
U-Pb dating of Ordovician felsic volcanism in the Schistose Domain of the Galicia-Trás-os-Montes Zone near Cabo Ortegal (NW Spain)

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ABSTRACT

The northern termination of the Schistose Domain of the Galicia-Trás-os-Montes Zone is a tectonic slice named the Rio Baio Thrust Sheet, which is sandwiched between the Cabo Ortegal Complex and the Ollo de Sapo Domain of the Central-Iberian Zone. The Rio Baio Thrust Sheet is formed by two volcanosedimentary series, the Loiba and the Queiroga Series. The Loiba Series contains calc-alkaline dacite and rhyolite, while the overlying Queiroga Series has alkaline rhyolite. These series were considered to be in stratigraphically upwards continuity and believed to be Silurian in age. U-Pb dating of an alkaline rhyolite in the Queiroga Series provides an Arenig age of 475 ± 2 Ma. This age makes the Queiroga Series the oldest known stratigraphic unit in the Schistose Domain of the Galicia-Trás-os-Montes Zone, impeding correlation between the lithostratigraphic sequences of Ortegal and Central Galicia. As well as providing evidence of an unforeseen structural complexity within the Rio Baio Sheet, the new data supports the notion that the Schistose Domain is not parautochthonous, but a separate lithotectonic unit in thrust contact with the underlying Central-Iberian Zone.

KEYWORDS | Iberian Massif. Schistose Domain. U-Pb dating. Ordovician.

INTRODUCTION

The Schistose Domain of the Galicia-Trás-os-Montes Zone (Farias et al., 1987; Farias and Marcos, 2004) forms part of the internal zone of the Variscan Belt in the northwest Iberian Peninsula (Pérez Estaún et al., 1991). Due to its position, it has been interpreted as the outermost sedimentary apron of the Iberian Palaeozoic continental margin of Gondwana (e.g., Ribeiro et al., 1990; Martínez Catalán et al., 1997). This domain contains a low-grade sedimentary sequence with volcanic intercalations believed to be Silurian in age and in parautochthonous relationship with the underlying stratigraphy of the Central-Iberian Zone (Matte, 1968; Romariz, 1969; Ferragne, 1972; van der Meer Mohr, 1975; Iglesias and Robardet, 1980; Arce Duarte and Fernández Tomás, 1976; Arce Duarte et al. 1977; Bastida et al., 1984, 1993). The suspected Silurian age has led to the claim that the Schistose Domain lies unconformable on a Central-Iberian substrate (Fernández Pompa and Piera Rodríguez, 1975; Fernández Pompa et al., 1976). Recent detailed field studies of the relationship between rocks of the Schistose Domain and the underlying formations indicate that the former Santa Baia Group (Farias et al., 1987) and the previously reported Silurian graptolite faunas belong to the Central-Iberian footwall of the Schistose Domain (Marcos and Farias, 1997; 1999; Marcos et al., 2002; Marcos and Llana Fúnez, 2002; Farias and Marcos, 2004). This work questions the previously accepted Silurian age of the Schistose Domain. The northern sector of the Schistose Domain, around Cabo Ortegal, contains abundant felsic volcanic rocks and forms a separate structural unit tectonically emplaced over the Palaeozoic rocks of the Central Iberian Zone. New palynological findings of acritarch and chitinozoa in this sector suggest a Mid-Late Ordovician age for some of the volcanosedimentary sequence (Rodríguez et al., 2004). U-Pb dating of the interbedded volcanic rocks has been done to clarify the age of the Schistose Domain at Ortegal. The new geochronological result provides a precise Early Ordovician age, which implies that earlier notions regarding the age and stratigraphy of the Schistose Domain of the Galicia-Trás-os-Montes Zone have to be reassessed.

GEOLOGICAL SETTING: THE SCHISTOSE DOMAIN OF CABO ORTEGAL AND ITS AUTOCHTHON

The Galicia-Trás-os-Montes Zone is formed by two separate domains: the Domain of the Allochthonous Complexes and the Schistose Domain (Farias et al., 1987). The Domain of the Allochthonous Complexes contains the remains of a reworked Variscan suture (e.g. Pérez Estaún et al., 1991). This domain includes a thrust stack of "exotic" continental rocks, high-pressure units, and ophiolitic rocks (e.g., Martínez Catalán et al., 1996, 1997, 1999). The Schistose Domain lies structurally between the Allochthonous Complexes and the underlying Central-Iberian Zone. It con-

tains a siliciclastic sedimentary sequence in excess of 4000 m thick with volcanic intercalations and suspected "Iberian" affinity (Farias et al., 1987; Ribeiro et al., 1990; Martínez Catalán et al., 1999). The base of the domain is defined by a regional thrust that cuts earlier folds in the autochthon (Farias, 1987; Marcos and Farias, 1999). This autochthon is formed by the Palaeozoic sediments and felsic porphyroids of the Ollo de Sapo Domain of Central-Iberian Zone (Parga Pondal et al., 1964; Díez Balda et al., 1990).

In our area of study (Fig. 1), the Allochthonous Complexes are represented by the crystalline klippe of the Cabo Ortegal Complex (Vogel et al., 1967). Underneath this complex lies the Schistose Domain, represented by the Rio Baio Thrust Sheet (Marcos et al., 2002). This sheet is 3 Km thick and separates the Cabo Ortegal Complex from the underlying Lower Palaeozoic rocks of the Ollo de Sapo Antiform of the Central Iberian Zone (Marcos and Farias, 1997, 1999). The structural position of the Rio Baio Thrust Sheet is identical to that of the rocks of the Schistose Domain underneath the Ordenes Complex in central Galicia and the Bragança and Morais complexes of northern Portugal (Farias et al., 1987; Ribeiro et al., 1990; Martínez Catalán et al., 1997).

The Rio Baio Thrust Sheet

The rocks of the Rio Baio Thrust Sheet describe a monocline with scarce folds and a pervasive cleavage developed under greenschist facies conditions. The base of the sheet is marked by a 50 to 120 m thick zone with intense phyllonitization parallel to bedding in the hangingwall (Fig. 2). The Rio Baio Thrust Sheet contains a volcanosedimentary sequence formed by two lithostratigraphic units: the Loiba and Queiroga series (Arce Duarte and Fernández Tomás, 1976; Arce Duarte et al., 1977; Fernández Pompa and Piera Rodríguez, 1975; Fernández Pompa et al., 1976; Marcos and Farias, 1997). Felsic volcanic and volcanoclastic rocks are intercalated in both series (Arenas, 1984, 1988; Ancochea et al., 1988), but are more abundant in the Loiba Series. The entire sequence has been considered Silurian in age (Matte, 1968; Romariz, 1969; Iglesias and Robardet, 1980). However, new mapping shows that the Silurian fossil localities are located structurally below the Rio Baio Thrust Sheet in the rocks of the Ollo de Sapo Antiform (Fig.2; Marcos and Farias, 1997, 1999). Palynological findings in the phyllites of the Loiba Series point to an Upper Dobrotivian to Lower Caradocian age (Rodríguez et al., 2004). The Queiroga Series, which we sampled for U-Pb dating, was considered the youngest unit due to its position structurally above the Loiba Series.

The Loiba Series

The Loiba Series has an approximate thickness of 2000 m. It is dominated by green, purple, grey and black

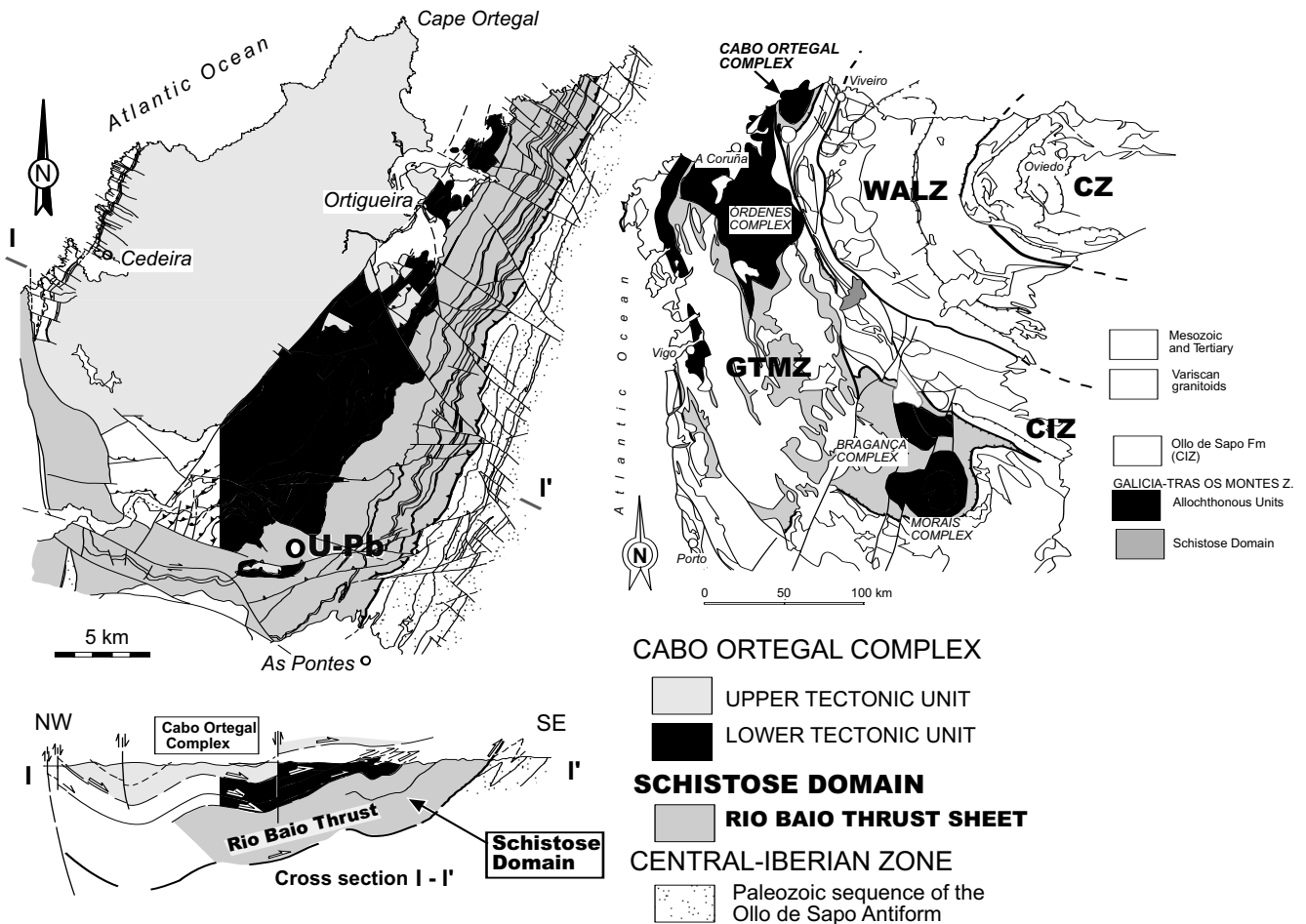


FIGURE 1 | Location of the Schistose Domain within the main lithotectonic zones of the northwest Iberian Massif. Simplified geological map and geological cross-section of the Cabo Ortegal area showing the location of the Schistose Domain (Rio Baio Thrust Sheet; modified from Farias and Marcos, 2004).

phyllite with subordinate light-grey to white quartzite. These quartzites are coarse-grained, sometimes conglomeratic, and show cross bedding locally. Volcanic intercalations are significant, particularly towards the base of the series (Fig. 2). There, volcanic rocks form bands, locally up to 200 m thick, which pass laterally into volcanogenic sandstone. The upper part of the Loiba Series contains a few thin layers of rhyolite with limited lateral extension. These volcanic rocks bear evidence of low-grade recrystallization produced during the first Variscan metamorphic event (Arenas, 1988). The two main layers of volcanic rocks in this unit are the Loiba dacites and Costa Xuncos rhyolites, which have been described in detail by Arenas (1984, 1988). These volcanic units are located on the lower section of the sequence. The two volcanic strata are separated by 200 to 300 m of siliciclastic rocks, although in the map they are represented as a single unit which gradually disappears towards the south (Fig. 2).

The *Loiba dacites* form an irregular layer, approximately 100 m thick, of great lateral extension (Fig. 2). This is the volcanic unit in the lowest structural level of the thrust sheet. The dacites contain centimetric to metric intercalations of pelite and psammite, which are interpreted as pinch-outs of the original volcanic deposit (Arenas, 1988). Rhyolites rich in quartz phenocrysts are sporadically found along with the dacites.

The *Costa Xuncos rhyolites* overlay the Loiba dacites. These rhyolites constitute the thickest (150-200 m) and, with 30 km of lateral continuity, the largest single volcanic unit within the thrust sheet (Fig. 2). The rhyolites exhibit a remarkable textural, mineralogical and compositional homogeneity, and do not have sedimentary intercalations. Despite recrystallization, flame structures, pointing at a pyroclastic origin, are still preserved in places. Grain size and phenocryst content decrease towards the top of the volcanic unit, where the pyroclastic character becomes more pronounced (Arenas, 1988). Enclaves of

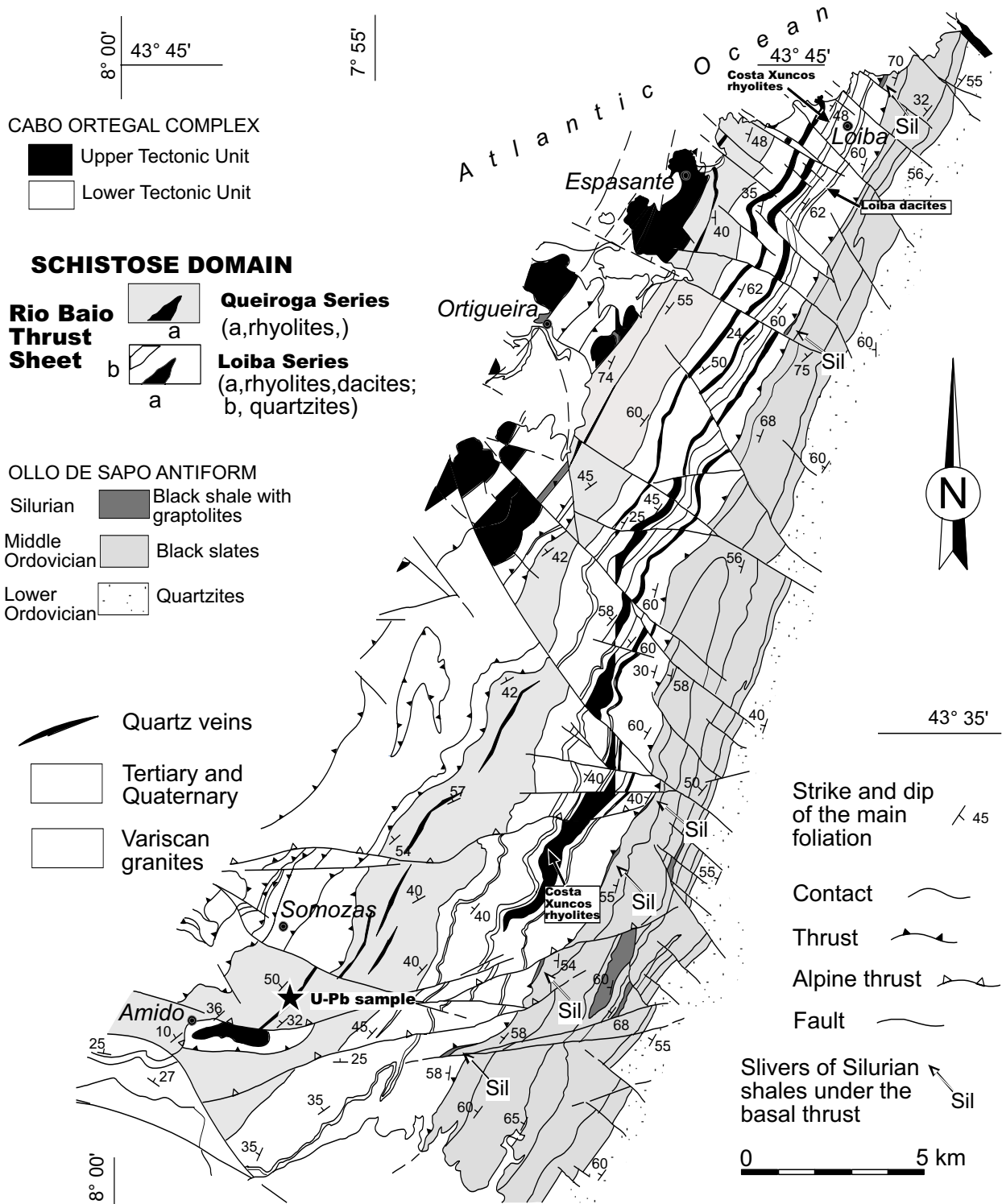


FIGURE 2 | Geological map of the Rio Baio Thrust Sheet and surrounding rocks along the eastern border of the Cabo Ortegal Complex, and location of the sampling site.

microgranite and quartz-syenite are locally enclosed in the rhyolites. A level of micro-syenite approximately 30 m thick and 100 m long in the upper levels of the rhyolitic unit is interpreted as an intrusive sill or plug associated the volcanic event (Arenas, 1988).

The Queiroga Series

The Queiroga Series is in contact with the Cabo Ortegal Complex. This is the uppermost unit of the Rio Baio Thrust Sheet, and it is formed by a monotonous succession (approximately 1100 m thick) of phyllite and quartzite alternating with medium to coarse-grained greywacke and feldspathic lithic sandstone. Volcanic layers are relatively abundant in the upper section of the Queiroga Series near the basal thrust of the Cabo Ortegal Complex (Fig. 2). Due to the strong and pervasive deformation that affected the unit, only the most massive rock types are well preserved. The latter correspond to rhyolite and dacite showing restricted lateral continuity and frequent sedimentary intercalations. This volcanic unit contains small rhyolitic domes. Like the underlying Loiba Series, the volcanic rocks underwent low-grade recrystallization during Variscan metamorphism (Arenas, 1988).

The most abundant volcanic rock type is a medium-grained porphyritic rhyolite containing variable proportions of phenocrysts (< 4 cm) of quartz, plagioclase, alkali feldspar and biotite in a recrystallized schistose mesostasis. Microphenocrysts of apatite and zircon are present in some of the rhyolites. There is also coarse-grained rhyolite, which locally grades into fine-grained, cinerite-like, rhyolite and medium porphyritic massive dacite. The rhyolites often alternate with volcano-sedimentary lithic and feldspathic greywackes along with pelite and psammite. The coarse-grained porphyritic rhyolites form strain resistant, homogeneous, dark grey domes of decameter scale. It is one of these domes that has been sampled for U-Pb dating.

GEOCHEMISTRY AND VOLCANOGENIC CONSIDERATIONS OF THE VOLCANIC ROCKS IN THE RIO BAI Thrust SHEET

The first major element geochemical characterization of these volcanic rocks done by Arenas (1984, 1988), who suggested that they had high-K calc-alkaline to shoshonitic affinities. Subsequent trace element work showed the presence of two different and separate series (Ancochea et al., 1988). The high-K calc-alkaline to shoshonitic volcanic rocks coincide with the Loiba Series, here described, while alkaline rhyolites are exclusive of the Queiroga Series. These geochemical differences are reflected in two representative samples taken from the Costa Xuncos rhyolites (Loiba Series) and the Queiroga

Series (Appendix, Table 1). The sample from the Queiroga Series corresponds to the rhyolite used for U-Pb dating.

These two rhyolites have a similar major element composition, although that from Queiroga is poorer in MgO, CaO and Na₂O and richer in K₂O than the Costa Xuncos one. Immobile trace element characterization (Fig. 3A; Winchester and Floyd, 1977) shows that the Costa Xuncos rhyolite plots in the calc-alkaline dacite-rhyodacite field, in agreement with previous results (Ancochea et al., 1988), while the Queiroga rhyolite is an alkaline comendite-pantellerite. The REE normalized patterns (Evensen et al., 1978) display the difference in chemical composition between both volcanic rock units. The rhyolite from Queiroga is distinctly richer in REE and exhibits a marked Eu negative anomaly in contrast to that from Costa Xuncos (Fig. 3B). The ORG-normalized multielement diagram (Fig. 3C; Pearce et al., 1984) of the Costa Xuncos rhyolite displays concentrations and patterns typical of orogenic calc-alkaline granite (VAG field). The rhyolite from the Queiroga Series shows a strong negative Ba anomaly with an enrichment in Nb, Ce, Zr and Sm contents similar to those observed in within-plate granite (WPG; Pearce et al., 1984). Such pattern is typical of alkaline felsic magmas (Whalen et al., 1996) and is in agreement with its high REE content.

The geochemical characterization of these two samples agrees with the results of previous studies (Arenas, 1984, 1988; Ancochea et al., 1988). These studies suggest that the Loiba dacites are derived from massive subaerial eruptions of calc-alkaline lava flows. The overlying Costa Xuncos rhyolites are interpreted as high-K calc-alkaline tuffs formed during a subaerial ignimbritic eruption with associated syenitic intrusions forming sills or plugs during the same event. The Queiroga Series contains a different and more complex episode of volcanism with massive lava and ignimbrite eruptions of alkaline rhyolite alternating with siliciclastic sedimentation. It is suggested that the massive rhyolitic domes were formed during several effusive and shallow intrusive pulses (Arenas, 1988; Ancochea et al., 1988)

U-Pb GEOCHRONOLOGY

The volcanic rock sampled for U-Pb geochronology belongs to a rhyolite dome from the upper part of the Queiroga Series located 2 km south of the village of Somozas (Fig. 2). The rock has a porphyritic texture with 1.5 cm long (locally up to 5 cm), idiomorphic phenocrysts of quartz, plagioclase and alkali feldspar (originally sodic sanidine), with sporadic microphenocrysts of zircon and opaques. The microcrystalline microlithic mesostasis contains idiomorphic to subidiomorphic albite, alkali feldspar, quartz, minor altered biotite and accessory apatite, zircon and opaques.

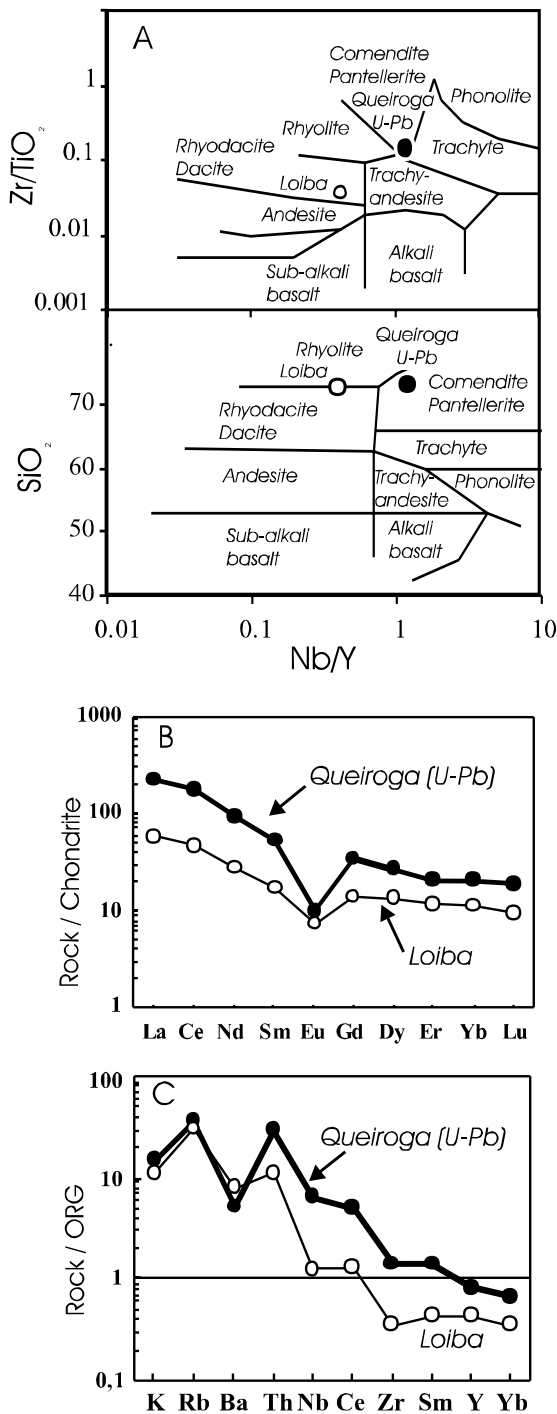


FIGURE 3| Geochemical characterization of the Costa Xuncos and Queiroga rhyolites. A) Immobile trace element characterization (Winchester and Floyd, 1977). B) Chondrite normalized rare element pattern (Evensen et al., 1978). C) Ocean Ridge Granite (ORG) normalized multielement pattern (Pearce et al., 1984).

Analytical method

Sample preparation was done at Universität Giessen (Germany). After crushing with a jaw crusher and a disk mill, the heavy minerals were separated with a Wilfley

table and heavy liquids (bromoform and diiodomethane). Further separation was done with a Frantz isodynamic magnetic separator. Final selection of the zircon crystals for analysis was done under a binocular microscope. These zircons belong to the J4 to D type of Pupin (1980).

The zircon fractions were air abraded (Krogh, 1982) and washed with 4N HNO₃, ultra pure H₂O and ultra pure acetone. After weighting, the zircon fractions were spiked with a ²⁰⁵Pb-²³⁵U isotopic tracer before dissolution. The zircons were dissolved in Krogh-type Teflon dissolution vessels with HF (Krogh, 1973). In the case of the three analyses done at the Geological Survey of Canada (Ottawa, Canada), a ²⁰⁵Pb-²³³U-²³⁵U spike was added and the samples were dissolved in Parrish-type microcapsules (Parrish, 1987). A scaled-down version of the ion exchange procedure of Krogh (1973) was used to separate and purify U and Pb. The U and Pb were collected separately with H₃PO₄ and loaded in separate single Rhenium filaments. The samples analysed in Giessen were loaded with a mixture of silica gel and H₃PO₄. At the Geological Survey of Canada, the samples were collected with ultra pure H₂O and loaded on a base of silica gel. Both laboratories use Finnigan MAT 261 multicollector mass spectrometers. When the ion beam intensities allowed, measurement of the isotopic ratios was done in static mode. The ²⁰⁴Pb peak was measured with a calibrated secondary electron multiplier (SEM). In the case of the low lead content of the samples, peak jumping measurements were done on the SEM. At Universität Giessen, the SEM was operated in ion counting mode, while in Ottawa the SEM was used in analogue mode (Loveridge, 1986; Roddick et al., 1987). All reported isotopic ratios were corrected for mass fractionation, blank (3-10 pg Pb, 1 pg U) and initial common Pb (Stacey and Kramers, 1975). Isotopic ages were calculated using the decay constants of Jaffey et al. (1971).

Calculation of the ages and uncertainties of the analyses done at Universität Giessen (Fractions Z4 to Z10; Table 1) were calculated using PBDAT (Ludwig, 1991). An internal program of the Geological Survey of Canada (Parrish et al., 1987) was used for the analyses done in Ottawa (Fractions Z1 to Z3; Table 1). In all cases uncertainties are reported at the 2σ level. Total uncertainties of individual points are represented by 2σ uncertainty ellipses. The concordia diagram was traced using ISO-PLOT/EX v. 2.0 (Ludwig, 1999). Regression lines were calculated with this program using the least-squares method (York, 1969). Age and uncertainties of the intercepts are reported at the 95% confidence interval.

Result

A total of ten-zircon analyses were performed (Table 1). The initial set of analyses showed different degrees of

TABLE 1 | U-Pb data. Schistose Domain, Galicia-Tras-os-Montes Zone (NW Iberia).

Sample	weight µg	U ppm	Pb _{rad} ppm	Pb _{com} pg	Meas.*		Corrected atomic ratios**			Ages (Ma)		
					²⁰⁶ Pb	²⁰⁸ Pb	²⁰⁶ Pb	²⁰⁷ Pb	²⁰⁷ Pb	²⁰⁶ Pb	²⁰⁷ Pb	²⁰⁷ Pb
					²⁰⁴ Pb	²⁰⁶ Pb	²³⁸ U ±2σ	²³⁵ U ±2σ	²⁰⁶ Pb ±2σ	²³⁸ U	²³⁵ U	²⁰⁶ Pb
Rhyolite Queiroga Series												
Z1, 6 xtals 150 µm AB	38	194	15	98	376	0.120	0.07653 ±49	0.5969 ±87	0.05656 ±63	475	475	475
Z2, 2 xtals 150-200µm AB	16	273	21	16	1319	0.129	0.07640 ±28	0.5966 ±29	0.05664 ±15	475	475	477
Z3, 3 xtals 150 µm AB	22	279	22	30	969	0.132	0.07660 ±25	0.5992 ±32	0.05680 ±21	476	477	481
Z4, ca. 80 µm prisms AB	68	240	19	13	5991	0.135	0.07848 ±28	0.6210 ±35	0.05739 ±24	487	490	506
Z5, ca. 80 µm prisms AB	60	257	21	7	10514	0.130	0.07873 ±16	0.6234 ±19	0.05743 ±13	488	492	508
Z6, ca. 80-100 µm prisms AB	25	223	18	6	4340	0.130	0.07762 ±29	0.6243 ±34	0.05833 ±22	482	492	542
Z7, ca. 100 µm, incl. free pr. AB	115	136	11	54	1463	0.132	0.07898 ±35	0.6520 ±49	0.05987 ±36	490	510	599
Z8, single xtal., incl. free AB	13	163	13	4	2528	0.138	0.07764 ±45	0.6423 ±62	0.05999 ±45	482	504	603
Z9, single xtal, incl. free AB	14	91	7	2	2769	0.143	0.07805 ±64	0.6505 ±74	0.06045 ±45	484	509	620
Z10, ca. 150 µm prisms AB	43	356	30	46	1804	0.097	0.08540 ±46	0.6864 ±59	0.05829 ±39	528	531	540

AB, air abrasion (Krogh, 1982); NA, no air abrasion; pr., prisms; xtal, crystal; incl., inclusion

* Measured ratio corrected for blank and fractionation, spike removed.

** Atomic ratios corrected for fractionation, spike, laboratory blanks (2-10 pg Pb and 1 pg U) and initial common Pb (Stacey and Kramers, 1975). Absolute errors reported.

APPENDIX (TABLE 1) | Major and trace element analyses of two representative samples from the Loiba and Queiroga series.

Majors (%)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	L.O.I.	Total									
Loiba Series (Costa Xuncos)	72.85	13.79	2.63	0.02	0.98	0.26	3.11	4.39	0.34	0.17	1.65	100.19									
Queiroga Series (U-Pb)	73.06	13.34	2.66	0.01	0.16	0.09	2.81	6.07	0.38	0.10	0.92	99.6									
Traces (ppm)	V	Cr	Ni	Ba	Rb	Sr	Nb	Y	Zr	U	Th	La	Ce	Nd	Sm	Eu	Gd	Dy	Er	Yb	Lu
Loiba Series (Costa Xuncos)	34	15	9	396	124	83	12	30	118	4	9	21.3	46.0	19.8	4.0	0.6	4.2	5.3	2.9	2.8	0.4
Queiroga Series (U-Pb)	12	n.d.	4	260	144	50	64	57	483	5	23	83.0	173.1	67.6	12.6	0.9	11.0	10.2	5.3	5.2	0.7

Major elements analyses done by XRF on fused pellets. Trace elements (V to Th) done by XRF on pressed pellets (Univ. Oviedo, Spain). REE done by ICP-OES (UPV, Bilbao, Spain). Analytical precision is better than the last digit.

zircon inheritance. To avoid inheritance, large zircon crystals with acicular inclusions through their cores were hand picked (Fig. 4). This resulted in three analysis overlapping concordia at 475 Ma: Z1 (-0.2% discordant), Z2 (0.6% discordant), and Z3 (1.1% discordant). Fraction Z10 overlaps concordia at ca. 530 Ma, indicating the presence of a Late Neoproterozoic zircon inheritance with a maximum age of 635 Ma (upper intercept of a mixing line through Z10 anchored at 475 Ma; not shown) and a minimum age of 540 Ma (²⁰⁷Pb/²⁰⁶Pb age of fraction Z10; Table 1). The data allows two separate regression lines to be drawn (Fig. 5): L1 (Z1-Z2-Z3-Z6-Z7) and L2 (Z1-Z4-Z5). Line L1 with a MSWD of 0.4 has a lower intercept of 474.7 ± 1.6 Ma and an upper intercept of 2259 ± 200 Ma. Line L2 is anchored at 475 Ma by the concordant fraction Z1, and the resultant upper intercept has an age of 1040 ± 500 Ma.

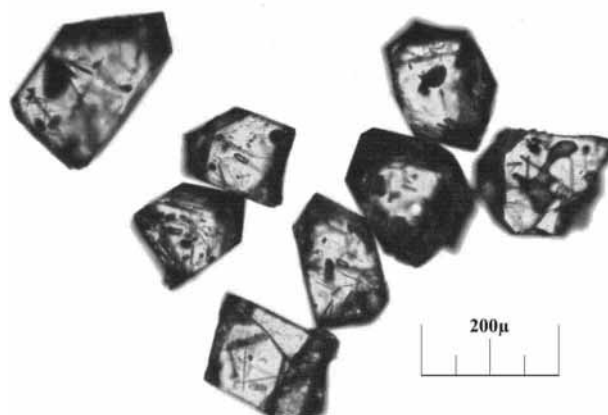


FIGURE 4 | U-Pb sample, euhedral zircon crystals with fluid inclusions (fraction Z1, Queiroga Series).

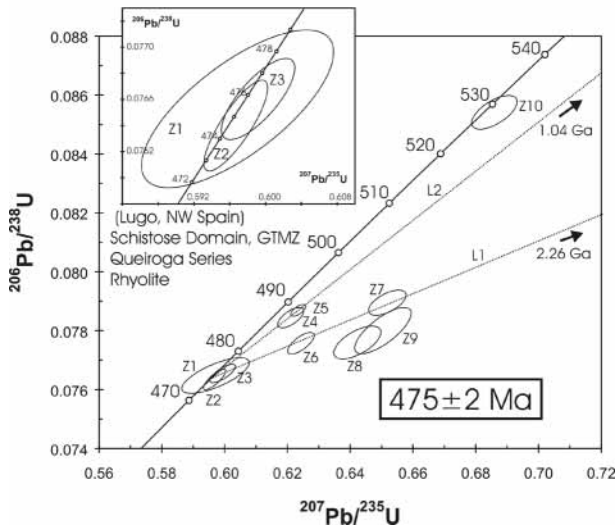


FIGURE 5 | U-Pb concordia diagram showing mixing lines L1 and L2, inset concordant fractions.

The weighted mean of the concordant fractions Z1, Z2, and Z3 provides an age of 475.4 ± 1.1 Ma. The concordance of the weighted age has an MSWD of 0.9 with a probability of 34% (calculated with decay constant errors; see Ludwig, 1999). This age is coeval within error with the lower intercept age of the regression line L1 (Fig. 5).

To avoid any underestimation of the uncertainty, the uncertainty of the weighted mean has been doubled. We consider that an age of 475 ± 2 Ma provides the best estimate for the age of crystallization of the magmatic protholith and formation of the rhyolite dome.

DISCUSSION

The Galicia-Trás-os-Montes Schistose Domain (Fariás et al., 1987) is also known as Para-Autochthonous Thrust Complex (Ribeiro et al., 1990). The name Parautochthonous (i.e., a unit whose tectonic character is intermediate between autochthonous and allochthonous) derives from the assumption that the Schistose Domain is formed by a group of rocks in stratigraphic continuity with the autochthonous sequence of the Central Iberian Zone. The Ordovician age of the volcanic rocks in the Queiroga Series demonstrates that the stratigraphic continuity is broken (Fig. 6), and therefore the Schistose Domain can not be para-autochthonous.

Stratigraphy of the Schistose Domain

The structural position of the Rio Baio Thrust Sheet, sandwiched between the Cabo Ortegal Complex and the Central-Iberian rocks of the Olló de Sapo Antiform, is

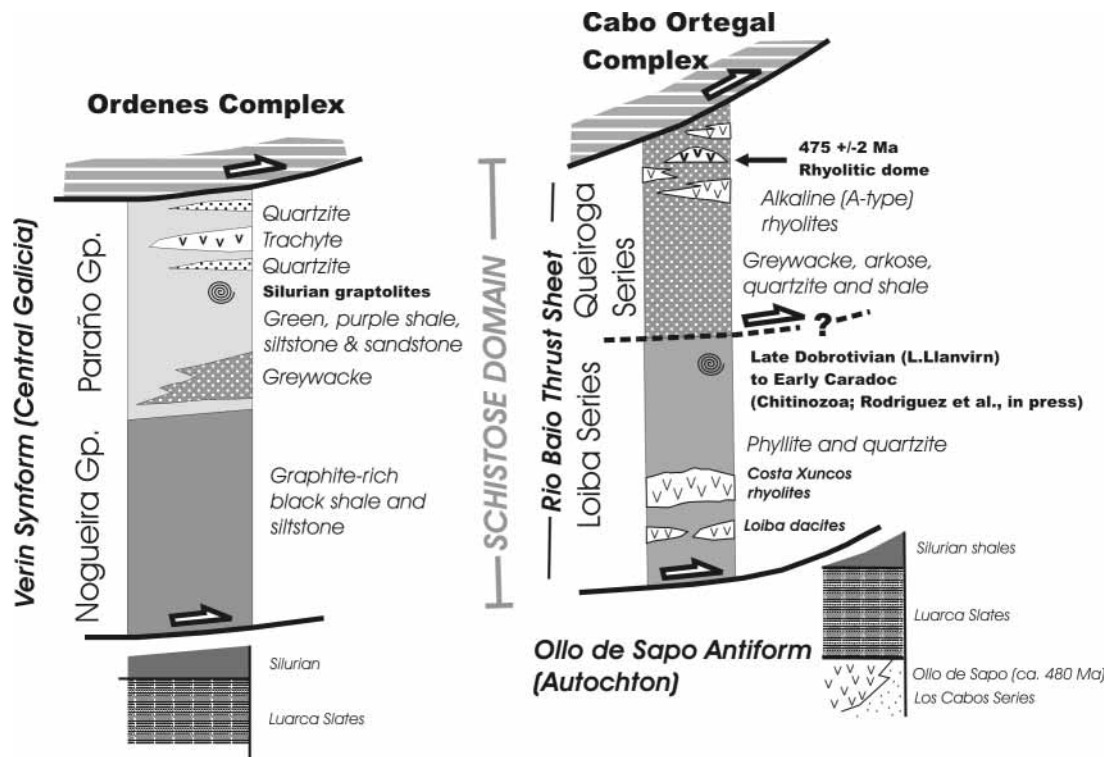


FIGURE 1 | Schematic comparison of the lithostratigraphy of the Schistose Domain of the Galicia-Trás-os-Montes Zone near Cabo Ortegal and Central Galicia.

identical to that of the Schistose Domain near the mafic/ultramafic complexes of central Galicia (Marquín, 1984; Farias, 1990; Martínez Catalán et al., 1996) and northern Portugal (Ribeiro, 1974; Ribeiro et al., 1990). In these locations the basal thrust of the Schistose Domain, like the Rio Baio thrust, cuts across kilometric isoclinal recumbent folds in the underlying Central-Iberian Zone (Farias, 1987; Marcos and Llana Fúnez, 2002; Farias and Marcos, 2004). Lithological similarities between the Schistose Area of Central Galicia (Verín Synform; Farias, 1990) and Ortegá have led to informal correlation of the Loiba and Queiroga series with the Nogueira and Paraño groups of central Galicia (Fig. 6; Farias and Marcos, 2004). The lowermost Nogueira Group was correlated with the level of dark grey phyllonites at the base of the Loiba Series, below the Costa Xuncos Rhyolites. The Paraño Group was correlated with the remaining of the Loiba and Queiroga series. This correlation was based on the presence of greywacke, quartzite and felsic volcanic rocks in both areas. The volcanic rocks in the Paraño Group are felsic rhyolite and trachyte, which occur stratigraphically above a reported horizon with Silurian graptolites (Romariz, 1969). Attempts to validate the fossil findings in the type locality have proved unsuccessful, but preliminary U-Pb dating of a trachyte in this unit indicates a Siluro-Ordovician age in agreement with the fossil age (Valverde-Vaquero, unpublished). The age of 475.4 ± 2 Ma for the rhyolite in the Queiroga Series indicates that the level we dated is Middle-Late Arenig according to the time-scale of Tucker and McKerrow (1995). This makes the Queiroga Series the oldest stratigraphic unit of Schistose Domain and invalidates the correlation with the Paraño Group. The presence of Upper Ordovician acritarchs in the underlying Loiba Series requires a thrust separating the Queiroga and Loiba series, unless the sequence is inverted. This reveals an unforeseen structural complexity in the Rio Baio Thrust Sheet. This consideration implies that the age of the high-K calc-alkaline dacites and rhyolites of the Loiba Series remains unconstrained and will have to be resolved in a future study.

Palaogeographic affinity of the Schistose Domain

The Schistose Domain has been interpreted as the outboard edge of the Iberian terrane formed by the Central Iberian, West Asturian-Leonese, and Cantabrian Zones (e.g. Martínez Catalán et al., 1997). Significant Early-Middle Ordovician felsic magmatism is present in the autochthon of the Schistose Domain, the Ollo de Sapo Domain of the Central-Iberian Zone (Gebauer et al., 1993; Fernández Suárez et al., 1999; Valverde-Vaquero and Dunning, 2000), which apparently corroborates such an idea. Our data could suggest that the 475 Ma alkaline rhyolites in the Schistose Domain contain inherited zircon from similar crustal sources as the Ollo de Sapo porphy-

roid of the Central-Iberian Zone (U-Pb LAM-ICP-MS data; Fernández Suárez et al., 1999). Zircon fraction Z10 indicates the clear presence of zircon inheritance with a late NeoProterozoic age of between 540 and 630 Ma. This allows us to infer participation of a Cadomian/Avalonian crustal source. The upper intercepts of the regression lines L1 (ca. 2.2 Ga) and L2 (ca. 1.04 Ga) might indicate "Icartian" and "Grenvillian" age sources. However, our analytical points are multigrain fractions, so there is good possibility that they represent averages of inherited zircon with different ages. Given the long projections of the regression lines, the geological significance, if any, of these upper intercept ages is uncertain and they can not be used as an argument to constrain the palaeogeographic derivation of the Schistose Domain. These new data suggest that the basal thrust of the Rio Baio Thrust Sheet is a significant thrust, not a minor décollement. Therefore, the palaeogeographic notion that the Schistose Domain of the Galicia-Trás-os-Montes Zone was the mere outboard edge of the neighbouring Central-Iberian Zone remains questionable.

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REFERENCES

- Ancochea, E., Arenas, R., Brandle, J.L., Peinado, M., Sagredo, J., 1988. Caracterización de las rocas metavolcánicas silíceas del Noroeste del Macizo Ibérico. *Geociencias*, 1-2, 23-34.
- Arce Duarte, J.M., Fernández Tomás, J., 1976. Mapa Geológico de España. Scale 1:50.000, Hoja 8 (7-3), Vivero. Madrid, Instituto Geológico Minero España, 45 pp, 1 fold. map.
- Arce Duarte, J.M., Fernández Tomás, J., Monteserín López, V., 1977. Mapa Geológico de España. Scale 1:50.000, Hoja 7 (7-2), Cillero. Madrid, Instituto Geológico Minero España, 47 pp., 1 fold. map.
- Arenas, R., 1984. Características y significado del volcanismo ordovícico-silúrico de la serie autóctona envolvente del Macizo de Cabo Ortegá (Galicia, NW España). *Revista Materiales Procesos Geológicos*, 11, 135-144.
- Arenas, R., 1988. Evolución petrológica y geoquímica de la Unidad alóctona inferior del Complejo metamórfico básico-

- ultrabásico de Cabo Ortegal (Unidad de Moeche) y del Silúrico paraautóctono, Cadena Herciniana Ibérica (NW de España). *Corpus Geologicum Gallaeciae*, 4, 545 pp.
- Bastida, F., Marcos, A., Marquínez, J., Martínez Catalán, J.R., Pérez-Estaún, A., Pulgar, J.A., 1984. Mapa Geológico de España. Scale 1:200.000, Hoja 1 (2-1), La Coruña. Madrid, Instituto Geológico Minero España, 155 pp, 1 fold. map.
- Bastida, F., Aller, J., Fernández Viejo, G., 1993. The structure of the Ollo de Sapo antiform in the Cantabrian coast (NW Spain). *Revista Sociedad Geológica España*, 6, 93-103.
- Díez Balda, M.A., Vegas, R., González Lodeiro, F., 1990. Structure (Central Iberian Zone). In: Dallmeyer, R.D., Martínez García, E. (eds.). *Pre-Mesozoic Geology of Iberia*. Berlin Heidelberg, ed. Springer-Verlag, 172-188 pp.
- Evensen, M.M., Hamilton, P.J., O'niions, R.K., 1978. Rare-earth abundances in chondritic meteorites. *Geochimica et Cosmochimica Acta*, 42, 1199-1212.
- Farias, P., 1987. La estructura herciniana del sector oriental del Sinclinal de Verín: Los cabalgamientos de Verín y Pradocabalos. *Cuadernos Laboratorio Xeolóxico Laxe*, 11, 295-303.
- Farias, P., 1990. La geología de la Región del Sinforme de Verín (Cordillera Herciniana, NW de España). La Coruña, Ediciones do Castro, Serie Nova Terra, 1-201.
- Farias, P., Gallastegui, G., González-Lodeiro, F., Marquínez, J., Martín Parra, L., Martínez Catalán, J.R., De Pablo Maciá, J.G., Rodríguez Fernández, L.R., 1987. Aportaciones al conocimiento de la litoestratigrafía y estructura de Galicia Central. *Faculdade de Ciências do Porto, Memórias do Museu e Laboratório Mineralógico e Geológico*, 1, 411-431.
- Farias, P., Marcos, A., 2004. Dominio Esquistoso de Galicias-Tras-os-Montes. In: Vera, J.A. (ed.). *Geología de España*. Madrid, SGE-IGME, 135-138.
- Fernández Pompa, F., Píera Rodríguez, T., 1975. Mapa Geológico de España. Scale 1:50.000, Hoja 22 (6-4), Puentevedume. Madrid, Instituto Geológico Minero España, 45 pp, 1 fold. map.
- Fernández Pompa, F., Monteserín López, V., 1976. Mapa Geológico de España. Scale 1:50.000, Hoja 7 (6-3), Cedeira. Madrid, Instituto Geológico Minero España, 73 pp, 1 fold. map.
- Fernández-Suárez, J., Gutiérrez-Alonso, G., Jenner, G., Tubrett, M.N., 1999. Crustal sources in Lower Palaeozoic rocks from NW Iberia, insights from laser ablation U-Pb ages of detrital zircons. *London, Journal of the Geological Society*, 156, 1065-1068.
- Ferragne, A., 1972. Le Précambrien et le Paléozoïque de la Province de l'Orense (Nord-Ouest de l'Espagne). *Stratigraphie-Tectonique-Métamorphisme*. Doctoral thesis. Université de Bordeaux. Bordeaux, 249 pp.
- Gebauer, D., Martínez García, E., Hepburn, J.C., 1993. Geodynamic significance, age and origin of the Ollo de Sapo Augengneiss (NW Iberian Massif, Spain). *Annual meeting of Geological society of America, Boston, Abstracts with Programs*, A-342.
- Iglesias, M., Robardet, M., 1980. Silúrico de Galicia Media-Central. Su importancia en la paleogeografía Varisca. *Cuadernos Laboratorio Xeolóxico Laxe*, 1, 99-115.
- Jaffey, A.H., Flynn, K.F., Glendenin, L.E., Bentley, W.C., Essling, A.M., 1971. Precision measurement of the half-lives and specific activities of ^{235}U and ^{238}U . *Physics Review Section C, Nuclear Physics*, 4, 1889-1906.
- Krogh, T.E., 1973. A low-contamination method for the hydrothermal decomposition of zircon and the extraction of U and Pb for isotopic determinations. *Geochimica et Cosmochimica Acta*, 37, 485-494.
- Krogh, T.E., 1982. Improved accuracy of U-Pb zircon ages by the creation of more concordant systems using an air abrasion technique. *Geochimica et Cosmochimica Acta*, 46, 637-649.
- Loveridge, W.D., 1986. Measurement of biases in the electron multiplier ion detection system of a Finnigan-MAT model 261 mass spectrometer. *International Journal of Mass Spectrometry and Ion Processes*, 74, 197-206.
- Ludwig, K.R., 1991. PBDAT version 1.23
- Ludwig, K.R., 1999. ISOPLOT/Ex. version 2.00.
- Marcos, A., Farias, P., 1997. La estructura de la sutura varisca en la transversal de Cabo Ortegal (NW de España). In: Pires, C.C., Gomes, M.E.P., Coke, C. (eds.). *Evolução geológica do Maciço Ibérico e seu enquadramento continental*. 14 Reunião de Geologia do Oeste Peninsular, VilaReal, Portugal, Comunicações, 109-114.
- Marcos, A., Farias, P., 1999. La estructura de las láminas inferiores del Complejo de Cabo Ortegal y su autóctono relativo (Galicia, NO de España). *Universidad de Oviedo, Trabajos de Geología*, 21, 201-218.
- Marcos, A., Farias, P., Galán, G., Fernández, F.J., Llana-Fúnez, S., 2002. The tectonic framework of the Cabo Ortegal Complex: a slab of lower crust exhumed in the Variscan Orogen (NW Iberian Peninsula). In: Martínez Catalán, J.R., Hatcher Jr., R.D., Arenas, R., Díaz García, F. (eds.). *Variscan-Appalachian dynamics: The building of the late Paleozoic basement*. Boulder, Colorado, Geological Society of America, Special Paper 364, 143-162.
- Marcos, A., Llana Fúnez, S., 2002. Estratigrafía y estructura de la lámina tectónica del Para-autóctono y de su autóctono en el área de Chantada (Galicia, NO de España). *Universidad de Oviedo, Trabajos de Geología*, 23, 53-72.
- Marquínez, J.L., 1984. La geología del Area Esquistosa de Galicia Central (Cordillera Herciniana, NW de España). *Instituto Geológico Minero España, Memórias*, 100, 1-231.
- Martínez Catalán, J.R., Arenas, R., Díaz García, F., Rubio Pascual, F.J., Abati, J., Marquínez, J., 1996. Variscan exhumation of a subducted Paleozoic continental margin: The basal units of the Ordenes Complex, Galicia, NW Spain. *Tectonics*, 15, 106-121.
- Martínez Catalán, J.R., Arenas, R., Díaz García, F., Abati, J., 1997. Variscan accretionary complex of northwest Iberia: Terrane correlation and succession of tectonothermal events. *Geology*, 25, 1103-1106.
- Martínez Catalán, J.R., Arenas, R., Díaz García, F., Abati, J., 1999. Allochthonous units in the Variscan Belt of NW Iberia (Terranes and Accretionary History). In: Sinha, A.K. (ed.). *Basement Tectonics 13*. Kluwer Academic Publishers, 65-84.
- Matte, Ph., 1968. La structure de la virgation hercynienne de

- Galice (Espagne). *Geologie Alpine*, 44, 157-280.
- Parga Pondal, I., Matte, Ph., Capdevila, R., 1964. Introduction a la géologie de l' "Ollo de Sapo ", Formación porphyroide antésilurienne du Nord Ouest de L'Espagne. Madrid, Instituto Geológico Minero España, Notas Comunicaciones, 76, 119-154.
- Parrish, R.R., 1987. An improved micro-capsule for zircon dissolution in U-Pb geochronology. *Chemical Geology (Isotope Geoscience Section)*, 66, 99-102.
- Parrish, R.R., Roddick, J.C., Loveridge, W.D., Sullivan, R.W., 1987. Uranium-lead analytical techniques at the geochronology laboratory. Geological Survey of Canada. Radiogenic Age and Isotopic Studies, Report 1, Geological Survey of Canada, 87-2, 3-7.
- Pearce, J.A., Harris, N.B.W., Tindle, A.G., 1984. Trace element discriminations for the tectonic interpretation of granitic rocks. *Journal of Petrology*, 25, 956-983.
- Pérez Estaún, A., Martínez Catalán, J.R., Bastida, J., 1991. Crustal thickening and deformation sequence in the footwall to the suture of the Variscan belt of northwest Spain. *Tectonophysics*, 191, 243-253.
- Pupin, J.P., 1980. Zircon and Granite Petrology. *Contributions to Mineralogy and Petrology*, 73, 207-220.
- Ribeiro, A., 1974. Contribution à l'étude tectonique de Trás-os-Montes oriental. *Memória Serviços Geológicos de Portugal*, 24, 1-168.
- Ribeiro, A., Pereira, E., Dias, R., 1990. Structure in the NW of the Iberian peninsula. In: Dallmeyer, R.D., Martínez García, E. (eds.). *Pre-Mesozoic Geology of Iberia*. Berlin Heidelberg, ed. Springer-Verlag, 221-236.
- Roddick, J.C., Loveridge, W.D., Parrish, R.R., 1987. Precise U/Pb dating of zircon at the sub-nanogram Pb level. *Chemical Geology (Isotope Geoscience Section)*, 66, 111-121.
- Rodríguez, R., Marcos, A., Farias, P., 2004. Palynological data on the age of the metasediments of the Parautochthonous Thrust Sheet in the Cabo Ortegal area (Galicia, NW Spain). *Neues Jahrbuch für Geologie und Paläontologie*, 10, 437-447.
- Romariz, C., 1969. Graptolites silúricos do NW peninsular. *Comunicações Serviços Geológicos de Portugal*, 53, 107-156.
- Stacey, J.S., Kramers, J.D., 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth and Planetary Science Letters*, 26, 207-221.
- Tucker, R.B., McKerrow, W.S., 1995. Early Paleozoic chronology: a review in light of new U-Pb zircon ages from Newfoundland and Britain. *Canadian Journal of Earth Sciences*, 32, 368-379.
- van der Meer Mohr, C.G., 1975. The Palaeozoic strata near Moeche in Galicia, NW Spain. *Leidse Geologische Mededelingen*, 49, 32-37.
- Valverde-Vaquero, P., Dunning, G.R., 2000. New U-Pb ages for Early Ordovician magmatism in Central Spain. *Journal Geological Society*, 157, 15-26.
- Vogel, D.E., Engels, J.P., Ho Len Fat, A.G., 1967. Geological map of the area around Cabo Ortegal (Spain). The Geological Institute, Leiden (Netherlands).
- Winchester, J.A., Floyd, P.A., 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chemical Geology*, 20, 326-348.
- Whalen, J.B., Longstaffe, F.J., Jenner, G.A., Robert, F., Gariépy, C., 1996. Geochemical and isotopic (Nd, O, Pb and Sr) constraints on A-type granite petrogenesis based on the Topsails igneous suite, western Newfoundland. *Journal of Petrology*, 37, 1463-1489.
- York, D., 1969. Least-squares fitting of a straight line with correlated errors. *Earth and Planetary Science Letters*, 5, 320-324.

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