Geological Mapping of Rates and São Félix of Laúndos Region (Northern Portugal)

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Abstract. The Rates and São Félix de Laúndos region is located in the NW extension of the Valongo Anticline (Northern Portugal), comprising Palaeozoic formations with ages ranging from the Cambrian to the Carboniferous, locally overlaid by Plio-Pleistocene beach deposits and dunes. Detailed geological mapping was developed. The fieldwork allowed distinguishing different lithostratigraphic units, some of them fossiliferous. The study under optical microscope and Scanning Electron Microscope (SEM) allowed noting the presence of volcanic rocks along the Palaeozoic succession. A rhyolite in the Cambrian-Ordovician transition, a likely ignimbrite in the Upper Ordovician, and the existence of a porphyry in the Carboniferous, were for the first time identified in this region. The palaeontological study focuses on the samples collected in the field, essentially belonging to the Middle Ordovician (Valongo Formation), but also to Silurian and Carboniferous. The Devonian formations are largely covered by agricultural fields and by urbanization, not allowing the collect of fossils, so the Devonian fossils studied belong to the Stratigraphical and Palaeontological Collection of the Department of Geosciences, Environment and Spatial Planning, Faculty of Sciences, University of Porto. The geological mapping previously developed in this region goes back to the XX century. In the present work a detailed geological mapping at a scale of 1:15 000 was developed, with reinterpretation of the stratigraphic succession.

1. Introduction

The region of Rates and São Félix de Laúndos is located in the District of Porto in NW of Portugal. The outcropping rocks in this area materialize an extension to NW of the Valongo Anticline, an asymmetrical anticline trending NW-SE whose axis plunges to the NW. This fold, located in the Central Iberian Zone was structured along the first phase of the Variscan Orogeny [1], being strongly controlled by the Porto-Tomar shear zone and by the Douro-Beira Carboniferous Trough [2, 3].

The previous geological mapping of the area dates back to the beginning of the 20th century. A detailed geological map, based on field observations, petrographic analysis of rock samples and the study of fossil specimens in the region allowed locally the reinterpretation of the stratigraphic succession and to sign the existence of volcanic rocks.
2. Geological setting
Rates and São Félix de Laúndos region, located in Central Iberian Zone, is an extension to NW of Porto of the Valongo Anticline structured during the 1st phase of the Variscan orogeny [4]. Tectonically the area is essentially controlled by the Porto-Tomar Shear Zone and by the Douro-Beira Carboniferous Trough.

The Palaeozoic rocks range in age from the Cambrian to the Carboniferous. In the Cambrian, interbedded slate, wackes, quartzite and quartz conglomerate occur [5].

Ordovician is divided into three formations: Santa Justa Formation of Tremadocian (?) to Floian age (Lower Ordovician), Valongo Formation of Dapingian-Darriwilian age (Middle Ordovician) and Sobrido Formation of Hirnantian age (Upper Ordovician) [6] [7]. The Santa Justa Formation, at the base, contains conglomerate, and massive quartzite with trace fossils, with a general NW-SE orientation [8]. The Valongo Formation (Middle Ordovician) is formed by grey slates [8]. In the Sobrido Formation greywacke and schists outcrop, with intercalations of quartzites [8]. More recently, new stratigraphic data from the Sobrido Formation have been recognized in the vicinity of this area including ice-distal (laminated diamictites) and ice-proximal deposits (massive diamictites, quartzites and conglomerates) [9].

Silurian gray to purplish clay slates and greywackes outcrop in the area. Occasionally lenticular intercalations of black shales with Monograptus occur [5]. In the Devonian, pale gray slates, very fossiliferous, outcrop, overlaid by limonitic concentrations and clayey-micaeous schists [5].

Between the Devonian (to the east), and the Middle Ordovician (to the west), there is a Carboniferous strip formed by conglomerate with large elements, followed by gray sandstones and clayey-micaeous slates [5], [10]. Along the Serra de Rates and the São Félix hill, there are several outcrops of modern covering deposits, deposits of old beaches and dunes of the Plio-Pleistocene, made up of conglomerates and sand, sometimes with ferruginous cement [5].

3. Fieldwork
Fieldwork was the main objective of this study. The area is very urbanized and cultivated fields proliferate, but it was possible to identify geological contacts, lithostratigraphic and biostratigraphic units, structures and to characterize the stratigraphic succession. Geological interpretative profiles were done. In total, 83 GPS points were observed during the fieldwork allowing proposing an actualized detailed geological map.

In the transition Cambrian–Ordovician underlying the massive quartzites of Lower Ordovician (Floian), a conglomerate with mainly quartz clasts, interbedded with reddish quartzites is overlain by intercalations of quartzites, slates and volcanic rocks (rhyolite and volcanogenic tuff).

SW of São Félix Chapel and Shooting Range, it is possible to follow a Floian (Lower Ordovician) quartzitic ridge with an average orientation of N120ºE. In these quartzites, sedimentary structures, such as ripple marks, were identified, giving normal polarity towards NE. Stratification is N100ºE to 130ºE subvertical. Westerly these quartzites contact the Cambrian – Ordovician transition and at E the slates of the Valongo Formation (Middle Ordovician). Overlying these quartzites interbedded slates and wackes occur. These are overlain by reddish siltstones overlaid with fossiliferous dark grey to purplish slates (trilobites, cystoids, brachiopods, gastropods, cephalopods and bivalves) of Valongo Fm (Middle Ordovician).

Taking into account the normal polarity to NE, the quartzite ridges that outcrop in the São Félix hill SE of this, in the Serra de Rates and relatively close to the Field of Shooting, are from the Hirnantian (Upper Ordovician). On the hill of São Félix (geodesic landmark), there is an outcrop of gray to pink quartzite, with interbedded finer layers. In this outcrop, a N150ºE/55ºNE stratification, ripples with crossed bedding and load structures. These sedimentary structures indicate the top of the succession to NE. To the SE of São Félix hill, in
Serra de Rates a quartzite ridge, N170°E, subvertical, with Skolithus indicating the top of the succession to NE. Overlying the Upper Ordovician quartzite, there is a very altered volcanogenic rock.

Northeast of the Serra de Rates, there are Silurian dark gray sometimes yellowish, greenish or purplish red shales. No fossils were found. The stratification/cleavage attitude is N120° to 140°E; subvertical. Near the primary school in Paradela, black shales outcrop with siliceous nodules and crenulation.

It is difficult to follow the Devonian outcrops marked in previous geological maps, because the land where they occur is converted into agricultural fields.

However, on some small road slopes it was possible to identify light gray slates. Sometimes interbedded with fine quartzite with stratification plane N100°E, subvertical. A gray to orange friable quartzitic ridge, with direction N70°E was also observed. Near the Shooting Range, in contact with the Carboniferous, a very ferruginous quartzite with stratification N130°E/70°NE outcrops. This lithology is similar to the loose blocks found near the iron mine (Jazigo of Rates).

The continental Carboniferous lies between the Middle Ordovician and the Devonian. The contact observed with the Middle Ordovician is irregular, with an average attitude N160°E/80°NE. Slates of the Valongo Formation are in contact with the Carboniferous basal breccia, consisting of rolled and angular clasts. This breccia is very poorly calibrated with clasts (<1cm to 30cm long) of different lithologies (quartz, quartzite, granite), and a silty ferruginous matrix.

Altered porphyries occur in the contact with the Middle Ordovician. This succession seems to be correlated with the succession observed in the Douro Coalfield Basin in S. Pedro da Cova [11]. To northeast plant fossils were collected in whitish slates.

Around Monte de São Félix it is possible to observe Plio-Pleistocene deposits related with old beaches and dune deposits with ventifacts. These deposits make it difficult to observe the stratigraphic succession at this location, as they cover the older lithologies.

4. Palaeontology
A numerous diversity of fossils was identified in previous studies.

In the Lower Ordovician, only ichnofossils, like Vexillum, Cruziana and Skolithos are mentioned [12], [13]. In the Middle Ordovician several fossils of invertebrates are described, namely trilobites: Neseuretus tristani, bivalves: Orthonota (Cypricardia) amygdalina, brachiopodes: Orthis sp., and Cystoids: Calix murchisoni [12]. Of Silurian age, associated to black shales and phanmites, several species of graptolites are described: Climacograptus rectangularis, Monograptus lobiferus, Monograptus sedgwicki, Monograptus cf. bechi, Spirograptus spiralis, Rastrites peregrinus [14], [15]. In the Devonian, the fossiliferous record is vast and has been the subject of several studies and revisions. Regarding fish several remains have been identified: Onchus sp., Onchus tenuistriatus, Climatius sp., Ischnacanthiformes, Acanthodii [16], [17]. Several arthropods have been recognized like ostracoda: Beyrichia sp., Beyrichia devonica, trilobites: Cryphaeus laciniatus, Cryphaeus lethea, Cryphaeus aff. munieri, Cryphaeus aff. pectinatus, Phacops sp., Phacops aff. fecundus, Phacops potieri, Homalonotus Viannai, Homalonotus Knightii, Burmeisterella hexispinosa sp., also including Phyllocarida and Eurypteroidae [18], [19], [20], [21], [22], [23]. Several brachiopods were identified: Aviculopecten sp., Aviculopecten follmanni, Spirifer pararhachon, Discina (Orbiculoidae) cf. marginata, Orthis Gervillei, Spirifer decheni, Spirifer aff. hercyniae, Spirifer histericus, Spirifer aff. primaevus, Strophomena piligera, Strophomena steini, Strophomena subarachnoidea, Orbiculoidea tainei, Cyrtina utrimquesulcata, Howellella mercuril, Delthyris dumontiana, Brachyspirifer carinatus, Acrospirifer cf. rousseau, Anoplia theoreassensis, Euryspirifer cf. paradoxus, Euryspirifer pellicoi, Stropheodonta sp., Stropheodonta cp. Murchisoni, Stropheodonta cp. Sedgwicki, Schizophoria vulvária, Schuchertella septirecta [18], [19], [22]. Some bivalves, gastropods and cephalopods were also
identified: Modiolopsis, Grammysia, sp, Grammysia cingulate, Pterinea sp., Pterinea (Cornellites) pailletti, Pterinea cfr. Lineata, Pterinea retroflexa, Pterinea (Cornellites) costata, Pteronitella laevis, Orthoceras sp., Murchisonia sp., Euomphalus, sp. [16], [18], [19], [22]. Some phenesteliids, acanthoclatides and tentaculites are also referred: Fenestella infundibulum, Fenestella retiformis, Fenestella bouchardi, Fenestella ripistera, Pitlopora sp., Tentaculites sp., Tentaculites cf. Irregulares, Tentaculites elongatus [19], [22]. Of Carboniferous age, the following plant fossils were identified: Linopteris florini, Calamites and Cordaites [5].

Regarding the fossils studied in present work, some were collected during fieldwork, other (those of Lower Devonian) are from the Stratigraphic and Palaeontological Collection of the Department of Geosciences, Environment and Spatial Planning, Faculty of Sciences of the University of Porto. In the slates of the Middle Ordovician (Valongo Formation) fossils, such as: bivalves: Redonia, brachiopods: Orthis (?), cephalopods: Orthoceras) cystoids: Calix (?) (figure 1.a), gastropods and trilobites: Neseuretus, Asaphidae were identified. In Silurian only crinoids were found. In Carboniferous the genus Alethopteris was collected. In the Lower Devonian several specimens of the Stratigraphic and Palaeontological Collection, DGAOT were observed namely bivalves: Myalina, Aviculopecten, brachiopods: Rhynchonella, Chonetes plebeia, Spirifer paradoxus, Orbiculoidea tainei, cephalopods: Orthoceras, corals: Pleurodictyum (figure 1.b), crinoids, fenestellid: Fenestella (figure 1.b and figure 1.c), gastropods: Murchisonia, nautiloids: Cyrtoceras and trilobites: Asteropyginae, Burmeisterella hexaspinosa (figure 1.d and figure 1.e), Phacops potieri (figure 1.f), Homalonotus viannai.

5. Petrographic study
5.1. Optical Microscopy
The petrographic study allowed recognizing for the first time in the region the presence of volcanic rocks.

Two samples are from the intercalated volcano-sedimentary units underlying the Floian (Lower Ordovician) quartzite. Sample 15RT is a rhyolite. Microscopically, volcanic
characteristics with quartz phenocrysts with corrosion gulfs, sometimes very rounded (figure 2.a). Sericite skeins resulting from the pseudomorphosis of feldspar crystals. Sample 17RT is a volcanogenic tuff quite heterogeneous, with milimetric quartz crystals clearly visible to the naked eye and, the matrix is thin and grey locally oxidized, occasionally with quartzite rock elements. It rich in sericite, resulting from the alteration of feldspars. Alanite is an accessory mineral. This rock resembles the volcanogenic tufts of the “Olho de Sapo” Formation described by Montes [24] in Zamora (Spain).

Sample 7RT, from, overlying Hirnantian quartzite (Upper Ordovician), is a volcanogenic rock. Under the microscope, quartz crystals show rounded forms, sometimes with corrosion gulfs, dispersed in a very fine micaceous matrix. Fragments of recrystallized volcanic glass show the original texture, and sometimes vacuoles are preserved (figure 2.b). It is very similar to the ignimbrites described by Montes [24] for the “Olho de Sapo” Formation in Sanabria and Terra do Bolo (Zamora, Spain).

Sample 5RT is Carboniferous porphyry characterized essentially by quartz crystals with corrosion gulfs and very rounded shapes (figure 2.c), characteristics of volcanic origin. It has a clay matrix resulting, in part resulting from the alteration of feldspar, composed of sericite and kaolinite. This type of lithology had not yet been described in the studied area, however it resembles the lithologies described in São Pedro da Cova by Pereira [25], Fonseca & Thadeu [26] and Couto & Roger [11].

5.2. Scanning Electron Microscopy (SEM)

The SEM analyses were performed at the Materials Center of the University of Porto (CEMUP), using a High resolution (Schottky) Environmental Scanning Electron Microscope with X-Ray Microanalysis and Backscattered Electron Diffraction Pattern Analysis: FEI Quanta 400 FEG ESEM / EDAX Genesis X4M, by the analyst Dra Daniela Silva.

This study was restricted to the sample 7RT, a volcanogenic rock from the Upper Ordovician. It is quite altered, however under the optical microscope textures with vacuoles (filled with quartz and potassic feldspar) similar to volcanic glasses are evident, in addition to quartz grains with shapes compatible with a volcanic genesis. SEM analysis evidenced the presence of previous volcanic glasses (figure 3.a). Quartz is the most abundant mineral, with rounded forms, typical of volcanic origin (figure 3.c). A mineral from the muscovite-celadonite series was identified. It has a high content of silica and resulted from the alteration of volcanic glass, sometimes it is designed by the disused name of phengite (KAl\textsubscript{1.5}(Mg,Fe)\textsubscript{0.5}(Al\textsubscript{0.5}Si\textsubscript{3.5}O\textsubscript{10})(OH\textsubscript{2})) (figure 3.b). As accessory mineral, florencite was identified and the presence of Pb may be related to hydrothermal alteration. Zircon and titanium oxides were identified, probably anatase.
6. Geological mapping
Given the stratigraphic succession observed throughout the fieldwork, the palaeontology data collected, and the petrographic studies complemented with the SEM, some changes/improvements are proposed to the previous geological mapping in light of present knowledge (figure 4). A 1:15 000 scale geological map is proposed, (reduced in this paper) in which the previous fieldworks were also taken into account.

7. Discussion and conclusions
Teixeira & Medeiros, in 1965 [8], consider that, in the Rapijães area, there is a fault contact between the Middle Ordovician slates and the Carboniferous basal breccia, with the slates thrusting to the east over the breccia. More recently, in 1992, Pereira et al. [2] report that existing shear zones in the area acted with a strong upward component to the west, causing disorder in the stratigraphic succession. According to the same authors, in the Apulia region in the extreme North of Douro-Beira Carboniferous Trough, the style differs from that observed to south of Porto, with sub-vertical northeast vergent folding, showing a change in the structural style of the autochthonous that reaches the maximum expression to the east of the Carboniferous trough. We considered the shear movement associated to the Carboniferous Furrow as sinistral, according to the most recent studies of Pereira et al. [2]. However, we think that a more detailed structural study could better clarify this issue, since, as these authors also refer, there is a change in the structural style in the region.

NW of the Shooting Range a sequence underlying the Lower Ordovician quartzite was observed, with conglomerate at the base, interbedded with a reddish quartzite, overlapped by interbedded slate, quartzite and volcanic (rhyolite and volcanogenic tuff). This succession represents the Cambrian–Lower Ordovician transition already described by Couto [7], Couto et al. [27] and Couto & Roger [11] for the Valongo Anticline.

After what was observed in the fieldwork, the quartzitic ridge of the Monte de São Félix most likely materializes the Hirnantian (Upper Ordovician). Delgado [12], Medeiros [5] and Teixeira & Medeiros [8] consider that these quartzites are from the Lower Ordovician, correlating them with the quartzites from the Lower Ordovician that outcrop further south in the base of the Valongo Formation (Middle Ordovician).
Although not outcropping in the studied area, in the map of Nery Delgado [12] and in the Geological map 9-A of Póvoa do Varzim (1965) Sobrido greywackes are indicated, corresponding to the Hirnantian sequence described by Couto et al. [9], between Esposende and south of Castro Daire.

Based on field observations, NW of the São Félix hill, the quartzitic ridge marked by Delgado [12] and Teixeira & Medeiros [8], in geological map 9-A of Póvoa de Varzim, was not
observed. It’s a very flat area very urbanized and covered by agricultural fields with no traces of quartzite, where mainly Plio-Pleistocene dunes deposits and ancient beaches outcrop. It is a fact that being São Félix mountain a fossil cliff, marine erosion may have made some lithologies disappear and the dune deposits and ancient beaches that cover the surroundings of this mountain make it difficult to observe any Palaeozoic outcrops. During the fieldwork it was possible to verify that these quartzites also outcrop further south, close to the Shooting range, in an isolated ridge.

In contact with the Hirnantian quartzitic ridge, that outcrop to NW of the São Félix chapel, the presence of a highly altered volcanogenic rock, described for the first time in the region associated with these quartzites, was distinguished. However, there are mentions to this type of rock in the Upper Ordovician, in similar contexts, namely in North Wales [28].

According first studies, the Devonian in the area is Lower Devonian [5], [8]. More recent studies reviewing some fish fossil from this region, namely the genus Ischnacantus and Climatius confirmed a Lockovian (Lower Devonian) age for these rocks [17].

Remy Gourvennec (oral communication), a specialist in brachiopods, identified a Spirifer collected from the industrial zone of Laúndos, from the Lower Devonian.

The Carboniferous of continental facies was deposited and controlled by shears, evidenced by the breccification of the lithologies and by the abundance of iron oxides. Metasediments of this age are settled between the schists of the Middle Ordovician, and the schists and ferruginous quartzites of the Lower Devonian. There are porphyries interbedded in the basal breccia, similar to those described in São Pedro da Cova [25], [26], [11]. Thus, this succession could be correlated with the Lower Gzhelian (Lower Stephanian C) succession of the Douro Carboniferous Basin. According to Wagner & Sousa [29], given the fossiliferous content found in the Criaz – Serra de Rates strip, these metasediments are from Middle Westphalian to Lower Stephanian.

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