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Ruiniform relief in sandstones: the example of Vila Velha, Carboniferous of the Paraná Basin, Southern Brazil

Relevo ruiniforme en arenitos: o exemplo de Vila Velha, Carbonifero da Bacia do Paraná, Sudeste do Brasil

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ABSTRACT

Vila Velha is a remarkable group of natural sculptures in Palaeozoic sandstones of the Paraná Basin in Southern Brazil. The sculptures, which resemble the ruins of an old stone city, have resulted from the combination of Cenozoic weathering and erosive processes with the existing attributes of the sedimentary rocks (texture, cementing oxides, sedimentary and brittle structures). A particular geomorphologic setting with eroded inselbergs, and a differential iron and manganese cementation during lateritization phases are other factors controlling that exceptional landscape, the ruiniform relief. Despite being a natural heritage of inestimable value, Vila Velha is threatened by large-scale tourism, with severe risks for its conservation.

Keywords: Vila Velha Sandstone. Paraná Basin. Ruiniform Relief. Geomorphology. Southern Brazil

RESUMO

Vila Velha é um notável conjunto de esculturas naturais em arenitos paleozóicos da Bacia do Paraná, situado no Estado do Paraná, no sul do Brasil. As esculturas são muito ricas em ornamentos, e lembram as ruínas de uma velha cidade de pedra, daí o seu nome. As formas bizarras resultam da combinação de intemperismo e erosão cenozóicos com o efeito de feições preexistentes na rocha sedimentar, principalmente as estruturas sedimentares e rúpteis, e as diferenças texturais e de cimentação por óxidos de ferro de manganês. Estes constituem uma característica dos arenitos, conferindo-lhes cor avermelhada a amarelada muito intensa e variada. A evolução geomorfológica da região favoreceu o isolamento de morros testemunhos profundamente erodidos, o que, juntamente com a cimentação durante fases de laterização cenozóicas, favoreceu a formação da paisagem de exceção representada pelo relevo ruiniforme de Vila Velha. Embora constituam um patrimônio natural de valor inestimável, as esculturas em arenito encontram-se seriamente ameaçadas por uma exploração que privilegia sua utilização turística, e não tem logrado conferir-lhe o papel de uma unidade de conservação.

Palavras-Chave: Arenito Vila Velha. Bacia do Paraná. Relevos ruiniformes. Geomorfologia

EXTENDED ABSTRACT

Vila Velha is a remarkable group of natural sculptures in Upper Carboniferous sandstones of the Paraná Basin, situated about 80 km WNW from Curitiba, Paraná State, Southern Brazil. These sculptures resemble the ruins of an old stone city, and popular imagination has given them bizarre names such as the sphinx, the bottle, the ship's prow, the camel, the mushrooms, the turtle, the wineglass (the symbol of Vila Velha), and many others.

The Paraná Basin is a wide South American intracratonic trough, about 1.4 million km^2 in area, extending over Brazil (1.1 million km^2), Uruguay, Argentina and Paraguay. The basin is filled by up to 8,000 m of sedimentary and volcanic rocks, the later to a maximum depth of 2,000 m. The basin shows three main trends of tectonic structures:

a) NE-SW parallel to the structures of the Proterozoic basement;

b) NW-SE, related to the Gondwana breakup;
c) E-W parallel to oceanic fracture zones.

These three trends of structures appear in Vila Velha, mainly as long fractures with no or negligible displacement. Subhorizontal structures partially controlled by bedding and formed by a relaxing of stresses due to load removal also cut the sandstones.

Vila Velha is placed at the southwestern flank of a long NW-SE structure of the Paraná Basin, the Ponta Grossa Arch, which gave rise to some of the most remarkable geological and geomorphologic features of the eastern border of the Paraná Basin:

a) NW-SE fractures, faults and mainly diabase dyke swarms;
b) the marked erosive concavity in the limit of the Palaeozoic sedimentary rocks of the Paraná Basin over the Proterozoic basement;
c) *en échelon* relief, composed of erosive plateaux.

Vila Velha is near the eastern border of the Paraná Basin, about 10 to 15 km west of the erosive limit of the Palaeozoic sedimentary units over the Proterozoic basement. In this sector of the Paraná Basin lies the Devonian Furnas Formation (basal), which changes gradually to the top to the Ponta Grossa Formation. Sedimentary rocks of the Itararé Group (Carboniferous - Permian) overlie one or other of these formations, showing erosive contacts. Eastward the Itararé Group forms isolated inselbergs, while westward it is more continuous. The Vila Velha Sandstone belongs to this group.

The sandstone sculptures in Vila Velha appear in one of these very eroded inselbergs isolated from the principal outcrop area of the Itararé Group. Plateaux of reddish sandstones that form the natural sculptures top the inselbergs. Conglomeratic sandstones, diamictites, rhythmites, argillites and shales of the Itararé Group underlie the typical reddish sandstones of the top.

Most geologists consider the Vila Velha Sandstone as subaqueous lobes formed by dense gravitational flows coming from the base of coastal glaciers. Evidence of traction processes indicate shallow water, with alternate gravitational flows and hydrodynamic processes. In this model the associated Lapa Sandstone should be the material of the subaqueous channel upstream from the Vila Velha Sandstone. Fossil content of layers underlying and overlying the Vila Velha Sandstone indicates a Westphalian age (Upper Carboniferous).

The Vila Velha Sandstone is about 50 m thick. It overlies conglomeratic sandstones and sandy-clayey rhythmites of the Itararé Group with a concordant contact. Incipient bedding and massive-like rocks, layers with dispersed clasts up to 15 cm long and the presence of argillaceous intraclasts suggest resedimentation by gravitational flows. Low dipping cross-stratification and ripple marks suggest hydrodynamic processes, possibly in a tidal influenced shallow marine setting.

The essential constituents of the Vila Velha Sandstones are reddish quartzous sandstones with variable sorting. Grain size varies from fine to coarse sand, with basal conglomeratic levels. Cementing by iron and manganese oxides combined with differential erosion causes the formation of common mounds with wide tops and concave eroded basis.

Iron and manganese oxides cementation is a marked feature of the Vila Velha Sandstone, being the cause of the colours and shapes that make up the local scenic heritage. The oxides occur as the cement that joins the quartz grains and also as veins a few centimetres thick that fill vertical and horizontal rock fractures. Cementing is clearly a secondary process, and sometimes forms pseudostratification crossing the sedimentary structure.

Thin section analysis of samples of the Vila Velha Sandstone shows that it contains only quartz grains, without feldspars, but with some polycrystalline grains (mainly quartzite). Lithic fragments of sandy mudstones form pseudomatrix.

The grain size of the sandstones varies from fine to coarse sand, with predomination of medium sand. Sorting is moderate to poor, and the grains are subrounded to rounded. The framework is closed and the quartz grains show concave-convex to sutured contacts. Sometimes euhedral growth develops in secondary porosity.

Cementing by iron oxides form a thin coat over the grains. When cementing is more developed it closes the minor porosity in the vicinity of the contact between grains. Sometimes it fills even the major pores, forming ferriferous crusts. The EDS analysis showed that these oxides have changing rates of Fe, Al and Si, what indicates that the cement is, in fact, of an argillaceous-ferriferous nature, and contains some kaolinite together with the dominant Fe oxides.

Besides the ferriferous cementing that can form duricrusts, the Vila Velha Sandstone also shows the precipitation of manganese oxides. EDS analysis of these oxides showed changing rates of O, Mn, K, Ba, Na and Al. Dark botryoidal fringes are enriched in K while bright fringes are enriched in Ba. X-ray diffractograms revealed cryptomelane and hollandite in these alternate fringes, respectively.

The presence of rounded and subrounded grains side by side suggests resedimentation processes with distinct sediment sources. The relative abundance of polycrystalline grains indicates that transport was not effective to liberate the crystals that form them, what could be explained either by a short transport or by a viscous medium with no traction processes acting on grains. The apparent high mineralogical maturity of the sandstones (only presence of quartz grains) could be explained by the destruction of the grains of unstable minerals by processes after sedimentation (diagenesis, lateritization, weathering).

The Vila Velha plateau is a "ruined inselberg" contrasting with other nearby sandstone inselbergs, less destroyed by erosion. The natural sculptures are often 10 to 30 m high, which is the thickness of the typical reddish iron cemented sandstones, that are harder and tend to form plateaux and cliffs. The shape of the sculptures recalls towers, hourglasses or bulwarks with many smaller adornments due to the attributes of the rock, or to brittle structures and erosive processes.

Geomorphologic correlation provides criteria for the interpretation of the age of the ruiniform relief, admitted as being post-Neogene. The erosive processes have continuously exposed and cut the sandstones since then.

The texture and porosity of the sandstone, the ferriferous cementing distribution, the subhorizontal and vertical fractures, the topographic setting of the plateau, the action of rainwater and organisms and the differential insolation are the main factors controlling the erosive processes that shape the sculptures. In addition, the intense depredation caused by visitors is deeply affecting some of the sculptures.

Eroded surfaces, polygonal cracks, saliences, hollows, anastomosing tunnels, alveolar excavations, basal concave surfaces and fractures filled with iron and manganese oxides ornament the sculptures. The sedimentary structures, subhorizontal and vertical fractures and pseudostratification combine these features to make up the bizarre shapes and colours of the rocky sculptures.

There is no evidence of significant eolian processes in the construction of the Vila Velha natural sculptures. The concave bases of many of the sandstone figures are attributed to the differential erosion of less resistant layers that have less cementing, and to the emergence of the groundwater, which contributes to the growth of lichens and mechanical erosion.

Figure 1: The Paraná Basin and location of Vila Velha in South America. Cities: BA: Buenos Aires; BR: Brasília; CR: Curitiba; RJ: Rio de Janeiro. V: Vila Velha.

Figura 1: A Bacia do Paraná e localização de Vila Velha na América do Sul. Cidades: BA: Buenos Aires; BR: Brasília; CR: Curitiba; RJ: Rio de Janeiro. V: Vila Velha.

INTRODUCTION

Vila Velha is a remarkable group of natural sculptures in Palaeozoic sandstones of the Paraná Basin, situated about 80 km WNW from Curitiba, Paraná State, Southern Brazil (Fig. 1). These sculptures result from Cenozoic weathering and erosion of Carboniferous sandstones with unequal cementing by iron and manganese oxides.

In 1953 the Paraná State Government created the Vila Velha State Park, in order to provide support for the in-

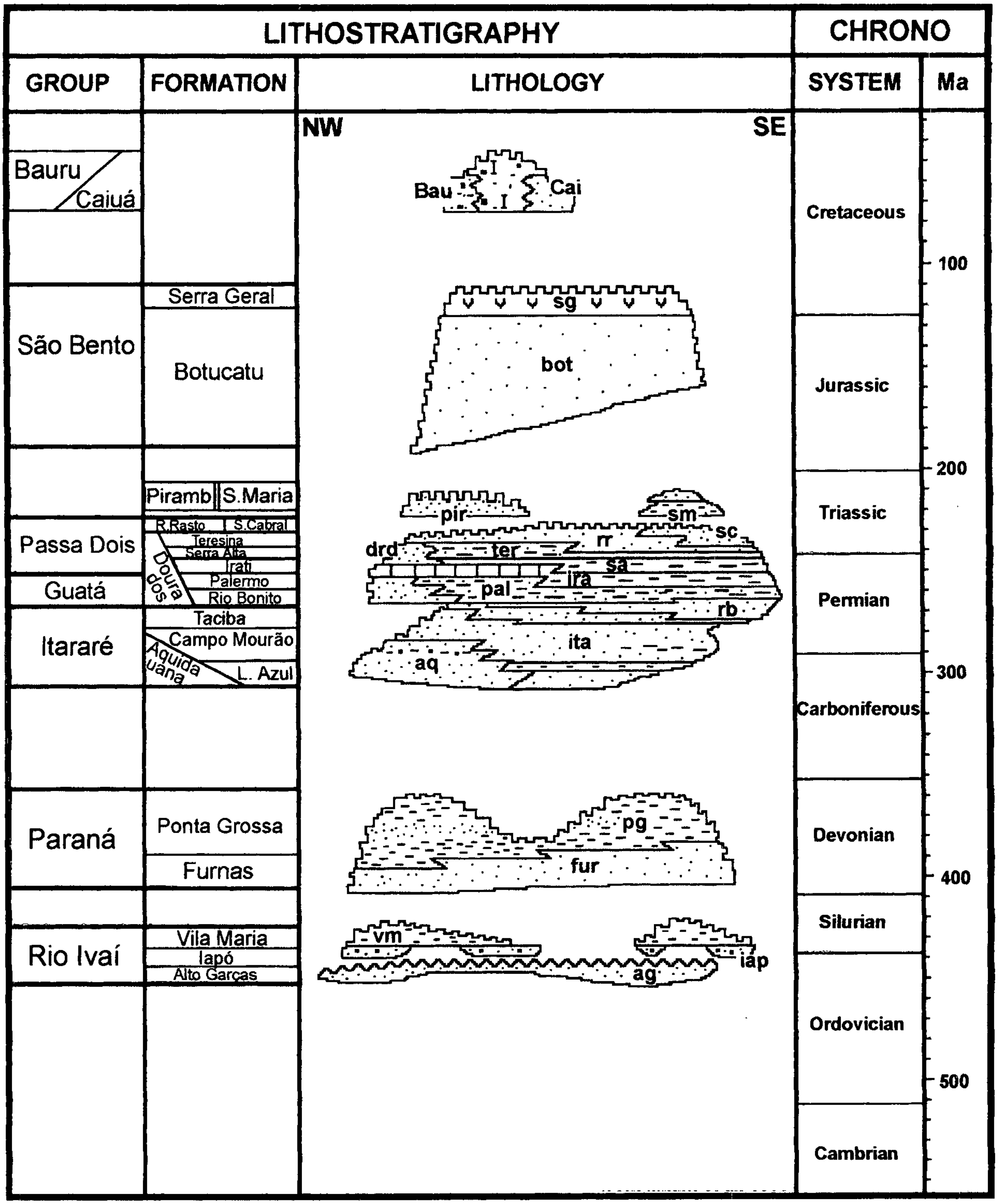

Figure 2: Stratigraphic chart for the Paraná Basin (Milani et al. 1998), showing six megasequences: 1) Ordovician - Silurian (Rio Ivaí Group); 2) Devonian (Paraná Group); 3) Carboniferous - Early Triassic (Itararé, Guatá and Passa Dois Groups); 4) Late - Triassic (Pirambóia and Santa Maria Formations); 5) Jurassic - Early Cretaceous (São Bento Group); 6) Late Cretaceous (Caiuá and Bauru Groups).

Figura 2: Estratigrafia da Bacia do Paraná (Milani et al. 1998), mostrando seis megassequências: 1) Ordoviciana - Siluriana (Grupo Rio Ivaí); 2) Devoniana (Grupo Paraná); 3) Carbonífera - Eotriássica (grupos Itararé, Guatá e Passa Dois); 4) Neotriássica (formações Pirambóia e Santa Maria); 5) Jurássica - Eocretácea (Grupo São Bento); 6) Neocretácea (grupos Caiuá e Bauru).

creasing number of visitors, which reached 200,000 a year in the 1990s.

The State Park consists of 3,122 ha, and the main sandstone outcrop is spread over an area of 10 ha, comprising about a hundred natural sculptures 10 to 30 m high. Popular imagination has given them bizarre names such as the sphinx, the bottle, the ship's prow, the camel, the mushrooms, the turtle, the wineglass (the symbol of Vila Velha), and many others.

Nevertheless, Vila Velha is much more than a place for enjoyment and leisure. It is also a notable outcrop of periglacial sandstones whose origin has been hotly debated, where the sandstone sculptures are the sum of many interacting factors, such as the changing attributes of the sedimentary rock, tectonic and non tectonic fractures, physical, chemical and biological weathering.

THE PARANÁ BASIN

The Paraná Basin is a wide South American intracratonic trough, about 1.4 million km^2 in area, extending over Brazil (1.1 million km^2), Uruguay, Argentina and Paraguay (Fig. 1).

Sedimentary and volcanic filling

The basin is filled by up to 8,000 m of sedimentary and volcanic rocks, the later to a maximum depth of 2,000 m (Milani et al., 1998). The oldest sedimentary rocks (Rio Ivaí Group) are from Late Ordovician to Early Silurian (Assine et al., 1994, Milani et al., 1994). The youngest sedimentary rocks (Caiuá and Bauru groups) are from Late Cretaceous (Fernandes and Coimbra, 1994). These younger groups filled depressions caused by the load of the basalt flows of the Serra Geral Formation, which had their climax in the Early Cretaceous.

The sedimentary filling of the Paraná Basin can be divided in six megasequences (Milani et al., 1998), as seen in fig. 2.

Brittle Structures

The Paraná Basin shows three main trends of tectonic structures (Zalán et al., 1991, fig. 3):

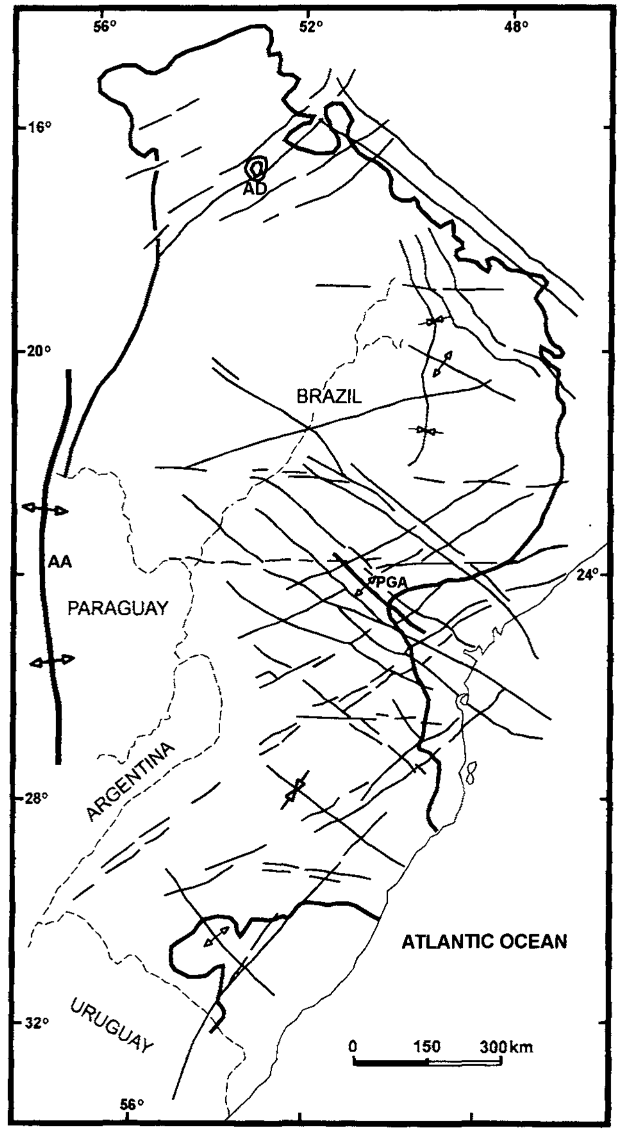

Figure 3. Structural framework of the Paraná Basin (Zalán et al., 1991). PGA: Ponta Grossa Arch; AA: Assunción Arch; AD: Araguainha "dome" (a large astrobleme structure).

Figura 3. Arcabouço estrutural da Bacia do Paraná (Zalán et al., 1991). PGA: Arco de Ponta Grossa; AA: Arco de Assunção; AD: "domo" de Araguainha (um grande astroblema).

a) NE-SW parallel to the structures of the Proterozoic basement of the basin (folded trends, shearing zones); these structures were recurrently reactivated during the basin evolution, with either horizontal or vertical movements;

b) NW-SE pre-existing, but mainly reactivated during Early Jurassic and Late Cretaceous, with dominant vertical displacements; these structures are related to the Gondwana breakup and magmatism of the Serra Geral Formation;

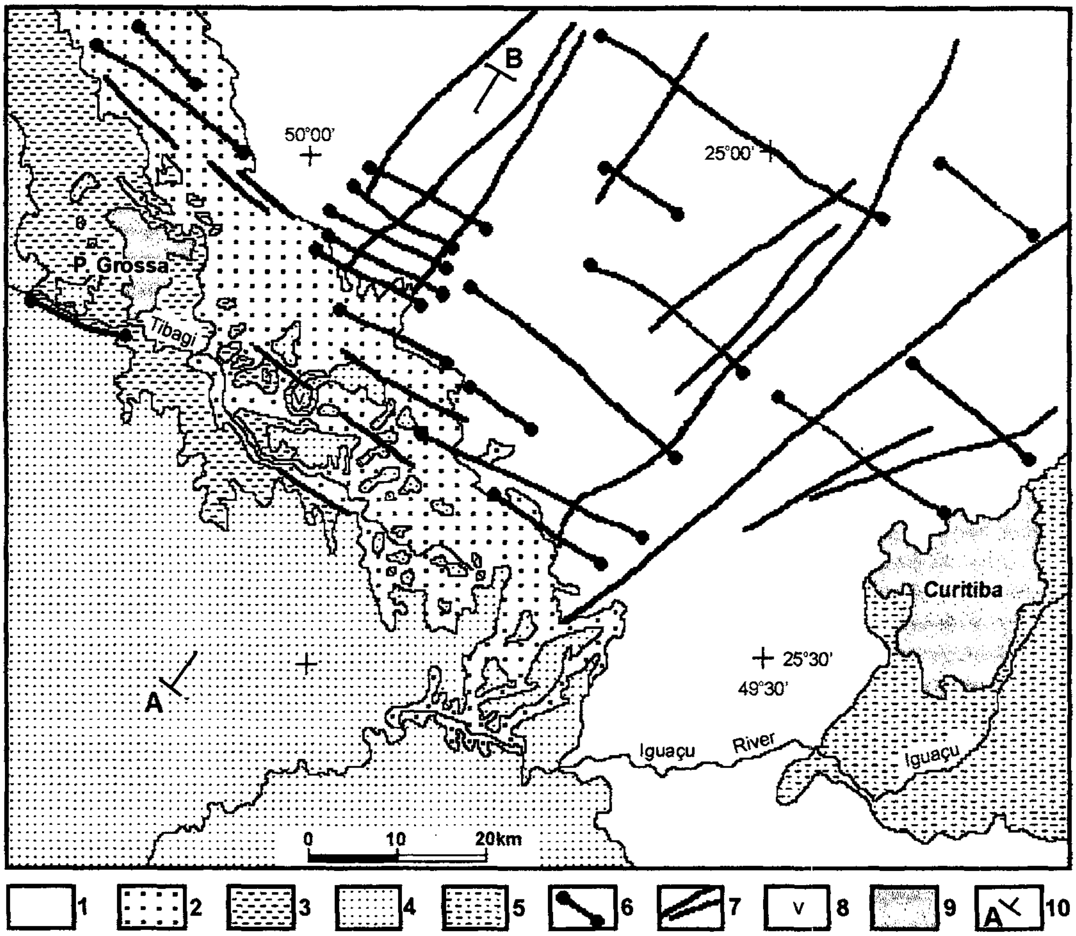

Figure 4. Geologic map of Paraná State between Curitiba and Ponta Grossa (Biondi et al., 1989). 1: Proterozoic basement; 2: Furnas Formation (D); 3: Ponta Grossa Formation (D); 4: Itararé Group (C-P); 5: Curitiba Basin (T); 6: diabase dykes (Mesozoic); 7: major faults; 8: Vila Velha; 9: urban areas; 10: cross section of Figure 5.

Figura 4. Mapa geológico do Estado do Paraná entre Curitiba e Ponta Grossa (Biondi et al., 1989). 1: embasamento proterozóico; 2: Formação Furnas (D); 3: Formação Ponta Grossa (D); 4: Grupo Itararé (C-P); Bacia de Curitiba (T); 6: diques de diabásio (Mesozóico); 7: principais falhas; 8: Vila Velha; 9: áreas urbanas; 10: seção geológica da Figura 5.

c) E-W parallel to oceanic fracture zones, presumably formed since the Triassic, linked to the opening of the South Atlantic.

These three trends of structures appear in Vila Velha, mainly as long fractures with no or negligible displacement.

The Ponta Grossa Arch

Vila Velha is placed at the southwestern flank of a long NW-SE structure of the Paraná Basin, the Ponta Grossa Arch (Figs. 3 and 5). This arch is a structural high with the axis tilting towards NW, so that the higher altitudes appear towards SE. Its main tectonic pulse took place during the Mesozoic, when deep vertical longitudinal fractures allowed the magma which formed the Serra Geral Formation to pass through.

The Ponta Grossa Arch gave rise to some of the most remarkable geological and geomorphologic features of the eastern border of the Paraná Basin:

a) NW-SE fractures, faults and mainly diabase dyke swarms, which control local relief and rivers;

b) the marked concavity in the limit of the Palaeozoic sedimentary rocks of the Paraná Basin over the Proterozoic basement; this concavity resulted from erosion of the sedimentary rocks in the highest areas of the arch;

c) *en échelon* relief, composed of erosive plateaux which result from the sum of the effects of the tectonic raising in the Ponta Grossa Arch, and differential erosion acting upon the Proterozoic basement and Paraná Basin rocks.

THE GEOLOGY OF VILA VELHA

Vila Velha is placed near the eastern border of the Paraná Basin, about 10 to 15 km west of the erosive limit of the Palaeozoic sedimentary units over the Proterozoic basement (Figs. 4 and 7).

The rocks of the Proterozoic basement (Açungui Group of the Brazilian Cycle and post-tectonic granitic stocks) appear in the Primeiro Planalto Paranaense (First Paraná Plateau), whose relief tops are levelled at 800 to 900 m above sea level. The Palaeozoic sedimentary units appear in the *Segundo Planalto Paranaense* (Second Paraná Plateau), which is levelled by a planation surface gently inclined towards the west, so that its higher altitudes appear in the east (about 1,150 m above sea level).

The limit between the First and the Second Paraná Plateau is called the Devonian Escarpment (Fig. 5), that is locally named *Serra de São Luiz do Purunã*, a mainly erosive cliff up to 200 m high.

In this sector of the Paraná Basin lies the Furnas Formation (basal), which changes gradually to the top to the Ponta Grossa Formation. Sedimentary rocks of the Itararé Group overlie one or other of these formations, showing erosive contacts. Eastward the Itararé Group forms isolated inselbergs, while westward it is more continuous.

The sandstone sculptures in Vila Velha appear in one of these very eroded inselbergs isolated from the principal outcrop area of the Itararé Group. Plateaux of reddish sandstones that form the natural sculptures top the inselbergs. Conglomeratic sandstones, diamictites, rhythmites, argillites and shales of the Itararé Group underlie the typical reddish sandstones on the top (Maack, 1946a, fig. 6).

Stratigraphy and Paleoenvironments

Maack (1946b) named the reddish sandstones that form the natural sculptures, "Vila Velha". Recent researches are not unanimous about the origin, stratigraphic setting and age of these sandstones and underlying deposits of the Itararé Group.

França et al. (1996) considered the Vila Velha Sandstone as subaqueous lobes formed by dense gravitational flows coming from the base of coastal glaciers. Evidence of

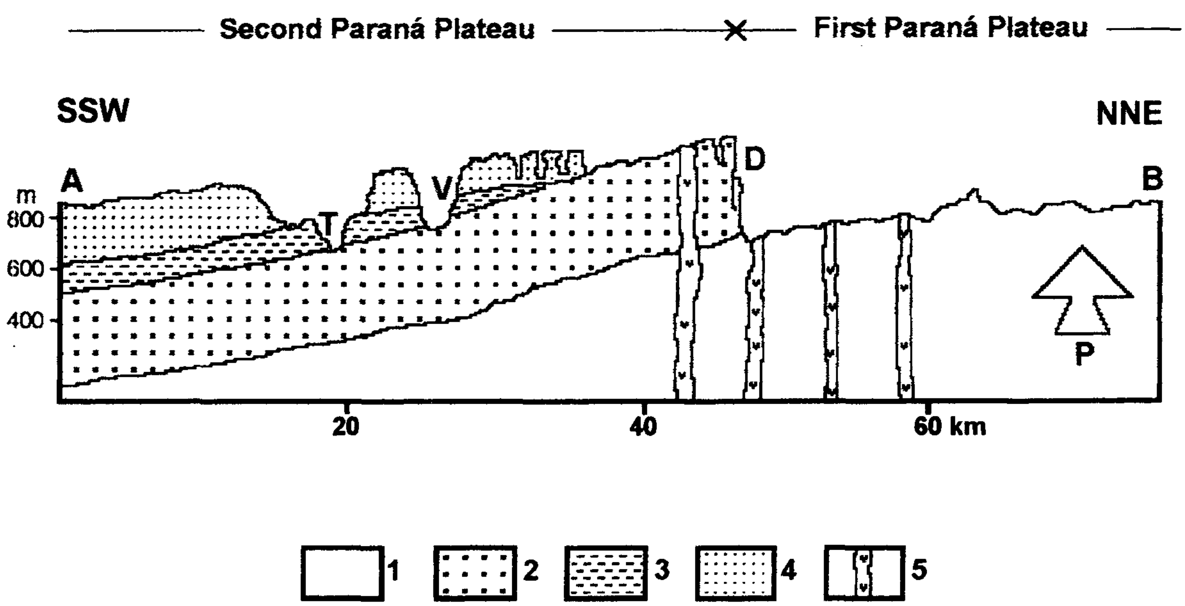

Figure 5. Schematic cross section passing through Vila Velha (AB in Figure 4). 1: Proterozoic basement; 2: Furnas Formation; 3: Ponta Grossa Formation; 4: Itararé Group; 5: diabase dykes; V: Vila Velha; T: Tibagi River; D: Devonian Escarpment; P: Ponta Grossa Arch major uplift.

Figura 5. Seção geológica esquemática passando por Vila Velha (AB na Figura 4). 1: embasamento proterozóico; 2: Formação Furnas; 3: Formação Ponta Grossa; 4: Grupo Itararé; 5: diques de diabásio; V: Vila Velha; T: Rio Tibagi; D: Escarpa Devoniana; P: arqueamento máximo do Arco de Ponta Grossa.

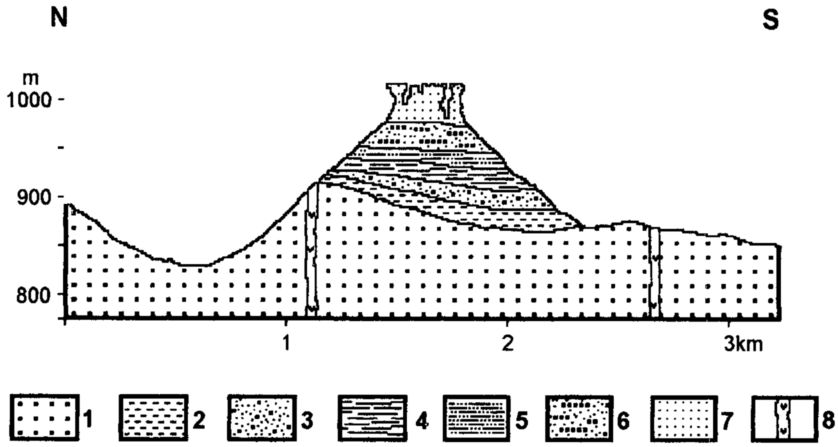

Figure 6: N-S cross section passing through Vila Velha. 1: Furnas Formation (D); 2: Ponta Grossa Formation (D); 3: basal Itararé Group sandstones (C-P); 4: shales and claystones (C-P); 5: rhythmites (C-P); 6: sandstones with conglomeratic layers (C-P); 7: Vila Velha Sandstone (C-P); 8: diabase dykes (Mesozoic) (from Maack 1946a).

Figura 6: Seção geológica N-S passando por Vila Velha. 1: Formação Furnas (D); 2: Formação Ponta Grossa (D); 3: arenitos basais do Grupo Itararé (C-P); 4: folhelhos e argilitos (C-P); 5: ritmitos (C-P); 6: arenitos com níveis conglomeráticos (C-P); 7: Arenito Vila Velha (C-P); 8: diques de diabásio (Mesozóico) (segundo Maack, 1946a).

traction processes indicate shallow water, with alternate gravitational flows and hydrodynamic processes. In this model the Lapa Sandstone is the material of the subaqueous channel upstream from the Vila Velha Sandstone. It shows a linear arrangement southward of Vila Velha (Fig. 7). Fossil content of shale layers in the Lapa Sandstone indicates a Westphalian age (Upper Carboniferous). The deposits underlying the Vila Velha and Lapa Sandstones are included in the Lagoa Azul Formation, which is the basal unit of the Itararé Group in this sector of the Paraná Basin. They also show a Westphalian age (Milani et al., 1994).

Canuto et al., (1997) also recognised a genetic relation among the Lapa Sandstone southward, and the Vila Velha Sandstone northward, this latter at least in part underlying the former. In this alternative model the Lapa Sandstone is seen as the filling (up to 80 m thick) of a subglacial tunnel-valley carved on older sedimentary rocks of the Itararé Group, and reaching the Furnas Formation (Devonian) towards the north. The Lapa Sandstone is included in the Itararé Group, but with an uncertain age. Lithosome geometry, low dipping cross-stratification and vertical and horizontal burrows suggest a tidal influenced shallow marine setting for the Vila Velha Sandstone.

Lithology

The Vila Velha Sandstone shows a few examples of clear sedimentary structures. Incipient bedding and massive-like rocks (Figs. 8 and 9), layers with dispersed clasts up to 15 cm long (Maack, 1946a) and the common presence of argillaceous intraclasts (Fig. 9) suggest resedimentation by gravitational flows, as presumed by França et al. (1996). The occasional presence of low dipping cross-stratification and ripple marks (Fig. 10) suggest hydrodynamic processes as presumed by França et al. (1996), possibly in a tidal influenced shallow marine setting, as supposed by Canuto et al., (1997).

The essential constituents of the Vila Velha Sandstones are reddish quartzous sandstones with variable sorting. Grain size varies from fine to coarse sand, with basal conglomeratic levels. According to Maack (1946a) sandstone minerals are quartz, feldspars (partially kaolinised), muscovite, chlorite and garnet. The author also described the role of a thin film of iron and manganese oxides in the shape of many of the Vila Velha natural sculptures. This cementing process combined with differential erosion causes the formation of common mounds with wide tops and concave eroded basis (Figs. 11 and 12).

Iron and manganese oxides cementation is a marked feature of the Vila Velha Sandstone, being the cause of the colours and shapes that make up the local scenic heritage. The oxides occur as the cement that joins the quartz grains and also as veins a few centimetres thick that fill vertical and horizontal rock fractures (Figs. 8 and 9). Cementing is

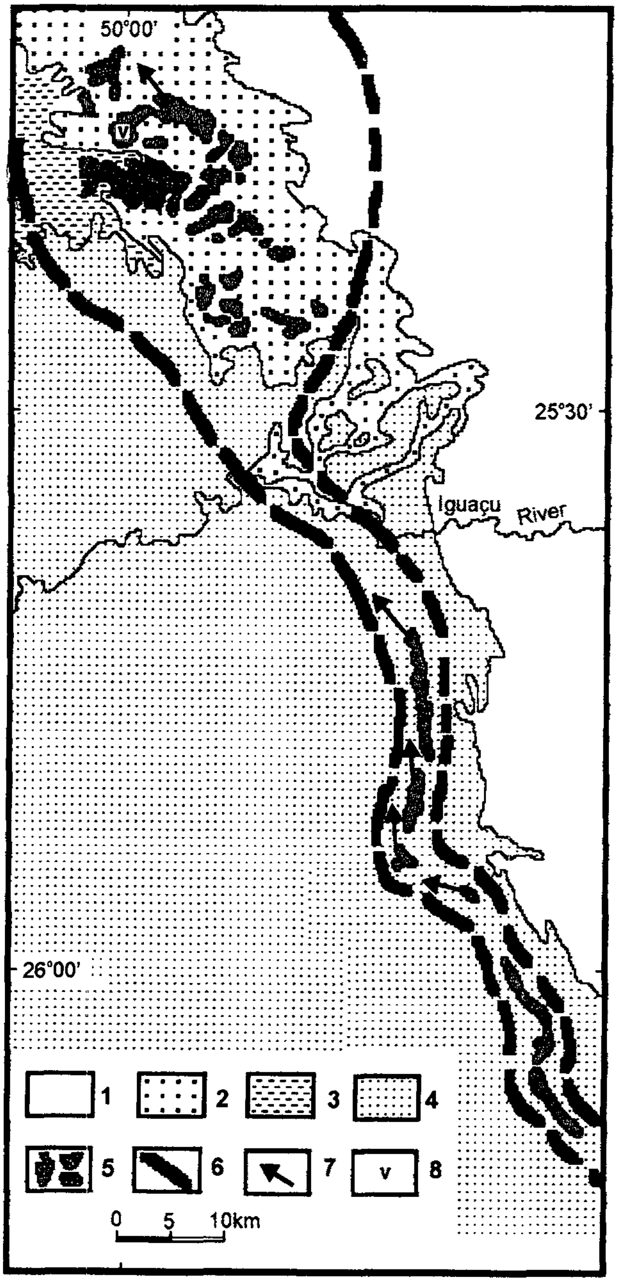

Figure 7. Subaquous channel-filling (Lapa Sandstone) and shallow subaquous lobes (Vila Velha Sandstone) as interpreted by França et al. (1996). 1: Proterozoic basement; 2: Furnas Formation (D); 3: Ponta Grossa Formation (D); 4: Itararé Group (C-P); 5: Lapa and Vila Velha Sandstones (C-P); 6: interpreted limits of subaquous channel and lobe; 7: paleocurrents; 8: Vila Velha.

Figura 7. Preenchimento de canais subaquosos (Arenito Lapa) e lobos subaquáticos rasos (Arenito Vila Velha) tal como interpretados por França et al. (1996). 1: embasamento proterozóico; 2: Formação Furnas (D); 3: Formação Ponta Grossa (D); 4: Grupo Itararé (C-P); 5: arenitos Lapa e Vila Velha (C-P); 6: limites interpretados para o canal e lobo subaquosos; 7: paleocorrentes; 8: Vila Velha.

clearly a secondary process, and sometimes forms pseudostratification crossing the sedimentary structure.

Cementing took place a long time after sedimentation. It is controlled either by the stratification of the sandstones (Fig. 12), or the tectonic (Fig. 9) and non tectonic (Fig. 8) rock fractures, or the interstratal sedimentary structures (Fig. 10). A frequent ferriferous encrustation on the rockwall surfaces shows a recent reworking of old cement by the pluvial water.

The Vila Velha Sandstone is about 50 m thick (44 m according to Maack, 1946a). It overlies conglomeratic sandstones and sandy-clayey rhythmites of the Itararé Group with a concordant contact.

Petrography

Thin section analysis of samples of the Vila Velha Sandstone in its typical area shows that it contains only quartz grains, without feldspars, but with some polycrystalline grains (mainly quartzite). Lithic fragments of sandy mudstones are also common and when crushed by compaction they form pseudomatrix. The minerals described by Maack (1946a) as the feldspars, muscovite, chlorite and garnet were not seen, so that they should occur at levels below the more typical sandstones of Vila Velha.

The grain size of the sandstones varies from fine to coarse sand, with a predomination of medium sand. Sorting is moderate to poor, and the grains are subrounded to rounded. The framework is closed and the quartz grains show concave-convex to sutured contacts. Sometimes euhedral growth develops in secondary porosity.

Cementing by iron oxides form a thin coat over the grains. When cementing is more developed it closes the minor porosity in the vicinity of the contact between grains. Sometimes it fills even the major pores, forming ferriferous crusts. The EDS analysis showed that these oxides have changing rates of Fe (56-58%), Al (4-8%) and Si (3-9%), Fe always being the main element. This composition indicates that the cement is, in fact, of an argillaceous-ferriferous nature, and contains some kaolinite together with the dominant Fe oxides. Nevertheless, the X-ray diffractograms do not show the presence of kaolinite, probably because of the low amount and poor crystallinity of this clay mineral in the sedimentary rock. Anyway the presence of kaolinite suggests the presence of feldspars (and other unstable minerals) in the original sediment, destroyed by subsequent processes, mainly during telogenesis.

Besides the ferriferous cementing that can form duricrusts, the Vila Velha Sandstone also shows the precipitation of manganese oxides. This can form continuous metallic veins only a few centimetres thick (Fig. 9) that fill open fractures of the NE-SW and E-W trends. The sandstones in the walls of these veins show unequal cementing as botryoidal fringes that are about 1 cm thick. The thin sections and SEM images of the massive metallic oxides show alternate dark and bright fringes 10 to 100 micra thick. The EDS analysis of these oxides showed changing rates of O (63-66%), Mn (30-33%), K (1-4%), Ba (1-3%) and some Na and Al (less than 1%). The dark fringes are enriched in K while the bright fringes are enriched in Ba. The X-ray diffractograms revealed that the mineral in the dark fringes is cryptomelane, while in the bright fringes the substitution of the K by the Ba gives rise to the mineral hollandite.

The petrographic features of the Vila Velha Sandstone indicate the following sequence of diagenetic processes:

a mechanical compaction (concave-convex contacts between the quartz grains);
b) chemical compaction in the mesogenesis (sutured contacts);
c) dissolution and formation of secondary porosity followed by the neoformation of the euhedral quartz grains (there are no sutured contacts between the neoformed portions of the crystals);
d) cementing by the iron and manganese oxides in telogenesis which is controlled by two factors, the first being the presence of pseudomatrix (crushed muddy lithic fragments), which makes percolation difficult and inhibits cementing, and the second being the position of the fractures in the rock massif.

The presence of rounded and subrounded grains side by side suggests resedimentation processes with distinct sediment sources. The relative abundance of polycrystalline grains indicates that transport was not effective to liberate the crystals that form them, which could be explained either by a short transport or by a viscous medium with no traction processes acting on grains. The apparent high mineralogical maturity of the sandstones (only presence of quartz grains) could be explained by the destruction of the grains of unstable minerals by processes after sedimentation (diagenesis, lateritization, weathering).

Age of the cementing processes

Several authors have described the presence of ferricretes associated with Cenozoic planation surfaces in Southern Brazil. These duricrusts are attributed to dry climatic phases with intense lateritization. Geomorphologic correlation provides the arguments for the interpretation of the age of the planation surfaces and associated ferricretes.

The most ancient and remarkable of these lateritization phases (Cretaceous-Paleogene limit) is recognised in the Serra de Itaqueri and near the city of Franca (v.g. Ranzani et al., 1972, Soares et al., 1973, Melo and Ponçano 1983), in the highest planation surface of the Planalto Ocidental (Western Plateau) in the State of São Paulo. This planation surface corresponds to the Terceiro Planalto Paranaense (Third Paraná Plateau). The second most important of these lateritization phases (Pliocene-Pleistocene limit) is recognised in several places in the Depressão Periférica Paulista (São Paulo Peripheral Depression) (v.g. Queiroz Neto, 1974, Penteado, 1976, Melo et al., 1998).

Vila Velha is situated on the Second Paraná Plateau, which is geomorphologically correlated to the Depressão Periférica Paulista. The cementing processes at Vila Velha could therefore be correlated to the second important lateritization phase (Pliocene-Pleistocene limit). Less permeable sedimentary rocks (rhythmites, diamictites) that underlie the Vila Velha Sandstone constituted a natural barrier for groundwater and the cementing processes.

Brittle Structures

Some fracture trends are very important in the Vila Velha State Park:

a) NE-SW, which is the most pervasive trend; this corresponds to the influence of the reactivation of the structures of the Proterozoic basement of the Paraná Basin, as stated by Zalán et al. (1991);
b) NW-SE, less common, corresponding to the structures reactivated in the Mesozoic, during the maximum activity in the Ponta Grossa Arch;
c) E-W, which shows the most extensive fractures; this corresponds to the structures formed in the Mesozoic during South Atlantic spreading, as stated by Zalán et al. (1991);
d) subvertical fractures of non-tectonic origin, exhibiting a concentric setting parallel to the borders of the rocky plateau;
e) subhorizontal structures partially controlled by bedding and formed by the relaxing of stresses due to load removal (Figs. 8, 11, 12 and 13).

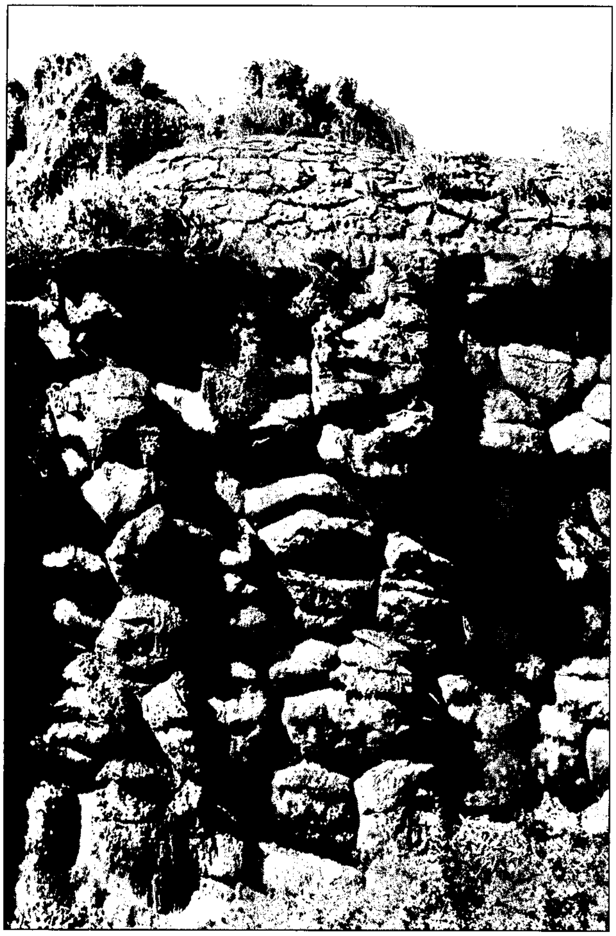

Figure 8. Massif aspect of sandstones showing polygonal thermal cracks in the upper surface (top) and in the rockwalls facing north, horizontal non-tectonic fractures with iron/manganese oxide filling and sharp erosion forms (lapiés-like) in the top.

Figura 8. Arenitos com aspecto maciço mostrando fraturamento poligonal na superfície de topo e paredes voltadas para norte, fraturas horizontais atectônicas com preenchimento de óxidos metálicos, e formas erosivas pontiagudas no topo, semelhantes a lapiés.

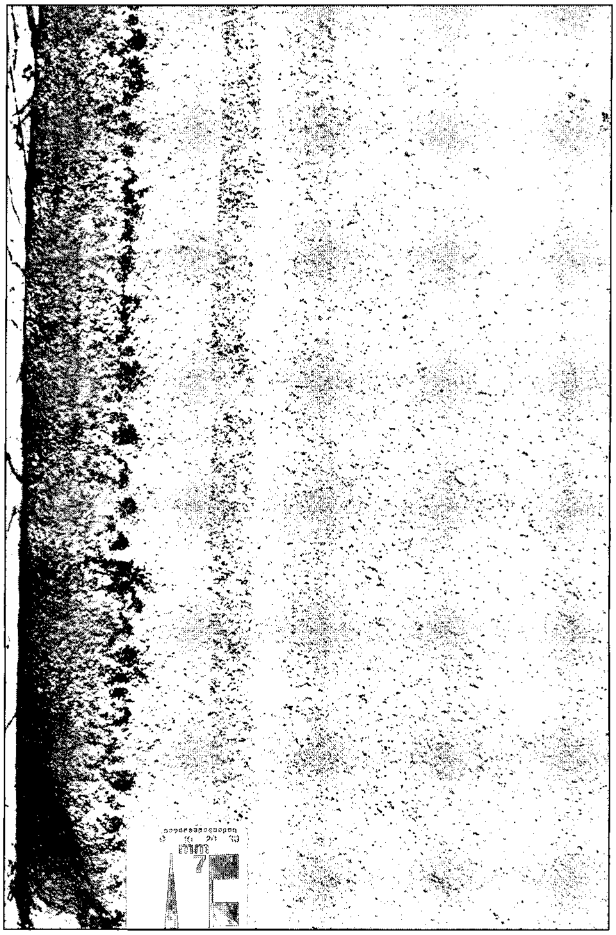

Figure 9. Vertical tectonic fractures with iron/manganese oxides filling (left) and parallel pseudostratification due to differential cementing; note clear argillaceous intraclasts less than 1 cm long.

Figura 9. Fraturas verticais tectônicas com preenchimento metálico (esquerda) e pseudoestratificação paralela dada por cimentação desigual; notar intraclastos argilosos claros menores que 1 cm.

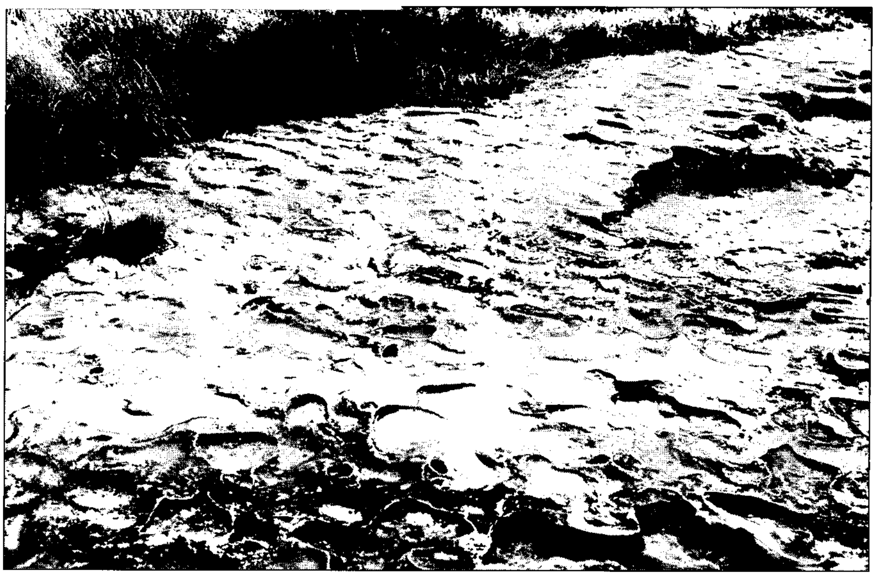

Figure 10. Ripple marks with ferricrust on the plateau of Vila Velha.

Figura 10. Marcas onduladas com crosta ferruginosa no topo do platô de Vila Velha.

LOCAL AND REGIONAL RELIEF FEATURES

The Vila Velha plateau is a "ruined inselberg" (Ab'Sáber 1977), which is sustained by very eroded sandstones. This contrasts with other nearby sandstone inselbergs, less destroyed by erosion. This difference indicates that the Vila Velha plateau is in a more advanced stage of erosion than the neighbouring inselbergs, giving rise to an exception landscape, marked by "the extravagance of its topographic forms, called ruiniform relief" (Ab'Sáber op. cit., p.3).

The top of the Vila Velha inselberg is 1,012 m above sea level. It is in the same level of the planation surface of the Second Paraná Plateau. Major rivers of this region (Tibagi, Guabiroba) have their riverbeds at about 785 m above sea level.

The Vila Velha natural sculptures are often 10 to 30 m high, which is the thickness of the typical reddish iron cemented sandstones, that are harder and tend to form plateaux and cliffs. The height of the sculptures may be less (only a few meters) when erosion processes have already isolated them from the rocky walls and lowered their original height.

The shape of the sculptures recals towers, hourglasses or bulwarks with many smaller adornments due to the attributes of the rock, or to brittle structures and erosive processes (Figs. 8, 11 and 12).

Geomorphologic correlation provides criteria for the interpretation of the age of the ruiniform relief. The Second Paraná Plateau is a physical extension of the Depressão Periférica, which is seen in the neighbouring State of São Paulo, to the north of the State of Paraná. The same planation surface levels these two geomorphologic provinces. In the State of São Paulo several authors consider that this planation surface dates back to the Neogene (Martonne, 1940, Soares and Landim, 1976, Penteado 1976, Melo et al., 1998), though the erosion of the ruiniform sculptures is post-Neogene. The erosive processes have continuously exposed and cut the sandstones since then.

Erosive Processes and Features in the Sandstones

The main erosive agents in Vila Velha are rainwaters, organisms (plants, animals and lichens) and the insolation.

Rainwaters, as they flow overland or infiltrate the sedimentary rock, cause mechanical erosion, dissolution and reprecipitation. The mechanical erosion with some associated dissolution of the cement can form lapiés-like features in the top of the plateau (Figs. 11 and 12). In the cliffs they can form vertical hollows that evolve to isolated tower-like features, with enlarged tops (Figs. 11 and 12).

As the rainwaters drain the rockwalls they also promote the excavation of superficial holes (Fig. 13). This process has already been called "alveolar erosion" (Fortes 1996). It results from the combined action of mechanical erosion and dissolution of some components. Otherwise, mainly in the northern rockwalls that are more exposed to the sunshine, surface waters reprecipitate a thin coat of iron oxide, which protects the sandstones for a while. When enriched with organic acids from plant decomposition the rain waters become more corrosive and can dig long, narrow furrows on the plateau surface.

The rainwaters that penetrate the rock massif through the fractures and pores can also give rise to strange excavation features, already named "anastomosing tunnels" (Fortes 1996). Usually such features show apertures of a few centimetres closely controlled by the horizontal fractures. Corrosion cones present in the anastomosing tunnels resemble dissolution and precipitation features, but in this case they must be regarded as a result of mainly mechanical erosion (Fig. 13).

Frequently the percolation and ground water emerge in the sandstones near the base of the natural sculptures, which increases mechanical erosion and dissolution, and aids the growth of lichens. This helps the formation of concave surfaces in the base of some sculptures (Fig. 12). Some authors have discussed a possible eolian origin for such surfaces (Soares, 1975; Ab'Sáber, 1977), but this hypothesis is not supported by any other known evidence of significant wind action in the area.

The organisms are important coparticipants in the erosive processes that form the natural sculptures. Tree roots give the clearest evidence of this coparticipation. They penetrate far across the fractures, forcing them to increase their apertures. Minor rupestre plants (ferns, orchids, mosses) grow in the irregularities of the rockwalls (fractures, holes), and help to enlarge them.

The lichens are abundant in the damp walls of the sculptures (Fig. 14), which are more common in the places protected from direct sunshine, such as the southern face of the Vila Velha plateau. The lichens contribute to create favourable local conditions for the erosive

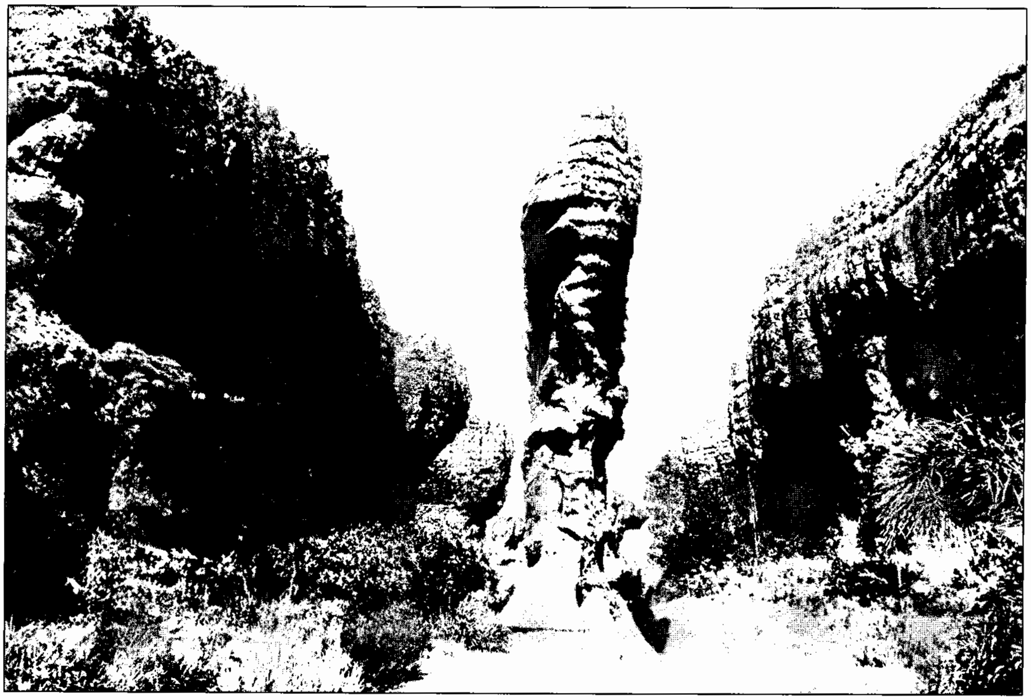

Figure 11. The "ship's prow", a tower-like sandstone form (concave base and larger top), showing horizontal non-tectonic fractures, and sharp erosion forms (lapiés-like) on the top of some sculptures. See text for further explanation.

Figura 11. A "proa do navio", escultura com cabeço mostrando fraturas horizontais atectônicas e formas erosivas pontiagudas no topo.

Figure 12. The "wineglass", a sculpture made up of sandstones with incipient stratification showing differential erosion of layers due to differential cementing by iron oxides, horizontal non-tectonic fractures, sharp erosion forms (lapiés-like) in the top and concave base. See text for further explanation.

Figura 12. A "taça", elaborada em arenitos com estratificação incipiente mostrando erosão diferencial das camadas devido a cimentação variável por óxidos metálicos, fraturas horizontais atectônicas, formas erosivas pontiagudas no topo (semelhantes a lapiés) e base côncava.

Figure 13. Anastomosing tunnels with little erosion cones along horizontal non-tectonic fractures in massif sandstones; note also small holes of alveolar erosion due to pluvial waters washing rockwalls.

Figura 13. Túneis anastomosados com pequenos cones de erosão em fraturas horizontais atectônicas em arenitos maciços; notar pequenas perfurações de erosão alveolar devidas ao escorrimento das águas pluviais nas paredes rochosas.

Figure 14: Polygonal thermal cracks in the upper surface of the sandstone plateau with profusion of lichens aiding disintegration and erosion.

Figura 14: Gretas poligonais na superfície de topo do platô arenítico com profusão de líquens contribuindo para a desintegração e erosão da rocha.

processes, as in the formation of concave surfaces in the base of some sculptures (Fig. 12), and in the deepening of fractures, alveoles and tunnels.

Swallows and "blackbirds" (*Gnorimopsar chopi*) make their nests in the inaccessible rockwalls, and they also contribute to the erosion and ornamentation of the sandstones. Termites dig deep narrow burrows which are often used by roots after the colony moves out, so that animals and plants work together for the disintegration of the rock.

The insolation heats the surface of the sandstones and creates fractures (cracks) by successive expansion and contraction. This process is known in other Palaeozoic sediments in tropical Brazil (*v.g.* Fortes 1996). It forms many features of the top surface of the plateau (Fig. 14) and also of the north-facing cliff surfaces (Fig. 8). When the sandstones are uniform (massif-like) the cracks tend to form regular hexagons, which are the shapes that require less energy for rupture. The action of rainwater and organisms then opens and deepens the superficial fractures initiated by insolation.

Recently, besides the natural factors that promote the erosion of the sandstones, large numbers of tourists have resulted in deep erosion of the paths, while vandals' inscriptions are destroying the rockwalls.

FACTORS CONTROLLING THE RUINIFORM RELIEF

The following factors control, in an active or passive manner, the evolution, the ornamentation and the final shape of the natural sculptures in Vila Velha:

a) the texture (including the presence of pseudomatrix) and porosity of the different layers of the sandstones;
b) the effectiveness of the cementing processes, mainly by iron and manganese oxides, but also by kaolinite;
c) the presence of vertical and/or subhorizontal fractures;
d) the present topographic setting of the sandstone plateaux, at the top of an inselberg which is subject to intense overland flow of rainwater and strong insolation;
e) the action of the rainwater, either by overland flow or infiltration inside the fractures and pores of the sedimentary rock;
f) the action of organisms (trees and bushes, ferns, orchids, moss, lichens, digging animals);
g) the insolation of the top surface and the northern face of the plateau;
h) the erosion and depredation (inscriptions) caused by the visitors.

There is no evidence of significant eolian processes in the construction of the Vila Velha natural sculptures. The concave bases of many of the sandstone figures are attributed to the differential erosion of less resistant layers that have less cementing, and to the emergence of groundwater, which contributes to the growth of lichens and the mechanical erosion.

CONCLUSIONS

The sandstone natural sculptures in Vila Velha are an impressive example of ruiniform relief, due to the combination of erosive processes with the existing attributes of the sedimentary rock. The area lies within a State Park, which receives about 200,000 visitors a year, what causes some risks to the preservation of the rich natural heritage.

The Vila Velha sandstone appears in Paraná State, in Southern Brazil. It is part of the Itararé Group (Late Carboniferous to Early Permian) of the Paraná Basin. This sandstone occurs only in the eastern flank of this large intracratonic basin. Its lithology and geometry suggests deposition by subaquous gravitational flows in a tidal affected shallow marine environment, under close influence of coastal glaciers.

The sandstones that form the Vila Velha sculptures are markedly reddish due to the presence of ferriferous cementing. Grain size ranges from fine to coarse sand and stratification is incipient, which often gives a massive aspect, with dispersed argillaceous lithic fragments.

The natural sculptures are 10 to 30 m high. Eroded surfaces, polygonal cracks, saliences, hollows, anastomosing tunnels, alveolar excavations, basal concave surfaces and fractures filled with iron and manganese oxides ornament the sculptures. The sedimentary structures, subhorizontal and vertical fractures and pseudostratification combine these features to make up the bizarre shapes and colours of the rocky sculptures.

The texture and porosity of the sandstone, the ferriferous cementing distribution, the subhorizontal and vertical fractures, the topographic setting of the plateau, the action of rainwater and organisms and the differential insolation are the main factors controlling the erosive processes that shape the sculptures. In addition, the intense depredation caused by visitors is deeply affecting some of the sculptures.

The age of the eroded figures is interpreted by geomorphologic correlation. Vila Velha is placed in the Second Paraná Plateau, which is a southward extension of the Depressão Periférica Paulista. These two geomorphologic provinces are levelled by a Neogene planation surface. In addition, an important phase of lateritization with associated ferriferous cementing is recognised in Southeastern and Southern Brazil, in the Pliocene-Pleistocene limit. The erosive processes that carved the sculptures have been acting since then.

Vila Velha is a natural heritage of inestimable value. The impressive sculptures have a strong scenic impact, and attract a lot of visitors from Brazil and the entire world. The large sandstone outcrop is a unique exposure of the petrographic attributes and erosive features of the Vila Velha Sandstone, which helps the study and understanding of this widely discussed stratigraphic unit. The State Park is very suitable for environmental teaching, having not only the sandstone outcrops and ruiniform relief, but also preserved natural ecosystems, with endemic species, some of them under the risk of extinction. However, the integrity of this heritage is threatened by mass tourism, so that the State Park is not fulfilling its principle role, which is to be a conservation area.

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