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Abstract

The Terras de Cavaleiros Geopark (TCG), a UNESCO Global Geopark, is located in Northern Portugal and is established on rare and unique geological, scenic, ecological and cultural values. The most significant geological value is related to the most complete sequence of Pre-Mesozoic allochthonous geological units in NW Iberia. The Vilariça fault is an important geomorphological feature in the TCG related to the evolution of landforms such as push-up blocks and strike-slip basins. Forty-two geosites were selected in the TCG, 16 of them being of geomorphological interest. A set of programs, including cultural heritage, biodiversity and leisure, has been prepared for scientific, educational and touristic use.

Keywords

Geopark • Allochthonous complex • Fault • Geosite • Geotourism

long tradition in research and scientific visits. The Geopark territory is also nationally recognized for having a significant range of traditional quality products with national certification (olive oil, sausage, ham, cheese, potatoes, olives, chestnuts, honey and veal and lamb meat, among others). In addition, there are several reference sites for tourism, as the Azibo Reservoir, with a beach ranked as the best lake beach of Portugal, or the Sabor Valley, where visitors can enjoy landscape diversity with floristic richness and unique fauna.

The Terras de Cavaleiros Global Geopark project is ongoing since 2010, promoting geological and environmental conservation, social justice and sustained economic development for the territory and its inhabitants. The tourism is based on scenic, geological, ecological, cultural, historical and local identity values, pointing out what is authentic and unique (Pereira et al. 2013).

Within the Geopark, a detailed inventory and assessment of 42 geosites were accomplished. Seven of them are already listed in the national geosites inventory, which justifies their higher national and/or international significance (Pereira et al. 2012). Sixteen geosites were selected based on the geomorphological and tectonic features.

25.1 Introduction

The Terras de Cavaleiros Geopark (TCG) or The Land of Knights Geopark covers an area of 699 km² corresponding to the administrative limits of the Macedo de Cavaleiros municipality in northern Portugal (Fig. 25.1). The TCG was established in recognition of rare and unique geological, scenic, ecological and cultural values. The local geology and geomorphology have a well-documented scientific value and

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25.2 Geological Setting

The TCG is located in the Iberian Massif, the largest morphotectonic unit of the Iberian Peninsula, which is composed of pre-Mesozoic units consolidated during the Variscan orogeny. In many cases, the bedrock includes relics that have allowed the definition of the geological aspects preceding that cycle (Ribeiro 2013). The Iberian Massif is the westernmost segment of the European Variscan orogen (560–245 Ma), with which it was connected before the opening of the Bay of Biscay, between 110 and 75 Ma. The territory of TCG has a rich and complex geology (Fig. 25.2), mainly expressed in the following geological units (Pereira 2006a; Pereira et al. 2012):



Fig. 25.1 Location of Terras de Cavaleiros Global Geopark in Northern Portugal

- Pre-Mesozoic allochthonous geological units,
- Variscan granitoids,
- Cenozoic sediments.

25.2.1 Pre-Mesozoic Allochthonous Geological Units

The Pre-Mesozoic allochthonous geological units are composed by the:

- Parautochthonous Complex, a unit that moved a few miles and shows paleogeographic affinities with the Central Iberian Zone, with schists, greywackes and quartzites as the most representative lithologies.
- Allochthonous Basal Complex, a unit that moved more than 100 km over the Parautochthonous Complex and is

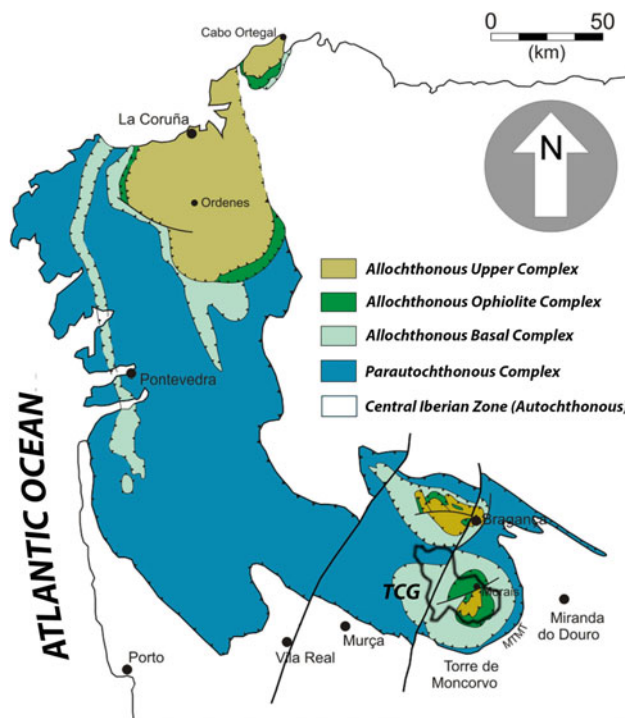


Fig. 25.2 Location of the Terras de Cavaleiros UNESCO Global Geopark in the framework of the Allochthonous Complexes of NW Iberia [adapted from Ribeiro et al. (1990), Pereira et al. (2012)]

representative of the Gondwana continent, showing metavolcanic rocks, schists and quartzites.

- Allochthonous Ophiolitic Complex, a complete sequence of the oceanic crust constituted by several types of mafic and ultramafic rocks. This ophiolite sequence results from the obduction of oceanic lithosphere over the Allochthonous Basal Complex. The ocean corresponded to the south branch of the Rheic Ocean, known as the Galiza/Trás-os-Montes—Central Massif Ocean. The complete Ordovician to Devonian oceanic crust sequence comprises, from top to bottom, amphibolites, complexes of dykes, flaser gabbros, gabbros, mafic cumulates and ultramafic rocks with the generic designation of peridotites.
- Allochthonous Upper Complex, representing a whole sequence of continental crust from an ancient continent located far away from the autochthonous domain. This complex is represented by metasediments, orthogneisses and mafic and ultramafic rocks. It represents a complete sequence of continental crust derived from a distant margin, relatively to the autochthonous domain. Presumably, this complete fragment of continental crust had its origin at the Armorica microplate, a continental

fragment independent from the north of Gondwana (Ribeiro et al. 2007).

Thus, one of the most complete and continuous sections of the Variscan chain in the Iberian Peninsula is represented in the TCG. The Allochthonous Ophiolitic Complex and the Allochthonous Upper Complex, as well as the thrust faults that mark the contacts between the units, are particularly well represented at the core of the TCG, known as the Morais Massif.

25.2.2 Variscan Granitoids

Some igneous rocks occur in the TCG, cutting the metasedimentary and metavolcanic units mentioned above. Beyond the veins, mostly of quartz, different granitoid facies may be distinguished, such as two-mica granites, muscovite granite and granodiorites. These granitoids are contemporary of the Variscan Orogeny and show a clear relation with the third orogenic phase, ranging between the so-called syn-D3 and post-D3 (Noronha et al. 2006).

25.2.3 Cenozoic Sediments

The sedimentary units that fill strike-slip basins and paleovalleys in the western border of the Cenozoic Douro Basin are well represented in the TCG. Up to the 1990s, these sediments had been systematically included in the so-called Iberian *Raia* facies, a gravelly deposit with significant coverage in the Douro Basin and also in the Iberian Massif. *Raia* refers to an alluvial fan model, chronologically placed near the Plio-Pleistocene limit, an episode related to the transition from the endorheic drainage of the Cenozoic Iberian basins to the present Atlantic drainage. More detailed investigations on these sediments (Pereira 1997, 1998, 1999, 2006a; Pereira et al. 2000) have revealed a fluvial network in the proximal sector of the Douro Basin and diverse tectonosedimentary units as described below (Pais et al. 2012).

The Bragança Formation (Upper Miocene to Lower Pliocene) is defined in north-eastern Portugal as a lithostratigraphic unit recording a proximal fluvial paleodrainage to the Cenozoic Douro Basin in Spain (Pereira 1997, 1998, 1999; Pereira et al. 2000). The fluvial sediments fill incised paleovalleys in response to two tectonic episodes and the consequent orogenic uplift. These paleovalleys remain well preserved in TCG (Vale da Porca, Salselas and Castro Roupal outcrops), where they are oriented E–W, and to the east, near Vimioso (Vimioso outcrop) and Miranda do Douro (Silva, Sendim and Atenor outcrops), where they are oriented NW–SE and N–S, respectively. Given the context

of the major Vilariça fault, the fluvial system was strongly influenced by the development of strike-slip basins (De Vicente et al. 2011; Pais et al. 2012), especially in the TCG.

The Bragança Formation comprises two members with similar composition and depositional architecture. An unconformity based on the recognition of a regional erosion surface and a well-developed paleosoil occurs. Deep channel gravel deposits and gravelly bars are the most characteristic lithofacies of the Bragança Formation. The sediments are immature and contain moderately weathered feldspars in the sand fraction and a predominance of smectite and kaolinite in the clay fraction. The gravel units are mostly red in colour with lutite being brown, grey or green.

Geomorphological features suggest that prior to the deposition of the Bragança Formation river valleys incised in the bedrock developed as an erosional response to mountain uplift occurring since the Eocene (Pereira et al. 2000; De Vicente et al. 2008, 2011). Subsequently, the activity of this major tectonic episode, which corresponds to the Betic compression at about 9.5 Ma (Calvo et al. 1993), caused a staircase organization of large fault blocks in northern Portugal and the development of strike-slip basins associated with the Vilariça fault detachment (Ferreira 1991; Cabral 1995).

The Aveleda Formation (Upper Pliocene to Lower Pleistocene) is located in two different geomorphological settings: i. occurrences surrounding the TCG lie over the North Iberian Plateau, which marks a discontinuity with the older units, and have its source on the resistant reliefs; ii. occasionally, the unit lies within tectonic depressions associated with the Vilariça fault (Pereira 1997), especially in the TCG. The Aveleda Formation consists of reddish deposits mainly of muddy matrix-supported gravel. Clasts of several metasedimentary rocks and quartz are subangular. Kaolinite and illite dominate the clay fraction. The lithofacies and architecture of the Aveleda Formation indicate nearby sources and debris flows deposited as alluvial fan bodies. The unit establishes the transition between the previous endorheic drainage network and the Atlantic fluvial network (Pereira 2006b).

25.3 Geomorphology

The TCG area consists mostly of small plateaus, with altitudes between 700 and 800 m asl, and the Bornes and Nogueira mountains reaching 1200 and 1300 m asl. These push-up compressive structures are related to a major fault-oriented NNE–SSW and showing neotectonic activity—the Vilariça fault. Associated with it, several small strike-slip basins filled with Cenozoic sediments occur (Pereira and Pereira 2019). The deeply carved Sabor River defines the eastern limit of the TCG. West of the fault, the drainage is

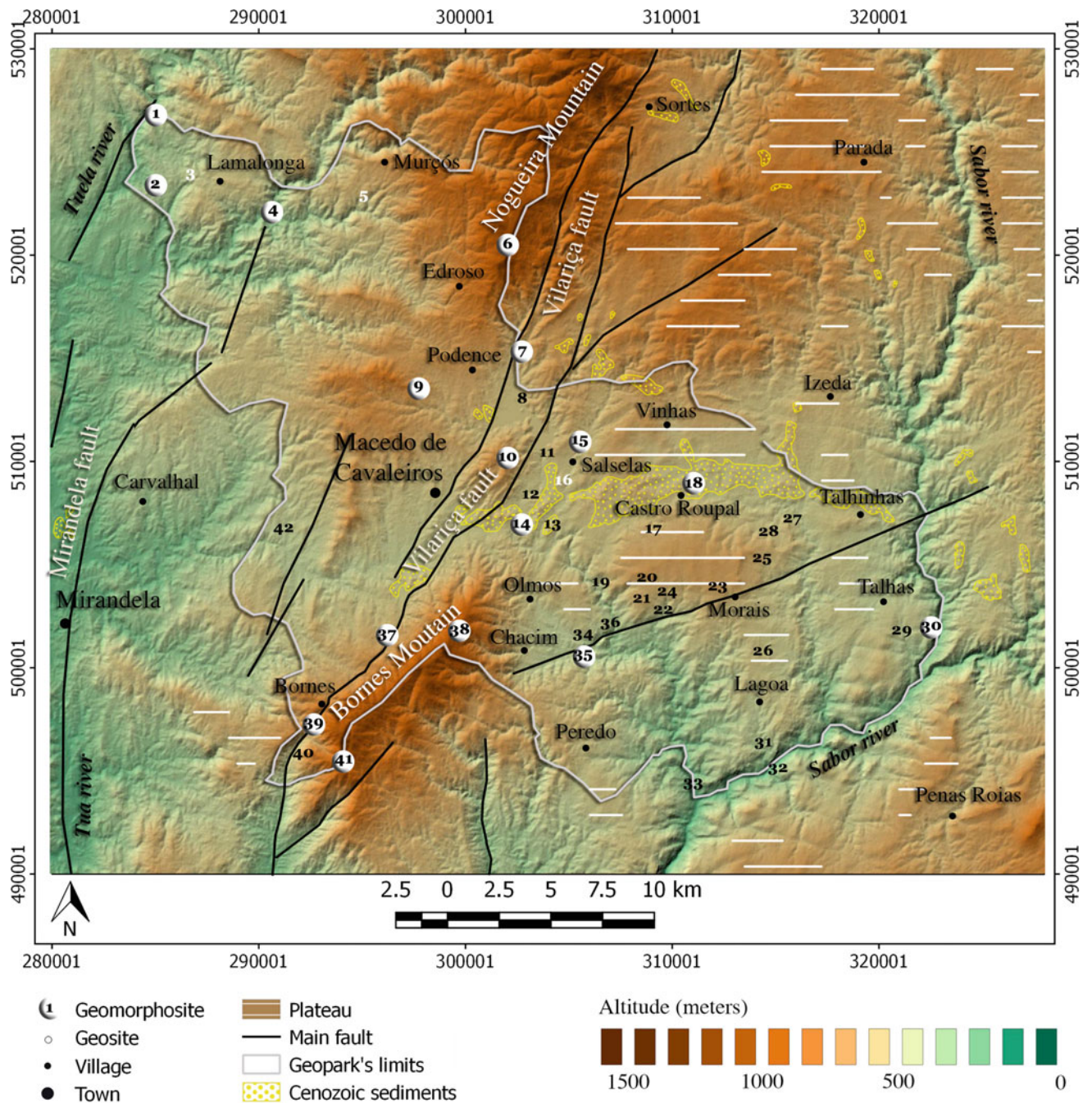


Fig. 25.3 Simplified geomorphological map of the Terras de Cavaleiros UNESCO Global Geopark

towards the Tua River (Fig. 25.3). The Sabor and Tua sub-catchments are part of the Douro River catchment, one of the largest Iberian rivers, which has its mouth in Oporto.

The regional significance of the Vilarica fault is widely recognized in studies of the landscape of northern Portugal (e.g. Cabral 1995; De Vicente et al. 2008, 2011; Pais et al. 2012). This strike-slip fault has great morphological expression in the TCG, through several strike-slip basins such as the Santa Combinha, Macedo de Cavaleiros and Vilarica

basin to the south, as well as uplifted compressive structures in a push-up model, like the Borne and Nogueira mountains (Cabral 1995; Pereira 1997, 2006). In the NW sector of the TCG, the south flank of the Nogueira Mountain stands out, reaching an altitude of 1231 m in the Pombares Massif granites. This NNE-SSW tectonic block is located to the west of the main branch of the Vilarica fault. In the south, the Borne Mountain (1,200 m asl) stands out as a tectonic relief, oriented NNE-SSW, parallel to the Vilarica fault



Fig. 25.4 Bornes Mountain, limited by the Vilarica fault, view from the Senhora do Campo geosite

(Figs. 25.3 and 25.4). In the southern limit of the TCG, the N-S fault scarp extends to the Vilarica depression.

Regionally, the Vilarica fault constitutes also the limit between the eastern sector, where the fundamental surface of the North Iberian Plateau (Meseta) is more regular, and the western sector where the fundamental surface is extensively dissected by the Douro fluvial network (Fig. 25.3). The regular flatish surface of the Morais Massif occurs to the north of the Morais fault, about 750 m asl and is representative of the North Iberian Plateau, also known as North Iberian Meseta. This surface, well preserved in the Morais Massif, represents a reference to the interpretation of all other regional surfaces. Portions of the same surface are also preserved to the north and east.

North of the Morais Massif, the Vale da Porca-Talhinhas depression is oriented E-W and 150 m below the fundamental surface. This depression is one of the paleovalleys that preserve sediments of the Bragança Formation, associated with a previous fluvial system flowing eastwards towards the Douro Cenozoic Basin, mentioned above (Fig. 25.5).

The NE-SW depression of Macedo de Cavaleiros is limited between faults of the Vilarica tectonic zone and preserves alluvial fan sediments of the Aveleda Formation. The fact that the Macedo de Cavaleiros tectonic depression is drained towards the Tuella River by the Macedo and the

Carvalhais tributaries is a noteworthy peculiarity that shows the tectonic control of the drainage system. The remaining territory lies within the Sabor Basin. The Sabor River, bordering the Geopark in the east, shows steep slopes and is incised about 400 m in the plateau (Fig. 25.6). The tributary streams also show deep valleys, except when crossing tectonic depressions.

In the western sector of the TCG, some planation surfaces are slightly lowered relative to the regular level of the plateau, which is due to differential uplift and subsidence. These surfaces are tectonic steps connecting to the Mirandela depression (Fig. 25.3).

25.4 Geosites

The selection of geosites in Terras de Cavaleiros Geopark was primarily focused on their scientific value. After the first identification of potential geosites, 42 were selected as effective geosites, based on a qualitative assessment. The selected geosites represent mineralogical, petrological, structural, geomorphological and hydrogeological themes. Sixteen geosites are specifically related to geomorphological and tectonic features (Table 25.1, Fig. 25.3).

For geotouristic and general touristic support, the TCG promoted the selection of geosites after an assessment of



Fig. 25.5 Sediments of the Bragança Formation filling the Vale da Porca-Talhinhas paleovalley (Castro Roupal geosite)

touristic interest. These geosites, which always show scientific value, also stand out for their cultural, economic and/or scenic values. In addition to the geoconservation and management issues, its valuation includes outreach with simplified explanations. Some of the TCG most representative geosites are described below.

25.4.1 Geomorphosites

(a) Senhora do Campo geosite

The Senhora do Campo geosite is an exceptional place to observe and understand the most significant features of the regional landscape, in particular (Fig. 25.7): (i) the surface of the Morais Massif, representing an isolated portion of the North Iberian Plateau, a planation surface, well-known and also recognized in other regions, (ii) the Nogueira and the

Bornes mountains, which are tectonic landforms associated with the Vilaríça fault, (iii) the Mogadouro Mountain, on the horizon, an excellent example of residual landform standing out from the plateau and (iv) the Azibo River valley carved in the plateau.

(b) Cabeço Berrão geosite

Cabeço Berrão geosite is a panoramic viewpoint to the deep incision of the Sabor River in the North Iberian Plateau (Fig. 25.6). In addition to the geomorphological value, the site presents cultural interest due to the presence of ruins of a fortification attributed to the Iron Age, in which local rocks were used, namely amphibolites, schists and gabbros.

(c) Bornes South geosite

The Bornes South geosite is a panoramic viewpoint located on the southwest slope of the Bornes Mountain, from where landforms connected to the Vilaríça fault can be observed.



Fig. 25.6 Sabor River deeply carved in the North Iberian Plateau, view from Cabeço Berrão geosite

The fault produces well-defined scarps and controls the Burga River course in a straight-lined valley (Fig. 25.8). Further to the south, the Vilariça strike-slip basin (Pereira and Pereira 2019) can also be seen from here.

(d) Vilariça fault gouge at Podence geosite

The Podence geosite is the best place to perceive the Vilariça fault at an outcrop-scale (Fig. 25.9). The vertical fault gouge, about 10 m wide, places metavolcanic rocks of the ancient bedrock (Silurian) in contact with Cenozoic sediments (Gelasian), testifying the recent movement of the fault.

25.4.2 Other Geosites

(a) Conrad and Moho discontinuities geosite

The Conrad and Moho discontinuities geosite is an important spot in TCG, where ophiolite and allochthonous

processes associated with the Variscan orogeny can be interpreted. The geosite includes the tectonic contact between the Earth's upper continental crust (represented by the Lagoa gneiss), the lower continental crust (represented by the granulite), and the mantle (represented by the peridotite). The geosite location offers a panoramic view to the thrust geological units differentially eroded in the opposite slope of the Sabor River valley (Fig. 25.10).

(b) Foz do Azibo thrust fault geosite

At the Foz do Azibo geosite, the tectonic stacking of the main geological units involved in the Variscan orogeny can be seen. It is possible to interpret the Armorica continent (represented by the Lagoa gneiss) overlapping the remains of the Paleozoic Rheic Ocean (represented by the amphibolite) (Fig. 25.11).

(c) Poço dos Paus geosite

The Poço dos Paus geosite combines scientific and scenic values of the Azibo valley, with the visitor being encouraged to observe rocks typical of the ocean floor (Fig. 25.12). The

Table 25.1 Main features of the 16 geosites with geomorphological interest (geomorphosites) in the TCG territory

Reference	Geosites	Main geological features
G1	Tuela valley	300 m deep canyon in the Tuela River
G2	Torre de Dona Chama granite	Granite boulders and other typical granite landforms
G4	Macedo river meanders	Meanders of the river Macedo canyon controlled by N-S faults
G6	Alto da Serra granite	Typical granite landforms like <i>tor</i> and <i>castle kopje</i>
G7	Vilariça fault gouge at Podence	Vilariça fault with a significant 10 m wide fault gouge
G9	Senhora do Campo panorama	A panoramic site to observe the major Bragança–Vilariça–Manteigas fault alignment, the Azibo Reservoir, the Morais Massif and the North Iberian Plateau
G10	Cubo panorama	A 360° panorama of the TCAG showing the main landforms
G14	Vale da Porca Cenozoic sediments	Cenozoic sediments affected by small faults as evidence of neotectonic events
G15	Salselas tectonic basin	Small basin filled with sediments is an example of a geomorphological feature with tectonic control
G18	Castro Roupal palaeovalley	Cenozoic sediments representing an ancient drainage system with cross-bedded stratification
G30	Cabeço Berrão panorama	Panorama over the Sabor River canyon
G35	Morais fault	ENE-WSW fault with neotectonic activity
G37	Vilariça fault at Vale Bemfeito	Breccia of the Vilariça fault with fragments of granites, quartz and boulders of the cenozoic sediments
G38	Bornes North panorama	Panorama over the general geomorphology of the Geopark area
G39	Vilariça fault scarp at Burga	Panoramic site to observe the geomorphological expression of the Vilariça fault scarp
G41	Bornes South panorama	Panorama over the Vilariça strike-slip basin

**Fig. 25.7** Main landforms observed in the Senhora do Campo geosite

site shows mafic dikes in bands of dark colour, that broke through gabbro, showing light and dark minerals of larger dimensions. A simplified explanation of when and how the rocks were formed and on their exotic condition is presented on-site.

(d) Lagoa Gneiss geosite

Lagoa Gneiss geosite has high scientific and scenic values. The approach is based on the beauty of the gneiss in the outcrop (Fig. 25.13), its exotic nature attending to its origin

hundreds of kilometres away and the doubt about the exact age of this occurrence. The outcropping also preserves very clear kinematic criteria that constitute a precious element for the geodynamic reconstitution of the Variscan orogeny in Iberia.

(e) Murçós Mine geosite

The Murçós mine geosite is dedicated to several outcrops of an open-air mine and to the ruins of support buildings separation of the ore took place between 1940 and 1980. This



Fig. 25.8 Panoramic view to the south at the Bornes South geosite, where the Burga River valley is controlled by the Vilarica fault

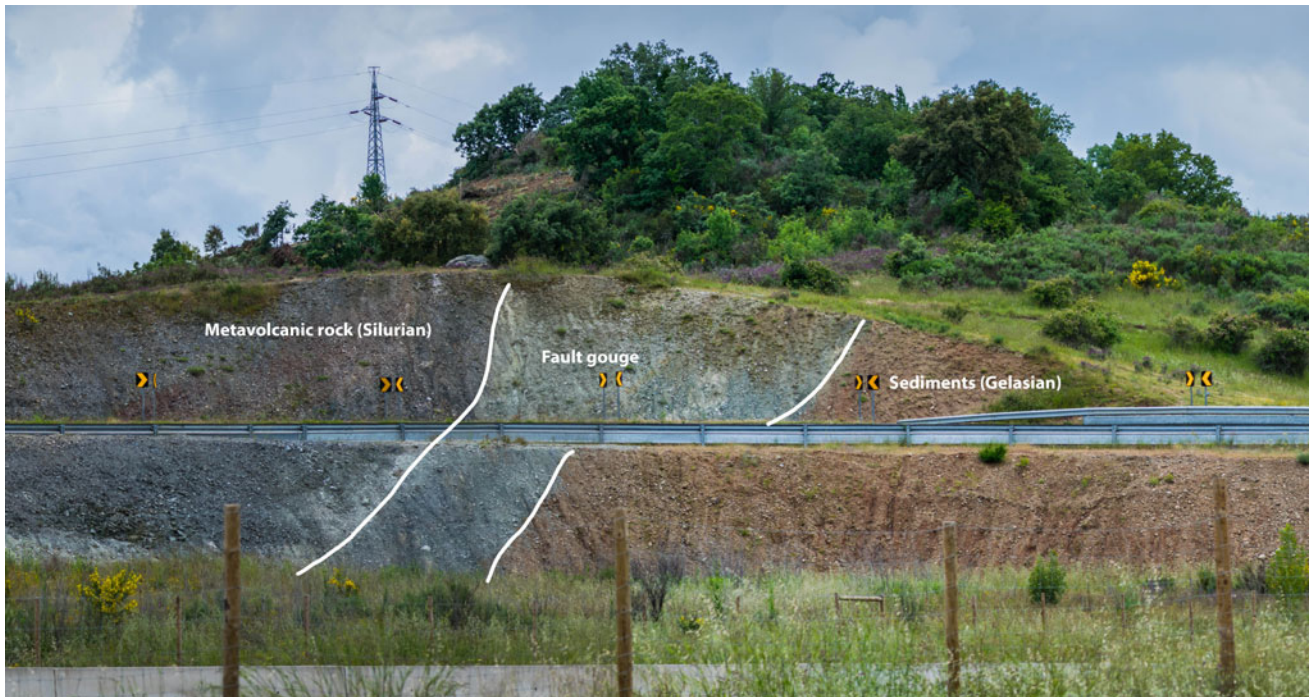


Fig. 25.9 Vilarica fault gouge at the Podence geosite



Fig. 25.10 Panoramic view from the Conrad and Moho discontinuities geosite, to the thrust geological units in the opposite slope of the Sabor River valley, where differential erosion occurs



Fig. 25.11 Foz do Azibo thrust fault geosite



Fig. 25.12 Poço dos Paus geosite has high scientific value attending to the large amount of mafic dikes cropping out at the riversides of the Azibo River (detail in the upper right corner). The scenic value is also considered for geotouristic purposes



Fig. 25.13 Lagoa Gneiss geosite (photograph Pedro Peixoto)



Fig. 25.14 Azibo's Reservoir, a protected area dedicated to biodiversity conservation

mine has served for the exploitation of tungsten and tin, which occur in quartz veins that can still be observed. The visit focuses on the observation of quartz veins with tungsten, on its industrial applications, strong relationship with the World War II and on an outlook to the future.

(f) **Limestone of Salselas geosite**

The geosite shows limestones, rare rocks in northern Portugal, that were exploited here in the past. Actually, this is an example of the utilization of a rare geological feature in the region, which constitutes the raw material of lime, produced in furnaces that still persist in the region.

25.5 Thematic Trails

The Terras de Cavaleiros Global Geopark offers thematic trails that link several geosites. Three trails are dedicated to the relation between geology, geomorphology and society, natural hazards and Earth's history: i. the trail "Geological resources in the TCG" links several geosites like the Murçós Mine geosite, the Limestone of Salselas geosite, the

abandoned talc mine geosite, or the Asbestos geosite, emphasizing the importance of the geological resources to society, ii. the trail "Geological faults and earthquakes in the TCG" links geosites related to active faults and tectonic landforms and iii. the "Morais Ocean" trail covers the theme of the ophiolite sequence, with the geosites presented as exotic occurrences of rocks and seismic discontinuities typical for ocean floor and the Earth's interior settings that rarely can be seen at the surface.

Within the TCG, the Azibo's Reservoir is a protected area dedicated to biodiversity conservation (Fig. 25.14). This area offers a network of pedestrian paths especially dedicated to biodiversity, namely the observation of different types of insects. In addition to other activities and leisure sites, the area was elected the best lake beach in Portugal.

25.6 Conclusions

The particularities of the Terras de Cavaleiros Geopark geology and geomorphology support its early recognition as a UNESCO Global Geopark. Besides the geoheritage and the geoconservation issues, the development of the Geopark

is also supported by the commitment of the municipality, the excellent accessibility, the engagement of the partners, the broad scientific support, as well as by the biodiversity and unique cultural heritage. In the TCG, several infrastructures support scientific research, school visits, recreation and nature sports.

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