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10th IAG INTERNATIONAL CONFERENCE ON GEOMORPHOLOGY

COIMBRA - PORTUGAL

« GEOMORPHOLOGY AND GLOBAL CHANGE »

FIELDTRIP GUIDEBOOK
Littoral (Figueira da Foz – Barra) and Bairrada

14 September 2022

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Coimbra, 2022

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Edition notice:

Title: *10th International Conference on Geomorphology. Fieldtrip Guidebook – Littoral (Figueira da Foz – Barra) and Bairrada*

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Edition: *Universidade de Coimbra, Faculdade de Letras*

Fieldtrip and Guidebook Coordination: *António Vieira (University of Minho)*

Cover: *Village of Costa Nova (photograph by António Campar Almeida)*

ISBN: *978-989-8511-03-4*

Introductory Note

The 10th International Conference on Geomorphology will take place in Coimbra (Portugal) from 12th to 16th September 2022, under the theme "Geomorphology and Global Change" and it is organized by the International Association of Geomorphologists (IAG) and the Portuguese Association of Geomorphologists (APGeom).

As in previous international conferences on Geomorphology, and as is the tradition in many geomorphological events organized around the world, the organizing committee of the 10th International Conference on Geomorphology proposed several fieldtrips to the participants, occurring before, during and after the main event.

These fieldtrips intend, above all, to show to geomorphologists from all over the world the diversity and richness of the geomorphological elements of the Portuguese territory (and also from Cape Verde) and to allow an exchange of experiences between the specialists that investigate these territories and the visitors, contributing for mutual scientific enrichment and for the valorization of this international conference.

The pre-conference fieldtrip is dedicated to the islands of Santiago and Fogo, in the Archipelago of Cape Verde. It will take place from 6th to 9th September and will be led by colleagues from the University of Cape Verde (Vera Alfama, Sónia Victória, Sílvia Monteiro, José Maria Semedo and Romualdo Correia). The volcanic geomorphology will dominate the visit (including well conserved structural volcanic forms such as cones, domes, craters and calderas), especially in the island of Fogo where recent volcanic activity has been registered.

The one-day mid-conference fieldtrips will take the visitors around the Portuguese mainland territory, the 14th September, allowing the visit of four different geomorphological realities.

In the Arouca UNESCO Global Geopark, internationally recognized territory since 2009, participants will be able to visit unique geological and geomorphological features (such as planation surfaces, bowl-shaped valleys and narrow river valleys) and witness the remarkable effort of protection and promotion of natural (abiotic and biotic) and cultural (tangible and intangible) heritage. The visit to the “516 Arouca” suspension bridge will be an excellent opportunity to observe the magnificent landscapes of this mountainous territory. This fieldtrip will be led by Artur A. Sá, António Vieira and Daniela Rocha.

The field trip to coastal areas of central Portugal will be led by Pedro Dinis and António Campar Almeida. Their proposal is to observe the different morphotectonic units of central west Portugal, namely the Coastal Mountain of Serra da Boa Viagem (revealing karstification features), the littoral plain (with aeolian dunes associated with some reliefs with higher elevation), the Cértima subsiding area (structurally-controlled morphology), and the Buçaco region (with the Syncline of Buçaco).

The visit to the Schist Mountains of Central Portugal will be centered in the mountains of Lousã and Açor, and will be conducted by Luciano Lourenço and Bruno Martins. It is proposed the observation of the main contrasts of the landscape, especially in terms of its physical geography, translated into geological, hypsometric, geomorphological, and hydrographic differentiation, or the land use and occupation and evolution of vegetation cover, namely following the recurrent large forest fires and the subsequent erosive processes they caused.

The fourth one-day fieldtrip will be oriented to the Estrela UNESCO Global Geopark, and led by Gonçalo Vieira, Emanuel Castro and Fábio Loureiro. The main geoheritage significance of the Estrela UGGp is the extent and richness of the Late Pleistocene glaciation(s) landforms and deposits (with spectacular morphological features such as the Zêzere glacial valley or the glacial cirques, moraine boulders, erratics or *roches moutounnées*) as well as the peculiar long-term geological evolution (revealing a significant diversity of granite types and landforms).

The three post-conference fieldtrips include a visit to the Lisbon Region, Serra da Estrela and, finally, Minho and Galicia (Spain), and will take place from 17th to 19th September.

The fieldtrip to the Lisbon Region will be guided by José Luís Zêzere, César Andrade, Sérgio Oliveira, Jorge Trindade and Ricardo Garcia, and will cover topics related with slope instability and landslides that affect the region of Lisbon, the floods occurring in the area north of Lisbon, and the coastal dynamics, morphology, cliff instability and beach erosion at north and south of Lisbon.

The three days field trip to the Serra da Estrela is led by Gonçalo Vieira, Emanuel Castro and Fábio Loureiro. Participants will be taken to visit some of the Geopark's most inaccessible geosites and observe breathtaking landscapes during two hikes: one in the Zêzere valley and the other between Penhas Douradas and Lagoa Comprida. The different geosites to visit include features of glacial, periglacial, granite weathering, fluvial, hydrogeological, petrological and tectonic themes, and aspects related with the management of a UNESCO Global Geopark will be discussed.

The third three-days fieldtrip is destined to the northwestern part of Portugal and the Spanish region of Galicia. Guided by Alberto Gomes and Antonio Perez Alberti, will be mainly devoted to the coastal area and to the observation and discussion of issues related to coastal dynamics, marine terrace staircases, differential uplift of coastal blocks, coastal geoheritage, coastal geoarchaeology, coastal erosion and coastal land planning.

It is our expectation that these visits will please all participants and promote the scientific enrichment of all involved, allowing a better understanding of the topics covered in each one.

We also hope that this set of fieldtrip guidebooks can help in the understanding of the themes discussed and that they can be a testimony of the commitment and dedication shown by all the scientific responsible for the several visits, to whom the organizing committee of the International Conference on Geomorphology expresses its greatest recognition and gratitude.

have a good fieldtrip!

Lúcio José Sobral da Cunha
António Vieira

on behalf of the ICG2022 Organizing Committee

ITINERARY AND SCHEDULE

Itinerary

08:00 - Departure from Coimbra (Largo D. Dinis)

9:15 – 9:45 - Stop 1 – Doline in Serra da Boa Viagem

10:00 – 10:20 - Stop 2 – Viewpoint of Bandeira

10:35 – 11:10 - Stop 3 – “Casa dos Cogumelos”

11:25 – 11:40 - Stop 4 – Pond of Braças (Quiaios dunes)

12:10 – 12:20 - Stop 5 – Vagueira

12:30 – 13:00 - Stop 6 – Barra de Aveiro

13:00 – 14:30 - (Technical stop and lunch)

14:50 – 15:15 - Stop 7 - “Pateira de Fermentelos”

15:35 – 15:50 - Stop 8 – Arcos de Anadia

16:30 – 16:50 - Stop 9 – Cruz Alta

17:15 – 17:35 - Stop 10 – Chã da Mata

18:00 - Arrival in Coimbra

Introduction

The field trip Littoral-Bairrada (Fig. 1) will cover different morphotectonic units of central west Portugal (Fig. 2). Considering the order of the stops, these units are: (1) the Coastal Mountain of Serra da Boa Viagem, which is associated with a northward thrusting in the Quiaios Fault, (2) the littoral plain, a very dynamic low elevation region, strongly affected by coastal processes, where aeolian dunes are associated with some of the reliefs with higher elevation and the outcrop of the phreatic level in lower locations allowed the development of small freshwater lakes; (3) the Cértima subsiding area, characterized by several structurally controlled sectors that experienced independent geomorphological evolution during the late Pliocene-Quaternary; and (4) the Buçaco region, where the Porto-Tomar Fault Zone, underlining the limit between the Variscan Massif and the Meso-Cenozoic coastal margin, and the quartzites of Buçaco syncline have a major influence on local geomorphology.

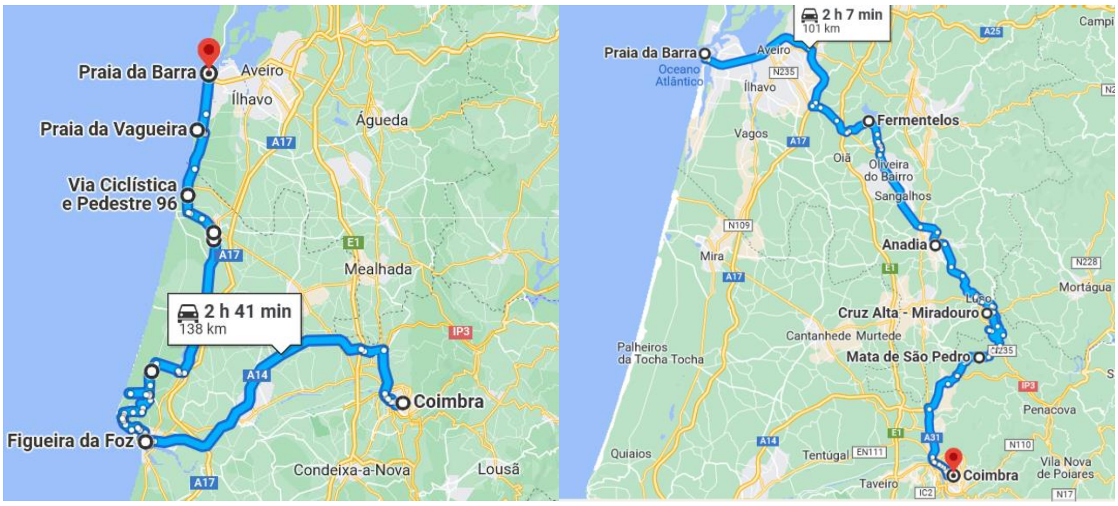

Figure 1. Morning itinerary (L) and afternoon itinerary (R) (Source: Google Maps).

Ten stops were selected for this field trip in order to provide snapshots of key positions for the understanding of the geomorphological evolution of West Iberia. Some of the following topics will be addressed:

- The Variscan deformation, which culminated with Pangea amalgamation, and its present imprint on the geomorphology of West Iberia;
- The Pangea break-up and the opening of the Atlantic Ocean, with reactivation of Variscan structures and deposition of diverse carbonate and siliciclastic series in the Lusitanian Basin of west Iberia;
- The sub-aerial exposure of Mesozoic carbonate successions and its karstification conditions, which affected even units with relatively high clay content

- The Neotectonic activity and the way it shaped drainage patterns in the fringe at the contact between the Atlantic Margin and the Variscan Massif;
- The Pliocene-Pleistocene landforms and nearshore deposits presently preserved in elevated regions of littoral mountains (Serra da Boa Viagem), in the eastern edge of the Variscan Massif, and in flattened regions between these reliefs;
- The history of aeolian sand invasion and its relation with the development of small and shallow freshwater lakes;
- The present forms of human occupation and use near a coastline that displays features typical of wave-dominated high energy settings with undoubtful associated risks.

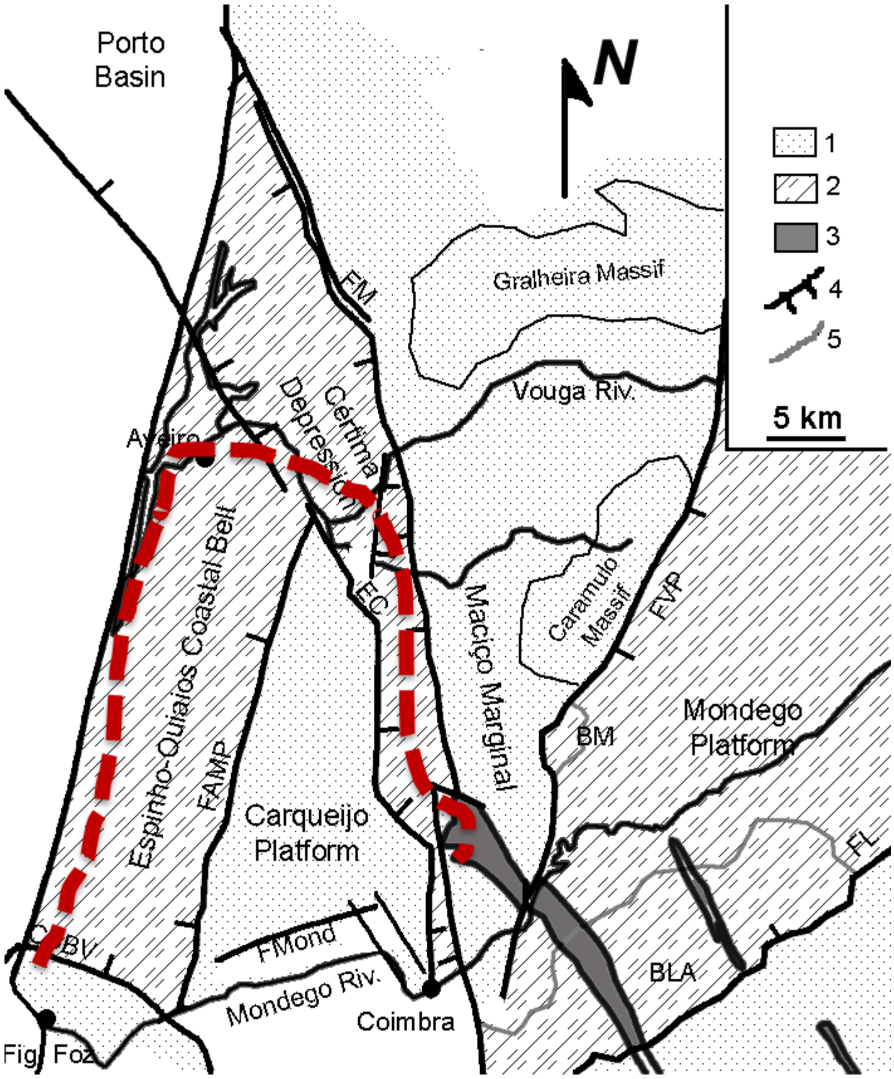

Figure 2. Main morphostructural units observed in the field trip. Approximate path indicated by dashed red line. 1: Uplifted sectors; 2: Subsiding sectors; 3: Quartzite ridge; 4: Major tectonic structure; 5: Main rivers; FM: Marginal Fault; FVP: Verin Penacova fault; FL: Lousã Fault; EAMP: Arunca Montemor Palhaça axis; CSBV: Serra da Boa Viagem thrust; Fmond: Mondego Flexure; BM: Mortágua Basin; BLA: Lousã Arganil Basin.

Stops are described below.

Stop 1. Dolines, karstification

The Serra da Boa Viagem with a carbonate succession that is covered by sandstones, particularly in the southern slope. Despite occasionally high clay and sand content, these units show an important karstification, especially with dolines. Nevertheless, other karst landforms are present such as lapies, swallow holes and caves. The lapies are spread through the upper surface and in the quaternary platforms. They are rounded because of the sandy cover and wave erosion when the sea was building these platforms during Quaternary interglacial periods. They can be classified as buried lapies (Cunha, 1988).

The swallow holes make, often, the linkage between dolines and caves because most of the dolines have a hole in their deepest points. The caves, which can be seen one or two in the landscape, are deduced when opened swallow holes let us listen water running in the depth. They must be narrow caves because the marly limestones are not favourable to the karstification.

There are about 150 dolines over the Serra da Boa Viagem (Fig. 3). Groups of them are oriented particularly W-E and N-S, which is more or less parallel to main geological lineaments and according to some transverse faults, respectively. In fact, the thicker and carbonate-enriched Bathonian, Oxfordian Kimmeridgian units allowed more intense chemical decomposition and faulting promoted water infiltration and thus increased rock dissolution. In general, the dolines can vary in size between 2 and 85 m length and 0.5 and 15 m in depth (Almeida, 1997). Curiously, the greatest ones appear in sandstones from the lower part of the Kimmeridgian succession (Fig. 4).

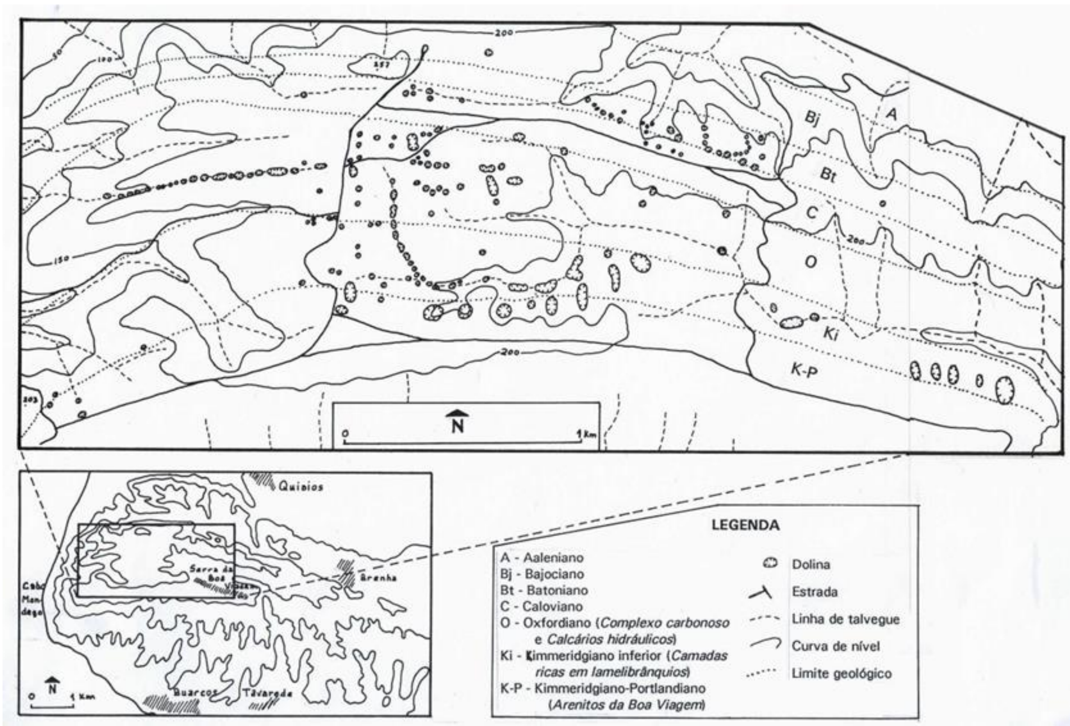

Figure 3. Doline distribution on the Boa Viagem mountain. From Almeida (2001).

Three types of dolines can be seen: funnel-shaped dolines, dish-shaped dolines and asymmetrical dolines. A lot of them are composite dolines with a funnel-shaped doline embedded into a dish-shaped doline (Almeida, 2001).

Usually, the holes in the dolines absorb all the water that flows on local watersheds.

Figure 4. A funnel shape doline, a year after a wildfire, and a swallow hole at the deepest point of a doline.

<u>Genetic process</u>
The dolines have almost all been developed on the upper part of the hill, between 257 m and 170 m above sea level. The beginning of its formation took place only after the retreat of the sea that had sculpted the surfaces where they stand, which is witnessed by coarse sandy to conglomeratic nearshore deposits, attributed to the end of the Pliocene or the early Pleistocene. With the marine regression, a fluvial incision developed with wide valleys that display rounded floors and, at the same time, the limestones were chemically attacked under a sandy permeable cover. The dish-shaped dolines would then have formed in this process. With the starting or continuation of the Serra da Boa Viagem uplift, the karstification deepen through the digging of pits and caves whose action has accelerated the vertical development of the dolines. A funnel shaped form can be ascribed to the fact that each doline have a little swallow hole in their bottom where the water flows down. The funnel-shaped dolines embedded in the dish-shaped dolines also resulted from the appearance of a swallow hole inside them.

A curious aspect is the presence of some of the largest dolines, such as the one to be visited, located in the outcrops of Upper Jurassic sandstones (Kimmeridgian- Tithonian), without calcium carbonate component. The explanation can be found in the local fracturing of these sandstones which allowed the attack of the underlying limestones, also fractured, and therefore with a greater surface of exposure to aggressive waters.

Stop 2. Viewpoint of Bandeira

Right below the viewpoint, a very steep scarp, about 150 m height, is very evident (Fig. 5, L). Its genesis has been attributed to an erosion scarp, but the contribution of a faulty movement must not be completely excluded. The possibility of thrusting of the Middle

Jurassic units over the marly Toarcian can be considered, but it still requires confirmation. Just at the northern end of the Serra da Boa Viagem, a lower scarp put in contact the Lower Jurassic limestones with Quaternary sands of Gândara. This contact also probably resulted from the action of an inverse fault (Cabral, 1993).

Figure 5. Scarp of Bandeira and scarp of Serra da Boa Viagem and Gândara in the background.

Looking to the northeast, a flat surface north of the Serra da Boa Viagem can easily be observed, where several villages stand out, interspersed with agricultural land and pine or eucalyptus forests (Fig. 5, R). It is Gândara, a term that etymologically means unproductive sandy land, despite offering various agricultural and animal productions at the expense of much effort on the part of its inhabitants. It consists of essentially parabolic dunes associated with transport from northwest to southeast, already very erased by runoff (Fig. 6). Gândara sands are associated with the oldest generation of dunes whose age has been attributed to the last glacial period (G. S. Carvalho, 1964) or, at least, a thousand years ago, if they are equivalent to dunes with similar soils near Cortegaça (Carvalho and Granja, 1997). In fact, they display well-developed podzols with a thick ferruginous hard horizon, Bs, which differentiates them from other more recent dune generations located to the west until the ocean (Almeida, 1997). At its western limit there is a sequence of interdune ponds which are thought to have been created by the advance of the most recent dunes to the east, having blocked the circulation of water towards the sea and contributed to the groundwater rising in the oldest dune forms.

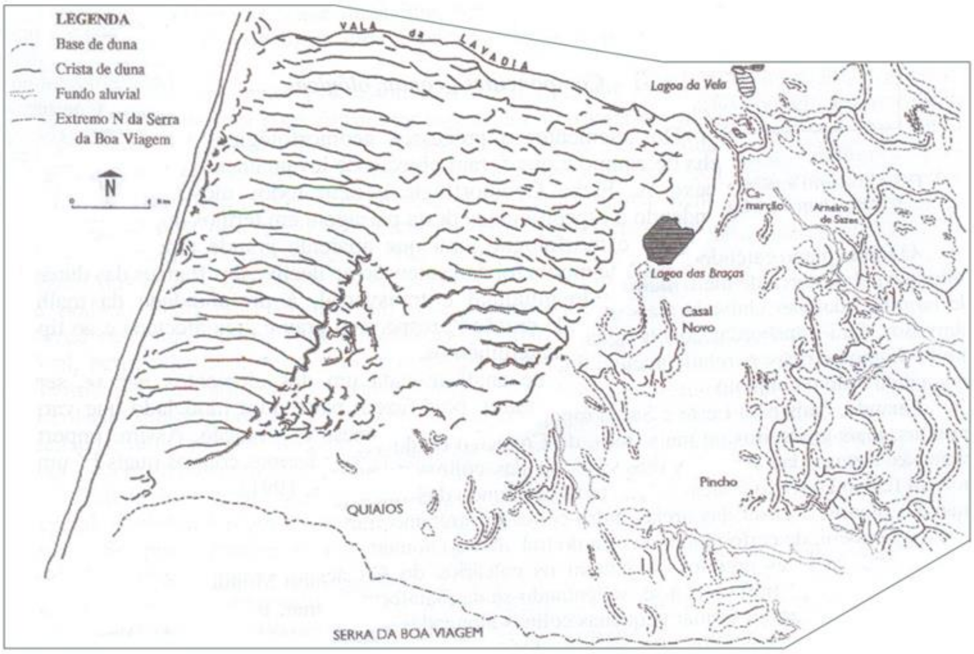

Figure 6. Dunes immediately north of Serra da Boa Viagem. From Almeida (1997).

Stop 3. Casa dos Cogumelos (Mushrooms' House)

At about 8 m high, there is a marine abrasion surface sculped on the Jurassic limestones that is a few tens of meters wide and finishes inland by a paleo-cliff close to Casa dos Cogumelos, easily remarkable where it was exhumed (Fig. 7). The abrasion surface is covered by coarse sand with well-rounded quartz pebbles, passing upwards to well sorted finer-grained sands, considered to be of aeolian origin. These deposits record a former beach level, Praia da Murtinheira, attributed to the last interglacial period and, thus, equivalent of the lower elevation fluvial terrace in Mondego valley (i.e., M5 level of Ramos *et al*., 2010). Occasionally, the beach succession at Praia da Murtinheira reaches a thickness of more than 1 m, and these sediments can be intercalated with heterometric calcareous and solifluxive beds (Soares *et al*., 1993).

Heterometric deposits covering the beach units were deposited in a continental environment, during marine regression and with a nearby source. At the base of the paleo-cliff, clasts are disposed chaotically, with limestone blocks and pebbled and some aeolian sandy matrix. It seems to be associated with talus deposits at the bottom of the cliff, after it was abandoned by the sea in sharp retreat.

Immediately to the west, the stratification begins to be noticed, revealing paraconglomeratic and orthoconglomeratic beds that are intercalated with aeolian sands. Sometimes, sands are observed only as the matrix of the coarser strata. The low percentage of fines, the persistence of aeolian sands, at least as a matrix, and the paraconglomeratic-orthoconglomeratic character of the coarser levels indicate a cold and dry environment (Soares *et al*., 1993).

Figure 7. Deposit of Casa dos Cogumelos above the present calcareous cliff.

Above and more or less in the middle of the deposit, there is a muddy-clayey, greyish-brownish sequence, with rhizoconcretions, which can be associated with a paleosoil, suggesting warmer and more humid period (idem, ibidem). The upper part of the deposit, better stratified and enriched in fine-grained matrix relative to the lower part, is organized in finning-upward sequences, suggesting transport by water and a topography already shaped by stream incision, with the cliff being practically fossilized. This would be the result of deposition by solifluction movements and torrential flows. Climatic conditions are said to be cold and humid (Soares *et al*., 1993).

Apparently independent of the development of the referred deposits, the Vale de Anta presents its slopes with frequent cryoclastic materials, in particular at the base of ledges (layer cliffs) (Ramos *et al*., 2018). They were formed by gravity fall and are constituted by angular calcareous clasts, with more or less fine sandy matrix, mostly aeolian. These deposits seem to be younger than the Casa dos Cogumelos unit but also belonging to the last glacial period (Almeida, 1997). More studies are required to improve their stratigraphic assignments.

Stop 4. Pond of Braças (Quiaios dunes)

The dune field developed to the north of Quiaios is composed of aeolian sands which were carried and deposited under favourable conditions at least since the last Quaternary glacial period. Using a methodology based on the analysis of borehole lithological sequences, of C14 dating and of palynological data it was possible to establish a coherent history of the dunes and pond formation in Quiaios region (Danielsen *et al*., 2012).

The truncated dunes from the Gândara were formed during the Pleistocene, mainly by the time of the Younger Dryas crisis. The last major sea retreat exposed wide beach and nearshore sediments that could be blown by strong winds. In fact, these sands cover a lacustrine layer with the minimum age of about 12000 yr BP (idem, ibidem).

In a triangular area north of Quiaios (Fig. 6) and in other small areas east of the recent dune field, there are generally parabolic dunes with a dominant SE orientation, lower in altitude than the younger dunes and showing more evolved soils (Almeida, 1997). This is a second generation of dunes, which would have developed after a phase of intense deforestation, which ended around 1600 yr BP, followed by a sparse heath favorable to the development of parabolic dunes (Danielsen *et al*., 2012).

Westwards from the lakes and up to the foredune, a 6 km wide dune field is maintained, with an undulating morphology thanks to the existence of linear dunes that overall strike W-E (Fig. 5). The degradation of the heathlands and the climate conditions around 500 yr BP, with the beginning of the Little Ice Age and the prevalence of a negative NAO (North Atlantic Oscillation) (Clarke & Rendell, 2006), allowed the rapid development of the third generation of dunes (Danielsen *et al*., 2012). At the beginning of the 20th century, they were still moving inland, which lead to human intervention through maritime pine seedlings, from 1924 to 1940, to fix them (Rei, 1940). The interdune lakes of Braças and Vela (Fig. 8), as the others to the north, were successively pushed to east because of the inland sand drifting (Danielsen *et al*., 2012).

Figure 8. Interdune lake of Vela, which is 1500x500 m long.

Stop 5. Vagueira beach

In 1978 was built the seawall of Vagueira and one year after a groin at its south. It was the result of the fast coastline retreat, the weakening or even disappearance of the foredune and the missing of sand on the beach. Nevertheless, the retention of the little longshore drifting sand in front of Vagueira has increased the downdrift coastline retreat and forced the construction of another groin on Labrego beach in 2002. After storms in 2001 and in October 2011 the spit just south of this groin was cut and the sea and Aveiro lagoon connected temporarily (Fig. 9, L). The deposition of sediments to rebuild the foredune was performed and that channel was closed. Finally, in 2015 an artificial foredune was raised between Labrego and Areão beach, with the contribution of dredged sediments from the lagoon of Aveiro. Numerous palisades have allowed the increasing of the dune height through the accumulation of aeolian sands (Fig. 9, R).

Figure 9. Road cut by the sea overtopping in Labrego (Nov. 2011) and artificial foredune close to Areão beach (2018).

Figure 10. The Vagueira seawall in collapsing process (Feb. 2014) and the new dyke (nowadays).

The surface where is settled Vagueira is only 3 to 5 meters above mean sea level, which is a major problem under the scenario of possible sea level rising of 1 m until 2100 (Andrade *et al*., 2006). At this moment, during the highest tides the sea water almost reaches that level in some places. In addition, it must be considered the effect of storm surges which may reach a little more than 1 m in northern Portugal (Gama *et al*., 1997). Thus, what must be done in the future to protect Vagueira? A dyke along the coast (Fig. 10) and another along the lagoon edge? How much costs the building and maintenance of this kind of hard structures? Is this sustainable?

An economical approach developed by Maia *et al*. (2015), comparing the costs and benefits in scenarios of protected coast and not protected coast, concluded that for Vagueira in the near future, although negative, the Net Present Value should be much lower in a not protected coast than in a protected coast. The difference could be about -2,4 million euros against -15,7 million euros, respectively.

Stop 6. Barra de Aveiro

With the stabilisation of the sea level for 3000-5000 yr BP (Dias *et al*., 2012), after the Flandrian rising, the coastline started evolving according to the balance between the sediment removal by coastal agents and sediment feeding. At least in the 9th century (eventually after the 1st/2nd centuries) a spit started to form southwards from Espinho, as a result of the south-directed littoral drift. In 1200 the spit tip was located in Torreira, in1500 in S. Jacinto, in 1643 in Vagueira and, finally in 1757 it reached Mira, almost closing the Aveiro lagoon (Pereira *et al*., 2020). During the first period of evolution of this spit, corresponding to the Medieval Climatic Optimum, the progression rate was the greatest (130 m/yr), decreasing significantly during the Transition period (40 m/yr) and increasing again during the Little Ice Age (70 m/yr) (idem, ibidem). The lagoon closure can be seen as a consequence of its natural evolution as a result of the action of oceanic and continental drivers. Due to the economic weight of Aveiro and its region, in 1808 was opened an artificial outlet close to this city. Its maintenance was not easy during the 19th century and the first half of the 20th, but in 1958 a jetty was built, to stop sand entrance in the inlet, which was increased in 1987, because the drift sands were entering again. Dredging has been maintained to ensure access conditions for the ships that use the port of Aveiro.

The jetties building started the coastline retreat to the south of the outlet. A maximum erosional rate of 10 m/yr happened between 1958 and 1973 (Oliveira *et al*., 1982, apud Dias *et al*., 2012). This coastline retreat forced the building of groins to hold the sands in front of Barra and Costa Nova towns. Other issues that are affecting natural foredune evolution in these beaches are the installation of walkways and cafés over the foredune (Fig. 11). These hard structures difficult or inhibit the growth of vegetation characteristic of this environment, such as the marram grass (Ammophila arenaria subsp. arundinacea H. Lindb.) the main dune builder. In front of the cafés, the vegetation growth is hindered to maintain the sea sight. In this case, the aeolian sand flow faster to inland, threatening houses located just at the back of the dune. An extreme situation can be seen in Costa Nova, where the foredune was cut to install a residential quarter (Fig. 12). All these examples have increased very much regional wave and wind exposure, turning the risk of being overtopped very high.

Figure 11. Walkway and cafés over the foredune in Barra (Nov. 2021).

Figure 12. Costa Nova. A residential quarter where there was the foredune and cafés over the beach.

Stop 7. "Pateira de Fermentelos"

"Pateira de Fermentelos" is a small lake in a subsiding area at the downstream sector of the structurally-controlled Cértima River valley. It is placed at the confluence of Cértima and Águeda rivers. Strictly speaking, the Pateira is 3.5 km long, but in a broader perspective it is related to a narrow subsiding strip that extends from further south for 12 km^2. In the vicinity of "Pateira de Fermentelos", the course of Cértima is influenced by tectonic structures striking roughly NW-SE and NE-SW, which also control the shape of the small lake (Fig. 13).

When the Águeda River crosses the constraint imposed by a SW uplifted block, its sediment load is directed to the "Pateira de Fermentelos", developing a deltaic accumulation with approximately 2 km^2. The Cértima River does not have the same capacity to build deltaic accumulations in the small lake, mainly because the sediment loads are transported along a subsiding corridor, with a trend for being deposited before reaching the maximum subsidence sector of "Pateira de Fermentelos". Furthermore, the average altitude and area of Cértimas's catchment are lower than those of the Águeda River, hence carrying less sediment.

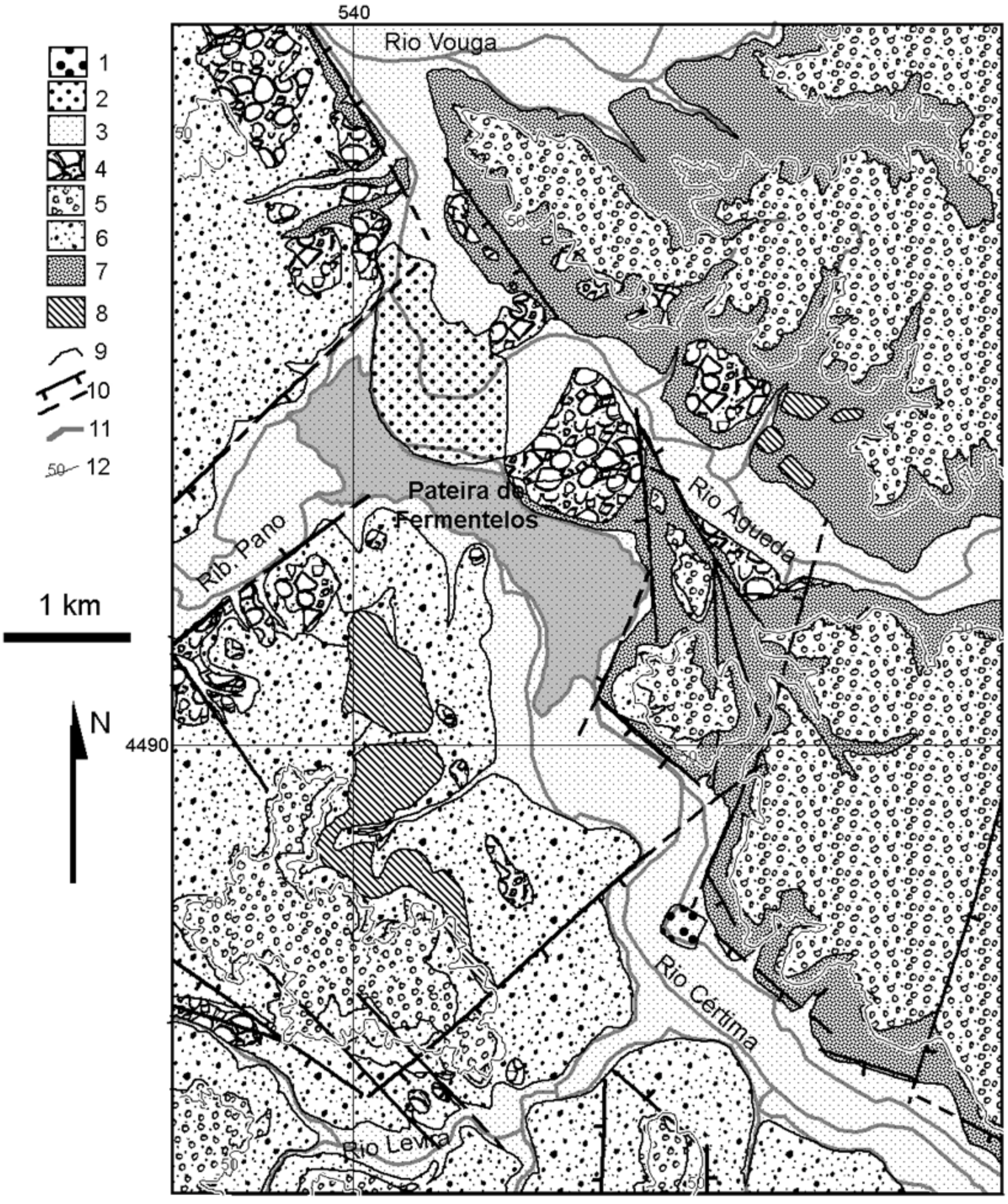

Figure 13. Morpho-sedimentary units in Pateira de Fermentelos. 1: Talus cone; 2: Águeda Delta in "Pateira de Fermentelos"; 3: Alluvium; 4: Terrace; 5: Pliocene and Quaternary sediments that precede fluvial incision; 6: Cretaceous; 7: Triassic; 8: Strath terrace associated with the fluvial incision level; 9: Geological contact; 10: Fault (with indication of the downed block)/hidden fault; 11: Hydrography. 12: 50 meters elevation. From Dinis (2004).

If today the "Pateira de Fermentelos" is a water body detached from the "Ria de Aveiro" (Vouga estuary), during the final stages of the Flandrian transgression (~5-3 ka), when the river valleys were not so filled with sediment, it must have been associated with an arm of that coastal system. About a century ago it was already argued that the outlet of the Vouga was placed in a wide gulf that extend through the lower reaches of rivers Águeda and Cértima (Girão, 1922; Souto, 1923). By the time of the maximum of the Flandrian transgression, the "Pateira de Fermentelos" would be linked to an arm of a structural estuary (Estuary of Vouga), with its limits conditioned by variations in sea level and sediment yields, but above all by tectonic activity.

Stop 8. Arcos de Anadia

Within the wide subsiding area of Cértima, some uplifted sectors are also recognized. The best examples are the horsts of Arcos and Quintela das Lapas. The Horst of Arcos is a tilted block with Upper Triassic to Lower Jurassic outliers that separates subsiding sectors where rivers Cértima and Serra are presently emplaced.

To the NW of Arcos Horst there is a linear valley, approximately 1-1.5 km wide, which follows the contact between two platforms at distinct elevation and where the trainline was constructed. The cross-sectional morphology of that valley does not seem compatible with the small stream that flows there, but is comparable to that of the Cértima valley upstream from the confluence with the Serra River. Given the position of the various uplifted and subsiding areas around Arcos Horst, is conceivable to assume that the valley to the NNW with the trainline records a former path of Cértima River (Fig. 14). Two sub-parallel north-flowing rivers were then separated by the Sangalhos Platform, which is aligned with Arcos Horst and displays similar width.

Diverse mud-dominated alluvial-lacustrine units, which can be intercalated with sand and gravel deposits, in particular in upper portions of the succession and closer to the uplifted marginal Massif were deposited in Pliocene-Pleistocene analogues of the Pateira de Fermentelos. The large variations in the thickness of these units in the region indicate that their deposition took place under strong structural control. Thickness is greater in the Cértima Depression, decreasing to the East and West, being highest (~50 m) in small localized sectors, allowing the definition of discrete sub-basins. This alluvial-lacustrine succession covers inner shelf to fluvial sand-dominated deposits that does not show significant variations in thickness, indicating that they precede the main phases of tectonic activity (Fig. 15).

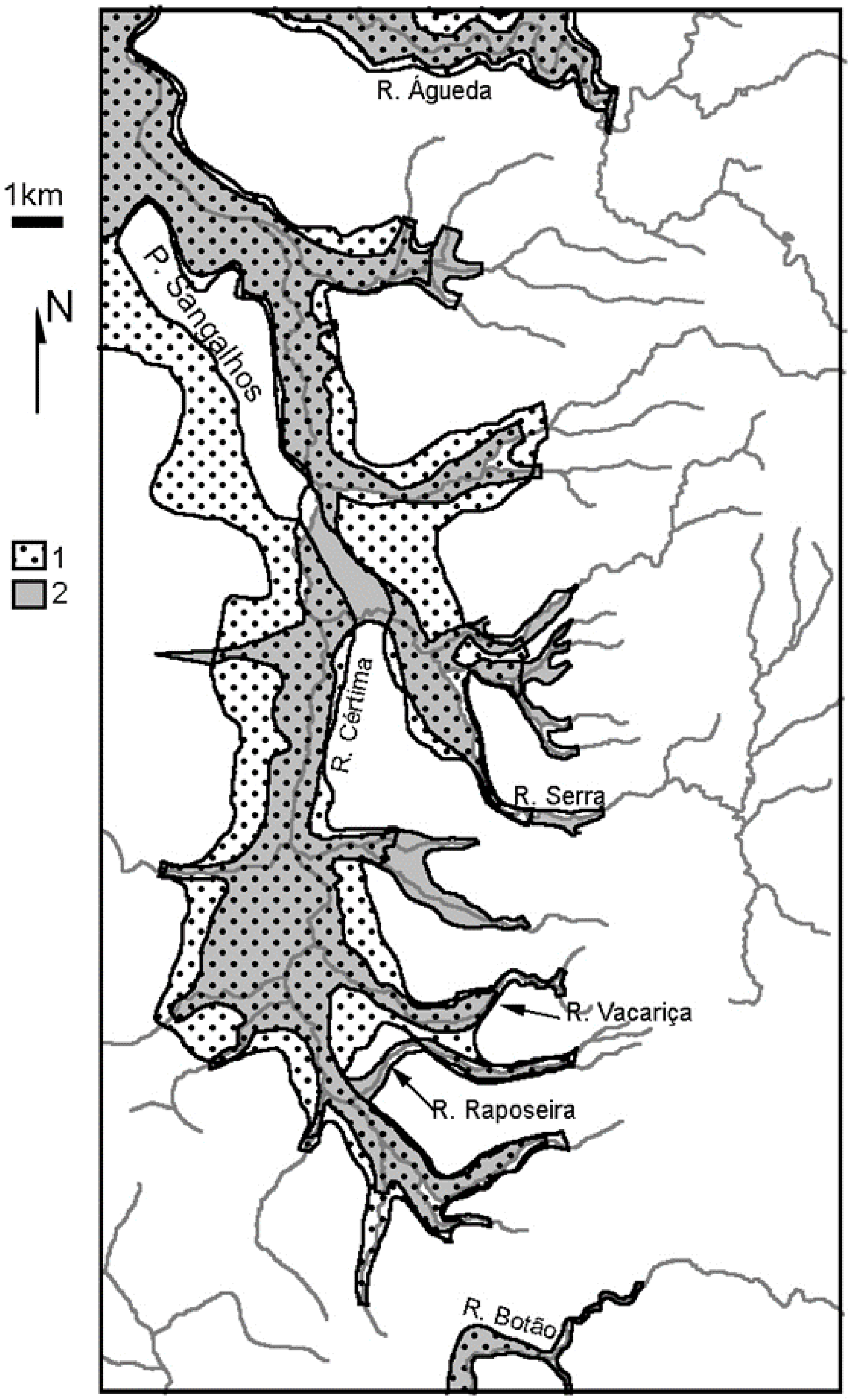

Figure 14. Different paths of the main rivers within the Cértima subsiding area based on the distribution of Pleistocene terrace deposits and alluvial-lacustrine units that precede Quaternary fluvial incision. 1: A former situation with Cértima path along a graben to the west of the uplifted Sangalhos area, which is aligned with the Arcos horst. The confluence of Cértima and Serra rivers took place in "Pateira de Fermentelos"; 2: Paths similar to present conditions. From Dinis (2004).

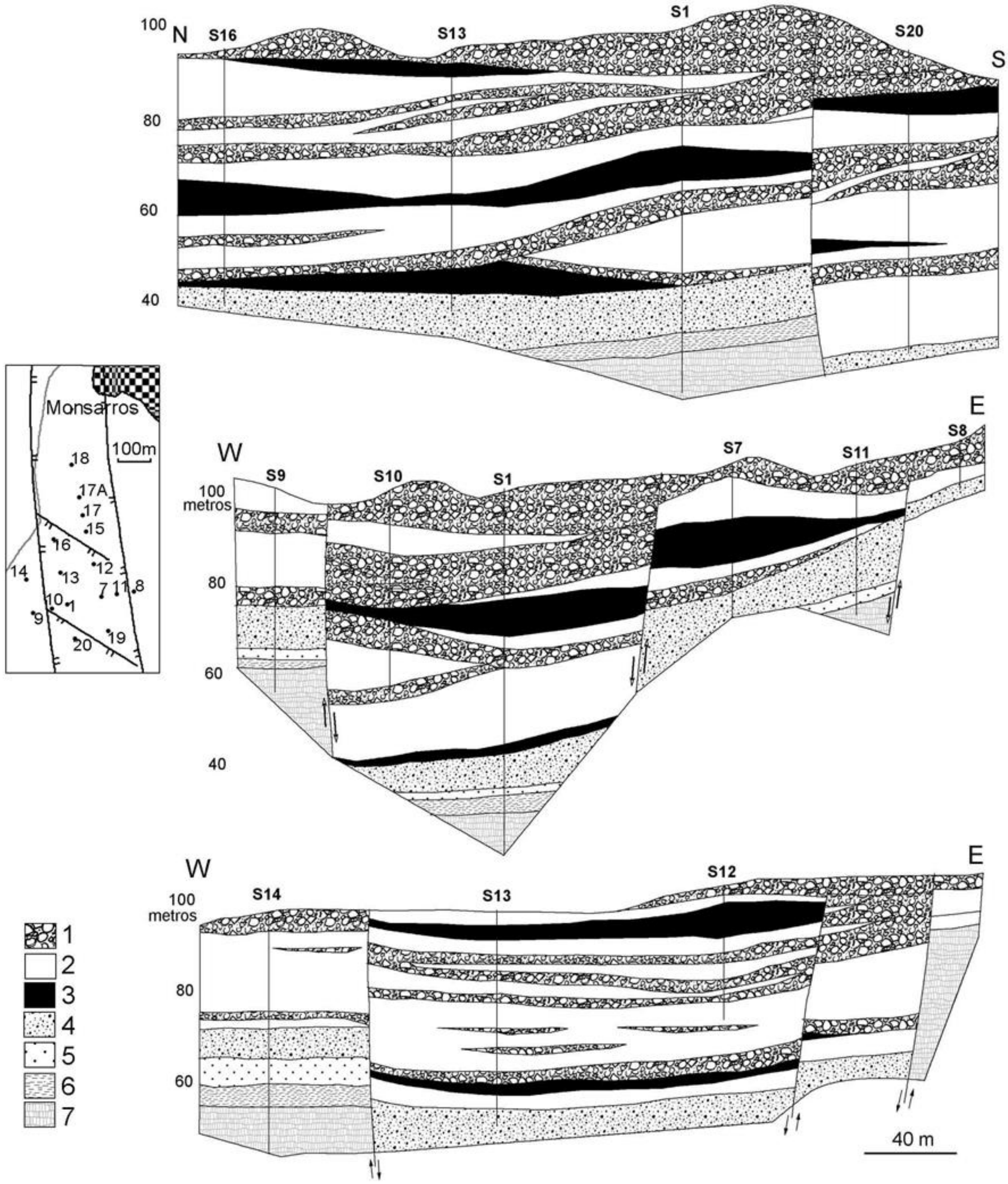

Figure 15. Synthetic, transverse and longitudinal geological sections of a graben (oriented North South) to the south of Arcos Horst. Sections based on field and borehole data. 1: Alluvial fan conglomerates; 2: Sandy-muds, usually stained; 3: Black clays and lignite; 4: Moderately sorted medium to coarse sands; 5: Fine to very fine inner shelf sands; 6: Decalcification clays covered pebbly-sands; 7: Jurassic marls and limestone. From Dinis (2004).

Stop 9. Cruz Alta

Cruz Alta is placed at the NNW end of "Serra do Buçaco", a ridge associated with the NE flank of Buçaco syncline. Orographically, Serra do Buçaco reaches its maximum elevation in the proximity of the Cruz Alta gate (560 m). It is associated with Ordovician quartzites that are commonly found close to the axes of major folds of the Variscan Massif of Iberia supporting quarzitic reliefs.

These reliefs are considered to result from the contrast in terms of resistance to mechanical breakdown and chemical decomposition between these rocks and the evolving and covering units, with tectonics playing a minor role (Molina *et al.*, 1989; Martín Serrano, 2000). However, at the contact between the Marginal Massif and the coastal region to the west we can see numerous evidences of deformation, which are known for long (Birot, 1949; Ferreira, 1991; Daveau *et al.*, 1985-86; Soares *et al.*, 1993). Thus, tectonics must have played a supplementary role, contributing to the uplift of the Syncline of Buçaco relative to the regions to the west and east (Fig. 16). Basically, the syncline of Buçaco was formed during the first phase of Variscan deformation (Ribeiro *et al.*, 1990; Simancas, 2019). It was then reshaped later Variscan or Alpine tectonic movements. Presently the axis of the syncline is oriented NW-SE, dipping NW. The ridge in the eastern flank of the syncline is responsible for the longest and most prominent relief – the "Serra do Buçaco".

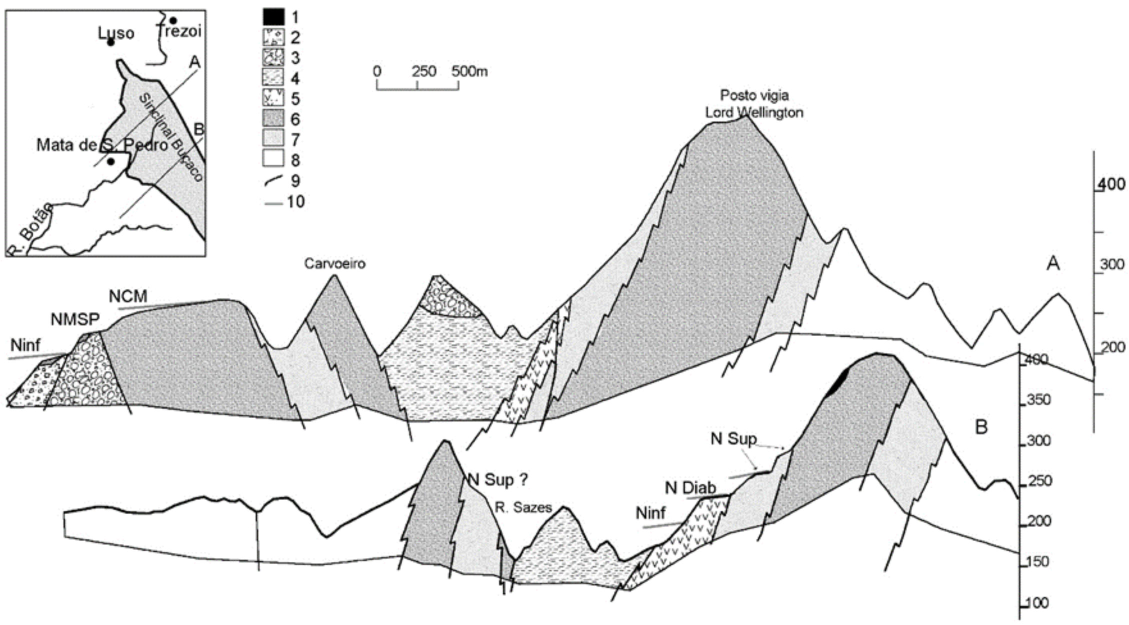

Figure 16. Geological cross-sections of the Buçaco Syncline. 1: Neogene alluvial fan deposits; 2: Triassic; 3: Upper Carboniferous; 4: Upper Ordovician-Silurian metasediments; 5: Ordovician diabases and schists with diabases; 6: Ordovician quartzites; 7: Ordovician schist, quartzite and greywacke; 8: Precambrian Metasediments; 9: Geological contact; 10: Strath terrace. From Dinis (2004).

The Ordovician quartzites are probably among the harder rocks that can endure best mechanical breakdown in the Variscan basement. The quartzites in the NE flank of the Buçaco syncline were thrusted over western units, complicating geological boundaries that otherwise presented linear N-S strike and probably affecting the distribution of uplifted and subsiding sectors in the western region with Mesocenozoic sedimentary units. The SW flank of the syncline does not have the same influence on the structure of the Mesocenozoic fringe due to its orientation closer to E-W.

In the view point of Cruz Alta and in other elevated locations of the quarzitic ridge is possible to have a general perspective of the western region that was crossed before in this field trip (Fig. 17). Another remarkable feature that is observed in the vicinity of Cruz Alta are silicifications affecting Upper Cretaceous alluvial units. The silicification resulted from prolonged weathering under hot weather (Cunha, 1992; Cunha *et al.*, 1993). The formations affected by these exogenous processes probably extended over wide areas, but are now better preserved in the vicinity of quartzite reliefs.

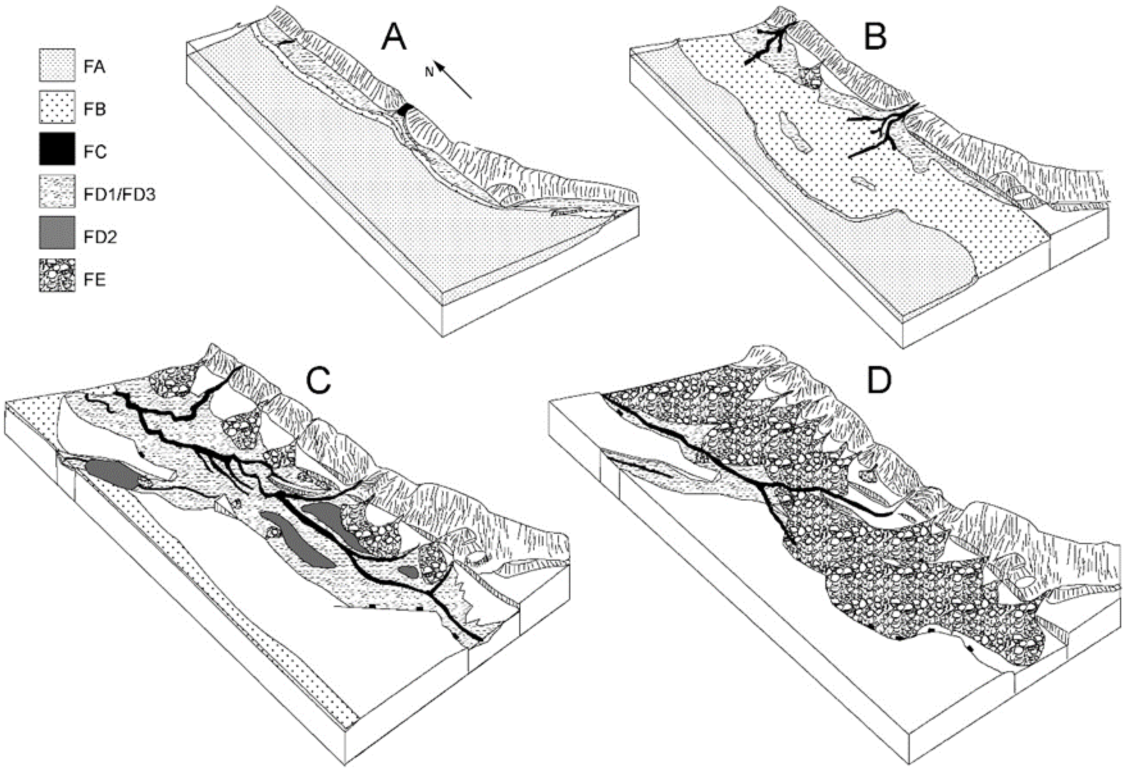

Figure 17. Paleogeographic evolution of the region seen from Cruz Alta viewpoint to the west. FA: Inner shelf; FB: Beach to transitional sand dominated; FC: Fluvial and transitional distributary channels; FD: Floodplain and lacustrine; FE: Alluvial fan. From Dinis (2006).

Stop 10. Chã da Mata

Chã da Mata is located in the western end of a fragment of the southern flank of the Buçaco Syncline, which is isolated from its eastern portion by the Ponte da Mata-Carvalheiras fault. This is a right strike-slip fault striking N-S to NNE SSW. This isolated fragment of the SW flank of Buçaco syncline is also cut by several N-S structures influenced by the Porto-Tomar Fault zone. Part of them control the outcropping area of the Upper Carboniferous continental basin and the contacts of this Basin with the Variscan Basement. They also mark the inner edge of the Iberian Atlantic Margin (Fig. 18).

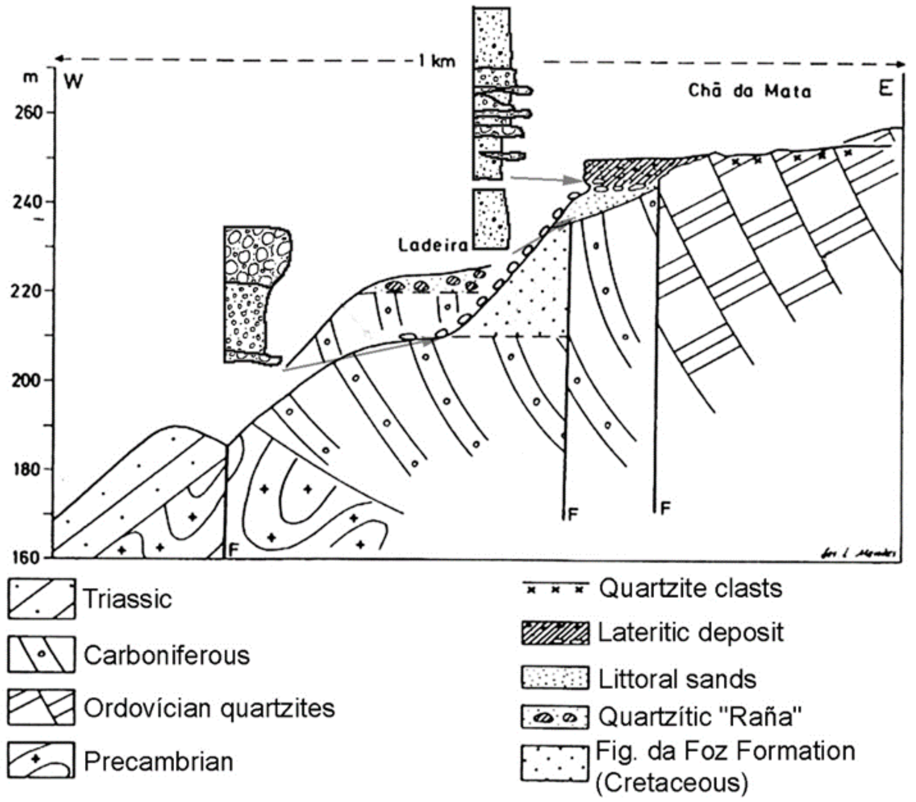

Figure 18. Cross sectional sketch at the latitude of Chã da Mata with the littoral levels of Chã da Mata and Serra da Vila (Adapted from Daveau et al., 1985-86) and the stratigraphic profiles for the deposits that record these two former littorals.

The Chã da Mata deposit and evolving area have unique characteristics. In this region it is possible to recognise two former littoral deposits that have been ascribed to the Piacenzian and Calabrian (Daveau *et al*., 1985-86; Dinis, 2004). The Upper Chã da Mata deposit also displays an unusual ferruginization. The diabases and some Fe-rich metasediments are probably the most important sources of iron for the Chã da Mata and the transport may have been accomplished both trough permeable surface deposits and deep circulation favoured by existing faults (Fig. 19).

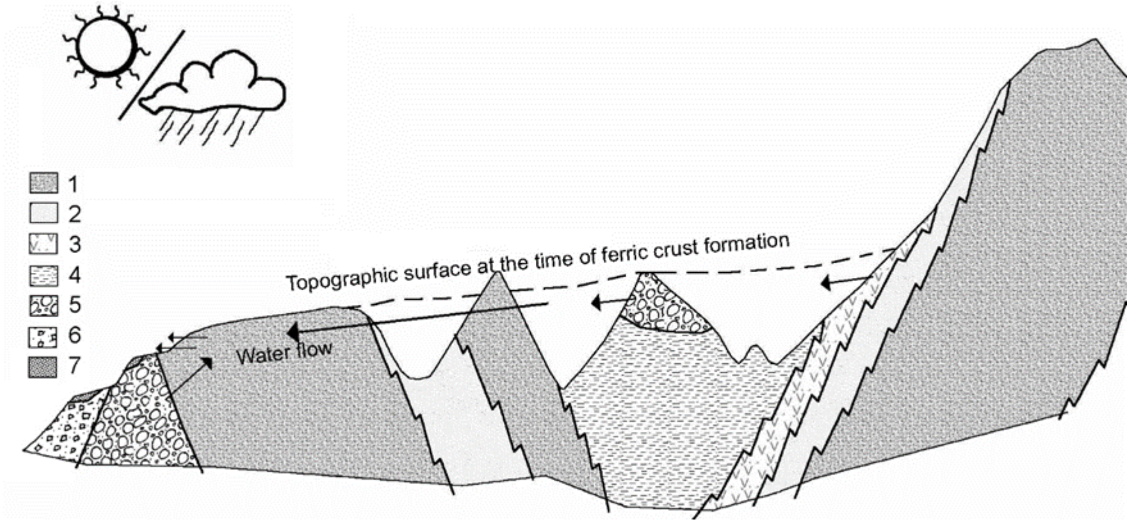

Figure 19. Explanatory model of cementation in Chã da Mata. Iron is fed by a phreatic circulation, from the East. There may be additional availability, linked to the mineralized waters circulating with spring in the Upper Carboniferous. Iron accumulation on the edge of flattened areas under oxidizing and slightly acidic or alkaline conditions. 1: Ordovician quartzites; 2: Ordovician with slates and quartzites; 3: Diabase, sometimes intercalated with shales; 4: Silurian shales; 5: Upper Carboniferous continental units; 6: Silves Group (Triassic); 7: Pliocene and Quaternary sediments. The arrows indicate water circulation associated to Fe-precipitation.

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Index

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