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Review of the areal extent and the volume of the Serra Geral Formation, Paraná Basin, South America

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Abstract - In the discussion of the origin of continental flood basalt provinces, one of the most important constraints is the volume of the mobilized magma. Concerning the Serra Geral Formation in the Paraná Basin (South America), most authors cite an actual areal extent of 1,200,000 km^2 and a volume of approximately 800,000 km^3. The same volume is often used for the Paraná-Etendeka Continental Flood Basalt Province, from which the Serra Geral Formation is the major part. We investigated the precision of these numbers through a complete historical review of their origin. We found that the areal extent cut off of 1,200,000 km^2 is only an estimate made in 1934, and that the volume cut off of 800,000 km^3 aroused using this areal extent estimate and an estimate of a mean thickness of 650 m of the flows made in 1966. Using a new map, we found that the area covered by the volcanic rocks in the Paraná Basin is of only 917,000 km^2 (+- 15,000 km^2). With isopach maps of 1987 and 1990, we calculated the volume of the extrusive rocks to be of at least 450,000 km^3 and of the intrusive sill-type bodies to be of at least 112,000 km^3. With these estimates, the volume of the Serra Geral Formation should be considered to be of more than 600,000 km^3. For the Paraná-Etendeka Continental Flood Basalt Province as a whole, a volume of at least 1,700,000 km^3 should be considered.
Keywords: Serra Geral Formation, Paraná-Etendeka Continental Flood Basalt Province.

Resumo - Revisão da Extensão Areal e do Volume da Formação Serra Geral, Bacia do Paraná, América do Sul. A discussão sobre a origem das Províncias de Basaltos de Platô Continentais tem como um de seus elementos mais importantes o volume do magma mobilizado. Em relação às rochas da Formação Serra Geral na Bacia do Paraná (América do Sul), a maioria dos autores cita uma extensão de 1.200.000 km^2 e um volume de aproximadamente 800.000 km^3. O mesmo volume é usado frequentemente para a Província de Basaltos de Platô Continental Paraná-Etendeka, da qual a Formação Serra Geral constitui a maior parte. Nós investigamos a precisão desses números através de uma revisão histórica completa acerca de sua origem. Verificamos que o valor relativo à extensão, de 1.200.000 km^2, é apenas uma estimativa apresentada em 1934 e que o volume de 800.000 km^3 foi obtido multiplicando este valor de extensão por uma estimativa da espessura média dos derrames de lava de 650 metros apresentada em 1966. Usando um mapa recente, verificamos que a área coberta por rochas vulcânicas na Bacia do Paraná é de apenas 917.000 km^2 (+- 15.000 km^2). Através de mapas de isópacas de 1987 e 1990, calculamos o volume das rochas extrusivas como sendo de pelo menos 450.000 km^3 e que o volume referente aos corpos intrusivos do tipo sill é de pelo menos 112.000 km^3. Através destas estimativas, o volume de rochas da Formação Serra Geral deve ser considerado como sendo superior a 600.000 km^3. A Província de Basaltos de Platô Continental Paraná-Etendeka como um todo possui um volume de no mínimo 1.700.000 km^3.
Palavras-chave: Formação Serra Geral, Província de Basaltos de Platô Continental Paraná-Etendeka.

1. Introduction

Among the subaerial Large Igneous Provinces (LIPs) of the world, the Cretaceous Paraná-Etendeka Continental Flood Basalt Province (CFBP) ranks as second largest, surpassed only by the Siberian Traps in the Tunguska Basin. The origin of the Paraná-Etendeka CFBP is related to the opening of the southern Atlantic Ocean, but the constraints of the volcanic events are still controversial, as in other CFB Provinces too (Self *et al*., 1996; Bondre *et al*., 2004). The triggering mechanism and the heat source has been seen in the hot spot of Tristan da Cunha by some authors (e.g. Hill, 1991; Hawkesworth *et al*., 1992; Wilson, 1993), but other contributions refuse the mantle plume influence in the volcanic event (Sheth, 1999; Ernesto *et al*., 2002; Marques *et al*., 2005). To refine the model, especially concerning alternative heat sources for the magma generation, one of the most important data concerns in the volume of magma produced during the volcanic activity. Despite hundreds of geochemical, geochronological, stratigraphical, petrographical, mineralogical and palaeomagnetic studies during the last decades, the areal extent and volume numbers presented for the Serra Geral Formation are highly variable. We made a complete historical review of the evolution of these numbers for the extrusive and intrusive rocks of the Serra Geral Formation in the Paraná Basin (South America) and calculated new values using available maps, now being able to define the precision of the used data and to present more realistic numbers.

2. Geological setting

The bulk of the Paraná-Etendeka CFBP is located in the Paraná Basin (Brazil, Argentina, Uruguay and Paraguay), an intracratonic basin covering 1,500,000 km^2, developed between the Ordovician and the Cretaceous (Zalán *et al*., 1987) (Fig. 1). The volcanic-sedimentary sequence is up to 7.5 km thick and is composed of six supersequences: Rio Ivaí, Paraná, Gondwana I, II and III and Baurú (Milani, 1997). The African part of the province is located in Etendeka-Namibia (Erlank *et al*., 1984) and in Angola (Alberti *et al*., 1992). A number of contributions outline the geochemical aspects of the volcanic rocks (e.g. Peate *et al*., 1992), of which general aspects can be found in Melfi *et al*. (1988). The volcanic rocks are called Serra Geral Formation in Brazil and Argentina, Arapey (flows) and Cuaró (sills) Formations in Uruguay, and Alto Paraná Formation in Paraguay. The most cited name, Serra Geral (White, 1908, v. 1, p. 17), derived from the name given to the eastern escarpment of the lava flows in the states of Paraná, São Paulo and Minas Gerais (Brazil). The age of the volcanic events was detailed through a number of contributions, becoming more accurate with the evolution of analytical methods. Turner *et al*. (1994) established an age of 137-127 Ma for the volcanic period.

3. Estimations for the Serra Geral Formation

3.1. Areal extent of the Serra Geral Formation

Two main figures are used to present the actual extension of the volcanic rocks of the Serra Geral Formation in the Paraná Basin. A value of 800,000 km^2 was established by Baker (1923) and referred to by much-cited contributions as Guimarães (1933), Sanford & Lange (1960), Almeida (1981) and Petri & Fúlfaro (1983). The number of 1,200,000 km^2 is an estimate made by Oppenheim (1934), who added to the volcanic outcroppings their probable extension in Uruguay and Argentina beneath post-Cretaceous sediments. This estimate was cited by Oliveira (1943) and Maack (1952), the latter being the most cited article with this number. Several other numbers, most of them of about 1,000,000 km^2, can be found in a number of other contributions.

The original area covered by the Serra Geral flows is very difficult to establish and depends on the decision to interpret all basic dykes outcropping within basement rocks and in the sedimentary filling of the basin as feeders of lava flows, as assumed by Baker (1923). The original area was estimated to be 1,000,000 km^2 (Baker, 1923) or 2,000,000 km^2 (Renne *et al.* 1992). When defining the original perimeter of the lava flow field, isolated occurrences of basalts and diabases, resting on sedimentary rocks some tens of kilometers in front of the actual escarpment of the volcanic rocks, always have been seen as erosive remnants of lava flows and have been included. But most of them are exhumed sill-type bodies (Davino *et al.*, 1984), whose true nature was difficult to recognize due to its deep weathering and the scarcity of good

outcrops.

For the measuring of the actual area we defined a perimeter that includes the area of occurrence of the volcanic rocks and the overlying younger sediments. It is evident that a great and variable retreat of the border of the volcanic rocks has occurred. The error increased due to the very irregular limit approximately between Uberaba (state of Minas Gerais) and Botucatu (state of São Paulo), and due to the mapping of flows and sills as a single unit. Furthermore, the border of the outcropping volcanic rocks is covered by Cenozoic sediments of the Fray Bentos, Ituzaingó and Pampeana Formations in northeast Argentina, and by Cretaceous sedimentary rocks (Asencio, Mercedes, Guichón and Migues Formations) in Uruguay.

The measured area includes (1) the area of outcropping basic volcanic rocks, (2) the area of outcropping acid volcanic rocks (64.000 km^2, Nardy *et al.*, 2002) in the southeast corner of the basin, and (3) the areas inside of the perimeter of outcropping volcanics covered by post-volcanic sediments, like the Bauru Group (350,000 km^2, Goldberg & Garcia, 2000, or 400,000 km^2, Milani, 1997) and minor Formations: Cachoeirinha (Milani, 1997), Tupanciretã (Favilla *et al.*, 1995), Moinho (Böger *et al.*, 1993) and Missões (Consórcio Hidroservice-Hidrened, 1972), the last three in the state of Rio Grande do Sul, Brazil.
The cartographic reference is the "Mapa de Integração Geológica da Bacia do Prata e Áreas Adjacentes" (Mercosul, 2001), on a scale of 1:2,500,000 and policonic projection. Considering the purposes of the review and the large number of uncertainties involved, a careful planimeter-based measurement was considered sufficient. A second apparatus was used for control, with each polygon measured at least four times, rendering a number of 917,000 km^2, with an estimated error of 10,000-15,000 km^2. In this way, considering an area of about 400,000 km^2 covered by post-volcanic sediments (Bauru Group and minor Formations), the remaining total area of exposed basalt is of approximately 500,000 km^2, as estimated by Cabrera (1971, p. 23).

3.2. Volume of the Serra Geral Formation

The first volume calculations for the Serra Geral Formation were done by Baker (1923). These calculations become more precise trough a number of contributions (e.g. Leinz, 1949; Teruggi, 1955; Leinz *et al.*, 1966). Volumes of individual lava flows from the Paraná Basin are available only from Uruguay. One flow is cited by Bossi & Caggiano (1974) having a volume of >135 km^3, and Bossi & Navarro (1991, v. 2, Tab. 14-6, p. 722) present a table of 38 flows ranging from 0.2 to 72 km^3, with a total volume of at least 300 km^3. The first "Isopach Map of the Basaltic Trapp in Paraná Basin", made by Leinz *et al.* (1966), does not represent the thickness of the lava flows, because it added to the thickness of the flows the thickness of the sills beneath them in the sedimentary rocks found during deep drillings (Bigarella & Salamuni, 1967, p. 30-31). Later, Leinz *et al.* (1968) presented a new map only with the thickness of the lava flows. The most cited value for the volume of the Serra Geral volcanics, of approximately 800,000 km^3, was based in part on an estimate of a mean thickness of the lava flows of 650 m made by Leinz *et al.* (1966) and the areal extent estimate of 1,200,000 km^2. However, this number did not take into account the intrusive bodies in the Paraná Basin and is absolutely not representative for the Province as a whole, since it did not consider the African part and the rocks that subsided in the marginal basins of South America and Africa.

The rock volumes lost horizontally and vertically by erosion process remain unknown. The lava flow pile of the Serra Geral Formation varies in thickness from few tens of meters at the borders of the basin to 1700 m (Almeida, 1986) near the city of Cuiabá Paulista (in the state of São Paulo), and scattered spots show thicknesses up to 2,5 km (Stanley *et al.*, 1985, fig. 10). The thickness of rocks removed by erosion was estimated, near the hydroelectric power plant of Itaipu, to be of 100-200 meters (Itaipu Binacional, 1994) and changes a lot in the basin due to the intense faulting and later erosion which leveled off the faulted blocks, as can be seen in the example of figure 2.

We obtained a reference value for the actual volume of the extrusive rocks of the Serra Geral Formation in the Brazilian part of the Paraná Basin through the "Isopach Map of the Extrusive Rocks of Serra Geral Formation" (Zalán *et al.*, 1987, Fig. 13), rendering at least 450,000 km^3 (Fig. 3). The number is of very low precision due to the scale of the map, and the occurrences in Uruguay, Argentina and Paraguay must be added. To underline the conservative character of the map, we brought a few new points indicated in figure 3: #a = 290 m (map indicates <100 m), #b = 1115 m (map indicates 400 m) and #c =

1000 m (map indicates 600 m). Data is from Machado (2005, #a, #b) and from B.L. Waichel (#c, personal comm.).

The intrusive sill-type bodies related to the Serra Geral Formation (Zalán *et al.*, 1985), emplaced in the sedimentary sequence of the Paraná Basin, show individual thicknesses of up to 400 meters and areas of up to 900 km^2 (Melfi *et al.*, 1988). The added thickness of the sills found through boreholes reach values of more than 1,000 meters and were compiled by Zalán *et al.* (1986) in the "Isopach Map of the Sill Type Intrusions of Serra Geral Formation" (Fig. 4). The map refers only to the intrusives in the Brazilian part of the basin and can be refined with more data gathered during the last 20 years, still kept as internal reports of the oil companies. The evaluation of this map rendered us a minimum value of about 112,000 km^3 for these sill-type intrusives. In this way, we believe that the intrusive bodies in the basin as a whole represent volumes close to the entire Columbia River Basalt Group (174,300 km^3, Tolan *et al.*, 1989).

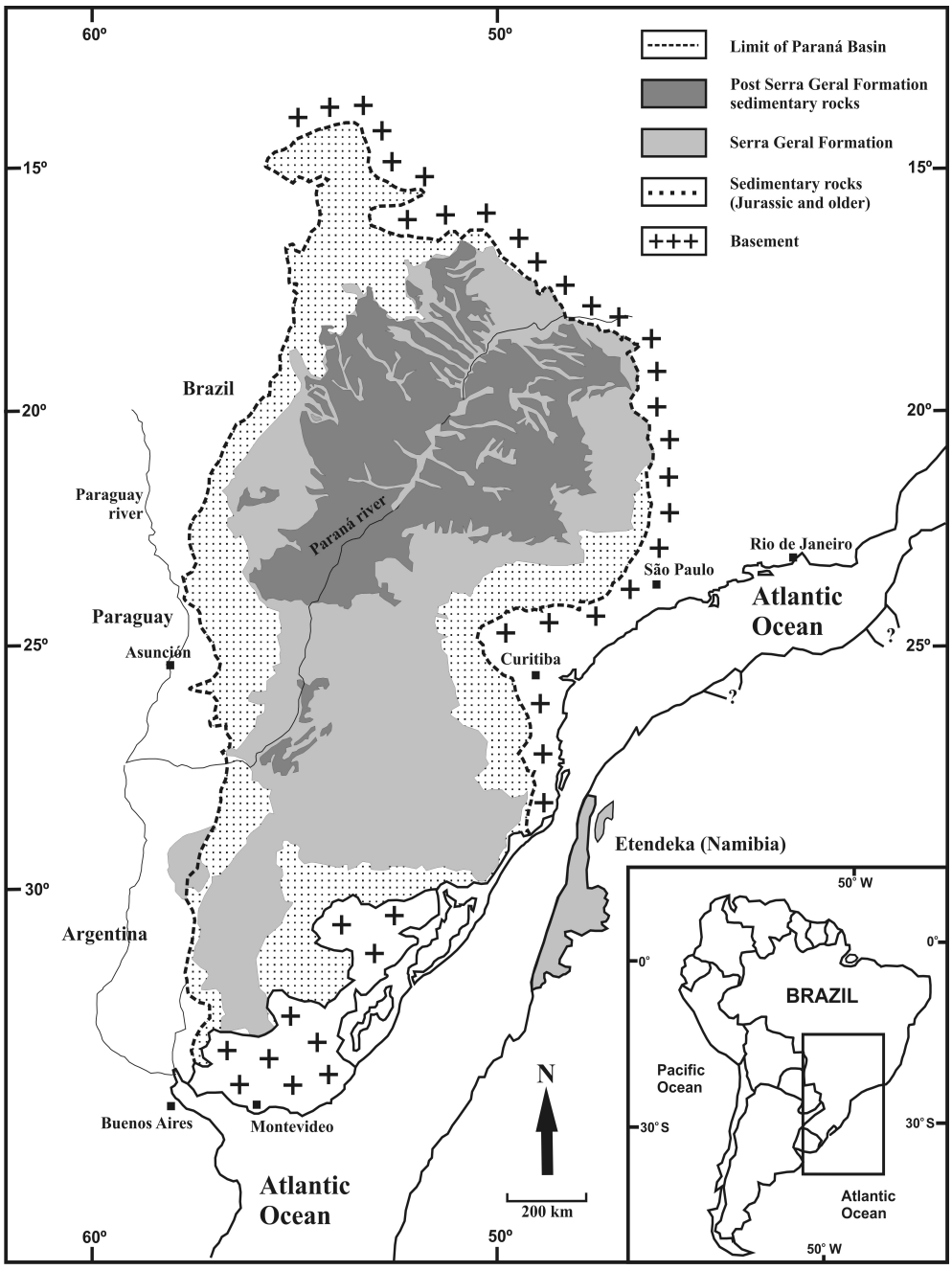

Figure 1. Outline of the distribution of the Serra Geral rocks in the Paraná Basin, juxtaposed with the African counterparts in Namibia (Modified from Mercosul, 2001; African part after Hawkesworth *et al.*, 1992).

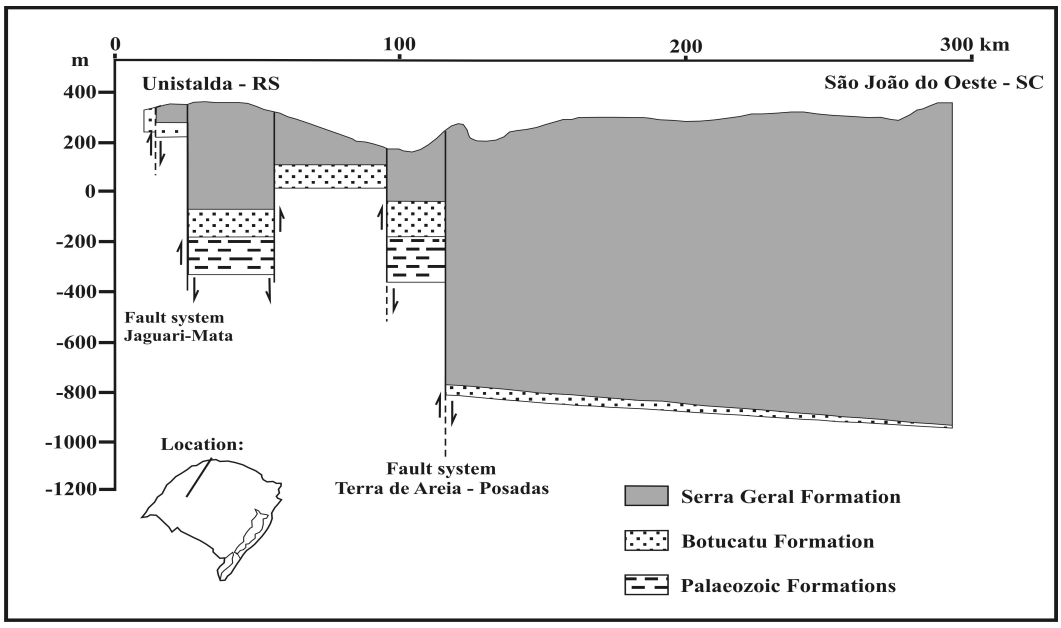

Figure 2. Geological section showing faulted blocks in Serra Geral volcanics in the states of Santa Catarina (SC) and Rio Grande do Sul (RS) (Mod. from Machado, 2005).

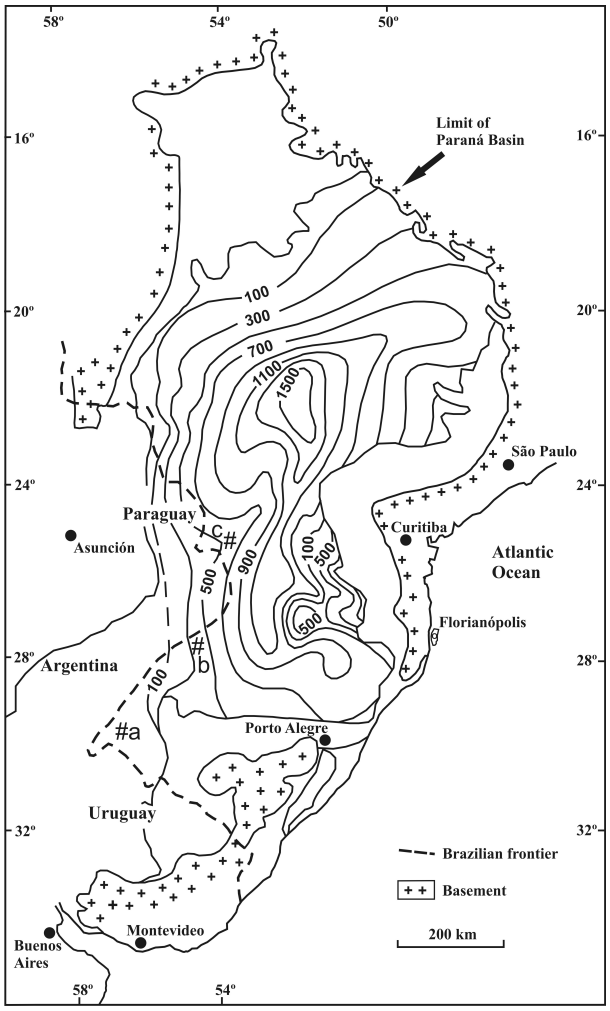

Figure 3. Isopach map of the extrusive rocks of the Serra Geral Formation (Mod. from Zalán *et al.*, 1986). "#" indicates locations of boreholes that provided some new data (see text).

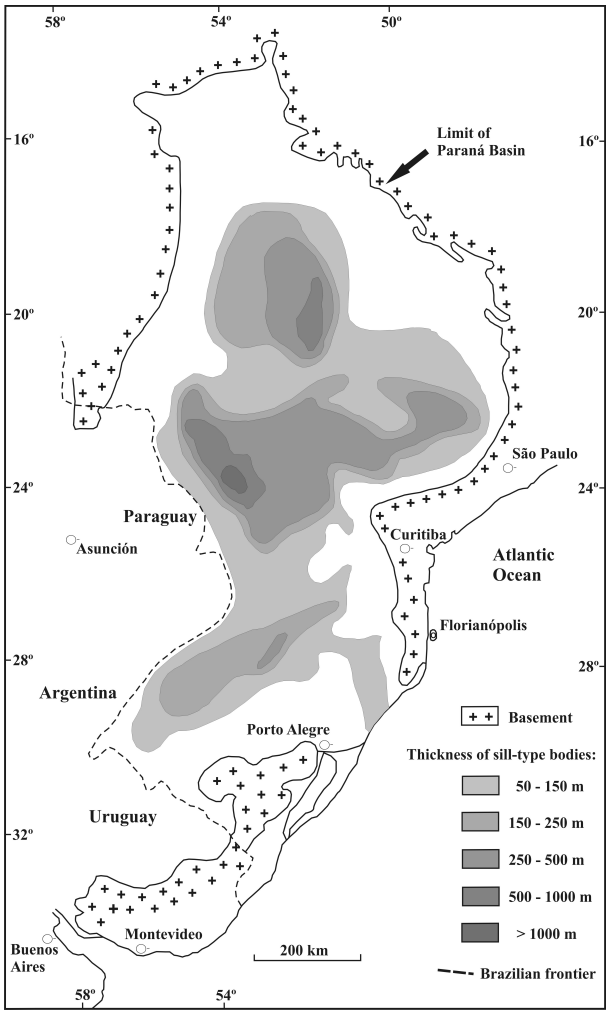

Figure 4. Isopach map of sill-type bodies of the Serra Geral Formation (Mod. from Zalán *et al.*, 1986).

4. Volume estimations for the Paraná-Etendeka CFBP

The volume of the Paraná-Etendeka Province as a whole is a sum of the volumes of the volcanics of the Paraná Basin and the related rocks in Etendeka (Namibia) and Angola, added to the ones now located in the continental margins of South America and Africa. A number of articles cite volumes for the Province between 800,000 km^3 (Peate *et al.*, 1990) and 2,350,000 km^3 (Gladzenko *et al.*, 1997).

In Africa, the rocks of the Etendeka Group in Huab Basin (Namibia) cover 78,000 km^2 (Erlank *et al.*, 1984) or 80,000 km^2 (Peate *et al.*, 1992, Hawkesworth *et al.*, 1992) with a maximum thickness of 900 meters, but the original thickness probably exceeded 2,000 meters (Reuning & Martin, 1957). Their volume, according to Milner *et al.* (1992), is of about 70,000 km^3. In Angola (Alberti *et al.*, 1992), an unknown volume of rocks (Novo Redondo and Lucira Formations) still awaits evaluation.The related volcanic rocks now situated in the marginal basins of Brazil and Africa (Fig. 5) are recognized as symmetrical provinces of seaward dipping reflectors (SDR), with the same composition, age and stratigraphical position as the Serra Geral Formation (Bueno, 2004). At the Brazilian margin, the volcanic rocks occur in the basins of Espírito Santo and Campos (Cabiúnas Formation), Santos (Camboriú Formation) and Pelotas (Imbituba Formation) (Fodor *et al.*, 1983; Fodor & Vetter, 1985; Almeida, 1986; Macedo, 1987; Macedo, 1989, p. 160 and fig. 5 to 7; Mizusaki *et al.*, 1992; Bueno, 2004), probably with volumes as large as the extrusive rocks in the Paraná Basin. At the African margin, in front of Namibia, the similar setting of the volcanic rocks is described by Gladczenko *et al.* (1997), who appoint volumes of 580,000 km^3 and 500,000 km^3 for the African and South American SDRs, respectively.

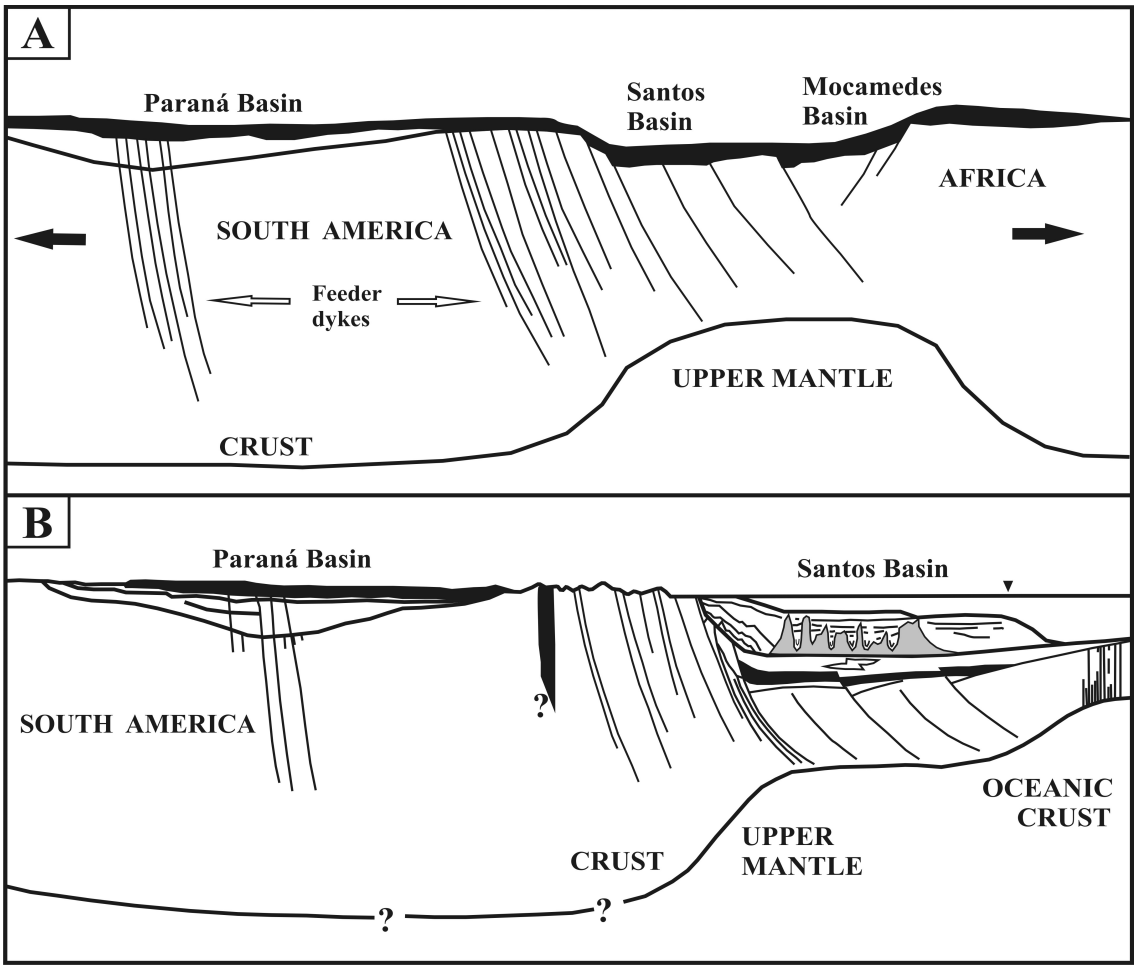

Figure 5. Tectonic evolution of Santos Basin (Brazilian platform) between the (A) Eocretaceous (130 Ma) and the (B) Neocretaceous (65 Ma) with the evolution of the extrusive rocks of the Paraná-Etendeka Continental Flood Basalt Province (in black) (Mod. from Macedo, 1987, fig. 10).

5. Discussion and conclusions

The discussion concerning the volumes of Serra Geral Formation and the Paraná-Etendeka CFBP is a complex task. After the volume estimate of Leinz *et al.* (1966, 1968) for the Serra Geral Formation, several hundred of deep drillings were made in the Paraná Basin, both in volcanic and sedimentary rock areas. In Brazil, the drillings are from PAULIPETRO (Consortium IPT-CESP), Companhia de Pesquisa de Recursos Minerais (CPRM - Geological Survey of Brazil) and PETROBRÁS (Petróleo Brasileiro SA). Some information from the drillings by PETROBRÁS was published by Northfleet *et al* (1969) and by Zalán *et al* (1990, p. 159, fig. 15). Other drillings were performed in Argentina by BRASPETRO (Petrobrás Internacional SA), in Paraguay by Texaco and PETROPAR (Petróleos Del Paraguay) and in Uruguay by ANCAP (Administracion Nacional de Combustibles, Alcohol y Portland) and by the Instituto Geológico del Uruguay. These drillings, added to a wealth of offshore reports from Brazil, provided a great amount of new data, but almost all information is not available for public access.

The most cited number for the areal extent of the Serra Geral Formation (1,200,000 km^2) is not consistent and should be avoided. Instead, we propose the value of 917,000 km^2 for the actual areal extent of the Serra Geral Formation in Paraná Basin, with some 500,000 km^2 of outcropping volcanic rocks. The estimated volume of the Serra Geral Formation rocks is of at least 600,000 km^3. For the Paraná-Etendeka CFBP, a magma volume estimate of at least 1,700,000 km^3 is far more realistic.

With these new estimates, the much cited proportion of different rock types of the Serra Geral Formation (90% of tholeiitic basalts, 7% of tholeiitic andesites and 3% of rhyodacites-rhyolites, Melfi *et al.*, 1988) requires a revision, reducing the participation of the more acid rock types. Future works coupling the existent unavailable borehole and geophysical data of Paraná Basin will provide more accurate estimates of area and volume of the Serra Geral Formation.

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