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HISTORICAL AND GEOMORPHOLOGICAL CHARACTERIZATION OF A BRAZILIAN KARST REGION

ZGODOVINSKE IN GEOMORFOLOŠKE ZNAČILNOSTI KRAŠKEGA PODROČJA CORDISBURGO (MINAS GERAIS, BRAZILIJA)

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Abstract UCD 551.44(81)

Luiz Eduardo Panisset Travassos & Heinz Charles Kohler: Historical and geomorphological characterization of a Vrazilian karst region

This work aims at presenting the geographical characterization of the Cordisburgo karst region, in the State of Minas Gerais, Brazil, by applying the consolidated concepts of the classical karst adapted to the reality of the intertropical karst. The characterization of the karst in the region, led to an exploratory mapping of the main karst features using the methodology proposed by the Commission of Karst Phenomena of the French National Geography Committee, adapted by Kohler. The choice of this methodology was made on grounds that the existence of many Dinaric and Intertropical Karst maps facilitates comparative analysis. As a result of this study, a map summarized the distribution of the karst features for the first time in this region, providing relevant information for the geoenvironmental compartmentation of the Cordisburgo area and important subsides for the sustainable management of that region. Due to its geological, geomorphological, hydrological and biogeographical characteristics, karst in this region is an expressive example of the Brazilian intertropical karst whose superficial and subterraneous evolution must be understood as a complex phenomenon. There is little research on the Lagoa do Jacare Formation. Thus, it is premature to state that the karst in Cordisburgo presents a low karstification rate in its entire carbonatic pack. Studies on the magnitude and the direction of underground water are still insufficient, however.

Keywords: geographical characterization, karst, map of karst phenomena, Cordisburgo region, Brazil.

Izvleček UDK 551.44(81)

Luiz Eduardo Panisset Travassos & Heinz Charles Kohler: Zgodovinske in geomorfološke značilnosti kraškega področja Cordisburgo (Minas Gerais, Brazilija)

Namen dela je predstaviti geografske značilnosti kraškega področja Cordisburga na podoben način, kot je predstavljen klasični kras, a prirejen za tropski kras. Za ugotavljanje značilnosti je bila najprej napravljena osnovna karta, skladno z metodologijo, ki jo priporoča Komisija za kraške pojave pri francoskem Nacionalnem kraškem komiteju, prirejeno po Kohlerju. Ta metoda je bila izbrana na podlagi dejstva, da so take karte na razpolago tako za Dinarski kot za tropski kras, kar omogoča primerjavo. Kot izsledek preučevanja je prvič na karti prikazana razporeditev kraških pojavov obravnavanega področja, kar so pomembni podatki za oddelek za okolje regije Cordisburga in pomembna podlaga za trajnostno upravljanje tega področja. Glede na geološke, geomorfološke, hidrološke in biogeografske značilnosti je kras tega področja izrazit primer brazilskega tropskega krasa, kjer morata biti razvoj površja in podzemlja razumljena kot med seboj prepleten pojav. Ker pa je malo raziskav o formaciji Lagoa do Jacare, je prezgodaj domnevati, da predstavlja kras Cordisburga kot celota področje s šibkim zakrasevanjem v obsegu celotne karbonatne skladovnice. Tudi preučevanje obsega in smeri odtekanja podzemeljskih voda je še nezadostno.

Ključne besede: geografske značilnosti, kras, zemljevid kraških pojavov, področje Cordisburgo, Brazilija.

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INTRODUCTION

According to Ford and Williams (2007) karst areas comprises 10 to 15% of the Earth's surface, mainly developed in carbonate rocks. In tropical regions, remarkable examples of karst features are developed in Southern China, Southeast Asia and Northern Australia as well as in the Middle East, Central America, the Caribbean and South America, comprising carbonate rocks of different ages ranging from the Paleozoic to the Holocene period (Day 2002; Ford & Williams 2007).

The karst phenomena that define the landscape display similar features throughout the world: these areas have active groundwater hydrology on soluble rocks. Secondary porosity is also well developed (Jennings 1985; Ford & Williams 2007). Moreover, the amount of $CaCO_3$ in a rock, its structure, fracture plans, water quantity and climate are to be considered key variables that contribute to the corrosion of the relief (Kohler 1989). The existing chemical and hydrological processes must be understood from the perspective of the General Theory of Systems.

This work presents the geographical characterization of the Cordisburgo karst region, in the State of Minas Gerais, Brazil, by applying the consolidated concepts of the classical karst adapted to the reality of the intertropical one. The characterization of the geomorphology of the Onça Creek basin, in the Velhas River basin led to an exploratory mapping of the main karst features, which was made possible by confronting data collected by LANDSAT 7 imaging, georeferrencied Google Earth images, topographic maps (1:100.000), aerial photography (1:60.000) and field work.

As a result of this study, and for the first time in this region, a map summarized the distribution of the karst features, providing relevant information for the geoenvironmental compartmentation of the Cordisburgo area and important subsides for the sustainable management of that region.

KARST STUDIES IN BRAZIL

Since the first studies of the Danish naturalist Peter W. Lund in 1833, the study of karst areas in Brazil has developed slowly in the last 176 years. So, it is relatively new in comparison to the age of karst studies around the world. Most scientific works on Brazilian karst regions was produced from the late 50's till the 90's. Kohler (1989) published a study that is considered the milestone of modern Brazilian Karstology: his work on the geomorphology of the Lagoa Santa Karst, in Minas Gerais, was the first doctoral dissertation on the subject (Travassos & Varela 2008).

According to Hardt (2004), after this there were other undergraduate and graduate researches that became public due the participation of speleological groups in the academic life of some universities, such as the University of Sao Paulo (USP) and the Federal University of Minas Gerais (UFMG).

Nowadays, it is possible to state that there are enough evidences that Brazilian karst regions were primitively *studied* and used by pre-historic man. Such evidences are made clear due to rock paintings and other archaeological remains such as ceramics, hunting and fishing tools found in rock shelters and caves.

Brazilian karst areas were used since the beginning of the Colonial Period and that continued until the end of the 17th century, especially with the exploitation of saltpetre. Although this material was also used to conserve meat, it was more used in the production of gunpowder.

It was in this same period that Brazilian caves started being used religiously: at the end of the 17th century (1691), a pilgrim called Francisco de Mendonça Mar settled down in a cave on the banks of the Sao Francisco River, where the Sanctuary of Bom Jesus da Lapa was later erected. This is considered to be the birthplace of the religious use of caves in Brazil.

A century later, there were reports of supposed appearances of images of Our Lady in other regions. This took place either inside or near the caves, as it was said to have happened at the Antonio Pereira Cave and the caves of Vazante, Minas Gerais State, in the 18th and 19th century.

However, it is correct to say that the use of caves in the Brazilian colonial period was not restricted to the exploitation of saltpetre, to religious use and their use as sources of water. The colonial period started when Brazil was discovered and continued up to when D. João VI and the Portuguese royal family left Portugal and arrived in this country.

In 1810, the ports were opened and so was the country to foreign naturalists. This was the beginning of a phase in which the use of caves became strategically valued and involved scientific discoveries. Noce and Renger (2005) say this event influenced research in the Colony deeply. The *Capitania de Minas Gerais* was one of the regions that got the most scientific benefits from foreign travellers, as it was the case with Peter Wilhelm Lund, who was one of the visitors.

When Ferraz (2000) explains the Portuguese domain in Brazilian lands, the author stresses that the importance of describing the materials that could be exploited and give profit to the Metropolis stood out in the orientations of the Portuguese rulers to their colonial representatives. This attitude was intensified with the Reform of the University of Coimbra, in Portugal, when the study of natural sciences was formally introduced.

Until 1822, only the Portuguese and the people who were born in the colony were allowed to exploit these materials and Ricardo Franco Serra (1786), Alexandre Rodrigues Ferreira (1790), Martin Francisco de Andrada (1803) and José Vieira Couto (1803) deserve their fame: they looked for more than the simple submission to the unknown world of caves for the first time then. Among their deeds, those precursors of cave studies worked on the description of some caves, such as Gruta do Inferno (Hell's Cave) in Mato Grosso do Sul (1786). Such a fact can be seen as the reflection of the Portuguese interest in exploring and holding the boundaries of the colony (Auler 2004).

One of the most important Brazilian naturalists in the eighteenth century was Alexandre Rodrigues Ferreira, who drew the first known map of a cave in Brazil (Gruta da Onça, MS). In 1791, his aides performed a special task: they represented the Gruta do Inferno (MS) by drawing it for the first time. From 1803 to 1805, Martin Francisco de Andrada first described some of the caves in the States of Sao Paulo and Parana, probably focusing on the Gruta dos Jesuitas (PR) and the Gruta de Santo Antonio (nowadays called Casa de Pedra) in Iporanga, Sao Paulo. In 1803, José Vieira Couto made a research on the Colony's saltpetre mines that turned out to be an interesting study in which several caves were mentioned (Auler 2004; Auler & Zogbi 2005).

The 19th century was extremely favourable to the development of the sciences in general and, after some time, 'catastrophic theories' or a simple *divine* explanation for natural phenomena lost room among naturalists. The list of naturalists who visited our territory then display some names such as Spix, Martius, Pohl, Rugendas, Riedel, Lagsdorff, Walsh, Burton, Fountain, Saint Hilarie and Castelnau, among others (Auler 2004). Even Emperor Dom Pedro II himself is cited by some authors for his enthusiasm for science.

Auler (2004) mentions that importance must be granted to Padre Casal for his *Chorographia Brasilica,* an 1817-publication which referred to caves in several parts of the country. This kind of work is evidence that many caves were already known then and we do believe that such studies should be regarded as the precursors of speleology, not of Brazilian karstology.

Peter Wilhelm Lund (1801-1880), a Danish naturalist, and the German Richard Krone (1861-1917) were two of the naturalists who travelled around Brazil and dedicated themselves to a more systematic study of the endokarst. For Dequech (2000), choosing either Lund or Krone to be considered the founder of the National Speleology is a difficult task for it would not be correct to compare only the scientific value of each one's work. This criterion would consider Lund the precursor of this science; however, one should also compare the nature and diversity of their scientific activities in the caves; when this is done, Krone is to be awarded that title.

It is worth to point out that at that time there was no systematic study of karst scenarios but only of part of this landscape: the caves. From 1840 on, the term *karst* will appear in scientific studies to identify the specific type of relief. For Kranjc (2001), it was in the second half of the nineteenth century, the appearance of important studies about karst areas encouraged debates and the organization of the knowledge that had been acquired until then and the first evolutionary models of karst started to be developed.

Discussions about the landscape and Earth Science evolutionary models became more frequent after World War II, which helped to update old concepts and models. From that moment on, there was new research on karst hydrology and geomorphology. Studies in caves valued the aspects of climate in the karst dynamics and provided paleogeographic reconstitutions. In the 80's, there was an intense theorization on the geochemistry of the relief and the morphological description of karst processes, a characteristic of both Bögli (1980) and Pfeffer (1981) works.

From the 90's on, the description of the regional features of Brazilian karst scenarios give way to more specific themes such as quantitative studies in the field of geomorphology, hydrology and hydrochemistry. And the development of karst geomorphology also followed the positive results of studies on the speleogenetic aspects of Brazilian caves.

Piló (2000) strongly believes that the works of Tricart (1956), Coutard, Kohler and Journaux (1978) and Kohler (1989), on the karst of Lagoa Santa, of Barbosa (1961), in Pains (MG), of Auler and Basilio (1988), on the geology and geomorphology of Santana do Riacho (MG), of Piló (1989), on the morphology of the valley of

Peruaçu (MG), among others, must be mentioned here. The author also points out that, in the beginning of that decade, the themes became more specific and equipped with a strong technical and theoretical content. It was then that the focus on the speleogenesis of caves and the Brazilian studies of the Quaternary period in Brazil emerged for the first time.

THE IMPORTANCE OF THE CORDISBURGO KARST REGION

The karst in the Cordisburgo region is one of the most important examples of the tropical karst in Brazil. It was in that site that Peter Wilhelm Lund made several of his important scientific discoveries in the second half of 19th century. In this region there are about 16 known and explored caves and the most prominent ones are the Gruta da Morena (4,620 m), Lapa Nova do Maquiné (1,312 m), Gruta do Salitre (1,098 m) e Gruta do Tobogã (1,000 m).

In the 50's, the county was also the scenery for the literary works of Joao Guimaraes Rosa. As Bezerra and Heidemann (2006) state, the area is well described in the novels *Sagarana, Primeiras Historias, Corpo de Baile* and *Grande Sertao Veredas,* which many consider to be this writer's masterpiece work, whose 50th anniversary was celebrated in 2006.

Due to the pioneering spirit of his studies on the geomorphology and speleogenesis in Brazil, Peter Lund, who is considered the *father of Brazilian paleontology,* is also known as the precursor of the Brazilian speleology, together with Richard Krone. In two of his works, Lund (1837, 1844) presents hypotheses for the genesis of Brazilian caves and refers to the sediments associated to them. Thus, Lund can be considered as the first karstologist in Brazil.

Lund came to Brazil in 1825. Up to 1829, he devoted himself to the study of the tropical flora and fauna in the outskirts of Rio de Janeiro. After three years of research, he returned to Europe in order to establish a closer relationship with key researchers of his times, among them, Alexander von Humboldt and Cuvier, the renowned paleontologist (Dequech 2000).

He eventually returned to Brazil in 1833, with the ambitious intention to organize an expedition to the states of Sao Paulo and Goias, but his expedition was put down by tiredness and diseases. So, he stayed in the city of Paracatu, Minas Gerais. When he went to Santo Antonio de Curvelo, he met there a fellow countryman, the paleontologist Peter Claussen by chance. Then he decided to change the focus of his works and focused on paleontology. Lund went from Curvelo to Cordisburgo and then to Lagoa Santa, where consolidated his pioneer studies describing the karst landscape.

Rubbioli and Auler (2002) point out that the maps of the endokarst in the region of Cordisburgo were drawn by Andreas Brandt at the request of Lund. These consist of the first registers of caves in that region. These maps were from the Lapa Nova do Maquiné, the Onça's Cave, Santo Amaro's Cave and Lagoa da Pedra Cave.

According to Cartelle (1994, 2005), Lund suggested that the Government paid special attention to the preservation and conservation of the impressive Lapa Nova do Maquiné cave in the city of Cordisburgo. He said that there would hardly be any other place of such beauty in the whole American continent but that unfortunately it had already suffered significant damage.

According to Piló (2002) the karst scenario was described by Lund in order to introduce the reader to the study of the paleontological materials associated to the sediment of caves. In addition to his pioneer scientific works, Lund was already worried about the conservation of the soil and forests of the State of Minas Gerais. Piló (2002) cites Lund when he says that the agriculture *practiced year after year by Brazilians transformed the most beautiful and fertile regions of the municipality into deserts.* He was referring to farming and exploitation practices that caused irreversible and indirect impact on karst at that time and that are still happening today.

THE LOCATION OF CORDISBURGO

The municipality of Cordisburgo is located about 110 km northwest of the capital city of Minas Gerais State (Fig. 1). The access is possible through two highways in the region: the BR-040 and the MG-231. Its population is estimated to be around 8,574 inhabitants (IBGE 2000) who are irregularly scattered in an area of 823 km^2. An average-sized city, Sete Lagoas, which is only 47 km away, is under constant risk of the disorderly exploitation of its

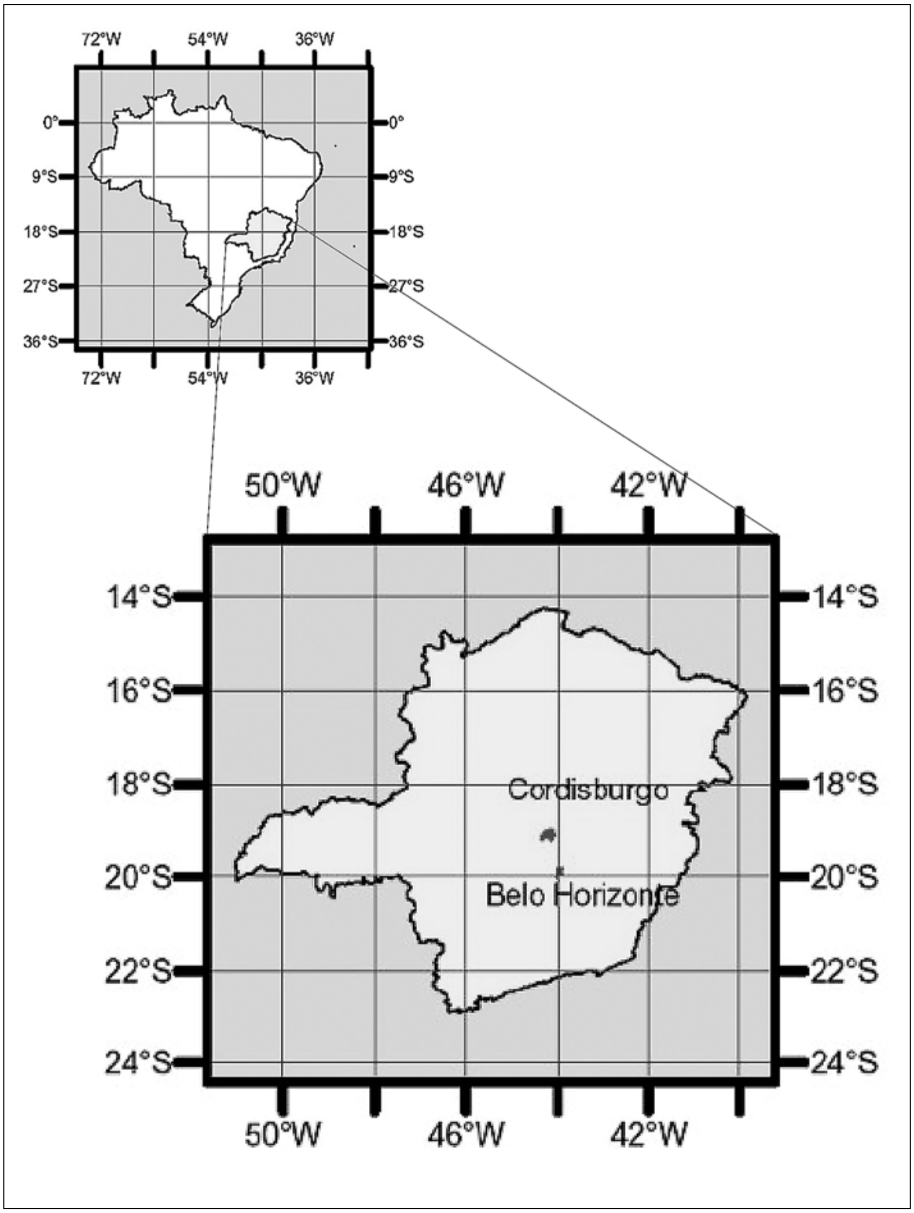

Fig. 1: Location maps of the State of Minas Gerais (on the left) and the studied region, north of Belo Horizonte (on the right).

Tab. 1: Cities and population around the area of study.

City	Population
Araçaí	2.250
Caetanópolis	9.303
Curvelo	72.835
Jequitibá	5.248
Sete Lagoas	210.468
Santana de Pirapama	8.243
Paraopeba	22.493
Presidente Juscelino	4.336

Source: IBGE 2000.

natural resources and it will be responsible for any kind of pressure that may be imposed in the future.

The region was first discovered in the 17th century by explorers called Bandeirantes. Later on it became a settlement which was officially established by a priest in 1883. The toponym reinforces the sacred meaning of the name of the place: *Cordis* = heart; *Burgo* = city, which is an allusion to the Sacred Heart of Jesus. The city is surrounded by the municipalities of Araçai, Curvelo, Jequitiba, Santana de Pirapama and Paraopeba. The largest populations belong to Curvelo, in the north, and Paraopeba, in the west (Tab. 1).

MATERIAL AND METHODS

The methodology follows the general lines adopted by the Commission of Karst Phenomena of the National Committee of Geography, adapted to the intertropical scenery by Nicod (1965) and Kohler (1989).

The investigation started by analyzing maps of the Dinaric karst and of the intertropical karst in order to compare them to the existing symbology.

An extensive bibliographic research on national and international karst studies was made so that the author could cross information and apply consolidated principles to the reality of the tropical karst.

The work was based on the topographic maps of Sete Lagoas (IBGE, scale 1:100.000), of Curvelo (Brazilian Geological Survey - Serviço Geografico Brasileiro, scale 1:100.000) and of Cordisburgo (Applied Geography Institute - IGA, scale 1:100.000).

Geology and geomorphology were based on the maps from the CETEC (1983), in 1:250.000 scales for later digitalization. Aerial photos (USAF 1:60.000), satellite images (LANDSAT 7 point 218-73 of 1998) and the Google Earth program were also used.

Secondary data were checked in field investigation and helped the elaboration of the Exploratory Map of the Karst Phenomena of the Cordisburgo Region, in Minas Gerais.

Several field trips took place in both the dry and the rainy seasons. Each field visit lasted about 8 hours and aimed at proving the information gotten through the interpretation of maps, aerial photos and satellite images was correct

GEOSYSTEMIC APPROACH

To Monteiro (2001) and Ross (2006), it is in the context of the application of geography in the development of the Soviet State that the concept of geosystems appears, proposed as it was by Sotchava (1962). As a pioneer of these studies, he has shown concern with the study of the geosystems (the integration of various elements) in the integrated analysis of the natural landscape. For him, it would be necessary to study not only the morphology of natural components but also the connections among them.

It is important to remember that in a way, this approach had already been used by Alexander von Humboldt in the 19th century. He stated that everything is interconnected and that the path to knowledge is the understanding of these connections and the mutual dependency among the phenomena. Under the geosystemic perspective, which was not formal at that time, Humboldt preferred to connect the facts that were already known rather than discover new and isolated ones. Thus, science could only move on by putting together several natural phenomena in a long and inseparable chain of cause and effect. The description of rocks and minerals alone, for example, was not his interest for he always intended to search for the establishment of their relations with the soil and vegetation (Humboldt 1850).

The geosystemic approach in geographic studies should then be understood as a way to integrate different variables of open and dynamic systems. Sotchava, cited by Ross (2006), defines geosystems as natural phenomena, even though all economic and social factors affect their structure and space peculiarities. So, one can conclude that a geosystem can only be analyzed in a holistic approach, which can understand a dynamic system. Therefore, geographic studies can no longer occur without the quest for understanding the inter-relationships between natural and anthropogenic variables.

In Brazil, the concept of geosystem was introduced by Bertrand in 1971 when he talked about the *science of the landscape*. The importance of the contribution of the Russian school to the geosystemic studies is remembered by Monteiro (2001) in a well-elaborated review of the existing work.

On reading his work, one can assume that the anthropogenic variable was not sufficiently addressed during the evolution of the concept and that the integration of the human variable is to be considered in the triad *space, time* and *dynamism* (Monteiro 2001).

This triad was already implicit in Bertrand's work (1972) when he defined landscape. The author believed that this would not be the simple addition of different geographic elements, but the result of the dynamic combination of physical, biological and human elements in a particular portion of the space. This unstable and dialectic interaction transforms the landscape into a single and inseparable set in perpetual evolution. According to Tricart (1977), the concept of system emerges as the best logical instrument for a researcher to study the environment.

This dynamic combination can be understood as the result of the combination of geological, geomorphological, pedological, hydrological, climatic, and vegetational variables that influence or suffer influence from social and economic variables (Ross 2006). Hence, the integrated study should provide the theoretical basis for the necessary support for the interaction between the natural and the human systems (socioeconomic ones) in intersystemic relationships. This is why Monteiro (2001) states that in regions where human actions are already impregnated in the landscape, they can assume the role of *driving forces* of the processes besides interfering in the relationships among natural variables, thus reflecting their actions in the natural forms or structures. It is for this reason that we think karst studies should be carried out on a geosystemic basis.

Kohler (2003) presents the geosystem as the integrated study of the environment, based on the geoecosystic works of the German school. In analogy to a theatrical play, the geographical science would provide the script of a play which would be presented by man on a stage or space (geosphere) at a given moment (time). The geosphere would be the stage of both activities and the different space-time scenarios. From the perspective of the integrated study, the physical, chemical and biological processes work for a certain span of time, thus composing the contemporary landscape.

GEOLOGY

The Brazilian territory has developed on old geological structures, except for the Tertiary sedimentary basins of the Pantanal, in the State of Mato Grosso, the Amazon basin and parts of the coast line. In the case of the metasedimentary basins, their ages range from the Paleozoic to the Mesozoic; when it comes to the crystalline terrains of the South American Platform, it dates back to the Pre-Cambrian (Archaean/Proterozoic) period. The cratonic areas, the ancient folding belts and the sedimentary basins stand out (Schobbenhaus & Brito Neves 2003) among them.

The Brazilian continental area is 8.5 million km^2 large and, according to Karmann (1994), about 5 to 7% consist of karst terrains. The main units are located in the San Francisco Craton in the region of the states of Minas Gerais, Goias and Bahia, on carbonate and dolomite rocks of the Upper Proterozoic period. Minas Gerais stands out in the national scenery due to the important carbonate rocks occurrence and, consequently, the expressive karst areas that are associated to it. According to Piló (1997, 1998, 1999) the State of Minas Gerais has around 3 to 5% (17,600 to 29,419 km^2) of the country's total.

In geological terms, the investigated area is part of the geotectonic unit of the Sao Francisco Supergroup, the Bambui Group, the Paraopeba subgroup (Pedrosa Soares 1994) and it is composed of rock compartments of various ages. The units of the Bambui Group occupy approximately the extension of the current basin of the Sao Francisco River. In the east they are limited by the Espinhaço Range and in the south by granite-gneiss terrains (migmatites) from the crystalline base. To the north, the Bambui sequences extend up to the far north of Minas Gerais State to the State of Bahia. In the west they are limited by the Chapadas das Vertentes Ocidentais of the Sao Francisco (IGA 1983; Magalhães 1988; Piló 1998).

For Grossi Sad and Quade (1985), the Paraopeba subgroup can be divided into three main units: the first one is composed of a basal discordant conglomerate; there is an intermediary layer composed of limestone up to 95% of carbonates and thin sediments; and a third level composed of carbonate intercalated with fine sediments (Kohler 2007). Noce and Renger (2005: 253) believe that the formations that constitutes the Paraopeba subgroup, from bottom to top, are the Sete Lagoas Formation, the Serra de Santa Helena Formation and the Lagoa do Jacare Formation (Fig. 2).

Fig. 2: General aspect of the Lagoa do Jacaré Formation (Photo: L. E. P. Travassos).

In the area of study, there is a predominance of clay-carbonatic rocks gathered at the Paraopeba subgroup, in the Upper Proterozoic Lagoa do Jacare Formation. Slates, limestone and phyllites deposited on the irregular surface of the crystalline base of the primary unit (granite-gneiss) are commonly found (Noce & Renger 2005). It is believed that limestone of the Sete Lagoas Formation is also possible to be found.

The sedimentation of carbonates occurred in an epicontinental sea of shallow waters on the irregular and impermeable crystalline base that allowed the development of the largest Brazilian carbonate platform. Radiometric dating and estromatolite analyses identify the deposition of carbonates 900 to 600 million years ago. Regarding that platform, it is possible to say that in the central-south region of Minas Gerais, the depths of the rocks of the Bambui Group range from 50 to 250 m (Kohler 1989; Auler 1994; Piló 1998; Noce & Renger 2005) due to the unevenness of the base.

In Cordisburgo, a region covered with the phyllites of the Serra de Santa Helena and the carbonates of the Lagoa do Jacare Formation, one can find a few references

of karst features in comparison to the regions of Lagoa Santa and Sete Lagoas. However, this landscape set reveals important karst features of great historical, cultural and environmental meaning which are worth preserving (Fig. 3).

Fig. 3: General view of a limestone outcrop and the seasonal vegetation associated to it during the dry season (Photo: L. E. P. Travassos).

GEOMORPHOLOGY

The area of study is limited by the Velhas River *(Rio das Velhas)* to the east and by the drainage divide of the Velhas River and the Paraopeba River to the west. To the south, the region is limited by a monoclinal relief due to differential erosion up to Sete Lagoas. Marbles occur on the highest area of the Serra de Santa Helena indicating a high degree of metamorphism. To the north, in the extension of the karst units of Cordisburgo, the relief decreases.

The geomorphology of the Cordisburgo Plateau initially presents three distinct compartments: from the highest to the lowest, it is possible to identify an elongated relief, outcrops, caves, dolines, temporary lagoons and poljes.

In general, the region presents itself as gently rounded hills formed with metamorphic rocks, such as slates and phyllites, interrupted by limestone outcrops due to lithology and differential erosion.

The IGA (1983) identified three compartments or main units according to the shape, height and slope angles in the region. To the west, a *first compartment,* where there are hills or mountains developed over the carbonate base. It corresponds to the higher compartment with high slope angle classes, from 12 to 45%. The highest altitude of the municipality, 1,055 m, is registered in this compartment. Abrupt cliffs dominate the landscape and the existence of caves with varied horizontal projection is noticed in places where the limestone outcrops. Among the outcrops a wavy relief is noticed with gullies and some other depressions.

The *second compartment* occurs in the eastern side of the municipality and is marked by eroded tablelands due to thick river drainage. Their upper part is generally large and a little convex with lower average altimetry than the first compartment to the west. The sides have low inclinations, with 0 to 12 % slope angles. The region presents the lowest altimetry (580 m) on the floodplain of the Velhas River (IGA 1983).

The *third compartment* shows Tertiary coverage up to the municipality of Curvelo with a decreasing altitude level towards the north. The slope angles classes are also low, ranging from 0 to 12%. The highest region in this compartment is identified in the extreme northwest near the Lagoa dos Currais, at 850 m (IGA, 1983).

The karst of the region is located on a plateau, which Kohler (1989) named the Cordisburgo Plateau. Its altitude varies from 700 to 1,055 m. The most common morphologies are elongated limestone massifs, dolines (sometimes karst ponds) and *poljes*.

The highest spots registered on the massifs are elevations up to 950 m and the lowest ones are found on the bottom of the dolines (650 m). According to Kohler (1989), the upper parts of the plateau are to be regarded as witnesses of the South American surface, the starting point of the karst landscape in the region.

Based on the Digital Terrain Model and the field work which was carried out in the area, it was possible to

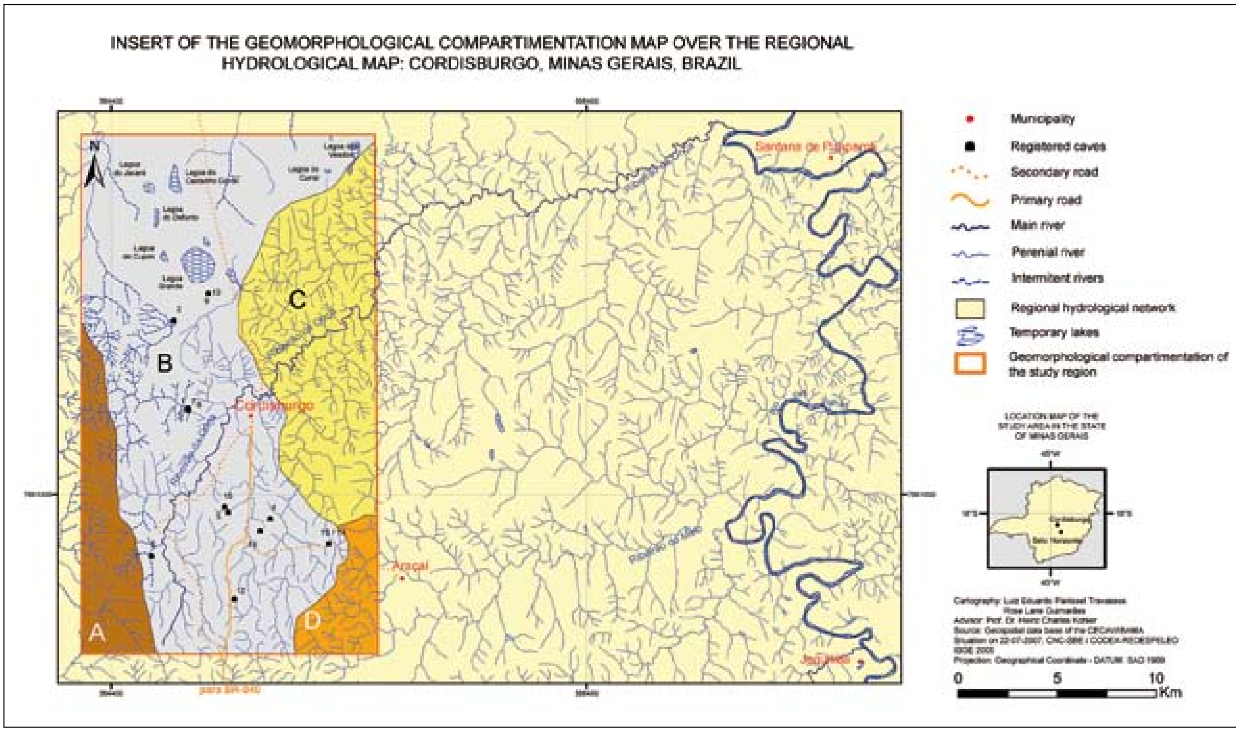

Fig. 4: Insert of the geomorphological compartmentation map over the regional hydrological map – Cordisburgo, Minas Gerais, Brazil. A) Compartimento Serrano (Hills Compartment) - B) Planalto Cárstico (Karst Plateau) - C) Planalto do Onça (the Onça Creek Plateau) - D) Planalto de Araçaí (Araçai Plateau), as showed on the geomorphological map.

propose a new geomorphological compartmentation to the region with four new main units: 1) Compartimento Serrano *(Hills Compartment),* 2) Planalto Cárstico *(Karst Plateau)* 3) Planalto do Onça *(the Onça Creek Plateau)* and 4) Planalto de Araçaí *(Araçai Plateau),* as showed on the geomorphological map (Fig. 4).

The Serra da Onça and the Serra do Palmital, which are part of the *Compartimento Serrano,* are mainly composed of the Serra de Santa Helena phyllites. The average altimetry is around 850 m. In lower altitudes one can identify quartz shingles with ferruginous crusts from 1 to 20 cm. They are homogeneously distributed along the surface, as an indication of the chemical decomposition of the phyllites interspersed by veins of quartz.

The *Planalto Cárstico* is predominant on the carbonates of the Lagoa do Jacare Formation, with altitudes ranging from 720 to 850 m. The altimetry decreases towards the north. In this compartment, it is possible to identify the most expressive exokarstic and endokarstic features in the region: massifs, outcrops, dolines, ponds, hums, sinks, springs and caves.

With altimetry ranging from 580 to 720 m, the third compartment is identified: the *Planalto do Onça.* In this compartment, there is a wavy landscape decreasing towards the base level of the Velhas River. In this compartment, the vision of the observer is easily interrupted by low hills where elongated hills fit the drainages of the Onça Creek toward its confluence with the Velhas River (580 m).

The fourth compartment, with altimetry ranging from 600 to 720 m, was called *Planalto de Araçaí.* It is characterized by low hills and the occurrence of karst features is very limited.

CLIMATIC ASPECTS

Since the CO_2 which in contact with H_2O will produce the carbonic acid elaborating karst scenarios, weather elements such as temperature and precipitation exert direct influence on the rock dissolution. The colder water is, the greater is the amount of carbon dioxide that is absorbed, making it more aggressive to the carbonate. Thus, climate influences the relief's development directly. It is important to stress that, in the case of karst scenarios, the past influence is more important in the drafting of the landscape. Therefore, they are a reflection of a past climate, although the dissolution has not ceased.

According to Köeppen classification, on a global scale, the IGA (1983) identifies the regional climate as mesothermic (Cwa), which is characterized by warm wet summers and dry winters.

The pluviometric data show that the local climate can be classified as tropical with two well defined seasons, as it is characteristic of the *Dominio do Cerrado* (Brazilian Savannah). The rainy season goes from October to March and the dry season coincides with the cold months, from June to September. The average annual temperature is 22°C and the average annual rainfall varies from 1,250 to 1,500 mm. The weather conditions are monitored by a conventional station in Sete Lagoas and an automatic one in Curvelo.

In relation to the average annual precipitation, it is possible to observe that the period from October to March showed higher values of precipitation. Therefore, it is considered the rainy season. In the dry season, the months of lower precipitation range from April to September.

The water balance of the region can be measured by the difference between the annual precipitation average and the annual evaporation average data, without using evapotranspiration values. Thus, the area presents a water deficit between the months of April - September, counterbalanced by the water surplus in the months of October - March, which enables the aquifer to recharge.

HYDROGRAPHY

The most important drainage basin is the Onça Creek which has its sources in the Serra da Onça (880 m), a water divide to the west that separates the drainage from the Paraopeba River and the Velhas River. Most of the drainage is received by the Onça Creek, establishing an important source for the autogenic recharge of the aquifer. The karst is inserted in the Onça Creek basin from the Velhas River (580 m) base level of the study area. The region has a carbonatic aquifer limited by the impermeable crystalline base.

The drainage network is well developed with perennial and intermittent watercourses. Captured to an underground system, some of them stop flowing on the surface at some times during the year as common in most karst areas (Fig. 5). Thus, the ponors can be easily identified, especially concentrated in the northern part of the study area.

The analyses of satellite images plus field work permit to state that the groundwater system follows the lodging of limestone, contributing mainly to the genesis of the lakes in the north of the municipality. It is possible to infer the direction of underground flow based on the heights of sinks and springs, hydrographic network, maps of caves and the identification of main flows inside the caves. However, such connections can only be effectively proven using tracers.

The lacustrine system in the region is considered part of the karst morphology. There are large dolines and uvalas in the north of the municipality. They are the Lagoa da Pedra in Cordisburgo and the Lagoa Grande, Lagoa do Cupim, Lagoa do Defunto, Lagoa do Jacare,

Fig. 5: Detail of one section of the Onça Creek showing its carbonatic bed and seasonal behavior (Photo: L. E. P. Travassos).

Lagoa do Castanho Gordo and Lagoa do Curral in Curvelo. The altimetry values were identified ranging from 600 to 690 m.

According to the hydrographic network analysis, it is possible to identify various dendritic patterns. It is also important to identify the structural alignment over the course of the Onça Creek in the SW-NW direction.

The region of Cordisburgo has been supplied by karst waters through tubular wells since 1976. The average flow of the system is 22.47 l/s and the municipality has a unit capable of storing 1.9 million liters per day (COPASA, 2007). The depths vary from 67 to 102 m between the active wells and the reserves.

In the study area, the greatest threat to groundwater comes from agriculture and deforestation. The population growth of the bordering municipalities suggests that the water level of karst lakes and therefore the aquifer are being changed.

VEGETATION ASPECTS

Agriculture is the anthropogenic activity that has been historically destroying the regional vegetation. It changes the original aspects of the Phytogeographic Domain of the Cerrados, units which are relatively homogeneously presented from the physiographic and ecological point of view, with a combination of physical, ecological and biotic factors (Ab'Saber 2003).

On a local scale, the original vegetation of the *Cerrado* is sometimes dense and sometimes sparse. Beyond the northern boundary of the municipality, already in the area of Curvelo, most of the vegetation gave place to agriculture and the sylviculture of eucalyptus. In the surroundings as well as in the outcrops, a seasonal forest is conditioned by the type of rocks and climate (Fig. 6). Over the major drainages it is possible to identify gallery forests even with no water in the river bed.

Fig. 6: General view of an carbonate outcrop covered with the seasonal forest during summer time (Photo: L. E. P. Travassos).

LAND USE

The peculiarities of the karst have always influenced the land use around the world, especially the agricultural use due to its positive and negative forms. In the Brazilian tropical karst low fertility soils are common due to the high degree of leaching. On the other hand, it is possible to find soils with some degree of fertility at the bottom of the dolinas, where sediments are accumulated.

The agriculture in the State of Minas Gerais is a traditional activity initiated in the first half of the 18th century with the process of clearing the country's hinterland *(sertoes)*. Barbosa (1978) as cited by Kohler (1989), says that the special nature of the karst favoured soil occupation and that there are many small villages and farms whose main activity was the agriculture and that are located near dolinas. However, such places came into decline when the railroad *Central do Brasil* reached the city of Sete Lagoas, considered the *mouth of the hinterland* at that time. In the 50s, when large industries and limestone quarries were installed, this decline increased.

According to the IGA (1983), the rural activity in the region is traditionally related to raising livestock. Currently, with the evolutionary process initiated in the 50's, the pastoralist vocation is developing towards cattle breeding along with the creation of fine breeds of cattle, horses and livestock. In addition to raising livestock, agricultural and forestry activities, mainly eucalyptus plantations for charcoal production are also increasing in the region. According to Gillieson (1996), regardless of the species, the roots can penetrate depths of 30 to 50 m in search for water, especially in humid seasonal climates. Therefore, in large plantations of eucalyptus, the water regime can be significantly changed.

Regarding mineral production, the region does not stand out in the national scenario as much as the regions of Lagoa Santa and Sete Lagoas do.

Another use of the municipality area is the rural and adventure tourism activities which impose changes in the landscape, especially by exercising a significant pressure on the environment and causing accelerated soil erosion, water exploitation and groundwater contamination.

The region has considerable scientific, recreational and cultural values. Due to its inherent fragility and anthropogenic actions, the karst scenario needs increasing care for its protection. Environmentally protected areas must be established and public-private partnerships should emerge as important strategies for conservational and sustainable use.

Hamilton-Smith (2006) states that the development of tourism must be accompanied of environment protection actions. Lima and Morais (2006) conducted a study to contribute with the development of the management plan of the Lapa Nova do Maquine in order to minimize the impacts generated by tourist visitation, in order to guide the implementation of a sustainable kind of tourism.

The cave environment is easily influenced by natural and anthropogenic factors; generally natural impacts cannot be avoided, resulting from the normal evolution of the system. The human impacts, however, must be kept at acceptable levels, taking into account social and economic factors.

In the case of caves adapted to tourism, a series of modifications can cause negative impacts on the environment. Footbridges damage the rock, but guide and discipline the flow of tourists preventing them from trampling on speleothems. The screens, placed at gates and other openings of a cave to prevent the entry of birds or bats, limits guano deposits and, consequently, limits the fauna associated to them. Regarding artificial lighting, the biggest impact is the favoring of algae and fungi growth. In addition to being aesthetically negative, they can also erode the speleothems. Even with such problems, however, it is believed that tourism is an important activity to help control visitation to caves and conserve them, especially the ones of high cultural and historical value.

In Cordisburgo, speleological discoveries were first made in the 19th century by Peter W. Lund; in the modern 1970's, 1980's and 1990's, they were made by the SEE, NAE and GBPE groups. The formal discoveries have stopped, although the region presents potential for the registration of other new small caves.

Lund (1837) believed that the caves were formed at the time when the limestone was still concealed by a sea or a lake and that the caves could have been generated by the action of waves. In a subsequent work, Lund (1844) presented a new hypothesis for speleogenesis: in this model, he stated that the caves were formed by water percolating through the phyllites cover to the limestone fissures, followed by the deposition of sediments in the caves.

As it is the case in Lagoa Santa, the depth potential of the caves in the region is highly limited by the thickness of the limestone base and the water level. Caves over 100 m of difference in level are difficult to be discovered (Auler 1994) since the known level difference in the caves of the region vary only from 5 to 68 m. This is due to the small difference between the Karst Plateau in relation to the Velhas River, the main drainage of the region.

CONCLUSIONS

Cordisburgo can be considered an icon of the karst regions in Brazil. It holds remarkable cultural, scientific and recreational values. Due to its inherent fragility and anthropogenic activities, the region needs increasing protection. Besides the Peter Lund Natural State Monument, created in 2005, other areas of environmental protection need to be established and it is essential that public-private partnerships be created as strategies for the conservation and sustainability use of karst.

The work had identified the most expressive features of the region using georeferenced images of the Google Earth program in a 1:25.000 scale, giving rise to the Exploratory Map of Karst Phenomena in a 1:50.000 scale (Fig. 7). In the map is possible to identify a vast drainage system on the surface. This is due to the layer of impermable rocks which is often overlaying the limestone represented in the map as the geological base of the region.

Due to its geological, geomorphological, hydrological and biogeographical characteristics, the karst in this region is a significant example of the Brazilian karst. Its surface and underground development should be understood as a complex phenomenon.

There has not been many studies on the Lagoa do Jacare Formation regarding the content of $CaCO_3$ and phyllites intercalations, quartz veins, and so on. Therefore, it is premature to say that the karst of Cordisburgo

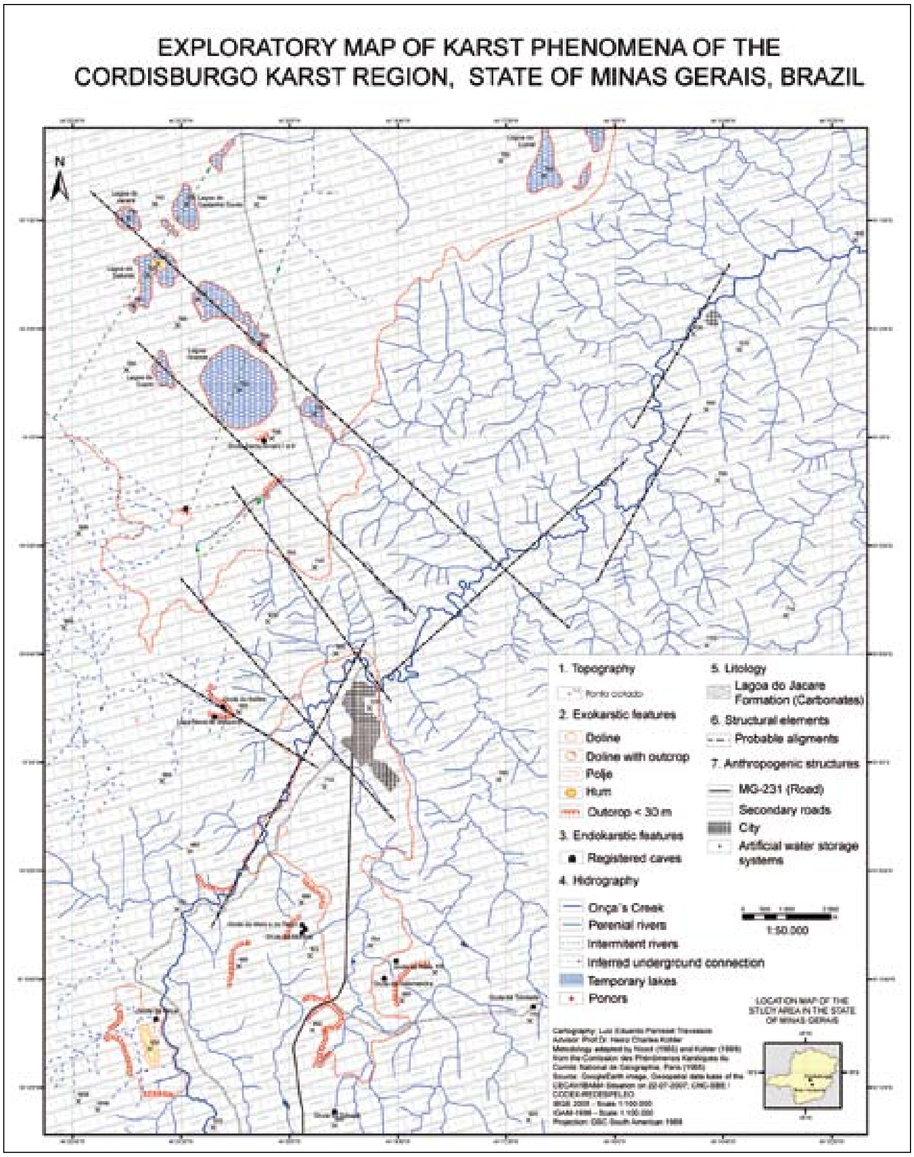

Fig. 7: Exploratory Map of Karst Phenomena of the Cordisburgo karst region.

presents low karstification. It is possible that there is occurrence of sites associated with pure limestone with sites of other non-carbonatic formations.

Studies on the magnitude and underground flow were not much explored as well. In the studied region, it seems that the endokarstic flow is controlled by the Onça Creek basin in the direction of the base level of the Velhas River. In the northern region, the endokarstic flow also appears to be associated with the drainage of the Velhas River; however, this seems to happen at lower levels, where more evolved karst features appear.

The human activities often involve profound changes in the landscape, especially quarrying, accelerated soil erosion, air pollution and groundwater exploitation. Thus, the combination of urban growth and increasing tourism exert a significant pressure on this karst scenario.

From the interdisciplinary perspective of Karstology, the researchers should always be aware of the fact that the anthropogenic changes and activities affect especially the water sources in these areas. For all this, it is important to develop systematic studies in the area.

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