Ordovician on the move: geology and paleontology of the “Túnel Ordovícico del Fabar” (Cantabrian free highway A–8, N Spain)

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Introduction

The Ordovician succession of the Cantabrian Zone (northwestern Spain) is very incomplete and sparsely fossiliferous, especially in comparison with to other areas in the Hesperian (or Iberian) Massif. Lower to lower Middle Ordovician rocks overlie the Cambrian succession in apparent conformity, but with a probable basal gap. In most areas of the Cantabrian Zone, younger Ordovician rocks do not exist and Arenigian sandstones (Armorican Quartzite facies of the Barrios Formation) are paraconformably overlain by Silurian, Upper Devonian or Lower Carboniferous rocks. The only record of post–Arenigian sediments eastwards of the Asturian Central Coal Basin is at the Laviana nappe, where upper Oretanian to lower Dobrotivian fossiliferous shales have been recently reviewed by Gutiérrez–Marco *et al.*, (1996, 1999). However, detailed knowledge of the Ordovician biostratigraphy of this area is severely limited by the absence of continuous sections, resulting from the softer rocks being differentially eroded and almost invariably covered.

The recent construction of a superhighway along the Asturian coast (Autovía del Cantábrico, A–8) opened a temporary window that provided the opportunity to study these usually unexposed shale units and interbeds, which comprise the Cambrian–Ordovician successions of the Laviana and Rioseco nappes. The excavation of El Fabar tunnel near Berbes provided complete, continuous, fresh exposure of the stratigraphy in the tunnel walls and also in the talus along the highway south of Torre before it was subjected to hydrosowing (Figure 1). These continuous and remarkably fossiliferous Ordovician sections provided substantial stratigraphic and paleontological data that previously unavailable. Study of the tunnel section followed the daily rhythm of excavation. The important scientific discoveries and the model of collaboration between Science and Industry, *i.e.*, between the construction engineers and crews and the scientists, has been the subject of several recent articles in newspapers and magazines and of radio broadcasts. As a result of this publicity and scientific importance, the tunnel was officially renamed "Túnel Ordovícico del Fabar" (*Ordovician tunnel of El Fabar*), and an exhibition of fossils of Asturian tunnel is being prepared with financial support from the Spanish Government. FCC Construcción S.A., the company that built the tunnel and adjacent highway segments between 1998 and 2002, published a book that describes this unique and initially quixotic experience and the scientific discoveries in the tunnel.

Methodology

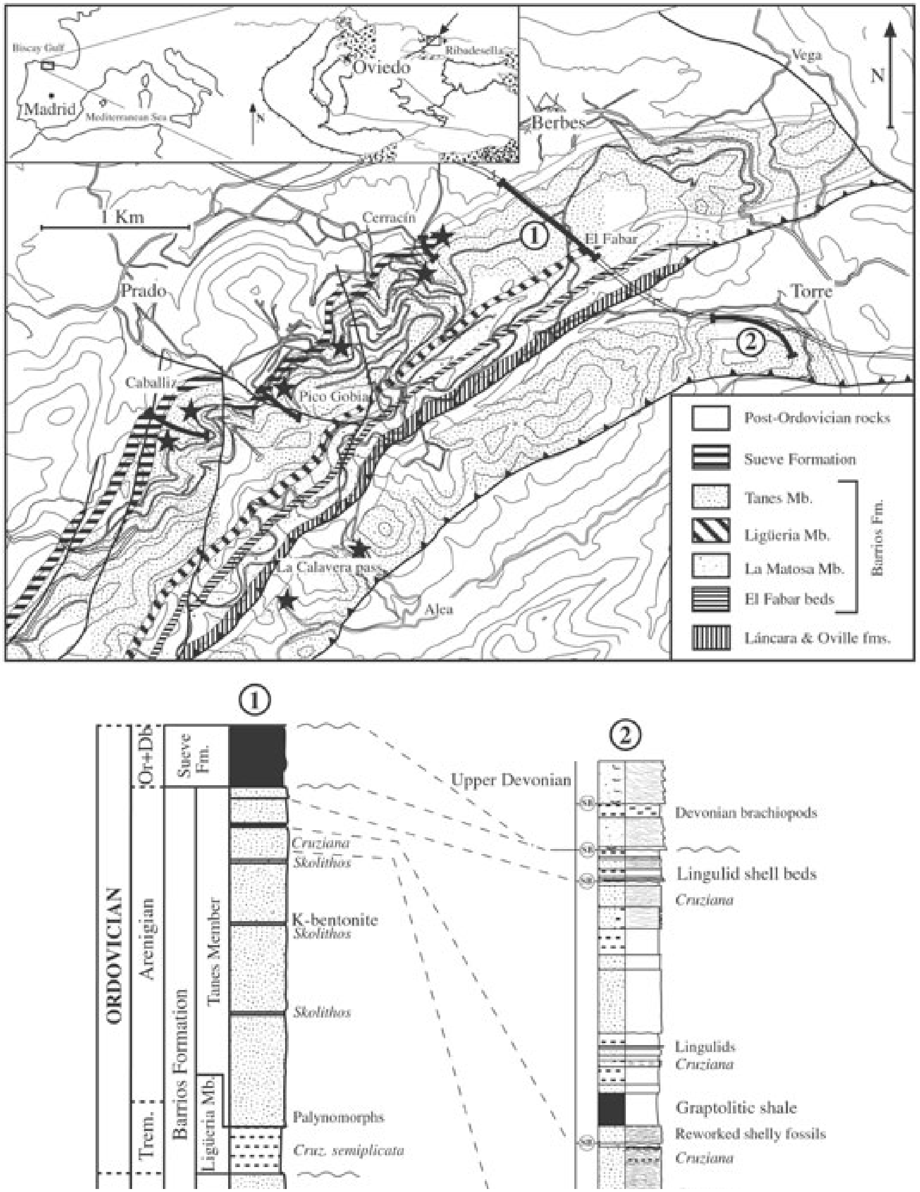
The complete Cambrian–Ordovician section was exposed during excavation of the tunnel, which employed the New Austrian Tunnelling Method (NATM) of rapid and active self supported concrete coating. The Fabar tunnel is actually two separate, parallel tunnels, approximately 1380 m long and 25 m apart. Each tube accommodates two lanes of traffic and during construction more than 10 m wide and about 6 m high with a cross section of 89 square meters (for technical summary see Díaz Reigadas and Mayo Martín, 2000). Geological observations and paleontological sampling were carried out in the southern tunnel during the second phase of the NATM construction. Because both tunnels were slightly oblique to geological structures, excavation of the northern tunnel was several days behind that of the southern tunnel, relative to the stratigraphic succession, and thus the northern tunnel was used, when necessary, for observations and sampling that required extra time and effort. The second phase of excavation of the tunnels advanced approximately 9 meters each day over a surface front of 33 square meters. Stratigraphical study and micropaleontological sampling were carried out along the lateral wall of the tunnel during two periods of 20–30 minutes (day and night) and immediately before the tunnel wall was covered with concrete. Some macropaleontological samples of about 14 tons each one were taken from rock excavated from the tunnel and deposited outside. The stratigraphic location of the excavated rock, approximately 801 tons each day, was carefully noted. The total Ordovician succession studied in detail is 639 m. Its dip is vertical to slightly overturned and it encompasses more than 800 m of the length of the tunnel. The stratigraphical observations were at the scale of 1:100 and are plotted on a column more than 6 m long. Upper Cambrian sediments were also studied but with much less detail.

On the basis of stratigraphic observations, the tunnel section (excluding the lower member of the Barrios Formation) is divided provisionally into 6 major depositional sequences and 54 parasequences. The significance and stratigraphic thickness of all are precisely measured, and the stratigraphic levels of 181 different paleontological samples (112 of which are post–Arenigian in age) are precisely located.

Stratigraphy

The temporary exposures at the highway (El Fabar tunnel and Torre) provided two continuous and valuable sections through the Barrios and Sueve formations, although the Sueve Formation occurs only in the western nappe (Figure 1). The Barrios Formation is composed by *ca.* 800 m of white quartz sandstone with some interbedded micaceous shale and a single K–bentonite bed. Sandy shale and conglomeratic beds occur in the middle of the formation and characterise the middle (Ligüeria) member of the formation. The quartzite unit conformably overlies Middle Cambrian glauconitic sandstone and green shale of the Oville Fm. (100–400 m). The location of the

Cambrian–Ordovician boundary in the Cantabrian Zone is uncertain, being either in the upper part of the Oville Formation (La Barca Member) or in the lower part of the Barrios Formation (La Matosa Member) because of the lack of shelly fossils and the discrepancies regarding often contradictory palynological records. The last record of *Cruziana semiplicata* is used here to place the top of Lower Tremadocian. The upper part of the Barrios Formation (Tanes Member) is currently correlated with the typical Armorican Quartzite, and for the same reason correlated the Arenigian. In addition to common ichnofossils with little biostratigraphical value, the Tanes Member provides an outstanding record of middle Arenigian graptolites in the Rioseco Nappe as well as lingulid coquinas with the problematic *Hanadirella* in the Laviana Nappe (for references see Gutiérrez–Marco *et al*., 1999 and 2002). Data from the tunnel have provided the precise stratigraphical position of these beds and expanded their known distribution to both nappes. Additionally, we discovered a thick K–bentonite bed that is at the same stratigraphic position as one to the west of the Central Asturian Coal Basin (Pedroso Bed). This eastern record greatly expands the geographic extent and fallout volume reached of this Arenigian ash fall, now estimated to have covered a pre–tectonic surface of about 45200 square kilometres and to have involved approximately 32 cubic kilometres of airborne ash (now completely devitrified and altered to bentonitic clays). This mass of airborne debris (that exclude the floating pumites) represents, for instance, more than 30 times the hurled ejecta of the 1980–eruption of the Mount St. Helens, and 10 times more than the ash emitted by the 1991–massive eruption of the Philippine Pinatubo volcano. Another interesting discovery was the recognition of a thick intercalation of dark shale (here named as "El Fabar beds") within the La Matosa Member, which unconformably overlie tidal delta sandstone.



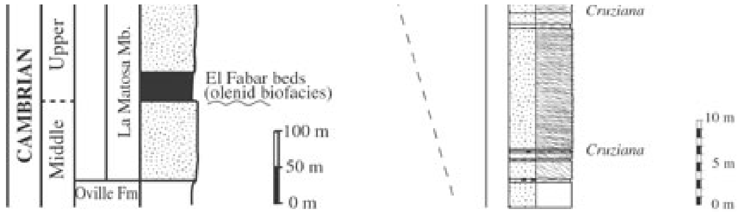
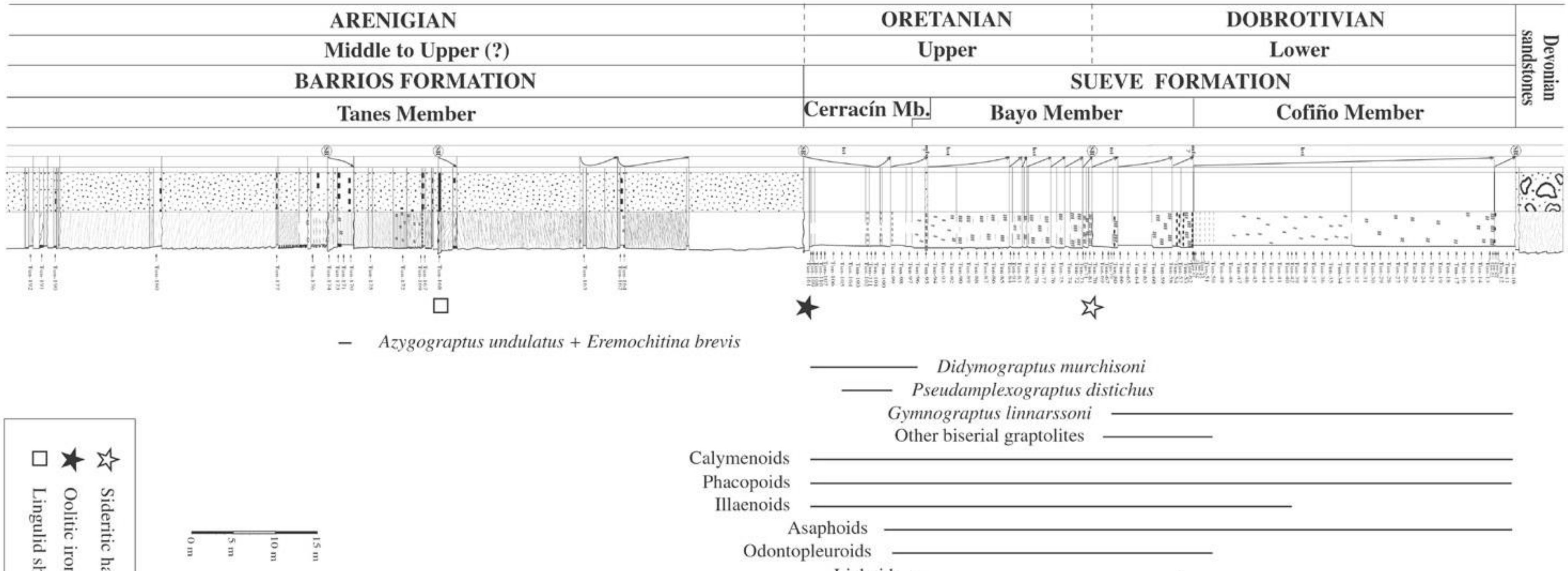


Figure 1. Geological sketch map of area between Caravia and Ribadesella (Asturias, N Spain) showing the northeastern ends of the Laviana (W) and Rioseco (E) nappes and the paleontological localities and sections. 1, El Fabar tunnel section (for complete stratigraphical scheme see below); 2, Torre section (the upper part of this sequence is detailed in the right column). Black stars denote additional fossiliferous outcrops, mainly discovered using stratigraphical information provided by the tunnel section. For details on the main lithological constitution of each unit see the text. Abbreviatures: Trem, Tremadocian; Or+Dv, upper Oretanian to lower Dobrotivian (both are stages from the north Gondwanan regional scheme); SB, sequence boundary. Significant beds and fossils from the Barrios Formation are indicated on the right side of columns.

The depositional setting of the Barrios Formation was recently interpreted as a braided plain delta with fluvial and alluvial influences and with the Ligüeria Member representing of lacustrine to lagoonal environments (Aramburu and García–Ramos, 1993). Our observations are consistent with the "more marine" traditional interpretation based, apart from some newly recorded sedimentary characteristics, on the repeated occurrence of nearshore trace fossils at multiple levels (inclusive of Ligüeria Member) and also by deeper marine facies that include olenid trilobite beds and graptolitic shales (Figure 1).

With regard to the sedimentary setting for the overlying Sueve Formation, we agree with recent reviews (Aramburu and García–Ramos, 1993; Gutiérrez–Marco *et al.*, 1999). However, the new data clarify the stratigraphical position of the higher ironstone bed, which lies within the Bayo Member instead of at the base of the Cofiño Member. The first occurrence of Ordovician oil in Spain is reported from the tunnel in beds lying at the transition between the Sueve and Barrios formations. This occurrence is consistent with organic maturity of the source and reservoir rocks as determined from TAI and CAI data. The Cantabrian Zone is the foreland thrust and fold belt of the Variscan Massif in the north–western part of the Iberian Peninsula. Its structure has a thin–skinned geometry complicated by its arcuate shape. Deformation in the Cantabrian Zone involved little metamorphism. The absence of penetrative cleavage is consistent with the local preservation of hydrocarbons.



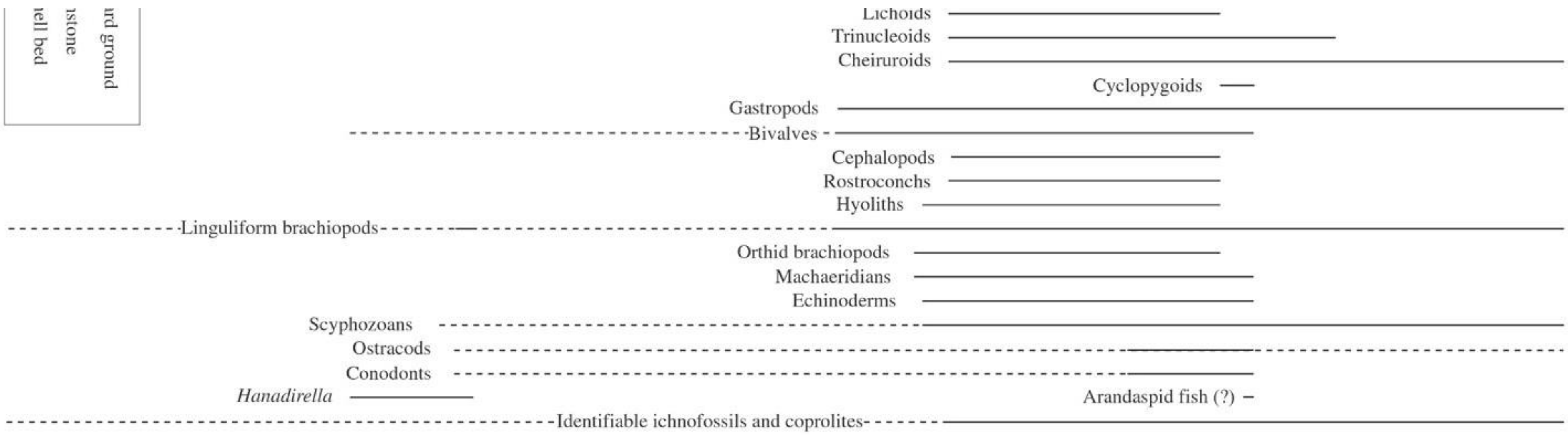


Figure 2. Stratigraphical column and paleontological sample from the upper part of the Barrios Formation (sandstone and quartzite, with interbeds of shale and siltstone), and from the Sueve Formation (shale with a middle sandy member). Vertical distribution of the main fossil groups and particular taxa, and location of significant stratigraphic layers are indicated to the right.

Paleontology and biostratigraphy

Preliminary paleontological records from the upper part of the Barrios Formation in the tunnel section are shown in Figure 2, and correlation of the tunnel section with corresponding beds in the Torre section is shown in Figure 1. The oldest fossiliferous horizons examined are in the La Matosa Member of Barrios Formation (El Fabar beds). They yield abundant phyllocarids and palynomorphs and the first Upper Cambrian trilobites known from the Cantabrian Zone, which resembles olenid trilobites reported from the Borrachón Formation of the Iberian ranges. The overlying Ligüeria Member bear *Cruziana semiplicata* and Tremadocian palynomorphs, which range upward into the lower part of the Tanes Member. The upper part of the Barrios Formation yielded many horizons with ichnofossils. Different *Skolithos* beds are useful for regional correlation. Beds with *Cruziana* include ichnospecies produced by predator/scavengers (rusophyciform bathtub burrows) and by widespread particle feeders (the classical continuous trails). Shelly faunas are mainly recorded in the form of lingulid shell beds yielding some remains of trilobites, bivalves, conodonts (*Protopanderodus, Drepanodus, Drepanoistodus*), ostracods and small problematic taxa (*Hanadirella*). The "Chinese" graptolite *Azygograptus undulatus* abundantly occurs with associated palynomorphs in an interbedded shale placed relatively high in the succession. The bed also has chitinozoan species of the *Eremochitina brevis* Biozone, which has been identified by the first time in Spain and suggests a Middle Arenigian age. The associated acritarch assemblage is of high diversity (more than 40 species of 20 genera) and very well preserved in the Torre section with a very low color alteration.

Although the paleontological record of the Sueve Formation was previously known from discontinuous outcrops, it was remarkably enlarged and clarified by the tunnel section (Figure 2). Many taxa were identified and reported for the first time in the Cantabrian Zone or in Spain, but also in the Ordovician of western Europe as, for instance, the thecate polypoid cnidarian *Sphenothallus*. A total of 57 species of invertebrates, some of them new, have been identified so far. Trilobites are the most diverse group and are represented by genera of calymenoids (*Neseuretus, Colpocoryphe, Prionocheilus*), cheiruroids (*Placoparia, Eccoptochile, Pateraspis*), phacopoids (*Phacopidina, Eodalmanitina, Crozonaspis*), illaenoids (*Ectillaenus*), lichoids (*Uralichas*), odontopleuroids (*Selenopeltis, Primaspis*), asaphoids (*Isabelinia, Nobiliasaphus,?Basilicus*), cyclopygoids (*Parabarrandia*) and trinucleoids (*Dionide* and raphiophorids). The last two groups are indicative of open–shelf environments that are significantly deeper that the inshore settings represented by trilobite biofacies from Central Spain. The non–trilobitic invertebrate fossils are less abundant and of lower diversity than coeval invertebrate faunas from other areas in SW Europe. Particular beds contain relatively diverse ostracod associations (with new species and the oldest records of some paleocopes and binodicopes), conodonts preserved on bedding planes (*Drepanoistodus suberectus, Panderodus, Semiacontiodus*), possible icthyoliths (which if confirmed would evidenced the oldest vertebrate fossil from Europe), and rare fossils, such as machaeridians and conularids.

Graptolites and chitinozoans provide good biostratigraphic control for the Sueve Formation. Its basal unconformity represents a stratigraphic gap equivalent to the lower Oretanian–lower upper Oretanian and probably also to the uppermost Arenigian. The top of the formation in the tunnel section correlates with the lower Dobrotivian (*Gymnograptus linnarssoni* graptolite Biozone and *Linochitina pissotensis* chitinozoan Biozone). This level is older that the top of the formation in a nearby outcropping section (S–2 of Gutiérrez–Marco *et al.*, 1996) where the *Lagenochitina ponceti* chitinozoan Biozone (uppermost Dobrotivian) was tentatively identified. This diachroneity may be related to partial erosion of the Sueve Formation prior to Upper Devonian time and also with to topography of the pre–existing Ordovician basin.

Conclusions

Because of the significant geological and paleontological data it provides and the complete, continuous character of the temporary section, the El Fabar "Ordovician tunnel" merits consideration as an important Ordovician reference section for SW Europe and the European peri–Gondwanan realm. Study and sampling of the stratigraphy as the tunnel was excavated (and before the unique exposures were covered by concrete) represents a unique scientific endeavor provided by a major work of public infrastructure. This successful experience demonstrates that such "geology in real time" is possible and that this type of research was possible without interrupting the scheduled rhythm of the construction of these 11.6 Km of highway and tunnels with a final cost of more than US$ 90 millions.

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