Chapter 3: Geological Survey

3-1 Overview of the Geology

Fig. II-3-1-1 shows a sketch of the geology in the Paraná basin, meanwhile Fig. II-3-1-2 shows the simplified typical geologic columns.

3-1-1 Overview of the Geology in the Paraná Basin

The Paraná basin is located in the southeastern part of South America. The Paraná basins, having 1.6 million-km^2 areas in total, extend onto Brazil, Uruguay, Argentine, and Paraguay. The distribution area in Brazil occupies 1 million km^2, stretching in the north-south direction from the southern part of Minas Gerais Province to Rio Grande do Sul Province.

There are places forming geological arches stretching in the NW-SE direction on the boundary of the eastern part in the Paraná basin. These places cross the NE-SW axis, the direction of main structure in the Paraná basin.

Major arches include Ponta Grossa Arch, Campo Grande Arch, and Rio Grande Arch. The arches were formed by tectonic movements during the Devonian to the Jurassic (Fulfaro et al. 1982). For example, Ponta Grossa Arch, ranging 600 km in width inside the basin, is affected by sedimentation from the Devonian. The arches are characterized by the following:

- Many basic dykes are arranged in the NW-SE direction. These are the volcanic feeder part of the flood basalt.
- Magnetic anomaly trend in the NW-SE direction are observed (for example, Ferreira, 1983: Guapiara, São Geronimo and Rio Alonzo, etc.).

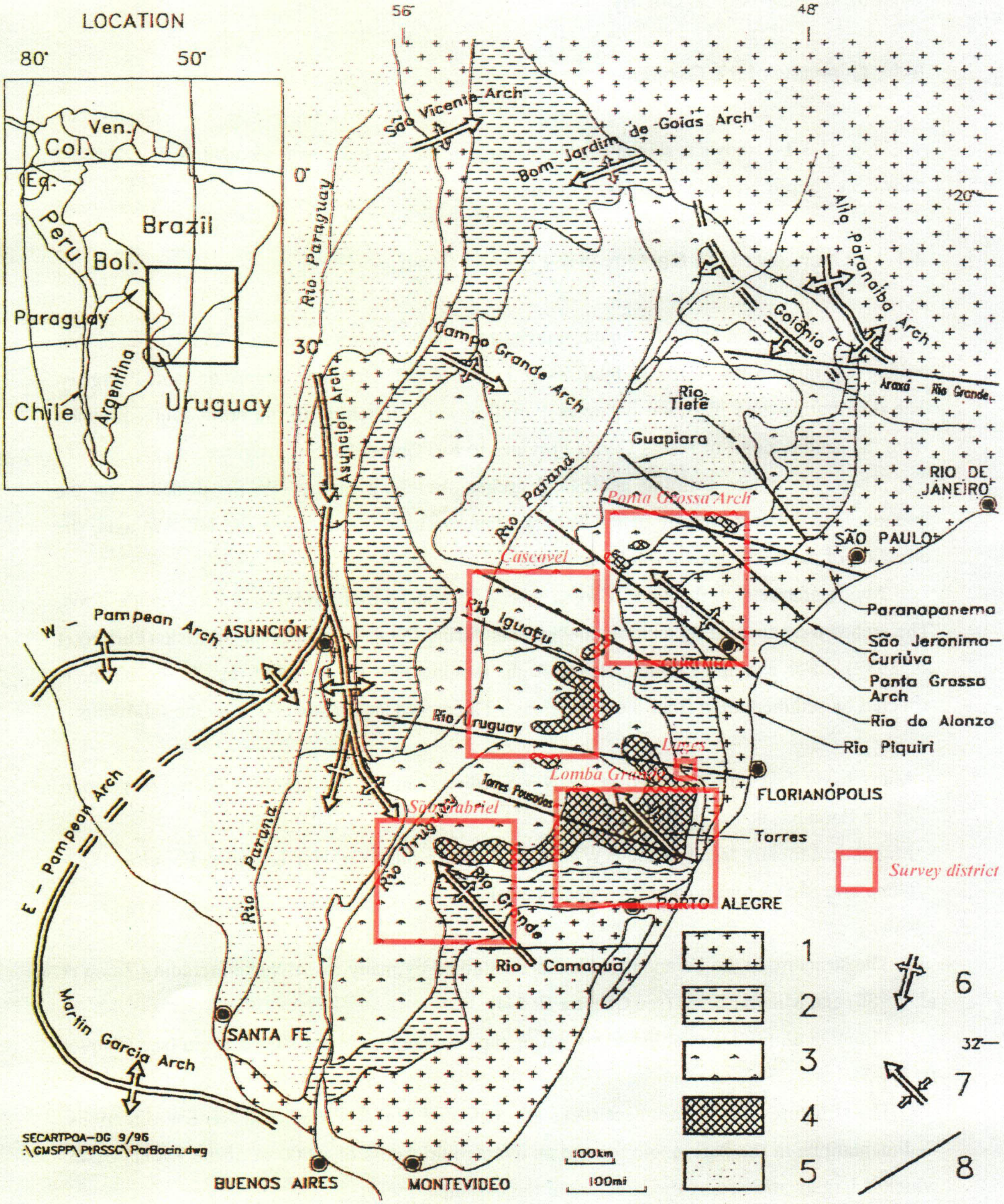
The structure in the Paraná basin has been studied by many researchers, including Zalan et al. (1986) and Milani (1998) (see Chapter II: 1-4).

Milani et al. (1997) established six major super sequences in the Paraná basin (see Chapter II: 1-4-3).

The structures of the basement rocks are regulated in the NW-SE and NE-SW directions. Sedimentations in the Palaeozoic formed an average thickness of 2,000 m of the Paraná basin, which is largely affected by the structure of the basement rocks.

The structure is controlled by a large rift in the NE-SW direction, as proposed by Milani (1998).

The upper part of sediments in the Paleozoic has an extrusion and sedimentation of basic



– Generalized geological sketch map of Paraná Basin (Melfi et al, 1988)

1. Pre-Devonian crystalline basement; 2. Pre-volcanic sediments (mainly Paleozoic); 3. Basic to intermediate flood volcanics (Serra Geral Formation: Lower Cretaceous); 4. Acid stratoid lava flows (Serra Geral Formation); 5. Post-volcanic sediments (mainly Upper Cretaceous); 6. Arch-type structure; 7. Syncline-type structure; 8. Tectonic and/or magnetic lineament.

Fig. II-3-1-1 Generalized geological sketch map of Paraná basin (Melfi et al, 1988)

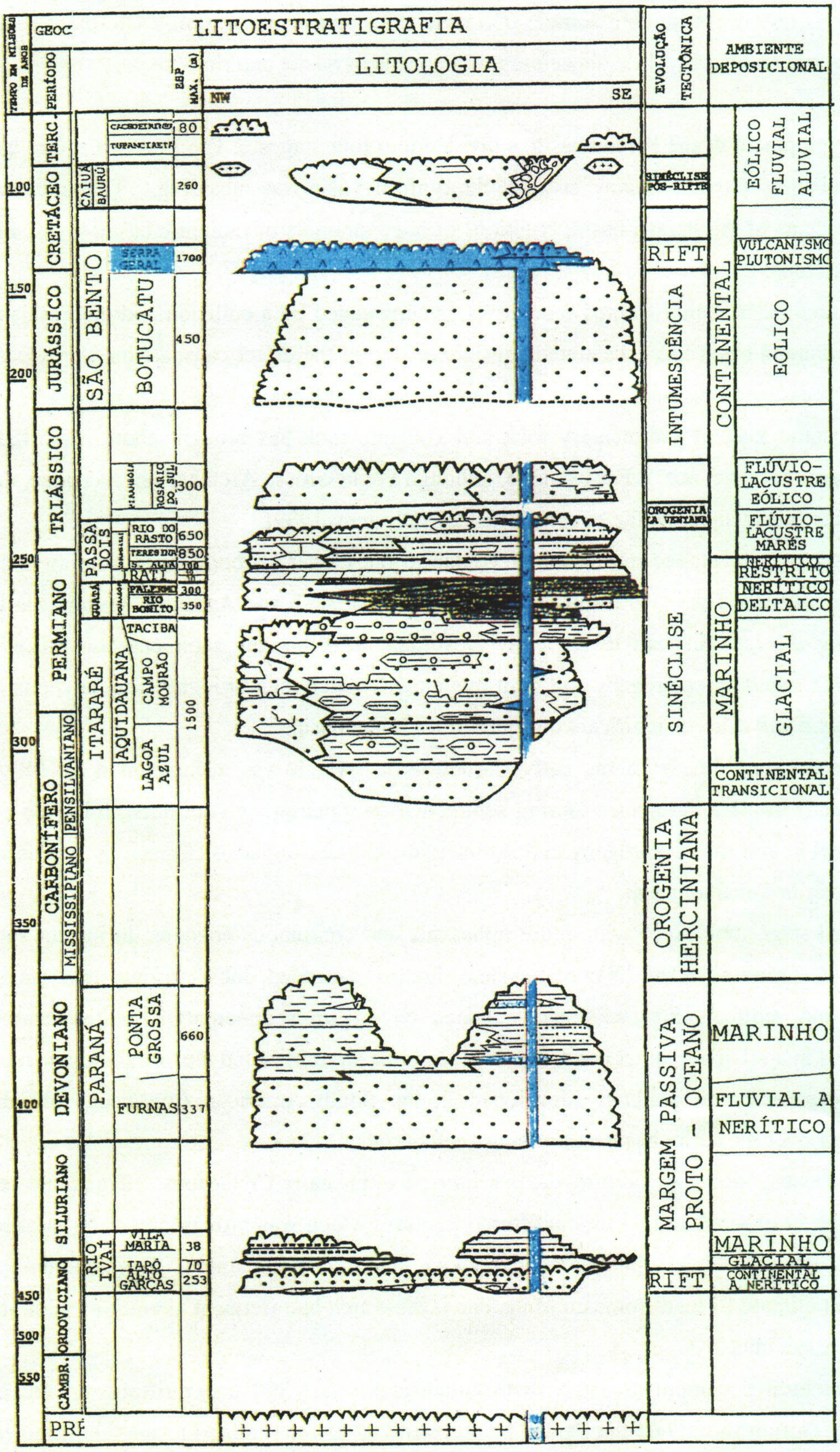


Figure 2 - Sequence-stratigraphic chart for the Paraná Basin (simplified from Milani et al., 1994).

Fig. II-3-1-2 Sequence-stratigraphic chart for the Paraná basin (simplified from Milani et al., 1974)

and acidic volcanic rocks ranging some 3,000 m in thickness at maximum. The basic rocks consist of gabbro and basalt while the acidic rocks consist of dacite and rhyolite.

The development of the Paraná basin is divided into four stages. The first two stages had two structural and sedimentation cycles while the synform basin was subsiding. The latter two stages had ascents of the Paraná basin, eruptions of huge amounts of tholeiitic basalt lavas, and their intrusive rocks involved.

The Paraná basin, being formed on cratons, is surrounded by a collision and the Foreland basin. The Paraná basin has accelerated subsidence due to the effect caused from the release of structural pressure along weak lines in the plate (Milani and Ramos, 1998).

The isostatic load of sedimentary rock and volcanic rock has brought about more than 50 % of the entire subsidence. For example, although Ponta Grossa Arch has not ascended, the hinge zone has subsided due to the effect of isostasy (Oliviera, 1989).

The first stage developed during the Devonian to the Lower Carboniferous forming thick marine sediments called the "Paraná group." Ponta Grossa Arch and Asuncion Arch began to ascend during the late Silurian to the early Devonian, affecting the sedimentation process. This stage was ended by epeirogeny and fault movement, which then brought about erosions in the Paraná basin and caused significant discontinuities in the basin.

The second stage began in the early Carboniferous which was accompanied by active epeirogeny until the late Permian. During sedimentation, epeirogeny continued, followed by marine formation and then epeirogeny and sedimentation under a glacial climate, as is seen in the Itararé layer in Tubarao group.

The third stage took place with entire upheavals and continuous erosions during the late Palaeozoic to Jurassic. The NW-SE system arches ascended most during this stage. Epeirogeny and sedimentation were characterized by stream sedimentation, which caused concentrations in a relatively quiet condition as is seen in a stratum called the "Piramboia layer." Meanwhile desertification gradually developed in the South American Continent, forming Borucatu layer over the entire basin comprising aeolian rocks.

The fourth stage developed during the late Jurassic to the early Cretaceous. This indicates that the Paraná basin transformed into antiform structure, which was brought about by marked tension structure and a hot spot that bought about tholeiitic magmatism. Development of desertification climate formed Botucatu sandstone layer which had frequent alterations of strata between old basalt lava.

This structural development and growth ended at the last 700 meter rifting in vertical movements. During this stage, the Paraná basin consisted of fine-grained to medium-grained red sandstone accompanying crossbed in bimodal under alluvial to delta environments and had sediments of Caiura layer, which was formed during the Middle Cretaceous (Fulfaro and

Barcelos, 1993).

This tectonic activity led to the formation of the Paraná basin that is characterized by a straight fracture (fault, fault belt, arch structure) that crosses the other straight fracture. These fractures are divided into three major trends, N45-65° W, N50-70° E, and E-W. The basin inherited the first two groups from basement rocks in the Precambrian age. They became active again during Phanerozoic.

3-1-2 Paraná Flood Basalts

(1) Lavas

Paraná flood basalts are part of the Gondwana III Super sequence and are called Serra Geral Volcanism (Alemeida, 1964: Zalan et al., 1988: Fig. II-3-1-2).

Igneous rock body, which is the same as Paraná flood basalts, is found in Etendeka on a small scale in Namibia (Erlank et al., 1984; Bellieni et al., 1984). These rocks are closely related to the expansion of the Atlantic Ocean in the early Cretaceous.

The distribution areas of the flood basalts found in Paraná and Etendeka are recognized by past geological investigation and drilling data. The distributions of these flood basalts are very asymmetrical. The flood basalts in Paraná measure a distribution area of 1.2 x 106 km^2, which are approximately 15 times larger than the flood basalt in Etendeka. The cubic volume of the Paraná flood basalts measures 8 x 105 km^3, which is 660 m in average thickness (Leinz, 1949; Leinz et al., 1996). However, this cubic volume does not include the eraption phase. Meanwhile the distribution area of the flood basalt in Etendeka measures 78,000 km^2 and has 900 m thickness at largest (Tafelberg field: Eelank et al., 1984). This accounts for less than 4% of the both basalts of Paraná and Etendeka.

The thickness of the lava generally reflects the structure of the Paraná basin. The lava is thickest at the northern part where the basin is deepest, having more than 1 km of thickness. The lava becomes thicker as approach the center. For example, Pontal of Paranapanema in the western part of São Paulo Province has a lava whose thickness exceeds 1,500 m (according to I-CB-2-SP drilling data). The thickness of the lava even exceeds 1,700 m when the intrusive rocks in the sedimentary rocks are included in the calculation (PAULIPETRO, 1982: Zalan et al., 1988). In this connection, the sedimentary rock in this area is 6,500 m in thickness.

In general, one lava flow ranges from several to a few hundred meters. The lava flow here is considered as some 50 m except the outcrop which ranges 10 to 20 m (Pacca and Ernesto, 1982; Bellieni et al., 1983; Montes-Lauar et al., 1987; Ennesto and Pacca, 1988).

Tholeiitic basalt accounts for some 90 % of the entire Paraná flood basalts, and the rest includes tholeiitic andesite and acidic rock (dacite to rhyolite). These rock types are classified into gabbro, alkali basalt, tholeiitic basalt, andesitic basalt, andesite, dacite, hawaiite rhyolite, and trachybasalt. Acidic rocks account for some 4 % of the entire lava, and the thickness measures a maximum of 400 m.

The K-Ar method dating indicated 160-100 Ma as the age of the volcanic rock in the Paraná flood basalts (Piccirillo, 1988; Melfi, 1988). According to ground surface samples measured with the Ar-Ar method and drilling cores, the lava measured 137-126 Ma as its eruption time (Turner et al., 1994).

(2) Sills

Fig. II-3-1-3 shows the distribution of the intrusive rock bodies related to activities of the Paraná flood basalts.

Some 200 m thick sills were formed in sedimentary rock (especially, in the Iratí formation and Itararé formation) during the Palaeozoic, accompanied by activities of the Paraná flood basalts (Zalan et al., 1986; Piccirillo, 1988). According to Zalan (1986), the Itararé formation and the Iratí formation have the largest sill width in the sedimentary rock. Likewise, sills were found in the Botucatu formation. Sills are also identified in the Paraná flood basalts (Melfi and Girargi, 1983; Marini et al., 1967; Davino et al., 1982). The thickness of these sills ranges 2 to 200 m, intruding other sills (for example, Piracicaba-Limeira). The area identified as consisting of sills ranges some 900 km^2 (Cordani and Vandoros, 1967).

In particular, a large scale sills were recognized in the central part of the northern Paraná basin where thick lava is distributed (Fig. II-3-1-3).

Most of the sills are tholeiite, except picrite sill in the Lomba Grande district.

(3) Dykes

It is known that with the development of fracture structure and igneous activity, dykes in the NW-SE direction concentrate in sedimentary rock in the Ponta Grossa Arch. The dykes range several to 500 m in width, some of their extensions exceed several km. Since dykes have similar chemical and mineral compositions in lavas, however, locating of dykes is difficult.

Also, on a eastern coast of Brazil, groups of parallel dykes are recognized (near Rio de Janeiro).

3-1-3 Mineral Occurrences and Geochemical Anomaly

Lavas, sills, and dykes tend to accompany native copper and pyrite as filling for reside and fracture. This is particularly remarkable in sills and dykes.

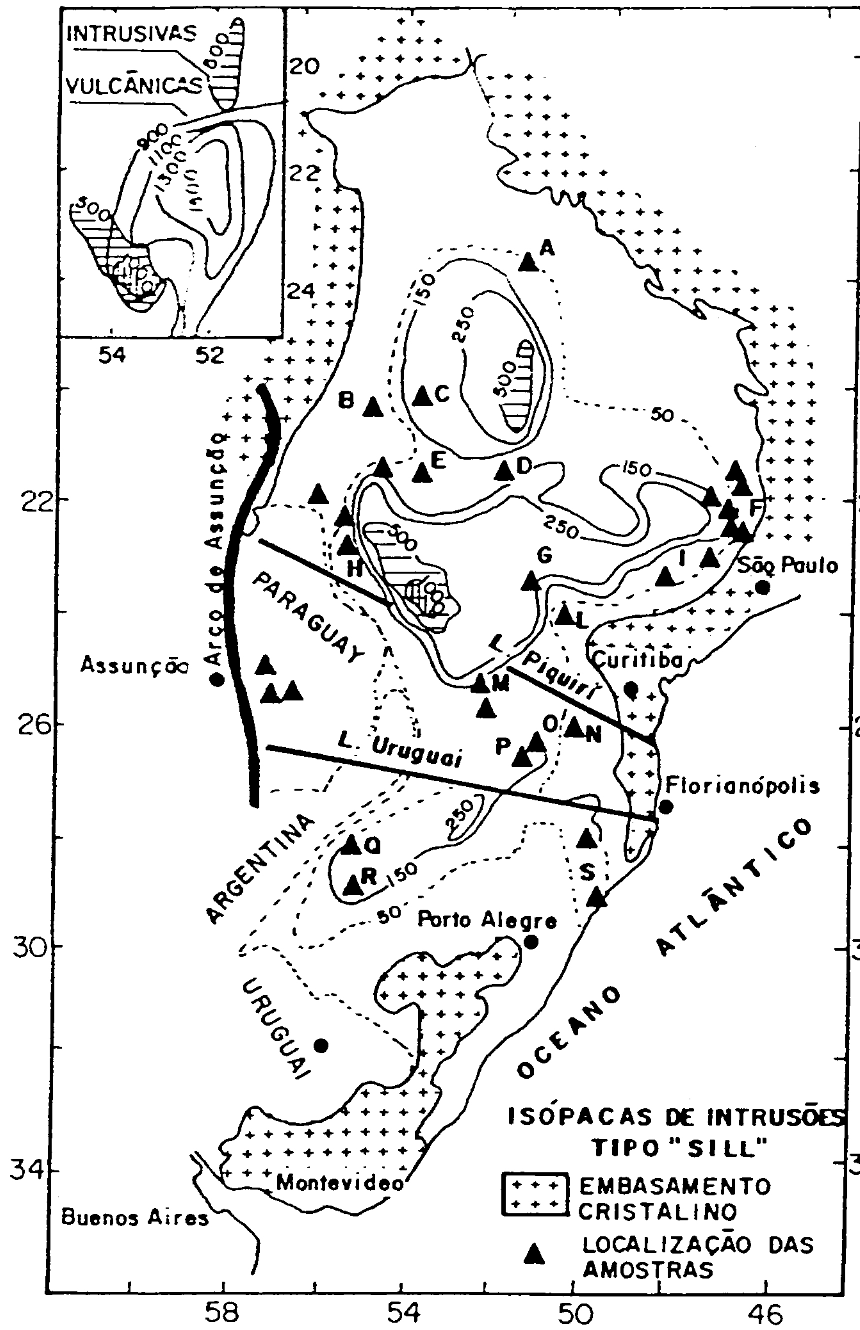


Figure 4- Isopachs of combined sill thicknesses within Paraná basin sediments (after Bellieni et al., 1984).

Fig. II-3-1-3 Isopachs of combined sill thicknesses with Paraná basin sediments (Bellieni et al, 1984)

Regarding the distribution area of the Paraná flood basalts, geochemical prospection of stream sediments, conducted by MINEROPAR, recognized the geochemical anomaly of Cu, Ni, Cr, Pt, Pd and other metallic elements in the southwestern part of Paraná Province.

3-2 Contents of the Study

3-2-1 Sampling

Fig. II-3-2-1 shows sample collecting points. A list of the samples is attached to appendices of this report.

(1) Collecting of Rock Samples

We conducted the survey from Porto Alegre into the northwestern direction, crossing the Paraná basin. During the survey, we observed outcrops of lava in the Paraná flood basalts and collected samples for analysis. Also, we observed outcrops of intrusive rocks in Ponta Grossa Arch and outcrops of lava in São Gabriel district, and collected samples for analysis.

In addition, we checked Pt occurrence in the Lages area.

(2) Collecting of Drilling Cores Conducted by DNPM and CPRM for Coal Prospection

DNPM and CPRM executed drilling for coal exploration in the distribution area of sedimentary rocks along the eastern marginal part of the Paraná flood basalts. In this survey, we tried to recognize the distribution of sills and dykes, and core samples of main sills and dykes ware collected on the basis of the geologic columns obtained from DNPM-CPRM's survey.

(3) Collecting of Samples of Stream Sediments and Water

We collected samples of stream sediments and water in investigated areas where sill of picrite was recognized in the southern part of Lomba Grande district. Also, we collected the stream sediments at the São Gabriel district. The all samples of stream sediments were arranged into -80 mesh for analysis by CPRM at Port Alegre, and were analyzed.

3-2-2 Laboratory Test

The analysis types, quantities and analysis contents are listed below. The results of laboratory tests are included in appendices of this report.

- Whole-rock chemical analysis: 198 cases, 61 elements (Major elements: SiO_2, TiO_2, $A1_2O_3$, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O; P_2O_5; Trace elements: Ag, As, Au, Ba, Be, Bi, Br, Cd, Co, Cr, Cs, Cu, Hf, Ir, Mo, Nb, Ni, Pb, Rb, S, Sb, Sc, Se, Sw, Sr, Ta, Tl , V, W, Y, Zn, Zr, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, U, Th; Platinum group elements: Pt, Pd, Au)

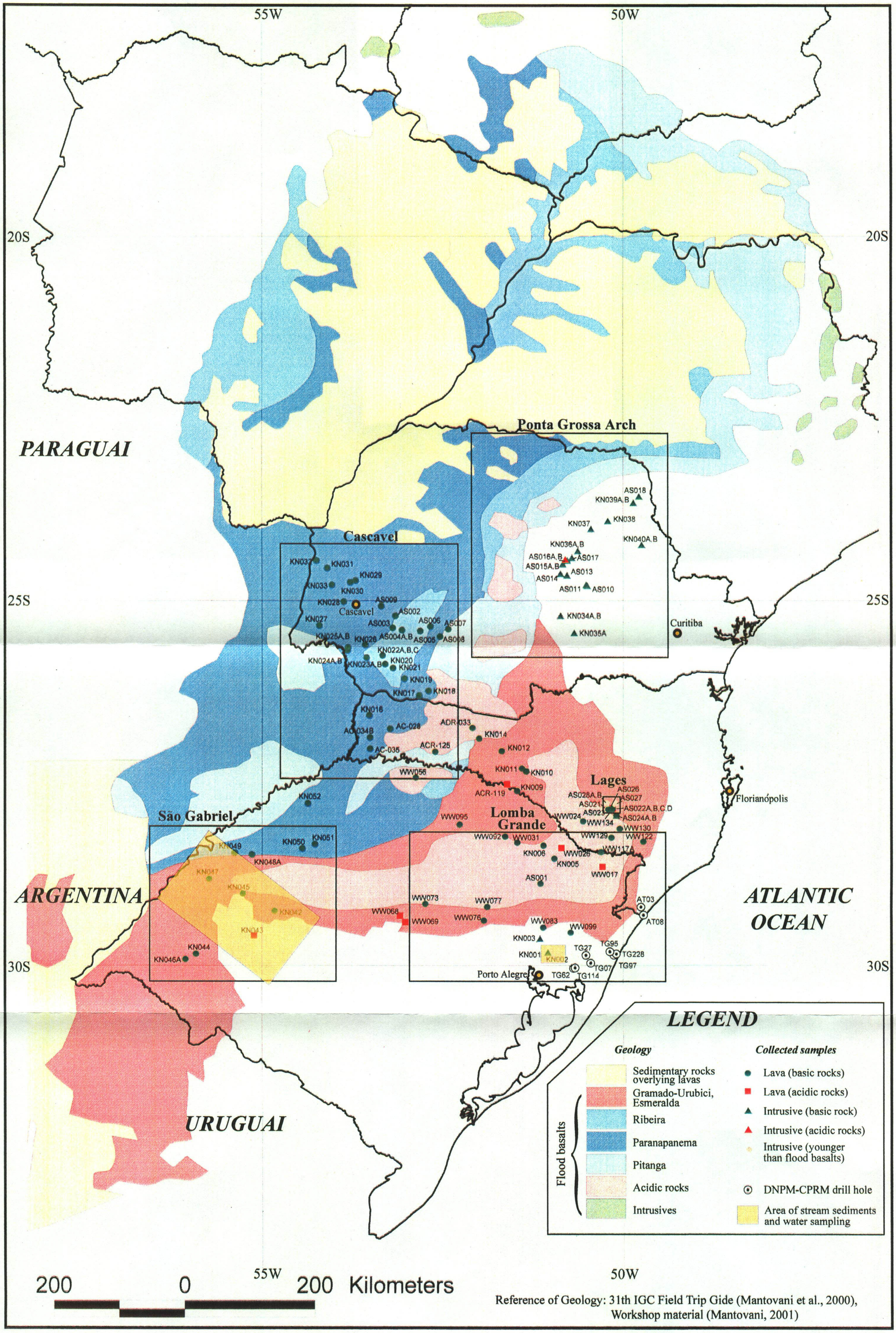


Fig. II-3-2-1 Distribution of collected samples and Paraná flood basalts

- Thin section making and appraisal: 189 cases
- Polished thin section making: 3 cases
- Polished section making: 5 cases
- EPMA analysis: 10 cases (qualitative analysis)
- S isotope ratio analysis: 4 cases
- Rb and Nd isotope ratio analysis: 34 cases
- Panning sample analysis: 5 cases, 11 elements (Ag, Cd, Cu, Mn, Mo, Ni, Pb, Zn, S, Pd, Pt)
- Powder X-ray diffraction test: 4 cases
- Bog sand analysis: 316 cases, 30 elements (Ag, Cu, Cd, Mn, Mo, Pb, Ni, Zn, S, As, Ba, Sb, W, Al, Be, Bi, Ca, Co, Cr, Fe, K, Mg, Na, P, Sc, Sn, Ti, V, Y, Zr)
- Mountain stream water analysis: 182 cases, 69 elements (Li, B, Be, Na, Mg, Al, Si, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Rb, Sr, Y, Zr, Nb, Mo, Ru, Pd, Ag, Cd, In, Sn,Sb, Te, I, Cs, Bs, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, W, Re, Os, Au, Pr, Hg, Tl, Pb, Bi, Th, U, (Sulphate ion))