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Tectonophysics 259 (1996) 201–212

TECTONOPHYSICS

Strike-slip faulting, thrusting and related basins in the Cenozoic evolution of the southern branch of the Bolivian Orocline

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Received 10 November 1994; accepted 19 July 1995

Abstract

The evolution of the Cenozoic deformation of the Cordillera Oriental and of the contact zone with the Altiplano in southern Bolivia is well documented in the Tupiza, Nazareno and Estarca basins. The tectonic evolution started at about 29 Ma. The period between 29 and about 22–21 Ma is marked by development of a pull-apart basin related to N–S-trending left-lateral strike-slip faulting. During this period, initial deposition consisted of andesitic lavas and detrital sediments (breccias; matrix-supported red conglomerates; sands and silts...) of the Catati and Tupiza Formation, deposited in alluvial fan and flood plain environments. From 21 to 20 Ma, the tectonic setting evolved to N–S-oriented thrusts, which had a dextral component. This event caused the Tupiza basin to evolve into a full-ramp basin, and triggered the development of two piggy-back basins: Nazareno and Estarca. Both basins record detrital deposition (Nazareno Formation) in an alluvial fan environment. At 10–9 Ma, deformation in this area stopped allowing peneplanation during which time the San Juan de Oro erosional surface was formed and the fluvial conglomerates of the Oploca Formation were deposited. This segment of the Andes was then tectonically transported to the east, while uplift due to thrusting continued in the eastern Andean front and in the Subandean zone.

1. Introduction

During the Cenozoic Andean orogenesis E-vergent thrusts and associated back-thrusts uplifted the Bolivian Andes and formed syn-tectonic sedimentary basins (Fig. 1; Roeder, 1988; Baby et al., 1989; Sempere et al., 1990; Sheffels, 1990; Hérail et al., 1990). This deformation has also shortened the crust by 250 km in the Subandean Thrust and Fold Belt, Cordillera Oriental and Eastern Altiplano (Sheffels, 1990; Baby et al., 1992a,b). However, in the Bolivian Altiplano there is evidence for transcurrent faulting prior to the Cenozoic thrusting. These movements generated compressive flower structures, as for example the Pululus structure (Fig. 2), and probably, pull-apart basins only observed in seismic sections (Baby et al., 1990; Barrios, 1991). Because, in the Altiplano the Cenozoic strata are covered by extensive Quaternary deposits, studying Andean tectonic structures prior to the thrusting event is very difficult.

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SSDI 0040-1951(95)00108-5

In contrast, uplift of the Cordillera Oriental during the Cenozoic enhanced the erosion of the Cenozoic basins which, in turn, exposed the complete Cenozoic series. In the Tupiza, Estarca and Nazareno basins located in the southern branch of the Cordillera Oriental of Bolivia, Cenozoic rocks are extensively exposed. In the Tupiza basin, the Cenozoic sedimentary strata deposited prior to Miocene thrusting are well exposed. The purpose of this paper is to present new data on the stratigraphy, sedimentology, geochronology and structure of these Cenozoic syntectonic basins and to discuss the tectonic context in which they formed.

2. The Cenozoic basins: sedimentation, magmatism and associated erosional surfaces

2.1. Geological and geomorphological background

The Cenozoic basins of the southern part of the Cordillera Oriental of Bolivia developed on two main, tectonostratigraphic domains which compose this segment of the Andes (Figs. 1 and 2); these are the Charazani–Ayoma–Atocha domain to the west and the Tarabuco–Villazon domain to the east (Sempere et al., 1988). The dextral transcurrent Aiquille–Tupiza Fault (FAT) marks the boundary

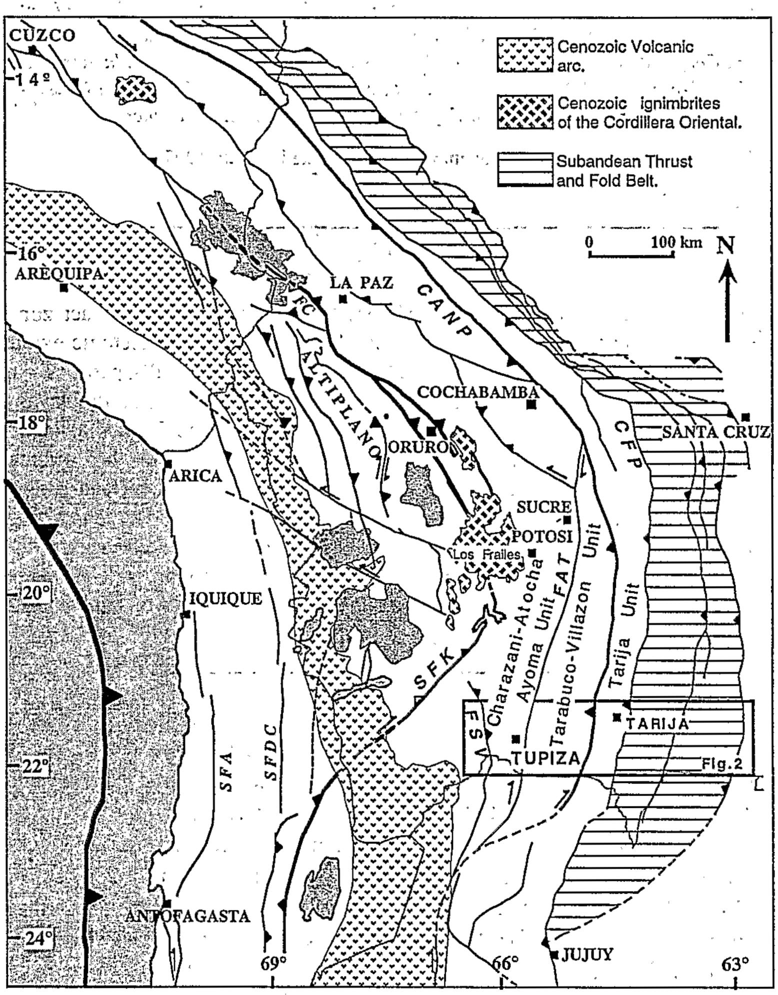

Fig. 1. Location of the studied area. Tectonic sketch map after Sempere et al. (1988) modified. Main boundary faults (abbreviations for spanish names). *CANP* = Main Andean thrust; *CFP* = Main Frontal Thrust; *FAT* = Aiquile–Tupiza fault; *FC* = Coniri fault; *SFK* = Khenayani fault system; *FSV* = San Vicente fault; *SFCD* = Cordillera de Domeyko fault system; *SFA* = Antofagasta fault system.

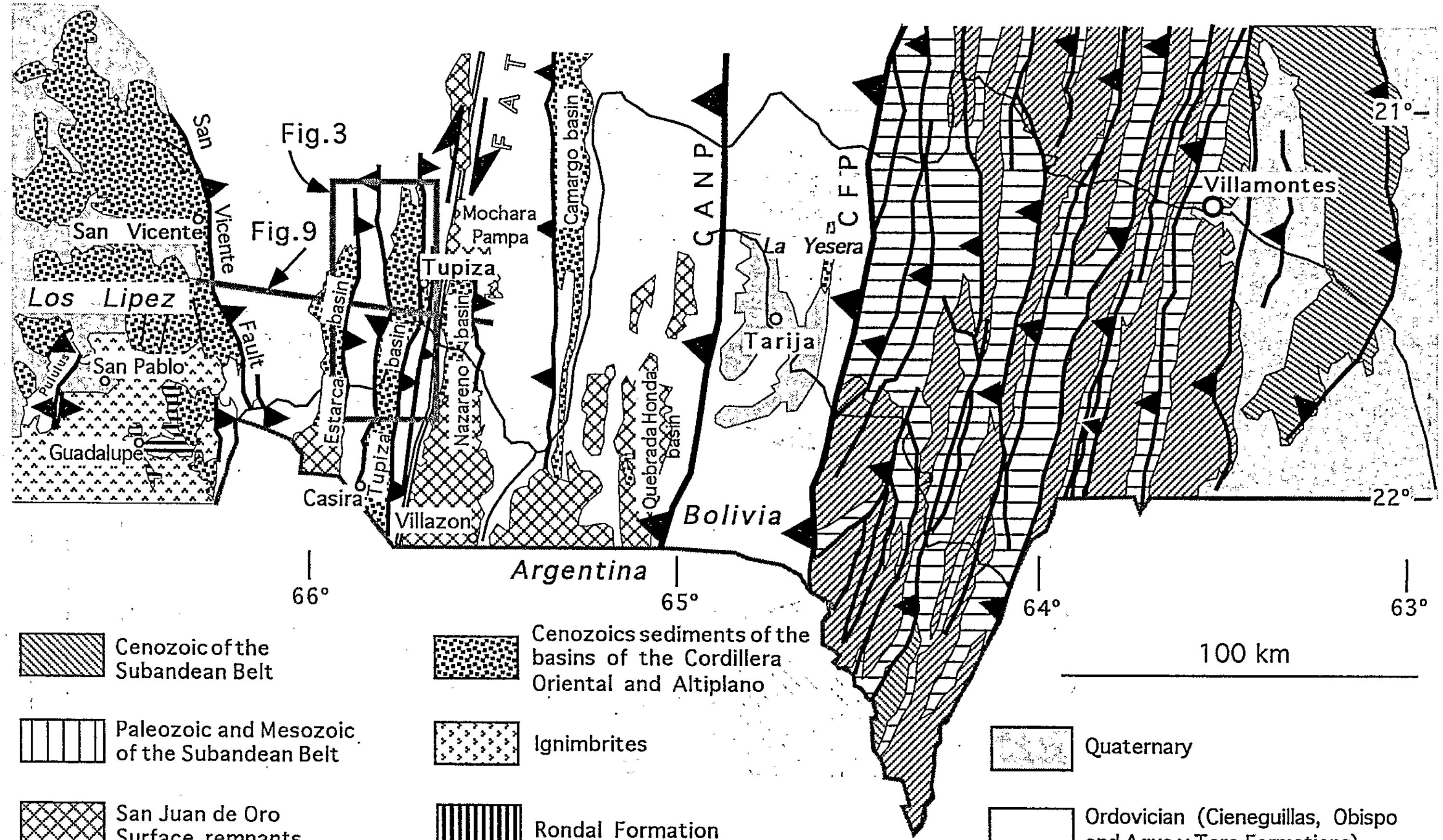
Fig.3
Fig.9
San Vicente Fault
San Vicente
Los Lipez
San Pablo
Pululus
Guadalupe
Casira
Estarca basin
Tupiza basin
Tupiza
Villazon
Nazareno basin
Mochara Pampa
F A T
Camargo basin
C A N P
Quebrada Honda basin
La Yesera
C F P
Tarija
Bolivia
Argentina
Villamontes
21°
22°
66°
65°
64°
63°
100 km
Cenozoic of the Subandean Belt
Paleozoic and Mesozoic of the Subandean Belt
San Juan de Oro Surface remnants
Cenozoics sediments of the basins of the Cordillera Oriental and Altiplano
Ignimbrites
Rondal Formation
Quaternary
Ordovician (Cieneguillas, Obispo and Agua y Toro Formations)

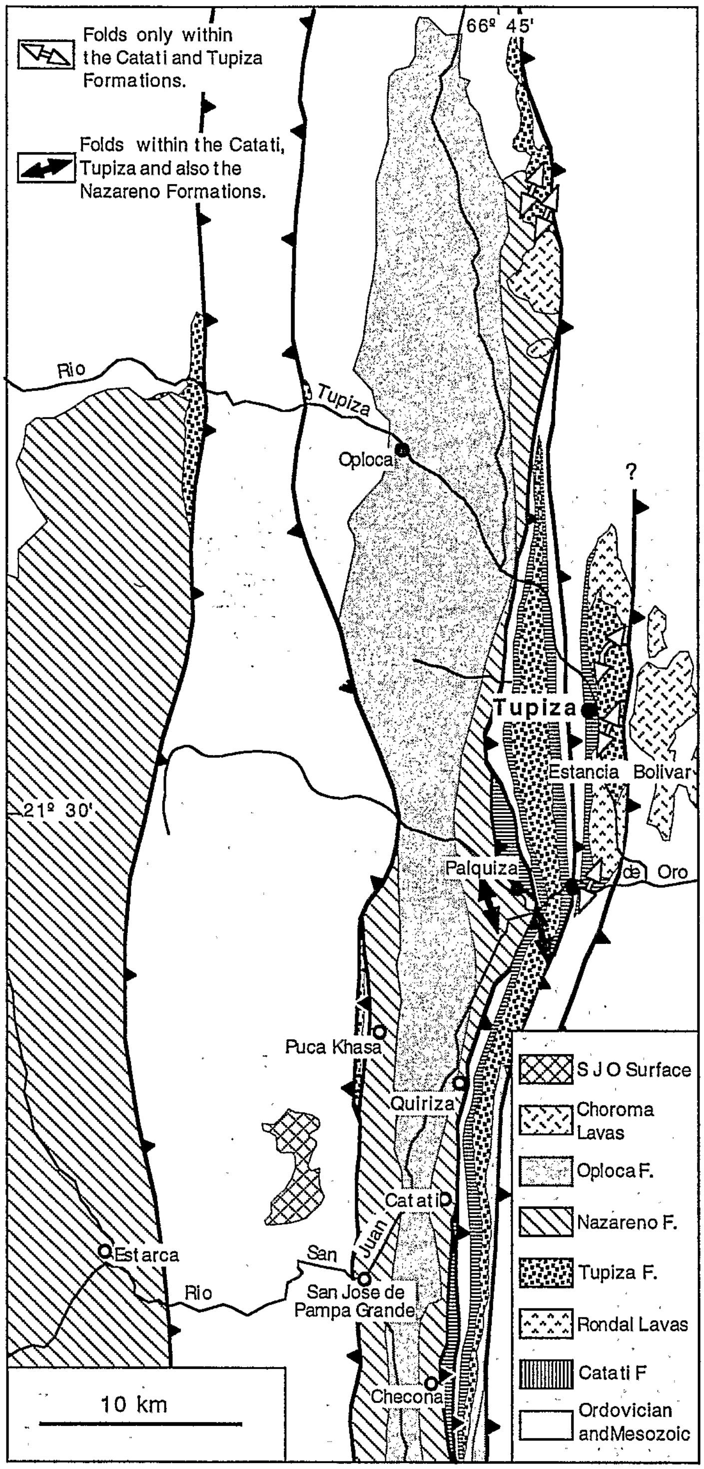

Fig. 3. Geological map of the central part of the Tupiza basin.

between the two. In the Charazani–Ayoma–Atocha domain, the pre-Cenozoic sedimentary sequence consists of Ordovician sedimentary rocks (black shales of the Cieneguillas Formation and grey shales with interbedded sandstone of the Obispo and Agua y Toro formations) which were strongly deformed during the Ocloyic phase (Ashgillian in age). Jurassic and Cretaceous strata overlie these units in some localities. The Tarabuco–Villazon domain consists of Late Proterozoic to Middle Ordovician strata that were only slightly affected by the Ocloyic deformation, but form an angular unconformity beneath Jurassic, Cretaceous and Tertiary sequences (Sempere et al., 1988).

In the Tupiza region, three Cenozoic basins are well developed: Tupiza, Estarca and Nazareno (Fig. 2). These basins, together with the Camargo and Quebrada Honda basins further east (Fig. 2) form a group of characteristic basins of the southern Cordillera Oriental of Bolivia. This segment of the Cordillera Oriental is separated from the Altiplano (Los Lipez basin) by the San Vicente Fault and from the Tarija Block by the Main Andean Thrust (CANP); the Tarija Block is separated from the Subandean zone by the Main Frontal Thrust (CFP) (Fig. 2).

In the Tupiza, Estarca and Nazareno basins, the valley floors are at an elevation of approximately 2800 m, while the divides which separate the basins reach 4000–4200 m and are cut by well-preserved erosion surfaces: the Chayanta Surface at more than 4000 m (Servant et al., 1989) and the San Juan de Oro Surface at 3500–3800 m (Servant et al., 1989; Sempere et al., 1990; Gubbels et al., 1993).

2.2. The Tupiza basin: sedimentation

The Tupiza basin is 6–12 km wide; it extends north–south almost 100 km in Bolivia (Ahlfeld and Branisa, 1960; Montaño, 1966; Claure, 1969) and continues southward to Argentina (Turner, 1964, 1978). The basins' eastern and western boundaries are two converging N–S-trending thrusts which place Ordovician rocks of the Cordillera on top of the Cenozoic continental sediments. The Cenozoic sediments preserved in the Tupiza basin (Fig. 3) consist of conglomeratic facies with minor carbonate intercalations (Ahlfeld and Branisa, 1960) which form four distinctive units (Fig. 4).

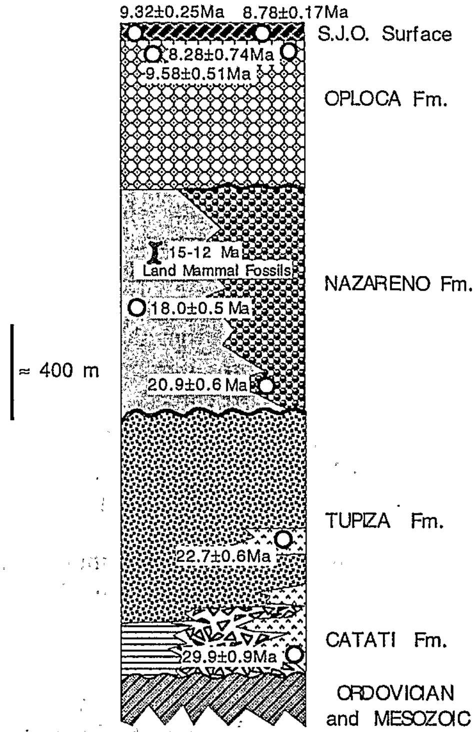

Fig. 4. Synthetic section of the Tupiza sedimentary pile. Explanations are given in the text.

2.2.1. The Catati Formation

The Catati Formation lies at the base of the sequence and has a variable thickness which does not exceed 100 m. It crops out throughout the eastern margin of the basin, and along the western margin it is locally exposed in the Tupiza river valley, upstream from Oploca and at Puca Khasa (Fig. 3). The Catati Formation consists of red breccias composed of Ordovician shale fragments, and of red gypsiferous clays. In the deeper parts of the basin (e.g., Palquiza, Quebrada Catati), a more complete sequence which contains fluvial sandstones laterally grading to the breccias is locally preserved. These sediments grade vertically and laterally to green, purple or reddish clays with gypsum veins, gypsum and halite beds, and fossiliferous (fish teeth and gastropod shells) limestone beds that were deposited in lacustrine and evaporitic environments. In the Bella Vista (Fig. 5) and Puca Khasa area, breccias of the Catati Formation rim the former basin margin.

2.2.2. The Tupiza Formation

The Tupiza Formation conformably overlies the Catati Formation and varies in thickness from 500 to 1000 m. It consists of a thick sequence of red conglomerates that form narrow ridges giving the basin a characteristic landscape (Montaño, 1966). The conglomerates contain mainly fragments of Ordovician rock, whose diameters reach more than 50 cm, but also intraformational andesite clasts derived from interbedded volcanic layers, clasts of Mesozoic sandstone, and clasts of stromatolites limestones (*Pucalithus*). The latter are characteristic of the El Molino Formation (Maastrichtian), but El Molino limestones are not presently exposed near the basin. The conglomerates are interpreted to represent debris flows and mud flows, deposited in a proximal alluvial fan environment.

Andesitic lavas and dikes occur within the Catati and Tupiza formations. Well-preserved lavas crop out at Cerro Estancia Bolivar (Figs. 3 and 5) and also just north of Tupiza (Fig. 3). These rocks are compositionally similar to those of the Rondal Formation (Kussmaul et al., 1975, 1977) at Los Lipez (Fig. 2). Clasts eroded from such volcanic rocks are extremely scarce in the Catati Formation but quite common in the Tupiza Formation. Biotites from an interstratified lava flow near the base of the Catati Formation (just north of Tupiza), yielded a K-Ar age of 29.9 ± 0.9 Ma. In the Tupiza Formation, a sample from the lava flow from Estancia Bolivar (Fig. 5) gave a whole-rock K-Ar age of 22 ± 0.2 Ma.

2.2.3. The Nazareno Formation

The Nazareno Formation with a thickness no greater than 1000 m, overlies the Tupiza Formation. The Nazareno Formation is commonly overthrusted by Ordovician strata and the Catati and Tupiza formations. In the central parts of the basin, at Que-

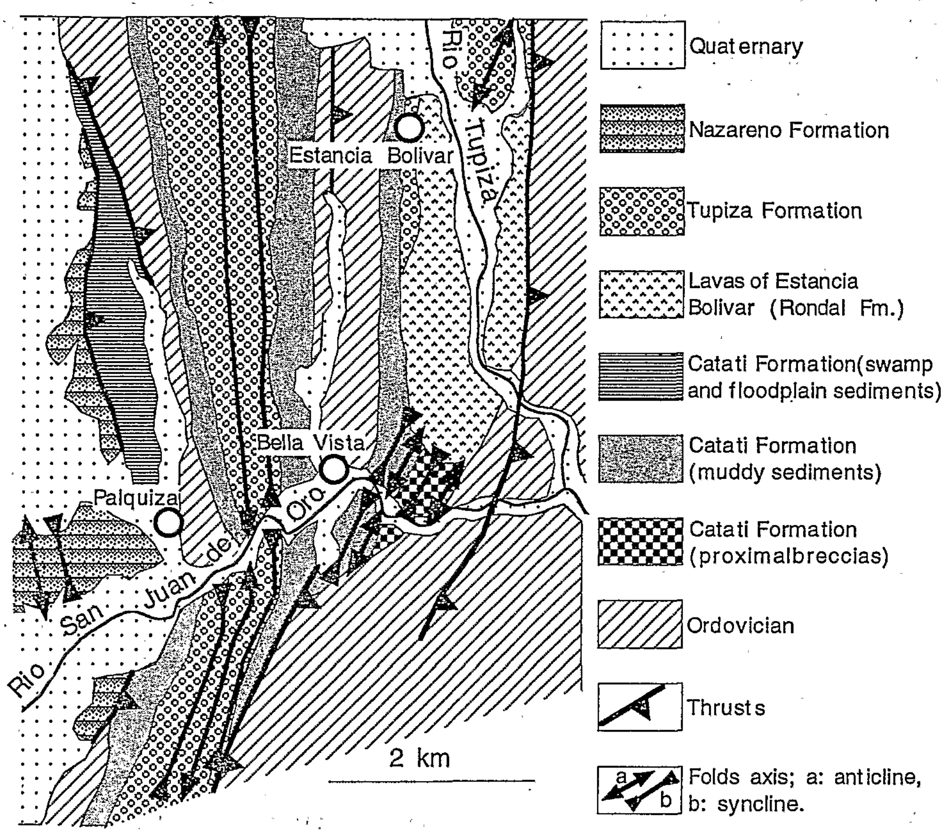

Fig. 5. Geology of the area of Bella Vista.

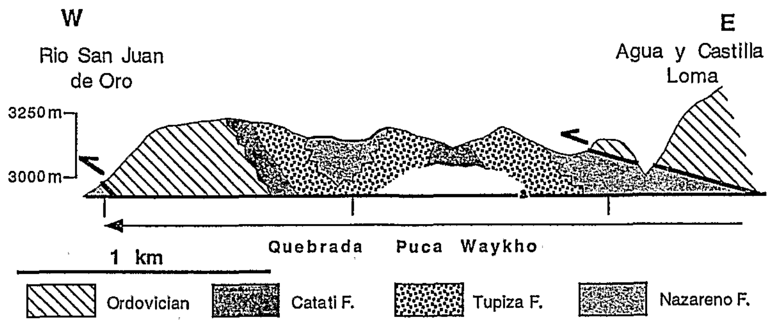

Fig. 6. Cross section along the Quebrada Puca Waykho.

bradas Catati and Puca Wayko or at Quebrada Checona, the observed contact between the Nazareno and Tupiza formations is an erosional unconformity. Upstream of the Quebrada Puca Wayko, however, conglomerates of the Tupiza Formation are weathered right at their upper contact, and basal beds of the overlying Nazareno Formation contain reworked fragments of the Tupiza Formation (Fig. 6). At Quebrada Checona, the Tupiza and Nazareno formations are separated by an angular unconformity (Fig. 7).

The proximal facies of the Nazareno Formation are conglomerates several hundred meters thick, that are composed of clasts of Ordovician rocks, and are interpreted to be debris flows deposited on alluvial fans. Along the basin's axis, the Nazareno Formation consists of pink sands and clays deposited in an intermediate to distal fluvial environment. These lithofacies contain scarce tuff beds and clasts of dacite probably associated with the Choroma volcanic event (Montaño, 1966).

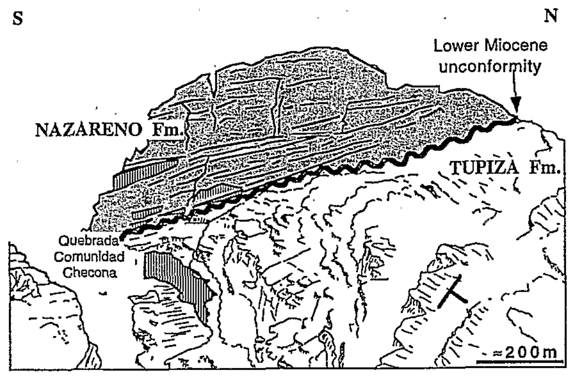

Fig. 7. The discordance of the Nazareno Formation abowe the Tupiza Formation (for location of the Checona area see Fig. 3).

Near Catati (Fig. 3), a 18 ± 0.5 Ma K-Ar biotite age was obtained from a dacitic tuff interbedded with fluvial sands.

2.2.4. The Oploca Formation

The Oploca Formation (Montaño, 1966), 600 m thick of pale-beige coloured sedimentary strata, overlies the Nazareno Formation and locally unconformably covers the Ordovician series (Fig. 3). It consists of conglomerates with sandy matrix and subordinate sand beds. The conglomerate is predominantely clast supported. The clasts are well rounded and fragments of volcanic origin (mainly lavas and tuffs of dacitic composition) are abundant. Most of this widespread sedimentary strata is formed by beds several meters thick. The Oploca Formation was deposited in a braided river system. Paleocurrents directions indicate transport parallel to the basin axis, while in the older formations the flow was directed from the margin to the center of the basin.

The transition from the Nazareno Formation to the Oploca Formation does not document a change in the composition of the sediments, but the clast/matrix ratio increases. At the outcrop scale, both formations appear concordant, but locally the Oploca Formation covers the underlying rock units in progressive unconformity and, at regional scale, and particularly in the northern part of the basin, it is clearly discordant (Fig. 3).

The only tuff bed of the Oploca Formation, which does not contain reworked material located high in the unit, yielded a biotite K-Ar age of 8.28 ± 0.74 Ma. In the Casira region (Fig. 1), the stratigraphic level equivalent of the Oploca Formation is the Rio Seco Formation (Cherroni and Cirbian, 1969); a tuff intercalated with fine-grained sediments at the top of the Rio Chico Formation gave a biotite K-Ar age of 9.58 ± 0.51 Ma.

2.3. The Tupiza basin: deformation and tectonics

In the Tupiza basin, syn- and post-depositional deformation varies in intensity and nature from one sedimentary formation to the other.

Deformation in the Catati and Tupiza formations is intense and is marked by widespread fractured pebbles in the conglomerates and fracture cleavage in clay layers. Distinctive structures are superposed. The oldest ones are scarce synsedimentary N130°-striking normal faults having displacements of only a few meters. In the Bella Vista area (Fig. 5), the sediments of the Catati Formation, deposited near the basin's margin are deformed in N025°E-oriented folds, their axes plunge to the northeast. These folds, which affect massive layers of breccia, include no brittle component and are interpreted to represent syndepositional soft-sediment deformation. Other folds, having amplitudes of hundreds meters trending obliquely to the basin axis, and metric sinistral-reverse faults are present near Tupiza and in the northern part of the basin (Fig. 3). The fold axis trending is N25–N30°E and plunges to the northeast; the sinistral reverse faults are oriented N150° and dipping to the southwest. This fold geometry is consistent with N–S-trending faults with sinistral movements, but the deformation is difficult to date because only the Catati and Tupiza formations crop out here.

The most continuous and recent structures, affecting the Catati and Tupiza formations, involve also the Nazareno Formation and are folds with subvertical limbs striking N160° to north–south. The fold axes are subparallel or slightly oblique to the thrusts which bound the basin, and are consistent with E–W- to ENE–WSW-oriented shortening. These folds are dipping to the south, and in the Quebrada Checona, the sedimentary data indicate that this deformation might have been active during the deposition of Nazareno Formation (Fig. 6). Locally (south of Palquiza, in the central and southern parts of the basin), the Nazareno Formation is affected by oblique folds oriented in NNW–SSE direction.

In addition to the observed folds, the Nazareno Formation is affected by E- or W-dipping N–S-striking thrust faults which place Ordovician rocks over the basin fill (Fig. 3). The detachment level of the thrusts is located in the Ordovician shales (Cieneguillas Formation). The dip of the thrusts is very shallow in places: for example 10–15° upstream of the Quebrada Epicaya and Quebrada Catati.

The Oploca Formation is deformed by open N–S-trending folds (with limbs dipping less than 10°) and rarely by reverse faults.

2.4. The Nazareno basin: sedimentation and deformation

The Nazareno basin is located 5 km east of the Tupiza basin (Fig. 2). It is 80 km long, 15 km wide and N–S oriented. Its eastern edge is a W-vergent thrust fault which places Ordovician rocks on top of Cenozoic sedimentary strata (cf. Fig. 9). The western margin is not deformed. The only Tertiary sedimentary formation present in these basin is the Nazareno Formation.

The Nazareno Formation, 950 m thick, was defined in this basin (Montaño, 1966). It starts with a basal conglomerate (Lower member) some tens of meters thick, composed of poorly rounded clasts of Ordovician slate. Interbedded clay and poorly sorted, fine-grained sands with minor conglomerate (Middle and Upper member, Oiso, 1991) overlie the basal conglomerates. To the north, these three sedimentary members are interlayered with dacitic pyroclastic deposits.

A 20.9 ± 0.6 Ma biotite K-Ar age was obtained from pumice of an interbedded ignimbrite deposit near the base of the Lower member. A fossil land mammal fauna collected (Oiso, 1991) in the Middle member and in the lower part of the Upper member was assigned to the Middle Miocene (Colloncuran age; 15–12 Ma); and a mammal fossil found near Suipacha (Castellanos, 1925) was considered to be Late Miocene in age (Hoffstetter, 1977).

2.5. The Estarca basin: sedimentation and deformation

The Estarca basin is located 10 km west of Tupiza basin (Fig. 2). It is N–S oriented, 70 km long and 6–12 km wide. Its geometry is similar to that of the

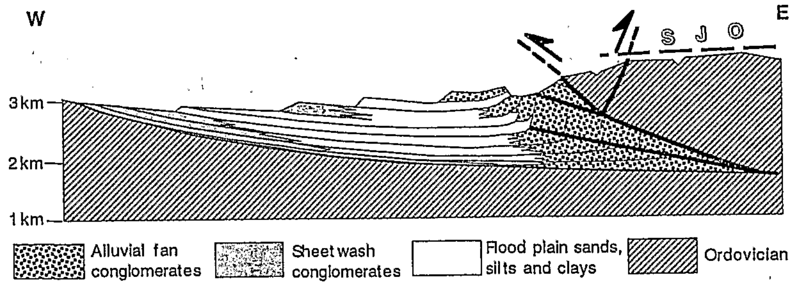

Fig. 8. Cross section in the Estarca piggy-back basin.

Nazareno basin with a tectonically active eastern border formed by a W-vergent thrust, but an undeformed western border (Fig. 8).

The detrital sedimentary fill consists of a conglomerate containing fragments of Ordovician rocks, and fine-grained deposits with some intercalated reworked tuff. The series thickens eastward, across the basin. Along the eastern border, 1000–1500-m-thick syntectonic conglomerate was deposited in an alluvial fan environment fed from reliefs located to the east, and activated by N–S-oriented westward verging thrusts (Fig. 8). Along the western border of the basin, the sediments consist of a reddish conglomerate with angular clasts of Ordovician rocks. They onlap the Ordovician bedrock to the west. These conglomerates were deposited by sheet floods events in a gently sloping pediment environment at the back of the reliefs generated by the San Vicente fault (Figs. 2 and 9). The conglomerates grade laterally towards the center of the basin to fine sediments representing flood-plain deposits (Fig. 8). The sediments of the Estarca basin are of the same lithofacies and clast petrology composition as the sediments which compose the Nazareno Formation. Moreover, in the northern part of the Estarca basin, they overlap the Tupiza Formation (Fig. 3). Therefore, the infill of the Estarca basin can be assigned to the Nazareno Formation.

2.6. Erosional surfaces marking the end of the sedimentary infill

The topographic highs that separate the different basins rise nearly 4000 m and bear remnants of the Chayanta Surface (Servant et al., 1989; Sempere et al., 1990), which is not covered by sediments. At 3500–3800 m, a more widely developed flat or smoothly dissected surface referred to the San Juan de Oro erosion surface (SJO, Fig. 2) extends across both the Cenozoic deposits and adjacent Ordovician strata. The SJO surface is more widely developed than the Chayanta Surface and has a discontinuous sedimentary cover (south of the Estarca basin, Mochara Pampa, Villazon area), composed by conglomerates deposited either in fluvial or pediment environments, or in places, by flood-plain and lacustrine deposits. These deposits are undeformed.

Biotites of volcanic tuffs interbedded in sediments covering the San Juan de Oro Surface have been dated by the ^{40}Ar-^{39}Ar method (Gubbels et al., 1993). A sample from Salitre Pampa near Villazon was dated at 8.78 ± 0.17 Ma and another from Nekheta,

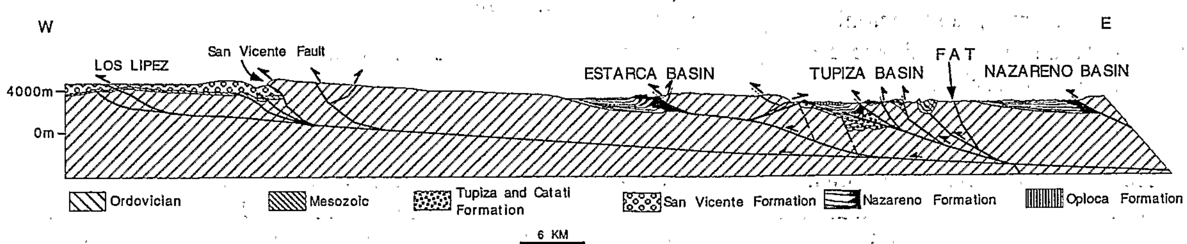

Fig. 9. Interpretative W–E cross section from the Nazareno basin to the San Vicente fault.

north of Mochara Pampa (Fig. 4), at 9.32 ± 0.25 Ma. These ages are similar to those from tuffs at the top of the Oploca Formation.

3. Tectonic significance and deformation of the Cenozoic sediments

The presence of N130°-oriented normal synsedimentary faults, the abundance of breccias of local provenance in the Catati and Tupiza formations indicate that they were deposited in an extensional environment. It is very likely that several basins coexisted; the main one being the one to the east of the Tupiza basin, while small outcrops might represent small subsidiary basins (Fig. 3). The geometry of the Tupiza basin, narrow and N–S elongated, and the presence of a N25–30° fold axes trend, probably synsedimentary in origin, suggest that the sediments were deposited in a pull-apart basin developed along N–S-striking sinistral wrench faults. To the north of Bella Vista (Fig. 5), the uplift of Ordovician rocks is also compatible with a sinistral N–S-oriented wrench tectonics.

In contrast, the Nazareno Formation was deposited in a compressional environment during the activity of marginal thrust faults, as indicated by the sedimentary facies and paleoflow directions. The relations between Miocene sedimentary bodies and thrust faults show that the Nazareno and Estarca basins formed on active thrust sheets, and, thus, correspond to piggy-back basins. The S-dipping N160°-trending folds observed south of Palquiza (Fig. 5) and in the southern margin of basin are oblique to the thrusts which bounded the basin. They are compatibles with a dextral movement of the thrusts.

The upper levels of the Oploca Formation, north and northeast of the Tupiza basin, overlap the thrusts and unconformably overlie Ordovician rock (Fig. 3).

This sedimentary and tectonic study shows that the Tupiza basin evolved successively under two different tectonic regimes:

(1) The Tupiza basin initially opened between 29 and 22–21 Ma as a pull-apart basin along N–S-trending sinistral transcurrent faults, during the deposition of Catati and Tupiza formations. The existence of N–S-trending sinistral faulting has also been described in the Altiplano (Baby et al., 1990) and neighbouring latitudes in the arc domain (e.g., Reutter et al., 1993) for the same period.

(2) The evolution continued, between 21–20 and 10–9 Ma, with E- or W-dipping N–S-striking thrusts, giving rise to the present morphology. The Tupiza basin was shortened and overthrusted, while the Nazareno and Estarca basins formed. The three basins were filled by sediments of the Nazareno Formation while being carried piggy-back on moving thrust sheets (Fig. 9).

The N160°-trending folds, oblique to the thrusts and involving the Nazareno Formation, are consistent with dextral strike-slip movement, well documented in the southern part of the Cordillera Oriental and the Bolivian Subandean fold-and-thrust belt (Sempere et al., 1988; Baby et al., 1993).

In the Estarca basin, the upper part of the sedimentary fill is onlapping against the relief generated by the San Vicente fault (Figs. 2 and 9); it has recorded a decrease in the activity of this fault. This is supported by the weak deformation exhibited by the ignimbrites dated at 15.05 ± 0.5 Ma, which in the Guadalupe region (Fig. 2), west of the San Vicente Fault, cover the Lower Miocene San Vicente Formation (Hérail et al., 1993). On the contrary, further east, between the CANP and the CFP (Fig. 2), the Cenozoic La Yesera Formation of the Tarija basin is folded with N–S-striking axes; a K-Ar biotite age of 6.4 ± 0.4 Ma was obtained from tephra interbedded with the sediments. This indicates that the folding event was younger east of the CANP than west of it. In the Subandean thrust and fold belt, east of the CFP, deformation began at around 10 Ma (Marshall et al., 1993; Gubbels et al., 1993; Allmendinger et al., 1993) and is still active (Jordan et al., 1983) as a consequence of thrusting of this portion of the Andean belt.

4. Conclusions

The sediments and the tectonic structures preserved in the Tupiza and neighbouring basins were generated during a period which started at the end of the Oligocene, at about 29 Ma and ended in the late Miocene (10–9 Ma) (Fig. 10).

Between 29 and 22–21 Ma, the basin opened as a pull-apart related to N–S-striking sinistral wrench faulting.

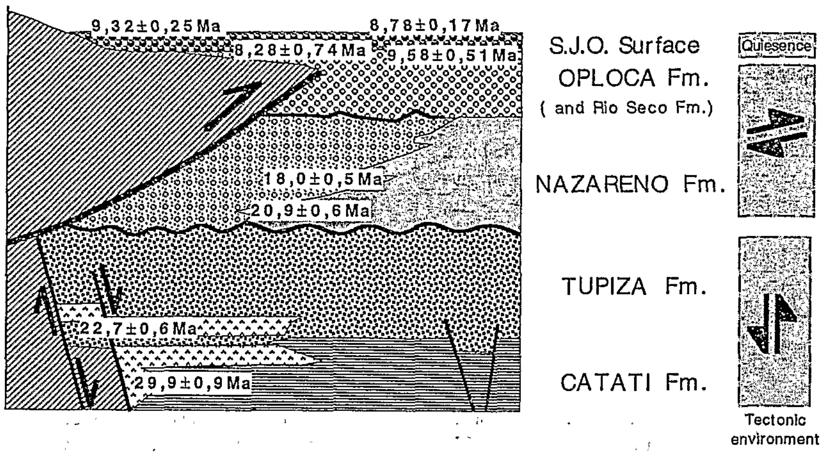

Fig. 10. Summary of the chronology, sedimentary and tectonic evolution of the basins of the Tupiza region.

After 20–21 Ma, both sedimentation and deformation were controlled by the activity of N–S-striking thrusts. The change of the tectonic setting coincides with a great increase in the convergence velocity between the Nazca and South America plate (Pardo-Casas and Molnar, 1987) that triggered thrusting to absorb the shortening. Their geometry results in that of the Nazareno and Estarca basins which developed as piggy-back basins while the Tupiza basin acquired a characteristic geometry with marginal thrusts with centripetal vergence (full ramp basin, Cobbold et al., 1993). The dextral motions along the Aiquille–Tupiza Fault (FAT) are probably contemporaneous with some oblique folds (N160°) which deformed the Nazareno Formation, and consistent with the dextral wrench component of Miocene thrusting which characterize the southern branch of the Bolivian Orocline.

At around 10 Ma, thrusting was limited or had stopped, as indicated by the weak deformation of the Oploca Formation. During this tectonic quiescence, the San Juan de Oro erosional surface developed; producing a great part of the sediments which were deposited in the Oploca Formation. Although by this time tectonic deformation ceased in this area, it was still active at the same latitude further east in the Subandean Zone. At 10 Ma the deformation "jumped" towards the foreland, probably due to blocking of the deformation in the upper crust west of the CANP. However, uplift of the western part of the Cordillera Oriental continued, while being carried passively on the moving CANP, CFP and Subandean thrusts.

Acknowledgements

Logistical and financial support was supplied by ORSTOM (Institut Français pour la Recherche Scientifique pour le Développement en Coopération) and Yacimientos Petrolíferos Fiscales Bolivianos. We thank J. Blanco and L. Barrios (YPFB) for assistance and discussions during the field work, Jose Cembrano, Reynaldo Charrier, Francisco Hervé and Roland Brady (Departamento de Geología de la Universidad de Chile) for constructive discussion during the writing of the paper. Finally, the paper has benefited from critical review of two anonymous referees to whom the authors express their thanks.

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TECTONOPHYSICS

INTERNATIONAL JOURNAL OF GEOTECTONICS AND THE GEOLOGY AND PHYSICS OF THE INTERIOR OF THE EARTH

Tectonophysics 259 (1996) 201–212

Strike-slip faulting, thrusting and related basins in the Cenozoic evolution of the southern branch of the Bolivian Orocline

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Received 10 November 1994; accepted 19 July 1995

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