# Two-step obduction of the Porvenir Serpentinite: a cryptic Devonian suture in SW Iberian Massif (Ossa-Morena Complex)

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**Key Points:**

- The Porvenir serpentinites represent a section of upper mantle obducted in Iberia during the Variscan Orogeny

- Obduction took place in two steps, one related to Devonian subduction/accretion, and another during Carboniferous out-of-sequence thrusting
- The Porvenir serpentinites could be a dismembered part of a rootless Devonian suture zone that may extend up to NW Iberia


**ABSTRACT**

The Porvenir serpentinites is a ~600 meters thick body of meta-peridotites exposed in SW Iberia (Variscan Orogen). They occur as a horse within a Carboniferous, out-of-sequence thrust system (Espiel thrust). This thrust juxtaposes the serpentinites and peri-Gondwanan strata onto younger peri-Gondwanan strata, the serpentinites occupying an intermediate position. Reconstruction of the pre-Espiel thrust structure results in a vertical juxtaposition of terranes: Cambrian strata below, Porvenir serpentinites in the middle, and the strata at the footwall to the Espiel thrust culminating the tectonic pile. The reconstructed tectonic pile accounts for yet another major thrusting event, since a section of upper mantle (Porvenir serpentinites) was sandwiched between two continental tectonic slices (a suture zone *sensu lato*). The primary lower plate to the suture is now overlying the upper plate due to the Espiel thrust. Lochkovian strata in the upper plate and the Devonian, NE-verging folds in the lower plate suggest SW-directed accretion of the lower plate during the Devonian, i.e. Laurussia-directed underthrusting for the closure of a Devonian intra-Gondwana basin. Obduction of the Porvenir serpentinites was a two-step process: one connected to the development of a Devonian suture zone, and another related to out-of-sequence thrusting that cut the suture zone and brought upwards a tectonic slice of upper mantle rocks hosted in that suture. The primary Laurussia-dipping geometry inferred for this partially obducted suture zone fits the geometry, kinematics

and timing of the Late Devonian suture zone exposed in NW Iberia, and may represent the continuation of such suture into SW Iberia.

**Keywords**: Obduction, Ophiolite, Suture Zone, Variscan Orogen, Iberian Massif

## 1. INTRODUCTION

Ultramafic massifs represent a common and fundamental component of ophiolite complexes, and may occur at surface after obduction related to subduction zones (*Dewey*, 1976; *Dilek and Furnes*, 2014). The distribution of ophiolite-related ultramafic massifs in an orogen may give us an idea on the number and location of suture zones (and subduction zones) that contributed to orogenesis. Such an approach is valid as long as there is proof that each of the exposures analyzed represents the rooting zone for a suture zone. Ophiolite complexes may occur as allochthonous klippen (e.g., *Corfield et al.*, 2001; *Dewey*, 1976), their location being neither indicative of the actual root zone for a suture, nor their current local orientation being a reflection of the primary dip-direction of subduction planes. Obduction of oceanic crust and/or mantle rocks can be achieved through combination of processes (e.g., *Coleman*, 1981; *Dewey*, 1976; *Godfrey et al.*, 1997; *Robertson*, 2006; *Topuz et al.*, 2013). As a result, regions around suture zone exposures are usually characterized by multiple deformation events, the recognition of each of them being a must-do task to evaluate whether a given exposure accounts for the root of a suture zone and the mechanisms involved in their obduction.

Suture zones are traceable, even if dismembered, due to the contrasting nature of the terranes they separate, their structural position relative to major continental blocks involved in the collision, or the protolith age, and timing and kinematics of accretion of the ophiolites they include. But just like any other vertical juxtaposition of geological elements, the upper and lower structural position of the fault-bounded domains defining a suture zone can be switched by superimposed thrusting of those below onto those above (e.g., out-of-sequence thrusts). Such a consideration impacts dramatically on the reconstruction of major tectonic processes in mountain belts, as upper and lower plates relative to subduction zones may be observed in the opposite position they had during the suturing process (Fig. 1).

With the aforementioned ideas in mind, we present a structural analysis of a region around a several hundred meters thick tectonic slice of meta-peridotites (Porvenir serpentinites) that is exposed in SW Iberia. Reconstruction of the several phases of deformation that affected the meta-peridotites and the rocks resting on top and below them demonstrates that the obduction of the ultramafic massif was achieved through a two-step process during the Variscan Orogeny. In the Late Devonian, the meta-peridotites were part of a suture zone, in which upper mantle rocks ended up bounded by two tectonic slices of peri-Gondwanan continental crust. Then, during the Carboniferous, (steeper) out-of-sequence thrusts cut across the former suture zone, and transported onto its upper plate a dismembered section of the suture zone (meta-peridotites) along with the lower plate. A short discussion frames this sequence of events in the geological evolution of the region and analyzes the impact of our two-step obduction model for the evolution of the Variscan Orogen in Iberia.

## 2. GEOLOGICAL SETTING

The pre-Mesozoic structure of the Iberian Massif resulted from the progressive collision between Gondwana, Laurussia and their peripheral terranes after the closure of the Rheic Ocean (Variscan Orogen; *Díez Fernández et al.*, 2016; *Martínez Catalán et al.*, 2009; *Matte*, 2001; *Ribeiro et al.*, 2007; *Simancas et al.*, 2013). The origin of the peripheral terranes are, in most cases, somewhat related to the opening, widening and eventual closure of the Rheic Ocean (*Albert et al.*, 2015; *Arenas and Sánchez Martínez*, 2015; *Chichorro et al.*, 2008; *Díez Fernández et al.*, 2010; *Linnemann et al.*, 2008; *Sánchez-García et al.*, 2003). A number of peri-continental, Gondwana-derived terranes (Ediacaran – Ordovician arc-related terranes) are found as tectonic slices on top of inboard sections of the platform of mainland Gondwana, both in the NW section (*Arenas et al.*, 1986; *Martínez Catalán et al.*, 2007; *Ribeiro et al.*, 1990) and SW section (*Araújo et al.*, 2005; *Azor et al.*, 1994; *Díez Fernández et al.*, 2017) of the Iberian Massif (Fig. 2).

Whether or not the Gondwanan terranes of Iberia were part of a single, currently dismembered, peri-Gondwanan micro-continent (*Díez Fernández and Arenas*, 2015), or individual terranes transferred to such structural position by means of different processes across the margin of Gondwana (*Martínez Catalán*, 1990; *Ribeiro et al.*, 2007; *Simancas et al.*, 2013), relies on the existence of a common major thrust (or thrust system) able to explain their emplacement. According to *Díez Fernández and Arenas* (2015), the suturing of an intra-Gondwana Devonian basin, carried out in the context of Laurussia-directed subduction-accretion and underthrusting, can explain the uppermost structural position this collection of peri-Gondwanan terranes share today. This way, the exposures of this putative suture zone should contain lithological assemblages that experienced high-P metamorphism roughly at the same time, and be accompanied by ophiolitic assemblages that were located in a Devonian basin before obduction. These two requisites are fairly met by the lithological assemblages that have been proposed as tracers for this single intra-Gondwana suture zone across the Iberian Massif (*Abati et al.*, 2018; *Díez Fernández and Arenas*, 2015; *Díez Fernández et al.*, 2016, 2017). There is also good similarity and geochemical and isotopic affinities between the sedimentary series involved in the suture zone of the Devonian basin that are now observed hundreds of kilometers away from each other in NW and SW Iberia (*Díez Fernández et al.*, 2017).

Another angle to test the verisimilitude of the model would be to prove that the primary regional dip of the major thrust that emplaced the suture zone, and therefore the peri-Gondwanan terranes to their current upper structural position, is the same across the Iberian Massif (in paleogeographic terms). Subduction polarity for the closure of the intra-Gondwana Devonian basin and subsequent underthrusting is well-constrained in NW Iberia. Structural and tectonometamorphic analyses carried out in the Basal Allochthonous Units of NW Iberia strongly support Laurussia-directed subduction and underthrusting (W-dipping in present-day coordinates; *Díez Fernández et al.*, 2011, 2012; *Martínez Catalán et al.*, 1996). Should this major thrusting event affect rocks now exposed in other parts of the Iberian Massif (e.g., SW Iberia), the regional dip of thrust planes for those events (subduction + underthrusting) should be compatible. So far subduction polarity for the Central Unit, which is considered a member of the single intra-Gondwana suture zone in SW Iberia by *Díez Fernández and Arenas* (2015) (Fig. 2), is assumed to be towards Gondwana (NE-dipping in present-day coordinates; *Azor et al.*, 1994; *Pereira et al.*, 2010), i.e., opposite that inferred for equivalent rocks in NW Iberia.

We have selected a study area located in the Obejo-Valsequillo Domain (Ossa-Morena Complex of SW Iberia; Figs. 2 and 3), a section of the Iberian Massif dominated by tectonic slices with continental crust affinity that also contains minor and dispersed units with oceanic crust or upper mantle affinity. From a paleogeographic point of view, the sedimentary sequences of this domain are widely accepted as deposited in basins connected to Gondwana (*Robardet and Gutiérrez Marco*, 2004; *Talavera et al.*, 2015), whose age range from Ediacaran up to Carboniferous (see revision by *Martínez Poyatos*, 2002; *Matas et al.*, 2015a). Although Cadomian (Ediacaran-Cambrian) deformation has been inferred for the oldest rocks of this domain (e.g., *Blatrix and Burg*, 1981; *Dallmeyer and Quesada*, 1992; *Eguíluz et al.*, 2000; *Llopis et al.*, 1970; *Martínez Poyatos et al.*, 2001), its current regional architecture is largely controlled by structures formed during the late Paleozoic, in the course of the Variscan Orogeny (*Apalategui and Pérez-Lorente*, 1983; *Azor et al.*, 1994; *Martínez Poyatos et al.*, 1995b, 1998a).

In the Obejo-Valsequillo Domain, Ediacaran through to Devonian and Carboniferous lithostratigraphic series are affected by folds, faults and ductile shear zones. A NE-verging train of overturned to recumbent folds has been identified as the first Variscan (Devonian) deformation in this domain (*Azor et al.*, 1994; *Martínez Poyatos et al.*, 1995a, 1995b, 1998a). These folds only affect pre-Late Devonian rocks and were generated under low- to- medium-grade metamorphic conditions (*López Munguira et al.*, 1991; *Martínez Poyatos*, 2002). A numerous set of NE-directed thrusts is a contributor to the Variscan structure of the Obejo-Valsequillo Domain (Fig. 3). These thrusts cut across the aforementioned Devonian folds and are in close relation to the development and evolution of (syn-orogenic) Carboniferous sedimentary basins, which in some cases post-date and in other cases are affected by Variscan structures (*Martínez Poyatos et al.*, 1998b; *Wagner*, 2004). Among these thrusts, the Espiel thrust stands out as being responsible for the duplication of the Precambrian and Paleozoic lithostratigraphy across this domain and for the overriding of metamorphic onto non-metamorphic rocks (*Apalategui and Pérez-Lorente*, 1983; *Martínez Poyatos et al.*, 1995b, 1998a; *Matas et al.*, 2015a).

The boundaries of the Obejo-Valsequillo Domain are late Variscan shear zones. The Puente Génave – Castelo de Vide detachment (*Martín Parra et al.*, 2006) marks the contact with the Central Iberian Zone, located to the North (Fig. 2; *Díez Fernández and Arenas*, 2015). The Matachel normal fault (*Azor et al.*, 1994), along with the Ojuelos-

Coronada igneous complex (*Delgado Quesada*, 1971), can be taken as the southern boundary of the Obejo-Valsequillo Domain (Fig. 3).

South of the Obejo-Valsequillo Domain, the Central Unit represents a Variscan suture zone (*Azor*, 1994). High-P metamorphism in this unit (*Abalos et al.*, 1991b; *Mata and Munhá*, 1986) has been dated at Late Devonian (*Abati et al.*, 2018), whereas post-eclogite metamorphic evolution related to its exhumation is constrained to Late Devonian through to Carboniferous (*Dallmeyer and Quesada*, 1992; *Pereira et al.*, 2010). The Central Unit consists of mid- to high-grade gneisses and minor amphibolites (including retroeclogites) that is thrust onto an ensemble of low- to mid-grade metamorphic rocks referred to as the Albarrana Domain (Fig. 2), which is considered the relative autochthon to the Central Unit suture (*Azor*, 1994; *Azor et al.*, 1994; *Simancas et al.*, 2001). Many of the thrusts and extensional faults of the region show a component of left-lateral oblique-slip, their functioning being attributed to a Variscan, oblique plate boundary system (e.g., *Pérez-Cáceres et al.*, 2016).

The study area is located well inside the Obejo-Valsequillo Domain (Fig. 3). It includes an exceptional exposure of the rocks and structures that are non-affected (post-date), are affected by, or are affecting the Espiel thrust (Fig. 4a), making it a good site to constrain the tectonic record of this major fault. Given that the Espiel thrust transported Middle-Late Devonian folds in its hanging-wall (*Simancas et al.*, 2001), a reconstruction of the deformation by this fault would provide clues to the geometry of Middle-Late Devonian structures. First descriptions of the Espiel thrust reported the existence of a body (several hundred meters thick) of serpentinites (meta-peridotites) along its trace (*Apalategui and Pérez-Lorente*, 1983). This occurrence represents a first-order anomaly in SW Iberia, as it represents a tectonic slice of upper mantle bounded by continental crust above and below, thus reproducing the essentials for an exhumed suture zone.

## 3. LITHOSTRATIGRAPHY OF THE STUDY AREA

The bedrock geology of the study area is defined by five groups of rocks (Fig. 4a). Two of them correspond to the hanging wall (Cambrian metasedimentary rocks; low-grade metamorphism) and footwall (Cambrian-Ordovician and Silurian-Devonian metasedimentary and metaigneous rocks; very low-grade metamorphism or non-metamorphosed) of the Espiel thrust. A third group occurs in an intermediate position within the Espiel thrust, and features a complex fault zone separating the fault's hanging wall and footwall. It includes lens-shaped fault-bounded domains, in which the most salient, internally coherent domain is made of meta-peridotites (Porvenir serpentinites). The rest of the fault-bounded domains are dispersed along the fault trace and include variably deformed meta-igneous (granitoid) rocks and phyllonites after Carboniferous metasedimentary rocks. Each outcrop of the fault zone is made of the same, yet variably strained, lithology, and the set of fault-bounded domains do not share a matrix of any sort (either serpentinitic or sedimentary), i.e. they do not show block-in-matrix structure. A fourth group is represented by Carboniferous (Variscan) syn-orogenic sedimentary rocks, whereas the fifth group consists of a discordant, non-deformed Cenozoic sedimentary cover.

### 3.1. Hanging wall to the Espiel thrust

Three main concordant members can be distinguished in the upper part of the hanging wall to the Espiel thrust. Local way-up criteria such as cross-bedding and normal graded bedding, together with structural criteria (see section 4.1), were used to solve stratigraphical polarity.

The lower (older) member consists of thin-bedded, grey to dark-grey phyllites alternating with white to light-grey metasandstones (greywackes). The thickness for both ranges between few millimeters up to several centimeters, whereas a minimum thickness of 2.5 Km can be inferred for the whole member. Quartzite beds observed towards the lower part of the member could be part of a quartzite-rich horizon that extends for several Km over the study area.

The intermediate member includes phyllites (similar to those of the lower member) and more abundant and thicker layers of metasandstones (greywackes) and quartzites. Quartzites do not define a mappable layer within this unit, as they occur at any level in this succession. This member is ~1 Km thick and represents a transition towards the upper member.

The upper member consists of quartzites and feldspar-rich metasandstones that alternates with light-grey to pinkish phyllites. Metasandstone beds range between several decimeters and several meters in thickness, the thickest ones being at the top of the series. Minimum thickness for this member is at ~150 m.

This succession, especially the two lower members, are lithologically identical to the Azuaga Formation (*Delgado Quesada*, 1971), also referred to as the Villares Formation by *Liñán* (1978). This idea has been put forward before (e.g., *Apalategui et al.*, 1985; *Matas et al.*, 2015a). The age of the Azuaga Fm. (based on fossil content) is Early-Middle Cambrian (*Azor*, 1994; *Liñán*, 1978; *Liñán and Quesada*, 1990; *Jensen et al.*, 2004), so a similar age is assumed for the series described here.

## 3.2. Intermediate fault-bounded domains of the Espiel thrust

### *3.2.1. Porvenir serpentinites*

This unit consists of ~600 meters of serpentinized ultramafic rocks that crops out NE of the El Porvenir village (Fig. 4a). The maximum thickness of this unit has been calculated assuming an average dip of 40º for the foliation. Previous works mentioned the existence of lenses metabasites and gneisses within this unit (*Apalategui et al.*, 1982), but recent fieldwork has not confirmed those observations yet. Those lenses were located on top and below the main body of serpentinites, thus suggesting they could be part of different tectonic slices. Most of the serpentinites in this body show massive structure, although foliated serpentinites occur as variably thick (cm to m) layers separating beds of massive serpentinites (Fig. 5a). The serpentinites are green to yellow-brown-green, and include serpentine minerals, pseudomorphs after olivine and minor pyroxene, dark red spinel, magnetite, phlogopite, chlorite, sericite, and talc (Fig. 5b) (*Apalategui et al.*, 1982). Olivine pseudomorphs represent more than 80% of the rock volume in all the samples collected. The serpentinized mineral assemblage points to dunite as the most likely protolith for the Porvenir serpentinites. Dunite is one major constituent of Earth's upper mantle, and is typically found in the lower sections of ophiolitic complexes.

*3.2.2. Undifferentiated metaigneous rocks*

A series of variably deformed and recrystallized igneous rocks occurs along the Espiel thrust. In most cases they show heterogeneous mylonitic fabric. These metafelsic rocks are dominantly made of cm-scale grains of quartz, K-feldspar and plagioclase surrounded by a matrix of fine-grained quartz, feldspar and mica (mostly biotite) that are compatible with a primary porphyritic texture for their plutonic protoliths. The absence of individual lens-shaped, highly stretched layers rich in feldspar or quartz in these rocks suggest that most of the mylonitic foliation developed at the expense of the ground mass of porphyritic granitoids. Quartz and feldspar porphyroclasts are partially recrystallized, the former phenocrysts being now an ensemble of quartz and feldspar subgrains and newly crystallized grains of quartz, feldspar, plagioclase, mica, sericite and opaques. The fine-grained matrix is made of a statistically oriented mass of those same minerals, slightly richer in quartz, mica and sericite. No age constraints are available for their protoliths. Straightforward recognition of lithostratigraphic affinities with other units of the region is not possible due to the limited and poor-quality of the outcrops and by intense strain.

Metavolcanics are another type of metaigneous rock found in the fault zone, including acid volcanic tuffs and volcaniclastic sandstones with fragments of limolite or quartzite (*Apalategui et al.*, 1982).

*3.2.3. Gneisses*

Descriptions of the fault zone of the Espiel thrust suggested the presence of gneisses, amphibolites, mylonites and phyllonites equivalent to those that occur in the Central Unit (*Apalategui and Pérez-Lorente*, 1983). We were only able to find an outcrop of mylonitic gneisses, which certainly reminds rocks of the Central Unit. The gneisses are different and accumulate more strain than any other type of rock in the hanging wall or footwall to the Espiel thrust, and must be considered exotic within the fault zone like, for instance, the Porvenir serpentinites.

The mylonitic gneisses show a compositional banding defined by quartz-feldspathic-rich layers, which contain minor mica, alternating with layers richer in mica, and layers made exclusively of quartz and mica. Individual grains of quartz, feldspar, plagioclase, and mica (mostly biotite) parallel the main foliation, as do lens-shaped aggregates of biotite, opaque minerals, minor white mica and rare garnet.

### 3.3. Footwall to the Espiel thrust

#### *3.3.1. Cambrian - Ordovician series*

The older metasedimentary succession is terrigenous. The lower part of the series includes meta-arkoses, quartzites, metaconglomerates and some felsic metavolcanics, while the upper part contains quartzites, slates and minor metalimestones. The lower part of this series has been considered as Cambrian-Ordovician (*Matas et al.*, 2015a), whereas the upper part has been correlated with the Armorican quartzite on the basis of lithological composition and fossil content (*cruziana* and *skolithos*, among other), which indicates a Paleozoic age, most likely Ordovician (*Gutiérrez-Marco et al.*, 2002).

#### *3.3.2. Silurian-Devonian series*

The structurally lower metasedimentary succession that can be recognized in the study area consists of Fe-rich quartzites, metasandstones, brown and black slates, metavolcanics, and minor dark-grey, bioclastic limestones. The slates alternate with the metasandstones and quartzites at the millimeter- to centimeter-scale, but the latter can reach up to several meters in thickness and tens of meters in lateral continuity. The distribution of these lithologies does not follow an homogeneous pattern, but the limestones are more common towards the lower part of the succession. The lowermost limestones contain Ludlowian fossils, whereas the rest contain Lochkovian fauna (*Apalategui et al.*, 1982), indicating that the Silurian-Devonian transition occur within this succession and a lack of early Silurian and mid-late Devonian strata. The nature of the basal contact of this series has not been observed.

### 3.4. Carboniferous syn-orogenic series

The age of the youngest Devonian and the oldest Carboniferous series in the region is younger than the (Devonian) onset of Variscan deformation in SW Iberia, and the youngest Carboniferous series is affected by Variscan deformation. For these reasons, the Late Devonian and Carboniferous sedimentary rocks are considered as syn-orogenic (e.g., *Wagner*, 2004). Late Devonian rocks are not exposed in the study area. The Carboniferous series are divided in three groups according to their age and facies (*Martínez Poyatos*, 2002).

*3.4.1. C1: Tournaisian – Upper Viséan to Serpukhovian (Culm facies)*

This series consists of an alternation of slates and metagreywackes at the cm- to dm-scale, and minor metaconglomerates, marbles, and metavolcanics (whole rock, K/Ar crystallization ages of 348 ± 17 Ma and 334 ± 17 Ma; *Bellon et al.*, 1979). Commonly referred to as *Culm facies*, similar rocks of this type are intruded by igneous rocks dated at 332 ± 17 Ma (whole rock, K/Ar; *Bellon et al.*, 1979) and ~307 Ma (U-Pb in zircon, single grains; *Carracedo et al.*, 2009). Marine fossils yielded Upper Tournaisian – Upper Viséan ages (e.g., *Garrote and Broutin*, 1979), Lower through to Upper Tournaisian ages, and Lower Tournaisian up to Serpukhovian ages (*Matas et al.*, 2015a), depending on the section. Deposition of the lower part of this series has been interpreted as related to an extensional event, whereas the upper part has been related to crustal shortening (*Armendariz et al.*, 2008; *Martínez Poyatos*, 2002).

*3.4.2. C2: Upper Viséan – Serpukhovian (Granja de Torrehermosa Beds)*

This series includes sandstones, conglomerates, lutites, limestones, some rhyolites and minor coal beds. Limestone beds occur in an intermediate level of the series, while coal is found towards the top. Pebbles of rocks from the *Culm facies* were found in some conglomerates (*Pérez Lorente*, 1979). Marine and continental fossils collected in this series constrain the age to Upper Viséan – Serpukhovian (*Apalategui et al.*, 1985; *Mamet and Martínez*, 1981; *Ortuño*, 1971).

*3.4.3. C3: Bashkirian – Moscovian (Peñarroya Beds)*

The base of this succession includes a 50m to >400m thick layer of conglomerates that alternates with minor sandstones and lutites, and is overlain by sandstones, silts, and lutites that intercalate coal beds. Conglomerate pebbles include black, red, and white quartzites, slates, other conglomerates and sandstones, and limestones from the Granja de Torrehermosa Beds (*Andreis and Wagner*, 1983). Previous authors (e.g., *Andreis and Wagner*, 1983; *Pérez Lorente*, 1979) suggested a provenance from the North (present-day coordinates). However, several observations of SW-dipping imbricated clasts in the basal conglomerates suggest NE-directed flow, i.e., a source area probably located to the SW.

## 4. PHASES OF DEFORMATION

Variscan deformation in the study area can be grouped in three major phases. The first phase ($D_1$) produced NE-verging overturned folds and an associated axial planar foliation ($S_1$). The second one ($D_2$) corresponds to the development of the NE-directed Espiel thrust and related local fabrics ($S_2$). The third one ($D_3$) produced local foliation ($S_3$), the re-folding of $D_1$ folds, the folding of the Espiel thrust, and a new generation of NE-directed thrusts.

### 4.1. NE-verging overturned folds ($D_1$)

The rocks of the hanging wall and, to a minor extent, the footwall to the Espiel thrust show a penetrative foliation ($S_1$; Figure 5c). $S_1$ (for metapelites) in the hanging wall is defined by recrystallized quartz, plagioclase, chlorite, white mica, opaques, and minor biotite and garnet (low-grade metamorphism), whereas in the footwall the main foliation is marked by reoriented sedimentary clasts of quartz, feldspar, plagioclase and mica and the preferred orientation of newly-formed chlorite and sericite (very low-grade metamorphism). $S_1$ ranges between slaty and phyllitic, the more granular facies showing spaced and rough cleavage.

An intersection lineation ($Li_1$) varies across the study area. The cleavage-bedding relationship, together with local way-up criteria, were used to identify upright and overturned limbs of major $D_1$ folds, for which $S_1$ maintains an axial planar geometry. Two fold closures of the same major syncline (Espartal syncline) are observed. That syncline dominates the internal structure of the hanging wall to the Espiel thrust, its upright limb occupying the northern exposures and the overturned limb the southern ones (Fig. 4c).

Regional dip-direction for both limbs ($S_0$) changes, but a SW-dipping direction is common (Fig. 6a). $S_1$ shows dominant SW-dipping geometry (Fig. 6b) although it dips to the NE in some parts. $Li_1$ trends NW-SE and is gently-plunging, plunging NW and SW (Fig. 6c), explaining two consecutive fold closures of the Espartal syncline in a NW-SE direction (Fig. 4a).

The maximum age for $D_1$ is constrained by the age of the youngest series affected by $S_1$, the Early Devonian (Lochkovian to Emsian) rocks of the footwall to the Espiel thrust (*Matas et al.*, 2015a). The minimum age is defined by the Late Devonian (Famenian) to Early Carboniferous (Tournaisian) rocks that are affected by the Espiel thrust (*Matas et al.*, 2015a), which cuts across $D_1$ folds (see section 4.2).

### 4.2. The Espiel thrust ($D_2$)

The juxtaposition of Cambrian onto Cambrian-Ordovician and Silurian-Devonian rocks resulted from the second phase of deformation. The contact between the upper (Cambrian) and lower (Cambrian-Ordovician and Silurian-Devonian) series is featured by fault breccias, gauges, cataclasites, mylonites, and phyllonites (Fig. 5d). This fault cuts across the ($D_1$) folded contacts between units located at its hanging wall (Fig. 4a), and produces the juxtaposition of domains showing $S_1$ fabrics developed under higher metamorphic conditions (biotite-garnet) onto domains either showing colder $S_1$ fabrics (chlorite-sericite) or non-metamorphic.

The fault zone of the Espiel thrust varies in thickness between 5 and 600 meters. Such variation is due to the occurrence of variably-sized fault-bounded domains within the fault zone, some of which reach significant size and lateral continuity as to be represented in regional maps (see lithological description of these rocks in section 3.2). All of the fault-bounded domains that have been mapped show lens-shaped geometry and the upper and lower fault rocks wrapping around these domains exhibit similar kinematic criteria. Out of the fault zone, the hanging wall and footwall maintain internal coherence. The lack of block-in-matrix structure (see section 3.2) suggests an internal imbricate structure for the fault zone of the Espiel thrust.

A local planar fabric within the fault zone ($S_2$) is coincident with the fault zone. Although local obliquity may exist, the angle between internal foliation and border is less than 30º, typically less than 20º. In all cases, the dip direction of tectonic borders and internal foliation is the same. Some differences in orientation can be observed between the borders (and $S_2$) of the hanging wall and footwall and their internal layering ($S_0$ and $S_1$).

$S_2$ is defined by preferred orientation of clasts in fault breccias, by oriented porphyroclasts in cataclasites and mylonites, by mylonitic fabrics, and by C planes in phyllonites formed in metapelitic rocks (Fig. 5d). $D_2$ kinematic criteria include S-C structures (Fig. 5e), sigma structures (Fig. 5f), and minor drag folds. At the microscopic scale, $S_2$ is associated with S-C structures, C' shear bands, sigma and delta structures (Fig. 7a), and with the grain-shape alignment of quartz grains oblique to development of $S_2$ (Fig. 7b). Minerals grown during $D_2$ include quartz, chlorite and sericite, in metapelites and metaigneous rocks, suggesting $D_2$ deformation conditions within the upper crust, ranging between low-P/low-T (chlorite) ductile conditions and brittle deformation (gauges and breccias). $D_2$ kinematic criteria indicate consistent top-to-the-NE shear sense, a vector coincident with the trend of slickensides observed over $D_2$ fault planes (six confident measurements; Fig. 6d).

The cross-cutting relationship between $D_1$ folds (Espartal syncline) and the $D_2$ Espiel thrust constrains the primary geometry of the thrust relative to that of the folds that now occur at its hanging wall. Most of the upright limb of the Espartal syncline defined by the lowermost metasedimentary rocks (micro-banded phyllites) has been removed by the Espiel thrust in the northeastern exposures of the study area. The reverse limb of the Espartal syncline defined by those same rocks is widely exposed towards the southwest, thus indicating obliquity between $D_2$ thrust planes and the axial plane of $D_1$ folds. The asymmetric exposure of $D_1$ fold limbs relative to the Espiel thrust indicates that the thrust dips steeper than the $S_1$ axial planes (Fig. 4c), i.e. the Espiel thrust cut upwards to the NE through the $D_1$ structure.

The Espiel thrust is younger than $D_1$, and is coeval or younger than the Culm facies rocks that are intercalated as fault-bounded domains within the fault zone (Tournaisian – Viséan). The youngest syn-orogenic strata (Peñarroya Beds) unconformably overlie the Espiel thrust, placing a minimum Bashkirian – Moscovian age for $D_2$.

## 4.3. Upright folds and late thrusts ($D_3$)

The trace of the Espiel thrust shows a sinuous pattern that reveals its folded nature (Fig. 4a, 4b and 4c). Two $D_3$ upright folds (Peñarroya antiform and Tejonera synform) affect the Espiel thrust, the bedding in its hanging wall and footwall (Fig. 7c), $S_1$, and $S_2$. Pi-diagrams for bedding (Fig. 6a), $S_1$ (Fig. 6b), and $S_2$ (Fig. 6d), indicates that $D_3$ fold axes trend NW-SE and plunge to the SE, parallel to minor $D_3$ fold axes (Figs. 6e and 7d). Those minor folds are related to a near-vertical (SW-dipping) crenulation cleavage ($S_3$) that is superimposed on $S_1$ (Fig. 7d) and $S_2$ (Fig. 7e), and is parallel to the axial plane of $D_3$ folds. In metapelites, $S_3$ is defined by reoriented minerals of $S_1$ and, locally, $S_2$, and by newly formed quartz, chlorite, sericite and opaque minerals (low-grade metamorphism). Some Carboniferous syn-orogenics, especially the Culm facies rocks, show a variably developed, near-vertical slaty cleavage that fits with the geometry and mineral composition of $S_3$. The main and only foliation in those Carboniferous rocks is considered as $S_3$.

The Peñarroya antiform and the Tejonera synform constitute a paired fold structure with two long inclined backlimbs connected by a shorter forelimb (Fig. 4c). Such fold asymmetry implies a local vergence to the NE for $D_3$ structures. The common limb between the Peñarroya antiform and the Tejonera synform is cut by a NE-directed reverse fault with left-lateral movement (Fig. 4a), as constrained by local exposures of its fault zone. Some meso-scale $D_3$ folds occur in the footwall to this fault (Peñarroya thrust). Southwest of the Peñarroya thrust, NE-directed thrusts cut across geometrically equivalent upright folds in a similar way (Fig. 4a), suggesting that the latter thrusts and the folds they cut are equivalent to the Peñarroya thrust and $D_3$ folds, respectively.

The Bashkirian – Moscovian Peñarroya Beds cover discordantly the Peñarroya antiform, but are cut by the NE-directed thrusts (Belmez thrust; Figure 4b) and occupy a footwall position relative to the progressively older Carboniferous series that rest on top of them. The Peñarroya Beds are folded by equivalent upright folds to the southwest, suggesting a progressive development for the upright folds and thrusts in the region. The structural relationship and kinematic compatibility between $D_3$ folds and later NE-directed thrusts fit models for the formation of fault-propagation folds *s.l.* (*Suppe and Medwedeff*, 1990). According to the crosscutting relationships observed in the study area, an overstep sequence (younger thrusts to the southwest) of NE-directed thrusts and related folds can be inferred for $D_3$. The overstep sequence follows the previous development of the $D_2$ Espiel thrust.

## 5. DISCUSSION

The most salient geological anomaly is the presence of a 600 meters thick tectonic slice of upper mantle (Porvenir serpentinites) emplaced between two blocks with continental affinity that are regionally separated by a single major thrust (Espiel thrust). Such a geological scenario can be considered as a suture zone involving subduction-accretion of the lower tectonic block underneath the slice of upper mantle represented by the Porvenir serpentinites. The upper mantle slice could represent the lowermost part of a dismembered ophiolite *s.l.* (oceanic lithospheric mantle) or the mantle wedge under which subduction took place (subcontinental lithospheric mantle). The lack of continental lower crust (granulitic-eclogitic), plus the absence of a major normal fault to explain the removal of such piece of lower crust, and the lack of block-in-matrix structure within the fault zone (typical for subduction mélanges), suggest a complex evolution. In other words, the obduction of the Porvenir serpentinites was achieved through a multi-step process.

A qualitative reconstruction of Variscan structures allows identifying the primary geometry of deformed (e.g., re-folded) structures. Given that the Espiel thrust cut across previous Variscan structures (e.g., $D_1$ folds), it is expected that this fault has cut other structures. Bearing this in mind, we present a reconstruction of Variscan structures in order to identify the processes involved in the obduction of the Porvenir serpentinites.

### 5.1. Qualitative reconstruction of Variscan structures

The NE-directed tectonic transport of the Espiel thrust imposes an overall SW-dipping component for its main fault plane (*Martínez Poyatos et al.*, 1995b, 1998a). Such paleo-dip-direction would have favored the development of an asymmetric pair of later ($D_3$) upright folds at the expense of it upon NE-SW shortening, such as the Peñarroya antiform and Tejonera synform (Fig. 4). The crosscutting relationship between the Espiel thrust and $D_1$ folds implies that $D_2$ thrust planes had greater SW-dipping values relative to the axial planes of those folds, i.e. the Espiel thrust cut upwards to the NE (see also *Martínez Poyatos et al.*, 1995b). This means that the structural planes of reference (e.g., axial planes, fault planes, etc.) had either lower SW-dipping values compared to the Espiel thrust, or even dipped to the opposite direction (i.e., to the NE). The NE-vergence of $D_1$ folds is at odds with a primary NE-dipping geometry, thus a SW-dipping character is inferred for the primary geometry of $S_1$.

Reconstruction of the pre-Espiel thrust structure results in a vertical juxtaposition of fault-bounded terranes in which the Cambrian strata would then occupy the lower structural position. The Porvenir serpentinites, together with some other variably deformed rocks that crop out as fault-bounded domains within the main fault zone, would occupy an intermediate structural position. The Cambrian-Ordovician and Silurian-Devonian strata of the footwall to the Espiel thrust would represent the culmination of the pre-$D_2$ tectonic pile. This restoration reveals a pre-$D_2$ tectonic thrust stack with upper mantle rocks (Porvenir serpentinites) sandwiched between two continental tectonic slices. The apparent suture zone was modified by the $D_2$ thrust. The body of serpentinites is a horse within an imbricate $D_2$ thrust system, since the current upper and lower boundary of the Porvenir serpentinites are $D_2$ thrusts that merge to the East and West (Fig. 4a). Such a geometry explains the lack of a lower crust section close to the exposure of the serpentinites (e.g. Fig. 1b), regardless of the primary location of the Porvenir serpentinites either in the subcontinental mantle of the upper plate or as part of oceanic lithosphere in the lower plate.

Should the pre-$D_2$ thrusting event represent a phase of deformation linked to the development of a suture zone, note that its timing matches that of $D_1$ folds, and both of them account for Devonian contractional tectonics. The $D_1$ folds were in the footwall to the suture zone and seem coeval to the development of the alleged Devonian suture zone.

Studies on the non-coaxial component of deformation associated with $D_1$ (microstructural approach) showed that top-to-the-SE and top-to-the-NW kinematics characterize $S_1$ (*Azor*, 1994; *Martínez Poyatos*, 2002). Those shear senses are parallel to $D_1$ fold axes, what could account for shear strain during fold amplification and lateral spreading linked to superimposed flattening. Petrofabric analyses on $S_1$ showed that a component of simple shear existed during the development of $D_1$ folds (*Azor*, 1994; *Martínez Poyatos*, 2002). The sense of rotation of major forelimbs (vergence) could represent a regional indicator of the shear sense for asymmetric folds generated in relation to simple shear (*Sanderson*, 1979). In this regard, the NE-vergence of $D_1$ folds is compatible with top-to-the-NE shear sense, i.e. SW-dipping thrust planes and SW-directed subduction polarity for $D_1$.

*5.1.1. Regional perspective for a structural reconstruction*

Before the Espiel thrust ($D_2$), the Azuaga Formation exposed in the study area was most probably located under the Porvenir serpentinites, i.e. in the footwall to a Devonian suture zone *s.l.* 20 kilometers southwest of the study area, in the Albarrana Domain (Fig. 3), the Azuaga Formation is in the footwall to a suture zone (*Abalos et al.*, 1991b; *Azor et al.*, 1994; *Díez Fernández and Arenas*, 2015; *Pereira et al.*, 2010; *Ribeiro et al.*, 2007; *Simancas et al.*, 2003). The suture zone in that area is marked by a high-P metamorphic belt that includes gneisses, micaschists, and mafic rocks (including MORB-type; Gómez-Pugnaire *et al.*, 2003), some of which experienced eclogite facies metamorphism (Central Unit; *Azor et al.*, 1994). High-P metamorphism in the Central Unit is Devonian (377 ± 19 Ma; *Abati et al.*, 2018), and is coincident with the age of $D_1$ folds (see section 4.1).

The synchrony between the development of the suture zone exposed in the Central Unit and the development of $D_1$ folds, and then $D_2$ thrusts, in the study area, has been explained with a model that acknowledges NE subduction polarity (*Azor et al.*, 1994). In that model, the whole area of study in our work would occupy an upper plate position, the ($D_1$) NE-verging folds and subsequent ($D_2$) NE-directed thrusts representing back-folding and associated back-shearing, respectively. That way the upper plate would be subjected to NE-SW shortening upon progressive NE-directed subduction + underthrusting and plate coupling through the subduction zone (*Simancas et al.*, 2001).

Previous models are based on the assumption that the Devonian subduction-related high-P metamorphism of the Central Unit was directed to the NE *s.l.* Such assumption finds support in the current NE-dipping geometry of the Central Unit in some areas (*Azor et al.*, 1994; *Simancas et al.*, 2003). However, such models fail to explain why the Azuaga Formation occurs in the upper and lower plate to the suture zone and, more importantly, how a several hundred meters thick tectonic slice of upper mantle (Porvenir serpentinites) could override the upper plate and bring previously folded rocks of the lower plate (Azuaga Formation) along with it. Those models conceive a simple, NE-dipping geometry for the whole Central Unit, based on a seismic profile (*Simancas et al.*, 2003) and a field-based structural analysis (*Azor et al.*, 1994) that are restricted to one particular section of the Central Unit. Other structural analyses (e.g., *Abalos et al.*, 1991a) and geological maps of the Central Unit (e.g., *Apalategui et al.*, 1982) suggest that the internal structure of that suture zone is controlled by late upright folds (see also *Azor*, 1994), the current NE-dipping geometry in some parts being the result of rotation about subhorizontal axes during late upright folding (*Díez Fernández and Arenas*, 2015, 2016). If that is the case, the high-P belt exposed southwest of the study area (Central Unit), and the upper mantle section currently exposed as a tectonic slice within the Espiel thrust, could be (dismembered) parts of the same Devonian suture zone. They both account for individual exposures of a suture zone that share timing (Middle-Late Devonian) and lower plate (Azuaga Formation). The rock association that would account for that suture zone is different in each of its exposures, although some rocks that occur alongside the Porvenir serpentinites could be equivalent to the Central Unit (see section 3.2.3; *Apalategui and Pérez-Lorente*, 1983). This implies that at least one mechanism is required to dismember that suture zone.

The SW-directed polarity for the Devonian subduction-accretion is supported by the NE-directed vergence of $D_1$ folds developed in the lower plate and, indirectly, by the regional consequences of a crosscutting relationship between a ($D_1$) SW-dipping suture zone and later ($D_2$+$D_3$) NE-directed thrusts. $D_2$ and $D_3$ thrusts cut upwards through previous $D_1$ structures (see section 4.2). We cannot evaluate quantitatively to what extent $D_1$ thrust planes rotated by the effect of superimposed thrusting. However, if thrust-related rotation existed, it probably had local consequences only. In other words, if the primary regional dip of $D_1$ thrust planes was to the SW, that dip would not have changed at the regional scale by $D_2$ and $D_3$ thrusts. Accordingly, $D_2$+$D_3$ NE-directed thrusts cutting across $D_1$ SW-dipping thrusts planes (with lower dip values) would allow exposure of $D_1$ thrusts towards the SW (Figs. 1a-c). On the contrary, should the primary geometry of $D_1$ thrusts be NE-dipping (NE-directed subduction), superimposed $D_2$+$D_3$ NE-directed thrusts would have progressively moved the $D_1$ thrusts to upper structural positions, as to eventually impede their observation to the SW (Figs. 1d-f).

The region is characterized by extensional faults (not observed in the study area). The NE-dipping Matachel fault (*Azor et al.*, 1994) separates exposures of the Central Unit to the SW (in its footwall) from the exposures of our study area to the NE (in its hanging wall) (Fig. 3). The down-thrown movement of the NE block of the Matachel fault makes it unlikely that $D_1$ NE-dipping thrusts in its NE block (Porvenir serpentinites) could be seen in its SW block (Central Unit). Therefore, we conclude that a SW-dipping primary geometry for $D_1$ thrusts (and for the suture zone they account for) explains the regional concerns.

The lower Culm facies (Tournaisian) sequences (see section 3.4.1) suggest that $D_1$ folding was followed by extension. The resulting vertical juxtaposition of terranes acquired during the previous ($D_1$) suturing process would be the same. At most, some of the units that once defined the Devonian suture zone would have been removed and/or attenuated before $D_2$ thrusting, thus introducing another reason why we observe a so dismembered suture zone today.

## 5.2. Tectonic model for the obduction of the Porvenir serpentinites

The structural analysis and qualitative reconstruction of Variscan structures allow a reinterpretation of the Espiel thrust. The model can be summarized in three events: (i) Devonian subduction-accretion directed to the SW (Fig. 8a); (ii) Early Carboniferous out-of-sequence thrusting directed to the NE; (Fig. 8b); and (iii) Late Carboniferous upright folding and thrusting directed to the NE.

Deformation in this section of the Variscan orogen started in Devonian times with subduction that involved continental lithosphere (Central Unit) and the upper mantle. Devonian subduction of continental crust gave way to progressive SW-directed underthrusting of continental lithosphere (Azuaga Formation, among others; $D_1$ folds), which became the lower plate to a suture zone that would include high-P metamorphic rocks with continental crust affinity (Central Unit), ophiolites? (to be found in the study area or nearby), and tectonic slices of upper mantle, either from the overlying mantle wedge of the former subduction zone (continental mantle lithosphere) or from the lowermost part of an ophiolitic ensemble (oceanic mantle lithosphere). The Porvenir serpentinites could potentially account for one of those two options for upper mantle rocks. The upper plate to the Devonian suture zone in the study area would be (at least) the Cambrian-Devonian series exposed in the footwall to the Espiel thrust.

After transient extension between $D_1$ and $D_2$ (not represented in the model), further SW-directed underthrusting of continental lithosphere during the Early Carboniferous produced steeper and out-of-sequence thrust faults that accommodated shortening. NE-directed $D_2$ thrusts, such as the Espiel thrust, cut upwards across the overlying Devonian suture zone, thus concluding the obduction of the Porvenir serpentinites (Fig. 8b). The Devonian suture zone was variably dismembered along the imbricate structure of $D_2$ breaching thrusts, while lower and upper plate switched structural position in the process.

Normal faults, such as the Matachel fault, characterized the subsequent stage in the tectonic evolution of SW Iberia. Most of these faults formed during the Carboniferous (late Viséan through to the Bashkirian), and drove lithosphere attenuation by extension (*Dias da Silva et al.*, 2018; *Díez Fernández et al.*, 2019; *Expósito et al.*, 2002; *Pereira et al.*, 2009; *Simancas et al.*, 2001).

Variscan shortening resumed after Carboniferous extension and affected the whole Iberian Massif during the Bashkirian through to the Gzhelian (*Díez Fernández and Pereira*, 2017; *Martínez Catalán et al.*, 2009; *Simancas et al.*, 2001). In the foreland of the orogen, subhorizontal shortening translated into thin-skinned fold-thrust belts, while in the hinterland such shortening was accommodated by strike-slip shear zones and associated upright folds (*Díez Fernández et al.*, 2016). In the study area, NE-SW shortening nucleated upright folds and produced the inversion of Carboniferous sedimentary basins ($D_3$ thrusts).

### 5.3. Major tectonic implications for the Variscan Orogen in the Iberian Massif

The traditional understanding maintains that the Iberian Massif is an ensemble of continental blocks separated by suture zones, the most relevant of which would be the one that separates the South-Portuguese Zone from the rest of the massif (Fig. 2). That suture has been regarded as a reworked suture zone of the Rheic Ocean (*Azor et al.*, 2008; *Díez Fernández and Arenas*, 2015). The rest of the exposures recognized as Variscan suture zones have been collectively interpreted in two contrasting ways: (i) as correlatives to the Rheic suture zone exposed in SW Iberia (e.g., *Ribeiro et al.*, 2010; *Simancas et al.*, 2013); (ii) as secondary suture zones of minor oceanic basins formed in peri-Gondwana at some point during either the opening or closure of the Rheic Ocean (e.g., *Arenas et al.*, 2014; *Díez Fernández and Arenas*, 2015; *Simancas et al.*, 2009). Two main models are currently under debate for the second line of thinking. In the one hand, there are models that interpret the exposures of rocks that may represent a Variscan suture zone (high-P rocks, ophiolites, etc.) as the rooting zone for several sutures (e.g., *Azor et al.*, 1994; *Simancas et al.*, 2001), and therefore several continental microblocks other than Gondwana and Laurussia (e.g., *Simancas et al.*, 2009). On the other hand, the model proposed by *Díez Fernández and Arenas* (2015) maintains that most, if not all the exposures of Variscan suture zones other than the one that separates the South-Portuguese Zone from the rest of the Iberian Massif, are actually part of a single, yet dismembered intra-Gondwana suture zone that is rootless and several times repeated across the hinterland of the orogen. This model explains repetition by a combination of faults and late upright folds superimposed to the primary structure of that suture zone. In this view, the latter model recognizes one main continental micro-block besides Gondwana and Laurussia (e.g., Armorica microplate; *Matte*, 2001), and whose boundaries would have been the site for subduction nucleation, accretion and subsequent underthrusting during the Variscan Orogeny (*Díez Fernández et al.*, 2016).

Each of the two lines of thinking exposed before has its own implications. If each suture zone exposure accounts for an independent suture zone, there is no need for them to share subduction-accretion polarity. However, they should probably be diachronic (especially in cases where they are few kilometers away from one another), as they would represent the juxtaposition of terranes located across the margins of Gondwana or Laurussia. All the suture zone exposures that separate terranes with Gondwanan affinity in Iberia formed during the Devonian (see revision by *Díez Fernández et al.*, 2016; and recent data by *Abati et al.*, 2018). If there is only one Devonian suture zone that is repeated across the Variscan hinterland, then there should be a way to connect each exposure with the rest throughout the Variscan structure (as tentatively solved by *Díez Fernández and Arenas*, 2015). Second, the primary subduction polarity for all the cases must be the same. Our contribution in this regard is that the timing for the formation of the suture zone that is inferred from a qualitative reconstruction of the Espiel thrust fits the age of other independent suture zone exposures that occur elsewhere in the Iberian Massif, and so it does its primary (SW-directed, i.e. Laurussia-directed) subduction-accretion polarity. These two deductions provide further verisimilitude to the single intra-Gondwana suture zone model.

## 6. CONCLUSIONS

The Porvenir serpentinites are a ~600 meters thick body of deformed ultramafic rocks (meta-peridotites) that occurs within a Carboniferous, NE-directed thrust system (Espiel thrust) and affected by upright folds. The obduction of the Porvenir serpentinites was a two-step process: (i) the development of a suture zone during the Devonian; and (ii) the development of the Espiel thrust, which cut across and carried a tectonic slice of upper mantle rocks that belonged to the alleged Devonian suture. Stratigraphic and structural data suggest SW-directed tectonic accretion of the lower plate during the Devonian, and implies Laurussia-directed underthrusting during closure of a Devonian basin that separated two sections of peri-Gondwanan continental crust.

The NE-directed nature of the (Carboniferous) Espiel thrust system is compatible with a SW-dipping geometry for the (Devonian) pre-Espiel suture zone. The Porvenir serpentinites and Central Unit are proposed as part of the same suture zone. Late upright folding rotated the Central Unit, as well as other exposures of this Devonian suture zone in the Iberian Massif, to their current geometry. The primary SW-dipping nature of the

Devonian suture zone fits the polarity, kinematics and timing of the Late Devonian suture zone that crops out in the Allochthonous Complexes of NW Iberia, and may represent the continuation of such suture zone into SW Iberia.

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## FIGURE CAPTION

**Figure 1**: Cartoon showing the upper and lower block of a suture zone switching places by superimposed NE-directed thrusting. Sections (a), (b) and (c) show a case example for a primary SW-dipping suture zone, whereas sections (d), (e) and (f) represent the case for

a NE-dipping suture zone. Note that forward modelling from (a) to (c) provide several possibilities for a primary SW-dipping suture zone to occur (stars) towards the SW of a series of NE-directed thrusts (e.g., Espiel thrust) and normal faults (e.g., Matachel fault) with down-thrown movement of their NE block, whereas that possibility is much less likely in the case of a primary NE-dipping geometry for the suture zone (forward modelling from (d) to (f)). Dip values and crosscutting relationships are not intended to reproduce those of the study case. The primary geometry of the suture zone is oversimplified (rather continuous and tabular-shaped) for clarity.

**Figure 2**: Zonation and major tectonic elements of the Iberian Massif after *Díez Fernández and Arenas* (2015). Abbreviations: AF — Azuaga Fault; BToIP — Basal Thrust of the Iberian Parautochthon; BAO — Beja–Acebuches Ophiolite; CA — Carvalhal Amphibolites; CF — Canaleja Fault; CMU — Cubito–Moura Unit; CO — Calzadilla Ophiolite; CU — Central Unit; EsT — Espiel Thrust; ET—Espina Thrust; HF— Hornachos Fault; IOMZO —Internal Ossa-Morena Zone Ophiolites; J–PCSZ — Juzbado-Penalva do Castelo Shear Zone; LFT — Lalín-Forcarei Thrust; LPSZ — Los Pedroches Shear Zone; LLSZ — Llanos Shear Zone; MLSZ — Malpica–Lamego Shear Zone; MF — Matachel Fault; OF — Onza Fault; OVD — Obejo–Valsequillo Domain; PG–CVD — Puente Génave–Castelo de Vide Detachment; PRSZ— Palas de Rei Shear Zone; PTSZ — Porto–Tomar Shear Zone; RF — Riás Fault; SISZ —South Iberian Shear Zone; VF — Viveiro Fault; ZSI — Zalamea de la Serena Imbricates.

**Figure 3**: Geological map of the Obejo-Valsequillo Domain (see location in Figure 2). Regional synthesis based on maps published by the Spanish Geological Survey (*Matas et al.*, 2015a, 2015b, and references therein), *Martínez Poyatos et al.* (2012), and our own

data. The Espiel thrust has been discriminated from the rest of the thrusts of the region due to its bearing on the geology of the study area and on the discussion presented in this work.

**Figure 4**: (a) Geological map and (b and c) cross-sections of the study area (see regional location in Figure 3). Names of main structures referred to in the text are indicated in cross-sections.

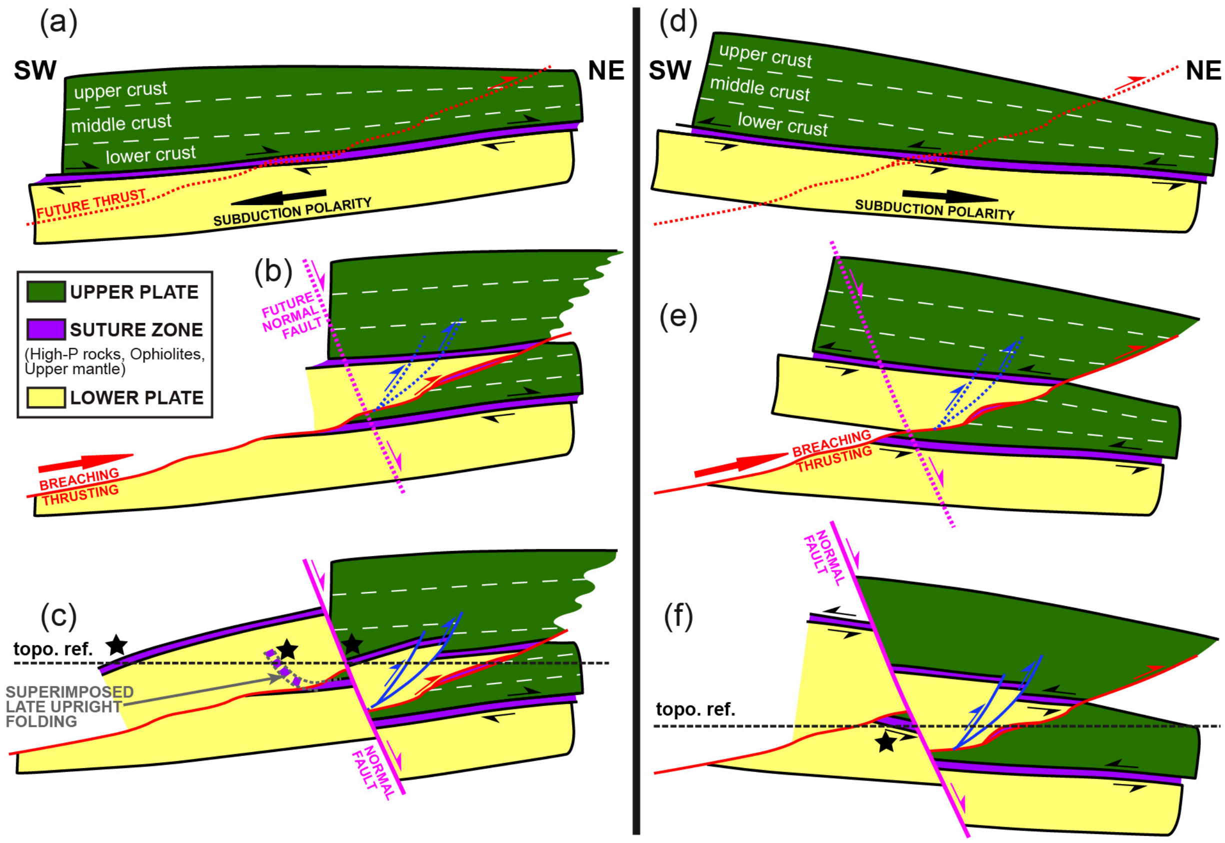
**Figure 5**: (a) Field exposure of the Porvenir serpentinites. Note their general massive aspect and spaced planar anisotropy ($S_n$). (b) Thin-section to the Porvenir serpentinites. Note olivine being replaced by serpentine and the presence of spinel. Olivine was the major constituent of this meta-peridotite, likely a serpentinized dunite. (c) Crosscutting relationship between bedding ($S_0$) and $S_1$ in the Azuaga Formation. (d) Phyllonites within the fault zone of the Espiel thrust. (e) S-C structures in phyllonites within the fault zone of the Espiel thrust (top-to-the-NE shear sense). (f) Porphyritic metagranitoid showing sigma structures defined by a quartz porphyroclast and a K-feldspar porphyroclast (undifferentiated metaigneous rocks) surrounded by mylonitic foliation ($S_2$) within the fault zone of the Espiel thrust (top-to-the-NE shear sense). The absence of lens-shaped, highly stretched layers rich in feldspar or quartz in these rocks suggest that most of the mylonitic foliation was likely developed at the expense of the ground mass of a porphyritic granitoid.

**Figure 6**: Pi-diagrams constructed for (a) bedding and (b) $S_1$. (c) Stereoplot showing the orientation of $D_1$ intersection lineation between $S_0$-$S_1$ ($Li_1$). (d) Pi-diagram for $S_2$ and

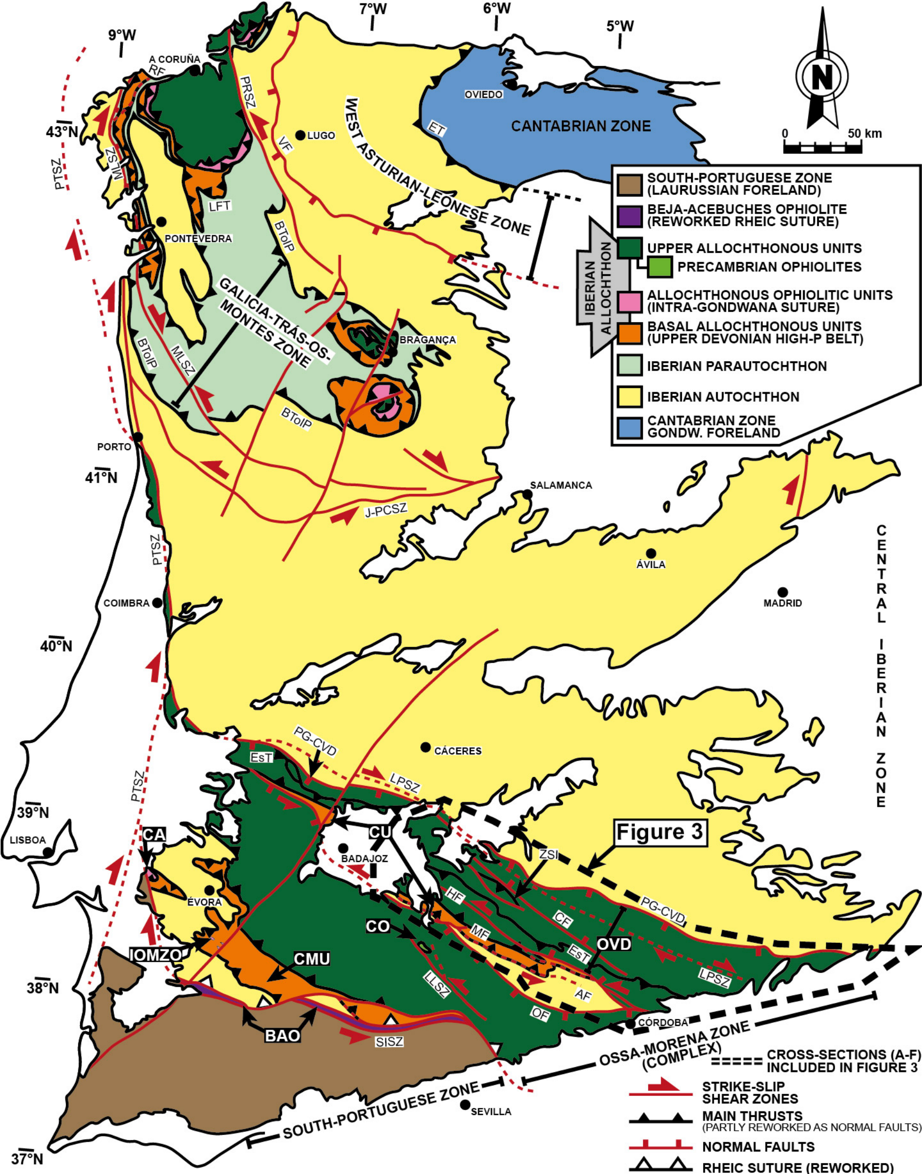
shear sense and orientation of $D_2$ slickensides. (e) Stereoplot showing the orientation of $D_3$ fold axes ($F_3$).

**Figure 7**: (a) Sigma (σ) and delta (δ) structures associated with $S_2$ (top-to-the-NE) in mylonites within the Espiel thrust. (b) Shape fabric defined by quartz subgrains (yellow line) oblique to $S_2$ (top-to-the-NE) in mylonites within the Espiel thrust. (c) Panoramic view of the Peñarroya antiform. Cambrian-Ordovician metasandstone layers show the local dip direction for each fold limb. Picture taken from Pueblonuevo village and looking to the NW. (d) $D_3$ minor upright folds affecting $S_1$ (Azuaga Formation). Note incipient $S_3$ crenulation cleavage. (e) $D_3$ upright folds affecting a mylonitic fabric ($S_2$) within the fault zone of the Espiel thrust. $S_2$ in this porphyritic metagranitoid includes sigma structures defined by K-feldspar porphyroclasts indicating top-to-the-NE shear sense.

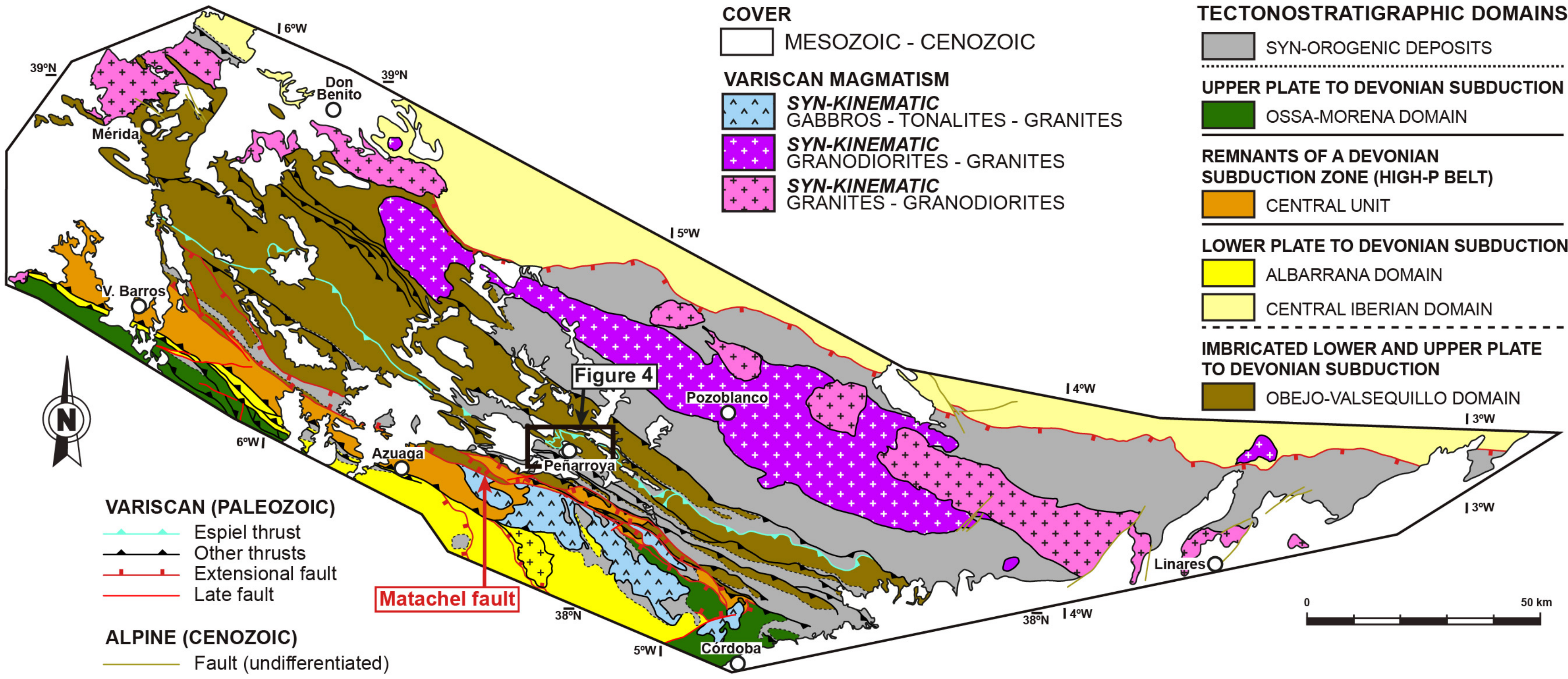
**Figure 8**: Tectonic model for the Variscan obduction of the Porvenir serpentinites. (a) Devonian subduction-accretion directed to the SW. (b) Early Carboniferous out-of-sequence thrusting directed to the NE. Note that erosion is required to conclude the exhumation process. The primary geometry of the units within the suture zone are oversimplified (rather continuous and tabular-shaped) for clarity.



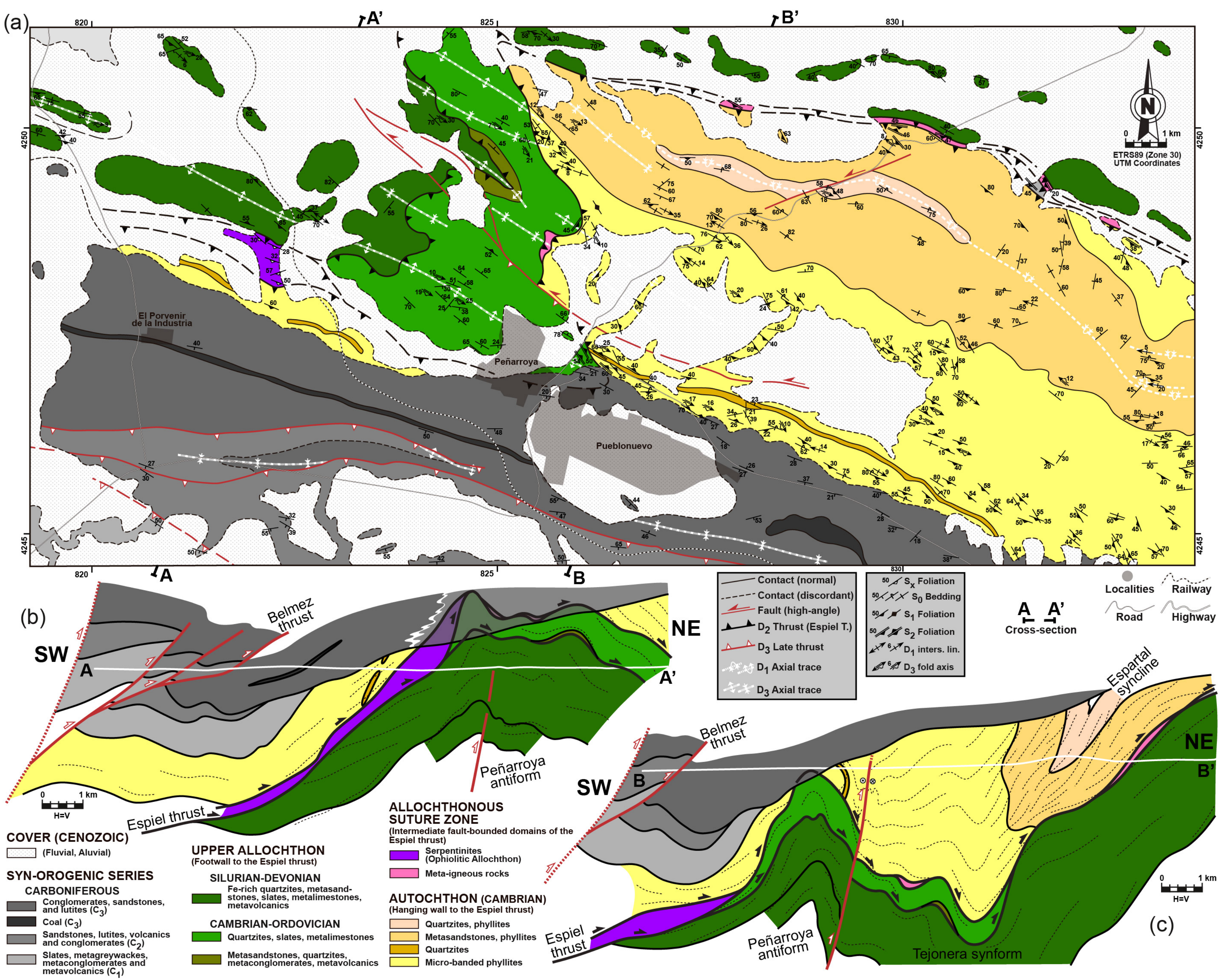
(a)
SW
NE
upper crust
middle crust
lower crust
FUTURE THRUST
SUBDUCTION POLARITY
(b)
FUTURE NORMAL FAULT
BREACHING THRUSTING
UPPER PLATE
SUTURE ZONE
(High-P rocks, Ophiolites, Upper mantle)
LOWER PLATE
(c)
topo. ref.
SUPERIMPOSED LATE UPRIGHT FOLDING
NORMAL FAULT
(d)
SW
NE
upper crust
middle crust
lower crust
SUBDUCTION POLARITY
(e)
BREACHING THRUSTING
(f)
NORMAL FAULT
topo. ref.



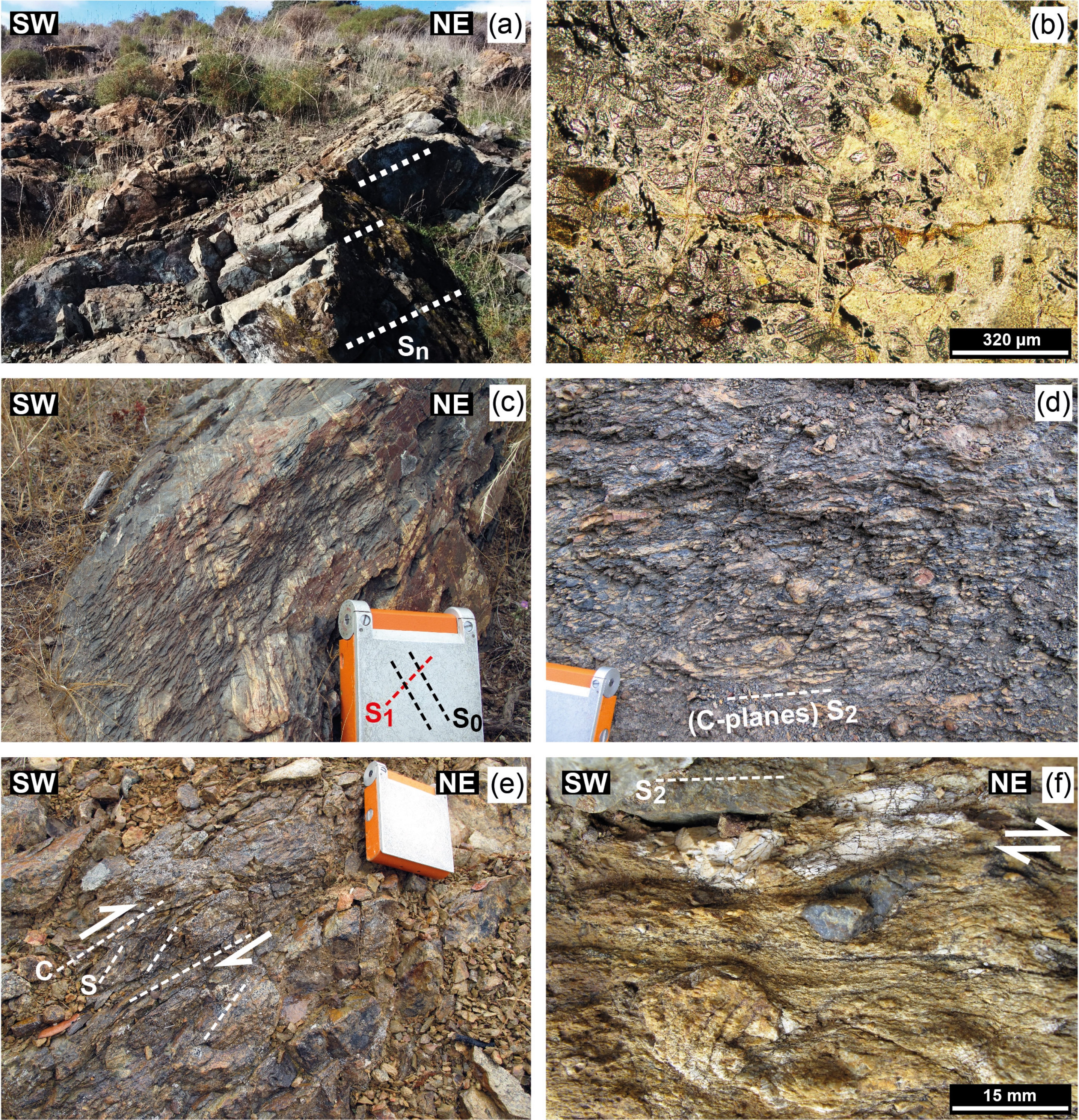
9°W
7°W
6°W
5°W
43°N
41°N
40°N
39°N
38°N
37°N
N
0
50 km
A CORUÑA
OVIEDO
LUGO
PONTEVEDRA
BRAGANÇA
PORTO
SALAMANCA
ÁVILA
MADRID
COIMBRA
CÁCERES
LISBOA
BADAJOZ
ÉVORA
CÓRDOBA
SEVILLA
CANTABRIAN ZONE
WEST ASTURIAN-LEONESE ZONE
GALICIA-TRÁS-OS-MONTES ZONE
CENTRAL IBERIAN ZONE
OSSA-MORENA ZONE (COMPLEX)
SOUTH-PORTUGUESE ZONE
RF
MLSZ
PTSZ
PRSZ
VF
ET
LFT
BToIP
J-PCSZ
PG-CVD
EsT
LPSZ
CA
CU
ZSI
HF
CF
MF
CO
OVD
IOMZO
CMU
LLSZ
AF
OF
BAO
SISZ
Figure 3
SOUTH-PORTUGUESE ZONE (LAURUSSIAN FORELAND)
BEJA-ACEBUCHES OPHIOLITE (REWORKED RHEIC SUTURE)
IBERIAN ALLOCHTHON
UPPER ALLOCHTHONOUS UNITS
PRECAMBRIAN OPHIOLITES
ALLOCHTHONOUS OPHIOLITIC UNITS (INTRA-GONDWANA SUTURE)
BASAL ALLOCHTHONOUS UNITS (UPPER DEVONIAN HIGH-P BELT)
IBERIAN PARAUTOCHTHON
IBERIAN AUTOCHTHON
CANTABRIAN ZONE GONDW. FORELAND
CROSS-SECTIONS (A-F) INCLUDED IN FIGURE 3
STRIKE-SLIP SHEAR ZONES
MAIN THRUSTS (PARTLY REWORKED AS NORMAL FAULTS)
NORMAL FAULTS
RHEIC SUTURE (REWORKED)



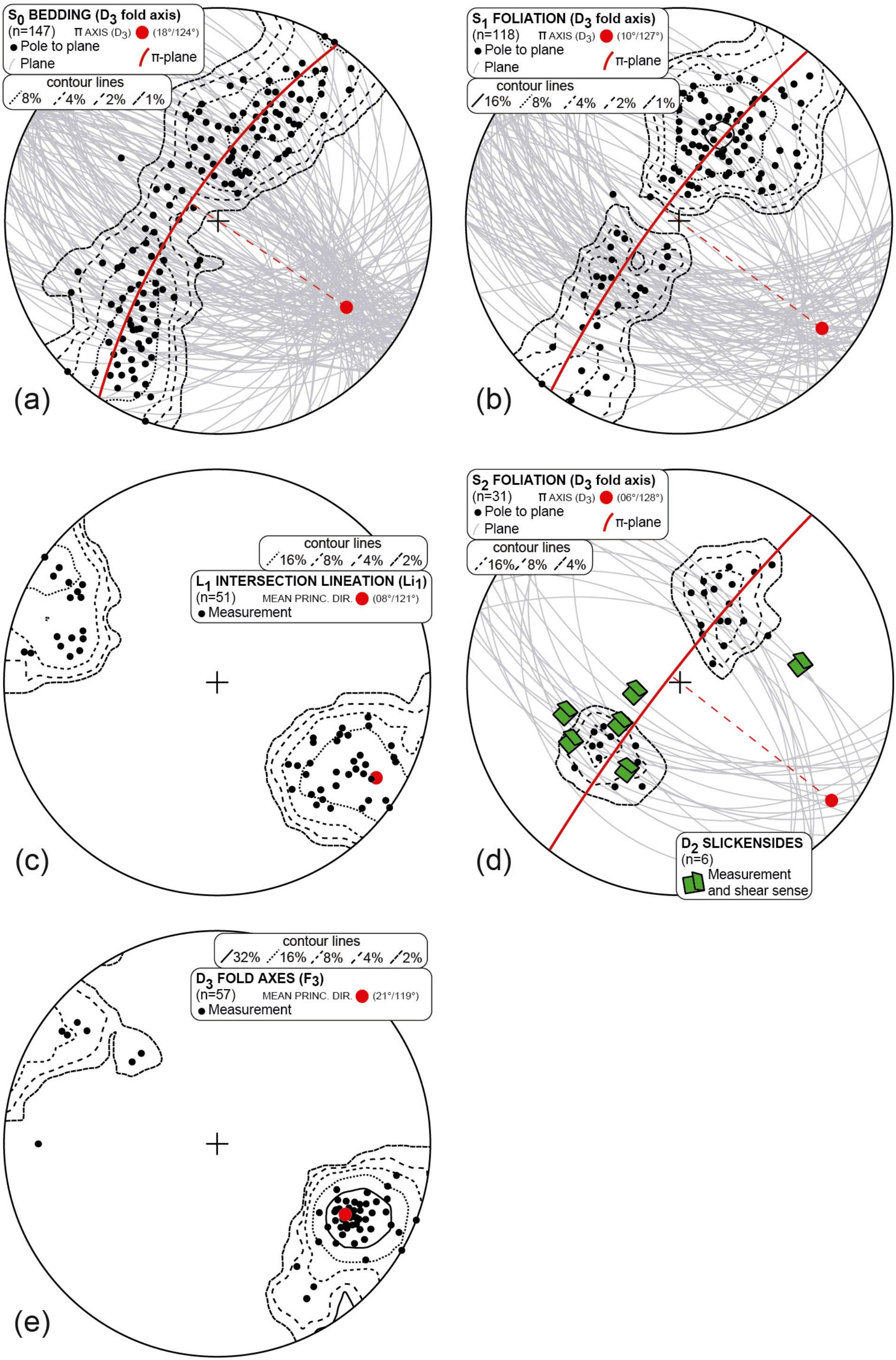
COVER
MESOZOIC - CENOZOIC
VARISCAN MAGMATISM
SYN-KINEMATIC GABBROS - TONALITES - GRANITES
SYN-KINEMATIC GRANODIORITES - GRANITES
SYN-KINEMATIC GRANITES - GRANODIORITES
TECTONOSTRATIGRAPHIC DOMAINS
SYN-OROGENIC DEPOSITS
UPPER PLATE TO DEVONIAN SUBDUCTION
OSSA-MORENA DOMAIN
REMNANTS OF A DEVONIAN SUBDUCTION ZONE (HIGH-P BELT)
CENTRAL UNIT
LOWER PLATE TO DEVONIAN SUBDUCTION
ALBARRANA DOMAIN
CENTRAL IBERIAN DOMAIN
IMBRICATED LOWER AND UPPER PLATE TO DEVONIAN SUBDUCTION
OBEJO-VALSEQUILLO DOMAIN
VARISCAN (PALEOZOIC)
Espiel thrust
Other thrusts
Extensional fault
Late fault
ALPINE (CENOZOIC)
Fault (undifferentiated)
Matachel fault
Figure 4
Mérida
Don Benito
V. Barros
Azuaga
Peñarroya
Pozoblanco
Córdoba
Linares
N
6ºW
5ºW
4ºW
3ºW
39ºN
38ºN
0
50 km



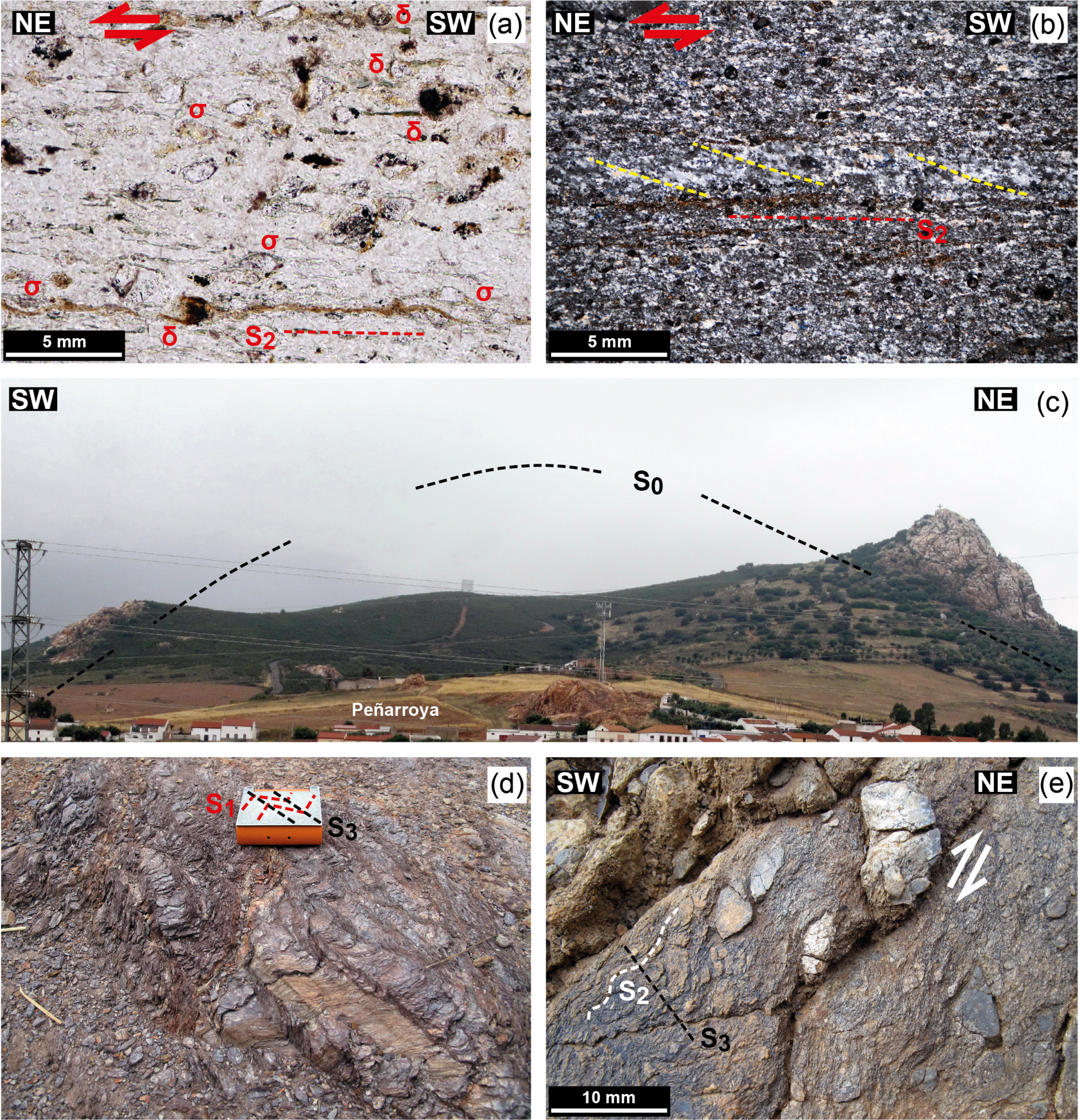
(a)
A'
B'
820
825
830
4250
4245
A
B
ETRS89 (Zone 30)
UTM Coordinates
0
1 km
N
El Porvenir
de la Industria
Peñarroya
Pueblonuevo
(b)
SW
NE
A
A'
Belmez
thrust
Espiel thrust
Peñarroya
antiform
0
1 km
H=V
(c)
SW
NE
B
B'
Belmez
thrust
Espartal
syncline
Espiel
thrust
Peñarroya
antiform
Tejonera synform
0
1 km
H=V
Contact (normal)
Contact (discordant)
Fault (high-angle)
D2 Thrust (Espiel T.)
D3 Late thrust
D1 Axial trace
D3 Axial trace
Sx Foliation
S0 Bedding
S1 Foliation
S2 Foliation
D1 inters. lin.
D3 fold axis
Localities
Railway
Road
Highway
Cross-section
COVER (CENOZOIC)
(Fluvial, Aluvial)
SYN-OROGENIC SERIES
CARBONIFEROUS
Conglomerates, sandstones, and lutites (C3)
Coal (C3)
Sandstones, lutites, volcanics and conglomerates (C2)
Slates, metagreywackes, metaconglomerates and metavolcanics (C1)
UPPER ALLOCHTHON
(Footwall to the Espiel thrust)
SILURIAN-DEVONIAN
Fe-rich quartzites, metasandstones, slates, metalimestones, metavolcanics
CAMBRIAN-ORDOVICIAN
Quartzites, slates, metalimestones
Metasandstones, quartzites, metaconglomerates, metavolcanics
ALLOCHTHONOUS
SUTURE ZONE
(Intermediate fault-bounded domains of the Espiel thrust)
Serpentinites
(Ophiolitic Allochthon)
Meta-igneous rocks
AUTOCHTHON (CAMBRIAN)
(Hanging wall to the Espiel thrust)
Quartzites, phyllites
Metasandstones, phyllites
Quartzites
Micro-banded phyllites



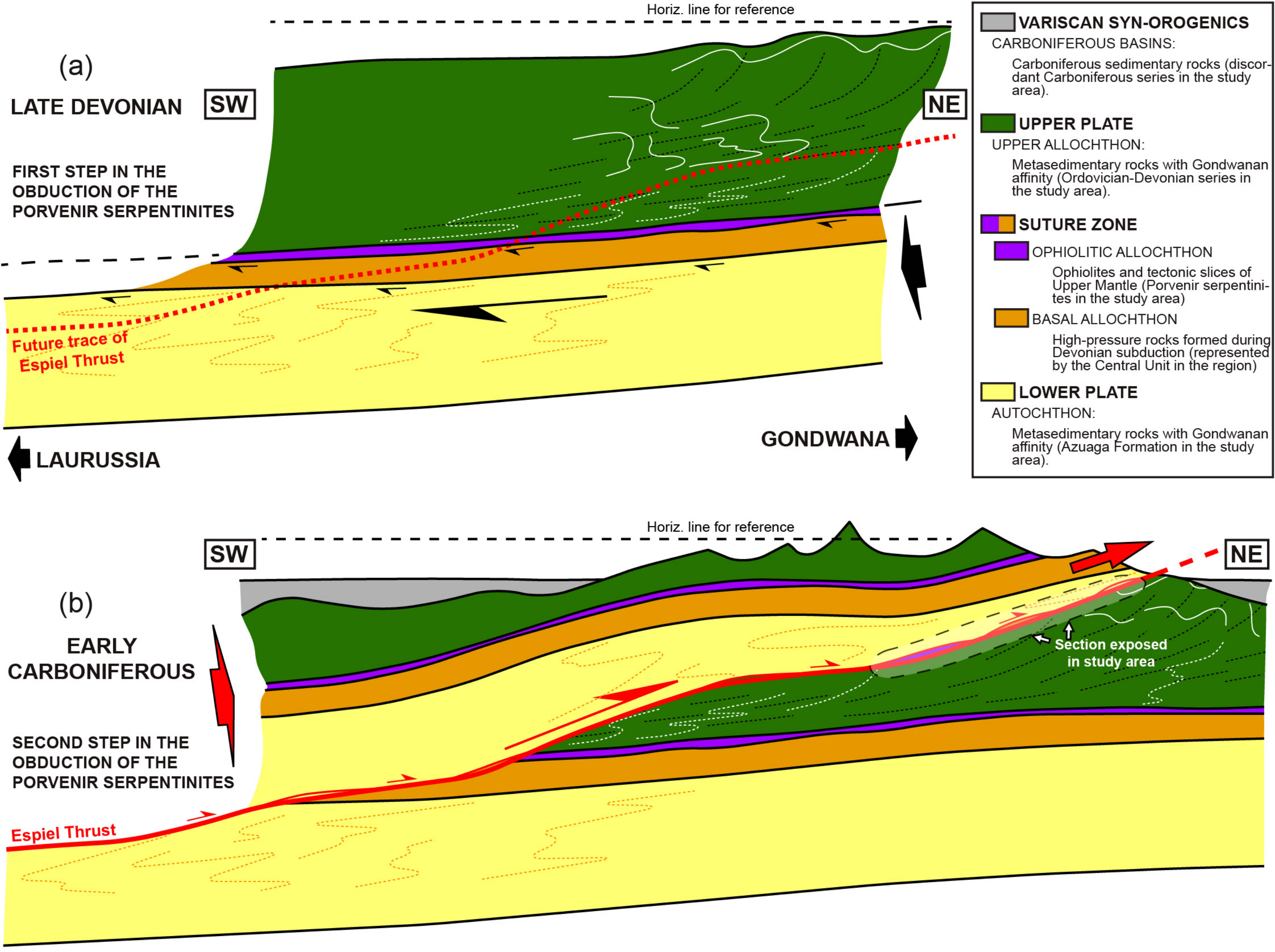
SW
NE
(a)
Sn
(b)
320 µm
SW
NE
(c)
S1
S0
(d)
(C-planes) S2
SW
NE
(e)
C
S
SW
S2
NE
(f)
15 mm



S0 BEDDING (D3 fold axis)
(n=147)
π AXIS (D3) (18°/124°)
Pole to plane
Plane
π-plane
contour lines
8% 4% 2% 1%
(a)
S1 FOLIATION (D3 fold axis)
(n=118)
π AXIS (D3) (10°/127°)
Pole to plane
Plane
π-plane
contour lines
16% 8% 4% 2% 1%
(b)
contour lines
16% 8% 4% 2%
L1 INTERSECTION LINEATION (Li1)
(n=51)
MEAN PRINC. DIR. (08°/121°)
Measurement
(c)
S2 FOLIATION (D3 fold axis)
(n=31)
π AXIS (D3) (06°/128°)
Pole to plane
Plane
π-plane
contour lines
16% 8% 4%
D2 SLICKENSIDES
(n=6)
Measurement and shear sense
(d)
contour lines
32% 16% 8% 4% 2%
D3 FOLD AXES (F3)
(n=57)
MEAN PRINC. DIR. (21°/119°)
Measurement
(e)



NE
SW
(a)
δ
σ
σ
σ
δ
δ
S2
5 mm
NE
SW
(b)
S2
5 mm
SW
NE
(c)
S0
Peñarroya
(d)
S1
S3
SW
NE
(e)
S2
S3
10 mm



Horiz. line for reference
(a)
LATE DEVONIAN
SW
NE
FIRST STEP IN THE
OBDUCTION OF THE
PORVENIR SERPENTINITES
Future trace of
Espiel Thrust
LAURUSSIA
GONDWANA
VARISCAN SYN-OROGENICS
CARBONIFEROUS BASINS:
Carboniferous sedimentary rocks (discordant Carboniferous series in the study area).
UPPER PLATE
UPPER ALLOCHTHON:
Metasedimentary rocks with Gondwanan affinity (Ordovician-Devonian series in the study area).
SUTURE ZONE
OPHIOLITIC ALLOCHTHON
Ophiolites and tectonic slices of Upper Mantle (Porvenir serpentinites in the study area)
BASAL ALLOCHTHON
High-pressure rocks formed during Devonian subduction (represented by the Central Unit in the region)
LOWER PLATE
AUTOCHTHON:
Metasedimentary rocks with Gondwanan affinity (Azuaga Formation in the study area).
Horiz. line for reference
(b)
SW
NE
EARLY
CARBONIFEROUS
SECOND STEP IN THE
OBDUCTION OF THE
PORVENIR SERPENTINITES
Espiel Thrust
Section exposed
in study area