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Author(s): Ricardo Arenas, José R. Martínez Catalán, Sonia Sánchez Martínez,
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ARTICLES

The Vila de Cruces Ophiolite: A Remnant of the Early Rheic Ocean in the Variscan Suture of Galicia (Northwest Iberian Massif)

Ricardo Arenas,[1] *José R. Martínez Catalán,*[2] *Sonia Sánchez Martínez,*
Javier Fernández-Suárez, Pilar Andonaegui, Julian A. Pearce,[3]
and Fernando Corfu[4]

Departamento de Petrología y Geoquímica e Instituto de Geología Económica (CSIC),
Universidad Complutense, 28040 Madrid, Spain
(e-mail: arenas@geo.ucm.es)

ABSTRACT

The Vila de Cruces ophiolite is one of the ophiolitic units involved in the Variscan suture of the northwest Iberian Massif. This ophiolite consists of a tectonically repeated succession of greenschist facies volcanic rocks, common alternations of metasediments of pelitic or siliceous character, and scarce orthogneisses, metagabbros, and serpentinites. The protolith age of a granitic orthogneiss that intruded the mafic rocks is dated at 497 ± 4 Ma (U-Pb in zircons). This age can be considered a reference for the generation of the ophiolite. According to their contents of some of the most immobile trace elements, the greenschist and the metagabbros are derived from basaltic magmas with compositions similar to those of island-arc tholeiites. The influence of a subduction zone in the generation of the original basaltic magmas can be deduced from the marked negative Nb anomaly observed in all the metabasic rocks of this ophiolite. The granitic orthogneisses can also be genetically related to the basic rocks because they are similar to granitic rocks generated in volcanic arcs. The Vila de Cruces ophiolite is interpreted as a suprasubduction zone ophiolite generated in Late Cambrian times, during the early stages of the opening of the Rheic Ocean. The ophiolite was probably generated in a back-arc basin developed during the first stages of the pulling apart and later drift of one or more peri-Gondwanan terranes, one of them represented by the upper allochthon of the northwest Iberian Massif.

Online enhancements: data tables.

Introduction

Early Paleozoic paleogeographic reconstructions for the northern peri-Gondwanan realm show that the rift of the Avalon microcontinent and its later drift to the north gave rise to an oceanic domain known as the Rheic Ocean (Stampfli and Borel 2002; Winchester et al. 2002). It is conceivable that other smaller terranes were also detached from Gondwana during this time. This could be the case of the allochthonous terrane currently located to the south of Avalon and occupying the uppermost structural position in the European Variscan Belt. This terrane has been preserved in the allochthonous complexes of northwest Iberia forming the upper units, or upper allochthon (Abati et al. 1999; Fernández-Suárez et al. 2003; Gómez-Barreiro et al. 2006), and can be followed across western Europe, forming part of a nappe stack with high-pressure units and ophiolites within the Variscan allochthonous complexes (fig. 1*a*; Arenas et al. 1986; Martínez Catalán et al. 2002).

In spite of the possible existence of a young Rheic Ocean already in the Late Cambrian, and consid-

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[1] Author for correspondence.

[2] Departamento de Geología, Universidad de Salamanca, 37008 Salamanca, Spain.

[3] School of Earth, Ocean and Planetary Sciences, Cardiff University, CF10 3YE Cardiff, United Kingdom.

[4] Department of Geosciences, University of Oslo, N-0316 Oslo, Norway.

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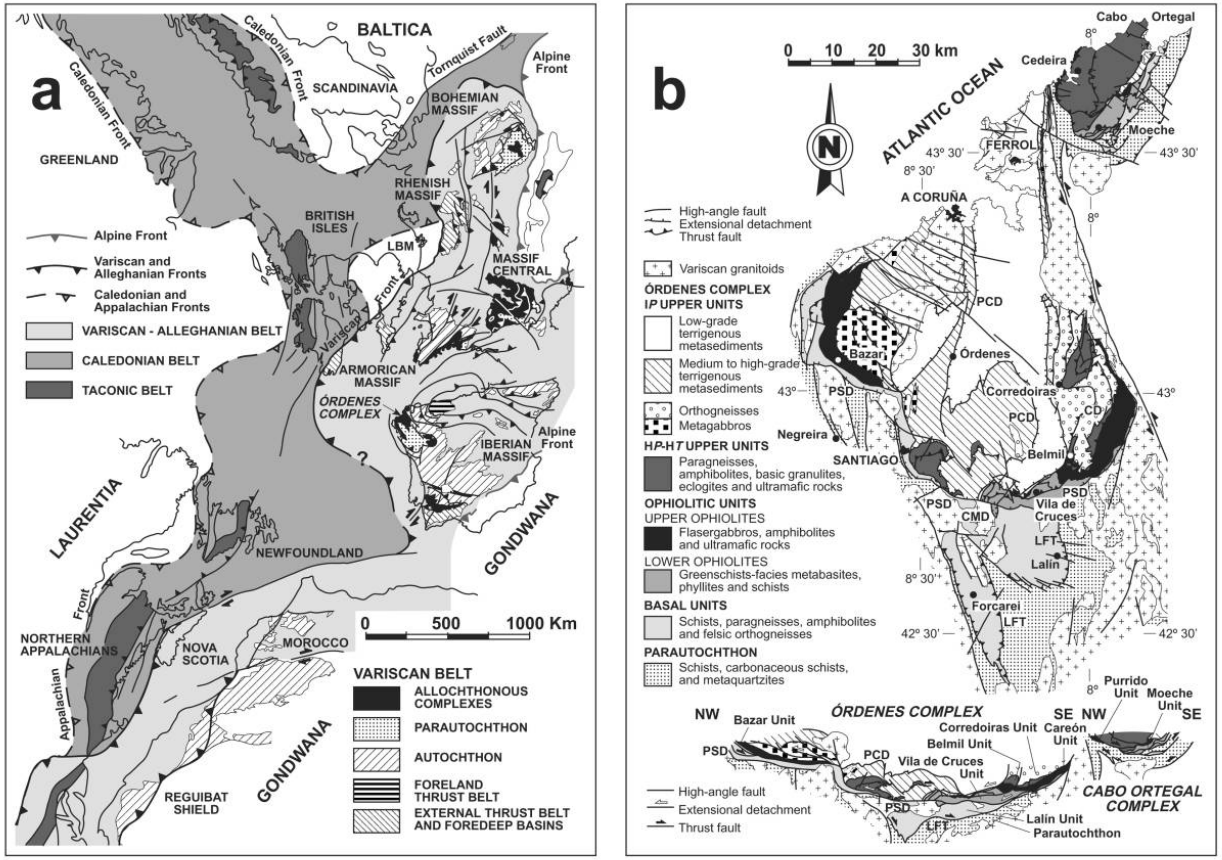

Figure 1. *a*, Location of the Órdenes Complex in a Late Carboniferous continental reconstruction, showing the main Paleozoic orogenic belts. Modified from Neuman and Max (1989) and Martínez Catalán et al. (2002). *LBM* = London-Brabant Massif. *b*, Sketch map and cross section of the Órdenes and Cabo Ortegal complexes in northwest Iberia, showing their allochthonous units and main tectonic contacts. *CD* = Corredoiras detachment; *CMD* = Campo Marzo detachment; *LFT* = Lalín-Forcarei thrust; *PCD* = Ponte Carreira detachment; *PSD* = Pico Sacro detachment.

ering the subsequent opening of a wide oceanic domain during the Ordovician and part of the Silurian, the ophiolites preserved in the Variscan allochthonous complexes are too young to date those early stages because their ages are Late Silurian to Early Devonian. This is the case for the Ślęza ophiolite in the Bohemian Massif (Dubińska et al. 2004), the Lizard ophiolite in Cornwall (Clark et al. 1998), and the Careón ophiolite in Galicia (Díaz García et al. 1999). The scarcity of older oceanic lithosphere in the European Variscan Belt, or even its frequent absence, can be readily explained by consumption of the older, colder, and denser oceanic lithosphere by subduction (e.g., Molnar and Atwater 1978). In this way, only the youngest lithosphere of the Rheic Ocean would have escaped subduction, and it would have been eventually obducted over the continental margin of Gondwana during the Variscan orogeny (Sánchez Martínez et al. 2007).

It is possible, however, that the paleogeographic models so far postulated for the Lower Paleozoic are incomplete, because old oceanic lithosphere representing the Late Cambrian Rheic Ocean may in fact exist in the European Variscan Belt, although it is apparently scarce and has not received much attention. This is the case for some low-grade allochthonous units designated as the lower ophiolitic units in the northwest Iberian Massif (Arenas et al. 2007). These ophiolites consist of thick successions of greenschist facies volcanic rocks, with common interbedded pelitic or siliceous metasedimentary rocks and scarce orthogneisses, metagabbros, and serpentinites. They can be found associated with other more common ophiolitic sequences that appear in an upper structural position and have been dated as Early Devonian (Díaz García et al. 1999; Arenas et al. 2007). Located in the Órdenes Complex, the Vila de Cruces ophiolite attains 3500–4000 m in thickness, although its internal structure is imbricated. This article describes the structure, lithology, age, and geochemistry of the Vila de Cruces ophiolite. We suggest that the ophiolite can be interpreted as a remnant of the oldest Rheic Ocean.

Geological Setting

The allochthonous complexes of the northwest Iberian Massif, and their equivalents in the rest of Europe, are located in the more internal part of the Variscan Belt (fig. 1*a*). They appear as megaklippen with synformal structure, including a number of allochthonous units with the characteristics of far-traveled terranes (Arenas et al. 1986; Martínez Catalán et al. 1999). Five different allochthonous complexes exist in Galicia and in the Portuguese region of Trás-os-Montes. According to their lithological constitution and structure, the allochthonous complexes of Órdenes and Cabo Ortegal are representative of the ensemble (fig. 1*b*). They include three different terranes, which, from bottom to top, have been named basal units (or lower allochthon), ophiolitic units (or middle allochthon), and upper units (or upper allochthon).

The middle allochthon has a composite character, including lithological assemblages and ophiolites with contrasting ages (Arenas et al. 2007). Two groups can be distinguished according to their structural relative position, the upper and lower ophiolitic units. Both occur to the southeast of the Órdenes Complex, where the Careón ophiolite overlies the Vila de Cruces ophiolite (fig. 2). The gabbroic protoliths of the Careón ophiolite have been dated at 395 Ma (U-Pb in zircon; Díaz García et al. 1999). To date, these are the only protolith age data in the ophiolites of northwest Iberia.

The upper units (or upper allochthon) structurally overlie the ophiolites. The upper units have been subdivided in two assemblages with contrasting tectonothermal evolutions: the lower was affected by high-pressure, high-temperature (HP-HT) metamorphism, whereas the upper assemblage is characterized by intermediate-pressure (IP) metamorphism (fig. 1*b*). In spite of their different tectonothermal evolutions, both assemblages have been considered parts of a single peri-Gondwanan terrane (Martínez Catalán et al. 2002). This terrane was rifted from Gondwana during the Lower Paleozoic, and its drift to the north, probably coeval with the described motion of Avalonia (Murphy et al. 2006), is the currently accepted scenario for the opening of the Rheic Ocean (Abati et al. 1999; Fernández-Suárez et al. 2003; Arenas et al. 2007). This drifted terrane was subsequently accreted to Laurussia, roughly coinciding with the moments of largest width of the Rheic Ocean (Gómez-Barreiro et al. 2006).

Underlying the ophiolites, the basal units consist of a lithological assemblage with continental affinity (schists and paragneisses, orthogneisses, and metabasites), which is considered to represent the most external part of the Gondwanan margin (Martínez Catalán et al. 1996). This margin was subducted below the ophiolitic units during the initial stages on the Variscan Orogeny in Gondwana and affected by high-pressure and low- to intermediate-temperature metamorphism (Arenas et al. 1995).

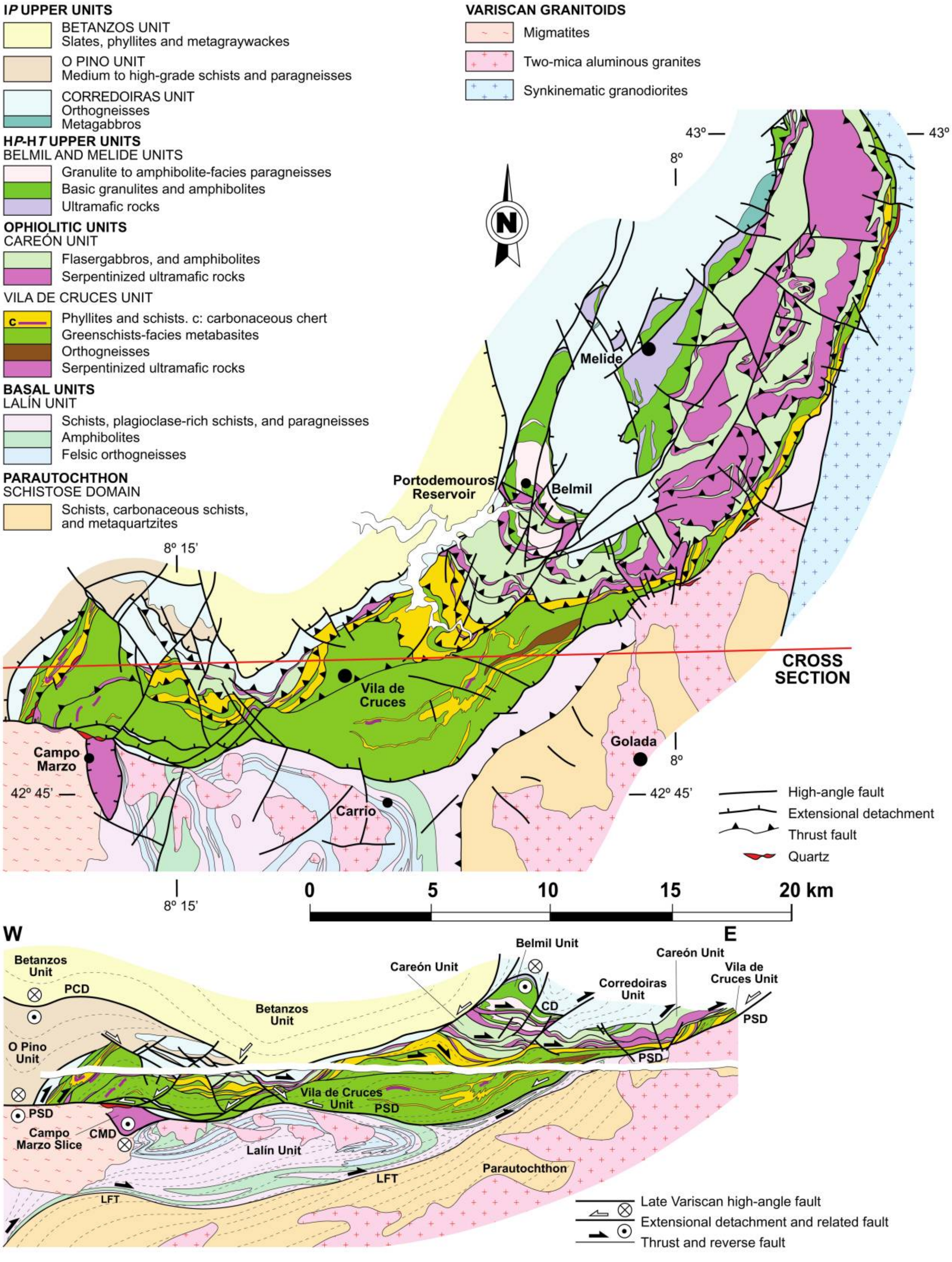

Figure 2. Geological map and cross section of the Vila de Cruces and surrounding allochthonous units. Abbreviations as in figure 1.

Structure

The Vila de Cruces ophiolite is typical of the mode of occurrence of units in the allochthonous complexes of northwest Iberia. Instead of being a continuous thrust sheet, it has a lensoidal outcrop shape and is isolated from the comparable Moeche ophiolitic unit in the Cabo Ortegal Complex (fig. 1*b*). This type of occurrence is a consequence of the dismembering of the units that took place through repeated thrusting and extensional events, producing normal detachments. The lens is about 26 km long and up to 4 km wide, elongated east-west, and pinched in the middle, continuing another 24 km to the northeast by a narrow strip less than 500 m wide (fig. 2). Its upper boundary is a thrust fault, which is commonly regarded as separating the Vila de Cruces Unit from the overlying Careón ophiolitic unit. In the hanging wall to the thrust, dragging of the Corredoiras Unit during eastward motion left a tail of orthogneisses more than 15 km long behind the main body, cropping out around Melide. Furthermore, the thrust left several isolated horses of orthogneisses, HP-HT amphibolites, and Careón flasergabbros, amphibolites, and ultramafics. The lower boundary of the Vila de Cruces Unit is a curved normal fault of late Variscan age known as the Pico Sacro detachment (PSD). South and southeast of the PSD, the Lalín Unit, representative of the basal units, is exposed and carried to its present position by the Lalín-Forcarei thrust, below which crop out the parautochthon and abundant synkinematic Variscan granitoids (fig. 2).

The Vila de Cruces Unit consists of an alternation of metabasites and metapelitic phyllites and schists, with scarce and thin layers of granitic orthogneisses, serpentinites, and metacherts. The dominant lithology is greenschist facies metabasites exhibiting an intense deformation, though the occasional preservation of igneous textures suggests a metabasaltic origin with minor presence of coarse- to middle-grained gabbros. Metapelites dominate in the upper part, whereas the main body of orthogneiss occurs in the central part of the unit, to the east of Vila de Cruces, and that of ultramafics in the Campo Marzo slice, to the south of the PSD (figs. 2, 3).

In the upper part of the unit, greenschists and metapelites alternate, with the latter commonly showing phyllonitic character at the contacts with underlying greenschists. Thin layers of intensively sheared serpentinite and talc schists also occur at some of these boundaries and in the greenschists. Shear bands are common in the phyllonites, but clear and consistent kinematic criteria are rare, as often occurs in very low-temperature fault rocks. A couple of outcrops yielded a top-to-the-east and east-southeast sense of movement, consistent with criteria found in thrust faults in the surrounding units (Martínez Catalán et al. 1996, 2002). Conversely, low-temperature fault rocks are rare in the lower half inside the unit. There, to the east of Vila de Cruces, metapelites form rather continuous and thin bands, some of which join each other (fig. 3).

Petrographic studies show the pervasive presence of a regional greenschist facies cleavage and one or more generations of crenulation or poorly developed crenulation cleavage. The regional cleavage seems to be the first one in many of the metabasites, where it shows a mylonitic character, but in some of them, mainly in the metapelites, a former cleavage strongly microfolded can be identified. The regional cleavage is axial planar to overturned folds recognizable in thin sections, outcrops and to map scale (fig. 3). The folds show east vergence and axial surfaces dipping between 20° and 70° and parallel to the main cleavage. Fold axes and intersection lineations associated with the main cleavage plunge to the north-northwest–south-southeast or north-south except when close to the PSD (Divar Rodríguez and Iglesias P. de León 1982). Mineral lineations can be seen mostly in the orthogneisses, with an attitude similar to fold axes and intersection lineations (fig. 3), suggesting that they also represent a composite fabric (intersection lineation) rather than a stretching lineation. Often, the main cleavage has a low-dipping attitude to the west, north, or east because of late open folds that overprinted the unit. The crenulations are related to these late folds (roughly north-south, steeply dipping) and to the PSD (low dips, often to the east or southeast).

According to these data, and based on the geological map, the Vila de Cruces Unit is interpreted as an imbricated thrust sheet (see cross section in fig. 2). The unit includes an upper thrust sheet to the north, where imbricates are abundant, and a lower thrust sheet in the southern part, more continuous and where only two imbricates exist. Furthermore, it includes the Campo Marzo slice, entirely made up of ultramafics and probably representing a vestige of the mantle that once underlay the supracrustals.

In the upper thrust sheet, every horse consists of metapelites (phyllites) at the base and greenschist facies metabasites on top, although in the westernmost horse, metabasites occur both below and above the phyllites, suggesting that the metapelites were intercalated. Phyllonitization occurs systematically at the bottom of the metapelites, adjacent to the thrust faults.

In the lower thrust sheet, the metapelites clearly

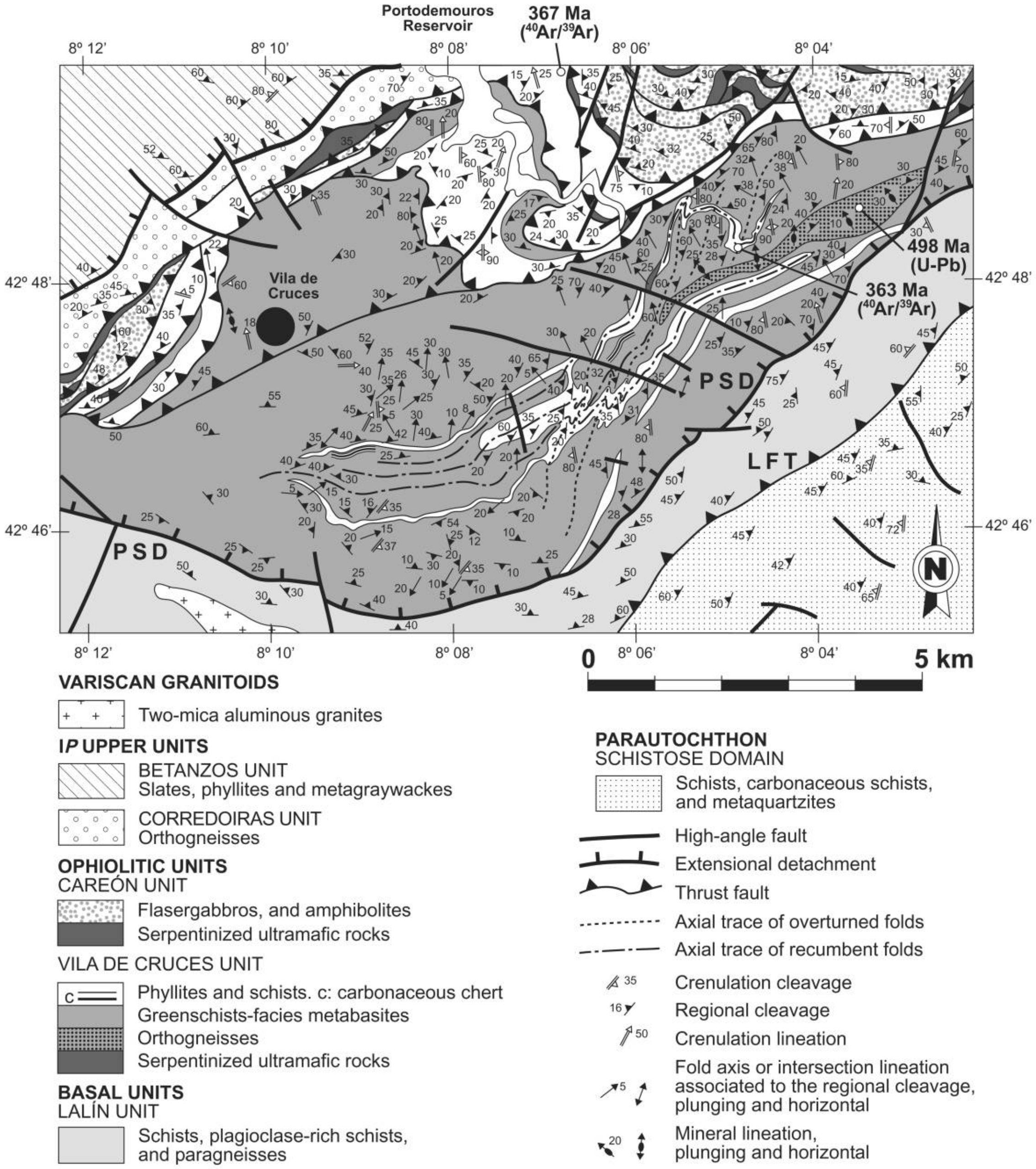

Figure 3. Detailed geological map of the Vila de Cruces area showing the axial traces of recumbent and overturned folds and several of the thrust imbricates. The sampling localities and ages obtained by the ^{40}Ar/^{39}Ar method in phyllites by Dallmeyer et al. (1997) and by the U-Pb method in an orthogneiss (this article) are also shown. *LFT* = Lalín-Forcarei thrust; *PSD* = Pico Sacro detachment.

alternate with the metabasites. Two thin strips of pelitic schists run nearly parallel for about 5 km to the southeast of Vila de Cruces, until they join each other to the east in an area where the metapelites turn thicker (figs. 2, 3). This suggests the presence of large recumbent isoclinal folds with extraordinarily thickened hinges and thinned limbs. Their presence would not be surprising because a huge recumbent anticline has been identified in the underlying Lalín Unit (see cross section in fig. 2; Martínez Catalán et al. 1996). In addition to the recumbent folds, several kilometer-scale overturned folds have been identified (fig. 3). Both the main cleavage and the axial surface of the overturned folds cross-cut the hinge and limbs of the proposed recumbent folds. Therefore, the huge recumbent folds would be previous to the main cleavage and possibly associated with the earlier cleavage identified in the metapelites.

The imbricate structure of the Vila de Cruces Unit forms the base of a spectacular duplex also involving the ophiolites and the upper units (figs. 2, 4). In the uppermost part of the duplex, south of Belmil, horses of the ophiolitic Careón Unit and the HP-HT Belmil Unit alternate, locally disturbing the typical order of stacking (fig. 2). In some cases, thrusts are responsible for the absence of units such as (i) the Careón Unit southwest of Belmil, (ii) the HP-HT upper units along most of the contact between the IP upper units and the ophiolites, and (iii) the Vila de Cruces Unit to the west of the Órdenes Complex. This is partly due to superposition of two thrust generations, as can be seen in the Careón Unit, where young, low-temperature thrusts cut an older imbricate stack. This results in an out-of-sequence character of the thrusts that developed the Vila de Cruces–Belmil duplex (Martínez Catalán et al. 2002).

Figure 4 shows the proposed evolution of the Vila de Cruces–Belmil duplex. It includes horses for which displacement is less than (hinterland-dipping duplexes), equals (antiformal stacks), or exceeds (foreland-dipping duplexes) fault spacing (Mitra and Boyer 1986). If length of the greenschist/metapelite contact (38 km) is compared with its sectional length (30 km), a shortening of 8 km due to imbrication can be estimated only for the upper thrust sheet. The two imbricates in the lower thrust sheet represent a shortening of 18 km, predominantly accommodated by the horse where Vila de Cruces is located (fig. 2). Tectonic superposition of the upper thrust sheet over the lower thrust sheet requires 23 km of shortening, which gives a minimum of 49 km of total shortening within the Vila de Cruces Unit, without considering previous folding.

Tectonothermal Evolution

Using the map and cross section, microscopic analysis of the cleavages and mineral assemblages, and available geochronological data of tectonothermal events, we propose a structural evolution. Serpentinites and talc schists occur often in the thrust faults, but they can be seen also at folded metabasites/metapelite contacts, suggesting that they were there before recumbent/overturned folding. These can be explained by an early phase of imbrication of mafic rocks and the overlying pelites. These thrusts could have rooted in the mantle, explaining the presence of serpentinites at the contacts between metapelites and metabasites. Alternatively, the early phase would have emplaced portions of the oceanic mantle that would have detached and glided over the pelitic sediments. Subsequently, the Vila de Cruces Unit underwent ductile deformation, giving rise to the first cleavage and possibly to large recumbent folds. This event explains the thickening of the unit and its burial and pressurization and can be related to the high-pressure/low- to intermediate-temperature event identified in the upper imbricates (Martínez Catalán et al. 2002).

The first cleavage was followed by the development of the main one. Its low-dipping attitude and the asymmetry of the associated overturned folds suggest a general ductile shear mechanism with a top-to-the-east movement. This cleavage has been dated by Dallmeyer et al. (1997) at 367–363 Ma (^{40}Ar/^{39}Ar, muscovite concentrates in phyllites; see fig. 3 for sampling localities) and at 364 Ma in similar rocks of the equivalent Moeche ophiolite in the Cabo Ortegal Complex.

The early imbricates and the recumbent folds are interpreted to be a consequence of accretion and subduction of the Vila de Cruces Unit beneath an active orogenic wedge being developed to the north or west of the ocean represented by the ophiolitic units (Martínez Catalán et al. 1996). The main cleavage would then correspond to a subsequent phase of exhumation, and its age, 367–363 Ma, is consistent with the diachronous character of deformation established for the allochthonous units (Dallmeyer et al. 1997). The migration of deformation with time, younging toward the lower units of the nappe stack, is interpreted in terms of their progressive accretion to the orogenic wedge. The main phase of thrusting and imbrication is not precisely dated, but ^{40}Ar/^{39}Ar ages around 330 Ma in metapelites of the upper IP unit (Dallmeyer et al. 1997; Gómez Barreiro et al. 2006) could reflect its activity or represent a minimum age limit for this event.

The PSD, with a top-to-the-northwest movement, represents the final extensional collapse of this part of the orogen. It is younger than 323 ± 11 Ma, the age of the Negreira granodiorite (Rb-Sr method; Bellido et al. 1992), and roughly synchronous with the late upright folds, dated at 314 ± 6 Ma (Rb-Sr and K-Ar methods; Capdevila and Vialette 1970; corrected by Ries 1979). The PSD partially reactivated the out-of-sequence sole thrust at the base of Vila de Cruces. Coeval with this detachment, high-angle normal faults formed in two conjugate families in the central area of the Vila de

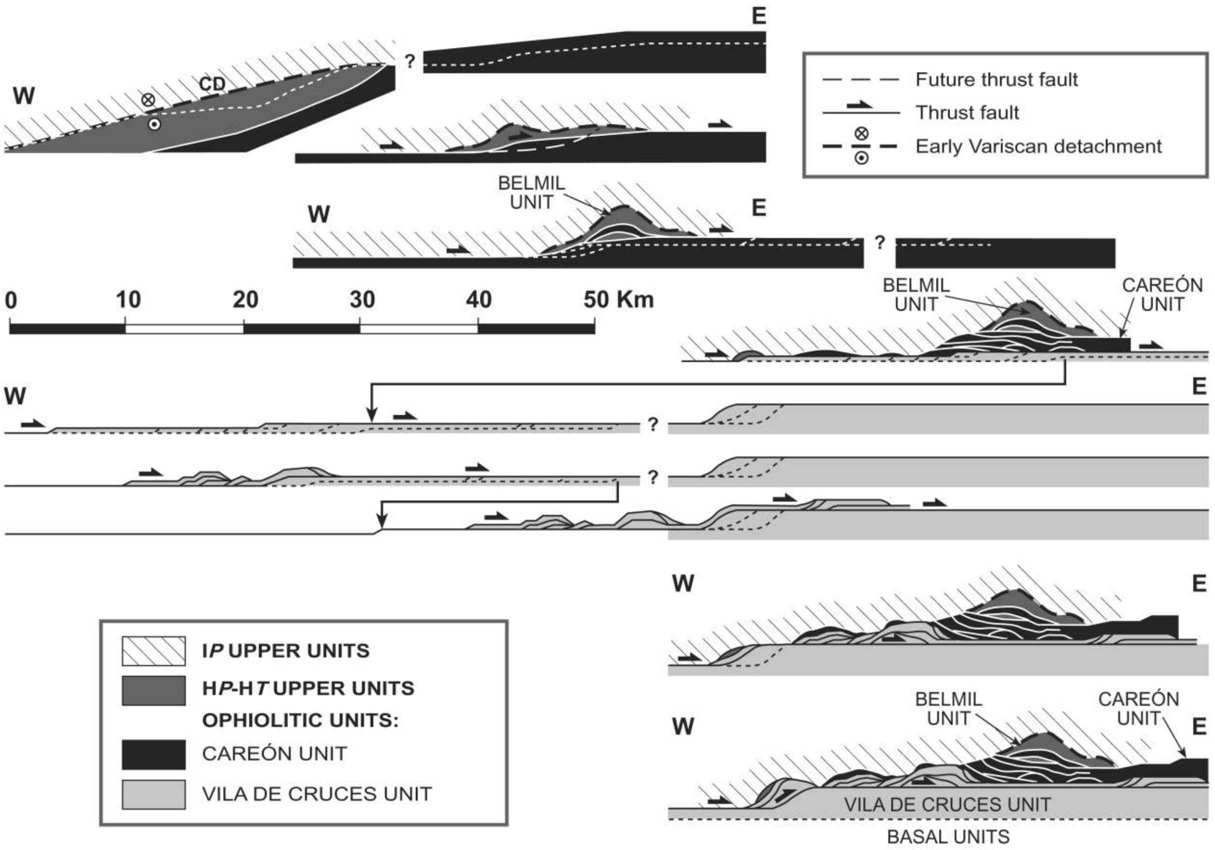

Figure 4. Proposed structural evolution of the Vila de Cruces–Belmil duplex.

Cruces Unit, where they contributed to form the neck between two megaboudins where the unit exhibits its maximum thickness (fig. 2).

Ophiolite Constitution

The Vila de Cruces Unit exhibits an imbricate internal structure, where the original ophiolite section is not preserved. A composite schematic section has been compiled from the geological map and field observations (fig. 5). The estimation of the original ophiolite thickness is hampered by its pervasive imbrication and by the possible existence of large recumbent folds.

The ophiolite may represent an oceanic sequence of thick basalts and interbedded pelitic and siliceous sediments, intruded by stocks of gabbros and granitoids. The complex internal structure of the ophiolite hinders an accurate estimation for the thickness of the original oceanic crust. The mafic and sedimentary components of the ophiolite rest over the serpentinized ultramafic rocks of the Campo Marzo slice, which can be interpreted as a piece of suboceanic upper mantle. This contact is tectonic (PSD) and hides the original basal contact of the basaltic-sedimentary sequence. Therefore, it is not known whether a basal plutonic sequence occurred in the ophiolite. As a result of the structural complexities, the present section of the ophiolite cannot be compared with typical ophiolites generated in divergent (mid-ocean ridge basalt [MORB] type; Hawkins 2003; Pearce 2003) or convergent (suprasubduction type; Pearce et al. 1984*b*) settings. Accordingly, the tectonic setting of the Vila de Cruces ophiolite may be more appropriately interpreted by considering the geochemical characteristics of the mafic and granitic metaigneous rocks.

U-Pb Dating: Analytical Methods and Results

One sample of the largest body of granitic orthogneisses (G-126) was selected for U-Pb dating, and its location is shown in figure 3 and in table A1, available in the online edition and from the *Journal of Geology* office. The metagranitic rocks are as-

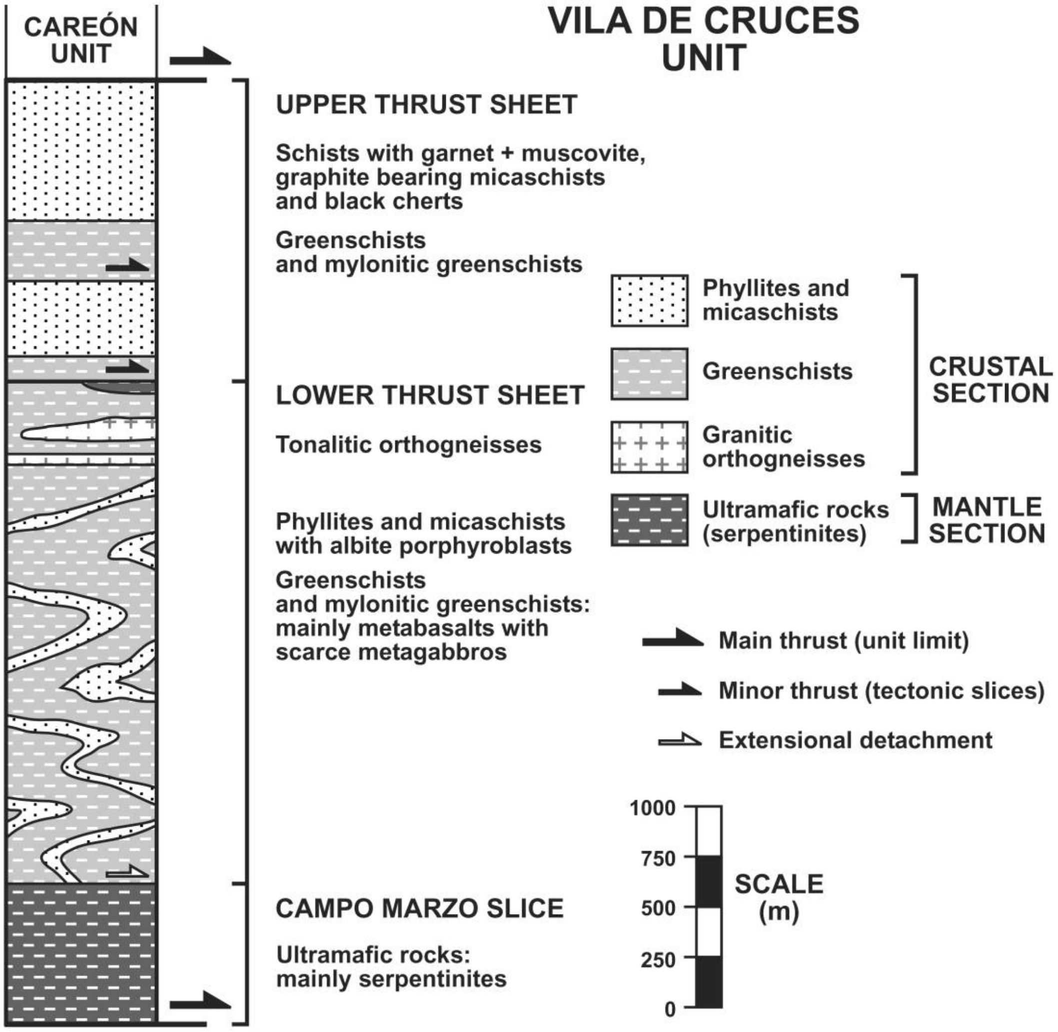

Figure 5. Schematic section showing the internal constitution of the Vila de Cruces ophiolite. It contains three main tectonic slices, the lowest one representing the mantle section.

sociated with gabbros and leucogabbros showing mutual intrusive relationships. The contact between the plutonic rocks and the greenschists, supposedly of metabasaltic origin, is pervasively sheared. However, an original intrusive relationship seems reasonable, suggesting that the age of the granitic body represents a minimum age for the ophiolitic ensemble. In any case, if a simple scenario is considered (i.e., a context related to the evolution of a single oceanic domain), the granitoids and the mafic rocks should be coeval. Moreover, as will be shown below, the chemistry of the granitic and mafic rocks is in agreement with a common dynamic setting.

U-Pb analytical work was performed at the Mineralogical-Geological Museum, University of Oslo. The orthogneiss was crushed with a jaw crusher and pulverized with a hammer mill. Heavy-fraction enrichment on a Wilfley table, magnetic separation in a Frantz isodynamic separator, and density separation with di-iodomethane (CH_2I_2) were used to separate the zircons. Grains to be analyzed were hand-picked in alcohol under a binocular microscope, and all the fractions were subsequently air-abraded following the method of Krogh (1982). The selected zircon fractions were washed in 4N HNO_3 on a hot plate and rinsed repeatedly with H_2O and acetone. A mixed $^{205}Pb/^{235}U$ spike was added to the sample after weighing and transfer to the dissolution vessel. Zircon was dissolved in HF ($+HNO_3$) in Teflon minibombs at ca. 185°C. The solutions were subsequently evaporated, redissolved in 3.1N HCl and passed through anion exchange columns in HCl medium to purify U and Pb. U and Pb were finally collected together in the bombs used for dissolution and loaded together on outgassed Re filaments with H_3PO_4 and silica gel. Isotopic ratios were measured on a Finnigan-MAT 262 mass spectrometer using up to four Faraday detectors in multicollection mode. Very small fractions were measured by peak jumping on a secondary electron multiplier (ion counting mode). Total procedural blanks were less than 2–5 pg Pb and 0.1–0.3 pg U. The Stacey and Kramers (1975) model was used to subtract initial common Pb in excess of the laboratory blank. Regression lines were calculated using the model 1 algorithm of Ludwig (1989) with intercept errors quoted at 95% confidence level. Decay constants are those of Jaffey et al. (1971).

Four zircon fractions were analyzed; the results are given in table 1 and presented in the concordia plots of figure 6. The general features of analytical data and the results are reported below.

Fraction Z1 consisted of four equant prisms with milky appearance. The error ellipse of this analysis overlaps the concordia curve at the 2σ confidence level and has a concordia age of 496.5 ± 2.1 Ma with 23% probability of concordance (Ludwig 1998). However, this fraction is 1.2% discordant and has a $^{207}Pb/^{206}Pb$ age of 501.6 Ma. Fraction Z2 consisted of three slightly turbid prism fragments from the magnetic split at ca. 1 A. The analysis is 12.6% discordant and has a $^{207}Pb/^{206}Pb$ age of 503.6 Ma. Fraction Z3 consisted of seven clear prisms slightly longer than those of Z1. The analysis is 2.7% discordant and yielded a $^{207}Pb/^{206}Pb$ age of 494.7 Ma. Finally, fraction Z4 consisted of three clear long prisms. The analysis is highly discordant, with a $^{207}Pb/^{206}Pb$ age of 1223.6 Ma, implying the presence of an inherited lead component. This fraction is also different from the other three fractions with regard to U content, model U/Th, and common Pb content (table 1). Fraction Z1 is the most concordant and constrains the crystallization age of the rock to between ca. 496 and 502 Ma. Given that inherited zircon is present in the rock (fraction Z4), fraction Z1 could be slightly displaced to the right owing to the presence of minor amounts of inherited lead, in which case the concordia age would best constrain the crystallization age of the zircons. If no inherited lead component is present, then the $^{207}Pb/^{206}Pb$ age is the best estimate for the crystallization age. A discordia forced through 0 ± 50 Ma using fractions Z1, Z2, and Z3 yields an upper intercept age of 497 ± 12 Ma, and a discordia using fractions Z1 and Z4 yields a lower intercept age of 495.1 + 2.8/ − 3 Ma.

Considering the above and taking into account that fraction Z3 has the youngest $^{207}Pb/^{206}Pb$ age and therefore is the least likely to contain inherited lead, whereas fractions Z1 and Z2 may be affected by minor inheritance, the crystallization age of this metagranitoid would be best constrained as 497 ± 4 Ma, which includes the uncertainty associated with analyses Z1, Z2, and Z3.

Table 1. Results of ID-TIMS U-Pb Dating for Sample G-126

	Analysis			
Parameter	Z1	Z2	Z3	Z4
Weight[a] (mg)	2	3	12	5
U (ppm)	417	343	594	164
Th/U[b]	.39	.26	.34	.15
Pbcom[c] (pg)	1.6	.5	3.6	34.7
$^{206}Pb^{d}/^{204}Pb$	2588	8699	9627	175
$^{206}Pb^{e}/^{238}U$	.07996	.07098	.07761	.10610
$2\sigma^{f}$ (abs)	.00037	.00025	.00023	.00038
$^{207}Pb/^{238}U$	.6313	.5609	.6108	1.1863
2σ (abs)	.0034	.0020	.0021	.0162
$^{207}Pb/^{206}Pb$	.05726	.05731	.05708	.08109
2σ (abs)	.00020	.00014	.00008	.00106
Apparent age (Ma):				
$^{206}Pb/^{238}U$	495.9	442.0	481.8	650.1
$^{207}Pb/^{235}U$	496.9	452.1	484.1	794.2
$^{207}Pb/^{206}Pb$	501.6	503.6	494.7	1223.6

[a] Weights better than 10% when sample weight is more than 10 mg.

[b] Model Th/U ratio estimated from $^{208}Pb/^{206}Pb$ ratio and age of the sample.

[c] Total common Pb in sample, including initial and blank Pb.

[d] Measured ratio, corrected for fractionation and spike contribution.

[e] Corrected for spike, fractionation, and blank and initial common Pb (Stacey and Kramers 1975).

[f] 2σ uncertainty calculated by error propagation procedure that takes into account internal measurement statistics and external reproducibility as well as uncertainties in blank and common Pb correction.

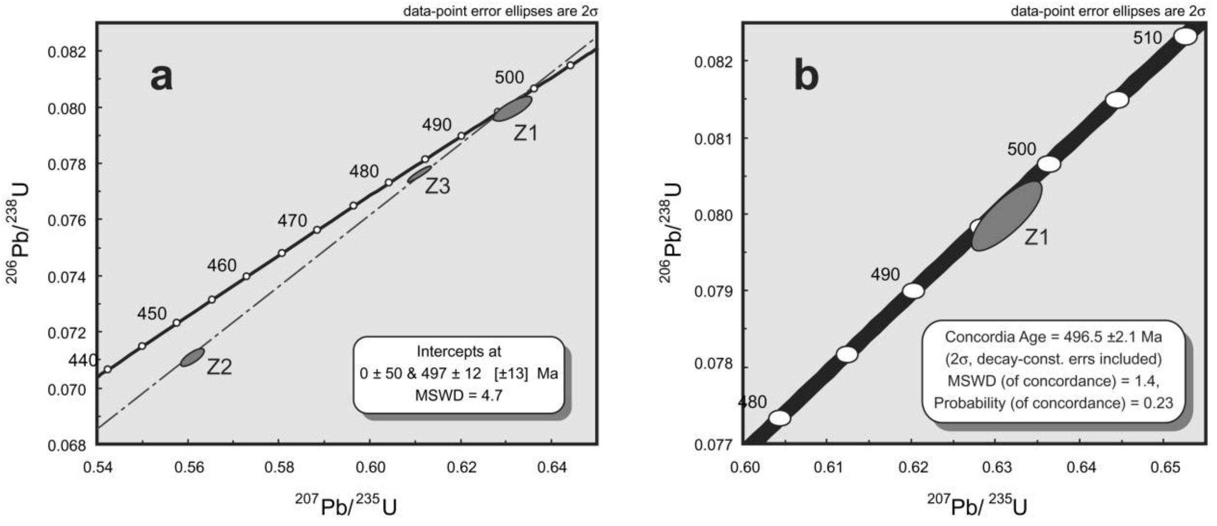

Figure 6. U-Pb concordia diagrams showing the results of U-Pb dating of zircon in a sample (G-126) of granitic orthogneisses of the Vila de Cruces ophiolite. Errors are given at the 2σ level.

It is very important to note that fraction Z4 proves the participation of a Precambrian crustal component (1.2 Ga or older) in the genesis of this orthogneiss. This datum is also considered significant in order to determine the tectonic setting of the Vila de Cruces ophiolite because it rules out a large open oceanic basin. In this way, the presence of a Precambrian crustal component suggests that the ophiolite was probably generated in the area surrounding a continental domain rather than a MORB-type environment.

Chemical Characteristics of the Igneous Suite

A set of 20 samples of the most representative metaigneous lithologies in the Vila de Cruces ophiolite was selected for study of their geochemical characteristics. The location and classification of these samples appear in table A1. Twelve samples are variably deformed greenschists, four are metagabbros, and the remaining four samples are granitic orthogneisses similar to that used for U-Pb dating (including the dated sample; table A1). Crushing and powdering of the samples were performed at the Universidad Complutense of Madrid, and the subsequent chemical analyses were carried out at the Activation Laboratories (Actlab) in Canada. The digestion procedure was the lithium metaborate/tetraborate fusion, and the analytical technique used to measure the elemental concentrations was inductively coupled plasma mass spectrometry (ICP-MS). The results are given in tables A2 and A3, available in the online edition and from the *Journal of Geology* office. The quality of the data was tested in the laboratories of the Earth, Ocean and Planetary Sciences department at Cardiff University (acid digestion, ICP-MS). Analyses are generally within 10% of accepted values for standards, except in cases of concentrations close to the detection level, where errors can be larger. The metabasic rocks of the Vila de Cruces ophiolite generally show very low concentrations in some of the key elements used to infer the tectonic setting of the ophiolite, Cr, Nb, and Ta. For these elements, the detection levels reported by Actlab are 20, 0.2, and 0.01 ppm, respectively.

Classification of the Igneous Suite. According to their SiO_2 content, most of the greenschists and metagabbros have basic compositions, though some of them exhibit intermediate compositions (SiO_2 = 47.65–54.03 wt%). In relation to the rest of the major elements, the compositional range is relatively low for Al_2O_3 (12.49–16.98 wt%), MnO (0.15–0.33 wt%), Na_2O (1.70–6.22 wt%), K_2O (0.01–0.34 wt%), TiO_2 (0.71–1.84 wt%), and P_2O_5 (0.05–0.17 wt%), and slightly higher for Fe_2O_3(T) (9.56–16.11 wt%), MgO (4.51–11.26 wt%), and CaO (3.14–11.39 wt%). The orthogneisses are acid rocks (SiO_2 = 73.08–77.49 wt%) with a rather restricted compositional range for the rest of the major elements (Al_2O_3 = 12.52–13.86 wt%; Fe_2O_3(T) = 1.03–3.28 wt%; MnO = 0.01–0.05 wt%; MgO = 0.49–1.40 wt%; CaO = 1.90–2.47 wt%; Na_2O = 4.51–5.15 wt%; K_2O = 0.20–0.48 wt%; TiO_2 = 0.14–0.26 wt%; P_2O_5 = 0.03–0.05 wt%).

It is known that processes such as hydrothermal alteration, metamorphism, and ductile deformation can cause chemical variation in the concentration of many elements, especially most of the major elements and the large-ion lithophile trace elements. Accordingly, problems may arise in obtaining an accurate chemical classification of the altered igneous lithologies. Considering this problem and using a combination of mobile and immobile elements (fig. 7*a*, 7*b*), we can see that most metabasites of the Vila de Cruces ophiolite show compositions characteristic of subalkaline basalts, though a few samples plot in the field of basaltic andesites (fig. 7*a*, 7*b*). According to their overall geochemical characteristics (tables A2, A3; see also figs. 7–10), and considering the rather limited compositional variation in the set of samples, the metabasic rocks can be identified as members of a tholeiitic suite. Regarding the granitic orthogneisses, they show chemical characteristics typical of subalkaline acid rocks, and in figure 7, they plot in the

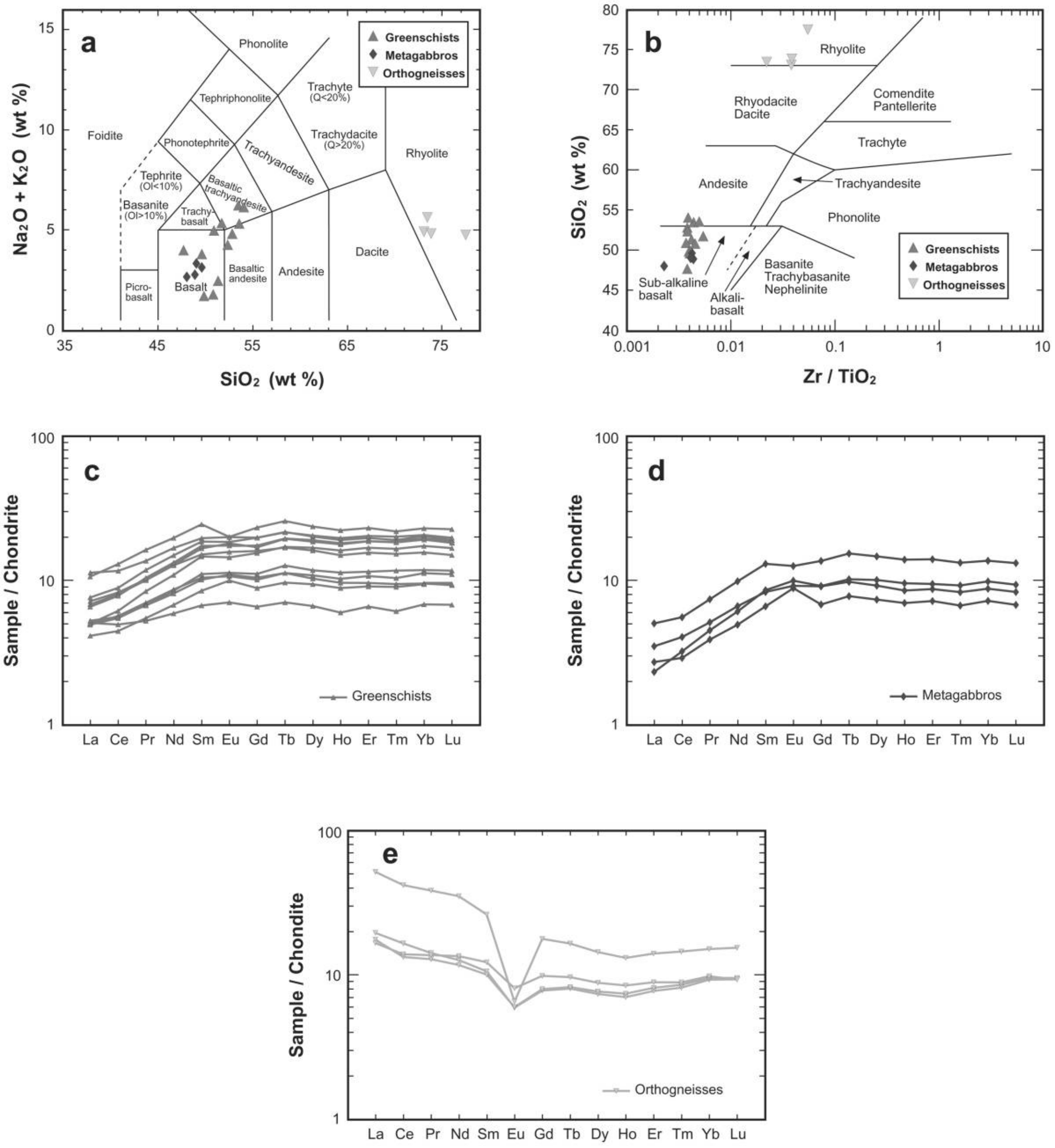

Figure 7. *a*, Total alkalis versus SiO_2 diagram (Le Maitre et al. 1989). *b*, SiO_2–Zr/TiO_2 diagram of Winchester and Floyd (1977). *c–e*, Chondrite-normalized rare earth elements plots; normalizing values are from Nakamura (1974).

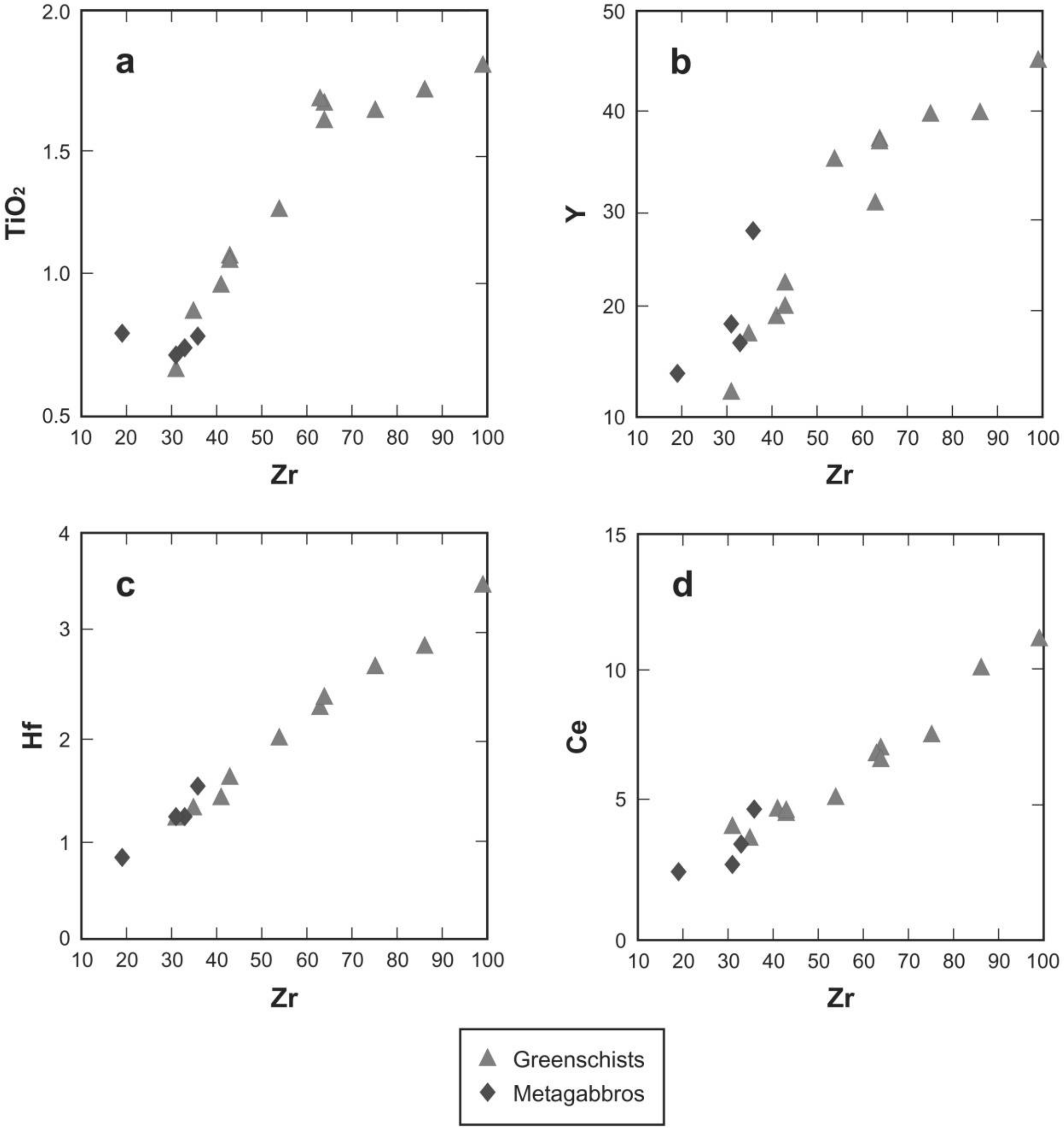

Figure 8. Variation diagrams of selected trace elements (Ti, Y, Hf, Ce vs. Zr) for the greenschists and metagabbros of the Vila de Cruces ophiolite.

rhyolite fields. The general absence of intermediate members between the mafic and acid rocks, since it is considered characteristic of normal calc-alkaline series, suggests that a single igneous suite with tholeiitic affinity is represented in the ophiolite. Although it should be used very carefully, owing to its high mobility, the very low content of K_2O in the orthogneisses (<0.50%) is also in agreement with the suggested tholeiitic affinity.

The greenschists have total rare earth element (REE) contents ranging between 20.58 and 64.91 ppm, with concentrations between four and 26 times the chondritic abundances (Nakamura 1974). Their chondrite-normalized REE patterns (fig. 7*c*) are almost flat for the heavy REEs (HREEs; $[\mathrm{Gd/Yb}]_N$ = 0.88–1.06), with the light REEs (LREEs) variably depleted in relation to the HREEs ($[\mathrm{La/Sm}]_N$ = 0.34–0.76) and slightly positive or negative Eu

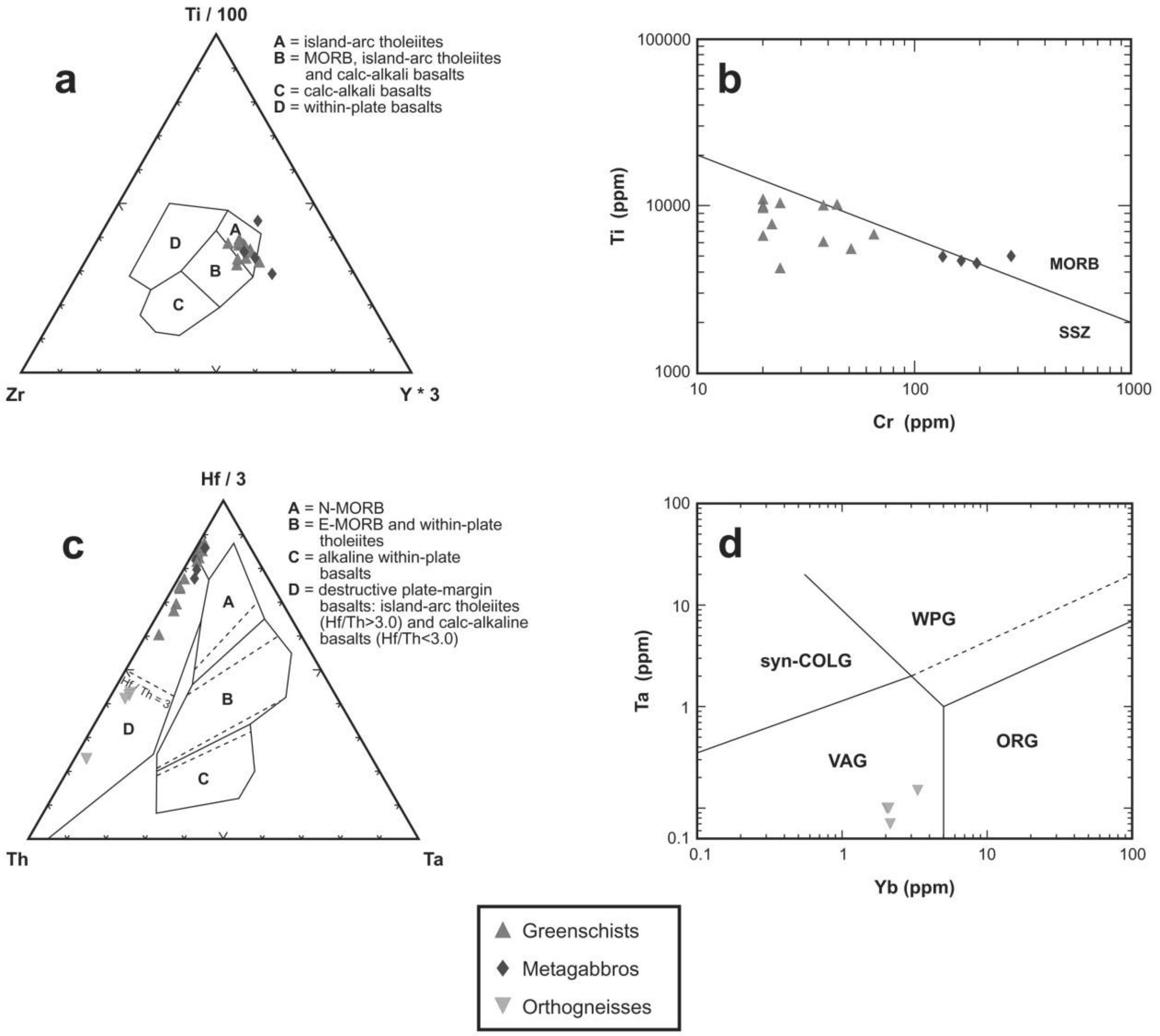

Figure 9. Trace elements tectonic discrimination diagrams for the samples of the Vila de Cruces ophiolite. *a*, Ti-Zr-Y (Pearce and Cann 1973); *b*, Ti-Cr (Pearce 1975); *c*, Th-Hf-Ta (Wood 1980); *d*, Ta-Yb (Pearce et al. 1984*a*).

anomalies (Eu/Eu* = 0.84–1.15, calculated according to Taylor and McLennan 1985). The metagabbros have lower REE concentrations than the greenschists, with total contents ranging between 18.16 and 35.18 ppm. They show abundances between two and 15 times the chondritic values, and their normalized REE patterns (fig. 7*d*) are very similar to those of the greenschist, almost flat for the HREEs ($[\mathrm{Gd/Yb}]_N$ = 0.93–1.04), with variable depletion in LREEs ($[\mathrm{La/Sm}]_N$ = 0.27–0.42) and slightly positive or negative Eu anomalies (Eu/Eu* = 0.94–1.32). According to their REE contents, the metagabbros can be considered less evolved lithologies than the greenschists. However, the two patterns are parallel, which probably suggests a genetic relationship between the protoliths of greenschists and metagabbros. The granitic orthogneisses show the highest REE contents, ranging between 39.18 and 105.29 ppm. They show abundances of six to 52 times the chondritic values and show fractionated REE patterns (fig. 7*e*) characterized by moderate enrichment of the LREEs ($[\mathrm{La/Sm}]_N$ = 1.36–1.97), flat HREE patterns ($[\mathrm{Gd/Yb}]_N$ = 0.83–1.18), and a marked negative Eu anomaly (Eu/Eu* = 0.30–0.74).

Tectonic Setting of the Ophiolite. Chemical mobility can be evaluated by studying the correlation between the most significant incompatible elements (fig. 8). TiO_2, Y, Hf, and Ce show a systematic positive correlation with increasing Zr, which suggests that their contents were not affected by sig-

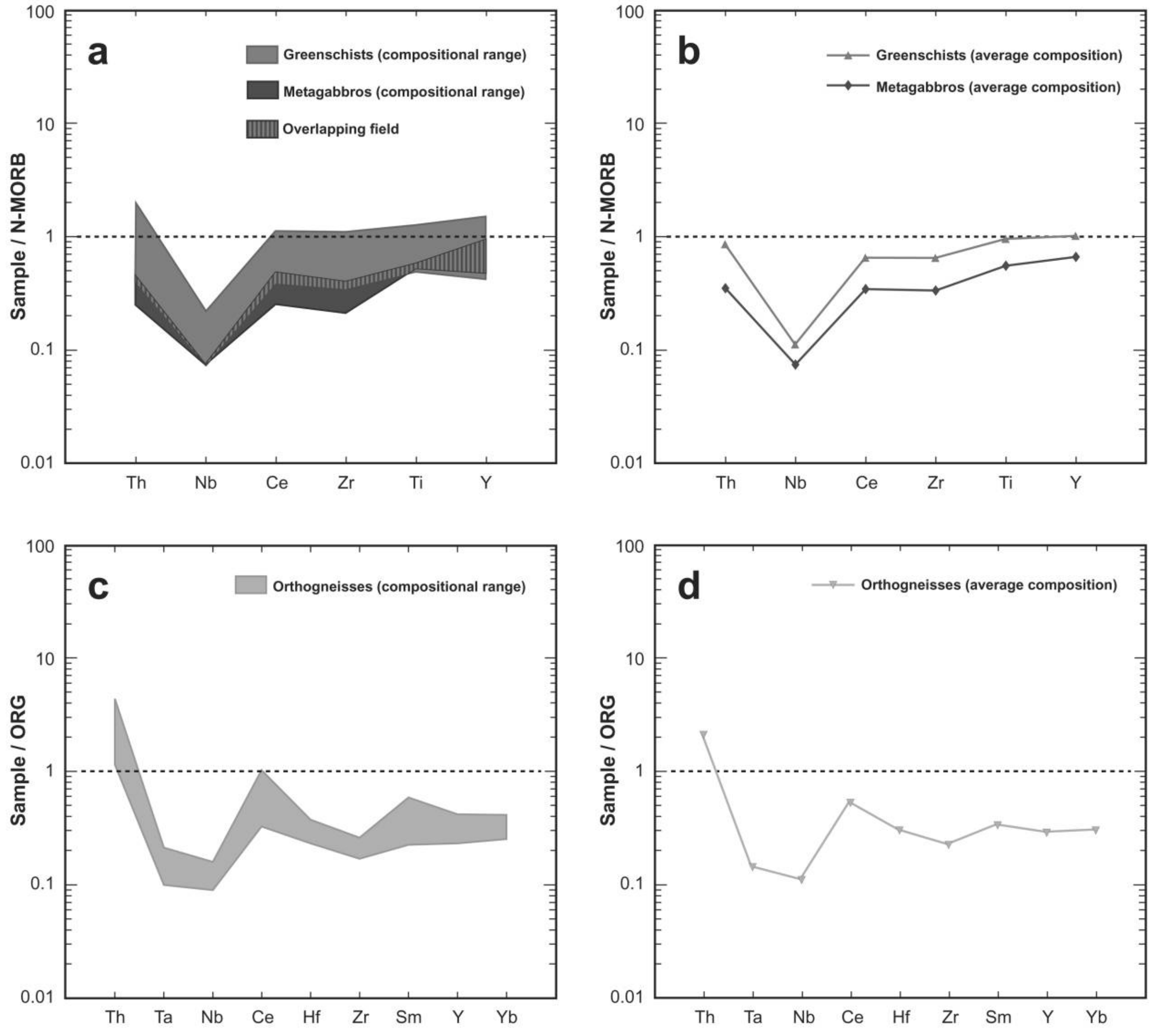

Figure 10. Immobile trace element plots of the most representative metaigneous lithologies of Vila de Cruces ophiolite. *a*, *b*, Greenschists and metagabbros plots corresponding to the compositional range for each set of samples and their average composition, respectively. Normalizing values corresponding to N-MORB average composition according to Pearce (1996). *c*, *d*, Orthogneisses plots corresponding to their compositional range and average composition respectively. Normalizing values corresponding to ORG average composition according to Pearce et al. (1984*a*).

nificant modification during alteration. The metagabbroic rocks appear as the less evolved lithologies, with the lowest contents in Zr; they plot in the origin of the evolving line defined by the igneous suite. These plots confirm that the immobile trace elements can be used to investigate the tectonic setting of the Vila de Cruces ophiolite.

The geochemical diagrams that have proved to be most useful in identifying the tectonic setting of the Vila de Cruces ophiolite are Ti-Zr-Y (Pearce and Cann 1973), Ti-Cr (Pearce 1975), Hf-Th-Ta (Wood 1980), and Ta-Yb (Pearce et al. 1984*a*). The last two diagrams can also be used for acid rocks, especially the Ta-Yb diagram, which is specific for granitoids. In the Ti-Zr-Y diagram, most of the basic rocks plot in the field of the island-arc tholeiites (fig. 9*a*), while in the Ti-Cr diagram the same rocks plot in the region characteristic for suprasubduction zone basalts (fig. 9*b*). The Hf-Th-Ta projection (fig. 9*c*) is probably the most significant to identify subduction-related basaltic rocks. Most of the greenschists and metagabbros show very low Ta contents, which explains their plotting in the field of the destructive plate-margin basalts. Moreover, the ratios Hf/Th ≥ 4.8 shown by these rocks are characteristic of island-arc tholeiites. In this same diagram, the granitic orthogneisses are also identified as lithologies generated in destructive plate-margin settings, which is confirmed by the Ta-Yb diagram, where they plot in the field of volcanic-arc granitoids (fig. 9*d*).

Trace element abundances normalized to the average composition of a rock of known origin are an alternative approach to deciphering the tectonic setting of an igneous suite. This kind of representation is even more significant using just a few elements with the most immobile behavior and highest discriminating power (Pearce 1996). The normalizing factor used to plot the metabasic rocks was the average N-MORB composition (Pearce 1996), whereas the orthogneisses have been normalized to the average oceanic ridge granite composition (Pearce et al. 1984*a*). As can be observed in figure 10*a*, the compositional range is more restricted in metagabbros than in greenschists, although this is probably influenced by the fewer samples analyzed of the first lithology. As a whole, the metabasic rocks show a pattern depleted in all the selected trace elements in relation to the N-MORB. This depletion is more marked in the metagabbros. The normalized trace element abundance pattern corresponding to the greenschists is relatively similar to that of the N-MORB (fig. 10*b*), but it shows slight depletions in Th, Ce, Zr, and Ti. The most outstanding characteristic in this pattern is the marked negative anomaly of Nb. This type of anomaly is considered characteristic of magmas generated in a subduction zone, in which the preferential retention of Nb into some mineral phases during dehydration of the subducting slab causes depletion of Nb relative to Th and Ce, in the subduction-related magmas (Pearce and Peate 1995; Pearce 1996). The pattern of the metagabbros is parallel to that of the greenschists, though slightly more depleted, which suggests a similar tectonic setting.

The range observed in the normalized trace element abundance pattern of the orthogneisses is markedly narrow (fig. 10*c*). Except in the case of Th content, they show a general depletion in relation to a typical ORG. The average normalized pattern shows an important negative anomaly in Ta and Nb (fig. 10*d*), which together with the low contents of Y and Yb and the slight fractionation in Th are typical of granitoids generated in volcanic arcs or suprasubduction zones (Pearce et al. 1984*a*).

Given the information obtained from the trace elements with the most immobile behavior and with the highest discriminant ability, the greenschists and metagabbros of the Vila de Cruces ophiolite show compositions characteristic of island-arc tholeiites. Similarly, the granitic orthogneisses can be classified as granitoids generated in a volcanic arc. Therefore, it can be concluded that the geochemical characteristics of the igneous lithologies of the ophiolite are consistently different from those typical of mid-ocean ridge ophiolites generated in divergent settings and are compatible with a convergent plate tectonic setting. We therefore conclude that the Vila de Cruces ophiolite formed in a suprasubduction zone environment.

Discussion: Implications for the Opening of the Rheic Ocean

Evidence based on stratigraphic (Linnemann et al. 2000), paleontologic (McKerrow et al. 2000; Fortey and Cocks 2003), paleomagnetic (Tait et al. 2000), igneous (Sánchez-García et al. 2003), and tectonothermal (Martínez Catalán et al. 2002) data suggest that the opening of the Rheic Ocean occurred in the Late Cambrian to Early Ordovician, while its closure took place in Devonian to Carboniferous times during the long collision between Gondwana and Laurussia that generated Pangaea. Recently, it has been proposed that the opening of the Rheic Ocean occurred by rifting along a Neoproterozoic suture (Murphy et al. 2006). In spite of the large amount of available data concerning the history of this ocean, which is currently included in plate tectonics reconstructions for Paleozoic times (Stampfli and Borel 2002; Winchester et al. 2002), ophiolitic ensembles representing its oldest oceanic crust are elusive. Many uncertainties exist regarding the opening itself, which may have been preceded by an Early Cambrian rifting event described in the paleo margin of Gondwana and marked by abundant alkaline magmatism (Floyd et al. 2000; Linnemann et al. 2000; Sánchez-García et al. 2003). The ophiolites currently considered related to the Rheic in the Variscan Belt have ages ranging between Late Silurian and Early Devonian (Clark et al. 1998; Díaz García et al. 1999; Dubińska et al. 2004). Hence, these ophiolites can be considered representative of only the youngest oceanic lithosphere originated in the Rheic Ocean, shortly before its closure, and they were probably generated during intraoceanic subduction associated with the destruction of older oceanic lithosphere (Sánchez Martínez et al. 2007). The common elimination by subduction of the oldest cold and dense oceanic lithosphere could explain the infrequent preservation of oceanic lithosphere generated in the

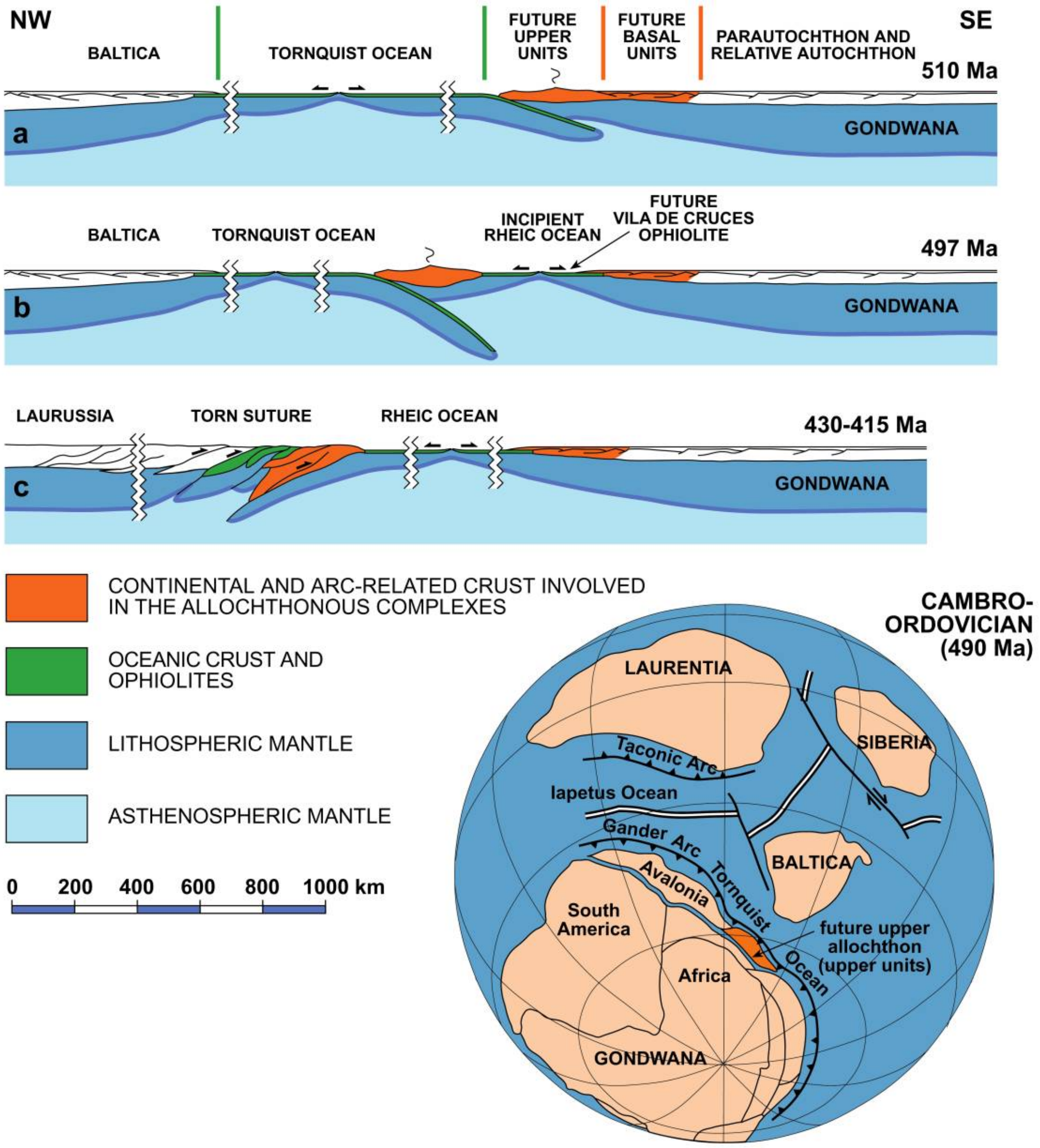

Figure 11. Schematic cartoon showing three significant steps in the evolution of the Vila de Cruces ophiolite. *a*, Tornquist Ocean begins to close in a destructive plate margin in the periphery of Gondwana. *b*, Individualization of a peri-Gondwanan terrane by slab rollback related to the subduction of the Tornquist lithosphere. This terrane will be emplaced on top of the allochthonous nappe stack of northwest Iberia. *c*, Closure of the Tornquist Ocean, accretion of the future upper allochthon to Laurussia, and maximum width reached by the Rheic Ocean. Plate tectonics reconstruction for the Cambro-Ordovician boundary based on Winchester et al. (2002).

first stages of oceanic opening (Molnar and Atwater 1978).

The Vila de Cruces ophiolite can be interpreted as a remnant of the oceanic lithosphere generated during the first stages in the opening of the Rheic Ocean (fig. 11). The lithologies, characterized by greenschist series of basaltic origin interbedded with sediments and minor metagabbros and orthogneisses, suggest that it is not representative of common oceanic lithosphere generated in mid-oceanic spreading centers (Anonymous 1972; Boudier and Nicolas 1985). Its geochemical characteristics suggest generation in a suprasubduction zone environment—more precisely, in a back-arc basin caused by subduction directed to Gondwana (fig. 11). The U-Pb age of 497 Ma obtained in the metagranitoids represents a minimum age for the opening of the back-arc basin, which was probably followed by separation from Gondwana and subsequent drift of the terrane currently forming the upper allochthon of the northwest Iberian Massif. This terrane includes huge massifs of gabbros and granitoids dated at 500 Ma (Abati et al. 1999), with geochemical characteristics typical of volcanic arcs, and its accretion to Laurussia occurred at approximately 430–415 Ma (Gómez Barreiro et al. 2006; Fernández-Suárez et al. 2007), when the Rheic Ocean reached its maximum width.

According to the model of figure 11, the Vila de Cruces ophiolite represents an incipient stage in the development of the marginal basin that eventually spread to the Rheic Ocean. The geochemical arc affinity of the basic rocks and the presence of sedimentary rocks favor this interpretation. The ophiolite probably represents a piece of the oceanic lithosphere located close to the Gondwana margin. The abundance of detrital sediments in this section probably accounts for its final preservation because they are less prone to being subducted. As younger oceanic lithosphere developed later and was progressively more separated from the continental margin, it was sediment starved and was eliminated by intraoceanic subduction later than 430–415 Ma (Sánchez Martínez et al. 2007). This intraoceanic subduction, in turn, gave way to the most common arc-related ophiolites preserved in the European Variscan Belt, generated around 400 Ma.

Conclusions

The evolution of the Rheic Ocean included a first stage of continued opening that extends from 500 Ma, when subduction-related arcs and back-arc basins began to develop in the periphery of Gondwana, until around 430–415 Ma, the time when the island arcs originally rifted from Gondwana were accreted to Laurentia-Baltica. This arc-continent collision immediately preceded the beginning of convergence between Laurussia and Gondwana and the progressive closure of the ocean. If the relative abundance of Early Devonian ophiolites in the European Variscan Belt is taken into account, and considering that most of these ophiolites are characterized by lithological sequences typical of suprasubduction contexts, it could be suggested that most of the Rheic lithosphere was consumed very quickly, probably by intraoceanic subduction, developed between 415 and 390 Ma. Closure occurred just before the onset of subduction of the outermost margin of Gondwana, which is currently considered to mark the beginning of the Variscan Orogeny in Europe. The high-pressure metamorphism developed during this event has been dated in northwest Iberia at around 370–365 Ma (Rodríguez et al. 2003). Consequently, it can be considered that the Rheic Ocean existed during some 135 m.yr., and its evolution can be regarded as a model in plate tectonics. The Vila de Cruces ophiolite is a remnant of the oldest oceanic lithosphere generated in this ocean, and its preservation in the most internal part of the northwest Iberian Massif allows the study of the first stages of its evolution.

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