 3). The importance of NW trending basement faults was already discussed for the Tres Cruces basin by Boll and Hernández (1986) and on a regional scale by Salfity (1985). The Tres Cruces basin has been explored for hydrocarbons in the 1980s, resulting in a dense network of seismic lines and drilling of four wildcat wells. Interpretations of some seismic lines have been published by different authors (Boll and Hernández, 1986; Coutand et al., 2001; Gangui and Götze, 1996; Gangui, 1998). While Gangui and Götze (1996) and Gangui (1998) interpreted inversion structures and high-angle faults near the northern termination of the Tres Cruces basin, lines across the basin center (Boll and Hernández, 1986; Coutand et al., 2001) were interpreted to show a simple structural style with listric thrust faults that sole into a detachment in early Paleozoic rocks or the underlying very low grade metamorphic schists, contrasting with the complexity evident in map view.

The two seismic lines we present and interpret here were acquired in 1990 for a consortium headed by Texaco Argentina. They were recorded with a SERCEL 368-E instrument and dynamite source, 25 m group interval and 240 data channels. The lines were processed in 1991 using standard procedures, including a 4-pass post-stack migration. We used hardcopies of the processed lines for our interpretations.

On most seismic lines from the Tres Cruces basin, the stratigraphy is clearly imaged down to the prominent reflector of the Yacoraite Formation near the base of the postrift succession. Below, the interpretation is often ambiguous. Nevertheless, in some cases fanning reflector patterns can be recognized immediately beneath the Yacoraite reflector and adjacent to the major faults. We interpret them to indicate Pirgua synrift strata thickening into fault-bounded half grabens and hence an origin of thrust faults in the Tres Cruces basin as Cretaceous listric normal faults. Figs. 4–6 present three examples of this type. Apart from the thickening wedge of Pirgua strata, the western part of Line 1 (Vicuñayoc structure, Figs. 4 and 5) suggests imbricated thrust faults in the footwall of the steeply dipping major fault. These structures underlie the west flank of a footwall syncline where converging and truncated reflectors may indicate growth of the inversion structure during deposition (Fig. 5). The base of the Pirgua synrift succession can only be imprecisely located where clearly marked reflectors disappear. Its

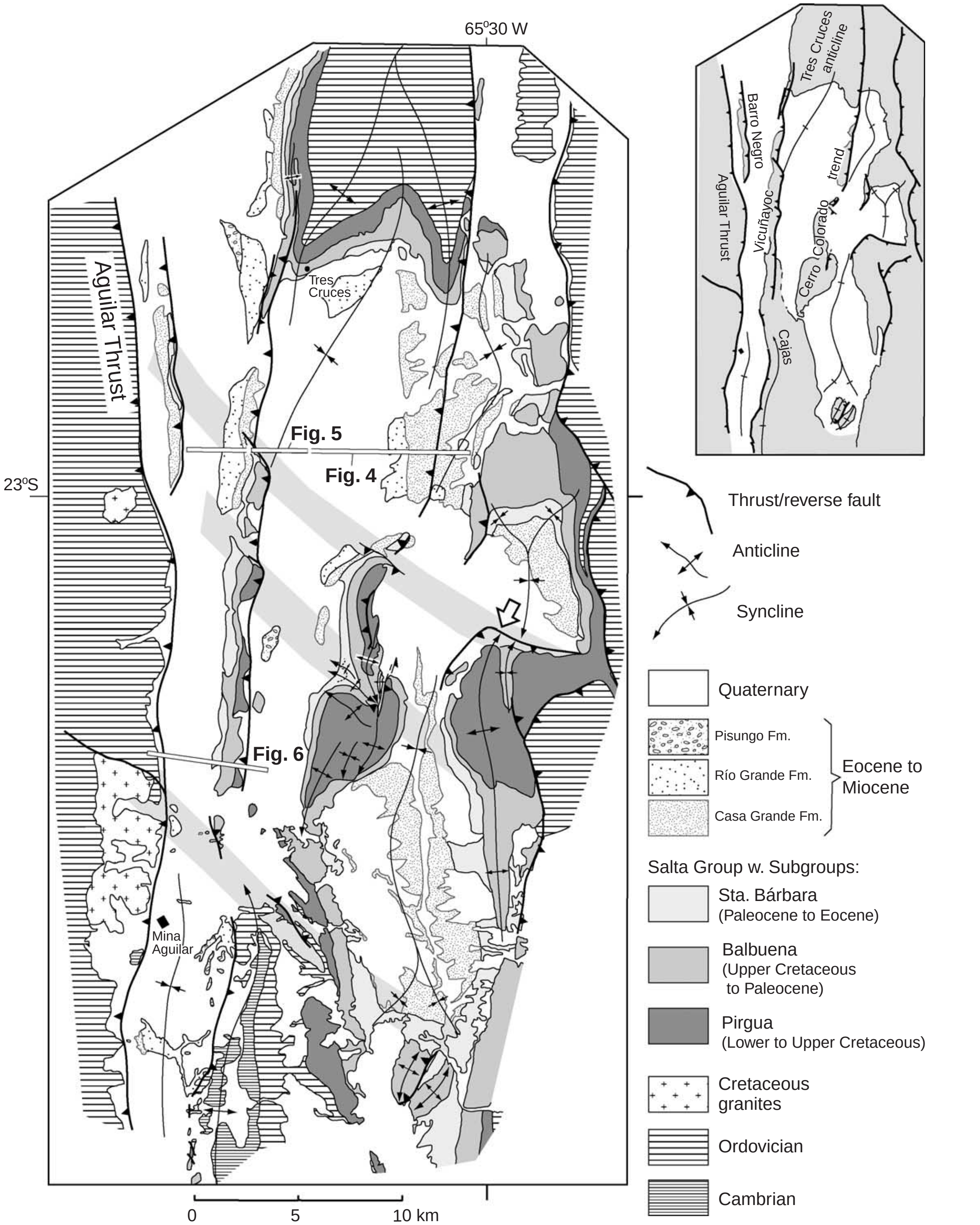


Fig. 3. Geologic map of the Tres Cruces basin, based on oil company data and own observations. The locations of the seismic lines shown in Figs. 4–6 are indicated. Shaded bands crossing the basin are probable basement faults. Notice N–S contraction structure on right-stepping western basin margin (open arrow). Inset indicates fault and fold trends mentioned in the text.

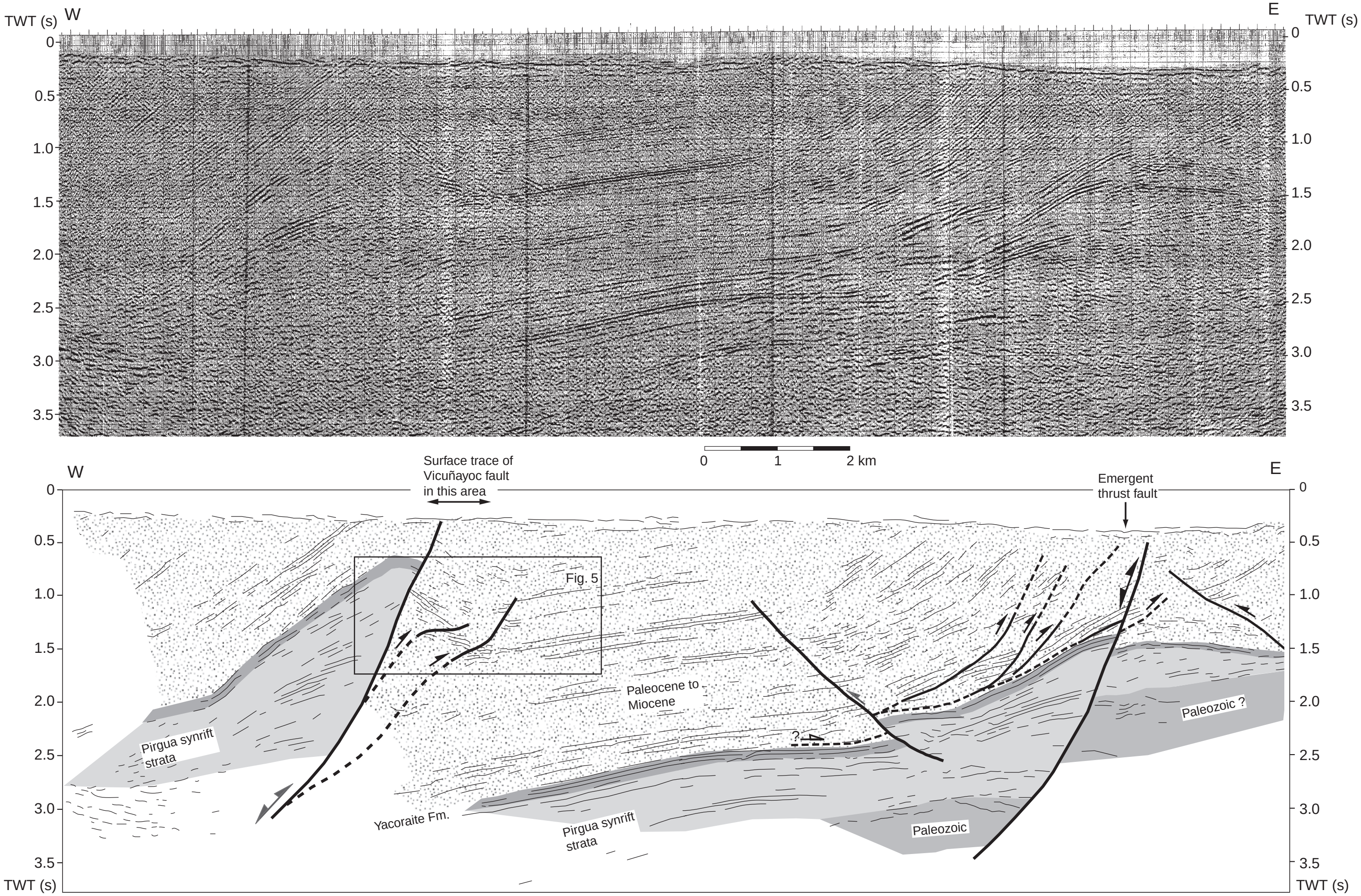


Fig. 4. (a) Seismic line across the Vicuñayoc and Cerro Colorado trends and (b) interpreted line drawing. Notice fanning reflectors in the Pirgua synrift strata and different degrees of inversion on both faults. Uncertain interpretation of bedding-parallel décollement overlying inverted Cerro Colorado structure is shown dashed. Also notice probable angular unconformity between Paleozoic and Pirgua synrift successions in the east. Location of seismic line in Fig. 3.

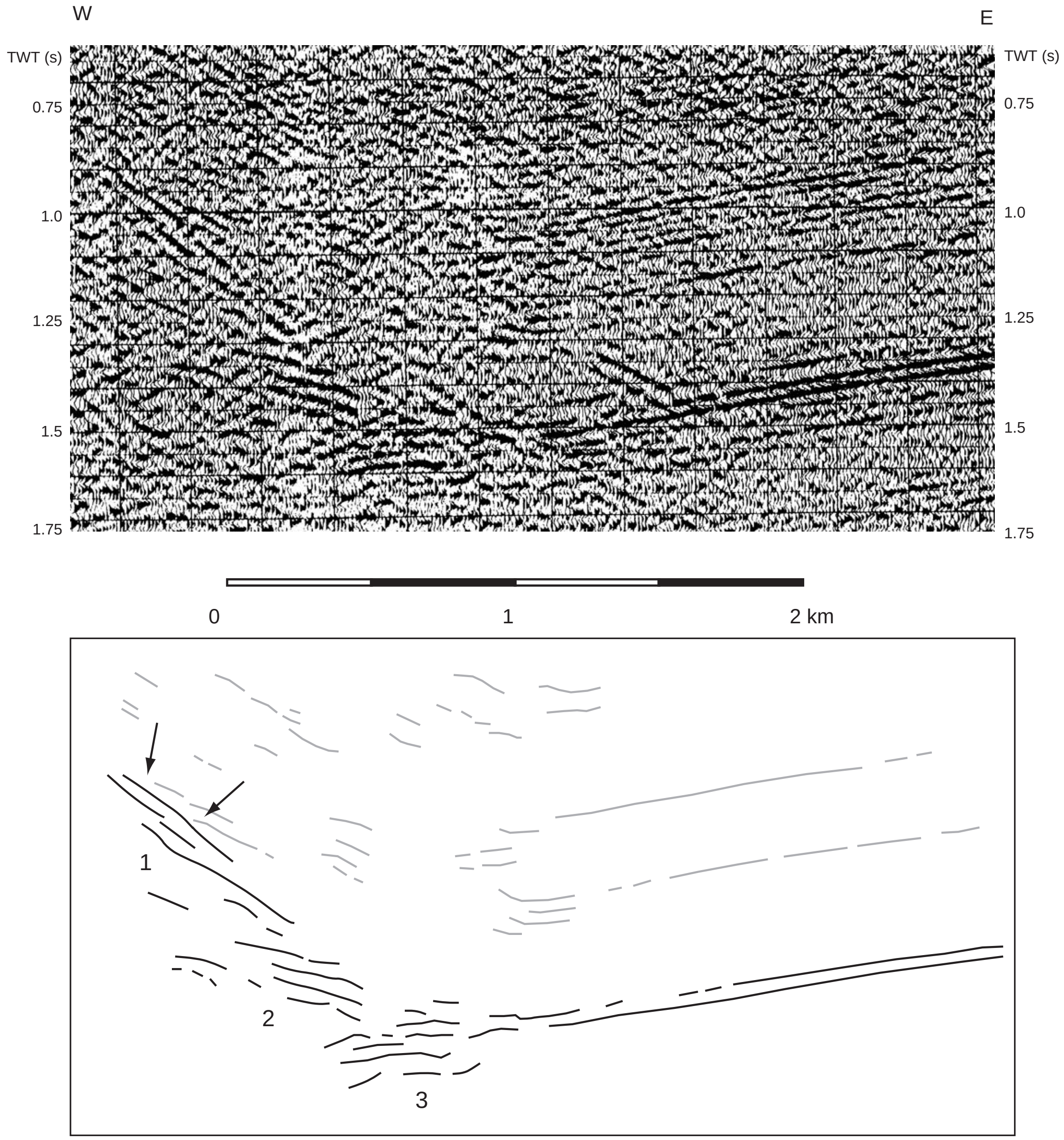


Fig. 5. (a) Detail from the footwall of the Vicuñayoc fault (western part of the seismic line in Fig. 4) and (b) interpreted line drawing. Notice discontinuous reflector packages 1, 2 and 3 interpreted as footwall imbricates and suggestion of westward thinning and onlap in syntectonic Paleocene to Miocene strata (marked by arrows). Outline of figure indicated in Fig. 4b.

thickness appears to jump from about 0.4 s TWT in the footwall to a maximum of about 1.3 s TWT in the hanging-wall.

The eastern part of line 1 (Fig. 4) shows a different structure on the Cerro Colorado trend where little reactivation of the major normal fault has occurred. Normal offset on the main fault was probably of the order of 1500 m in this example. During inversion, a broad anticline has formed across it and a minor antithetic, west directed thrust fault is suggested by offset Yacoraite reflectors where the bedding dip changes from subhorizontal to moderately steep on

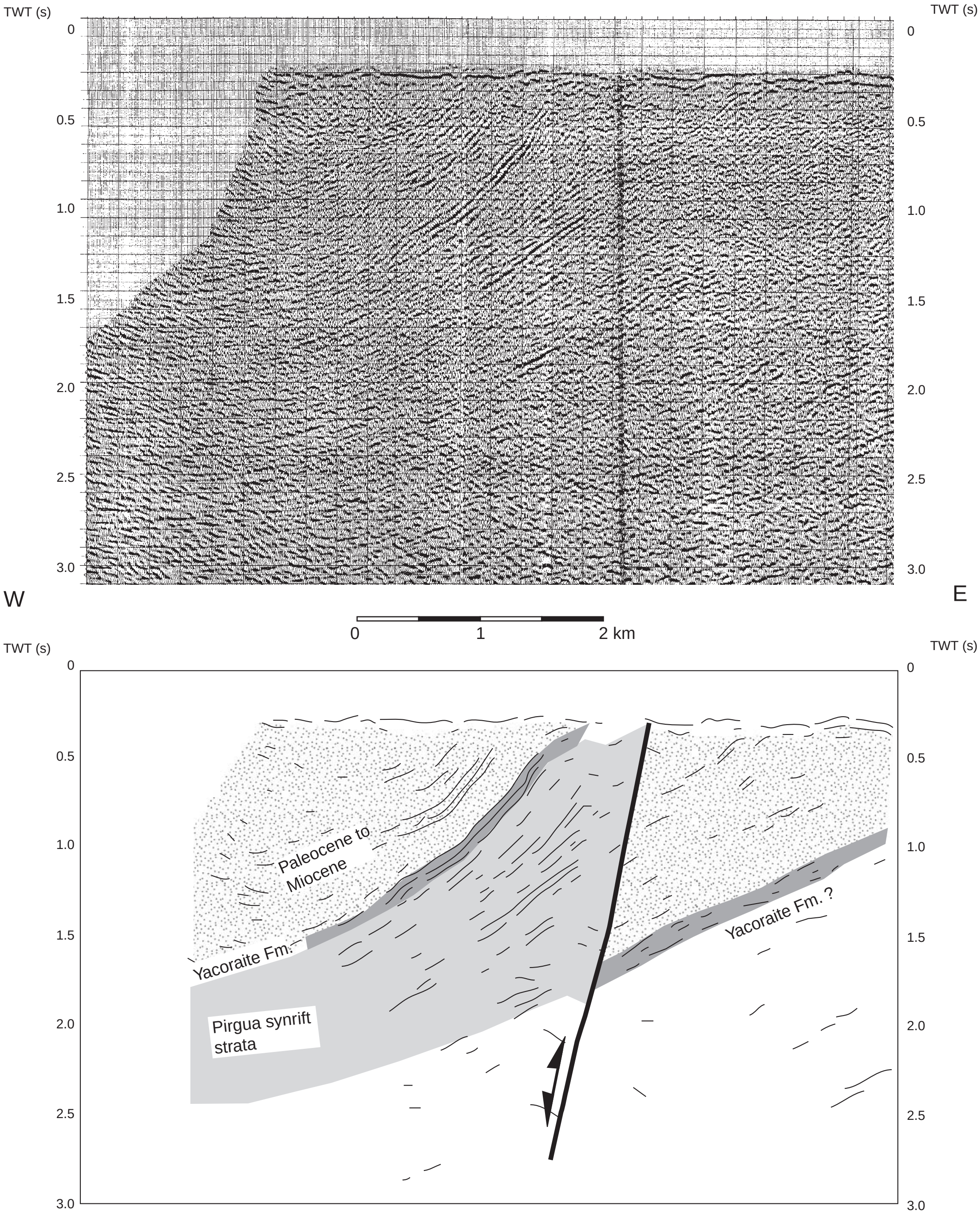
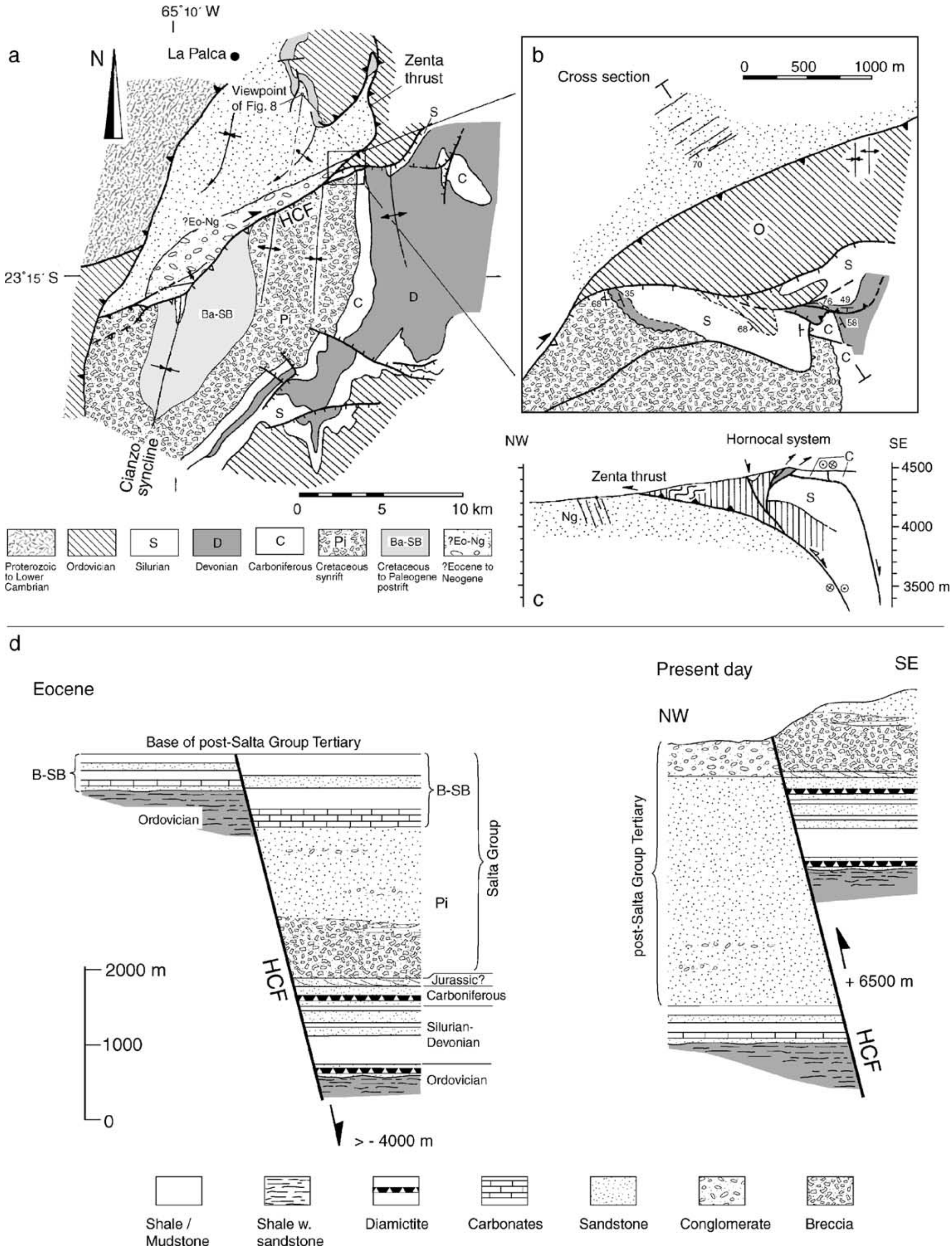


Fig. 6. (a) Detail of seismic line and (b) interpreted line drawing. This line crosses the Vicuñayoc trend some 15 km south of Fig. 4. The entire inversion structure is tilted westward on the forelimb of the regional Cajas anticline. Location of seismic line in Fig. 3.


a
65°10′ W
N
La Palca
Viewpoint of Fig. 8
Zenta thrust
HCF
?Eo-Ng
23°15′ S
Ba-SB
Pi
C
D
S
Cianzo syncline
0 5 10 km
Proterozoic to Lower Cambrian
Ordovician
Silurian
Devonian
Carboniferous
Cretaceous synrift
Cretaceous to Paleogene postrift
?Eocene to Neogene
b
Cross section
0 500 1000 m
O
c
NW
SE
Hornocal system
Zenta thrust
Ng
4500
4000
3500 m
d
Eocene
Base of post-Salta Group Tertiary
B-SB
Ordovician
Salta Group
Pi
Jurassic?
Carboniferous
Silurian-Devonian
HCF
2000 m
1000
0
> - 4000 m
Present day
post-Salta Group Tertiary
+ 6500 m
Shale / Mudstone
Shale w. sandstone
Diamictite
Carbonates
Sandstone
Conglomerate
Breccia

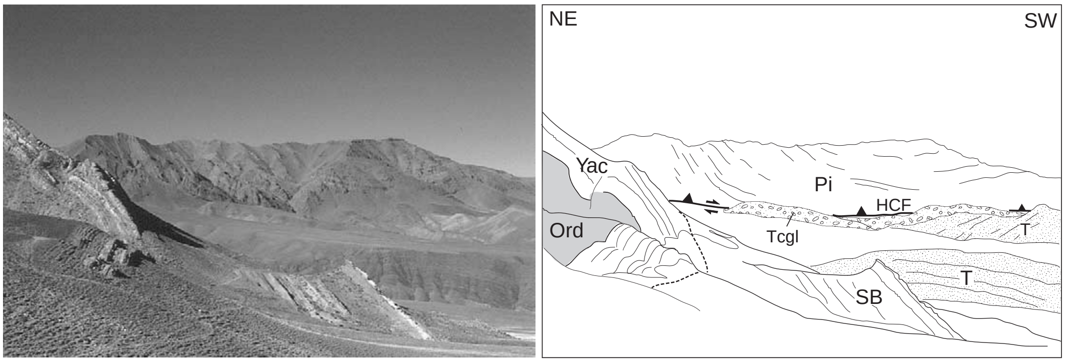


Fig. 8. Field view of the Hornocal fault. In the foreground, a thinned postrift succession and Tertiary strata overlie Ordovician rocks. In the background, a thick Pirgua synrift sequence is thrust over the Tertiary rocks along the Hornocal fault which runs along the foot of the distant hills. Abbreviations are: Ord Ordovician, Pi Pirgua Subgroup (synrift strata), Yac Yacoraite Fm. and SB, Santa Barbara Subgroup (postrift strata), T Eocene(?) to Miocene, Tcgl Neogene conglomerates, HCF Hornocal fault. View is to the SE; viewpoint is indicated in Fig. 7a.

the west limb of the anticline. Imbricated east directed thrust faults appear to overlie but not to offset the Yacoraite reflectors, suggesting a bedding-parallel décollement that formed before the reactivation of the normal fault(s). The thrust fault mapped at the surface seems to coincide with one of the detached thrust faults, not with the major normal fault. These relations are shown as a tentative interpretation in Fig. 4.

Line 2 (Fig. 6) crosses the Vicuñayoc structure some 15 km farther south than line 1. The overall geometry of the structure is similar to the western part of line 1, but there is no indication of footwall imbrications on this line where the footwall is poorly imaged. Furthermore, the entire inversion structure has here been tilted westward on the front limb of the Cajas anticlinal trend, rotating the reactivated normal fault to a very steep dip.

3.2. Hornocal fault near Cianzo

Some 45 km east of the Tres Cruces basin, the Cianzo area presents unusual stratigraphic and structural characteristics. The N trending and gently N plunging regional Cianzo syncline is cut in the north by the NE striking, steeply SE dipping Hornocal fault (Amengual and Zanettini, 1973; "HC" in Figs. 1b and 7). North of the fault a condensed Balbuena to Santa Bárbara postrift sequence overlies Ordovician strata, whereas to its south some 2 km of coarse Pirgua synrift clastics overlie a Silurian through Carboniferous succession on top of Ordovician strata (Starck, 1995; Figs. 7 and 8). Away from the fault, the Pirgua sediments become finer grained. This is clear evidence that the Hornocal fault was a Cretaceous normal fault (Salfity and Marquillas, 1994), which at this location formed the northwestern basin margin (Fig. 1b) and, according to stratigraphic thicknesses, had a throw of about 4000 m. Today, inversion of the Hornocal fault has thrust the Cretaceous to Paleogene strata of the Cianzo syncline over a thick succession of sandy and conglomeratic Tertiary strata, involving a vertical displacement of about 6500 m (Fig. 7d). In the east, the Tertiary rocks are overthrust by Ordovician strata along the gently E-dipping, N-striking Zenta thrust. As it approaches the Hornocal fault, the Zenta thrust turns smoothly into a NE trend and eventually merges with the Hornocal fault (Fig. 7b,c). To the northeast of their junction, the Hornocal fault has preserved its normal offset, suggesting that its southwestern segment is connected to the strongly curved southern end of the Zenta thrust, whereas its

Fig. 7. (a) Geologic map of the Hornocal fault (HCF) and surroundings. Location in Fig. 1b. Notice E to NE trending normal faults offsetting Ordovician to Pirgua strata in the southeast corner of the map. (b) Detailed map and (c) cross section illustrating the relation of the steeply dipping Hornocal fault with the low angle Zenta thrust. (d) Schematic representation of stratigraphic relationships across the Hornocal fault (HCF) at the end of Salta Group deposition (left) and today (right). Figures indicated are stratigraphic throws but are close to actual normal and reverse displacement components on the Hornocal fault.

northeastern segment has been carried more or less passively in the hanging-wall of the linked Zenta and SW Hornocal faults. The kinematic link with the east directed Zenta thrust and minor structures indicate a substantial dextral strike slip component of motion on the Hornocal fault during reactivation.

3.3. El Zorrito fault

The description of the El Zorrito fault ("EZ" in Fig. 1b) is based on the work of Grier et al. (1991) and Strecker and Marrett (1999). The approximately E trending fault (Fig. 9) is curved and southward convex. It forms a jog in the generally N trending Calchaquí-Las Chacras thrust system. The presence of thick Pirgua synrift strata only north of the El Zorrito fault indicates that it was an active fault during rifting with possibly as much as 3000 m of vertical displacement. Since the local Cretaceous extension direction is unknown, it is not clear if the El Zorrito fault was a normal or a transfer fault (see Discussion). Kinematic data indicate predominantly dip slip reverse motion during Tertiary reactivation of the El Zorrito fault (Grier et al., 1991; Strecker and Marrett, 1999; Fig. 9).

4. Preserved normal faults

Well documented examples of Cretaceous normal faults that have not suffered inversion are even scarcer than those of inverted ones. In an earlier paper (Kley et al., 1999), we have proposed that ENE trending normal faults have not been inverted in the 22–23°S foreland segment because they trend at a low angle to the Andean contraction direction. However, this conclusion was based on regional scale observations and the existence of ENE trending faults was inferred from the general trend of the subbasin and from subsurface information (Bianucci et al., 1982; Cominguez and Ramos, 1995). In the following section, we describe an example of preserved normal faults exposed in the Eastern Cordillera.

4.1. Humahuaca valley

The eastern flank of the Quebrada de Humahuaca valley ("Hu" in Fig. 1b) near Huacalera exposes a panel of Proterozoic to Cretaceous strata dipping steeply W due to Andean folding and thrust faulting (Figs. 1c and 10). One major W dipping thrust repeats the lower part of the succession. In addition, several

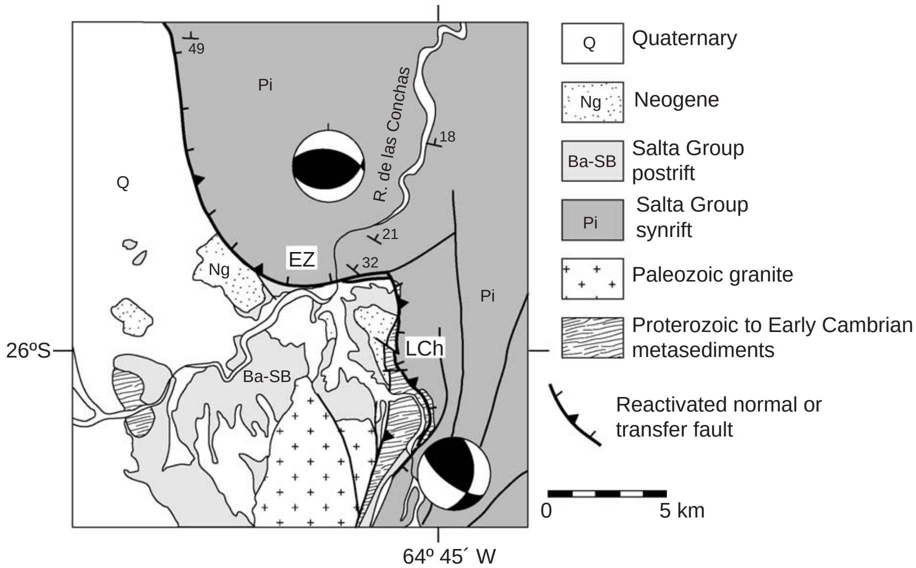


Fig. 9. Map of the El Zorrito/Las Chacras fault system (after Grier et al., 1991; Strecker and Marrett, 1999). Location in Fig. 1b. EZ is El Zorrito fault, LCh is Las Chacras fault. Postrift strata overlie basement in the footwall and a thick Pirgua synrift sequence in the hanging-wall. Kinematic data shown as fault-plane solutions (from Strecker and Marrett, 1999) indicate a thrust/strike slip regime with N to NE contraction during inversion.

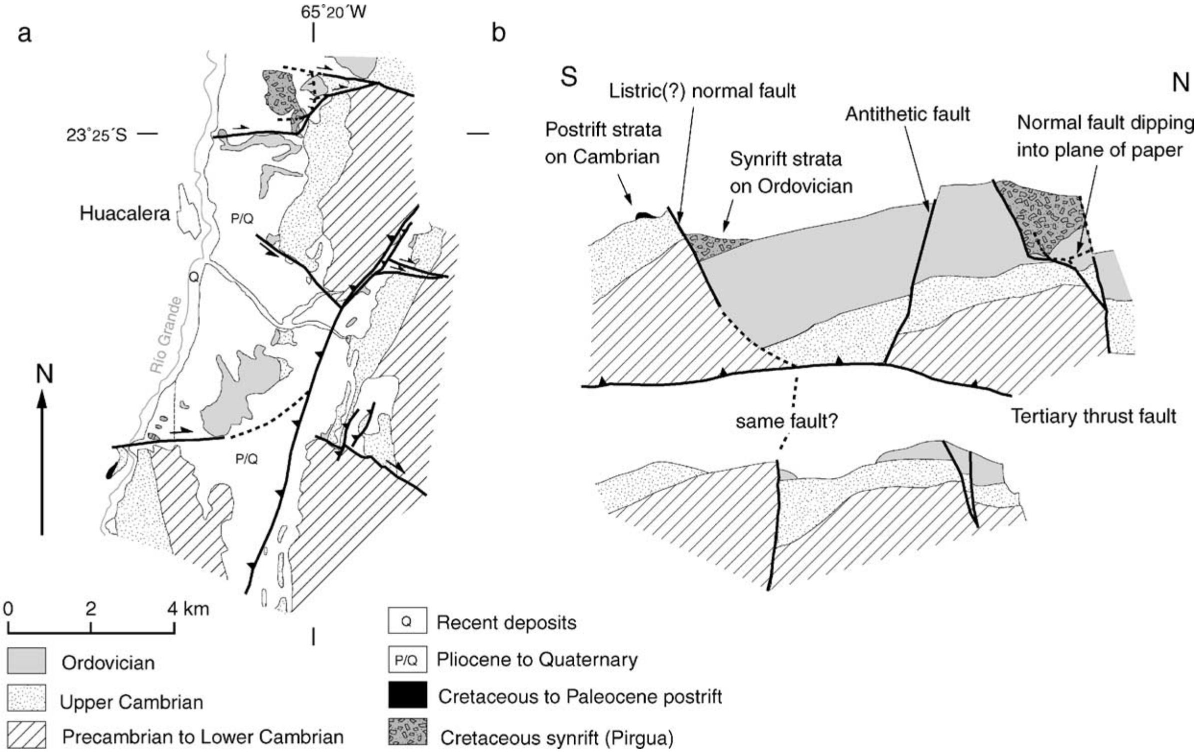


Fig. 10. (a) Detailed geologic map of the eastern flank of Quebrada de Humahuaca near Huacalera (simplified after Habighorst, 2002); location in Fig. 1b. All pre-Neogene units dip steeply W today. (b) Rotated clockwise, the map pattern (with youngest units removed) can be viewed as two approximate N–S sections across the rift. Notice that these are not true cross sections. Stratigraphic relations reveal that at least part of the E to SE trending transverse faults were active during Cretaceous rifting.

steeply dipping E to ESE trending faults crosscut the panel, producing map view offsets of up to a few kilometers. Today, these faults appear as dextral and sinistral strike slip faults according to their separations and kinematic indicators. However, across some of them, the thickness of the Pirgua synrift succession changes sharply. The largest fault juxtaposes postrift limestones overlying Cambrian rocks with synrift redbeds overlying a thick succession of Ordovician strata. Thin Pirgua sections also correlate with incomplete Paleozoic successions in other places. These relations indicate that the steeply dipping faults originated as growth normal faults in Cretaceous time and were later rotated with the entire panel. The thickness data suggest normal displacement of as much as 2500 m and considerable erosion from the uplifted footwall blocks. It is not clear if some of these Cretaceous faults were reactivated as tear faults in Neogene time, because the kinematics are undistinguishable from normal motion before tilting. If such reactivation occurred, it has hardly changed the configuration of the rift structures, which can now be read almost directly from the geologic map (Fig. 10).

Similar steep E to SE trending normal/strike slip faults are also observed in the Hornocal area (Fig. 7a). The regional occurrence of such faults suggests that also the oblique SE trending lineaments segmenting the Tres Cruces basin (shaded bands in Fig. 3) may have been active during Cretaceous rifting.

5. Discussion: patterns of rifting, inversion and Neogene finite strain

The structural pattern of inversion depends on both the original trends and geometries of rift normal and transfer faults and on the orientation of the later contractional strain(s) (Lowell, 1995). For the Salta rift, this was already discussed by Grier et al. (1991), but it is difficult to obtain a clear picture of its structural geometry during extension. Most of the inverted Cretaceous normal faults that have been identified in the subsurface are approximately parallel to the Neogene NNE structural grain. By contrast, many of the best exposed examples are transverse or oblique structures (Salfity and Marquillas, 1994; their Fig. 17). This may imply that many exposed NNE trending normal faults have been so strongly modified during inversion that any vestige of their origin was lost, or that NE, E and SE trending faults were quite numerous in the rift, as one would possibly expect from the overall shape of the Salta rift system and the isopach trends in some subbasins (Fig. 1b). It is not clear if the NE to SE trending faults acted as strike and oblique slip faults or as dip slip normal faults during rifting (Fig. 11). In the former case, they might have formed a linked system with the dip slip normal faults and transferred displacement between them (Fig. 11b). In the latter case, normal faults of differing trend

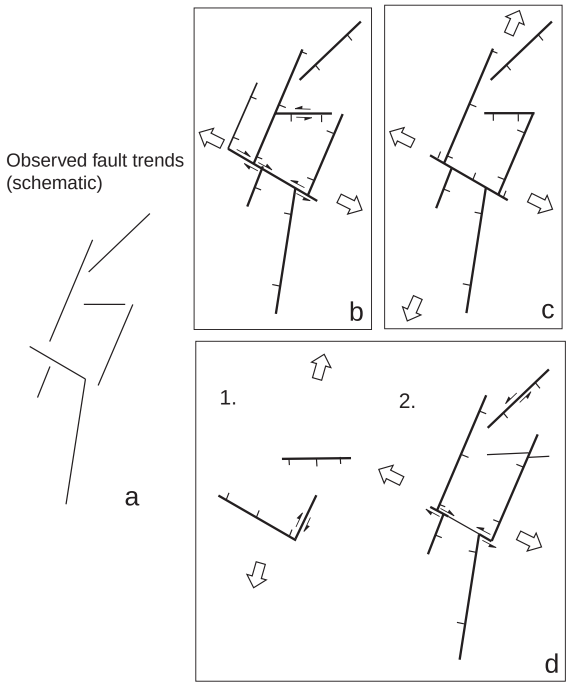


Fig. 11. The Salta rift faults of highly variable orientation (a) could have formed (b) in a single phase of extension with transverse and oblique faults acting as transfer faults, (c) in a single phase with a poorly defined extension direction or (d) during consecutive non-coaxial phases of extension.

could either have originated simultaneously, accommodating a nearly uniaxial flattening strain with the short strain axis vertical and the remaining two horizontal and of similar dimension (Fig. 11c) or at different times in a sequence of non-coaxial extension phases (Fig. 11d). It is not yet clear if a temporal sequence of different fault trends can be established on a local scale. Assessing this question on a regional scale for the differently trending subbasins requires reliable correlation and high resolution dating of the synrift successions they host. The available data (Salfity and Marquillas, 1994) suggest that rifting began in the south in basins elongated in ESE direction and then propagated northward to form the other N to NE trending basins. This may indicate that the extension direction rotated from SW–NE to WNW–ESE.

The relative timing of the individual rift faults was probably of minor importance during inversion. However, the presence of many differently oriented faults has allowed inversion structures to form at almost any contraction direction. In spite of a practically constant plate kinematic framework through the past 25 Ma (Somoza, 1998), the history of Andean deformation is not uniform on a regional to local scale. A two-stage evolution has been deduced where an earlier thrust regime with WNW–ESE contraction was followed by a more varied but dominantly strike slip regime with SW–NE contraction since about 4–1 Ma (Allmendinger, 1986; Marrett and Strecker, 2000; Marrett et al., 1994). Strecker and Marrett (1999) interpreted that E trending faults were reactivated during the second stage in places where they form restraining bends to right lateral motion on N to NNE trending faults. However, also faults forming right-stepping (releasing) bends show evidence of contraction, as illustrated by an example from the Tres Cruces basin (indicated by an arrow in Fig. 3). This NE contraction is difficult to explain in terms of regional kinematics.

Space geodetic (GPS) data show that present-day displacements in the Central Andes tend to be subparallel to the plate convergence vector (Bevis et al., 2001; Norabuena et al., 1998). The present-day velocity field is similar in magnitudes and directions to velocity fields derived from geologic data for the past 25 Ma (Hindle et al., 2002; Kley, 1999; Lamb, 2001), suggesting that the Central Andes have been built in a simple and essentially constant long-term displacement field that is strongly controlled by the plate convergence direction. This apparently contradicts the observation that Neogene shortening directions in the southern Central Andes as derived from fault kinematic data and trends of fold axes are rotated clockwise by some 40° with respect to the plate convergence direction (Marrett et al., 1994). However, the marked along-strike displacement gradients in the Central Andes (Isacks, 1988; Kley and Monaldi, 1998) induce a component of map view shearing, leading to faulting and folding strains that differ in orientation from the plate convergence and displacement vectors (Fig. 12a; Hindle et al., 2000). Strain axes calculated from the proposed long-term and measured present-day GPS displacements are therefore not parallel to the displacement vectors but agree well with each other and with the regional structural grain, with no need to invoke post-shortening block rotations, strain partitioning or plate kinematic changes (Hindle et al., 2002). In the region discussed here, however, the calculated strain axes give orogen-parallel (NNE) extension, not contraction. Unless the strong similarity of the long-term and very short-term displacement fields is merely coincidental, NE contraction must therefore have been a transient phenomenon that just punctuated the long-term kinematic regime, which has resumed today. The presence of favorably oriented weak zones has very probably enhanced the structural expression of this pulse and may have rotated local contraction directions, but it is not clear why NE contraction occurred at all. Marrett and Strecker (2000) proposed that it reflects a change in plate motion that occurred about 3 Ma ago. If this were true, NE contraction should prevail today, but the GPS data do not seem to support this. Since strain orientations depend on displacement gradients, changing strain axes could reflect variations of these gradients. Such variations may arise where the displacements vary unsteadily across major transfer zones. An important NE trending transfer zone, the Tucumán transfer zone (TTZ in Fig. 1), has been described near the southern termination of our study area (De Urreiztieta et al., 1996). If this zone, or similar ones at a more local scale, lock and unlock, shortening axes may switch

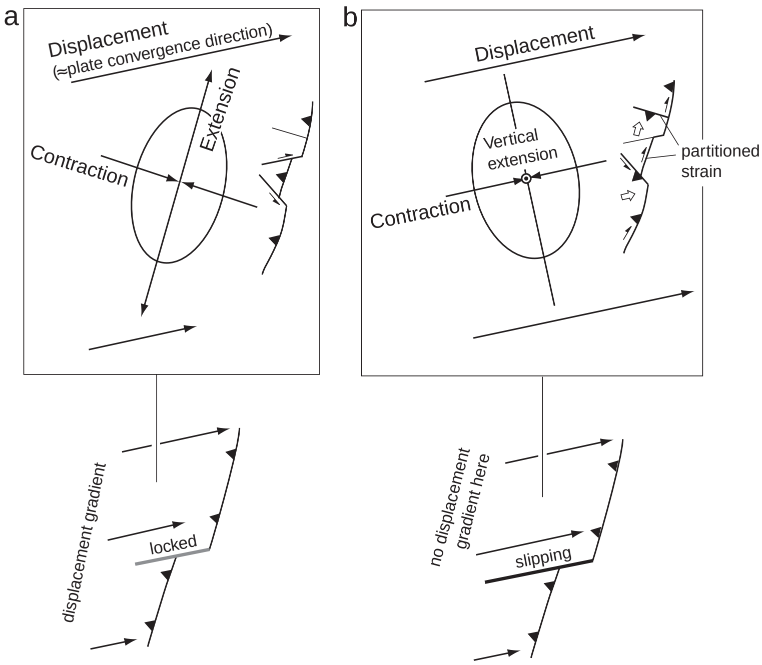


Fig. 12. The short-lived switch from ESE to NE contraction and back may reflect rapid changes in along-strike displacement gradients. These changes could be linked to intermittent activity of NE trending transfer zones, such as the Tucumán transfer zone south of the area discussed here (Fig. 1).

from SE to NE on a short time scale (Fig. 12). The strong local scatter of shortening directions from ENE to almost N may reflect strain partitioning on the preexisting faults.

6. Conclusions

The Cretaceous to Paleogene Salta rift of northwestern Argentina had subbasins trending N, NNE, NE and SE. Faults that were active during rifting are similarly variable in their orientations. Documented examples trend N to NNE, NE, E and SE, and include both inverted and non-reactivated rift faults. Faults oblique or transverse to the present-day NNE oriented Andean structural grain are remarkably frequent, but it is not clear if this reflects their actual importance in the rift. With a dominant E to ESE contraction direction during Andean folding and thrusting in Neogene time, N to NNE trending rift faults were particularly prone to strong reactivation as reverse faults and the traces of their origin may often have been obliterated. Where transverse rift faults have been strongly rotated during Neogene deformation, the kinematics of normal faulting and later strike slip reactivation can be undistinguishable. The lack of kinematic information from the rifting phase hampers attempts to reconstruct the original rift configuration. It is not clear if all the variably trending faults were active as normal faults at some time or if faults of some direction were exclusively transfer faults. Consequently, it is also unclear if all faults formed during a single rifting episode with a nearly uniaxial strain or during several non-coaxial phases of extension.

Reactivation of the rift faults during the Andean orogeny is in general compatible with a relatively uniform and constant regime of E to ESE directed contraction. N to NNE trending faults were reactivated as thrust and reverse faults. Oblique faults, such as the NE trending Hornocal fault, were reactivated as reverse faults with a major strike slip component. Rift faults trending E to ESE, parallel to the Andean shortening direction, are sometimes preserved in their original configuration. However, inversion locally also affected those faults, indicating a component of N to NE directed contraction. In contrast, estimates of large-scale finite strain in the Central Andes and the present-day velocity field from GPS data indicate N to NE extension resulting from along-strike velocity gradients. Rapid variations of these gradients may explain the short-lived shifts of the contraction direction between about ESE and NE and could be due to intermittent activity of major transverse fault zones.

Acknowledgements

The ideas on shortening directions and displacement gradients exposed here were shaped during discussions with David Hindle (then GFZ Potsdam, now at Michigan State University). We thank Patrice Baby, Thierry Nalpas and Francesc Sàbat for their constructive reviews, and Ralf Freitag (Jena) for helpful suggestions. This work was supported through Deutsche Forschungsgemeinschaft (DFG) grant Kl 495/4-1.

References

Allmendinger, R.W., 1986. Tectonic development, southeastern border of the Puna plateau, northwestern Argentine Andes. Geological Society of America Bulletin 97, 1070–1082.

Allmendinger, R.W., Jordan, T.E., Kay, S.M., Isacks, B.L., 1997. The evolution of the Altiplano–Puna plateau of the Central Andes. Annual Review of Earth and Planetary Sciences 25, 139–174.

Amengual, A., Zanettini, J.C.M., 1973. Geología de la comarca de Cianzo y Caspalá (Provincia de Jujuy). Revista de la Asociación Geológica Argentina 28 (4), 341–352.

Belotti, H.J., Saccavino, L.L., Schachner, G.A., 1995. Structural styles and petroleum occurrence in the sub-Andean fold and thrust belt of northern Argentina. In: Tankard, A.J., Suárez, R.S., Welsink, H.J. (Eds.), Petroleum Basins of South America. AAPG Memoir, pp. 545–555. Tulsa.

Bevis, M., Kendrick, E., Smalley, R., Brooks, B., Allmendinger, R., Isacks, B., 2001. On the strength of interplate coupling and the rate of back arc convergence in the Central Andes: an analysis of the interseismic velocity field. Geochemistry, Geophysics, Geosystems 2 (2001GC000198).

Bianucci, H.A., 1999. Estructura y evolución estructrural del rift-relación con la estratigrafía. Subcuenca de Lomas de Olmedo (rama oriental). In: González Bonorino, G., Omarini, R., Viramonte, J. (Eds.), Geología del Noroeste Argentino, Salta, pp. 292–300.

Bianucci, H., Homovc, J.F., Acevedo, O.M., 1982. Inversión Tectónica y Plegamientos Resultantes en la Comarca Puesto Guardian-Dos Puntitas. Dpto. Orán, Provincia de Salta, Primer Congreso Nacional de Hidrocarburos, Buenos Aires, pp. 23–30.

Boll, A., Hernández, M.R., 1986. Interpretación estructural del área Tres Cruces. Boletín de Información Petrolera, Tercera Epoca III (7), 2–14.

Cahill, T., Isacks, B.L., Whitman, D., Chatelain, J.-L., Perez, A., Chiu, J.M., 1992. Seismicity and tectonics in Jujuy Province, northwestern Argentina. Tectonics 11 (5), 944–959.

Cominguez, A.H., Ramos, V.A., 1995. Geometry and seismic expression of the Cretaceous Salta rift of northwestern Argentina. In: Tankard, A.J., Suárez Soruco, R., Welsink, H.J. (Eds.), Petroleum Basins of South America. AAPG Memoir, pp. 325–340. Tulsa.

Coutand, I., Gautier, P., Cobbold, P.R., de Urreiztieta, M., Chauvin, A., Gapais, D., Rossello, E.A., Lopez Gamundi, O., 2001. Style and history of Andean deformation, Puna plateau, northwestern Argentina. Tectonics 20 (2), 210–234.

Cristallini, E., Cominguez, A.H., Ramos, V.A., 1997. Deep structure of the Metán-Guachipas region: tectonic inversion in northwestern Argentina. Journal of South American Earth Sciences 10 (5–6), 403–421.

DeMets, C., Gordon, R.G., Argus, D.F., Stein, S., 1994. Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. Geophysical Research Letters 21 (20), 2191–2194.

De Urreiztieta, M., Gapais, D., Le Corre, C., Cobbold, P.R., Rossello, E., 1996. Cenozoic dextral transpression and basin development at the southern edge of the Puna plateau, northwestern Argentina. Tectonophysics 254, 17–39.

Galliski, M.A., Viramonte, J.G., 1988. The Cretaceous paleorift in northwestern Argentina: a petrologic approach. Journal of South American Earth Sciences 1 (4), 329–342.

Gangui, A.H., 1998. A combined structural interpretation based on seismic data and 3-D gravity modeling in the northern Puna/eastern Cordillera, Argentina. Berliner Geowissenschaftliche Abhandlungen. B 27, 1–127.

Gangui, A., Götze, H.-J., 1996. The deep structure of the northern Puna, Argentina—constraints from 2D seismic data and 3D gravity modeling, XIII. Congreso Geológico Argentino y III. Congreso de Exploración de Hidrocarburos, Actas II, Buenos Aires, pp. 545–565.

Gomez Omil, R., Albarino, L.M., 1996. Análisis geológico petrolero del bloque Olleros, Sistema de Santa Bárbara-Prov. de Salta. XIII Congreso Geológico Argentino y III Congreso de Exploración de Hidrocarburos, Buenos Aires, pp. 27–44.

Grier, M.E., Salfity, J.A., Allmendinger, R.W., 1991. Andean reactivation of the Cretaceous Salta rift, northwestern Argentina. Journal of South American Earth Sciences 4 (4), 351–372.

Gubbels, T.L., Isacks, B.L., Farrar, E., 1993. High-level surfaces, plateau uplift, and foreland development, Bolivian Central Andes. Geology 21, 695–698.

Habighorst, B., 2002. Geologie und Tektonik der Quebrada de Humahuaca östlich der Ortschaft Huacalera in der Ostkordillere der Zentralanden bei 23°30′ Süd (Nordargentinien). Diploma Thesis, Universität Karlsruhe. 105 pp.

Hernández, R., Reynolds, J., di Salvo, A., 1996. Análisis tectosedimentario y ubicación geocronológica del Grupo Orán en el Río Iruya. Boletín de Información Petrolera 45, 80–93.

Hindle, D., Besson, O., Burkhard, M., 2000. A model of displacement and strain for arc-shaped mountain belts applied to the Jura. Journal of Structural Geology 22, 1285–1296.

Hindle, D., Kley, J., Klosko, E., Stein, S., Dixon, T., Norabuena, E., 2002. Consistency of geologic and geodetic displacements during Andean orogenesis. Geophysical Research Letters 29, 29-1–29-4.

Isacks, B.L., 1988. Uplift of the central Andean plateau and bending of the Bolivian orocline. Journal of Geophysical Research 93 (B4), 3211–3231.

Jordan, T.E., Alonso, R.N., 1987. Cenozoic stratigraphy and basin tectonics of the Andes mountains, 20°–28° south latitude. AAPG Bulletin 71 (1), 49–64.

Kley, J., 1999. Geologic and geometric constraints on a kinematic model of the Bolivian orocline. Journal of South American Earth Sciences 12, 221–235.

Kley, J., Monaldi, C.R., 1998. Tectonic shortening and crustal thickness in the Central Andes: how good is the correlation? Geology 26 (8), 723–726.

Kley, J., Monaldi, C.R., 2002. Tectonic inversion in the Santa Barbara System of the central Andean foreland thrust belt, northwestern Argentina. Tectonics 21 (6), 1–18.

Kley, J., Monaldi, C.R., Salfity, J.A., 1999. Along-strike segmentation of the Andean foreland: causes and consequences. Tectonophysics 301, 75–94.

Kocks, H., 1999. Geologie und Tektonik des Gebietes zwischen Palca de Aparzo und Abra de Zenta in der Ostkordillere der Zentralanden bei 23° Süd (Nordargentinien). Diploma Thesis, Universität Karlsruhe. 74 pp.

Kraemer, B., Adelmann, D., Alten, M., Schnurr, W., Erpenstein, K., Kiefer, E., van den Boogard, P., Görler, K., 1999. Incorporation of the Paleogene foreland into the Neogene Puna plateau: the Salar de Antofalla area, NW Argentina. Journal of South American Earth Sciences 12 (2), 157–182.

Kress, P., 1995. Tectonic inversion of the Subandean foreland—a combined geophysical and geological approach. Berliner Geowissenschaftliche Abhandlungen. Reihe B, Geophysik 23, 1–120.

Kumpa, M., Sánchez, M.C., 1988. Geology and sedimentation of the Cambrian Grupo Mesón (NW-Argentina). In: Bahlburg, H., Breitkreuz, C., Giese, P. (Eds.), The Southern Central Andes, Lecture Notes in Earth Sciences. Springer Verlag, Berlin, pp. 39–53.

Lamb, S., 2001. Vertical axis rotation in the Bolivian orocline, South America: 2. Kinematic and dynamical implications. Journal of Geophysical Research 106 (B11), 26633–26653.

Lowell, J.D., 1995. Mechanics of basin inversion from worldwide examples. In: Buchanan, J.G., Buchanan, P.G. (Eds.), Basin Inversion, pp. 39–57.

Marrett, R., Strecker, M.R., 2000. Response of intracontinental deformation in the Central Andes to late Cenozoic reorganization of South American Plate motions. Tectonics 19 (3), 452–467.

Marrett, R.A., Allmendinger, R.W., Alonso, R.N., Drake, R.E., 1994. Late Cenozoic tectonic evolution of the Puna plateau and adjacent foreland, northwestern Argentine Andes. Journal of South American Earth Sciences 7 (2), 179–207.

Mon, R., Salfity, J.A., 1995. Tectonic evolution of the Andes of northern Argentina. In: Tankard, A.J., Welsink, H.J. (Eds.), Petroleum Basins of South America. AAPG Memoir, pp. 269–283. Tulsa.

Moya, M.C., 1988. Lower Ordovician in the southern part of the Argentine Eastern Cordillera. In: Bahlburg, H., Breitkreuz, C., Giese, P. (Eds.), The Southern Central Andes, Lecture Notes in Earth Sciences. Springer Verlag, Berlin, pp. 55–69.

Moya, M.C., 1999. Sedimentología y paleogeografía del Grupo Mesón (Cámbrico). In: González Bonorino, G., Omarini, R., Viramonte, J. (Eds.), Geología del Noroeste Argentino, Salta, pp. 134–152.

Müller, J., Kley, J., Jacobshagen, V., 2002. Structure and Cenozoic kinematics of the Eastern Cordillera, southern Bolivia (21°S). Tectonics 21 (5), 1-1–1-24.

Norabuena, E., Leffler-Griffin, L., Mao, A., Dixon, T., Stein, S., Sacks, I.S., Ocala, L., Ellis, M., 1998. Space geodetic observations of Nazca–South America convergence along the Central Andes. Science 279, 358–362.

Pindell, J.L., Tabbutt, K.D., 1995. Mesozoic–Cenozoic Andean paleogeography and regional controls on hydrocarbon systems. In: Tankard, A.J., Suárez, R.S., Welsink, H.J. (Eds.), Petroleum Basins of South America. AAPG Memoir, pp. 101–128. Tulsa.

Reynolds, J.H., Hernández, R.M., Galli, C.I., Idleman, B.D., 2001. Magnetostratigraphy of the Quebrada La Porcelana section, Sierra de Ramos, Salta Province, Argentina: age limits for the neogene Orán Group and uplift of the southern Sierras Subandinas. Journal of South American Earth Sciences 14, 681–692.

Salfity, J.A., 1982. Evolución paleogeográfica del grupo Salta (Cretácico-Eogénico), Argentina, Quinto Congreso Latinoamericano de Geología, Buenos Aires, Argentina, pp. 11–26.

Salfity, J.A., 1985. Lineamientos transversales al rumbo Andino en el noroeste Argentino. In: Arias, J., Campano, P., Espinoza, S. (Eds.), 4 Congreso Geologico Chileno. Universidad del Norte Chile, Antofagasta, Chile, pp. 2119–2137.

Salfity, J.A., Marquillas, R.A., 1994. Tectonic and sedimentary evolution of the Cretaceous–Eocene Salta Group basin, Argentina. In: Salfity, J.A. (Ed.), Cretaceous Tectonics of the Andes. Vieweg, Braunschweig, pp. 266–315.

Salfity, J.A., Monaldi, C.R., Marquillas, R.A., Gonzáles, R.E., 1993. La inversión tectónica del Umbral de los Gallos en la cuenca del grupo Salta durante la fase Incaica, XII. Congreso Geologico Argentino y II. Congreso de Exploración de Hidrocarburos, Mendoza, Argentina, pp. 200–210.

Salfity, J.A., Gorustovich, S.A., González, R.E., Monaldi, C.R., Marquillas, R.A., Galli, C.I., Alonso, R.N., 1996. Las cuencas Terciarias posincáicas de los Andes Centrales de la Argentina. XIII Congreso Geológico Argentino y III Congreso de Exploración de Hidrocarburos, Buenos Aires, pp. 453–471.

Sánchez, M.C., 1999. Sedimentología y paleogeografía del Grupo Mesón (Cámbrico). In: González Bonorino, G., Omarini, R., Viramonte, J. (Eds.), Geología del Noroeste Argentino, Salta, pp. 126–133.

Sempere, T., 1995. Phanerozoic Evolution of Bolivia and Adjacent Regions. In: Tankard, A.J., Suárez, R.S., Welsink, H.J. (Eds.), Petroleum Basins of South America. AAPG Memoir, pp. 207–230. Tulsa.

Servicio Geológico Argentino, 1996. Mapa geológico de la Provincia de Jujuy.

Somoza, R., 1998. Updated Nazca (Farallon)–South America relative motions during the last 40 My: implications for mountain building in the central Andean region. Journal of South American Earth Sciences 11 (3), 211–215.

Starck, D., 1995. Silurian–Jurassic stratigraphy and basin evolution of northwestern Argentina. In: Tankard, A.J., Suárez, R.S., Welsink, H.J. (Eds.), Petroleum Basins of South America. AAPG Memoir, pp. 251–267. Tulsa.

Strecker, M.R., Marrett, R., 1999. Kinematic evolution of fault ramps and its role in the development of landslides and lakes in the northwestern Argentine Andes. Geology 27 (4), 307–310.

Turner, J.C.M., 1960. Estratigrafía de la Sierra de Santa Victoria y adyacencias. Boletín de la Academia Nacional de Ciencias 41 (2), 163–196.

Uliana, M.A., Biddle, K.T., 1988. Mesozoic–Cenozoic paleogeographic and geodynamic evolution of southern South America. Revista Brasileira de Geociências 18 (2), 172–190.

Uliana, M.A., Arteaga, M.E., Legarreta, L., Cerdán, J.J., Peroni, G.O., 1995. Inversion structures and hydrocarbon occurrence in Argentina. In: Buchanan, J.G., Buchanan, P.G. (Eds.), Basin Inversion. Geological Society Special Publication, pp. 211–233.

Viramonte, J., Escayola, M.P., 1999. El magmatismo Cretácico–Paleoceno del Noroeste Argentino. In: González Bonorino, G., Omarini, R., Viramonte, J. (Eds.), Geología del Noroeste Argentino, Salta, pp. 284–291.

Welsink, H.J., Martinez, E., Aranibar, O., Jarandilla, J., 1995. Structural Inversion of a Cretaceous Rift Basin, southern Altiplano, Bolivia. In: Tankard, A.J., Suárez Soruco, R., Welsink, H.J. (Eds.), Petroleum Basins of South America. AAPG Memoir, pp. 305–324. Tulsa.

Willner, A.P., Lottner, U.S., Miller, H., 1987. Early Paleozoic structural development in the NW Argentine basement of the Andes and its implication for geodynamic reconstructions. In: McKenzie, G.D. (Ed.), Gondwana Six: Structure, Tectonics and Geophysics. American Geophysical Union, Washington, DC.