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Cenozoic lithospheric faulting in the Asunción Rift, eastern Paraguay

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Abstract

The Eocene magmatism of the western segment of the Asunción Rift (Asunción alkaline province) was controlled by deep NW–SE-trending faults with magnetic and gravimetric expressions that served as conduits for the ultra-alkaline magma coming from depths of more than 60 km and bearing mantle xenoliths to the surface. Petrologic data suggest that a short interval of time elapsed between the magma ascension and its emplacement at shallow crustal levels. Cooling and fracturing in relatively restricted areas indicate that the NW–SE-trending structural alignments represent deep faults whose activity caused great energy loss in the asthenosphere, leading to melting of the lithospheric mantle by decompression during a relatively short time interval. Families of fractures associated with intrusions in the ultra-alkaline bodies showed a stress regime with $\sigma 1$ horizontal, in the NW–SE direction, $\sigma 3$ horizontal, in the NE–SW direction, and $\sigma 2$ vertical, all of them compatible with the action of a right-lateral strike-slip shear couple oriented E–W. The validity of this regime during the Eocene is corroborated by the NW–SE orientation of the nephelinitic dykes. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Cenozoic; Mantle; Asunción Rift; Paraquay xenolith; Lithospheric faulting

1. Introduction

Eastern Paraguay is punctuated by a large number of alkaline rock occurrences, mainly distributed in six provinces: Alto Paraguay, Rio Apa, Amambay, Central, Misiones and Asunción. The alkaline magmatism in the Central and Asunción Provinces is associated with the evolution of the Asunción Rift (DeGraff, 1985), a striking tectonic feature of Mesozoic–Cenozoic age (Velázquez et al., 1998) showing variable widths between 25 and 40 km (Fig. 1). This eastward-developed structure, which is believed to start in the Asunción region, consists of three sections: the well-defined western segment with a NW–SE strike and extending over 90 km between the localities of Benjamin Aceval and Paraguarí; the central segment that is E–W oriented and about 70 km in extent, linking the cities of Paraguarí and Villarrica; and finally the less-defined eastern segment, 40 km long with an NW–SE strike, terminating in the Ybytyruzú Mountains.

Systematic studies were done in the region of the Asunción Rift in order to characterize the different tectonic structures and their distribution patterns so as to establish their local and regional relative chronology as well as to determine the possible changes in paleostress orientation during Mesozoic and Cenozoic times. A first phase of faulting took place in the Early Cretaceous (130–120 Ma), as judged by the expressive alkaline magmatism activity concentrated in the central segment of the rift (Gomes et al., 1996; Comin-Chiaramonti et al., 1997). Paleostress analysis of alkaline dyke swarms of this region enabled Velázquez et al. (1998) to suggest the action of a paleostress field with $\sigma 1$, NW–SE oriented /horizontal, $\sigma 2$ vertical, and $\sigma 3$ NE–SW/horizontal. This stress field is compatible with an E–W oriented right-lateral strike-slip binary. During the Eocene, the western segment of the Asunción Rift was the focus of important tectono-magmatic activity, with evidence of deep NW-trending faults acting as conduits for the emplacement of ultra-alkaline rocks of nephelinitic composition (Asunción Province) bearing spinel lherzolite mantle xenoliths. Alkaline bodies are concentrated in the neighborhood of Asunción, and the Benjamin Aceval, Lambaré, and Ñemby occurrences were selected for paleostress analysis. Determination of paleostress fields was based on structural analyses of fractures and dykes. Interpretations concerning evolution of the paleostress fields and their relationships with sedimentation are supported by stratigraphic analyses of Cenozoic sedimentary deposits of the region. These data were integrated with petrological and geophysical information in order to obtain a better definition of the tectonic control of Cenozoic magmatism in the western segment of the Asunción Rift.

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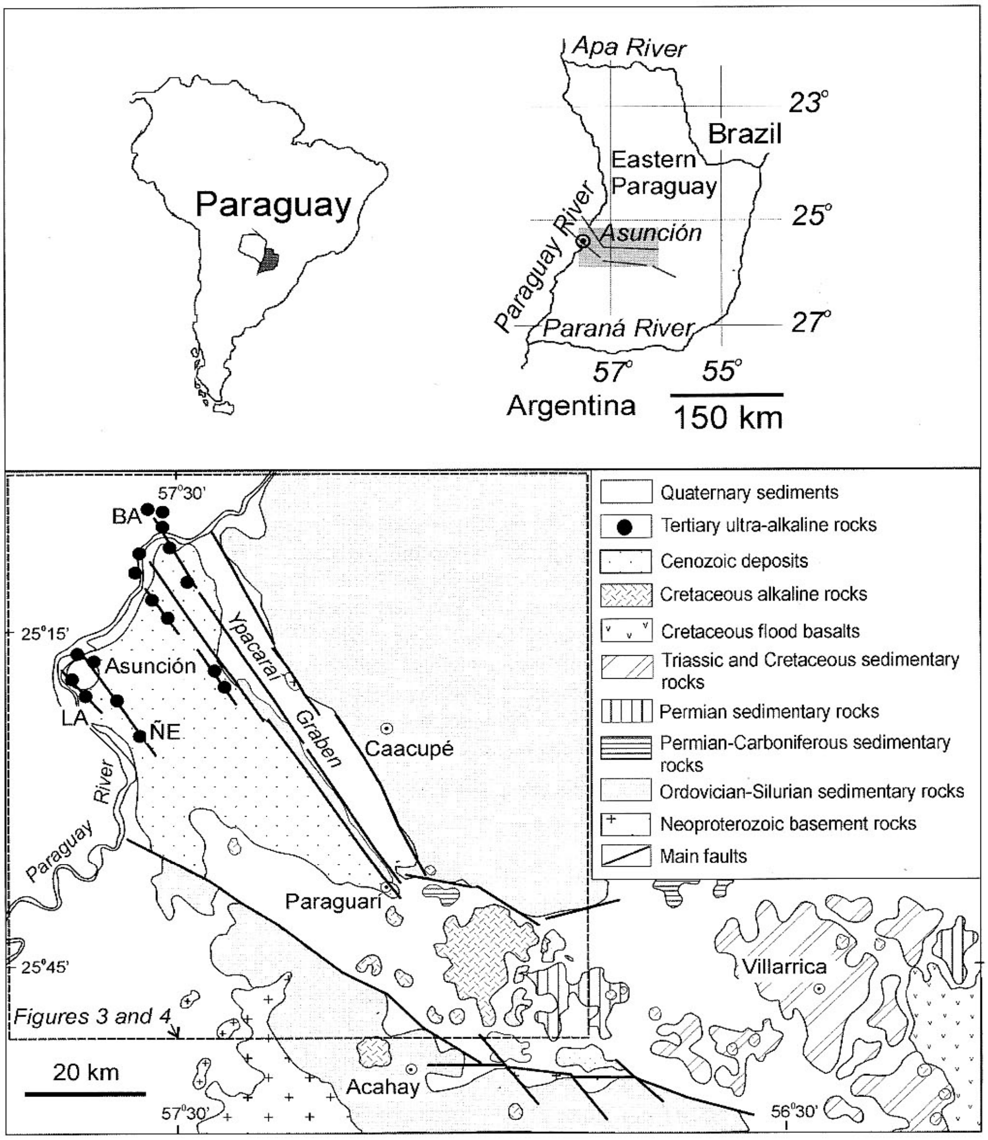

Fig. 1. Location and schematic geologic maps of the Asunción Rift and associated alkaline occurrences (after Velázquez et al., 1998). Abbreviations: BA, Benjamin Aceval; LA, Lambaré, ÑE, Ñemby Hill.

2. Cenozoic magmatism in the Asunción Rift

The association of rifting processes, particularly of the continental type, with alkaline magmatism is considered by many authors (e.g. Bailey, 1979; Bhattacharji and Koide, 1987) as of fundamental importance in the formation of rift valleys. Geophysical data indicate that this type of process is quite variable, including deformations of differing natures, such as block movement, complex faulting, crustal extension, ascension of mantle material, and seismic activity (Neugebauer, 1983; Wood, 1983; Zuber and Parmentier, 1986). From the magmatic point of view, a rifting zone represents a crustal portion subjected essentially to rupture accompanied by mantle perturbation (Bailey, 1980). The rupture can be started by any abrupt tension change in the lithosphere but is more frequently related to plate movement. The magma migration from deeper zones results from the increment of $P(H_2O)$ and CO_2 activity during the removal of the liquid, the compositional variation of the erupted magma being a direct consequence of changes in the geothermal gradient (Bailey, 1978, 1983). Le Bas (1987) suggested a diachronous character for the compositional changes of the alkaline magmatism from potassic to sodic along a continental rift. In its composition, the strongly unsaturated sodic ultra-alkaline magmatism (nephelinite, melilite, ijolite, etc.) reveals a direct migration from the mantle, independent of the evolution stage of the rift.

The Tertiary alkaline magmatism of the western segment of the Asunción Rift displays three basic characteristics: a very restricted geographical distribution, with the bodies

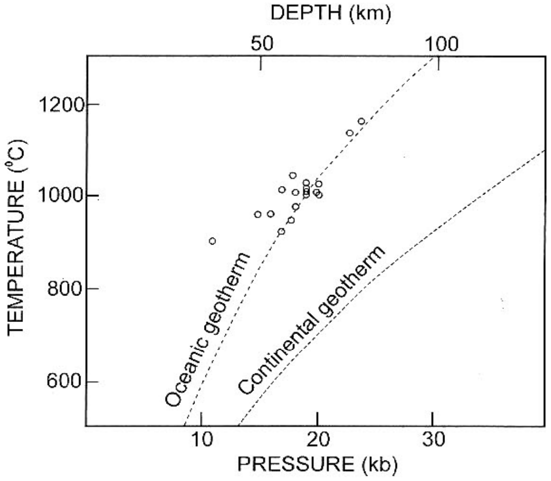

Fig. 2. Diagram showing the P and T fields of the mantle xenoliths from the Tertiary ultra-alkaline intrusions (data after Orué et al., 1991; Petrini et al., 1994). The oceanic and continental geotherms are those given by Green and Ringwood (1970).

spread over an area where the main axis is less than 45 km long; a strongly undersaturated sodic ultra-alkaline composition; and the presence of mantle xenoliths in the lavas. About twenty occurrences of ultra-alkaline rocks have been recognized in the region, the bodies found being characterized as plugs, necks, flows, and small dykes intruding Cenozoic continental sedimentary deposits of the Patiño Formation. The available geochronological data show ages ranging between 60 and 39 Ma (Comin-Chiaramonti et al., 1991), with a clear predominance of between 50 and 45 Ma (Eocene).

The ultra-alkaline rocks vary in composition from ankaratrites to nephelinites, the latter types being more abundant. Peralkaline phonolites occur more restrictively. The first rocks are fine-grained, porphyritic, and contain mainly olivine, clinopyroxene, and magnetite as phenocrysts. The groundmass, predominantly aphyric, is composed of clinopyroxene, olivine, opaque minerals, and nepheline; occasionally microlites of alkali feldspar, plagioclase, interstitial glass, and apatite are present (Stormer et al., 1975; Bitschene and Báez Presser, 1989; Comin-Chiaraminti and Gomes, 1996). On the other hand, the phonolitic rocks show porphyric to aphyric texture and hypocrystalline to hyaline groundmass. The pheno/microphenocrysts are mostly represented by alkali feldspar, nepheline, and clinopyroxene. Other minerals include amphibole, opaques, feldspathoids (leucite, analcime, cancrinite), and also apatite and sphene as accessories.

The geochemical data indicate that the nephelinites are mainly characterized by high contents of Mg, Ca, Ni, Nb, La, and Ce and strong K depletion. However, the non-linear behavior of SiO_2, K_2O, Rb, and Ba contents in relation to the initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ values seem to suggest that crustal contamination processes did not contribute significantly during the ascension of the magma (Comin-Chiaramonti et al., 1991).

The xenoliths found in the nephelinitic lavas (all placed into Group I of Frey and Green, 1974) have a variable composition, which includes lherzolites, harzburgites and, subordinately, dunites. They are constituted by Mg-olivine, Al-orthopyroxene, and Cr-diopside, and have Cr-spinel as the main minor phase. The texture is typically protogranular, where the olivine shows wavy extinction and lamellae deformation, while the pyroxene is xenomorphic with abundant exsolution lamellae. Cr-spinel occurs interstitially and irregularly (Comin-Chiaraminti et al., 1986; De Vito, 1987). The xenoliths show textural disequilibrium as indicated by the presence of clinopyroxene and Cr-spinel with exsolution lamellae of microcrystalline glass, besides the high concentration of incompatible elements (e.g. K, Ba, Rb, and Sr). These elements were introduced in the mantle, presumably by a metasomatic process involving a $H_2O + CO_2$-rich fluid, before the incorporation of the xenoliths in the nephelinitic magma, this one still in subsolidus state during the re-equilibrium of the mineralogical assembly (Demarchi et al., 1988).

The isotopic geochemical data suggest that the alkaline magmas were generated in the lithospheric mantle (Comin-Chiaramonti et al., 1991) from a compositionally different source as compared to that of the lherzolitic nodules. Likewise, pressure and temperature values (Orué et al., 1991; Petrini et al., 1994), as estimated from the re-equilibrium of the xenolith mineralogical assembly, point to conditions varying between 14–24 kb and 944–1054°C, respectively, thus making it possible to infer that the magma was originated at a depth greater than 60 km (Fig. 2). The ascension speed was extremely high, as there was not enough time for the xenoliths to react with the host magmas (Comin-Chiaramonti et al., 1991); considering a diameter of 45 cm (size of the largest well-known xenolith), a density of 3.3 g cm^{-3} and a magmatic source at 60 km depth, it is assumed that xenoliths would reach the surface in less than 10 h.

3. Structural setting of the western segment of the Asunción Rift

The Ypacaraí Graben, which hosts the homonymous lake and is located in the western segment of the Asunción Rift, is a conspicuous morphologic feature controlled by NW-trending faults. The aeromagnetic map of this portion of the rift, elaborated using data obtained by The Anchutz Corporation (1980), shows positive anomalies (more than 5100 nT) corresponding to straight structural-magnetic alignments, predominantly NW–SE-trending, which separate blocks marked by isolines of intermediate values (in general not greater than 4800 nT) and blocks of non-linear behavior, as also observed by Velázquez et al. (1998); Comim-Chiaramonti et al. (1999). These alignments coincide with the main faults and point to the deep character of

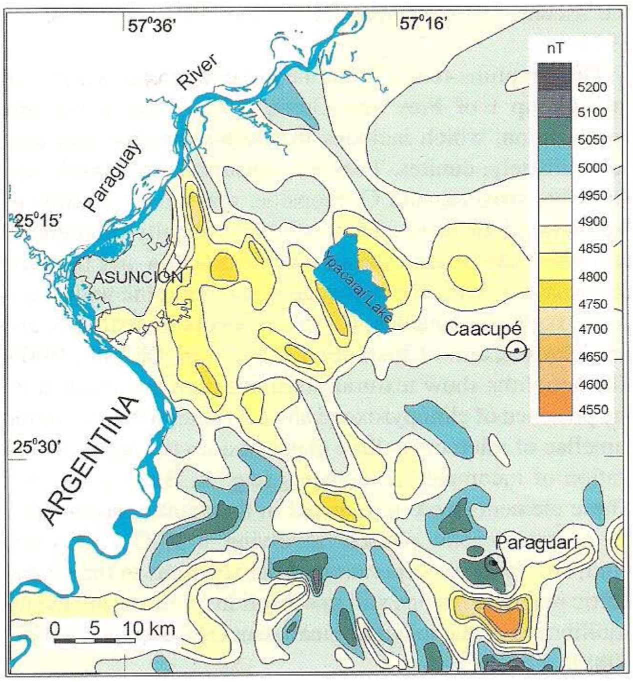

Fig. 3. Aeromagnetic map of the western segment of the Asunción Rift (data after The Anchutz Corporation, 1980).

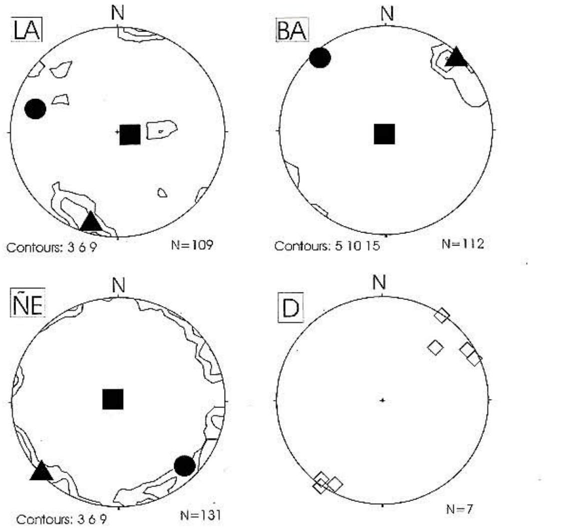

Fig. 5. Fracture populations of the Lambaré (LA), Benjamin Aceval (BA) and Ñemby (ÑE) bodies; the poles of Tertiary dykes (D) are also shown. All fractures were measured in the igneous bodies. Stress axes $\sigma 1$, $\sigma 2$, and $\sigma 3$ are represented by circles, squares, and triangles, respectively. All diagrams are lower hemisphere equal area projections.

these structures (Fig. 3). In the residual map of the Bouguer anomaly with a 5 mGal contour interval and under a reduction density pattern of 2.67 g cm^{-3} (The Anschutz Corporation, 1991), a circular anomaly in the Asunción region can be recognized, as evidenced by the presence of isolines of low gradient (less than -25 mGal) (Fig. 4). Such a feature is due to tectonic subsidence and the thick accumulation of Tertiary sediments (Patiño Formation). The small dimensions of the ultra-alkaline bodies (diameters less than 1 km) do not seem to affect the distribution of the regional gravimetric anomalies.

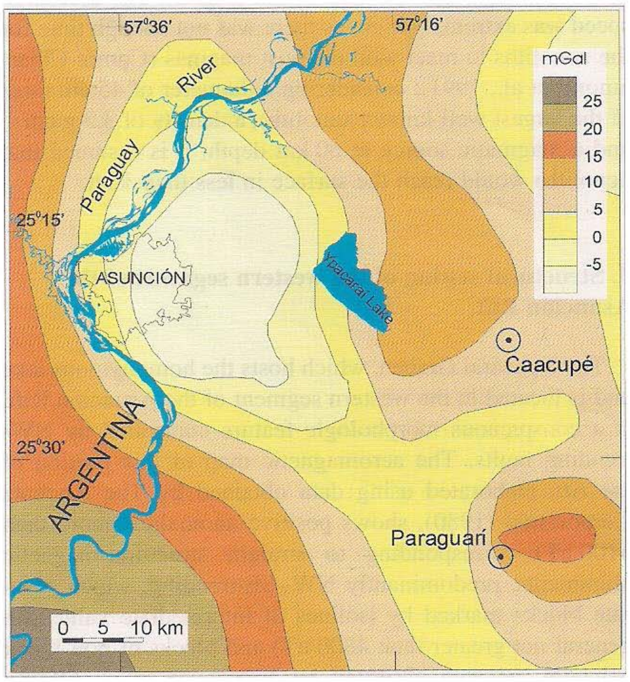

Fig. 4. Residual map of Bouguer anomaly of the western segment of the Asunción Rift (data after The Anschutz Corporation, 1991).

4. Paleostress data

The Benjamin Aceval (BA) nephelinitic body is a plug at least 150 m in diameter located in the Paraguayan Chaco region at approximately 30 km northeast of Asunción. Subvertical continuous fractures forming flat surfaces were identified; they are preferentially oriented to the NW and less commonly to the NNW and WNW. Secondarily, the fractures are also NE-trending; in this case, they are less

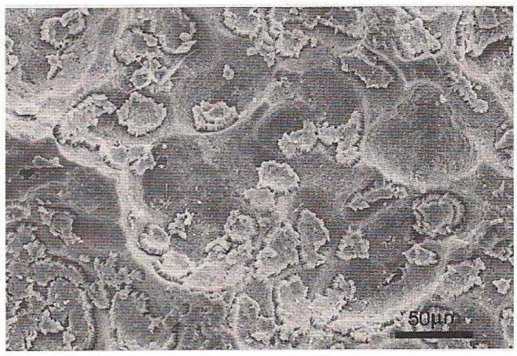

Fig. 6. Scanning electron micrograph (backscattered signal) of natrolite crystals growing perpendicular to the wall of a NW-trending fracture in the Ñemby plug.

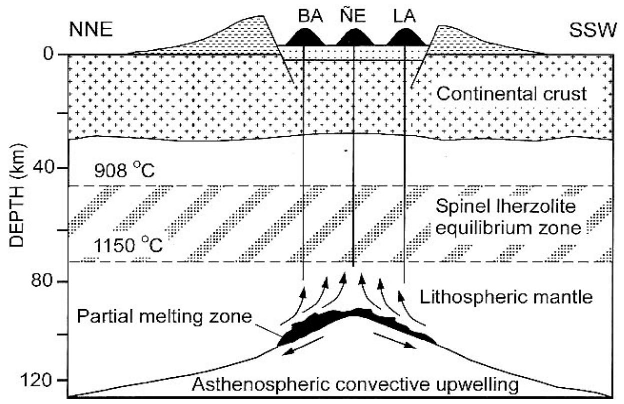

Fig. 7. Schematic tectonic model for the emplacement of the Tertiary ultra-alkaline intrusions of Benjamin Aceval (BA), Lambaré (LA) and Ñemby Hill (ÑE).

continuous, with more irregular surfaces and frequently interrupted by the former sets (Fig. 5, BA). The Lambaré (LA) nephelinitic neck, about 170 m in diameter, which is located 3.5 km from downtown Asunción, sustains a small hill that is 155 m high. There, the fractures display a higher degree of dispersion in comparison to those of the BA body, being subvertical and more frequently oriented to WNW–ESE. Subordinately, NE-trending subvertical fractures are also found (Fig. 5, LA). The Ñemby (NE) is a NW-elongated elliptic nephelinitic plug (900 × 500 m) located about 20 km southeast of Asunción. The fractures are continuous, subvertical, and mainly oriented to the NW, and in lesser scale to the NE (Fig. 5, ÑE). Commonly, they contain sodic zeolites (natrolite) with the crystals growing perpendicularly to the fractures (Fig. 6). Zeolites of similar composition fill random vesicles within the nephelinite and are sometimes found forming plume-like arrangements along the NW-trending plane joints.

The fan distribution of the different families of fractures, all oriented to the NW and WNW, led to their classification as a fracture spectrum (Dunne and Hancock, 1994). The principal maximum stress, $\sigma1$, lies on the symmetry axis of the spectrum and has an NW–SE/horizontal direction; the principal minimum stress, $\sigma3$, occupies an orthogonal position and is NE–SW/horizontal oriented; and the principal intermediate stress, $\sigma2$, is set on the vertical position. The NE fractures would correspond to cross joints (Hancock and Engelder, 1989) of non-systematic character.

Ultra-alkaline dykes are mainly subvertical and do not exceed 70 cm in thickness. They are NW–SE oriented (Fig. 5, D), also indicating a NE-trending extension. The paleostress field orientations are compatible with a right-lateral strike-slip binary of E–W direction.

5. Tectonic implications

A remarkable feature characterizing the western segment of the Asunción Rift is the persistence and coincidence at different scales of the NW–SE tectonic direction. Regionally, it is represented by structural alignments and extensive faults that cross this portion of the rift; locally, it is indicated by mesoscopic structures, such as the joints and faults of small displacement in the Benjamin Aceval, Lambaré, and Ñemby bodies. The validity of a right-lateral strike-slip regime with a binary oriented E–W during the Eocene is confirmed by the orientation of the nephelinitic (ankaratritic) dykes and also by the fracturing pattern affecting these intrusions. On the other hand, the close association between the compositionally homogeneous zeolites filling the vesicles and the fractures of the nephelinites seems to indicate that the joints were developed immediately after the solidification of the igneous bodies but still under the action of Na-rich residual solutions.

The possibility of hydraulic fracturing cannot be discarded, but it may be highly subordinated to the regional stresses, as indicated by the persistence in orientation of the different families of fractures.

Petrological data suggest that a short interval of time elapsed between the ascension of the magma from great depths and its emplacement at shallow crustal levels (cf. Comin-Chiaramonti et al., 1991). Cooling and fracturing in relatively restricted areas are evidence that the NW–SE-trending structural alignments represent deep faults whose activity caused great energy loss in the asthenosphere, leading to further melting of the lithospheric mantle by decompression during a relatively short time interval. The faults have acted as conduits for emplacement of the Cenozoic ultra-alkaline bodies in the western segment of the Asunción Rift (Fig. 7).

The paleostress orientations obtained from fracture analysis and direction of the Cenozoic dykes are compatible with the action of an E–W-trending right-lateral strike-slip binary that is coaxial with the one previously active in the installation of the Asunción Rift and the emplacement of the Early Cretaceus potassic alkaline rocks (Velázquez et al., 1998).

6. Conclusions

The Eocene magmatism of the western segment of the Asunción Rift was controlled by NW–SE deep faults that served as conduits for the nephelinitic (ankaratritic) magma coming from depths greater than 60 km and carrying mantle xenoliths to the surface. Rising emplacement, cooling, and fracturing of the ultra-alkaline bodies occurred within a short interval of time. The different families of fractures and the orientation of the dykes indicate a stress regime with $\sigma1$ in the NW–SE direction, horizontal; $\sigma3$ in the NE–SW direction, horizontal; and $\sigma2$ vertical — all of which are compatible with the action of an E–W-trending right-lateral strike-slip binary.

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