Title: Folded Variscan thrusts in the Herrera Unit of the Iberian Range (NE Spain)

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Abstract: The Variscan structure of the Herrera Unit (Iberian Chain, NE Spain) is characterized by a system of NNW-SSE striking, E-verging, foreland-dipping thrusts, generated in a thin-skinned context, whose formation was favoured by the presence of two main detachment levels (Precambrian and Silurian shales). During the formation of the thrust system (first phase of deformation, D_1), the thrust sheets were deformed internally, mainly by asymmetric folds with axial surface cleavage and E-verging thrusts; the normal evolution of the thrust system and the emplacement of an underlying thrust sheet resulted in progressive tilting and stacking, thus generating a foreland-dipping thrust system. These structures were folded and tilted by the emplacement of the Datos thrust, generating an associated deformation characterized by sub-vertical folds with axial surface cleavage, with slight E-vergence. These structures can obliterate the previous D1 structures in the sector near the Datos thrust. D_1 and D_2 structures have

not been observed in the same outcrops, but the relationship between bedding and cleavage as well as their relationship with other structures allows discriminating between the two cleavage sets. Based on the features of Palaeozoic rocks of the Iberian Range and the Iberian Massif, we support the idea that the Herrera Unit belongs to the Cantabrian Zone.

Several examples in the literature cover the issues of folded thrusts and duplex structures from different points of view: structural analysis, cross-section reconstruction, numerical modelling, analytical modelling, etc (i.e. Boyer & Elliot 1982; Butler 1986; Banks & Warburton 1986; Alonso 1987, 1989a; Wilson & Schumaker 1992; Muñoz, 1992; Casas-Sainz & Cortés-Gracia 1996; Gutiérrez-Alonso 1996; Couzens-Schultz et al. 2003 and references therein). Couzens-Schultz et al. (2003) carried out several analogue models in order to find the parameters that control the duplex formation and geometry; these authors conclude that both the strength of the detachment and the shortening rate appear to play a significant role in duplex evolution.

The Iberian Variscan belt provides several examples of duplex structures and folded imbricate thrust systems, mostly located in the fold-and-thrust belt of the Cantabrian Zone (CZ) and its contact with the slate belt (Western Asturian-Leonese Zone, WALZ) in its hinterland. Structures of this kind are not well known in areas separated from the main outcrops of Palaeozoic rocks in the Iberian Peninsula (Pyrenees, Catalan Coastal Ranges and Iberian Chain), probably due to the limited extension of the outcrops of Variscan rocks (see e.g. García-Sansegundo, 2011) complicating the interpretation of these structures, especially in the absence of a clear regional structural framework. Nevertheless, in the Variscan units of the Iberian Chain the folded-imbricate thrust model may be of key importance to understand and interpret its overall structure. In the Herrera Unit of Iberian Range, the Palaeozoic series lies uncomformably on Precambrian shales (Alvaro et al. 2008) which are the regional detachment level for the Variscan belt in this area. The Palaeozoic series consists mainly of alternating shales and sandstones with interbedded carbonates, including a 1000 thick shaly unit of Silurian age. The mechanical stratigraphy is suitable for the development of multiple detachment levels and the formation of duplex systems.

The interest for the study of this area is twofold: on the one hand, thrusts develop together with two cleavage systems what allow for detailed studies of kinematics of structures and determine thrust-cleavage relationships. On the other hand, an imbricate, foreland dipping thrust system has been recognized in this sector, allowing for insights into the geometry and kinematics in thick sedimentary sequences. Secondarily, an improved characterization of the Variscan structure of the Iberian Chain may facilitate its correlation with the Iberian Massif. Geological mapping and structural analysis, mainly considering bedding and cleavage relations, a study on the vergence of the structures and specially the integration of all these data into geological cross-sections, have allowed us to reconstruct the structure of the Herrera Unit and establish the existence of refolded thrusts and two main phases of deformation during the Variscan evolution of the area.

Geological setting

The Aragonese Branch of the Iberian Range (NE Spain) constitutes a NW-SE alignment of structures generated during the Alpine intraplate deformation of the Iberian Peninsula (Casas et al., 2000). The core for this region is formed by Precambrian and Palaeozoic rocks, deformed during the Variscan Orogeny according to NW-SE and NNW-SSE structural trends

The relationship between this region and other Palaeozoic outcrops (i.e. the Iberian Massif, W Spain) is difficult to establish because the areas in-between are covered with Mesozoic and Tertiary rocks. Julivert & Martínez (1983), Tejero & Capote (1987) and Alvaro (1991) support that the entire Iberian Range is included in the WALZ. On the other hand, Gonzalo & Liñán (1988) proposed, according to tectonostratigraphic criteria, that the limit between the CZ and the WALZ is located in the N of Iberian Range, materialized by the Datos or Jarque thrusts, first order structures with NW-SE direction and NE vergence (Fig. 1a), separating the Badules unit (to the West) and the Herrera unit (to the East).

The study area is located in the northern edge of Iberian Range, within the Herrera Unit (Fig. 1b). This unit constitutes the NE limb of a kilometre-scale Variscan major anticline, with a predominant NW-SE to NNW-SSE trend and NE vergence. This anticline is associated with the Datos thrust, that cuts across its core and superimposes Cambrian-Ordovician rocks of the Badules unit onto the Upper Cambrian-Devonian rocks of the Herrera Unit. In the core to the anticline there are Upper Proterozoic-Cambrian slates, which constitute the lower regional detachment level. Classically, the Variscan structure of the Herrera Unit is considered to result from a polyphase deformation (Tejero, 1987; Tejero & Capote, 1987), characterized by a set of kilometre-scale, E-verging folds later affected by an E-directed thrust system associated with the Datos thrust.

A more than 9000 m thick series characterizes the stratigraphic succession of the Herrera Unit (Fig. 2). The lower level, Upper Cambrian-Silurian, is formed by alternating, hectometre-thick sandstone and shale packages, topped by a shale unit approximately 1000 m thick. The upper level, Upper Silurian-Devonian, is composed by shales, sandstones and carbonates.

All these pre-Variscan rocks are uncomformably covered by a Lower Permian volcanoclastic and detrital succession, and by Lower Triassic (Buntsandstein facies) conglomerates and sandstones (Lago et al. 2004), overlain by Mesozoic and Tertiary units. The Permian unit is restricted to the Fombuena graben, limited by N-S normal faults. All in all, the Permian to Tertiary sequences reach maximum thickness of about 2000 m (Cortés-Gracia & Casas-Sainz, 1996).

Description of the structure

Macrostructure

The macrostructure represented in the geological map (Fig. 3) shows three main sectors according to their cartographic and structural features (Fig. 1c), consistent with a NNW-SSE structural trend (Fig. 4). The northern sector is characterized by repetitions of the stratigraphic series by NNW-SSE striking, E-dipping thrusts. Bedding shows in general steep dips to the E, and overturned, W dips in the western sector. The units involved in this system are Cambrian to Silurian in age. Between the localities of Aladrén and Cerveruela the series is apparently parallel to the thrust surfaces and only two cambro-ordovician units consisting of sandstone and shales are involved. Most thrust of this system abut against an E-W fault (that can be interpreted as a tear fault) limiting this sector to the S.

South of it, the Cambrian units disappear and the Silurian shales crop out extensively. In this sector (central sector in Fig. 1c), a hanging wall ramp, with younger rocks towards the S, can be observed. To the E, the tip line for each thrust is shifted northwards with respect to the thrust sheet below, except for the easternmost sheet, that reaches more southern position than the previous sheets and could cut the Devonian rocks. In the central sector the Silurian rocks are folded with a subhorizontal envelope, allowing for extensive outcrops.

In the southern sector younger rocks (Silurian to Devonian) crop out extensively, affected by an E-verging thrust-and-fold system, with shallow dips to the W, favoring the presence of klippes with Devonian rocks in their hanging walls. The most representative structures are two synclines, trending NNW-SSE in the North and NW-SE in the South, becoming subparallel to the Datos thrust. In this sector klippes of Cambrian rocks associated with the Datos thrust that limits the study area to the West and South can be observed. The Datos thrust strikes WNW-ESE in the S, dipping 30º to the South, progressively changing to a NNW-SSE strike and steep dips to the North

The palaeozoic rocks are surrounded by outcrops of Mesozoic rocks, folded in WNW-ESE direction, and unconformably covering the Datos thrust. To the South, they show similar dips to the Cambrian units. In the northern sector, Mesozoic units with NE dip lie unconformably the Ordovician-Silurian rocks. Only in the northern and southern limits of the studied area the Paleozoic rocks show a similar attitude to Mesozoic rocks.

Mesostructure

The most visible structures at outcrop scale are folds, minor thrust and two sets of cleavage, related to thrusts and folds (Fig. 5). Cleavage surfaces show different attitudes depending on their relationships with tectonic structures, and can be ascribed to three main families.

The best developed set of structures in the study area is an E-verging system of thrusts and asymmetric, cleavage-related folds. The folds (F_1) are asymmetric (Z-shape) and have an eastward vergence (Fig 6a), with shallow dipping axial surfaces (15º E to 20º W), locally leading to formation of synformal anticlines (Figs 6a-c). They can either associate with thrusts or appear as decametric-scale trains of folds. The associated foliation (S_1) is a slaty cleavage in shales and rough cleavage in sandstones, with shallow dips both to the E and W. A pervasive S_0/S_1 intersection lineation (L_{int-1}), parallel to F_1 axes (and also to axes of F_2 and L_{int-2} see below) can be observed.

Throughout the study area, but mainly in the overturned limb of the large anticline related to the Datos thrust there are NNW-SSE trending, upright to overturned, tight folds (F_2) with associated axial surface cleavage (S_2). These structures are developed preferably in shales, masking previous structures. S_2 is a slaty cleavage, dipping steeply (60-90º) both to W (dominant) and E. The folds are asymmetric (S-shape) and sub-vertical, with slight E-vergence. Cleavage can obliterate the stratification, recognizable only from subtle changes in lithology (Fig. 6d). As it occurs with F_1, the fold axes and the intersection lineation (S_0-S_1) show NNW-SSE trends and shallow plunge both to N and S (Fig. 6).

Finally, back-thrusts and brittle shear zones (Fig. 6e) with shallow dips (20-30º) deform the previously described structures. Locally, these structures can appear folded and tilted because of late deformation, of probable Alpine age.

Apart from indirect correlation according to orientation and relationship with other structures, in the study area it is difficult to define the relationships between S_1 and S_2, because they do not appear together in the same outcrops. S_1 can be seen in alternating sandstone-shale sequences, far from the Datos thrust, where S_2 is less visible. On the contrary, S_2 appears mainly in shaly series near the Datos thrust, probably obliterating previous structures.

Interpretation

The Herrera unit can be interpreted as to have a thin-skinned deformation style, in which the Precambrian-Cambrian shales would constitute the regional detachment level; these rocks can be observed in small outcrops along the trace of Datos thrust (Fig. 1b), although they are absent in the study area. Other shaly levels within the Cambro-Silurian sequence may form minor detachment levels, strongly conditioning the structure. The most important is constituted by the Silurian shales, located approximately in the middle of the pre-tectonic sequence, accommodating the deformation in two ways: (i) as a partial roof décollement, especially in the northern sector, of the thrust detached in the precambrian-ordovician shales (Fig. 7a, b) and (ii) as the floor décollement for the thrusts affecting the Devonian rocks (Fig. 7c). For this reason, we divided the stratigraphic series in a Lower Structural Level (LSL), constituted by Cambro-Silurian rocks, and an Upper Structural Level (USL), formed mainly by Devonian rocks. The Carboniferous, syn-tectonic sequence, with structural features similar to the USL, only crops out in the Montalbán anticline, South of the study area (Ferreiro et al. 1991),

The interpretation of the structure of the LSL is shown in cross-sections A-A´ and B-B´-B’’ (Fig. 4a, b). In the cross-sections, E-dipping thrusts with eastwards transport direction are interpreted, according with the minor folds and thrusts and the cross-cutting relationships (hanging wall and footwall cutoffs). Beds show steeper dips than thrusts, indicating the existence of hanging wall low-angle ramps. The apparent parallelism between the thrusts and the beds in their foot walls suggest the presence of flats except in the easternmost thrust, where a foot wall ramp can be interpreted.

Towards the S, the thrusts cut progressively younger units in their hanging walls and cannot be followed to the S, where extensive outcrops of Silurian shales can be found. We can interpret that the upper part of the Silurian shales partly constituted a roof décollement, thus forming a duplex system. However, the geometry of the easternmost thrust, cutting across the Devonian rocks, indicates that the geometry did not exactly correspond to a duplex system, and that there was probably an early, pre-thrusting stage of folding involving the Silurian and Devonian rocks.

Comparing cross-sections A-A' and B-B’-B" (Fig. 7) and considering the geological map (Fig. 3) a decrease in the number of thrusts to the S can be observed, coinciding with the location of the Cerveruela fault (Fig. 1c). This supports the hypothesis that the Cerveruela fault could be a tear fault, and the central thrust of the northern sector may be a complexity of the structure, forming a small duplex system favoured by décollements in the shale levels.

Towards the South the structure is simpler (Fig. 7c) and only a fold and thrust system with E vergence and shallow dips (consistent with the existence of klippes) can be observed.

The relationships between the northern-central sector and the southern sector are shown in Fig. 8. The Herrera Thrust System in the North cuts progressively younger beds towards the S by means of oblique ramps, so that in the southern sector it is located above the present-day topographic surface, cutting a Silurian-Devonian thrust and fold system. At the same time, the ramps of each hanging wall represent the boundary of each thrust towards the foreland (to E), and also probably represent their lateral termination thereof.

Finally, the Datos thrust, with along-strike dip changes, and steepening in a northward direction, cuts from the W the system described above. The similar dip between the hanging wall of the Datos thrust and the overlying, unconformable mesozoic beds in the southernmost sector of the studied area, indicate a subhorizontal original dip in this area, consistent with the existence of klippes of Cambrian rocks present in this sector. These changes of dip are consistent with a NNW-SSE large anticline (Fig. 8); a plunge of nearly 30º towards the south of the whole structure allow to observe a steep limb in the Northern and central sectors (Fig. 7a, b), with straight NNW-SSE trace (Fig. 3), whereas in the southern sector the hinge of this structure (Fig. 7c), with shallow S dipping and irregular, WNW-ESE trace can be observed (Fig. 3).

The original variscan structure apparently does not show major changes due to Alpine Orogeny. Only in the N and S limits of the studied area palaeozoic beds are folded according to the E-W trend, typical of Tertiary compressional deformation in this area (Cortés-Gracia & Casas-Sainz, 1996), can be observed. In the central sector, scattering of bedding poles from a cylindrical fit along a girdle defined by a NNW-SSE fold (Fig. 4) can be indicative of limited rotation and folding of variscan structures in a later compressive stage, probably during the Tertiary compression.

Tectonic evolution

The structure of the Herrera unit in the studied area can be interpreted as the result of three stages of deformation, probably some of them overlapping in time in different areas, but that can be each considered as responsible for complete series of structures with consistent vergence and structural style. D_1 structures are related to the formation of the E-verging thrust system involving the Cambro-Ordovician series and folding observed in the Devonian rocks. Folds (F_1), and associated S_1 formed simultaneously during the emplacement of the successive sheets of this thrust system.

The emplacement of underlying thrust sheets (Fig. 9a-b) resulted in progressive tilting and stacking, thus generating a foreland-dipping thrust system. This kind of imbricate structure appears when the distance between ramps is lower than the displacement on each thrust (Butler 1987). The sequence of emplacement cannot be totally defined, because of the absence of chronological criteria. Butler (1987) suggests that the formation of this type of tectonic stacking develops more easily in a piggy-back thrust sequence. According to observations, a piggy-back thrust system is more compatible with the structure; the first thrust sheet emplaced may be the easternmost, favouring its cutting across Devonian folds. The later locations of the other sheets generate progressive tilting in the other sheets, with steeper dips to the foreland to the E.

D_2 structures are concentrated mainly around the Datos thrust. They show steep dips and are consistent with large-scale eastward-verging folds, in agreement with the major structure (Fig. 9c). The cross-cutting relations between S_0-S_2 are consistent with the large antiform associated with the Datos thrust, and the intensity of deformation decreases with the distance to this fault, showing the relationship between these structures and the formation of the Datos thrust. However, the Datos thrust is also folded for this stage, indicating that a possible early location of this structure in relation with this deformation stage.

Late structures (D3) are scarce in the study area and do not seem related to any regional-scale tectonic process. Most of them are brittle structures, indicative of the transition to surface conditions, therefore allowing interpreting that much of the tectonic stack was eroded. This could happen either during the later stages of the Variscan orogeny (i.e. Permian) or during the Tertiary compressional stage, but up to date there are no clear criteria to bracket them within a particular period.

Discussion

In summary, the structure of this sector of the Herrera unit is characterized by a foreland-dipping imbricate thrust system affecting the Cambrian-Silurian series. The Silurian shales lie on a large hanging wall flat, that could possibly define a roof thrust for a foreland duplex system. Although because of the erosion level this hypothesis cannot be fully confirmed there are several evidences that support it:

- Large outcrops of the Silurian shales, with folds showing a subhorizontal envelope, can be interpreted as a footwall flat.
- Different structural attitudes between Cambrian-Silurian and Silurian-Devonian series may indicate that the Silurian shales define a level of channelling of

deformation, generating a disharmonic structure between series located below and above this level.

- Only the westernmost thrust cuts across Devonian rocks, and specifically the core of a syncline. This appears to show that this fold probably formed during the early emplacement of this thrust. Although difficult to interpret from outcrop observations, this kind of structures has been reproduced in analogue models with several detachment levels (Bonini, 2001).

- The shallow westwards dip of thrusts in the southern sector of the studied area, generating small klippes is more coherent with an upper detachment in the Silurian shales.

The origin of the forelandward dip of the northern thrusts can be due to two different processes: the own dynamic of the stacking of thrust sheets (Butler, 1987) or a later folding. The study area appears to be according whit the addition of the two processes; (i) the significant difference in dip between the thrust system (steep dips to the E) and the folds involving the Devonian thrust and fold system (shallow dips to the W) is more consistent with the first hypothesis, because a later folding should have affected the entire system but (ii) a post-thrust folding has also been recognized, and is the responsible for the folding that affect the Datos thrust and increases the eastwards dips of the thrust system, The different attitude between the northern and southern sectors implies an important difference in shortening between the two sectors. In the northern sector several thrust sheets appear, accommodating a significant shortening but towards the S these thrust sheets finish show oblique ramps, indicating a lower amount of shortening in this direction. In the southern sector, it could possible for deformation to be accommodated by other structures towards the foreland, but the limited extent of outcrops do not allow for detailed observations to confirm this hypothesis.

The deformation phases proposed in this paper for the Iberian Chain contrast with the tectonic scenario proposed by other authors, probably because of the different scale of the interpreted structures. Tejero & Capote (1987), from structural analysis in the sector located to the NW of the area covered by us, interpreted three phases of deformation. The first phase was characterized by NW-SE trending, E-verging hectometric folds, with axial surface cleavage. During the second phase thrust and fault developed, affecting mainly the overturned limbs of folds; the Datos thrust developed during this stage. Finally, the third phase is characterized by oblique folds (N 145º - N 100 º) unequally distributed over the unit with associated crenulation cleavage; in the study area, these late structures have not been recognized.

Vílchez (1986) also proposed three deformation phases for the Herrera unit. During the first stage, local, oblique folds (NE-SW) with SE-vergence, and associated axial surface cleavage, developed. However, we did not recognize these structures in the area studied by us. The second phase, according to this author, is the most important, and is characterized by E-verging, NNW-SSE trending folds with associated cleavage. These structures correspond to the folds generated during D_1 and D_2 phases proposed in this paper. Finally, during the third stage recognized by Vílchez (1986), thrusts (e. g. the Datos thrust) and back-thrust were generated; these back-thrusts correspond to the folded thrust proposed by us. A similar deformation pattern was defined by Cardellach et al. (1988).

Relationship with other areas of the Variscan Orogen

The relationship between Palaeozoic rocks of the Iberian Range and other areas of the Iberian Variscan Orogen has been a controversial matter. Different interpretations arise from the fact that the intermediate structural features of Herrera Unit between the CZ and the WALZ, the important thickness of Cambro-Ordovician series and the lack of metamorphic facies do not allow correlating the area directly with one or another domain. Julivert & Martínez (1983) considered all the variscan rocks of the Iberian Range as belonging to the WALZ. Conversely, Gozalo & Liñán (1988) and Gutiérrez-Alonso (2004) propose the continuity of the Narcea antiform to the Precambrian rocks of the Iberian Chain. Accordingly, the Herrera Unit would be a part of Cantabrian Zone (CZ) and the Badules Unit would then belong to the WALZ.

The structural style of the Herrera Unit is similar to the CZ, characterized by thin-skinned tectonics and weak internal deformation; thrusts and fault-related folds are the main structures (Aller *et al.* 2004), with several duplex system in its western sector (Alonso 1987, 1989 a, b; Gutiérrez-Alonso *et al.* 1990; Aller *et al.* 2004). The tectonic style of the Herrera unit is similar, in spite of the existence of a pervasive cleavage set.

In their comparison between Palaeozoic rocks of the Pyrenean area and the Iberian Massif, García-Sansegundo *et al.* (2011) concluded that the most deformed domains, affected by two cleavage families and metamorphism, correspond with the hinterland of the Variscan orogen (WALZ or Ollo de Sapo Domain) whereas the less deformed domain, characterized by thrust and thrust-related folds with axial surface cleavage corresponds with the foreland to the Variscan orogen. The change of vergence and structural style, however, makes difficult its correlation with the structural features found in the Herrera unit.

We interpret that a thrust system, with a foreland-dipping duplex geometry, can be interpreted to explain the structure of the Herrera Unit. Associated with the different deformation events two cleavages can be distinguished. Therefore, the Herrera Unit shows intermediate characteristics between the WALZ and the CZ. Nevertheless, significant variation in the degree of deformation, to either side of the Precambrian outcrops, has not been observed (Tejero & Capote 1987), in the way occurring at the boundary between the WALZ and the CZ. We propose that the Precambrian outcrops of the Iberian Chain, and more specifically the Datos thrust, may be the boundary between the WALZ and the CZ (that would include then the Herrera Unit) in the Iberian Range and that these Precambrian outcrops are equivalent to the core of the Narcea Antiform (Gozalo & Liñán 1988; Gutiérrez-Alonso 2004). However, the shortening accumulated by the Datos thrust (at least in the area cropping out at present) would be much lower than in the Narcea Antiform, thus separating tectonics domains showing smaller differences than in the Iberian Massif. .

Conclusions

The structure of the Herrera Unit is characterized by an imbricate thrust system with a foreland-dipping geometry. Some of these structures can be interpreted as a duplex system, whose formation was favoured by the presence of several detachment levels: the lower one (floor detachment) is probably constituted by Precambrian shales, the oldest rocks cropping out in the Iberian Range, or the base of the Cambrian sequence . The upper level (roof detachment) is constituted by Silurian shales which are about 1000 m thick; and constitute a preferential level of the deformation, generating a disharmonic structure between series located below and above.

The degree of deformation in the lowermost structural unit (Cambrian-Silurian) is higher than in the upper structural unit (Silurian-Devonian) and the superimposed generations of structures are better represented in the first one. The upper unit is characterized by an E-verging fold-and-thrust system with axial surface cleavage.

Based on the deformation style and S_0-S_x relations, structures related with two main stages of deformation can be distinguished: D_1 is associated with thrust emplacement; D_2 by the emplacement of the Datos thrust and wholesale folding. The tilting to the foreland of the duplex system was generated due to the very dynamic of the thrust system (D_1), developed in a piggy-back sequence and for the later folding associated with the emplacement of the Datos thrust (D_2). During D_1 horizontal, simple shear with top-to-the-East sense of movement was dominant, generating originally westwards, shallow-dipping structures, whereas during D_2, parallel bed folding, with the subsequent formation of upright to overturned folds and related axial surface cleavage.

The thrust and fold system in the Herrera Unit may be correlated with the CZ of the Iberian Massif according to its structural features. However, due to the important thickness of its Cambro-Ordovician series in the Herrera unit shows it has been traditionally included in the WALZ. We interpret that the NW-SE antiform associated to Datos and Jarque faults can be correlated with Narcea Antiform of the Iberian massif, considering in this way this antiform the boundary between the WALZ (towards the SW) and the CZ (towards the NE)

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Figure captions

Fig. 1.- (a) Pre-Variscan outcrops of the Iberian Peninsula showing their main tectonostratigraphic subdivisions: SPZ: South Portugese Zone, OMZ: Ossa-Morena Zone, CIZ: Central Iberian Zone, WALZ: West Asturian-Leonese Zone, CZ: Cantabrian Zone; red box shown in Fig. 1b. (b) Simplified geological map of the Aragonese Branch of the Iberian Chain; red box shown in Fig. 1c. (c) Structural sketch of the study area showing their main structures and sectors.

Fig. 2.- Synthetic palaeozoic stratigraphic profile of the Herrera Unit.

Fig. 3.- Geological map of the study area showing the cross-section and location of the main outcrops,(a) to (e), appearing in Fig. 7.

Fig. 4.- Stereoplot (Schmidt net, lower hemisphere) of bedding planes recorded throughout the study area; these are consistent with a NNW-SSE folding.

Fig. 5.- Stereoplot (Schmidt net, lower hemisphere) of the orientation of the main structural features recognized in the lower structural level (Upper Cambrian-Silurian).

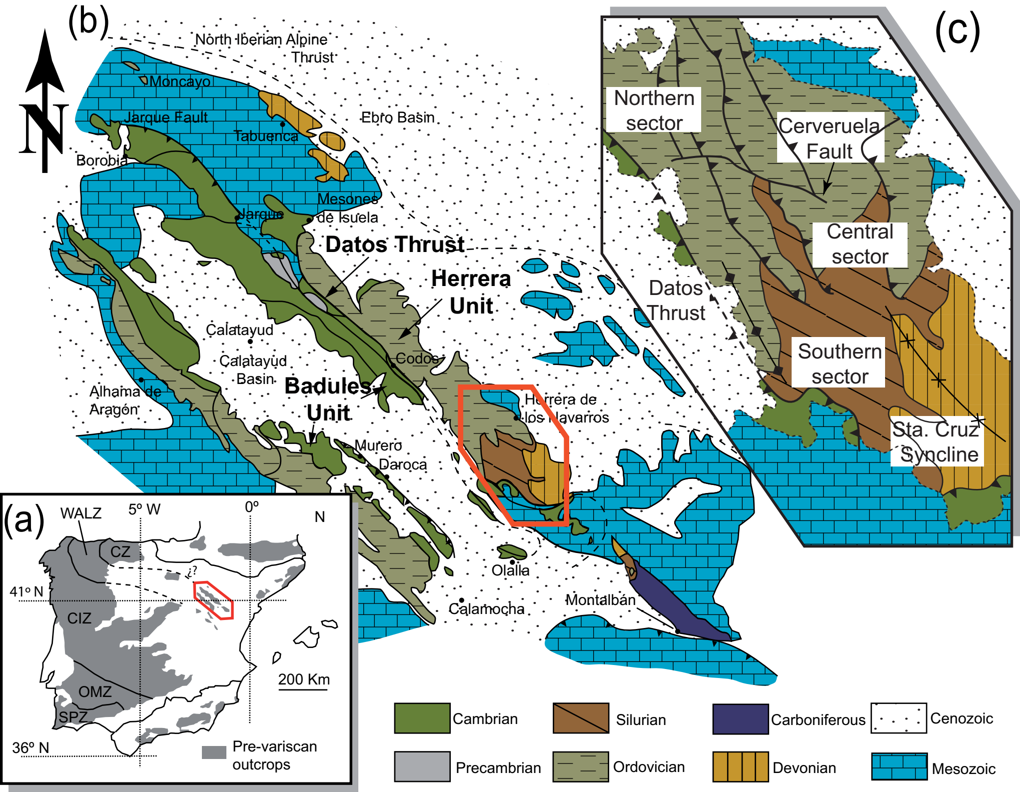
Fig. 6.- Structural features of selected outcrops relevant for the interpretation proposed; UTM coordinates are shown, and their location is also shown in fig. 3. (a) NNW-SSE E-verging, thrust-related fold, with axial surface cleavage (S_1). (b) Early structure similar to Fig. 7a, subsequently tilted to the E, showing a current dip towards the E. (c) Early thrust with associated drag fold, consistent with E-verging structures; as in Fig. 7b, it has been subsequently tilted towards the E. (d) Overturned, E-verging folds, with axial surface cleavage. (e) Back-thrust in Ordovician sandstones; note the brittle component of these structures that cut across beds formed during the main stages.

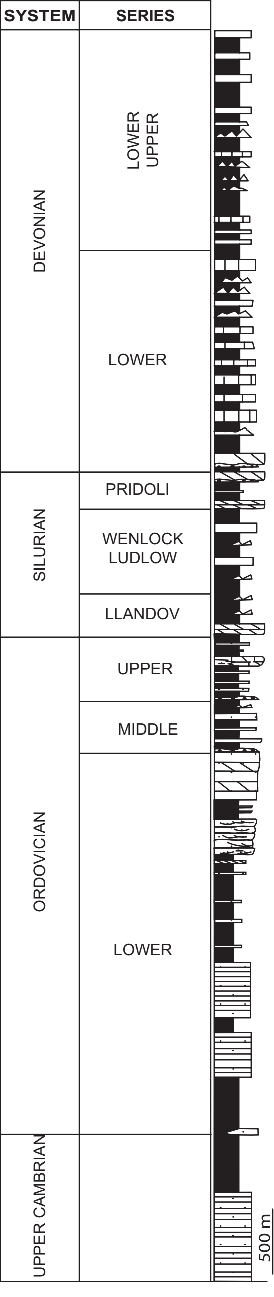
Fig. 7.- Geological cross-sections showing the main structural features of the study area.

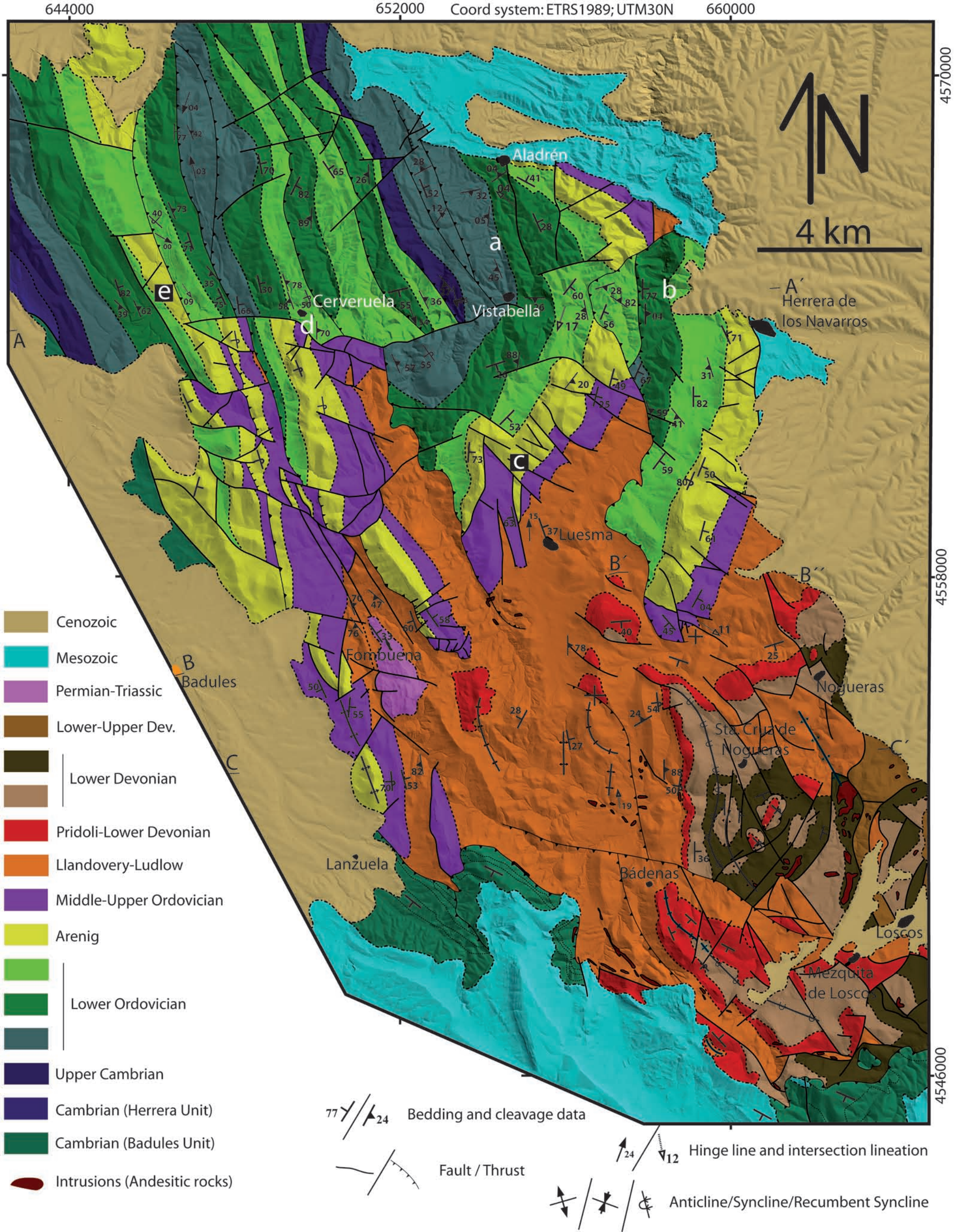
Location of the cross-sections is shown in Fig. 3.

Fig. 8.- 3D model shows the attitudes of the study area and the relationship between the

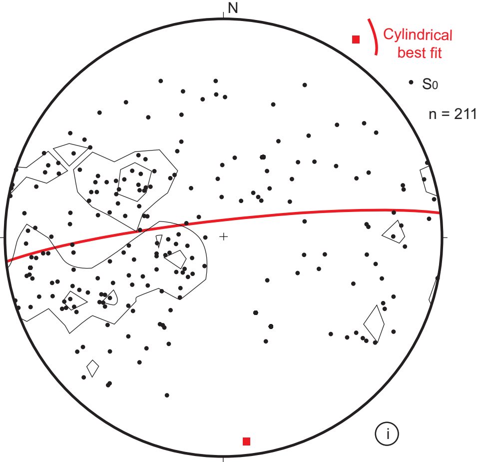
Fig. 9.- Evolutionary model of the main structure of North of study area. (a) Formation of the first thrust and related structures (F_1 and S_1), E-vergence. (b) Evolution of the duplex system, progressive tilting and stacking and formation of foreland-dipping duplex. (c) Formation of the out of sequence Datos thrust and folding with generation of axial surface cleavage (S_2).

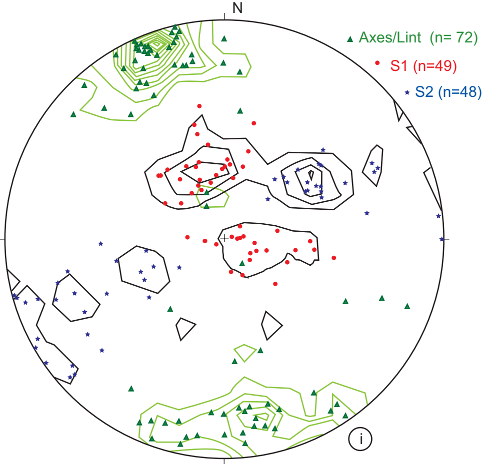

(b)
North Iberian Alpine Thrust
Moncayo
Jarque Fault
Tabuenca
Ebro Basin
Borobia
Mesones de Isuela
Jarque
Datos Thrust
Herrera Unit
Calatayud
Calatayud Basin
Codos
Badules Unit
Alhama de Aragón
Herrera de los Navarros
Murero
Daroca
Olalla
Calamocha
Montalbán
(c)
Northern sector
Cerveruela Fault
Central sector
Datos Thrust
Southern sector
Sta. Cruz Syncline
(a)
WALZ
5º W
0º
N
CZ
¿?
41º N
CIZ
OMZ
SPZ
200 Km
36º N
Pre-variscan outcrops
Cambrian
Silurian
Carboniferous
Cenozoic
Precambrian
Ordovician
Devonian
Mesozoic

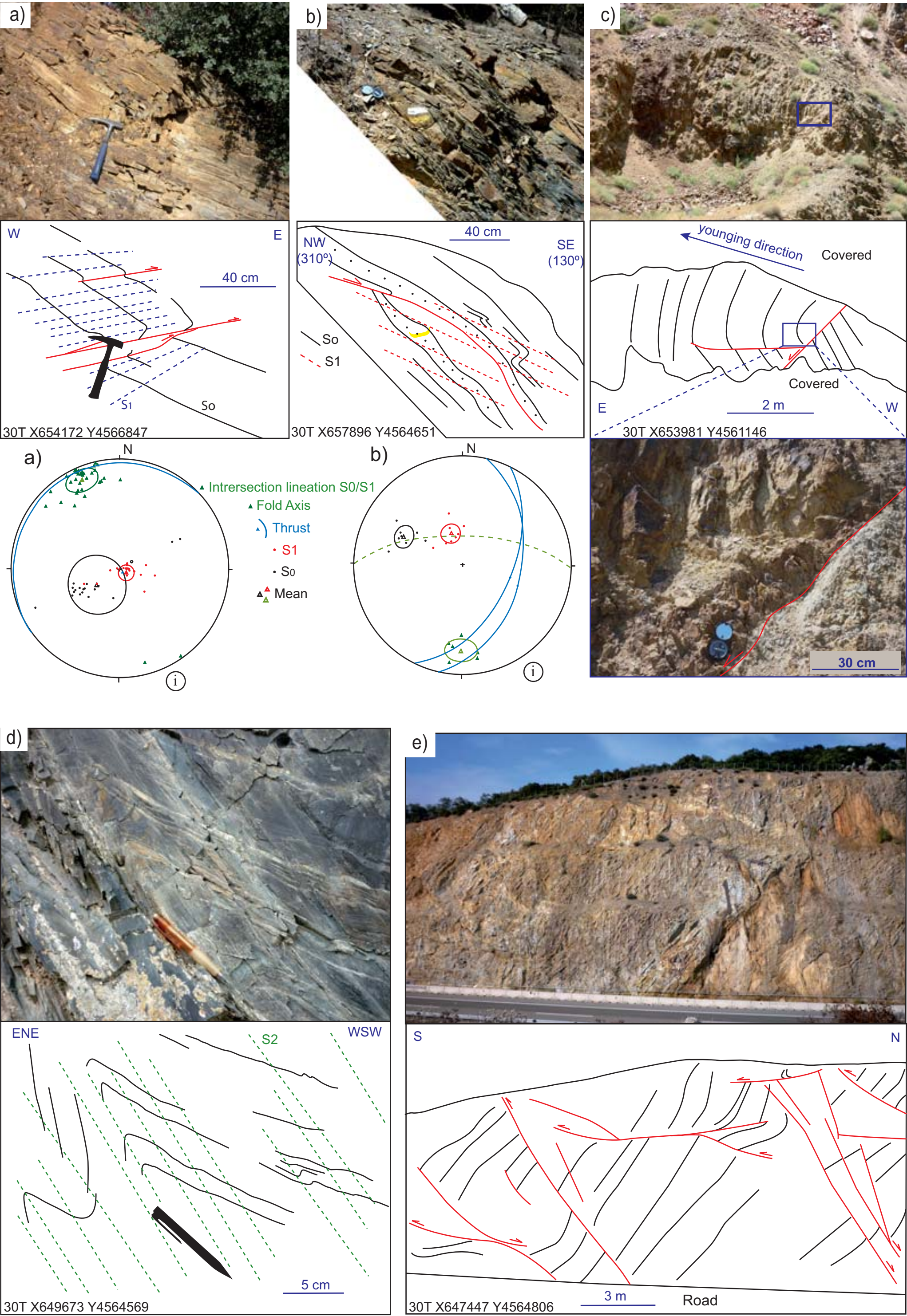

SYSTEM
SERIES
DEVONIAN
LOWER
UPPER
LOWER
SILURIAN
PRIDOLI
WENLOCK
LUDLOW
LLANDOV
ORDOVICIAN
UPPER
MIDDLE
LOWER
UPPER CAMBRIAN
500 m

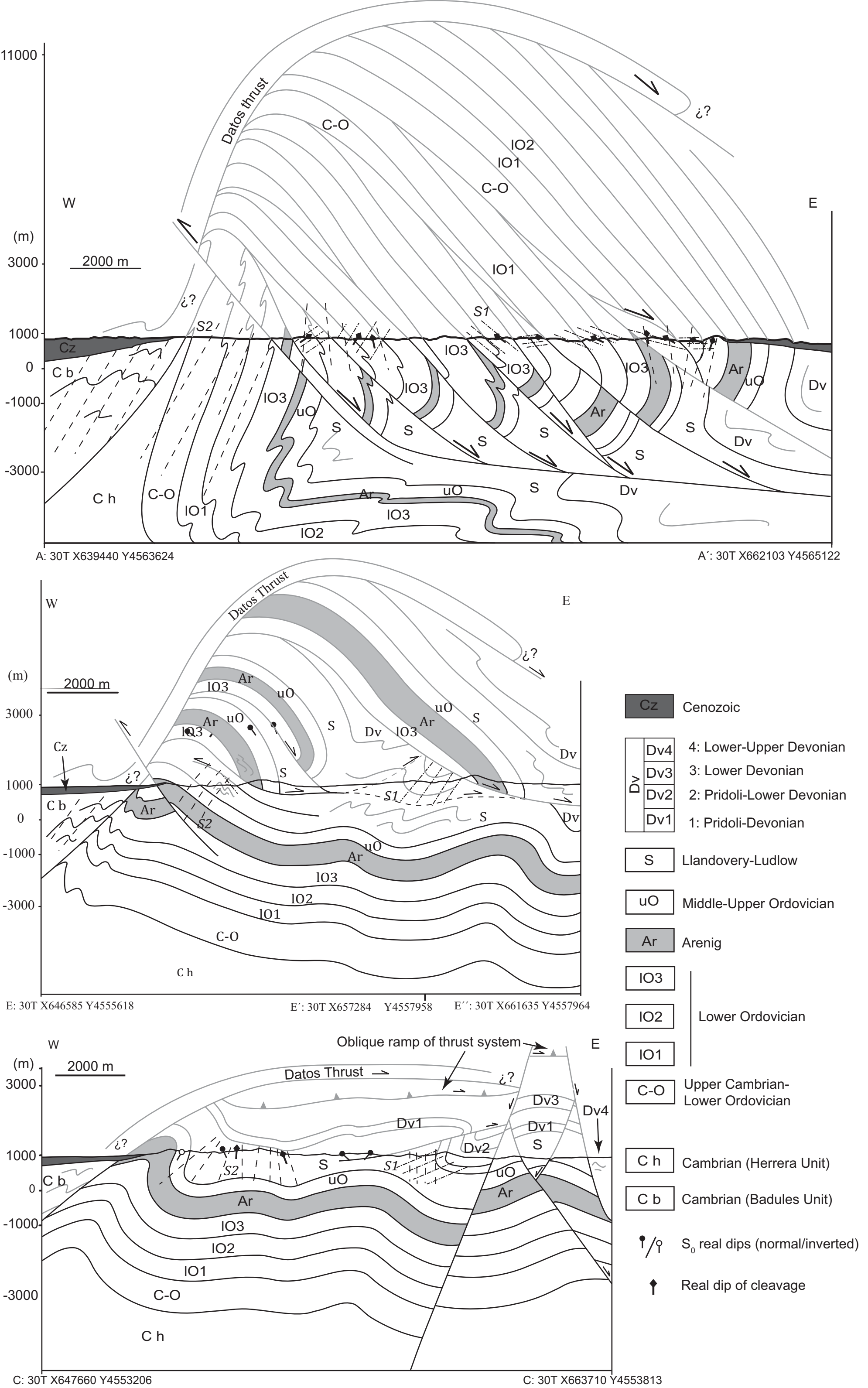


644000
652000
Coord system: ETRS1989; UTM30N
660000
4570000
4558000
4546000
N
4 km
Aladrén
Cerveruela
Vistabella
Herrera de los Navarros
Luesma
Fombuena
Badules
Lanzuela
Bádenas
Nogueras
Sta. Cruz de Nogueras
Loscos
Mezquita de Loscos
a
b
c
d
e
A
A´
B
B´
B´´
C
C´
Cenozoic
Mesozoic
Permian-Triassic
Lower-Upper Dev.
Lower Devonian
Pridoli-Lower Devonian
Llandovery-Ludlow
Middle-Upper Ordovician
Arenig
Lower Ordovician
Upper Cambrian
Cambrian (Herrera Unit)
Cambrian (Badules Unit)
Intrusions (Andesitic rocks)
Bedding and cleavage data
Fault / Thrust
Hinge line and intersection lineation
Anticline/Syncline/Recumbent Syncline

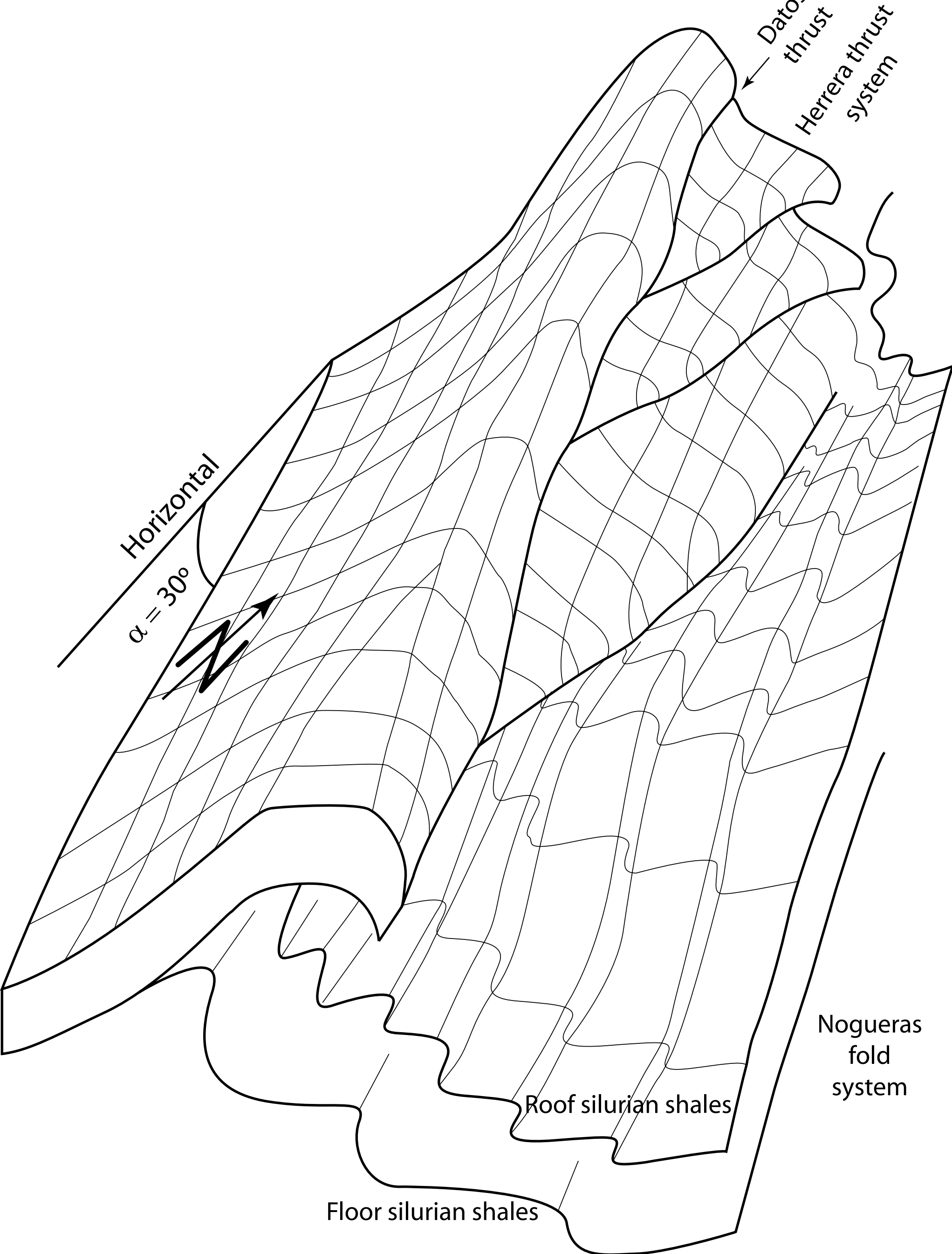

N
Cylindrical best fit
S0
n = 211
i


N
Axes/Lint (n= 72)
S1 (n=49)
S2 (n=48)
i

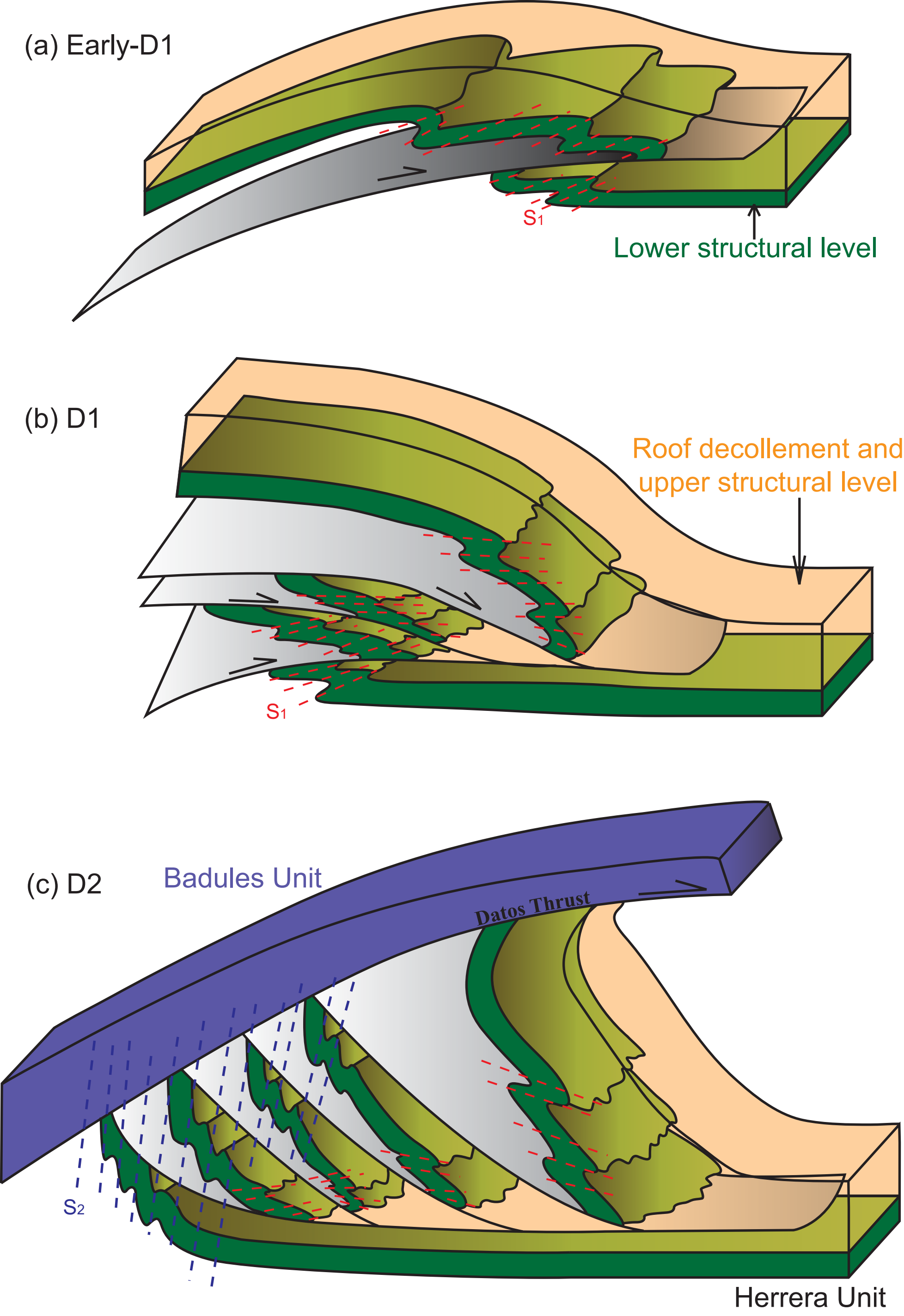

a)
W
E
40 cm
S1
So
30T X654172 Y4566847
b)
NW
(310º)
SE
(130º)
40 cm
So
S1
30T X657896 Y4564651
c)
younging direction
Covered
Covered
E
2 m
W
30T X653981 Y4561146
30 cm
a)
N
Intersection lineation S0/S1
Fold Axis
Thrust
S1
S0
Mean
i
b)
N
i
d)
ENE
S2
WSW
5 cm
30T X649673 Y4564569
e)
S
N
3 m
Road
30T X647447 Y4564806



Datos thrust
C-O
lO2
lO1
¿?
W
E
(m)
11000
3000
1000
0
-1000
-3000
2000 m
S1
S2
Cz
C b
C h
lO3
uO
S
Ar
Dv
A: 30T X639440 Y4563624
A´: 30T X662103 Y4565122
Datos Thrust
E: 30T X646585 Y4555618
E´: 30T X657284 Y4557958
E´´: 30T X661635 Y4557964
Oblique ramp of thrust system
Dv1
Dv2
Dv3
Dv4
C: 30T X647660 Y4553206
C: 30T X663710 Y4553813
Cz Cenozoic
Dv4 4: Lower-Upper Devonian
Dv3 3: Lower Devonian
Dv2 2: Pridoli-Lower Devonian
Dv1 1: Pridoli-Devonian
S Llandovery-Ludlow
uO Middle-Upper Ordovician
Ar Arenig
lO3
lO2
lO1
Lower Ordovician
C-O Upper Cambrian-Lower Ordovician
C h Cambrian (Herrera Unit)
C b Cambrian (Badules Unit)
S0 real dips (normal/inverted)
Real dip of cleavage



Datos thrust
Herrera thrust system
Horizontal
α = 30º
N
Nogueras fold system
Roof silurian shales
Floor silurian shales


(a) Early-D1
S1
Lower structural level
(b) D1
Roof decollement and upper structural level
S1
(c) D2
Badules Unit
Datos Thrust
S2
Herrera Unit