Volcanism and Stratigraphy of the Neoproterozoic Campo Alegre Basin, SC, Brazil

SERGIO B. CITRONI[1], **MIGUEL A. S. BASEI**[1], **OSWALDO SIGA JR.**[1] **and JOSÉ M. DOS REIS NETO**[2]

[1]Universidade de São Paulo, Instituto de Geociências, 05508-900 São Paulo, Brasil.
[2]DEGEOL, Universidade Federal do Paraná, 81531-990 Curitiba, Brasil.

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ABSTRACT

The depositional succession of the Campo Alegre Basin (Santa Catarina – southern Brazil) was investigated having the evolution of the volcanic activity as background. The different stratigraphic units are interpreted as belonging to different volcanic stages: Bateias Formation, conglomerates and sandstones, related with a pre-volcanic stage; Campo Alegre Group, at the main volcanic stage, with each different formation corresponding to different episodes of volcanism – Rio Negrinho Formation, corresponding to the basic volcanism, Avenca Grande Formation to ignimbritic event, Serra de São Miguel Formation to the acid volcanism and Fazenda Uirapuru Formation, related to an explosive event; Rio Turvo and Arroio Água Fria formations correspond respectively to inner and extra-caldera deposits.

Key words: Neoproterozoic Basin, volcanism, caldera deposits, paleogeographic evolution.

INTRODUCTION

In the eastern portion of Paraná and Santa Catarina states several Fini-Proterozoic/Eopaleozoic basins are filled with sedimentary and volcanic rocks. These basins (Castro, Camarinha and Guaratubinha, in Paraná and Campo Alegre, Corupá and Itajaí in Santa Catarina) register the role played by a series of terrains that clustered in that period (Curitiba and Luís Alves Microplates and the Paranaguá Batholith, Basei et al. 1998). Two of them, Camarinha and Itajaí, are located adjacent to folded belts (foreland basins). Volcanic activity was very weak or absent in these basins whereas in the other basins volcanic rocks represent predominant components in the sedimentary pile. The geologic and depositional evolution of the Campo Alegre basin is presented in this work.

Correspondence to: Miguel A.S. Basei
E-mail: baseimas@usp.br / jmreis@setuva.geologia.ufpr.br

LOCATION AND GENERAL CHARACTERISTICS

The Campo Alegre Basin occupies ca. 500km^2 mostly in the northernmost portion of Santa Catarina (Fig. 1). The basin has been deposited on Paleoproterozoic gneissic-granulitic terrains (Santa Catarina Granulitic Complex) to the south of the Rio Piên calc-alkaline granitoid belt (Machiavelli et al. 1993, Harara 1996). The latter is interpreted as a Neoproterozoic magmatic arc developed between the Luis Alves and Curitiba Microplates (Basei et al. 1992). Several anorogenic alkaline to peralkaline granitoid bodies with ages around 595$\pm$10 Ma (Siga Jr. et al. 1999) occur close to the basin, namely the Corupá Massif to the south, Agudos do Sul to the north and the Dona Francisca and Piraí massifs to the east.

The stratigraphy of the Campo Alegre Basin is marked by an important contribution of felsic and mafic volcanics, associated with epiclastic and pyroclastic sediments. Three contrasting depositional piles are distinguished: (1) coarse-grained, predominantly fluvial epiclastic sediments; (2) basaltic and trachytic flows associated with fine-grained epiclastic sediments and subordinated pyroclastic layers; and (3) fine-grained terrigenous and volcaniclastic sediments in lacustrine environment with subordinate subaerial rhyolitic volcanic rocks.

The thickness of the sedimentary and volcanic pile is estimated to be 990 m: 400 m correspond to the coarse-grained epiclastic sequence, 440 m to the volcanic portion and 150 m to the lacustrine sedimentary unit. The thickness of the subaerial rhyolitic volcanism was not determined, but is significantly less.

The felsic volcanics of the Campo Alegre and Guaratubinha basins were dated by the U-Pb zircon method at 598 ± 29 Ma and 604 ± 5 Ma (Basei et al. 1998). These ages suggested that the formation of these basins was almost coeval with the collage of the Luís Alves and Curitiba microplates (605 Ma) and also with the collision of the Paranaguá Batholith with the Luís Alves and Curitiba terranes (all these tectonic units are represented in the figure 1) .

The Corupá ''basin'' is located a few kilometers south of the Campo Alegre Basin, being separated from the latter by the Corupá granitoid. For this reason the designation Corupá sub-basin will be adopted.

PREVIOUS STUDIES

Acid and pyroclastic rocks in the Campo Alegre region were first described by Almeida (1949), who considered them as Eopaleozoic and compared these volcanics with the porphyritic rhyolites in the Itajaí Basin. Trein et al. (1969) included these rocks in the Guaratubinha Formation (defined by Fuck et al. 1967). Albuquerque et al. (1971) defined in 1:250,000 map scale the limits of this basin, referred to as Campo Alegre Formation and correlated with the Itajaí Basin sedimentary rocks.

Ebert (1971) proposed the first detailed stratigraphic scheme of the basin, defining three units: (1) the lower Bateias Formation, made of a thick conglomerate which grades upward to arkoses, with rare siltstones; (2) the thickest, intermediate Campo Alegre Formation, formed by basic and acid pyroclastic and volcanic rocks and subordinate detrital sediments; and (3) Rio Turvo Formation, made of laminated fine-grained siltstones, with rare tufaceous intercalations. The author suggests that the Campo Alegre Basin does not have stratigraphic similarities with the Itajaí Basin, which he considers to be older; it is compared with the Castro Group (in Paraná State) and with small basins that occur in the Serra do Mar in Paraná and Santa Catarina, in special the Rio Guaratubinha Basin, southeast of Curitiba, where the name Guaratubinha Group is taken from.

The detailed geological surveys of Daitx (1979a,b) and Daitx and Carvalho (1981) investigated the deposits of the Corupá and Campo Alegre basins. In the latter the authors identified five depositional sequences, included in the Guaratubinha Group: (1) Lower Sedimentary Sequence; (2) Lower Volcanic Sequence; (3) Intermediate Sedimentary Sequence; (4) Upper Volcanic Sequence; and (5) Upper Sedimentary Sequence. The first unit corresponds to the Bateias Formation as described by Ebert's (1971). Units 2, 3 and 4 correspond to sub divisions of the Campo Alegre Formation and the upper sedimentary sequence is equivalent to the Rio Turvo Formation.

According to Daitx and Carvalho (1981) the Lower Sedimentary Sequence can be divided into a conglomeratic and a sandy facies, within which fast gradations are observed, with rare siltstones and sandstones occurrences near the top of the sandy facies. The authors have not identified the depositional environment for these sediments.

The Lower Volcanic Sequence represents the base of the Campo Alegre Formation of Ebert

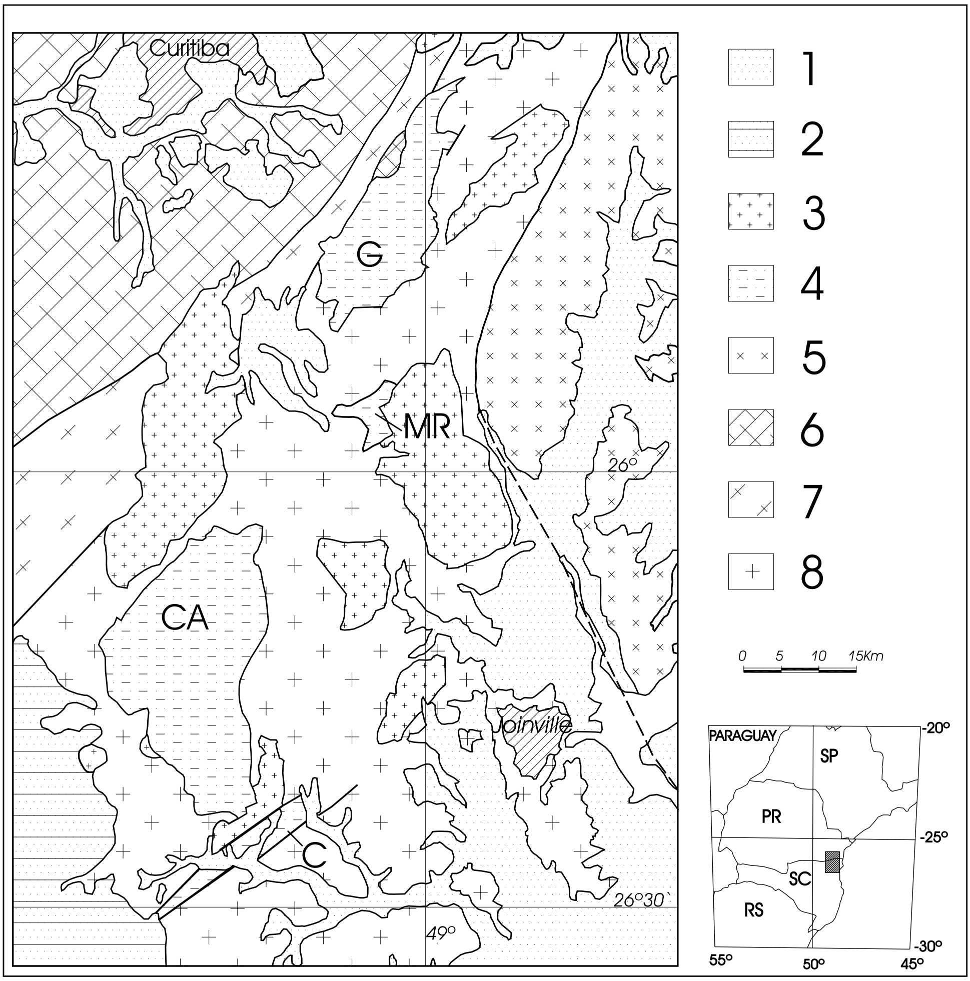

Fig. 1 – Simplified geological map showing the Campo Alegre (CA) and Guaratubinha (G) basins, the Corupá (C) sub-basin, and the volcanic rocks (MR) associated with the Morro Redondo Massif. Both basins are located within the Luis Alves domain, close to its northern border. 1) Quaternary alluvium; 2) Phanerozoic Paraná Basin; 3) Neoproterozoic Anorogenic Granitoid; 4) Fini-Proterozoic volcano-sedimentary basin; 5) Paraná Batholith (Neoproterozoic calc-alkaline granitoid); 6) Curitiba Domain (Paleoproterozoic to Neoproterozoic banded gneiss); 7) Piên Batholith (Neoproterozoic arc-related deformed granitoid); 8) Luis Alves Microplate (Paleoproterozoic high-grade orthogneiss).

(1971). It comprises basaltic and andesitic rocks, with rare dacites and rhyodacites. More differentiated volcanic rocks, such as quartz trachytes, are also present.

For Daitx and Carvalho (1981), the Intermediate Sedimentary Sequence is mainly constituted by pyroclastic sediments, with contributions of fine-grained to sandy epiclastic sediments. These rocks occur closely associated with mafic volcanic rocks especially at the base and close to the top of the unit. At the base, siliciclastic rocks predominate in special siltstones with commom tuff intercalations. The pyroclastic deposits are concentrated at the top of the sequence, varying from dust tuffs to coarse-grained breccias.

In the Upper Volcanic Sequence the acid volcanis rocks are more prominent, starting with explosive volcanic products, evolving to voluminous trachytic and rhyolitic flows. The trachytes predominate in the northern, western and northeastern areas of the basin, being overlain by rhyolites in its southern part. Varied pyroclastic rocks are intercalated with these lavas, markedly breccias, many of them polymictic, with accidental fragments of basement rocks and conglomerates in a tuffaceous matrix. Breccias and acid tuffs mark the top of the unit and are formed by fragments of volcanic rocks and crystals in a very fine-grained, siliceous and devitrified matrix.

The Upper Sedimentary Sequence, equivalent to the Rio Turvo Formation, is exposed only in the central part of the basin. It presents transitional contacts with the pyroclastic rocks of the underlying unit, being limited in its southern border by faults. Daitx and Carvalho (1981) identified two facies: at the base, fine-grained tuffs with less important intercalations of fine-grained epiclastic rocks; towards the top the epiclastic sediments (siltstones) tend to predominate. Shales and calciferous siltstones also occur, whereas tuffs are subordinate. Ebert's (1971) and Daitx and Carvalho's (1981) stratigraphic proposals are presented in Figure 2.

DEPOSITIONAL AND PALEOGEOGRAPHICAL EVOLUTION OF THE CAMPO ALEGRE BASIN

The stratigraphic division used in this paper agrees in great part with that presented by Ebert (1971) and Daitx and Carvalho (1981) and defends the existence of three different depositional stages related to the structural development of the basin: (1) Pre-Volcanic Stage, marked by fluvial sediments (Bateias Formation); (2) Volcanic Stage, which can be divided into two distinct phases and two short-lived events: the first phase is marked by mafic volcanism; an ignimbritic event separates it from the second phase, characterized by trachytic lavas; its evolution ends with an explosive volcanic event; (3) Caldera Stage, characterized by two different settings: a lacustrine environment inside the caldera and a rhyolitic volcanic setting outside the caldera.

The different stages reflect changes in the structural control of the subsidence of the basin. A fourth, late-depositional stage associated with the probable thermal subsidence is here suggested as being responsible for the preservation of the pile.

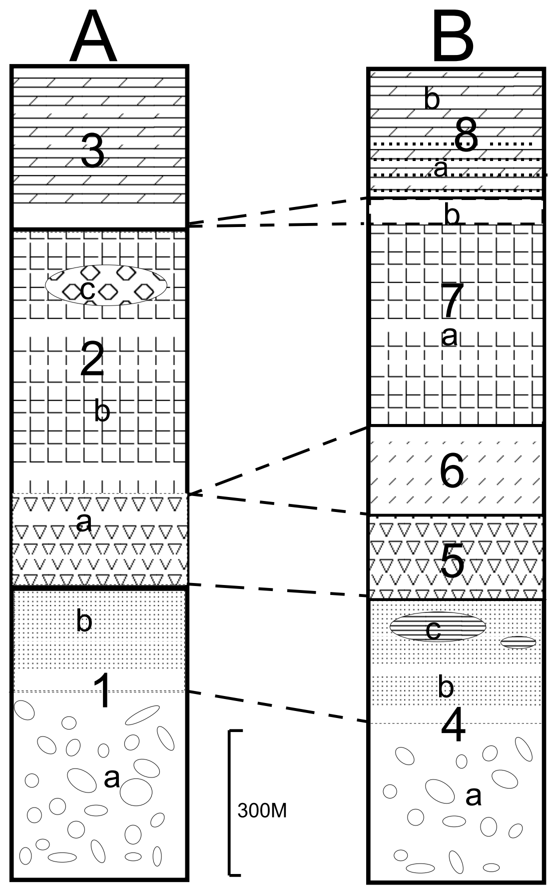

Fig. 2 – Comparison between the stratigraphic columns of the Campo Alegre Basin proposed by Ebert (1971) – A, and by Daitx and Carvalho (1981) – B. Units: **A:** 1 – Bateias Formation, a – Ruditic Member = conglomerates, b – Sandy Member = arkoses and siltstones; 2 – Campo Alegre Formation, a – basic lavas, b – acid lavas, c – acid tuffs; 3 – Rio Turvo Formation, fine-grained siltstones and tuff intercalations. **B:** 4 – Lower sedimentary sequence, a – conglomerates, b – sandstones, c – pelites; 5 – Lower volcanic sequence, basic and intermediate lavas; 6 – Intermediate sedimentary sequence, pyroclastic and epiclastic sediments; 7 – Upper volcanic sequence, a – acid lavas, b - volcanic breccia; 8 – upper sedimentary sequence, a – tuffs and tuffites, b – pelites.

Pre-Volcanic Stage

The initial stages of sedimentation of the Campo Alegre Basin is characterized by ruditic sediments deposited in a fluvial environment. It includes three facies: a wedge-shaped body of alluvial-fan conglomerates to the north, conglomerates with characteristics of braided-river deposits predominate towards the south, and fluvial sandstones replace the conglomerates to the east and towards the top of the sequence.

At this stage, the paleogeography was conditioned by the presence of a mountain ridge to the north: a fan system was being built with clasts derived from the deformed Rio Piên granitoid belt. The subsidence of the basin occurred in response to the tectonic load of the Rio Piên Belt and the sedimentary load of the alluvial fans (Fig. 3).

The fanglomeratic facies is characterized by poorly sorted conglomerates and breccias with angular to subrounded pebbles, blocks and small boulders, with diameters varying between five and 60 cm. This ruditic framework occurs in a feldspatic to arkosean sandy matrix, rich in mafic minerals (amphiboles), with variable contents of clay and common ferruginous cement. Matrix-supported rudites predominate, with punctual to linear contacts between the clasts, also occurring rare sand-supported portions. The disorganization of the clasts is conspicuous. Imbrication, orientation, grading or any other type of stratification is rare.

The conglomerates underlie an area of *ca.* 10km^2 in the northern part of the Campo Alegre Basin, covering an area of approximately 10km^2. Its minimum thickness, measured in one drill hole, is 80 m. Due to the difficulty in obtaining bedding measurements at the surface, it was only possible to estimate a thickness of 300 and 500 m.

Paleocurrent measurements are not available, but the position of the sediments restricted to the northern border, the presence of faulting in this sector and the reduction of the stratigraphic thickness southwards indicate transport from north to south, from the elevated blocks in the area now occupied by the Agudos do Sul Granite and by the Rio Piên Mylonitic Granitoids.

The alluvial fans discharged in an alluvial plain dominated by braided streams, where conglomerates were deposited in channel bars. These constitute the conglomeratic facies of largest distribution in the basin, formed by polymictic, clast-supported conglomerates, where subangular to rounded pebbles with grain-sizes varying mostly from 2 to 10 cm, predominate. The matrix is sandy, coarse- to medium-grained and, in general, arkosean. They present rough bedding given by the variation in grain size of the pebbles and the intercalation of decimetric to metric sandy levels. The planar orientation and imbrication of the pebbles are also observed, and low-angle planar cross bedding is rare. Intercalations of coarse- to fine-grained sandstones of arkosean composition are more common and extensive towards the top of the unit, to the eastern and southern parts of the basin. They present small-size tabular cross bedding, small conglomerate wedges and even isolated pebbles. Pelitic layers are rare and not thicker than 1.5 m.

The braided facies are exposed at the borders of the basin, occupying an area larger than 50km^2. The minimum thickness is 170 m measured in drill holes and 400 m estimated from the map. Pebble imbrication directions were measured in several occurrences at the eastern and western borders; the results show considerable dispersion, but with marked eastern and northern trends (Fig. 3). Therefore, the rivers ran from west to east/northeast, bordering the mountain chain towards the ocean (to the east) which separated the Luís Alves Microplate and the Paranaguá Domain.

The conglomeratic facies displays a clear retrogression from east to west, marked by the appearance of sandy fluvial deposits in the west resulting from the uplift of the base level and the reduction of the tectonic activity in the Piên Belt. The facies formed consists of medium- to fine arkosean, locally conglomeratic sandstones intercalated with sandy to clayey siltstones, also occurring thick siltstone and clayey-siltstone levels.

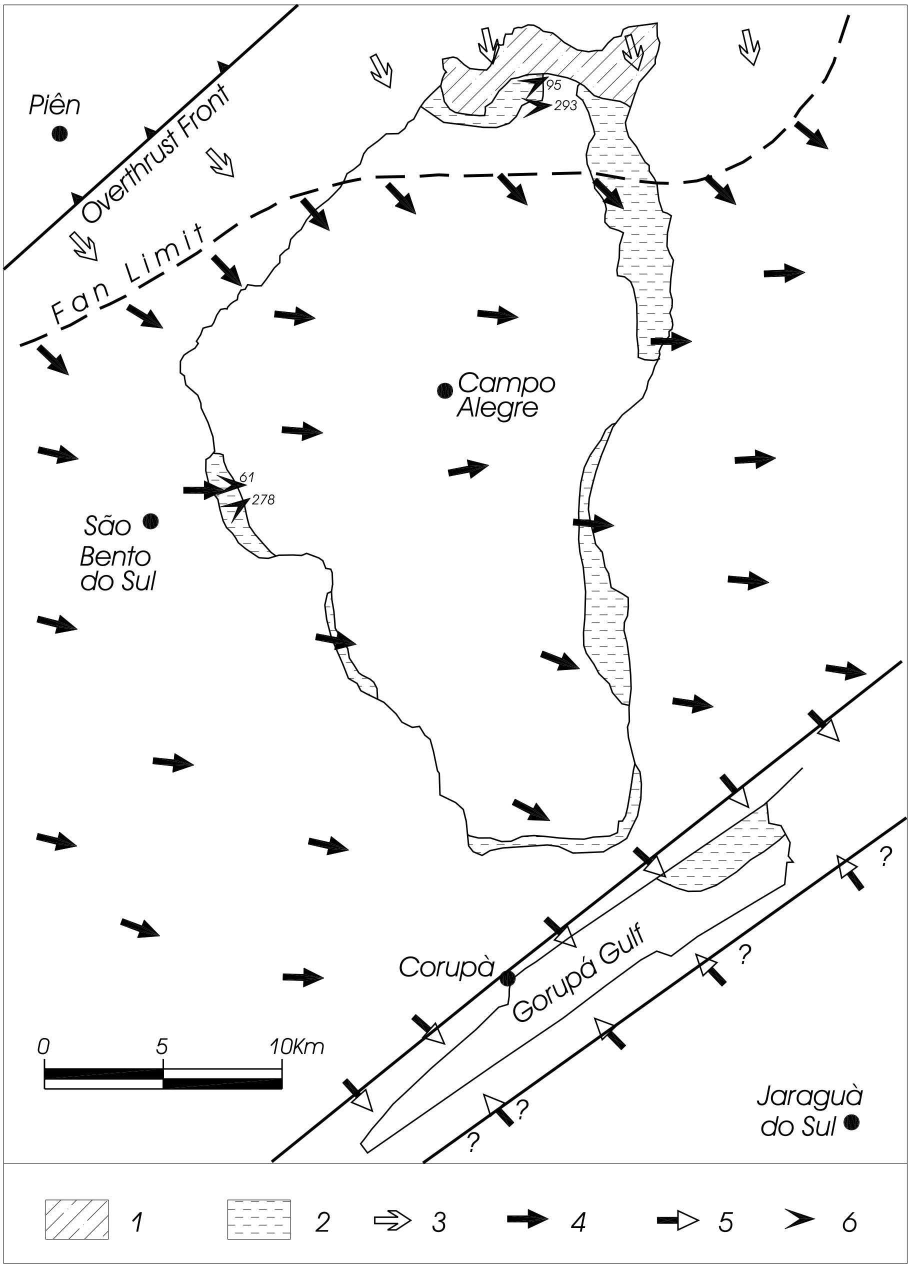

Fig. 3 – Location of the units deposited during the first stage of the Campo Alegre Basin with the paleogeographic situation. 1)- Papanduvinha Mb.; 2)- São Bento do Sul Mb.; 3)- alluvial fans; 4)- braided rivers; 5)- fan deltas; 6) paleocurrents.

Estimates of its thickness vary from 180 to 285 m. These rocks dispaly few depositional structures, such as tangential and tabular cross-bedding. Massive piles or piles with graded stratification predominate. It is absent in the western portion of the basin, where the sandstones are predominantly fluvial: these form thicker beds, commonly showing conglomeratic layers, trough and tangential cross bedding, with rare and thin pelite intercalaations (< 10 cm).

Substitution of the fluvial sandy sediments by laminated pelites marks the change to subaqueous conditions in the eastern portion of the basin and the beginning of tectonic activity in its western margin, with the development normal faults. Which might have been responsible for the progressive retrogression of the fluvial facies and its substitution for a more distal environment.

In the Corupá sub-basin to the south, the fanglomeratic facies is absent, the braided conglomerates are finer-grained and less widespread. In some outcrops conglomerates alternate with coarse- to fine-grained sandstones, quickly changing to sandstones and siltstones intercalations (rhythmites). The latter have structures that suggest shallow subaqueous environment, in sublitoral conditions. The conglomerates might have been deposited in deltaic fans. The sandy-pelitic sediments in this sub-basin are quite different from those in the Campo Alegre Basin: they are rhythmic intercalations between decimetric levels of massive sandstones, with reverse grading and with parallel stratification and centimetric to decimetric siltstone and shale beds with parallel and more rarely, wavy stratification. Such deposits are interpreted as turbidites.

The presence of a gulf can be considered, within which braided rivers discharged their loads in the form of deltaic fans. The subsidence of the basin was stronger in this area, with the development of deep-water turbidites at the same time as pelites and sandstones were deposited northwards, in rivers and in shallow waters.

It is still not possible to safely correlate the sedimentation of these turbidites with one of the facies of the pre-volcanic stage of the Campo Alegre Basin; the ''Corupá Gulf'' might have been present since the beginning of the deposition of alluvial fans, but it is also possible that its installation had occurred later, at the same time of the advance of the water body from the east which led to the progradation of the sandy facies on the ruditic fluvial sediments.

In the Guaratubinha Basin, located *ca.* 50km northeast of the Campo Alegre Basin, ruditic rocks with fanglomerate characteristics occur. The fragments are larger than those of the Campo Alegre Basin (30 cm to 1 m). These rocks may correspond to the proximal and intermediate facies of the Pre-Volcanic Stage deposits of the Campo Alegre Basin. Thus, the Guaratubinha and Campo Alegre basins may be chrono-correlated and were part of the same basin, situated at the margin of the Rio Piên Belt. U-Pb ages for felsic lavas present in both basins coincide (around 595 Ma) and support this correlation.

VOLCANIC STAGE

Acid and basic volcanics and varied pyroclastic rocks (tuffs, lapillistones, ignimbrites and pyroclastic breccias) characterize the volcanic stage of the Campo Alegre Basin. Besides two explosive events two distinct phases can be identified in this stage, corresponding to changes in the lava composition.

Phase 1 – Basaltic rocks and fine-grained epiclastic sediments

Mafic flows intercalated with pelites define the first volcanic phase of the Campo Alegre Basin (Rio Negrinho Formation). The lavas comprise basalts and andesites with rare dacites and rhyodacites; more evolved volcanic rocks, such as quartz trachytes, are also present. The sediments are laminated pelites, reflecting the continuity of the subaqueous depositional conditions installed at the end of the initial stage. The area of outcrop is very discontinuous, and the thickness estimated from drill holes reach 150 m (from which 50 m correspond to sediments).

Conduits for this volcanic eruptions were not identified, but the existence of several NNW-trending basic and acid dikes suggests that the fractures with the same orientation could have channeled the magmas. Faults with the same direction might have been responsible for setting the structure of the Campo Alegre Basin at this stage. The acid lavas to the west of the basin occur as a NNW elongate body maybe associated with one of the fractures.

The basic flows occurred in subaerial condi-

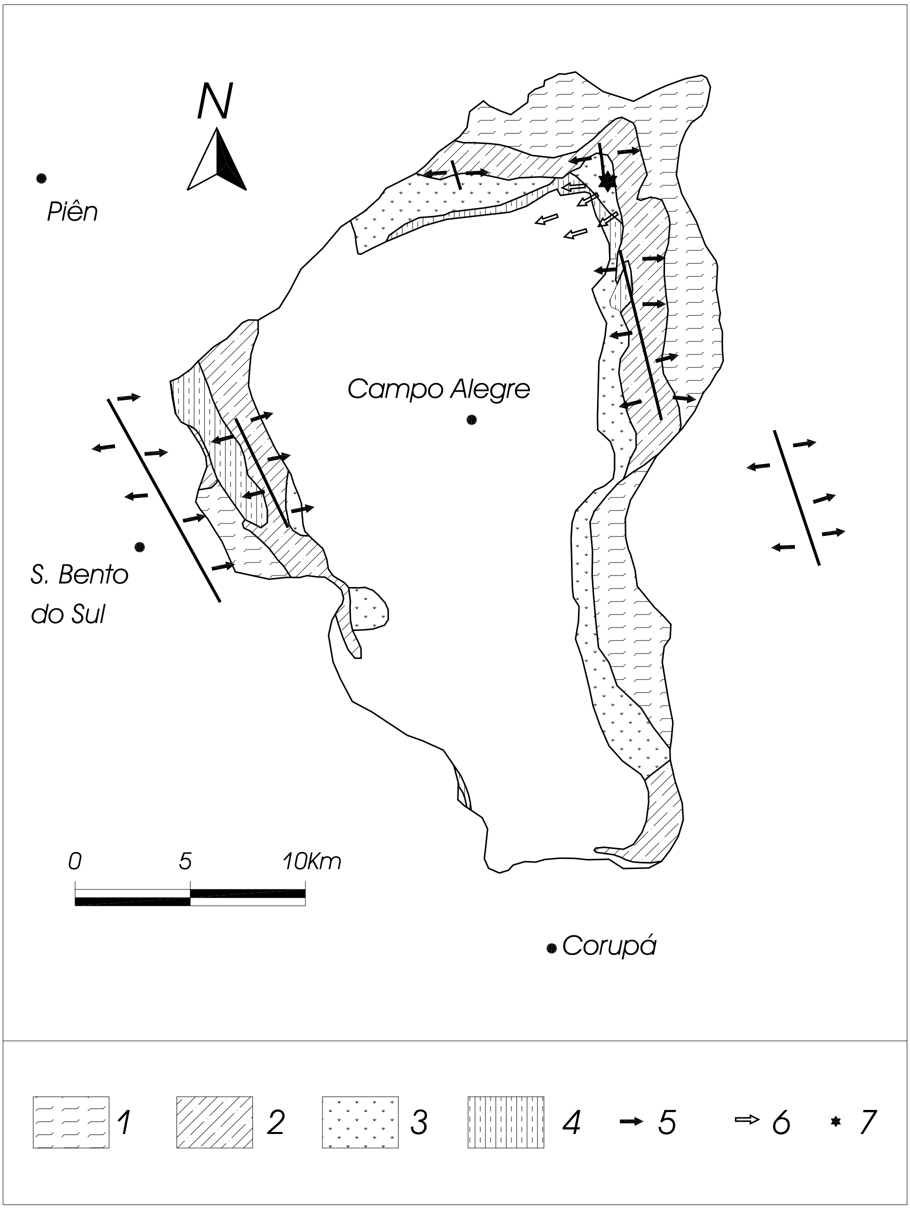

Fig. 4 – Paleogeography of the first phase of the volcanic stage: 1)- Rio Negrinho pelites; 2)- Rio Negrinho basalts; 3)- Rio Negrinho trachytes; 4)- Avenca Grande ignimbrites; 5)- basaltic flow directions; 6)- ignimbrite flow direction; 7)- possible volcanic center of the Avenca Grande ignimbrites.

tions in the west and partially subaqueous in the east. The fine-grained sediments with rare mafic lava intercalations are thicker in the east and to the south, and almost absent in the west, indicating that the general paleogeographic configuration is still preserved, with the lowlands to the east (Fig. 4).

The basic lavas occur as two main types: lavas with abundaant sub-millimetric to decimetric vesicles and amygdales, and lavas and/or subvolcanic microporphitic massive rocks with millimetric plagioclase phenocrysts. Both types in colour from dark gray to black, altering to shades of purple and gray; both plagioclase phenocrysts and amygdales alter to whitish colors.

In northeastern parts of the Campo Alegre basin lavas are intercalated with the siltstones displaying structures and textures typical of flows or shallow intrusions in unconsolidated sediments saturated with water, such as hyaloclastic fragmentation, mixture between fragments of lava and fine-grained sediments (possible peperites), lavas in pillows and isolated pillows within the sediments.

Acid to intermediate lava flows occur intercalated in the basalts and andesites. These are trachytes and quartz trachytes with rare potassic feldspar (sanidine) phenocrysts. The acid lavas have a predominant massive aspect, with rare horizontal fracture planes.

Basalts and andesites present intersertal to interstitial texture, with a plagioclase mesh limiting altered mafic crystals (pyroxenes, opaque minerals, olivine and carbonates, antigorite, chlorite and sericite as alteration minerals). More rarely intergranular and poikiloblastic textures are observed, in this case with large pyroxene crystals containing small plagioclase inclusions. The grain size of these minerals varies between 0.2 to 1.5 mm for the plagioclases, the phenocrysts are a slightly larger (2 mm), but can reach up to 1 cm. Rare radial plagioclase aggregates reach up to 2.5 cm of diameter (glomeroporphyritic texture). The mafic minerals are in general smaller, being often altered to oxides and calcite; more rarely antigorite is formed after olivine.

Typical modal compositions of these rocks are: plagioclase between 50 and 70%, pyroxenes between 15 and 25%, olivines from 0 to 15%, opaque minerals between 5 and 10%. Plagioclases were identified as oligoclase, andesine and labradorite, predominating the last two. Pyroxenes are either pigeonite or augite.

The acid intercalations present microlitic texture due to devitrification, with the development of patchy mesostasis with secondary recrystallized quartz, sometimes as larger crystals in optical continuity with other crystals and aggregates of fine-grained crystals. Relict spherulitic textures, masked by recrystallization can also be observed. The phenocrysts make up to 30% of the rock, but can also be rare. By far the potassic feldspar phenocrysts predominate, usually euhedral to subeuhedral sanidine, reaching up to 3.5 mm; quartz phenocrysts are rarer, smaller and corroded, quite often rounded.

The mineralogy of these rocks is simple: besides potassic feldspar and quartz, opaque minerals (magnetite) and secondary sericite were identified in the matrix. Zircon crystals are common, with some observed in small mineral aggregates. Basic xenoliths may be present locally.

Ignimbritic event

An ignimbritic event that affected the northern portion of the basin, marks of the onset of the progressively more acid magmatic activities. The thicckness is variable, possibly reflecting the paleotopography. Some portions seem to have penetrated a water body, whereas others seem to have eroded partially weathered basaltic rocks.

It is difficult to establish the starting point of this flow. The thicker area is situated northeast of the basin, whereas the outcrops that show flows eroding remains of the altered basalt are found westwards (Fig. 4); to the south the beds get thinner. These characteristics suggest that the flow direction was from northeast to south and southeast, which implies in an uplift of the northeastern portion of the basin, maybe with the construction of a volcanic edifice from which the ignimbrite originated. This ignimbritic bed can be traced continuously for half of the northern part of the basin by means of outcrops and drill holes. Its thickness varies from some tens of centimeters to more than 20 m. In most of the expositions a bed with braided foliation and maximum thickness of 1 m is observed intercalated in laminated siltites.

South of Avenca Grande a thick example of the ignimbbrite event is divided into five layers from base to top: (1) pyroclastic flow with braided foliation (due to imbricated pumice clasts, slightly welded) and lithic and crystal clasts; (2) very fine-grained ''sandstone'' with clay fragments; (3) fine-to medium-grained ''sandstone'' with clayey levels; (4) coarse-grained to conglomeratic arkosean ''sandstone'' with feldspar, quartz and lithic clasts; (5) fine-grained ''sandstones'' with cross bedding, linsens and clay balls; and (6) altered fine-grained ''sandstone''. It overlies a thin (few meters) bed of laminated pelites, with irregular layers of basalt further below (some portions with isolated pillows).

Phase 2 – Felsic volcanism

It corresponds to the thickest and the most characteristic volcanic unit of the Campo Alegre Basin; it is constituted mainly by trachytic to quartz trachytic flows, with subordinate rhyolitic and trachyandesitic members. Pyroclastic flows and fall deposits also occur.

It dominates the central-southern portion of the basin, forming the so-called Campo Alegre plateau. In the northern portion, they form a ring of cuestas, smoothly tilted towards the center of the basin. They also occur as isolated ridges in several localities at the margin of the basin. Evidence for subaqueous sedmentary or magmatic activity in subaqueous environment are not observed in this unit. It is likely that the volcanic activity progressively uplifted the region, causing the subaerial conditions to dominate throughout the basin.

The acid volcanism of this phase has very homogeneous characteristics throughout the basin. It is very thick, with maximum thickness in the northern portion. The eruption of large volumes of magma must have caused differential subsidence of the blocks limited by NNW- and also ENE-trending faults, as suggested by the differences in thickness observed in the drill holes.

The volcanic conduits are not clearly defined; as observed for the basic lavas, trachytes and rhyolites seem to be associated with linear fissures. Besides the NNW-trending fractures, ENE fractures must have conditioned the position of these conduits.

Three structural types of felsic volcanics are identified: massive, autoclastic and flow-banded. In the massive (homogeneous) type, potassic feldspar and subordinately quartz phenocrysts are common. Sub-horizontal discontinuities in the massive lavas mark the volcanic bedding and indicate the existence of successive flows or flow differences inside the same body (flow shearing). The thickness of the layers separated by these surfaces varies from tens of centimeters to a few meters.

The massive volcanics present devitrified, microcrystalline to cryptocrystalline matrix with patchy recrystallization texture. Recrystallization products such as submillimetric to centimetric spherulites are observed. Locally they display millimetric (1 to 8 mm, more commonly between 1 and 3 mm) potassic feldspar phenocrysts and more rarely polycrystalline aggregates of quartz.

The bands of the lavas with flow banding are commonly tightly folded and recumbent. Generally they also show auto-fragmentation. The models and field observations (Bonnichsen and Kauffman 1987) suggest that banding and autobrecciation occur mainly at basal and top portions, with the massive lavas restricted to the central parts of the flows. The banded rocks are marked by the intercalation between millimetric cryptocrystalline levels and others more recrystallized with granophyric texture or spherulitic structures. The more fine-grained levels present greater concentration of mafic minerals and an orientation parallel to banding.

The minimum thickness of the lavas is 240 m. The individual, better-defined flow with banded, massive and autoclastic layers is *ca.* 35 m thick. This outcrop, situated at Clube Tigre (Fig. 5), beside the large water fall close to the Prefeitura de Campo Alegre building, is a continuous 30 m-thick pile. The base is autoclastic, 3 m-thick, overlain by a 5 m-thick layer of banded lavas, followed by *ca.* 12 m of massive lavas and 10 m of banded lavas with tight folds at the top.

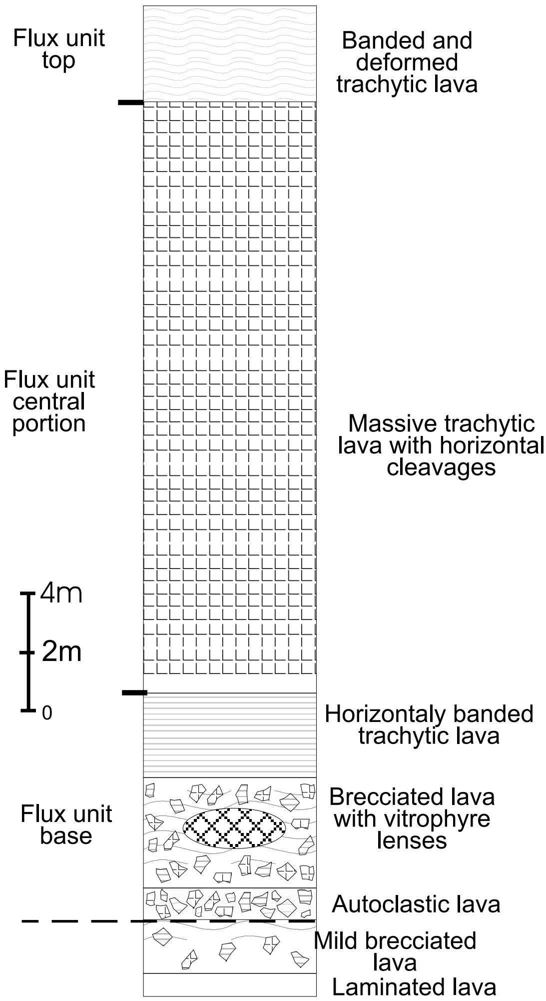

Fig. 5 – Section of the trachytic flow of the felsic phase (Serra de São Miguel Formation) located at Clube Tigre, showing the distribution of the different facies of these flows.

Deposits proximal to the explosive event

A coarse-grained breccia, with light green, very fine-grained matrix supporting angular pebbles and blocks, marks the explosive event possibly associated with the formation of a vitreous lava dome related to an ENE-trending fracture.

Locally the pebbles can be juxtaposed, forming a nearly perfect fit, like jigsaw pieces. Rare pebbles of basement lithologies (gneisses) can be observed in some places, probably xenoliths taken from the volcanic conduit.

The breccia is overlain by non-fragmented vitreous lavas with subhorizontal flow banding, similar to the underlying ones, indicating that that they are not volcanic conduit deposits, but products of explosions associated with a viscous flow. Under the microscope it is composed of a very fine glassy mass devitrified to microcrystalline quartz containing glassy pebbles, also devitrified showing structures resulting from chilling such as perlites and some spherulites.

The explosive pyroclastic flow was followed by fluid lavas showing autobrecciation and flow banding. This particularly violent event accelerated the subsidence in the northern portion of the basin, possibly as a response to the quick tapping of the lava reservoir.

The exposure area of this breccia does not exceed 2km^2 and is located inside the town of Campo Alegre City (Fig. 6). Descriptions of drill hole samples suggest the continuity of this unit under the sediments to the north. In outcrops, the breccia presents maximum thickness of 12 m, being overlain by 16 m thick banded and autoclastic lavas. The drill holes indicate thickness of *ca.* 10 m for the breccias.

Caldera Stage

The explosive event which ends the volcanic stage is remarkable in the history of the basin, is represented by the formation of a caldera which received the final mixed terrigenous-pyroclastic sedimentation of the basin. Apparently it was an emission of an abnormally large volume and with an explosivity not observed in the previous deposits. Figure 6 shows the location of the sedimentary deposits internal to the caldera and of the extra-caldera lavas and ignimbrites.

Intra-caldera sedimentation

The subsidence leads to the installation of a caldera lake, with the deposition, in its preserved portion, of fine-grained sediments, in part turbiditic, but always presenting fine grained, mainly glass shards, besides rare pumice lapilli. Fall tuffs beds, laminated by the

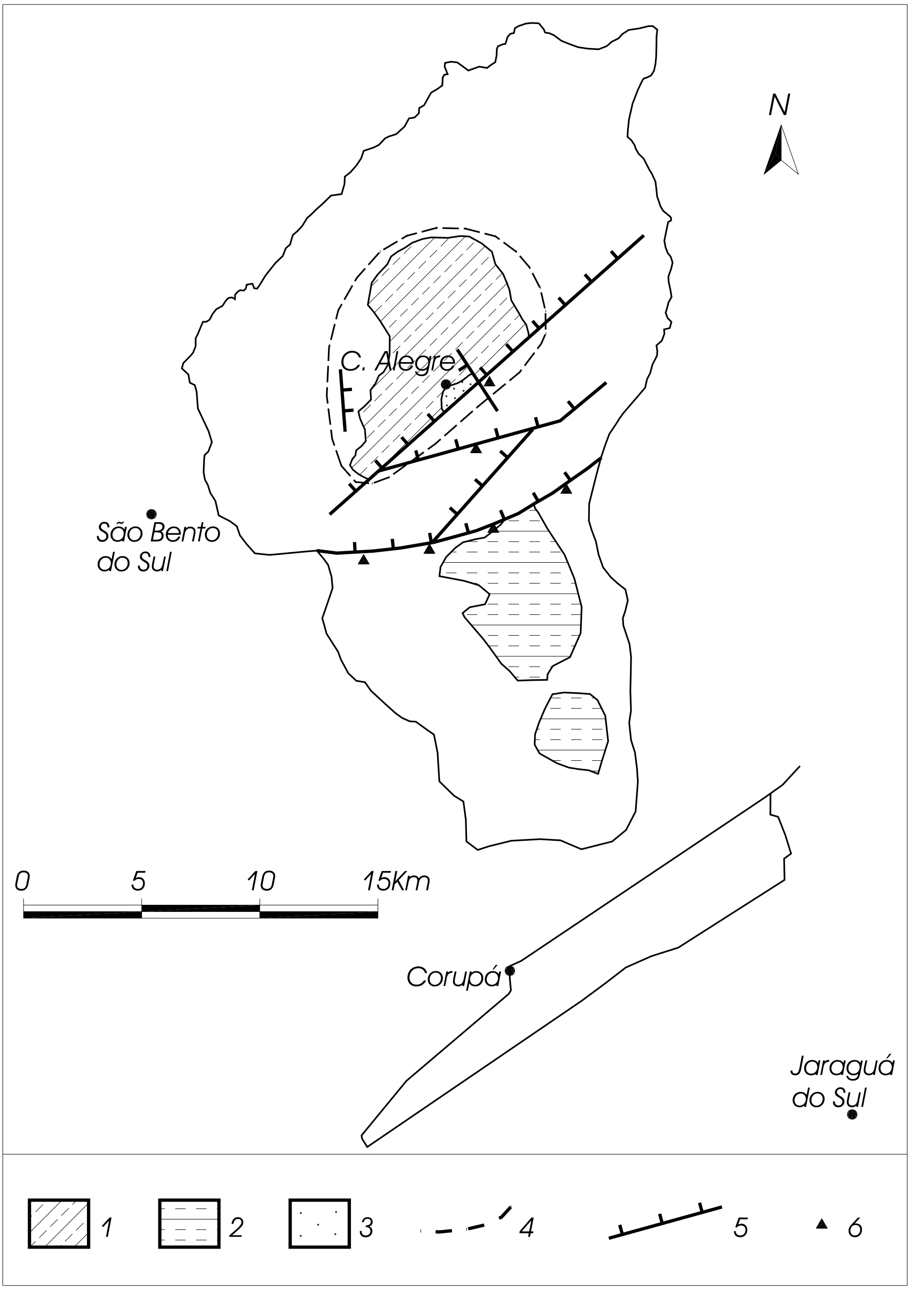

Fig. 6 – Paleogeography of the caldera stage of the Campo Alegre Basin, showing the outcropping area of the intra- and extra-caldera units: 1)- Rio Turvo Formation; 2)- Arroio Agua Fria Formation; 3)- Fazenda Uirapuru Formation; 4)- Caldera limit; 5)- extentional faults; 6)- volcanic center.

fall and decantation in the water. Small intercalations of acid flows and thick ignimbrites were also deposited in this caldera lake. The caldera deposits extend from Campo Alegre in the south, to *ca.* 3 km northwards, underlying an area of approximately 45 km^2. The maximum thickness determined in drill holes reaches 150 m.

The sedimentation seems to have taken place in a relatively calm environment, with parallel strata and laminae, with fine-grained turbidites intercalated with pelites and several fall tuff beds. Rare decimetric to metric levels of acid lavas and intercalated ignimbrites are also present.

Terrigenous sediments predominate, with subordinated contributions of volcano-derived material, such as millimetric glass-shard levels. Fine-grained sandstones present a large volume of fine-grained matrix, probably fine-grained devitrified and recrystallized volcanic ashes and rare larger quartz crystals and subordinately potassic feldspar. The pelites present variable proportions of glass-shards and isolated recrystallized spherulites. The contribution of volcanic ashes is evident mainly at the base of the unit.

Some igneous rocks are intercalated with the fine-grained sediments of this unit, suggesting resurgence processes inside the caldera. However, what most marks the unit's volcanic manifestations is the large volume of fall pyroclasts, present in several subaqueous fall tuff levels and mixed beds of tuffites. These glass-shards, by then extremely rare in the basin's record, mark an important modification of the volcanism characteristics. It possibly acquired more acid characteristics and its center was transferred south of the basin.

The ignimbrites are rare and densely welded, intensely recrystallized and with fiamme; weakly welded ignimbrites also occur, where pumices are not flattened and rich in lithic particles.

Extra-caldera volcanism

To the south, away from the caldera lake, the deposition of acid tuffs and weakly welded ignimbrites are found, accompanied by lavas with more acid characteristics, being mainly rhyolites. In this third stage the volcanic activity becomes more acid and more explosive than the previous one. Kaolin is found preferentially in this unit, indicating that the development of preferential alteration must reflect compositional and structural differences in relation to the lavas below.

The kaolin deposits is one of the criteria used to define these limits, because it seems to exist a chemical and textural control conditioning the development of this alteration; other criteria are topographic aspects (a relatively planar eroded topography) and the characteristics of some less altered expositions.

Several outcrops present very thick beds with homogeneous flow banding. Beds with millimetric to decimetric spherulites are intercalated. Very weathered homogeneous levels present potassic feldspar and quartz granules within a white fine mass; some of these levels were interpreted as fall tuffs or ignimbrites, depending on sorting and on the identification of some flow movement.

The ignimbrites vary from weakly to moderately welded. Types with crystal and lithic clasts predominate, with matrix constituted by very fine-grained recrystallized ashes. The rhyolitic lavas have foliated texture, with autoclastic portions and potassic feldspar and quartz phenocrysts. The matrix contains these minerals and sometimes plagioclase. It can be cryptocrystalline, massive or banded, besides recrystallization in spherulites and perlites.

Late-Depositional Stage

The Campo Alegre and Guaratubinha basins coincide with positive gravimetric anomalies (Hallinan et al. 1993). Regional thermal subsidence due to basic magma cooling, crystallized at the base of crust (underplating), is here suggested as having been responsible for the preservation of the basin. These basic rocks would correspond to the intermediate reservoir in which magmatic differentiation by fractional crystallization generated the volcanic rocks present in both basins.

STRATIGRAPHIC PROPOSAL

The different stages correspond to the predominance of different lithologies at the Campo Alegre Basin.

Below the characteristics of these lithologies are listed, organized as a new proposal of lithostratigraphic units, based mainly in Citroni (1998). Table I lists the evolution phases and the lithostratigraphic units of the Basin proposed in this paper.

Pre-Volcanic Stage (Bateias Formation)

It corresponds to the dominantly ruditic sedimentation of the Bateias Formation, as defined by Ebert (1971). The different depositional facies can be attributed to different members of this formation:

Papanduvinha member

They are the disorganized conglomerate deposits from the fanglomerates of the northern margin of the basin. The name suggested by Citroni (1998) was Papanduvinha Formation, taken from a small locality situated less than 2 km north of Bateias de Baixo, in Santa Catarina State; in the present paper the unit status was lowered to member. The type section chosen for this unit is located in the first 2 km of the road that links Bateias de Baixo to Agudos do Sul in the Paraná State.

São Bento do Sul member

Conglomerate facies with stratification and imbrication of pebbles, deposited predominantly by braided rivers. Its type section was taken in the quarries located on the road that links SC-280 Highway with the eastern part of São Bento do Sul (Bairro Pedreira). Citroni (1998) proposed the name São Bento do Sul Formation for the unit.

Rio do Bugre member

It is the sandy and pelitic facies of fluvial and subaqueous environments. The name of this unit (proposed as formation by Citroni 1998) was taken from a stream located close to the SC-280 Highway, east of São Miguel, in which irregularly laminated siltites and clayey siltites crop out.

Corupá Formation

Also belonging to the depositional stage, in the Corupá Sub-Basin, this formation corresponds to the turbiditic sediments. The type section is located in the road that links SC-301 Highway to the locality Poço da Anta, southeast of Corupá city.

Volcanic Stage (Campo Alegre Group)

The set of lithologies in which the volcanic rocks predominate were grouped in Ebert's (1971) Campo Alegre Formation; its great lithologic variety distinguishable in the field does not justify keeping the whole pile in a single formation. Citroni (1998) proposed the designation Campo Alegre Group to these rocks, characterizing them as constituted by a succession in which the volcanic activity record predominates in relation to the sedimentation.

Rio Negrinho Formation

The initial volcanic activity is marked by basaltic to andesitic lavas associated with fine-grained sediments, with subordinated trachytic lavas. Thus three facies can be defined: basic volcanic, acid volcanic and sedimentary pelitic facies. The first and the third facies occur in the northern region of the Campo Alegre Basin, in the Rio Negrinho region. The acid volcanic facies is best represented in the outcrops of the SC-280 Highway in the vicinities of São Bento do Sul city.

Avenca Grande (ignimbrite) Formation – The ignimbritic event that marks the transition of the predominance of mafic to felsic lavas can be perfectly distinguished in the field by its lithologic characteristics and can be mapped in the 1:100000 scale, which justifies its individualization as a formation. Its type section is located in a quarry in the Avenca Grande region.

Serra de São Miguel Formation – It corresponds to the felsic volcanism phase of the volcanic stage of the Campo Alegre Basin. Constituted almost exclusively by trachytes, its type section is located in the first 3 km of the road that links SC-280 highway

TABLE I

Summary of the relations between the stages and evolution phases of the Campo Alegre Basin and of the lithostratigraphic units proposed in this paper. See also Figure 7.

Stage	Phase/Event	Lithologies	Stratigraphic Unit	
Pre-volcanic (subsidence by tectonic/ sedimentary load)		Fanglomerates	Bateias Fm.	Papanduvinha Mb
		Conglomerates		S. Bento do Sul Mb.
		Sandstones and siltstones		Rio do Bugre Mb.
		Turbidites	Corupá Fm.	
Volcanic (subsidence by *dipslip faults* – NNW/SSE direction)	Mafic volcanism	Basalts and siltstones	Campo Alegre Group	Rio Negrinho Fm.
	Ignimbritic event	Ignimbrites		Avenca Grande Fm.
	Felsic volcanism	Trachytes		Serra de S. Miguel Fm.
	Explosive event	Volcanic Breccia		Fz. Uirapuru Fm.
Caldera	Intra-caldera	Siltstones and tuffs	Rio Turvo Fm.	
	Extra-caldera	Rhyolites and	Arroio Água Fria Fm.	
Thermal subsidence				

with the Bateias de Baixo region from São Miguel, east of Campo Alegre.

Fazenda Uirapuru Formation (event) – The last unit that takes part in the Volcanic Stage corresponds to the explosive volcanic event, having produced the proximal breccia located south of the Campo Alegre city, in the vicinities of the Fazenda Uirapuru, from where the name was taken.

Caldera Stage

After the collapse of the northern portion of the Campo Alegre Basin which followed the Fazenda Uirapuru event, two areas with different characteristics were individualized in relation the depositional characteristics and environment: intra and extra-caldera.

Rio Turvo Formation – Proposed by Ebert (1971), the name was taken from the river that runs north of Campo Alegre; it corresponds to the deposition that took place inside the collapsed caldera. Fine-grained sediments predominate with subordinate ignimbrites and felsic lavas. The most representative section of this formation starts in the Bela Aliança region, west of Campo Alegre and follows SC-280 to the town of Campo Alegre, entering a secondary road that borders the Turvo River in the east-southeastern direction.

Arroio Água Fria Formation – The presence of glass shards and volcanic ash remains sediments deposited inside the caldera (Rio Turvo Formation) indicate the increase of the explosive character of the felsic volcanism and its greater dispersion. South of the caldera, rhyolitic lavas, ignimbrites and subordinate tuff deposits mark the top of the trachytic lavas of the Serra de São Miguel Formation. The products of this acid volcanism compose the Arroio Água Fria Formation, a still badly defined unit due to weak outcrops.

CONCLUDING REMARKS

The Campo Alegre is the major volcano-sedimentary basin developed during the Proterozoic-Fanerozoic transition in the northern part of southern Brazil. The basin has been deposited on Paleoproterozoic gneissic-granulitic terrain (Santa Catarina Granulitic Complex) to the south of a Neoproterozoic magmatic arc (Rio Piên calc-alkaline granitoid belt). Several anorogenic alkaline to peralkaline

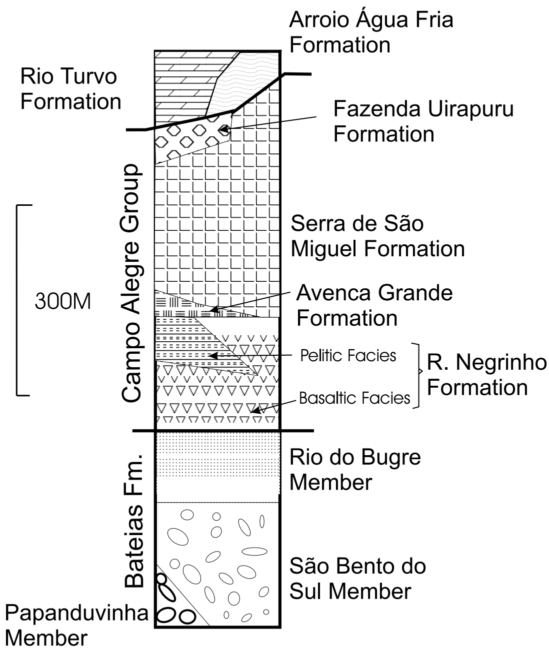

Fig. 7 – Stratigraphic column of the Campo Alegre Basin proposed: Bateias Formation- Members Papanduvinha (fanglomerates), São Bento do Sul (conglomerates) and Rio do Bugre (sandstone and siltstones); Campo Alegre Group: Rio Negrinho Formation- volcanic facies (basalts and andesites), pelitic facies (laminated siltstones); Avenca Grande Formation (ignimbrites), Serra de São Miguel Formation (trachytes and quartz trachytes), Fazenda Uirapuru Formation (volcaniclastic breccia); Rio Turvo Formation (pelites, tuffs and ignimbrites); Arroio Agua Fria Formation (rhyolites and ignimbrites).

granitoid bodies with ages around 595 ± 10 Ma occur close to the basin, namely the Corupá Massif to the south, Agudos do Sul to the north and the Dona Francisca and Piraí massifs to the east.

The nature of the volcanic and sedimentary rocks in the Campo Alegre Basin suggest that the basin evolved in the three distinct stages: 1) Pre-volcanic stage, in which fluvial sedimentation was controlled by a subsidence at the northern border of the Luis Alves domain caused by the adjacent mountain belt (whose roots are today represented by the Piên arc-related granitoids); 2) volcanic stage, during which magma ascent and basin subsidence were relatet to tensional faults with NNW direction. The volcanism evolved from basic to acidic (trachytic) compositions; 3) Colapsed caldera stage, with deposition of lacustrine sediments and intercalated volcanic ash beds inside the caldera, and acid lavas and ignimbrites outside.

RESUMO

A sucessão deposicional das rochas vulcânicas e sedimentares da Bacia de Campo Alegre (Santa Catarina – sul do Brasil) foi estabelecida tendo como ''background'' a evolução da atividade vulcânica. As diferentes unidades estratigráficas são consideradas como pertencentes a diferentes estágios do vulcanismo: Formação Bateias, constituída por conglomerados e arenitos, é relacionada a um estágio pré-vulcânico; Grupo Campo Alegre, depositado durante o estágio vulcânico principal, é constituído de diferentes formações que refletem os diversos momentos desse vulcanismo – Formação Rio Negrinho, relacionada ao vulcanismo básico, Formação Avenca Grande a eventos ignimbríticos, Formação Serra de São Miguel ao vulcanismo ácido e a Formação Fazenda Uirapuru a um evento explosivo; as formações Rio Turvo e Arroio Água Fria correspondem respectivamente a depósitos do interior e do exterior de uma caldeira abatida.

Palavras-chave: Bacia Neoproterozóica, vulcanismo, depósitos de caldeira, evolução paleogeográfica.

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