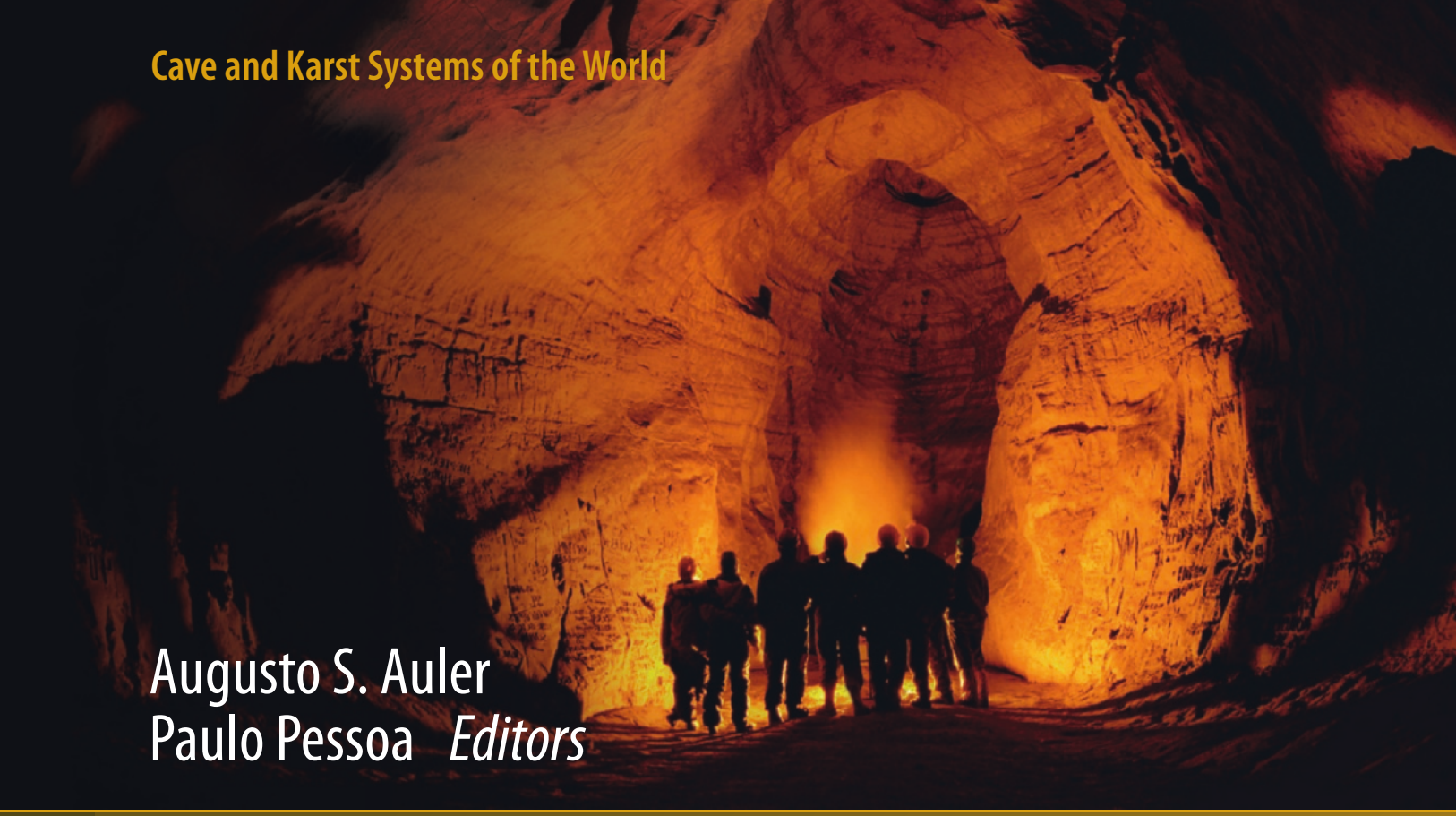
Cave and Karst Systems of the World



Augusto S. Auler
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Lagoa Santa Karst: Brazil's Iconic Karst Region

Springer

Cave and Karst Systems of the World

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Preface

If not for a fortuitous moment in 1835, the surroundings of the town of Lagoa Santa, in southeastern Brazil, would have been just another karst area among the extensive karst terrains in the state of Minas Gerais, Brazil. Fascinated by the caves and their fossil content, Danish naturalist Peter Wilhelm Lund decided to establish himself in the small town and start a detailed study of the abundant fossil remains in the caves. For about 10 years, Peter Lund researched approximately 1000 caves and brought to life a remarkable collection of, until then, unknown extinct species. As a naturalist, Lund maintained an interest in several other areas, and invited colleagues and welcomed visitors to join him in the solitude of Lagoa Santa. In the mid-nineteenth century, several lines of research were being pursued in Lagoa Santa, mostly related to paleontology, the living fauna, and botany. Lund's influence continued after his retirement from research and, ultimately, his death in 1880 in Lagoa Santa, without him ever having returned to his native Copenhagen. The bait provided by Lund worked as a magnet attracting a continuous stream of scientists until the present day. The Lagoa Santa Karst is by far the best-researched karst area in Brazil, with hundreds of publications in many fields of science. Lagoa Santa's proximity to the new state capital, Belo Horizonte (inaugurated in 1897), also facilitated access and made it a convenient study site for many generations of scientists.

The Lagoa Santa Karst is the cradle of Brazilian paleontology, archaeology, speleology, and karst research. The iconic saber-toothed tiger (*Smilodon populator*) was first described by Lund in the area. In the late nineteenth century, much of the contentious debate about the contemporaneity of humans and the Pleistocene megafauna centered on Lagoa Santa. The largest collection of early Holocene human skulls also comes from the Lagoa Santa Karst. The area contains Brazil's largest number of caves—in excess of 1500—as well as hundreds of archaeological sites. Although the area presents several scientific milestones, it is also experiencing challenging times. Encroachment of the suburban areas of Belo Horizonte and its satellite cities is threatening the integrity of the landscape as well as the groundwater quality and quantity. Approximately 500,000 people live at or near the karst, and several cement and lime plants have active quarries in the area. Sinkhole collapse, groundwater pollution, landscape degradation, deforestation, and cave vandalism are among the many ongoing impacts.

This book aims to contribute to knowledge of the Lagoa Santa Karst, while also aiding its conservation. It is an attempt to summarize in one comprehensive volume the vast amount of research, in several disciplines, performed over nearly 200 years. Each chapter is designed as a comprehensive review of its theme, and the book intends to integrate the many fields of research performed in the region.

This book starts with a historical review of research performed in the Lagoa Santa Karst. In chapter "History of Research in the Lagoa Santa Karst", Augusto S. Auler provides insights into the initial human involvement with caves in pre-history and the economic exploitation of caves for saltpeter mining since the eighteenth century. The arrival of Peter Lund is highlighted alongside the studies performed by several of his visitors. In the twentieth century, the area continued to attract the attention of many scientists, which resulted in continuing interest in the

Lagoa Santa Karst up to the present day. In chapter "The Geology of Lagoa Santa Karst", Paulo Galvão and Jorge Peñaranda present a synthesis of the geological knowledge of the Lagoa Santa Karst, emphasizing the main characteristics of the two carbonate units (Lagoa Santa and Pedro Leopoldo members of the Sete Lagoas Formation) where the karst is developed. The tectonic framework is also discussed, providing a basis on which to understand the geomorphology of the Lagoa Santa Karst.

In chapter "The Vegetation of Lagoa Santa Karst", Ana Elisa Brina reviews the vegetation of the area, first studied over 100 years ago by Eugen Warming. The vegetation is, in many ways, peculiar, being in a transition zone between two biomes (Atlantic Forest and Cerrado) and displaying species especially adapted to living in karst settings, such as limestone outcrops, under a highly seasonal climate. Over 2,000 species have been recorded in the area. The chapter points out the need for conservation in order to preserve the significant biodiversity of the area. In chapter "The Lagoa Santa Fauna: Historical Records", Gisele Lessa, Flávia Henriques e Souza, and Natália Lima Boroni present an updated review of the fauna in the Lagoa Santa Karst. This fauna is notable for presenting species related to both biomes and is among the best known in the country, with 70 species of fish, 25 species of amphibians, 41 species of reptiles, 240 species of birds, and 107 species of mammals recorded. A reduction in the number of species due to environmental impacts has been demonstrated. In chapter "The Waterbirds and Dynamics of Lagoa Santa Karst Temporary Lakes", José Eugênio Figueira and collaborators discuss one of the most remarkable features of the Lagoa Santa Karst: its shallow lakes, which represent a habitat for several bird species. The dynamics of the lakes are discussed, together with variations in the richness, abundance, and foraging guilds of species, depending on a lake's characteristics and the season. The list of waterbirds is updated, and initiatives for protecting the lakes and their fauna are highlighted.

The Lagoa Santa Karst is mostly soil covered. In chapter "Soils of the Lagoa Santa Karst", Luís B. Piló and Selma Simões de Castro discuss the karst's important soil cover. Red latosols predominate and can reach considerable thickness, masking the limestone. The soil has its origin in the upper metapelite cover, and two soil horizons (an upper red and a lower yellow) can be recognized throughout the region. Much of the initial development of karst occurs under soil at the epikarst zone. A detailed characterization of the soil and its importance in shaping the karst landscape is presented. In chapter "Karst Landforms in the Lagoa Santa Area", Augusto S. Auler presents an overview of the karst landforms in the Lagoa Santa area, starting with a new proposal of geomorphological domains. The area displays a full suite of karst landforms, but with some peculiar features, especially the ubiquitous lakes and limestone cliffs, which are discussed in detail. Karst forms are described, from the smaller ones initially generated under soil to the macroforms that evolve after exposure. The chapter closes with a schematic model for the evolution of the Lagoa Santa Karst. In chapter "Karst Hydrogeology of the Lagoa Santa Area", Paulo Pessoa discusses the hydrogeology of the area, showing how the distinct lithological units behave in terms of groundwater flow. Infiltrating waters percolating through complex vadose pathways allow for a conspicuous recharge distribution, interconnecting various portions of the karst aquifer system and flowing through deep epikarst zones. More than 500 pumping wells and dozens of karst springs serve as the main source of potable water supply. The chapter ends by highlighting that the Lagoa Santa Karst aquifer lacks spatial and seasonal hydrogeological monitoring plans. In chapter "Caves and Speleogenesis in the Lagoa Santa Karst", Augusto S. Auler describes the main characteristics of the large number of caves in the area. The area displays considerable speleogenetic variability, with both syngenetic and paragenetic caves, of which a significant number were formed by lakes or due to dissolution over a sediment cover. The morphological features of the caves and their chemical, clastic, and organic sedimentation are also discussed. The chapter closes with remarks on the caves' age and evolution.

The caves in the Lagoa Santa Karst harbour a remarkable cave fauna, which is discussed in chapter "Biospeleology of the Lagoa Santa Karst" by Rodrigo Lopes Ferreira, Marcus Paulo Alves de Oliveira, and Marconi Souza-Silva. The cave fauna is structurally diverse due to the

variety of habitats. It has 41 species of obligate cave dwellers, but only four have so far been formally described. The number of troglobitic species is likely to increase, as new research is being performed. The chapter highlights the many impacts taking place, leading to a highly vulnerable situation, which threatens the cave ecosystem. The fossil vertebrate fauna, first revealed by Peter Lund, is described by Cástor Cartelle in chapter "Cave Paleontology in the Lagoa Santa Karst". The chapter opens with a review of the life and works of Lund, his most iconic findings and the research of those who followed in his footsteps, such as the Danish zoologist Herluf Winge and other scientists during the twentieth century. This historical review provides a timely update on the nearly 200 years of paleontological studies in the area. Human occupation in the Lagoa Santa Karst is discussed by André Strauss and collaborators in chapter "The Archaeological Record of Lagoa Santa (East-Central Brazil): From the Late Pleistocene to Historical Times". The area is known for its archaeological sites and evidence of ancient occupation (since approximately 12,500 years ago). The chapter presents a comprehensive survey of several archaeological aspects, such as chronology, rock art, pottery, stone and bone technology, diet, funerary rituals, site formation, and so forth, providing the reader with an updated review of the Lagoa Santa Karst archaeology.

The Lagoa Santa Karst is presently being subjected to environmental impacts that must be addressed urgently. The two last chapters aim to describe these impacts and the conservation efforts. In chapter "Environmental Problems in the Lagoa Santa Karst", Paulo Pessoa, Dora Atman, and Gisele Kimura focus on the misuse of land and the inadequate occupation in the Lagoa Santa Karst aquifer system, showing that several environmental problems still persist. Besides the spread of urban centers and allotments, severe secondary issues related to inappropriate sanitation infrastructure, aquifer vulnerability, mining activity hazards, and deforestation in sensitive areas emerge. However, as happens at the root of most environmental problems, recent studies demonstrated how important it is to break away from current educational and social patterns, avoiding an unrestricted focus on basic water cycle reconnaissance studies. The chapter points out that stakeholders need to realize how important they are in order to preserve water resources. In chapter "Protection of the Environmental and Cultural Heritage in the Lagoa Santa Karst: History and Challenges", which brings the book to a close, Luciana Alt and Vitor Moura summarize the threats and conservation efforts in the Lagoa Santa Karst, and stress the gaps and challenges for adequate protection of the area. Although there are significant conservation units, the reality shows the need for more effective measures; otherwise, the environmental quality of the area may be jeopardized.

We would like to thank all the authors, who contributed their time to producing a synthesis of their field of knowledge. The chapters benefited enormously from the reviews provided by authorities, especially in areas beyond our field of expertise. We acknowledge the critical review of Dr. Renata Andrade (biospeleology), Dr. Ulysses Pardiñas (fauna), Dr. André Prous (archaeology), Dr. Alex Hubbe (paleontology), Dr. Luiz P. Travassos (history), Dr. Esther Sebastian (waterbirds), Pablo Hendrigo Melo (vegetation), Dr. Luis Piló (impacts), Dr. Paulo Galvão (hydrogeology), and Tatiana Souza (karst geomorphology and speleogenesis). The staff at Carste Ciência e Meio Ambiente and Hidrovia Hidrogeologia e Meio Ambiente provided continuous support during the long gestation of this book.

The Lagoa Santa Karst is where we started our scientific careers—first, as enthusiastic youngsters, looking for caves and being surprised by the intriguing karst landforms, and later, as young professionals learning how science should be done. After nearly 40 years, as we look back, we still see the Lagoa Santa Karst as mysterious and full of secrets, but also crying out for support. We are grateful for the continuous support provided by several local farmers, as well as industries and the staff at the conservation units. Friends from Grupo Bambuí de Pesquisas Espeleológicas, a caving club, helped in many ways.

The Lagoa Santa Karst is an emblematic karst area in Brazil, a classical site where much of what is known about Brazil's past humans and fauna was first brought to light. In its thousands of caves, cliffs, dolines, and lakes lies a significant portion of Brazil's pre-European history. We hope this book will help disseminate knowledge about this outstanding area, fostering new research, and prompting the enactment of effective protection measures in order to preserve the Lagoa Santa Karst.

Belo Horizonte, Brazil

Augusto S. Auler
Paulo Pessoa

Contents

History of Research in the Lagoa Santa Karst

Augusto S. Auler

Abstract

The Lagoa Santa Karst is the most researched and best-known karst area in Brazil; it is an emblematic karst area within the context of Brazilian karst. Its modern history spans over 200 years, since the arrival of the first European settlers, although prehistoric cultures had occupied the area since at least the early Holocene. The arrival of Danish naturalist Peter Wilhelm Lund in Lagoa Santa in 1835 started a period of intense research that continues to this day. Lund was responsible for bringing international recognition to the area through outstanding paleontological work that has formed, up to this day, the basis of Brazilian palaeontology. Numerous other European scientists, notably Johannes Reinhardt, Hermann Burmeister, Eugen Warming and Herluf Winge, took advantage of Lund's residence in Lagoa Santa (and later, of Lund's collection in Copenhagen) to perform additional research and publish original data in several disciplines. In the early twentieth century, members of the Academy of Sciences of Minas Gerais (mainly Aníbal Mattos and Harold Walter) and the National Museum of Rio de Janeiro resumed Lund's work in the caves and revived old controversies related to the antiquity of human remains and their contemporaneity with the extinct megafauna. In the second half of the twentieth century, major research continued to be performed by foreign scientists, including archaeologists and geomorphologists (respectively, led by Annette Laming-Emperaire and Heinz Charles Kohler), which helped create local research groups based in the Minas Gerais's state capital, Belo Horizonte. The area is still a hot spot of scientific research in various fields, mostly led by Brazilian groups, and continues to enjoy international scientific relevance.

Keywords

Lagoa Santa Karst • History • Saltpetre • Peter Lund • Cave science

1 Introduction

The Lagoa Santa Karst was the first karst area in Brazil to be the object of scientific studies in the early nineteenth century. Since then, research there has been continuous, including up through the present day. The total amount of research in the Lagoa Santa Karst far exceeds what has been produced in other karst regions in Brazil. The research has been interdisciplinary, from physical aspects such as geomorphology (including speleology and hydrogeology), to biological (fauna, flora, palaeontology) and social/cultural (archaeology) fields. However, it is unequivocal that the caves and their fossil content provided the initial impetus that later evolved into wide-ranging studies. The Lagoa Santa Karst owes much of its international recognition to the initial work of Danish naturalist Peter Wilhelm Lund. The Lagoa Santa Karst, although unique in some aspects, has some similarities with other sites throughout the vast limestone areas that occur throughout much of the states of Minas Gerais, Bahia and Goiás (Auler 2019). What made the Lagoa Santa Karst the focus of so much early attention was arguably the outstanding scientific contributions of Peter Lund's work.

In addition to Lund's own pioneering research in the caves, he also attracted to Lagoa Santa a considerable number of colleagues and visitors who expanded the scope of research in the area. The publications by Lund and his collections, which were sent to Copenhagen, also provided a rich field for discussion and reinterpretation by other scientists, many of them would never visit Lagoa Santa. This stream of research continued throughout the twentieth and twenty-first centuries.

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In addition to Lund's role in raising the scientific visibility of the Lagoa Santa Karst, the establishment of the new capital of the state of Minas Gerais, Belo Horizonte, in the surroundings of the karst, also played a major role. From an isolated area in the backlands of Brazil, suddenly the Lagoa Santa Karst was very close (approximately 40 km) from a fast-growing metropolis. The population living in Belo Horizonte and the adjoining areas grew rapidly, reaching 2.5 million in 2014. Previously small towns such as Lagoa Santa, Matozinhos, Pedro Leopoldo and Sete Lagoas also expanded over the karst. Presently, it is estimated that approximately 500,000 people live within or in the immediate surroundings of the Lagoa Santa Karst (Auler 2016). Although this massive population growth had major impacts in the region, it also facilitated access to the area, as being close to important universities and research centers made the Lagoa Santa Karst a natural target for research. Presently, a significant portion of the cement produced in Brazil comes from the Lagoa Santa Karst. Several other industries and the state's only international airport are also located in the area. Environmental assessment studies performed for the installation or due to compensation measures for these industries have also considerably expanded scientific knowledge of the karst. No other karst area in Brazil is located so close to such a sprawling urban metropolis, a dubious honour that carries positive and negative consequences.

This review will detail human involvement with the Lagoa Santa Karst, the main scientific landmarks and the people who worked in (or based their research on data from) the Lagoa Santa Karst, from pre-colonial times to the late twentieth century, excluding ongoing research.

2 Initial Human Occupation

Abundant archaeological data point to the start of human occupation over 12,000 years ago (Da-Gloria et al. 2017). These early Americans had a close relationship with the karst area, as attested by a large number of cave entrances and shelters associated with archaeological sites (see chapter "The Archaeological Record of Lagoa Santa (East-Central Brazil): From the Late Pleistocene to Historical Times", this volume). In contrast to pre-colonial humans in North and Central America, there is scarce evidence that these Paleo-Indians entered caves. The rock art and archaeological findings are mostly limited to the entrance zone. No major environmental impact can be attributed to these early populations. Unlike in other areas in Brazil, limited indigenous geographical denominations are known to be related to the Lagoa Santa Karst, with the exception of the word 'anhanhonhacanhuva', which was applied to the swallet at Sumidouro Lake (Silveira 1929).

The first experience Europeans had with the Lagoa Santa Karst took place during 'bandeiras', expeditions led by Portuguese frontiersmen with the goal of finding precious stones. There are records of one of these expeditions, led by Fernão Dias in 1674, having reached Sumidouro Lake (Lima Junior 1962) and founded the small hamlets at Fidalgo and Quinta do Sumidouro.

Gradually, over the eighteenth century, the area became occupied by large farms. The significant discoveries of gold in the surroundings of the town of Ouro Preto and diamond in the Espinhaço Ridge, near the town of Diamantina, made the Lagoa Santa area (located approximately midway between these two mining centers) a natural stopover. This time marks the initial settlement of most of the towns in the area. The town of Lagoa Santa is associated with the reportedly miraculous waters of its local lake. The name 'Lagoa Santa' means 'Holy Lake', and the healing properties of its waters were publicized in Lisbon in the eighteenth century (Anonymous 1749).

2.1 Saltpetre Mining

Saltpetre is a nitrate-rich soil that was an essential ingredient for producing gunpowder until the early twentieth century. Saltpetre occurs in many natural settings but is especially abundant in caves, where it forms fine-grained sediment that can be leached in order to concentrate the nitrates. The Lagoa Santa Karst was one of the areas where saltpetre was extracted from caves. Mentions of saltpetre-rich caves in the surroundings of Matozinhos, Fidalgo and Sete Lagoas are recorded in early saltpetre records, such as a series of documents dated from 1813 (Anonymous 1899), with some of the caves still retaining their names to this day.

The extent of the economic use of Lagoa Santa Karst caves cannot be assessed with precision. However, evidence of the extraction, normally pickaxe marks, can be observed in several caves, and entire passages have had their sediment completely or partially removed. Knowledge about the caves already existed when Peter Lund arrived in the area, and he had little problem finding guides to lead him into them, although he lamented that saltpetre extraction had damaged the paleontological content of several caves (Lund 1841a, b, c). Although saltpetre extraction peaked during the late eighteenth and early nineteenth centuries (Gomes and Piló 1992; Ferraz 2000), there has been little research performed on this subject, despite the abundant documentation available.

3 Peter Wilhelm Lund

The arrival of Danish naturalist Peter Wilhelm Lund (1801–1880) in Lagoa Santa in 1835 forever changed the scientific destiny of the then sleepy village. Lund's paleontological

Fig. 1 **a** Photograph of Peter Wilhelm Lund by Eugen Warming. Archives of the Natural History Museum, Copenhagen. **b** Portrait of Peter Andreas Brandt by an unknown artist

cave work lasted until 1845, but his influence endured for far longer. Not only did Lund produce highly original work—mostly related to palaeontology (see chapter "Cave Paleontology in the Lagoa Santa Karst", this volume), though with insights on archaeology and geomorphology as well (see chapters "Karst Landforms in the Lagoa Santa Area, Caves and Speleogenesis in the Lagoa Santa Karst and The Archaeological Record of Lagoa Santa (East-Central Brazil): From the Late Pleistocene to Historical Times", this volume) but he also welcomed numerous other scientists who performed complementary research or delved into other disciplines.

Peter Lund (Fig. 1a) came to Lagoa Santa with an open mind. A botanist with a comprehensive interest in and knowledge of natural history, he intended to perform botanical studies in his travels in the interior of Brazil with his German colleague, Ludwig Riedel (see Holten and Sterll 2011 for details). However, a fortuitous meeting with Dane Peter Claussen and his first visit to caves containing fossil bones almost immediately changed the focus of his research. His conversion to palaeontology was instantaneous, showing how prepared he was to delve into an area where he had never done any previous practical field or laboratory work. At the same period, an equally fortuitous meeting with the Norwegian artist Peter Andreas Brandt (1792–1862, Fig. 1b) provided Lund with a capable assistant in charge of drawing the caves (Fig. 2) and producing essential scientific drawings of fossil bones (Holten et al. 2012). In particular, Brandt produced several maps of caves in the Lagoa Santa Karst, showing considerable skill, despite the difficult conditions and his lack of experience with this highly specialized task (Auler and Piló 2017). Lund's work on palaeontology, archaeology,

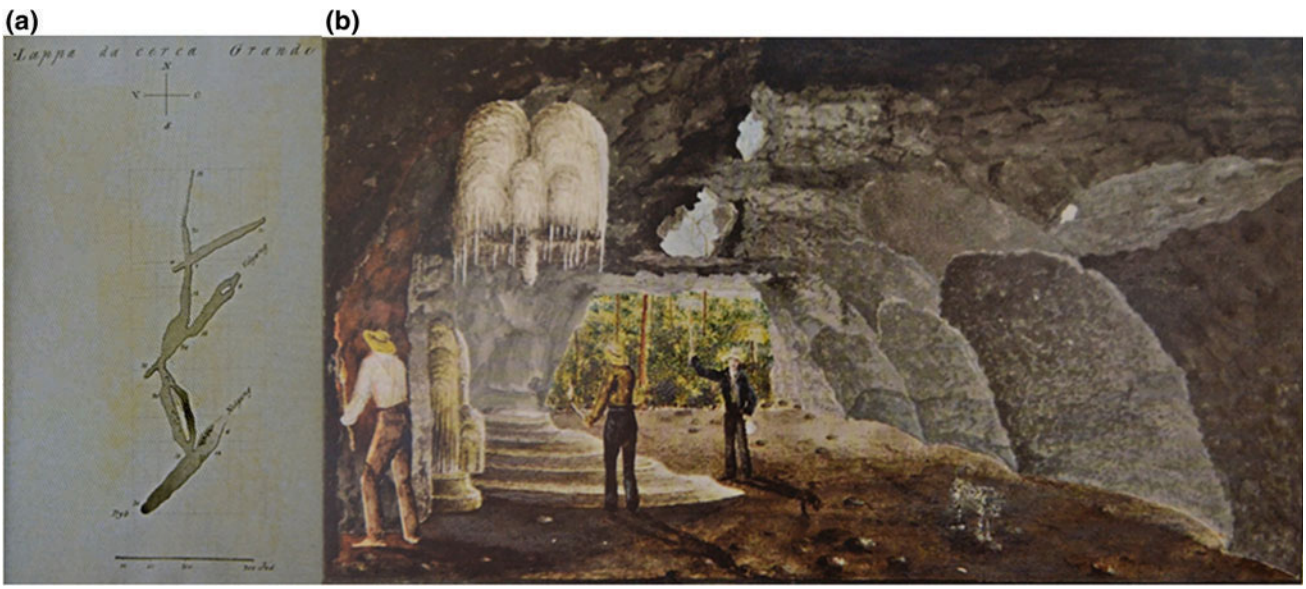

Fig. 2 **a** Map of Cerca Grande Cave. **b** A scene of Lapa Vermelha Cave. Both drawings by P.A. Brandt

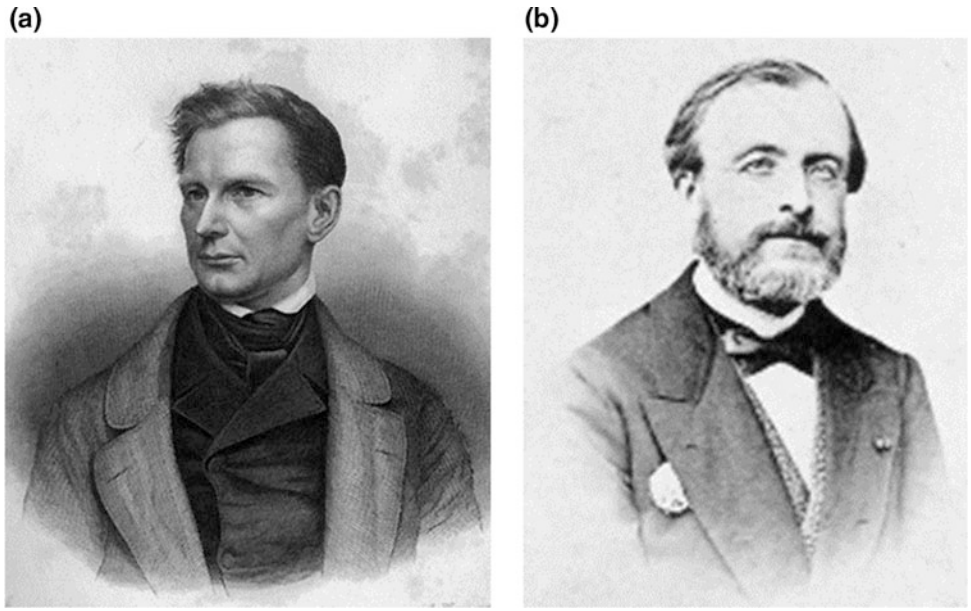

Fig. 3 **a** Hermann Burmeister and **b** Emmanuel Liais visited Lund and performed original research on the Lagoa Santa Karst

karst geomorphology, and speleology were initially published in Danish in a series of memoirs (Lund 1837, 1841a, b, c, 1845, 1846), which were later translated into Portuguese (Lund 1950), English (Lund 1840) and French (Lund 1845). Among Lund's main discoveries, one can list the scientific description of 22 fossil species and nine living species (see chapter "Cave Paleontology in the Lagoa Santa Karst", this volume), the proposition of the contemporaneity between Man and the extinct megafauna (Neves and Piló 2003) and the recognition of the old age of human remains (Holten and Sterll 2011). Although initially a proponent of the catastrophism view of his mentor, Georges Cuvier, Lund slowly abandoned these ideas to formulate his own original concepts. Lund's life has been portrayed in several biographical essays. Reinhardt (1880), Lund (1885) and Holten and Sterll (2011) are among the most comprehensive, while Marchesotti (2011) and Luna (2007) represent additional recent studies.

Peter Lund received several visitors in Lagoa Santa. Some of them were scientists who, attracted by Lund's research, came to Lagoa Santa to perform scientific studies —the Danes Johannes Reinhardt and Eugen Warming, for example, in addition to the German Hermann Burmeister and the French Emmanuel Liais. Others were in Lagoa Santa for short periods, and, although they were scientists, they did not contribute any significant new data about the Lagoa Santa area. Among this group were Joel Allen, Orestes St John, George Sceva, Virgil von Helmreichen, Richard Burton, Jakob Heusser, George Claraz and Marianne North. Among the non-scientists who visited were members of the royal entourage of the Duke of Saxe, including photographer Augusto Riedel, who provided important early photographs of Lagoa Santa (Riedel 1868).

Some of these scientists deserve special mention because they had the chance to visit karst sites and make original observations. The German Hermann Burmeister (1807–1892) (Fig. 3a) stayed in Lagoa Santa with Lund and Reinhardt for approximately three months (Burmeister 1853). Burmeister published work about the fossils in Lagoa Santa (Burmeister 1871, 1885). Frenchman Emmanuel Liais (1826–1900) (Fig. 3b) also visited caves and provided accounts of cave genesis, sedimentation and fossiliferous beds (Liais 1872).

There were major scientific contributions from colleagues who were among the continuous stream of visitors, particularly from Danish scientists somehow associated with Lund. Johannes Reinhardt and Eugen Warming were two such colleagues who stayed in Lagoa Santa for extended periods and organized collections that were later shipped to Denmark, enabling more detailed work to be performed later by other colleagues.

3.1 Reinhardt and Warming

Although isolated in a remote village in Brazil, Lund kept constant contact with his Danish colleagues. Johannes Reinhardt (1816–1882, Fig. 4a) was the son of one of Lund's mentors. Reinhardt remained in Lagoa Santa for an extended period during his three visits to Lagoa Santa—enough time to acquaint himself with the local fauna. Reinhardt's contributions were his own, mainly in the field of palaeontology (Reinhardt 1867, 1875a, b—see additional references in Mones 1986) but also covering the topics of vegetation (Reinhardt 1856) and birds (Reinhardt 1870). In addition to being nominated as the curator of the portion of Lund's

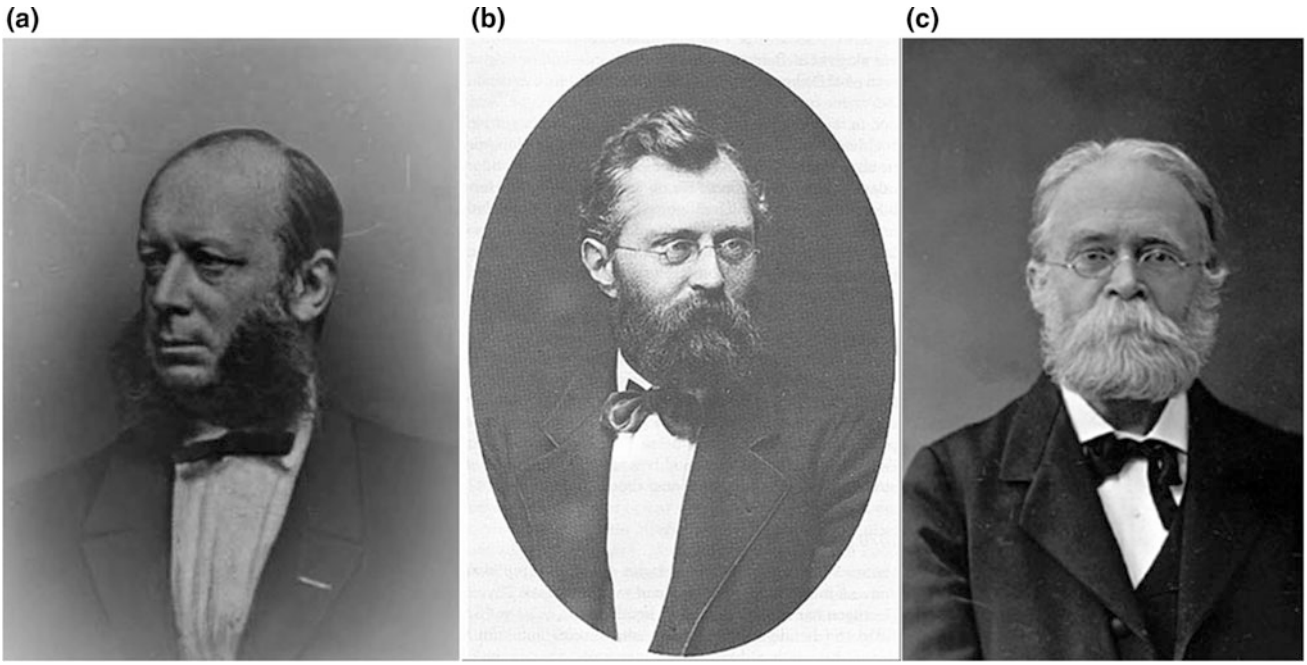

Fig. 4 **a** Johannes Reinhardt. **b** Eugen Warming. **c** Herluf Winge

collection that had been sent to Copenhagen, Reinhardt himself also made important collections that were used by other scientists to produce original work on fish, amphibians and reptiles (Lütken 1875; Reinhardt and Lütken 1861).

In addition to his own work, Reinhardt was able to reinterpret Lund's view on the formation of caves and the introduction of bones (Reinhardt 1867, 1888). This fact is important because it allows us to learn about a change in Lund's own interpretation that is only hinted at in his personal correspondence.

In need of a new secretary, Lund welcomed the assistance of young botanist, Eugen Warming, in 1863. Warming (1841–1924, Fig. 4b) was able to find considerable spare time away from his duties with Lund during his 3-year stay in Lagoa Santa and performed a pioneering and influential study on the ecology of plants in the Lagoa Santa area (Warming 1892).

3.2 Lund's Collection in Denmark

Lund's paleontological collection in Copenhagen remained in storage for many years, and proper studies on it were not performed until much later when its content was finally re-examined (Holten and Sterll 2011). The result of this re-evaluation was published as a set of five volumes entitled *E Museu Lundii* from 1888 to 1915. This massive and comprehensive work was coordinated by Herluf Winge (1857–1923—Fig. 4c) and contains detailed studies of the fossil bones, consisting of chapters on birds, rodents and mammals, including humans (see full references in Mones 1986). This re-evaluation added considerably to the knowledge of Peter Lund's findings in Lagoa Santa's caves. In particular, towards the end of the nineteenth century, Lund's concepts on the contemporaneity between man and the megafauna and on the antiquity of man, based on his findings at Sumidouro Cave (Lund 1845), attracted considerable international attention and generated a scientific debate that lasted many decades (see Piló et al. 2005; Neves et al. 2007; Hubbe and Neves 2017 and references therein). Some of these topics are subject to renewed interest being the focus of recent archaeological projects (Bernardo et al. 2017).

4 Early Twentieth Century

Limited original field research was performed in Lagoa Santa Karst in the years after Lund's death. In the first decade of the twentieth century, a local engineer named Cássio Umberto Lanari, whose family owned the large Mocambo Farm at the heart of the karst, resumed archaeological work in the area, making new findings of human remains, mainly at Caetano Cliff (Lanari 1909).

In approximately the same period, Álvaro Astolpho da Silveira, also a local engineer and naturalist (with an emphasis on botany), described a number of caves and the karst landscape in the area (Silveira 1921, 1929, 1931). Some of the Lagoa Santa Karst caves are mentioned in the first overview of Brazilian caves, by Antonio Olinto dos Santos Pires on the occasion of the centenary of the Brazilian independence (Pires 1929).

In 1937, students at the Federal University of Ouro Preto, led by Victor Dequech, established the first caving club in the Americas, the Sociedade Excursionista e Espeleológica (SEE). The very first field studies were performed at the Lagoa Santa Karst, including the mapping of many important caves, such as Morro Redondo, Poções, Lavoura and Estudantes (Dequech 1940; Bittencourt 1945; Parada 1949a, b). The SEE continues to have a strong link with the Lagoa Santa Karst to the present day. A few years later, the state government of Minas Gerais commissioned the creation of a catalogue of caves in the state (IBGE 1939), and caves in the Lagoa Santa Karst were briefly described.

4.1 The Academy of Sciences of Minas Gerais

During the first half of the twentieth century, amateur archaeologists and palaeontologists, belonging to the Academy of Sciences of Minas Gerais, based in Belo Horizonte, explored several caves and archaeological sites in the Lagoa Santa Karst. Among those, the most influential were artist and painter Aníbal Mattos (1886–1969) and the English vice-consul, Harold Walter (1897–1976) (Fig. 5). Other members of this group included medical doctor Arnaldo Cathoud and dentist Josaphat Penna. These members of the Academy, most notably Harold Walter, performed original excavations at several sites, such as Confins, Eucalipto, and Mãe Rosa, and published extensively about archaeology and palaeontology in the Lagoa Santa Karst (Cathoud 1935; Mattos 1941, 1961; Walter 1948, 1958; Walter et al. 1939). Harold Walter, the most scientifically inclined of the group, attempted to determine the first absolute ages of the ancient human skulls of the area (Stewart and Walter 1955). Anibal Mattos was responsible for bringing much of the Lund's work in Lagoa Santa back into the limelight and promoting Lund's legacy through a series of books (Mattos 1934, 1935). A recent review of the work performed by the Academy of Sciences of Minas Gerais has been presented by Costa (2017).

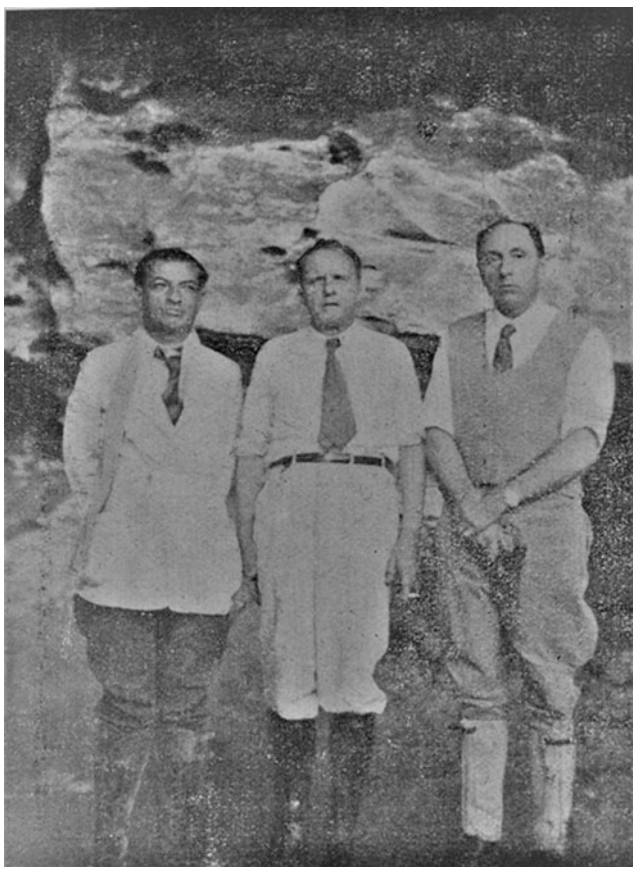

Fig. 5 The three main organizers of the Academy of Sciences of Minas Gerais at Lapa Vermelha Cave. From left to right, Aníbal Mattos, Arnaldo Cathoud and Harold Walter. From Walter (1948)

In the late 1920s, German Jorge Padberg-Drenkpohl, working for the National Museum at Rio de Janeiro, organized expeditions to the Lagoa Santa Karst (Gaspar Neto and Rodrigues-Carvalho 2017), during which general observations about the landscape and caves were performed. The expeditions focused on archaeology, and Padberg-Drenkpohl performed pioneering excavations at Confins Cave, where he unearthed human skulls that reignited the controversial debates with the members of the Academy of Sciences of Minas Gerais regarding the antiquity and contemporaneity of the extinct fauna (see Keuller 2017; Gaspar Neto and Rodrigues-Carvalho 2017). The expedition results remain in the form of unpublished reports in the National Museum's archives. J. Bastos Ávila, also from the National Museum, directed excavations at Carrancas site in 1936, but the results, mostly unpublished (but see Mattos (1941)), are short and descriptive in nature (Gaspar Neto and Rodrigues-Carvalho 2017).

5 Late Twentieth Century

The Lagoa Santa Karst continued to receive a steady stream of scientists during the second half of the twentieth century. Unlike the members of the Academy of Sciences of Minas Gerais, most of these were professional scientists working through official projects. Several nationalities were represented, and some of these scientists had a lifelong involvement with the Lagoa Santa Karst.

5.1 Palaeontology

Carlos de Paula Couto was Brazil's foremost palaeontologist in the late twentieth Century, and he organized a new complete annotated translation of Lund's writings (Lund 1950), which allowed Brazilians to be able to fully analyse

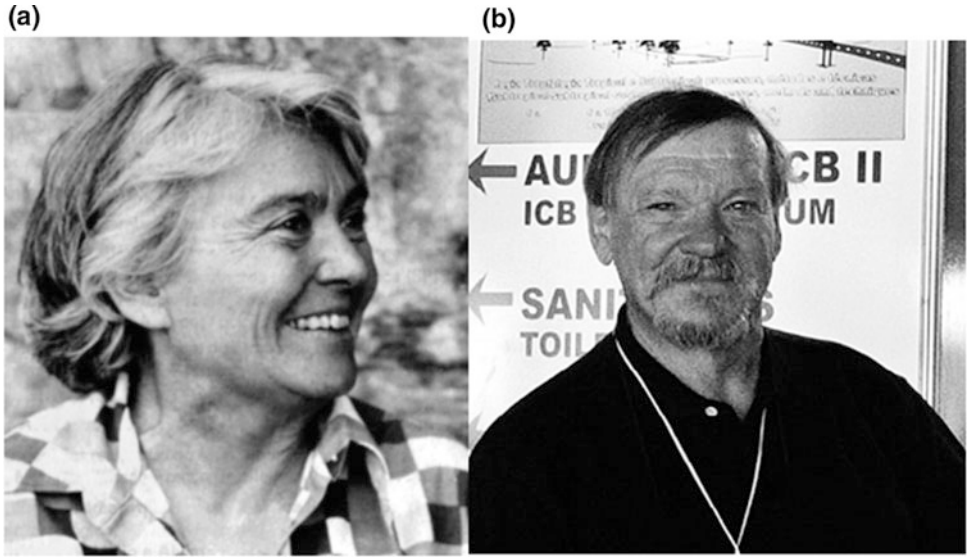

Fig. 6 **a** Annette Laming-Emperaire. **b** Heinz Charles Kohler (Travassos and Kranjc 2011)

Lund's ideas and findings. Paula Couto also performed new excavations in the area and described a new species of rodent (Paula Couto 1951). Paula Couto benefited from Harold Walter's paleontological collection, studying the fossil bear found in Lagoa Funda Cave (Paula Couto 1960) and re-describing some of the species initially found by Lund (Paula Couto 1947). Hoffstetter (1954), a French palaeontologist, studied material on Xenarthra from Lund's collection in Denmark. Some of the archaeological expeditions described in the following section by Hurt and Blasi and the French mission led by A. Laming-Emperaire also yielded significant paleontological material. For an updated review of paleontological research in the area see chapter "Cave Paleontology in the Lagoa Santa Karst", this volume.

5.2 Archaeology

To test Lund's hypothesis on the age of human remains, American archaeologist Wesley Hurt teamed up with Brazilian archaeologist Ondemar Blasi and palaeontologist Paula Couto to excavate a number of Lagoa Santa sites in 1954/1955, such as Boleiras (Escadas), Ballet and, mainly, the Cerca Grande site. This research resulted in the first reliable radiocarbon dating for the Lagoa Santa archaeological sites—over 9,000 years BP old (Hurt 1960; Hurt and Blasi 1969)—which demonstrated the considerable antiquity of human occupation in the area (see review in Prous 2017). A new impetus was provided by the French-Brazilian archaeological mission, which took place in Lagoa Santa between 1971 and 1977 (Laming-Emperaire et al. 1974). The mission was led by the French Annette Laming-Emperaire (1917–1977) (Fig. 6a) and had among its members a number of archaeologists who would later become important mentors in the field, including André Prous and Maria Beltrão, among many others (see Prous 2017 for a detailed account of the mission). Among the most publicized findings of the French-Brazilian mission is the skull belonging to 'Luzia'. Indirectly dated between 11,200 and 11,680 years BP (Bernardo et al. 2017), the skull would become an icon, representing the antiquity of South American human occupation. In the late 1970s, Hungarian amateur archaeologist Mihaly Banyai performed numerous excavations (Banyai 1997), mostly at the Lapinha outcrop, where he would later establish a private museum that would eventually be incorporated by the state of Minas Gerais.

5.3 Geomorphology and Speleology

Studies on karst geomorphology were largely dormant during the first half of the twentieth century. They were slowly resumed in the 1950s and intensified during the 1970s–1980s. Frenchman Jean Tricart produced a detailed description of karren types at the now largely destroyed Nova Granja outcrop in São José da Lapa (Tricart 1956). At about the same time, Elzio Dolabela, a native from the town of Lagoa Santa, published his monograph on karst landforms containing information on the Lagoa Santa area (Dolabela 1958). Brief descriptions of the karst were provided by archaeologists (Hurt and Blasi 1969; Laming-Emperaire et al. 1974) but merely as an introduction to the main archaeological focus of the research.

In the 1970s, due to an initiative of A. Laming-Emperaire, a cooperative project was established between French geomorphologists André Journaux and Jean-Pierre Coutard and the Federal University of Minas Gerais (Prous 2017), represented by the Swiss-Brazilian Heinz Charles Kohler; this

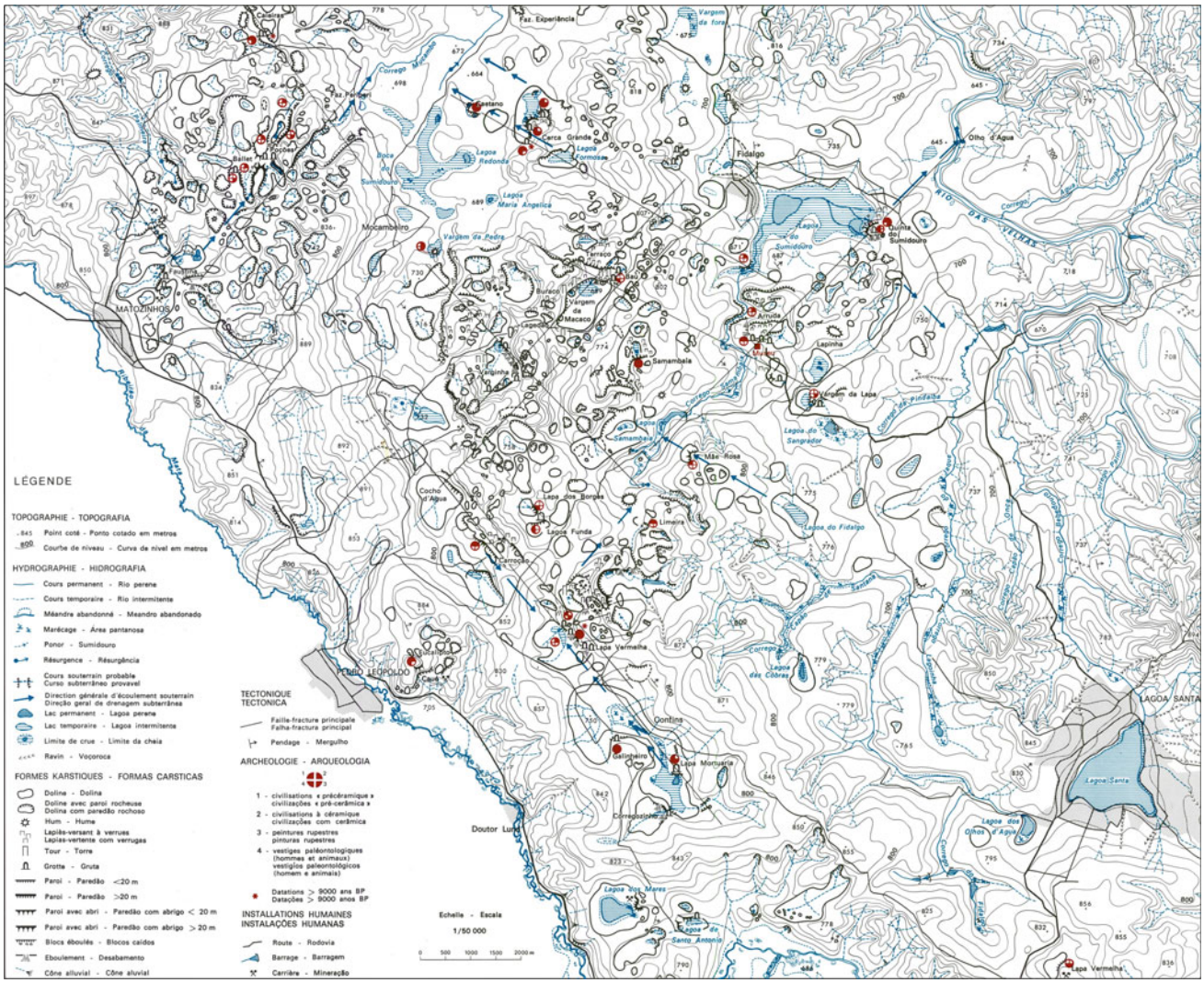

Fig. 7 The Lagoa Santa Karst map by Kohler et al. (1978)

project led to a marked advance in the understanding of the karst landforms (including caves) and their dynamics. The map of the Lagoa Santa Karst (Kohler et al. 1978) was the first of its kind in Brazil and showed the main features in the central portion of the karst, including caves and archaeological sites, on a 1:50,000 scale (Fig. 7). This map was accompanied by detailed text that described the main landforms and delved into topics such as cave genesis and karst evolution (Coutard et al. 1978). An original interpretation of the genesis of cliffs was published by Journaux (1977). Heinz Charles Kohler (1945–2010) (Fig. 6b) was instrumental in later years, as he performed additional research in the area (Kohler 1989; Kohler and Karfunkel 2002). An isolated initiative was provided by the geomorphological work of Hungarian Denes Balazs in the Lapinha outcrop (Balasz 1984). Descriptions of species sampled in caves in the Lagoa Santa Karst were also published during this period (Wygodzinsky 1950; Schubart 1956).

Cave exploration and research was limited to a few practitioners until the appearance of additional speleological groups in the late 1970s and particularly in the 1980s, most of which were based in Belo Horizonte. Exploration and mapping of caves became frequent, resulting in important discoveries, including some of the longest and deepest caves in the area. Among the groups, the Grupo Bambuí de Pesquisas Espeleológicas was the most productive. Two governmental cave and karst-related projects deserve mention. The 'Projeto Grutas' (CETEC 1981) produced a basic inventory of several caves in the state, including a number of important caves in the Lagoa Santa Karst. Starting in the early 1990s, the 'Projeto Vida' aimed to produce basic information to help achieve sustainable development for the

area. This project performed original work in several areas, including a new geological mapping effort. Several cave maps and detailed reports were produced that were later applied to the management plan of the Carste of Lagoa Santa Environmental Protection Area (IBAMA/CPRM 1998).

6 Present Times and Final Remarks

Starting in the late 1990s, research in Lagoa Santa Karst became more quantitative, with measurements taking the place of descriptions. Dating techniques (U-series, radiocarbon, thermoluminescence) were routinely applied to the archaeological sites and caves. Chemical analysis was used to characterize the origin and evolution of the soils. Palynological analyses were performed to better understand lake evolution in the area. The first hydrogeological inventories took place, with the application of tracing techniques, hydrochemical analysis and applied research related to sinkhole collapse. Additional archaeological sites have been excavated, and new paleontological research has improved our knowledge of the late Pleistocene fossil fauna. Exciting new research has been performed in areas such as fauna and biospeleology regarding ecology, parasitology and taxonomy, among others. Academic work in all areas is continuously being performed in the Lagoa Santa Karst, resulting in a significant number of theses and dissertations. The several chapters in this volume bring an updated review of the present status of research in Lagoa Santa Karst.

The implementation of Federal Decree 6640 (Brasil 2008) brought about new procedures for the classification of caves. Mining companies are now required to produce a comprehensive inventory of caves during the licensing process, including detailed biological and geological assessments, in order to classify caves according to their levels of significance (Auler and Piló 2015). This procedure has resulted in studies in hundreds of new caves, expanding knowledge about the speleological sites in the Lagoa Santa Karst considerably. The database of caves is ever increasing, reaching 1,400 in 2017. New conservation areas have been implemented, although increased urbanization, together with other threats (see chapters "Environmental Problems in the Lagoa Santa Karst and Protection of the Environmental and Cultural Heritage in the Lagoa Santa Karst: History and Challenges", this volume), has challenged attempts to protect the remarkable karst heritage in the area. As a karst area rich in history, the Lagoa Santa Karst and its future depend on a successful science-based approach to tackle existing threats in order to sustainably guarantee the karst's continued existence.

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The Geology of Lagoa Santa Karst

Paulo Galvão and Jorge Peñaranda

Abstract

This chapter provides information about the geological evolution and structural geometry of the Lagoa Santa Karst region, located in the São Francisco sedimentary basin, where Neoproterozoic rocks from the Bambuí Group are deposited. This group is constituted of karstified limestones from the Sete Lagoas and metapelites rocks from the Serra de Santa Helena Formation, covered by unconsolidated sediments of Cenozoic age, in a context of basin border. The area presents some detachment faults, displacing the whole stratigraphic succession, allowing formations of distinct ages to stand alongside. The Sete Lagoas Formation, most frequent in the region, is divided by the lower Pedro Leopoldo Member with karst dissolution features developed mostly in impure limestone bedding planes; and the upper and better exposed Lagoa Santa Member, with dissolutions in pure limestones in the form of caves, small cavities and sinkholes.

Keywords

Lagoa Santa Karst • Geology • Stratigraphy • Structural geology • Sete Lagoas Formation

1 Introduction

The Lagoa Santa Karst region is situated around 30 km north from Belo Horizonte, capital of the Minas Gerais state, Brazil, and it is an important example of the karst environment in South America. The region presents a dense set of karst geomorphological features associated with subaerial fluvial hydrography and underground karst components developed in the Sete Lagoas Formation's carbonate rocks. In some places, the rocks are covered by metapelites of the Serra de Santa Helena Formation and Cenozoic unconsolidated sediments (Berbert-Born 2000). Due to its geological particularities, the region provides significant economic resources for many surrounding cities, boosting the economy and nearby population growth.

The Bambuí Group, where the Lagoa Santa Karst is emplaced over, was first studied by Rimann (1917)—being further detailed by Freyberg (1932), who divided the previously known as Bambuí series into eastern and western facies, and Branco and Costa (1961), where the first stratigraphic column was proposed, modified in sequence by Oliveira (1967), Schöll and Fogaça (1979), Dardenne (1978) and Ribeiro et al. (2003). Moreover, other significant studies were developed to understand the region, such as structural and geological cartography (Magalhães 1989; Danderfer Filho 1991; Peñaranda 2016), geochronology (Babinski and Kaufman 2003; Babinski et al. 2007), hydrogeology (Pessoa 1996, 2005; Galvão et al. 2015a, b; Tayer and Velásques 2017; de Paula and Velásquez 2019), and geological evolution (Nobre-Lopes 1995; Uhlein et al. 2004; Vieira et al. 2007; Tuller et al. 2010; Galvão et al. 2016).

This chapter provides relevant information about the Lagoa Santa Karst geology and structural geometry. Geological mappings, aerial photography interpretations, lithological and image well profiles analyses, and a compilation of the most relevant studies were carried out to set up a geological framework of the region.

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2 Site Description

The Lagoa Santa Karst area is in the south-central of the Minas Gerais state, Brazil, around 30 km north from Belo Horizonte, the capital city (Fig. 1). The area covers more than 1,000 km^2, where the cities of Vespasiano, Confins, Funilândia, Pedro Leopoldo, Sete Lagoas, Matozinhos, Capim Branco and Prudente de Morais are located (red contour line, Fig. 1b). This karst area has the highest density of caves in Brazil, with more than 1,000 known caves, many with significant archaeological and paleontological values (Auler and Farrant 1996) (see chapter "Caves and Speleogenesis in the Lagoa Santa Karst", this volume). The Lagoa Santa Karst Environmental Protection Area (green contour line, Fig. 1b) is in the east-central area of the region, covering 39,957 hectares (98,740 acres). This area is known for containing hundreds of Early Holocene/Late Pleistocene archaeological sites, giving important anthropological pieces and information about the origin and age of human colonization in the Americas (Auler and Piló 2015).

Geologically, the area overlies the southeastern region of the Paleoproterozoic São Francisco Craton (Almeida 1977) (Fig. 1a), composed of crystalline rocks, being a result of an amalgamation of distinct Archean craton blocks. Between 900 and 600 Myr ago (Condie 2002) extension events occurred, resulting in the deposition of Neoproterozoic silicate–carbonate sediments, giving origin to the Bambuí Group.

The Bambuí Group occurs over an area of about 300,000 km^2 (Almeida 1977) in the states of Minas Gerais, Goiás and Bahia. Its genesis is related to subsidence due to the overloading of Brasiliano orogenic belts in a foreland basin context within the São Francisco Craton (Castro and Dardenne 2000; Alkmim and Martins-Neto 2001; Sial et al. 2010; Uhlein 2013; Perrella Júnior et al. 2017). The basement structure is controlled by faults responsible for sediment thickness variations (Misi et al. 2007). Seismic surveys made by Petrobras S. A. has indicated that the central area of this group may reach thicknesses of about 1,000 m (Pedrosa-Soares et al. 1994). Due to a shallow epicontinental sea with a low gradient ramp, the Bambuí Group sediments are regionally distributed, enabling the recognition of the same lithofacies sequences in large areas (Schobbenhaus 1984).

Regarding stratigraphy, three transgressive–regressive sedimentary cycles occurred: (1) transgressive pelite–carbonate cycle (Pedro Leopoldo Member of Sete Lagoas Formation); (2) regressive carbonate cycle (Lagoa Santa Member of Sete Lagoas Formation); and (3) transgressive pelite–arenaceous cycle (Serra de Santa Helena Formation) (Fig. 1c and Table 1).

Rested over the gneiss–migmatitic undifferentiated complex (the basement), the Bambuí Group is constituted, from the bottom to the top, by the Carrancas Formation (rhythmites, sandstones and diamictites); Sete Lagoas Formation (carbonaceous sequences); Serra de Santa Helena Formation (metapelites, and marlstones), Lagoa do Jacaré Formation (oolitic limestones); Serra da Saudade Formation (siltstones and sandstones); and Três Marias Formation (sandstones from fluvial platforms). Unconsolidated sediments of Cenozoic age overlay in some places those formations (Tuller et al. 2010).

Considering just the limits of the Lagoa Santa Karst region, the Bambuí Group displays only the Sete Lagoas and Serra de Santa Helena formations, being locally covered by Cenozoic unconsolidated sediments (Fig. 1c and Table 1), which will be further discussed in detail.

In terms of structural geology, normal and thrust faults trending NNW-SSE are common, where fractures and foliations are the main planar fabrics (Danderfer Filho 1991; Tuller et al. 2010; Galvão et al. 2016). Mineral lineations and stretching kinematically indicate tectonic transport towards the west, where interstratal ramp thrust belts were formed being accommodated in argillaceous upper planes. According to structural geological surveys, the Bambuí Group can be divided in four structural domains, considering its deformation magnitude (Tuller et al. 2010): (I) high intensity—the Espinhaço Supergroup rocks outcrop with mass movement signals towards the west; (II) intermediate —more deformed in the east than in the west, extending from the Velhas river to the extreme western limit of the city of Sete Lagoas. This is the domain where the Lagoa Santa Karst region is situated; (III) rocks with less intense deformation, which in some places no deformations can be found; and (IV) in the extreme west area, incipient deformation affects only the Serra da Saudade Formation's rocks, where sedimentary structures of the other formations are more preserved.

The Lagoa Santa Karst region has an important aquifer, named Sete Lagoas Karst Aquifer (Pessoa 1996; Galvão et al. 2015a), which consists of Neoproterozoic karstified limestones composed of the Pedro Leopoldo Member (bottom) and Lagoa Santa Member (top) (see chapter "Karst Hydrogeology of the Lagoa Santa Area", this volume). The primary porosity and matrix permeability are very low (Galvão et al. 2015b; Peñaranda 2016) and the secondary porosity (micro-fractures) is mostly filled by calcite and quartz (Tonietto 2010; Galvão et al. 2015b, 2016).

Most of the water flows through karst dissolution conduits classified as tertiary porosity. Image well loggings data in the Sete Lagoas' urban area indicated that two dominant karstified bedding planes have high permeability and significant storage capacity, being the most relevant discontinuities for groundwater circulation. In the same area, the overall aquifer is about 75 m thick (Galvão et al. 2015a).

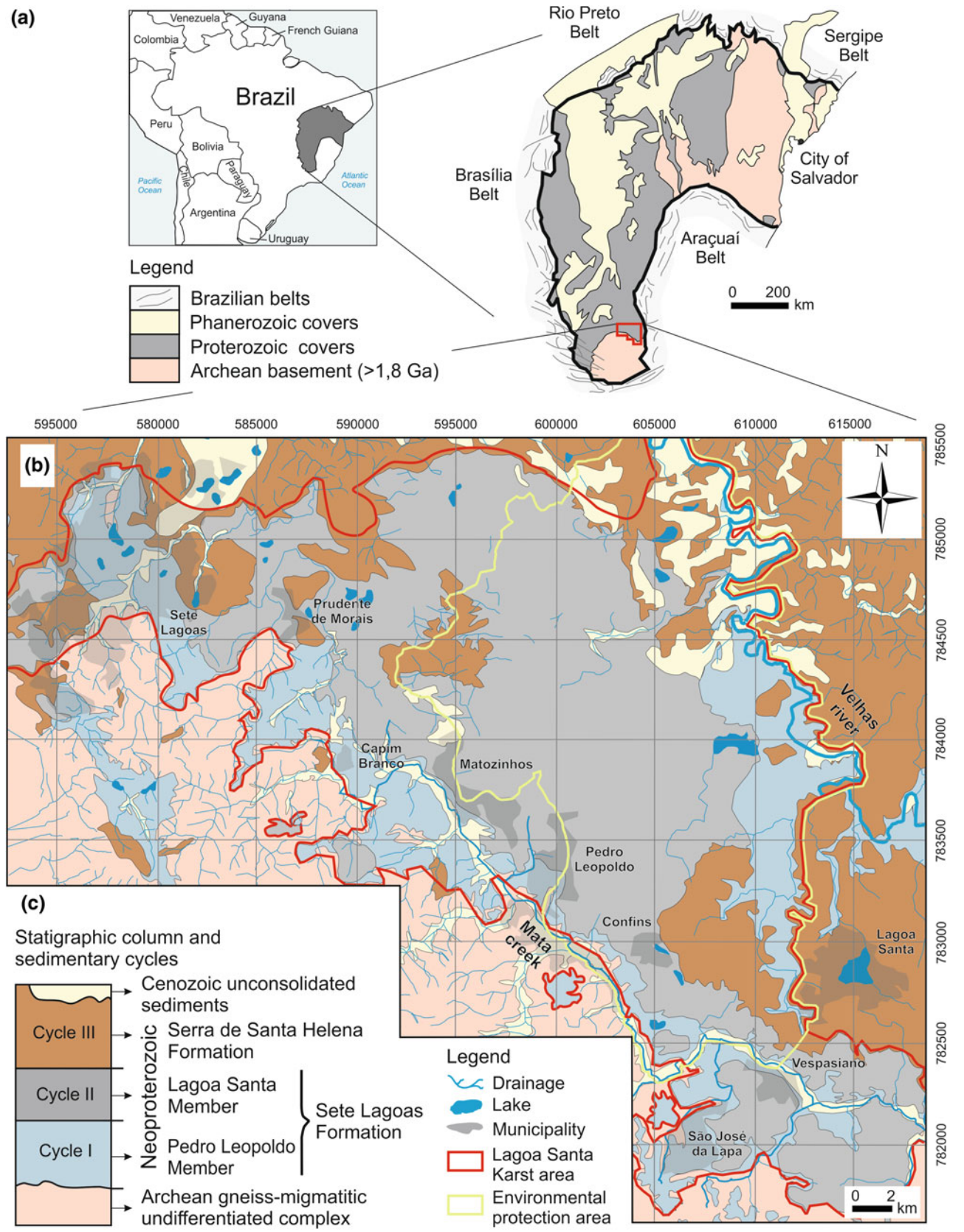

Fig. 1 **a** The Lagoa Santa Karst area in the São Francisco Craton (modified from Almeida and Hasui 1984; Alkmim et al. 1993); **b** geology of the Lagoa Santa Karst (simplified from Viana 1998); **c** stratigraphic representation and the sedimentary cycles of the Lagoa Santa Karst (modified from Ribeiro et al. 2003). Figure "**c**" can be used as the legend of the lithologies seen in figure "**b**"

Table 1 Summary of main lithostratigraphic units and their respective contact relationships and depositional systems of the Lagoa Santa Karst region (modified from Viana et al. 1998)

Chronostratigraphic unit			Lithostratigraphic unit		Lithology/Lithofacies	Contact relationship	Depositional system
Phanerozoic		Cenozoic	Quaternary		Alluvial terraces and alluviums	Discordant	Continental
			Tertiary		Detritic cover	Discordant	Continental
Precambrian	Upper Proterozoic	Bambuí Group	Serra de Santa Helena Formation		Silt-clay rhythmites, generally carbonaceous, dark shales, marble, siltstones, slate cleavage	Abrupt, tectonic and gradational contacts	Transgressive argillo-arenaceous cycle. Epicontinental marine
			Sete Lagoas Formation	Lagoa Santa Member	Medium-grained grey limestones. Grey calcarenites and calcisiltites, plane-parallel lamination, wave truncation, medium-sized crossed stratifications. Presence of stromatolites (type *gyminosolens*)	Gradational, or abrupt contact through detachment faults	Regressive carbonated cycle. Subtidal and supratidal marine
				Pedro Leopoldo Member	Fine-grained white limestones, dolomites, marlstones and pelites. Calcilutite, with truncated wave-ripple or plane-parallel stratification. Presence of aragonite crystals. Dolomite rocks	Faulting, abrupt and discordant contacts	Transgressive argillo-carbonated cycle. Structural highs and basin border
	Archean	Gneiss–migmatitic undifferentiated complex			Set of gneissic rocks and migmatite zones, with polymetamorphic features	–	–

Dry caves, dissolution features and sinkholes, an indicative of groundwater paleoconduits, are common in the Lagoa Santa Member (e.g., Rei do Mato cave—city of Sete Lagoas, and Lapinha cave—nearby the city of Lagoa Santa) (Auler and Piló 2015, Galvão et al. 2016, Peñaranda 2016).

3 The Geology of the Lagoa Santa Karst

3.1 The Stratigraphy of the Lagoa Santa Karst

The Lagoa Santa Karst region consists of the Sete Lagoas and Serra de Santa Helena formations, which overly the gneiss–migmatitic undifferentiated complex. Unconsolidated sediments of Cenozoic age are covering some of these rocks.

3.1.1 Gneiss–Migmatitic Undifferentiated Complex

This complex is generally composed of a set of migmatite zones, gneiss and granitoid rocks, corresponding to the São Francisco Craton, being the local crystalline basement (Ribeiro et al. 2003). The complex outcrops as narrow strips in the south and southwest of the area, indicating that the Lagoa Santa Karst lies in a basin border context (Fig. 1b).

In geochronological terms, Cordani et al. (1980) found an isochron age of 1 Ga for gneisses in the city of Sete Lagoas; Teixeira et al. (2000) recorded T_{DM} model ages varying between 3.4 and 3.1 Gyr, indicating continuous evolution to this complex.

Gneisses, migmatites and granitoids have usually transitional contacts (Fig. 2). Light grey to whitish, medium to coarse-grained granitoids with porphyroblasts of feldspars and xenoliths are common, where restites from partial fusion are also noted in those granitoids. Petrographically, the gneisses vary in composition with hornblende, biotite, or amphibole, indicating that granites and tonalites, in a context of metamorphism at the amphibole facies with hydrothermal alteration, would be the protolytes (Tuller et al. 2010). This crystalline basement was also latter cut by basic rock dikes (Ribeiro et al. 2003).

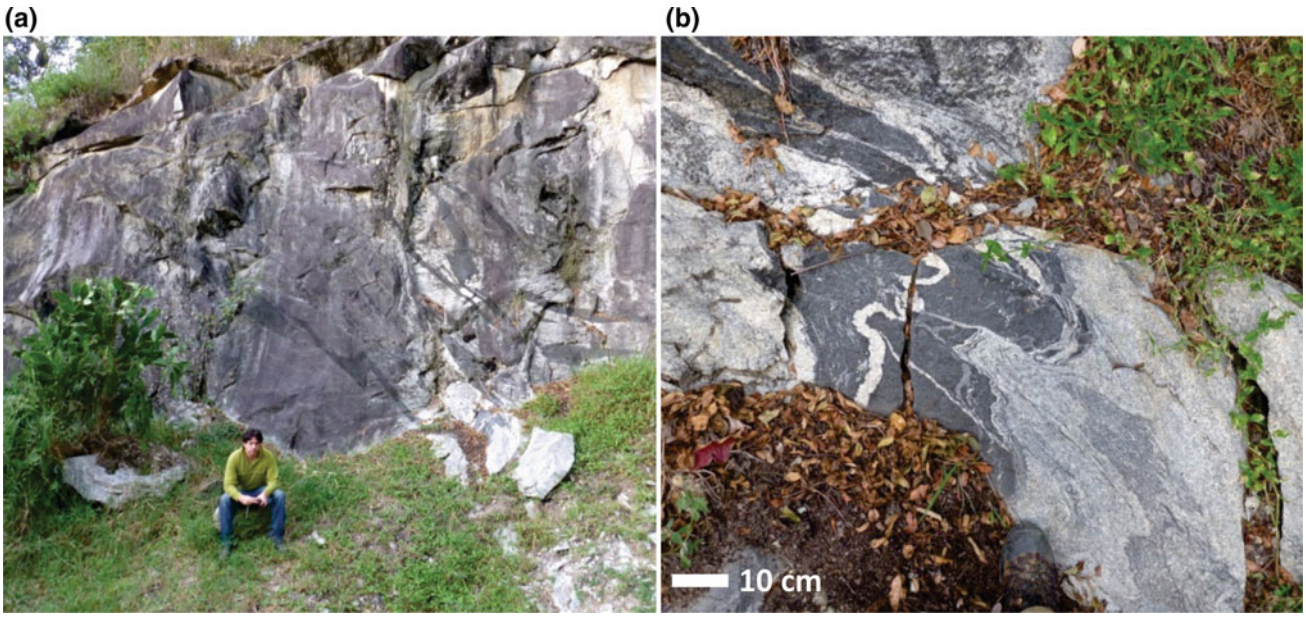

Fig. 2 Example of a gneiss–migmatite rock from the crystalline basement (left), characterized by mesoscopic migmatite features (right)—city of Sete Lagoas, northwest of the Lagoa Santa Karst region (modified from Galvão et al. 2016)

3.1.2 Sete Lagoas Formation: Pedro Leopoldo and Lagoa Santa Members

According to Dardenne (1978), the Sete Lagoas Formation regionally is over the Carrancas Formation or it is in contact with the gneiss–migmatitic undifferentiated complex. Geochronological data suggests that this formation ranges from 740 ± 22 Myr (Pb–Pb—Babinski et al. 2007) to 630 Myr (C-O-Sr—Caxito et al. 2012), or 540 Myr, via fossil investigations (Warren et al. 2014). The sedimentary depositional environment is characterized by a shallowing upward carbonate cycle, with three deposit systems being recognized, according to Lima (1997): internal, intermediary and external ramps. The Sete Lagoas Formation is separated by the members Pedro Leopoldo (bottom) and the Lagoa Santa (top), covering about 80% of the area (Fig. 1b). The lithological contact between the Pedro Leopoldo Member and the crystalline basement is abrupt and/or discordant (tectonic faults) (Table 1). The contact of the Lagoa Santa Member with the Serra de Santa Helena Formation is abrupt (Galvão et al. 2016).

Pedro Leopoldo Member

This member has a significant exposure in the region (about 20% of the total area), occurring especially on the western margin of the Velhas River, bordering the Mata Creek and the cities of Vespasiano, São José da Lapa, Pedro Leopoldo, Prudente de Morais, Capim Branco and Sete Lagoas (Fig. 1b). The Pedro Leopoldo Member overlies the crystalline basement usually by faulting, showing discordant contacts. Dolomites, marlstones, and pelites (less frequent) and fine-grained white limestones (more common) are the rocks from this member (Table 1). This limestone is composed of 85% micrite, 8% sparite and 7% quartz (microscopy analysis), being classified as micrite (Folk 1959) or mudstone (Dunham 1962) (Galvão et al. 2015b, 2016).

In the Sete Lagoas Formation, six lithological facies were described by Vieira et al. (2007), four being recognized in the Pedro Leopoldo Member: Facies A—light grey calcilutite intercalating yellowish pelite displaying hummocky and swaley cross-stratifications, indicating a tidal flat deposits with local storm influence; Facies B—tabular beds and layers of deep-sea sedimentation presenting aragonite crystals; Facies C—dolomites with metric to sub-metric dimensions; and Facies D—light grey calcilutites displaying plane-parallel stratifications and rhythmic terrigenous indicating zones of minor to major agitated marine sedimentation.

Lagoa Santa Member

With the largest exposure in the area (approximately 60%), this member occurs as NW-SE wide strip starting from the Mata Creek valley in the southwest, through the cities of Vespasiano, Confins, Matozinhos and bordering Prudente de Morais and Sete Lagoas (Fig. 1b). The Lagoa Santa Member superimposes the Pedro Leopoldo Member through gradational or abrupt contacts through detachment faults (Fig. 3). Near the contact, an intense occurrence of concordant/discordant calcite veins is observed.

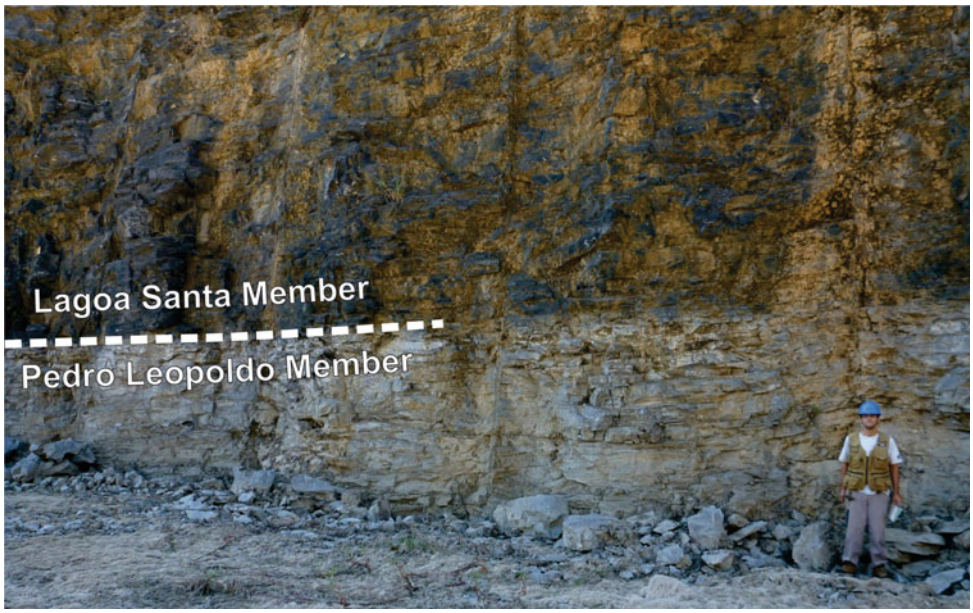

Fig. 3 Exposure of the abrupt contact (dashed white line) between the Pedro Leopoldo Member (impure white limestones at the bottom) and the Lagoa Santa Member (pure grey limestones on the top) in a quarry situated within the city of Sete Lagoas. The yellowish-orange areas are weathered rocks (modified from Galvão et al. 2016)

Overlying the member, metasedimentary rocks from the Serra de Santa Helena Formation occur, usually in tectonic contact (detachment fault). The Lagoa Santa Member is featured by medium-grained grey limestones (Table 1), being classified as grainstone (Dunham 1962), or oobiosparite (Folk 1959) because, in general, the limestones are constituted of 55% sparite, 30% ooids and 15% micrite (microscopy analysis) (Galvão et al. 2015b, 2016). The two remaining facies (Vieira et al. 2007) are: Facies E—grey calcarenites displaying plane-parallel laminations, hummocky and swaley cross-stratifications; and Facies F—well-preserved stromatolites mounds (type *gyminosolens*, Marchese 1974), typical of tidal flat sedimentation.

3.1.3 Serra de Santa Helena Formation

This formation occurs in the SE, NE and NW areas occupying approximately 15% of the region, bordering the cities of Prudente de Morais and Sete Lagoas (Fig. 1b). Regionally, the metapelite rocks overlie the Sete Lagoas Formation with gradational and abrupt contacts (Table 1), being recognized three stratigraphic members, according to Grossi-Sad et al. (1998): (1) lower—carbonaceous dark shales and silt-clay rhythmites (90 m thick); (2) medium—marble and shales (50 m thick); and (3) upper—shales and siltstones with bearing slate cleavage (140 m thick) (Galvão et al. 2016).

Extensional events generated subvertical fractures and relief zones that were filled by quartz veins with hexagonal prisms and, locally, by pegmatite veins composed of feldspar and calcite grains (Viana 1998; Tuller et al. 2010; Galvão et al. 2016). Schistosity (a type of secondary foliation) discordant and concordant with the bedding is present in the rocks, where intercalated slate with well-developed rock cleavage at the bottom of the formation are also noted (Fig. 4).

3.1.4 Cenozoic Unconsolidated Sediments

This Cenozoic unit can be separated into detrital cover, alluvial terraces and alluviums, which can be grouped as unconsolidated sediments (Table 1). They occupy about 5% of the Lagoa Santa Karst area, along the Velhas River and Mata Creek, in some depressions and bordering the cities of Vespasiano, Pedro Leopoldo, Matozinhos, Capim Branco and Sete Lagoas (Fig. 1b).

The detrital cover is characterized predominantly by red color, clayey and sandy sediments with levels of gravel, occurring over all the formations, mainly covering the rocks from the Serra de Santa Helena Formation. Alluvial terraces are common along main rivers (e.g. Velhas River) and streams (e.g. Mata Creek) and their tributaries, as well as in the central urban area of the cities of Sete Lagoas and Capim Branco due to their lower topographies. These terraces can reach 5 m in thickness and consist of yellowish to reddish clayey-sandy semi-consolidated sediments (Fig. 5). The alluviums are common along meanders of significant watercourses, being composed of fine to coarse-grained sediments, with levels of rounded and poorly sorted quartz pebbles.

Fig. 4 Well-developed cleavage slate rocks coinciding with the bedding planes at the Santa Helena ridge (city of Sete Lagoas) (modified from Galvão et al. 2016)

Fig. 5 Cenozoic clayey-sandy sediments with a thickness of about 5 m, with yellowish to reddish color. These sediments are mostly situated along the Velhas River

4 Geological Framework of the Lagoa Santa Karst

The crystalline basement outcrops in the extreme SW of the region and dips to NE direction in a basin border setting context. Because the framework is controlled by faulting, the basement may have different depths over short distances.

According to geological cross sections (Danderfer Filho 1994; Galvão et al. 2016), some detachment faults are observed placing side by side rocks from different formations (Figs. 6, 7 and 8). Rock layers from the Sete Lagoas Formation are horizontally continuous dipping and getting thicker towards the NE being covered in the SE and NE regions by rocks from the Serra de Santa Helena (Figs. 6 and 7). Both formations are thinner towards the SW where the basement outcrops. The thicknesses of the Sete Lagoas and Serra de Santa Helena formations within the Lagoa Santa Karst region can reach, in some places, 300 m and 160 m, respectively.

The Cenozoic unconsolidated sediment thickness is thin compared to other geological formations. According to Viana (1998), these sediments may vary from a few centimeters to several meters. Good examples are seen along the Velhas River, in some depressions, in the central urban area of the city of Sete Lagoas (Fig. 1b), where sediments may reach 40 m in thickness (Galvão et al. 2016), or in the vicinity of the city of Lagoa Santa, where the thickness can reach 100 m (Pessoa 2005).

5 Structural Geology of the Lagoa Santa Karst

The Lagoa Santa Karst region is in the structural domain II, extending from the Velhas River to the extreme western portion of the city of Sete Lagoas (Tuller et al. 2010), being more deformed towards the east and less deformed towards the west. The domain II is characterized by less intense deformation compared to the domain I, located right in the eastern side of the area. It is typical to the domain II the minor presence of isoclinal folds, being more common asymmetric west-verging folds influenced by interstratal sliding.

The structures mapped are foliations, lineations, fractures and faults. Fractures and faults are often associated with drainage valleys and surface alignments of karstified features, where numerous sinkholes and caves can be found. Structural features such as normal faults and low-angle detachment faults between layers were observed by Danderfer Filho (1994), Pessoa (2005), Galvão et al. (2016) and Peñaranda (2016), explaining lithological successions of different ages occurring side by side (Figs. 6, 7 and 8).

According to Danderfer Filho (1991), there were three stages of deformation associated with the Sete Lagoas and the Serra de Santa Helena formations and with the gneiss–migmatitic undifferentiated complex. In the crystalline basement, due to several stages of deformation making it difficult the

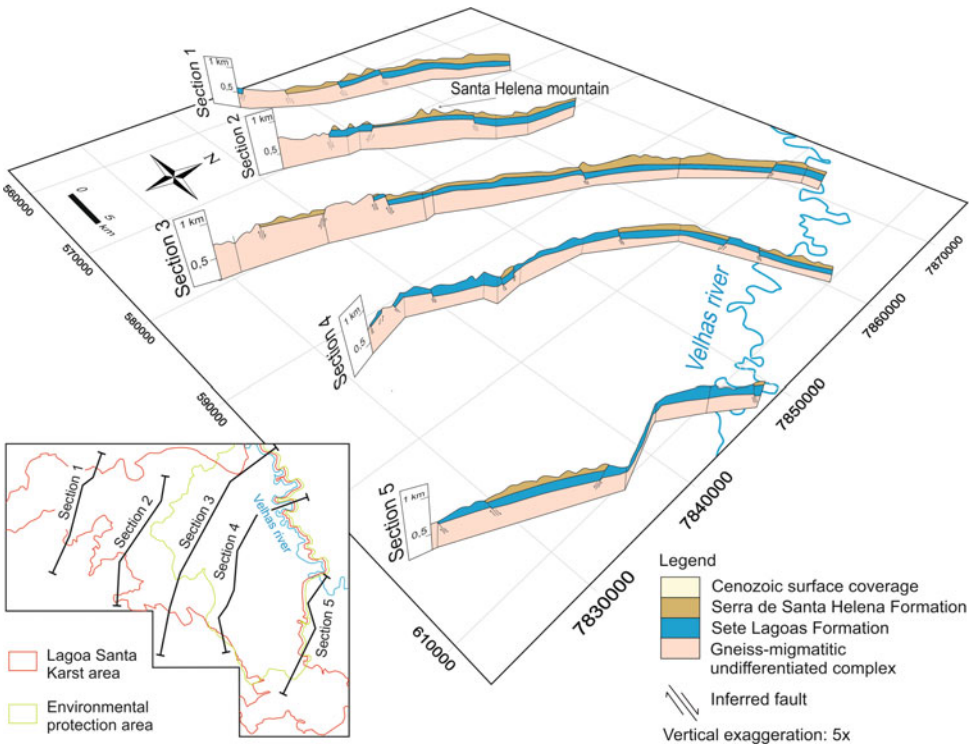

Fig. 6 Geologic SW-NE cross sections indicating the geometry of the basement border, where the gneiss–migmatitic undifferentiated complex outcrops in the SW region dipping to NE directions