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A CROSS-SECTION THROUGH THE NORTHERN PART OF THE IBERIAN MASSIF[1]

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ABSTRACT

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The Iberian Massif forms the western extremity of the Variscan Fold Belt in Europe, which from the Armorican Massif describes a sharp bend (the Ibero-Armorican arc) to cross the Iberian Peninsula from northwest to southeast. A cross-section through the massif shows the existence in the belt of two branches with an opposite polarity, which gives a certain mirror-image symmetry to the structure of the belt. An east-west section parallel to the Cantabrian coast provides the best cross-section of the northern branch of the Iberian Massif. This section shows the typical zonation of linear fold belts. It consists of an 'external' part (Cantabrian zone) formed by carbonaceous and terrigenous rocks in a varied platform facies (at least the pre-Carboniferous rocks) and with thin-skinned tectonics, and an 'internal' part with a more monotonous, pelitic facies, and in general with cleavage, metamorphism and plutonism. The facing of the main structures is towards the 'external' part of the belt.

During pre-Carboniferous Palaeozoic time, the geological evolution can be explained as the result of tension resulting in normal faulting, synsedimentary volcanism and intrusion of peralkaline and calcalkaline granitoids. The source of terrigenous supply was near the core of the arc, where an uplift tendency existed.

Coinciding with the Devonian-Carboniferous boundary there was a break in the geological history and the subsequent geological evolution has been controlled by compressional orogenic events. This break is shown by a change in terrigenous supply now derived from the rising chain, by the development of foredeeps in the frontal part of the chain, and by the change from anorogenic to orogenic conditions with folding, metamorphism and plutonic intrusion.

INTRODUCTION

The Iberian Massif forms the western extreme of the Variscan Fold Belt, which is intersected to the south by the Alpine Betic front of Southern Spain. The massif is crossed by SE-NW trending Variscan structures, and provides a cross-section of some 770 km wide. This is the most complete cross-section of the European Variscan Fold Belt, and several zones can be distinguished that can be correlated with similar zones in the other Variscan Massifs of Europe. Outstanding features of the structure of the massif are its arc-shaped pattern in the northern part (Asturian or Ibero-Armorican arc) and the symmetry shown in a NE-SW cross-section of the structure.

A division of the Iberian Massif into structural zones was established for the first time by LOTZE (1945-b) and this zonation has been accepted with little modification by later workers (BARD ET AL., 1971; JULIVERT ET AL., 1974). This zonation, together with the areal distribution of Late and Early Palaeozoic sedimentary rocks and granitoids is shown in figure 1. From this figure it can be seen that Late Palaeozoic rocks are concentrated in the two extreme zones of the massif (the Cantabrian and South-Portuguese zones) and that granitoids are lacking there. The distribution of high-grade metamorphic rocks is related to the occurrence of granitoids; they are concentrated in the inner zones of the massif. Nevertheless the pattern is more complicated than a simple increase of plutonism and metamorphism from the Cantabrian and South-Portuguese zones towards the inner parts of the massif. The distribution of plutonism and metamorphism, and the areal distribution of the Late Palaeozoic rocks, together with the opposite facing of the structures in the two sides of the massif, permits the definition of two branches of opposite polarity in the Iberian sector of the Variscan Fold Belt.

The northern branch is formed by the Cantabrian, the West-Asturian-Leonese and the northern part of the Central-Iberian Zone (Galician-Castilian Subzone) (Fig. 1). These zones have the following characteristics:

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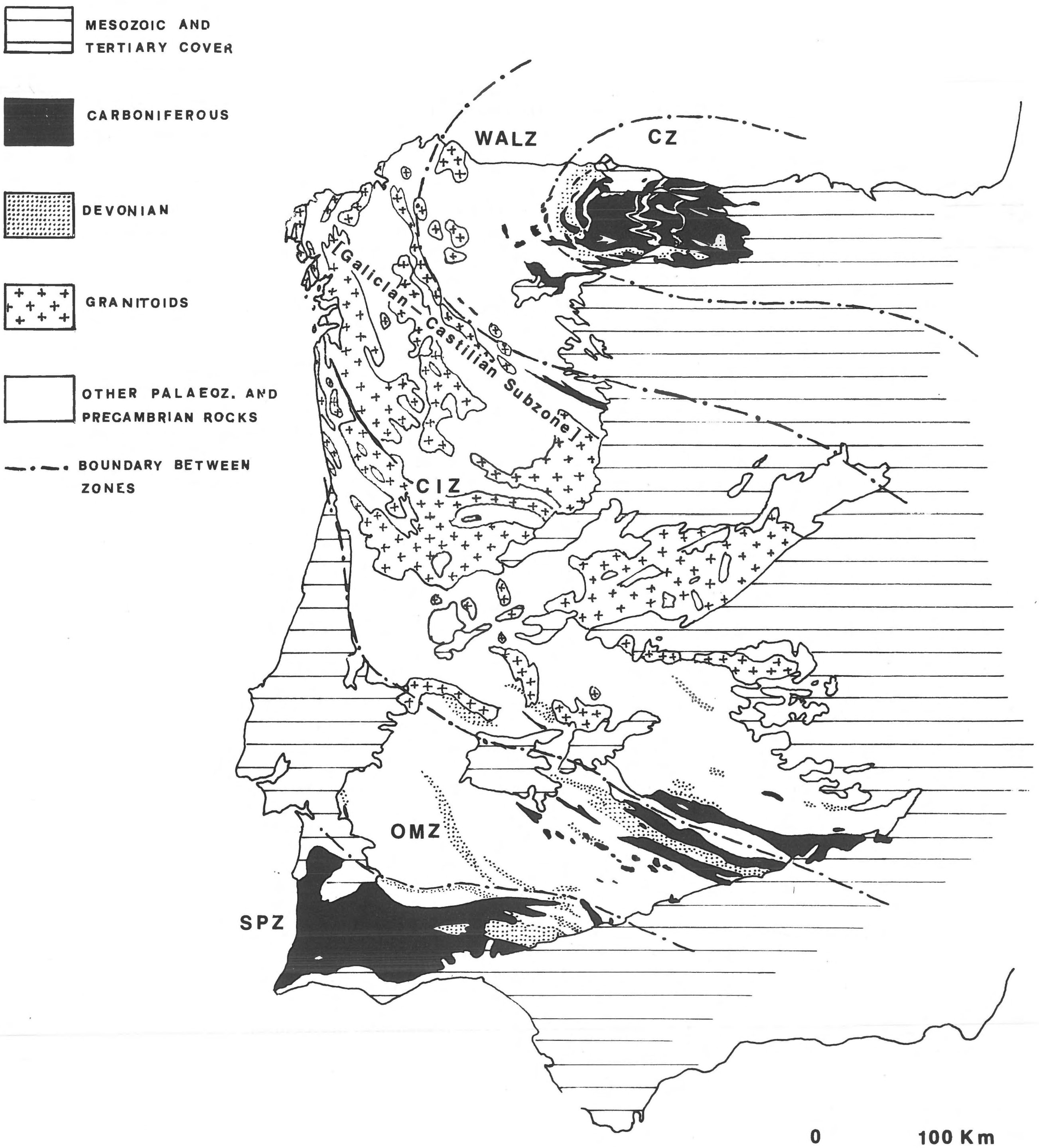


Fig. 1
Structural zonation of the Iberian massif according to Julivert et al. (1972), following Lotze (1954-b), and the distribution of Carboniferous and Devonian rocks and granitoids.

(1) Cantabrian Zone – An incomplete and comparatively thin Cambrian to Silurian sedimentary sequence; Devonian sediments are present in some areas and the Carboniferous is very well developed. Precambrian rocks only outcrop at the western boundary of the zone. Structures are controlled by slip along bedding planes and contrasts of ductility. Cleavage is generally absent. The zone is practically without metamorphism and plutonism and the structure is the result of a general décollement of the Palaeozoic sequence.

(2) West-Asturian-Leonese Zone – A thick Cambrian to Silurian sedimentary sequence. Post-Silurian rocks range from

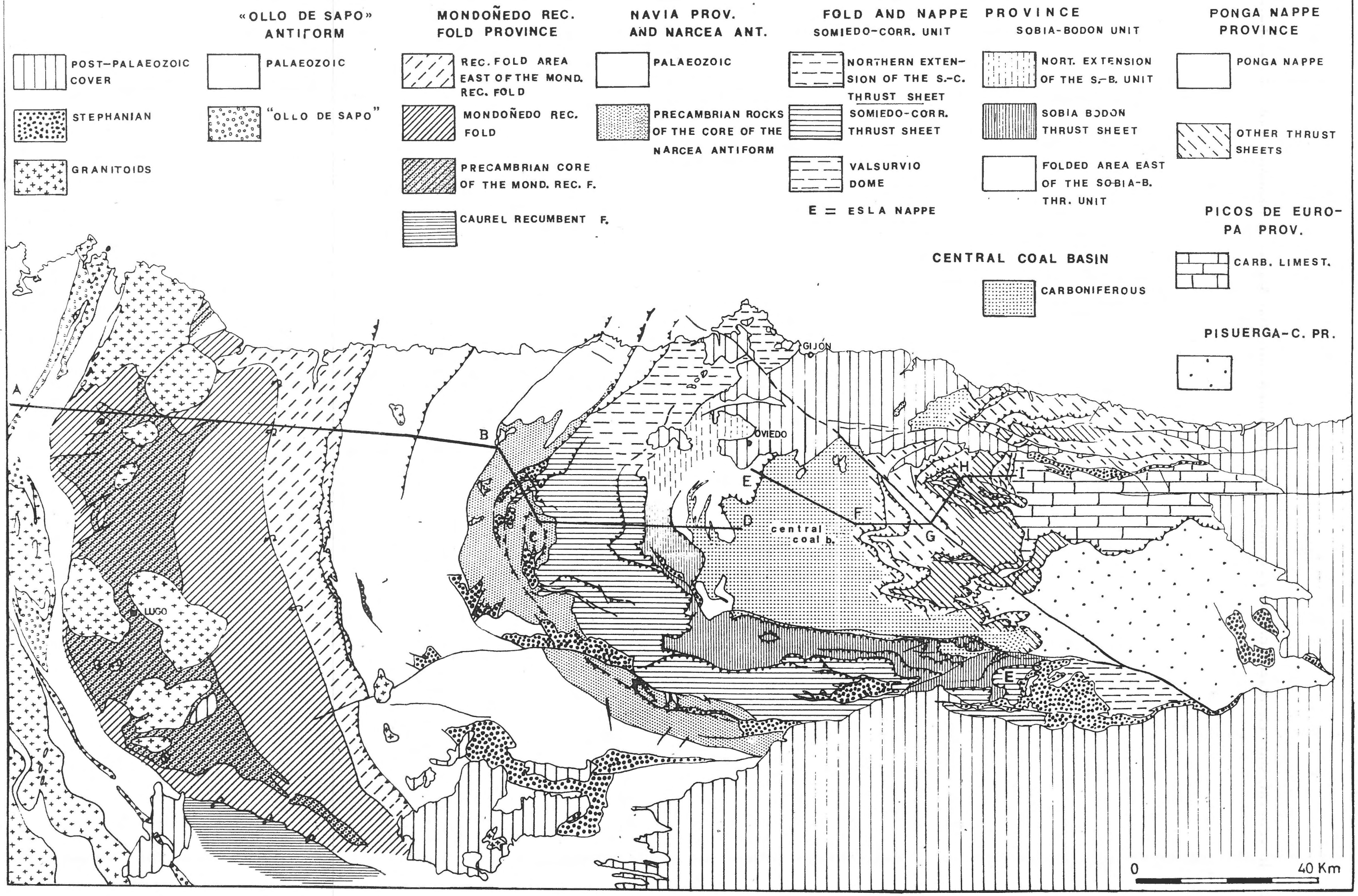


Fig. 2
Structural sketch of the West-Asturian-Leonese and the Cantabrian zones, showing the position of the cross-section of enclosure I.

Early Devonian to Stephanian, and occur in only a few, usually small outcrops. Precambrian rocks outcrop in the core of the largest structures (Narcea antiform and Mondonedo recumbent fold). In general, slaty cleavage and later crenulation cleavages have developed. Metamorphism and plutonism increase from east to west. Plutonism, represented chiefly by small posttectonic stocks, is concentrated in the western part of the zone.

(3) Galician-Castilian Subzone – Formed mostly by Precambrian and Lower Palaeozoic; granitoids form more than 55% of the surface. Regional metamorphism reaches amphibolite facies conditions. Slaty cleavage and later crenulation cleavages are common. Catazonal complexes form several circular massifs.

In this paper the Cantabrian and West-Asturian-Leonese zones will be described and an east-west cross-section through them will be given (Encl. I).

PRECAMBRIAN

Precambrian rocks outcrop in three different areas: in the core of the Mondonedo recumbent fold, in the West-Asturian-Leonese zone and along the eastern (Narcea antiform) and western ('Ollo de Sapo' antiform) boundaries of this zone (Fig. 2).

In the cores of the Narcea antiform and the Mondonedo recumbent fold, the Precambrian sequence consists of shales, siltstones and sandstones (or their metamorphic equivalents), and where sedimentary structures are preserved (in the Narcea antiform) they are characteristic of turbidites (PEREZ-ESTAUN, 1973). In the 'Ollo de Sapo' antiform separating the West-Asturian-Leonese and the Cantabrian zones Precambrian rocks, outcropping in the core, consist of 'porphyroids' with feldspar megacrysts and blue quartz in a quartz-micaceous matrix (PARGA-PONDAL ET AL., 1964). No direct evidence of the stratigraphical relationships between both Precambrian successions exists, but in the lower part of the Narcea succession 'porphyroid' rocks occur, which are finer grained than the 'Ollo de Sapo' and thus suggest that the 'Ollo de Sapo' may be older than the Narcea sequence (MATTE, 1968-a). For additional data on the Precambrian see the papers of MATTE (1968-a), PARGA & VEGAS (1972), FONTBOTE & JULIVERT (1974) and BARD ET AL. (1974).

CAMBRIAN AND ORDOVICIAN

Three important points may be made on the sedimentary history and palaeogeographic distribution of the older Palaeozoic sediments.

(1) The Variscan orogeny deformed a thick pile of sediments, laid down during practically the whole Palaeozoic era. There was no Caledonian orogeny in the area.

(2) Although only the Variscan orogeny took place, there were two major sedimentary cycles during Palaeozoic times. The first one developed during Cambrian and Ordovician and the second during Carboniferous times. Only the second sedimentary cycle was thus related with an orogenic event, although there was some thermal and plutonic activity in the internal parts of the chain during the Early Palaeozoic.

(3) The Palaeozoic palaeogeographic trends, even in the Early Palaeozoic, generally show a parallelism with the Variscan structural trends (MATTE, 1976; JULIVERT, 1978).

The distribution of Cambrian and Ordovician sediments: the trough of the West-Asturian-Leonese zone

For the following description the whole northern half of the Iberian Massif is considered, although more attention will be given to the West-Asturian-Leonese and Cantabrian zones. During Cambrian and Ordovician times the major palaeogeographic units coincide closely with the three major zones of the Northern branch of the Variscan chain, that is: Cantabrian, West-Asturian-Leonese, and Central Iberian zones (Fig. 3). These three zones are characterized by differences in sedimentary history, in structure, metamorphism and magmatism. During Cambrian and Ordovician times a trough developed in the West-Asturian-Leonese zone (LOTZE, 1961; MATTE, 1968-b; JULIVERT ET AL., 1972; MARCOS, 1973), especially in its eastern part; some 10,000 m of sediments including turbidites were deposited during the Late Ordovician. The trough was bounded by two slightly subsiding areas. To the east, the Cantabrian zone formed a large platform, with a thin and incomplete Early Palaeozoic succession. To the west and southwest, the western part of the West-Asturian-Leonese zone is found with a thinner Early Palaeozoic succession, and further west, the 'Ollo de Sapo' antiform occurs with a still thinner and less complete succession.

Southwest of the 'Ollo de Sapo' antiform (Central-Iberian zone), the early Ordovician quartzite is transgressive on Cambrian and Precambrian rocks (LOTZE, 1956; CAPDEVILA, 1965; JULIVERT, 1978). The importance of the pre-Ordovician deformation cannot yet be established, but it is probably not very strong. The thickness of the Ordovician sequence is not so great as in the trough referred to above (some 1000-2000 m), and no deep-water sediments have been recorded.

The Early Palaeozoic palaeogeography still presents important problems due to the lack of sufficient sedimentological data on some formations and the erosion in some areas of part of the sedimentary record. In addition it must be pointed out that in Galician the great abundance of granitoids and the high grade of metamorphism make it impossible to give precise stratigraphic details. In the following description, data on the Central-Iberian zone come from northern Portugal or

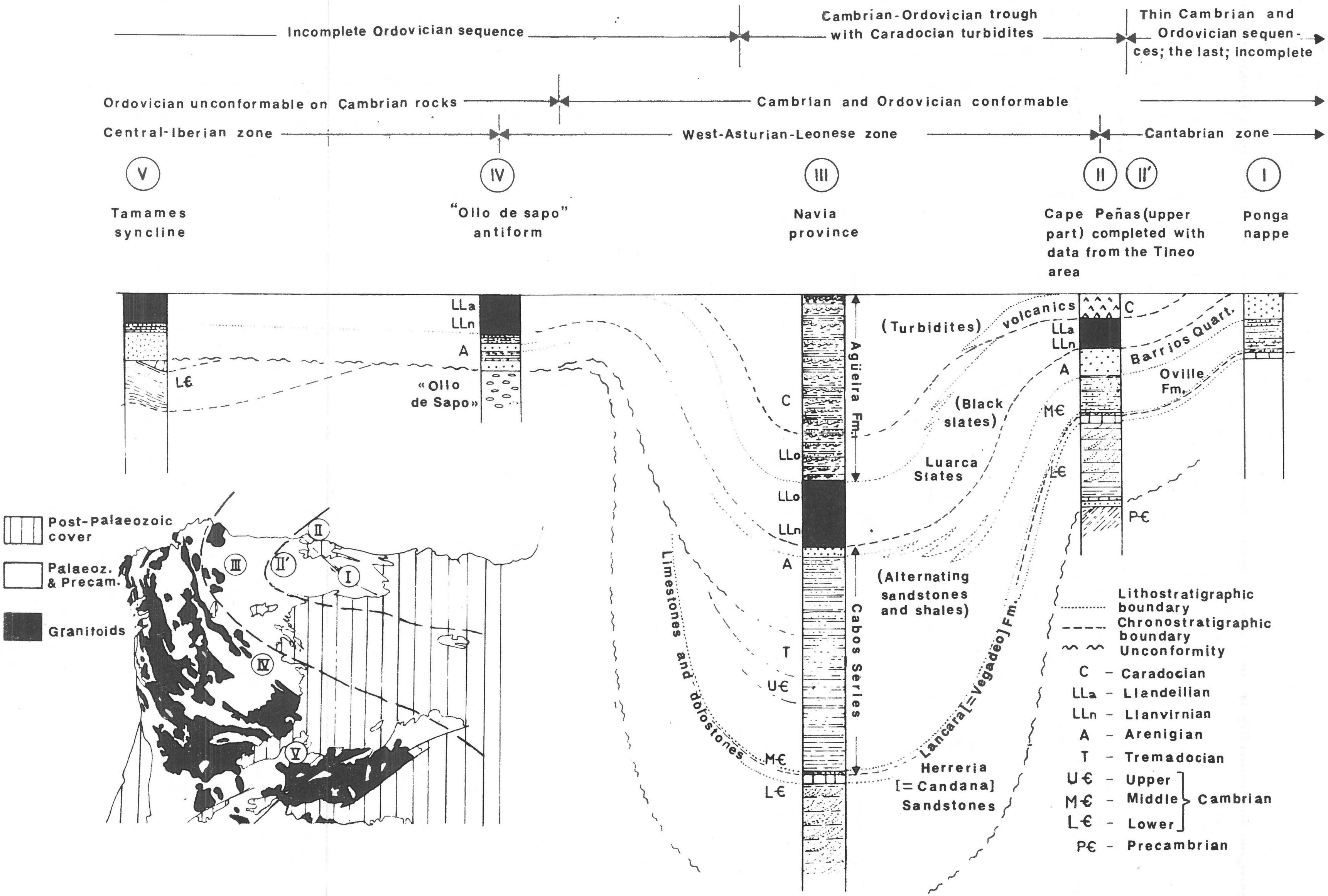


Fig. 3
Cambrian-Ordovician stratigraphic sections in the northern part of the Iberian Massif.

neighbouring areas in Spain. There are two breaks in the Early Palaeozoic succession. The first is clearly related to an important period of erosion and even to an angular unconformity (pre-Arenigian unconformity in the Central Iberian zone). During the second, a certain erosion also took place, but no unconformity is related to it (pre-Silurian break).

The first break is not found in the whole Iberian Massif, and this fact determines the existence of two areas with different Cambrian-Ordovician relationships (MATTE, 1976; JULIVERT, 1978): the Central-Iberian zone with the Early Ordovician succession resting unconformably on older rocks, and the West-Asturian-Leonese and Cantabrian zones where the Ordovician rests conformably on the Cambrian sequence. Consequently, complete Cambrian sequences only exist east of the 'Ollo de Sapo' antiform whilst in the Central-Iberian zone middle and late Cambrian rocks are lacking and even the lower Cambrian is restricted in occurrence. The absence of a great part of the Cambrian succession in the Central-Iberian zone is probably due to pre-Ordovician erosion rather than to non-deposition.

Pre-Silurian erosion has also played a role in the distribution of pre-Silurian rocks. Complete Ordovician sequences are only found in part of the West-Asturian-Leonese zone and in the southern part of the Central-Iberian zone. Between these areas Silurian sediments rest on the middle Ordovician shales, and in the Cantabrian zone they rest on the Arenigian quartzites (see Figs. 3 and 4). This disposition is due, at least in part, to the pre-Silurian erosion.

Due to the two periods of erosion mentioned, the present day thickness distribution, as represented in figure 3, does not represent the true shape of the basin or of the Ordovician or Cambro-Ordovician pile of sediments. It reflects the situation at the time of the Silurian transgression, following the pre-Silurian erosion.

Evolution of deposition in time

The following description is based on the trough of the West-Asturian-Leonese zone, where the Cambrian-Ordovician succession is complete. The sequence mainly consists of clastic rocks, with only one dolomite-limestone formation (Lancara-Vegadeo Formation of Early-Middle Cambrian age), and a subordinate level of dolomites near the base of the Cambrian. Shallow-water conditions persisted during Cambrian and Early Ordovician times throughout the Iberian Massif, the only differences being sediment thickness and grain size. Evidence for shallow-water deposition is provided by biogenic and inorganic sedimentary structures, found in the clastic sediments (OELE, 1964; BALDWIN, 1975, 1978), and by the tidal-flat and shallow-water facies found in the carbonates (OELE, 1964; VAN DER MEER MOHR, 1969; ZAMARREÑO, 1972, 1975, 1978).

The middle Ordovician (Llanvirnian-Llandeilian) sequence consists of black graptolitic shales and slates (Luarca slates) laid down in a reducing environment. These rocks are found in most of the West-Asturian-Leonese zone and in the Central-Iberian zone. They are absent, with a few exceptions, in the Cantabrian zone.

The Luarca slates are overlain by a mainly Caradocian turbidite sequence (Agüeira Formation: MARCOS, 1970; CRIMES ET AL., 1974), indicating rapid subsidence and accumulation under deep-water conditions. This sequence is confined to the narrow and deep trough of the eastern part of the West-Asturian-Leonese zone. Outside this trough, Late Ordovician rocks are either absent (in the whole Cantabrian zone for example), except at the very northwestern border where they form a volcano-sedimentary sequence (JULIVERT & TRUYOLS, 1972), or show a smaller thickness and no deep-water facies (southern part of the Central-Iberian zone: TAMAIN, 1971; HAMMAN, 1976; JULIVERT & TRUYOLS, 1974).

SILURIAN

The Silurian sequence is chiefly formed by black graptolitic shales with interbedded quartzites in some areas (TRUYOLS ET AL., 1974; MARCOS & PHILIPPOT, 1972). The black shales show rather uniform characteristics and thickness throughout the Cantabrian and West-Asturian-Leonese zones, as well as in most of the Central-Iberian zone. In the Cantabrian zone, and in the Palaeozoic outcrops of the Iberian chain (a southeasterly extension of the West-Asturian-Leonese zone), the upper part of the Silurian sequence is formed by ferruginous sandstones. This, and the lack of Silurian rocks in part of the Cantabrian zone (in the Ponga nappe province) suggests that in the core of the arc a tendency for uplift still persisted during Silurian times.

In spite of many common characteristics, the Silurian sequence also shows regional variations. These are chiefly due to differences in the content of volcanic rocks. Important Silurian volcanism can be seen in Galicia, northern Portugal, Zamora and Salamanca.

DEVONIAN

Devonian sediments are restricted to some scattered outcrops (DROT & MATTE, 1967) except in the Cantabrian zone, where they are abundant. Due to the scarcity of outcrops a palaeogeographic reconstruction can only be given for the Cantabrian zone.

In the Cantabrian zone, the Devonian presents two different facies (KULLMANN, 1963; BROUWER, 1964, 1968): Asturo-Leonese and Palencian facies. The Asturo-Leonese facies is characterized by an alternation of terrigenous and carbonate formations with shallow-water characteristics and bentonic faunas (COMTE, 1959; REIJERS, 1972-a,b; MENDEZ-BEDIA, 1976; ZAMARREÑO, 1976). The Palencian facies is characterized by an alternation of shales, siltstones and fine-grained nodular limestones with abundant pelagic fauna.

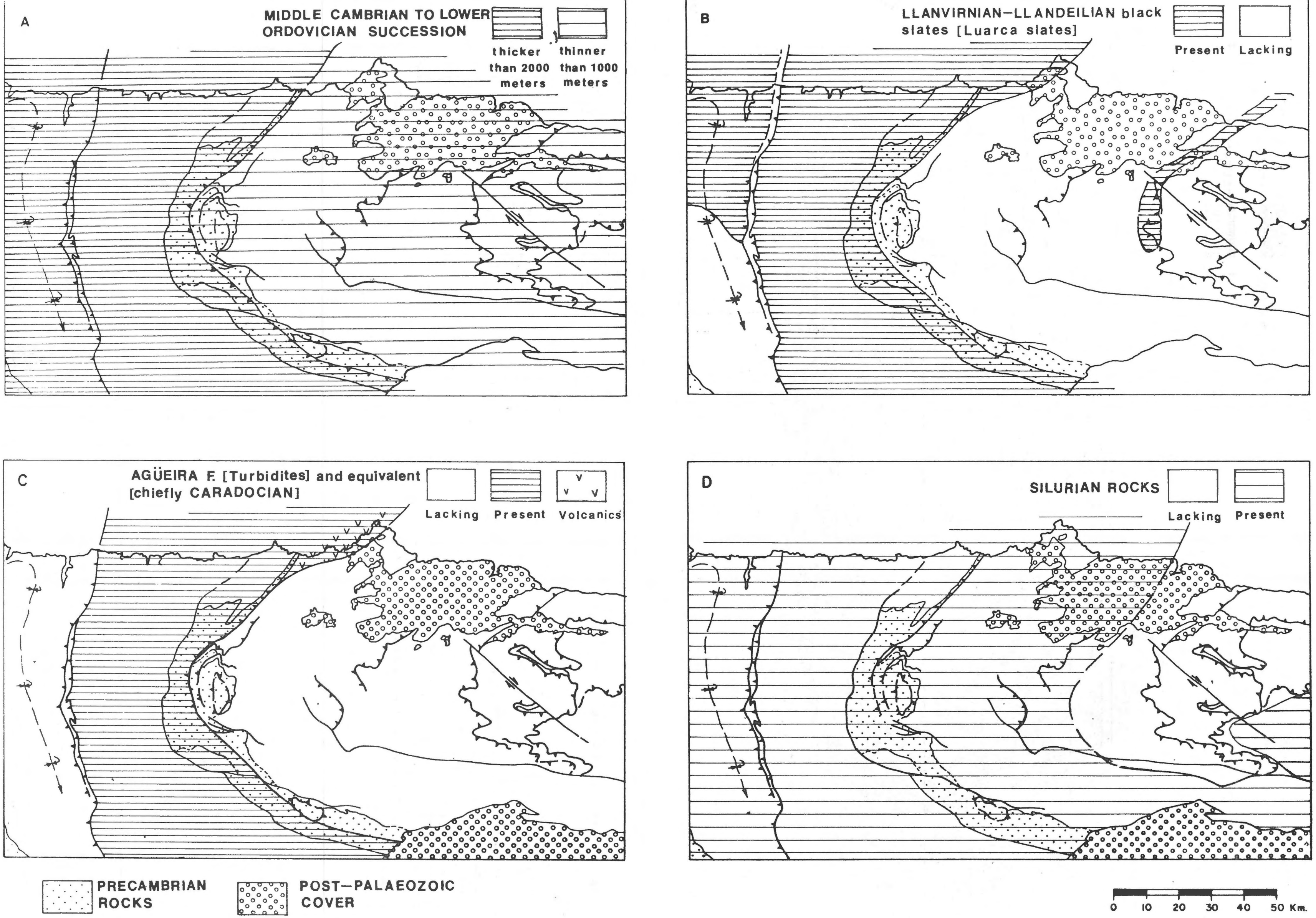


Fig. 4
Palaeogeographic maps of the Cantabrian and the West-Asturian-Leonese zones during Cambrian, Ordovician and Silurian times.

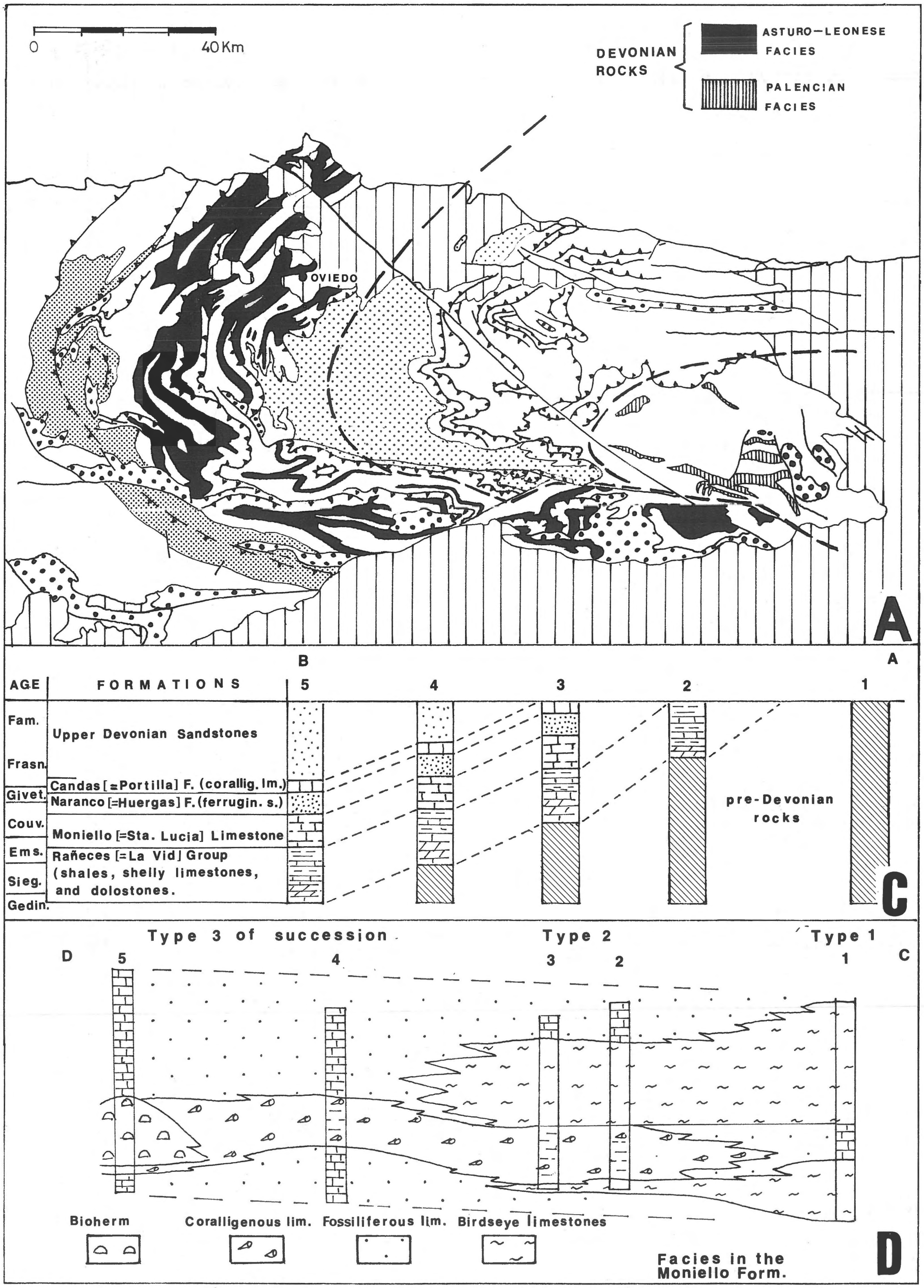
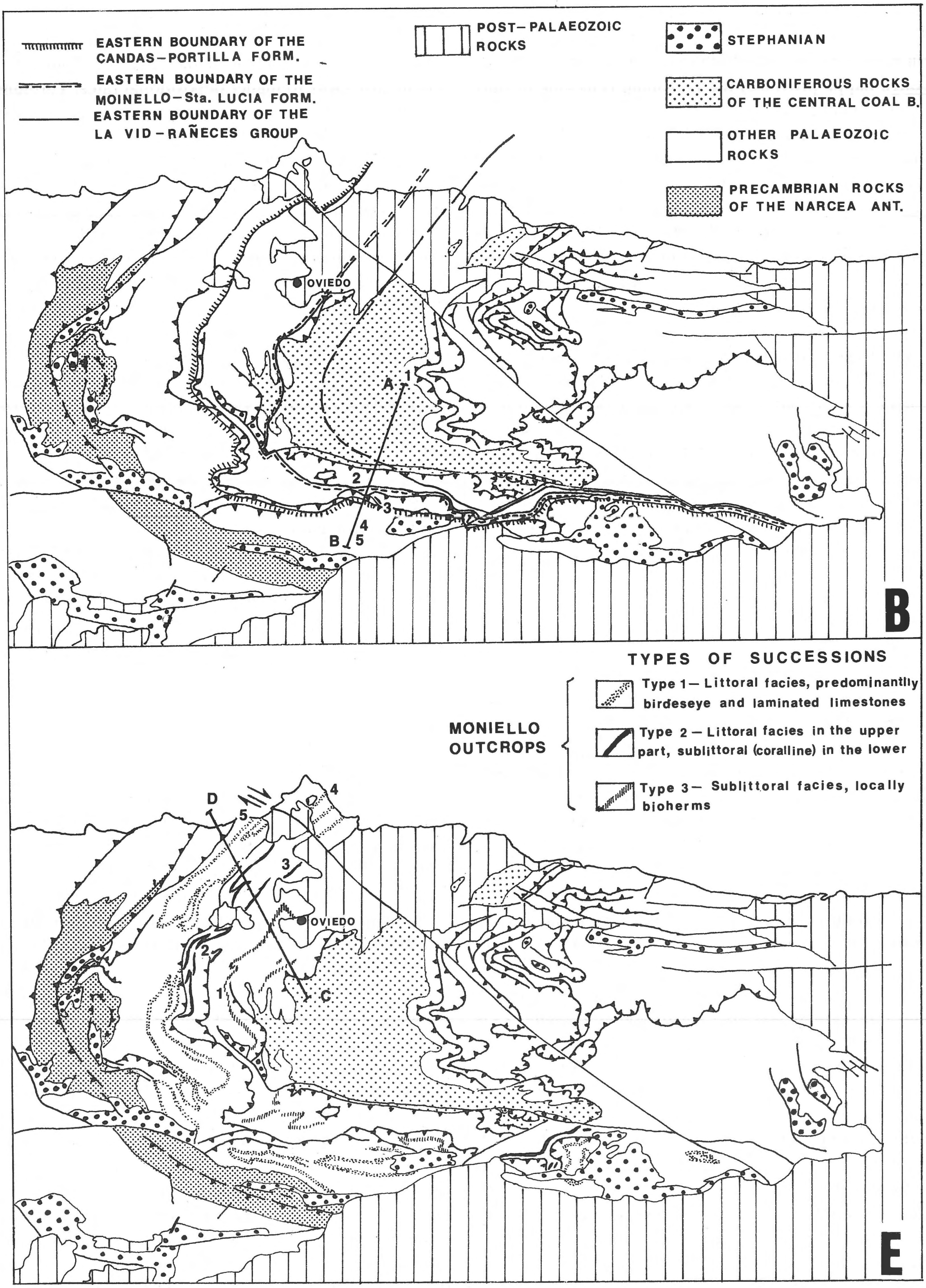


Fig. 5
Devonian palaeogeography. (A) = Devonian facies provinces in the Cantabrian zone. (B) = distribution of the different Devonian formations in the fold and nappe province (Asturo-Leonese facies). (C) = the Devonian succession in different localities throughout the fold and nappe



province showing the apparently regressive disposition of the different formations. For locations see B. (D) = different types of successions in the Moniello–Sta. Lucia Formation and their correlation. For locations see E. (E) = areal facies distribution in the Moniello-Sta. Lucia Formation, showing the increase of littoral conditions towards the core of the arc.

The first facies is peculiar to the fold and nappe province of the Cantabrian zone, and the second is found in the Pisuerga-Carrión province (Fig. 5A). In the areas between the provinces (Ponga nappe province) the Devonian is lacking or only represented by some late Famennian sandstones. The Devonian in Asturo-Leonese facies is found in the fold and nappe province, between the Narcea antiform and the central coal basin; in the eastern border of the central coal basin Devonian rocks are lacking. The Devonian succession is not complete over the whole area; it is complete towards the Narcea antiform and becomes less and less complete towards the central coal basin (Fig. 5B and C). In general terms, each Devonian formation has a more restricted extension than the formation underlying it. This disposition may be due to a regression or to tilting and erosion, or more probably to both reasons.

Thus, the Cantabrian zone during Devonian times was still a platform area with shallow-water sedimentation and uplift in some parts. The formations of the fold and nappe province that have been carefully surveyed (Moniello-Sta. Lucia: MENDEZ-BEDIA, 1976; Naranco-Huergas: GARCIA-RAMOS, 1978) show an increase of littoral conditions towards the concavity of the arc, while they grade into more open-sea facies in the opposite direction (Fig. 5D and E).

CARBONIFEROUS

During Carboniferous times, the Variscan orogeny took place while Carboniferous sedimentation continued. A synthetic view of the Carboniferous sedimentary cycle has recently been given by JULIVERT (1978); the following description summarizes the results described in that paper. Other general papers dealing with the Cantrabrian Carboniferous or giving sedimentological information are WAGNER (1962, 1966), BROUWER & VAN GINKEL (1964) READING (1970); VAN AMEROM ET AL. (1970) GARCIA-LOYGORRI ET AL. (1971); VAN LOON (1970, 1971, 1972, 1975, 1981); BOLL ET AL. (1976) and HEWARD (1978).

In the Cantabrian zone early Carboniferous sediments are very reduced in thickness, the whole Tournaisian and Visean sequence being no more than 30-50 m thick and consisting essentially of black shales, black chert (Tournaisian), radiolarites and red nodular limestones with goniatite faunas (Visean).

The first evidence of instability in the Cantabrian zone is found in the lower Namurian formed in some areas by turbidites and containing slump-breccias. These sediments reflect the instability caused by a deformation that probably took place in more internal parts of the chain. The youngest Carboniferous rocks correspond to the Stephanian, affected by late deformations. The Cantabrian zone shows a complete Carboniferous sequence and the progress of orogeny can be seen in it. In more internal zones of the chain, probable Carboniferous pre-Stephanian rocks have only been reported from a few localities (TEIXEIRA & PAIS, 1973; PEREZ-ESTAUN, 1974) and their age is poorly established.

The beginning of the Namurian coincides in the Cantabrian zone with an important change in the sedimentation, and the slow rate of deposition that characterized the Tournaisian and Visean gives way to higher depositional rates. Turbidites are laid down in some areas and the Cantabrian zone, which had persisted as a platform area since the beginning of the Palaeozoic, suffers active subsidence with differentiation of deep-water areas. These changes were a consequence of changes in more westerly areas; with the development of the Variscan orogeny, the Cantabrian zone became the frontal ('external') part of the growing chain. Slow subsidence of the platform gave way to active subsidence and deposition due to erosion of the chain.

Before the Carboniferous the supply of terrigenous material to the Cantabrian zone came from the concave part of the arc, but during the Carboniferous it came essentially from the chain on the opposite side. As deformation progressed important changes in the sedimentation took place. In the Westphalian B sequence the first coarse conglomerates occur, giving evidence of an active erosion of the chain, relatively high relief and deposition after a short transport. This active erosion continued during the entire Westphalian.

The thickness of sediments deposited during Westphalian times is as great as 5000 m in the central coal basin. Although subsidence in the Cantabrian zone continued, turbidite sedimentation was pushed out towards the more frontal part of the chain, while paralic conditions occurred over large areas. Figures 6 and 7 illustrate the Carboniferous stratigraphy and facies distribution and show the two Westphalian facies provinces, paralic (Asturian) and turbiditic (Pisuerga-Carrion) occurring in the Cantabrian zone.

Deformation during Westphalian times led to new changes in palaeogeography and sedimentation. Stephanian sediments have an essentially posttectonic character, affected only by late deformations. The outcrops of Stephanian rocks are scattered not only throughout the Cantabrian zone, but also throughout the West-Asturian-Leonese zone and they show a clearly unconformable disposition with respect to the structural Variscan trends and also with respect to earlier palaeogeographic trends.

Marine conditions still persisted during the early Stephanian in the eastern part of the Cantabrian zone, indicating that the sea receeded towards the east. But, during late Stephanian times, only terrestrial and fresh-water sedimentation took place. Coarse conglomerates, coarse-grained sandstones, shales and coal beds form the Stephanian succession (HEWARD, 1978). Channelling is common at the base of conglomerate beds (VIRGILI & CORRALES, 1966). These are typical posttectonic sediments laid down when the chain was already essentially built. They represent the deposits correlative to the erosional activity that led to the destruction of the chain.

This sedimentary history occurs in the most frontal part of the chain. In the inner parts, the events cannot be so closely monitored. In the West-Asturian-Leonese zone and neighbouring areas of the Central-Iberian zone, only a few outcrops

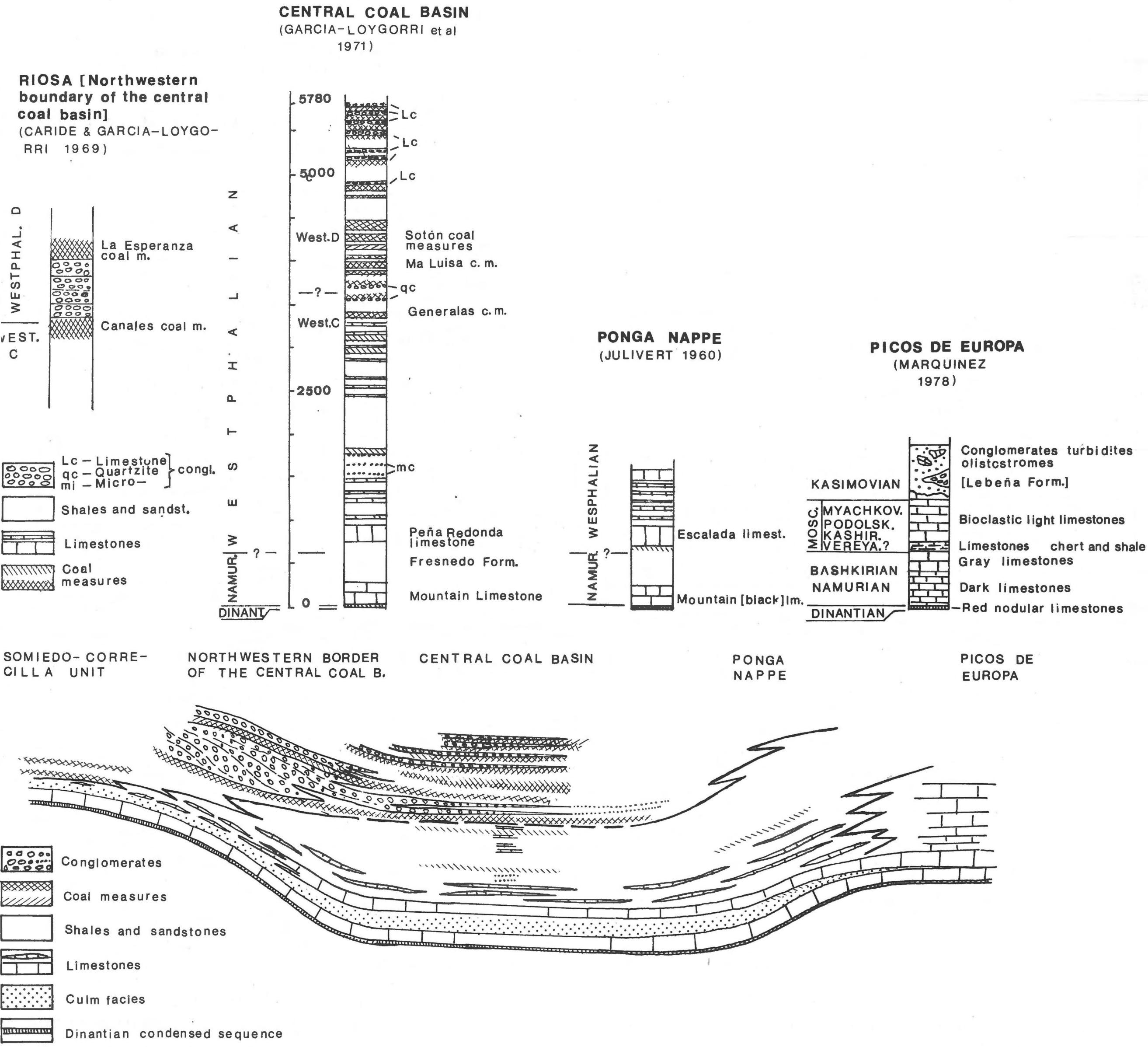


Fig. 6
Stratigraphic sections of the Carboniferous in the paralic province and idealized correlation and reconstruction of a cross-section throughout the province.

of pre-Stephanian Carboniferous rocks have been reported. The age of these rocks is still poorly known, but it seems to correspond to the Early Carboniferous (Portuguese authors have suggested even a Late Devonian age). If these ages are correct, they would indicate that instability in the basin and turbidite sedimentation started earlier in the inner parts of the chain than in the Cantabrian zone.

STRUCTURE OF THE CANTABRIAN ZONE

This zone is characterized by a deformation of a superficial type, without metamorphism and with only local cleavage development. The structure is the result of the superimposition of different kinds of structures, the most striking tectonic feature being the general décollement of the Palaeozoic succession. As a consequence, a series of thrust sheets were formed, some of them of nappe size (GOMEZ DE LLARENA & RODRIGUEZ-ARANGO, 1948; DE SITTER, 1959; JULIVERT, 1971). Folds are also evident and they deform the nappes and thrust sheets. Bedding played an important role in deformation, giving rise to detachment surfaces during nappe emplacement, and controlling the development of folds. The Palaeozoic sequence in the Cantabrian zone is lithologically very varied, consisting of an alternation of competent (quartzites, limestones) and incompetent (shales) beds. These lithologic

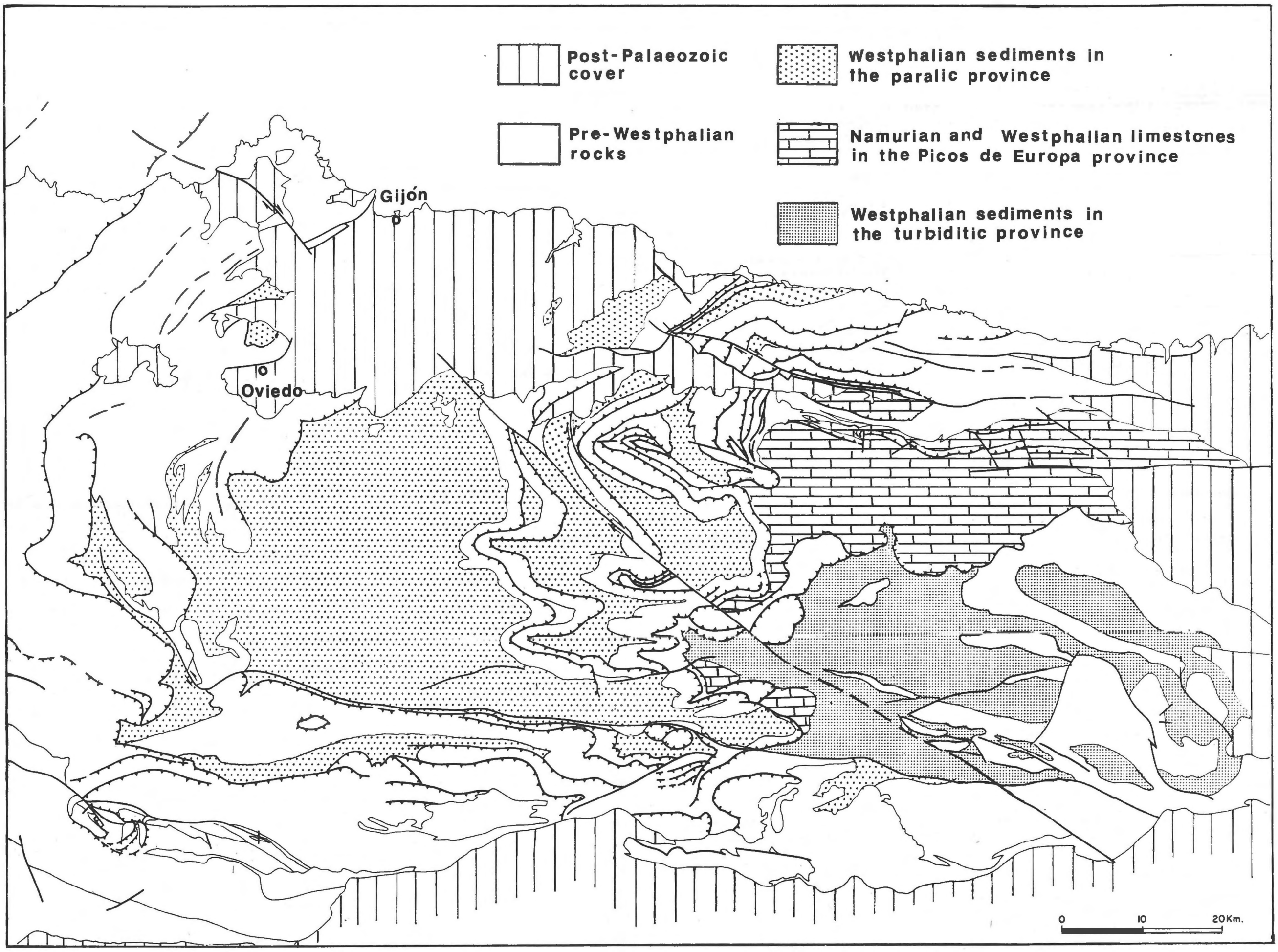


Fig. 7
Westphalian sediments in the Cantabrian zone.

characteristics, giving rise to strong ductility contrasts, favour the generation of such structures as décollement sheets and nappes and flexural folds, in which bedding surfaces played an important role.

The most relevant kinds of structures observed in the Cantabrian zone are: décollement nappes and thrust sheets, folds describing the Asturian arc and folds forming a radial system, and producing interference patterns with the first system (Fig. 8).

Décollement nappes and thrust sheets

All of these show the following characteristics (JULIVERT, 1971): (1) the thrust surface is parallel to the bedding; (2) the thrust surface is almost always located at the base of the Lancara Formation (Early to Middle Cambrian age) indicating a general décollement at this level, although some other décollement levels of lesser importance also exist; (3) in most sheets, the sequence, starting with the Lancara Formation, continues without showing any fold, until being cut by the next thrust surface; (4) the nappe emplacement took place without significant strain inside the body of the nappe, as shown by undeformed fossils and sedimentary textures; a single detached nappe unit can split laterally in several minor units.

In the Cantabrian zone there are three important detached units with the above-mentioned characteristics: the Somiedo-Correcilla unit, the Sobia-Bodon unit and the Ponga nappe. The Picos de Europa unit is also a detached thrust unit but it has different characteristics.

Each of the units mentioned has a peculiar more or less complete stratigraphic succession and in the formations surveyed in detail (Lancara Formation: ZAMARREÑO, 1972; and Moniello-Sta. Lucia Formation: MENDEZ-BEDIA, 1976) it has been seen that the facies changes from one unit to another. On the basis of the chief nappes, the stratigraphic characteristics, and also structural features the Cantabrian zone can be subdivided into five provinces (see Fig. 2): fold and nappe, central coal basin, Ponga nappe, Picos de Europa and Pisuerga-Carrion provinces.

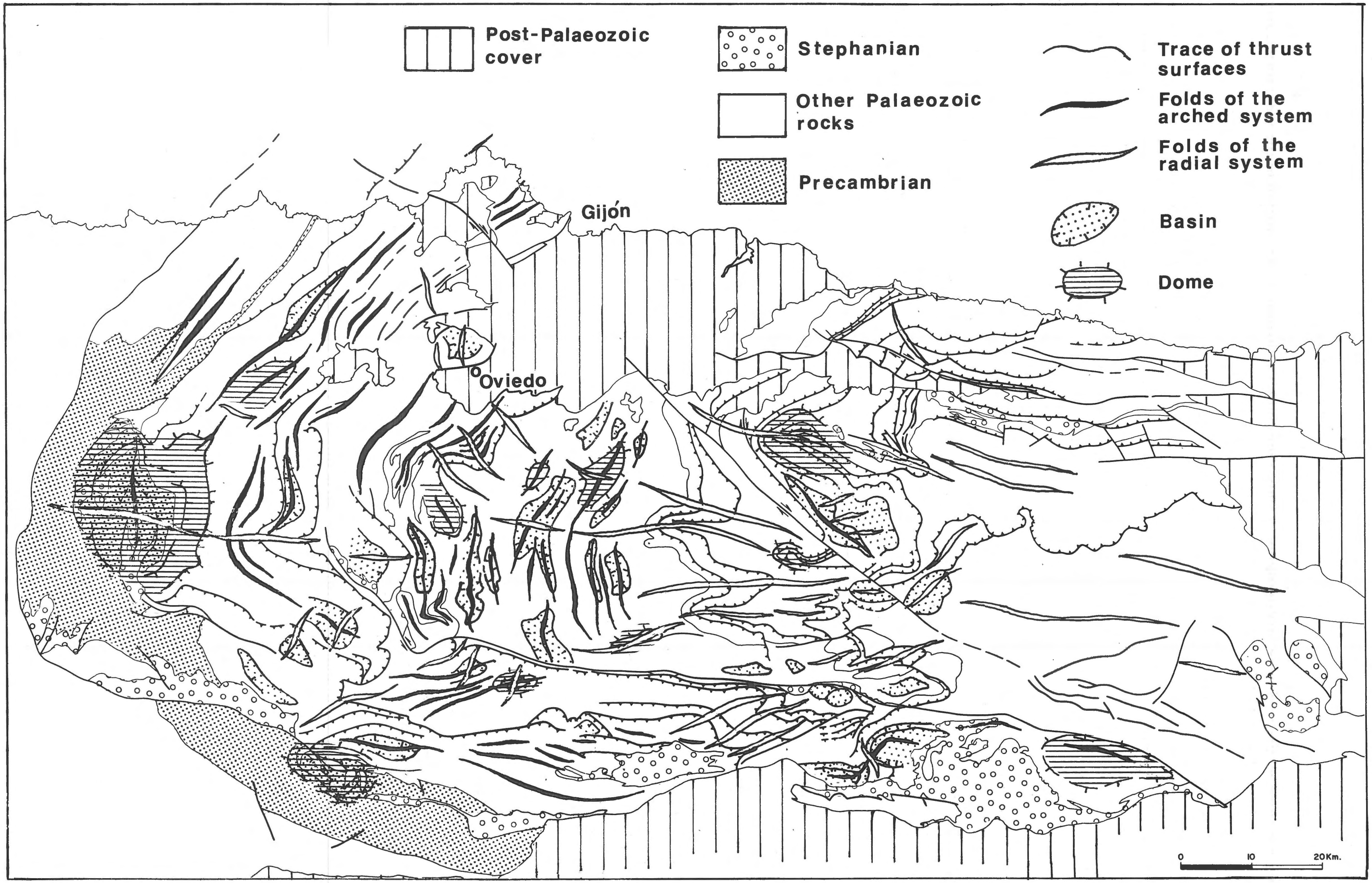


Fig. 8
Structural sketch of the Cantabrian zone showing the trace of the thrust surface of the nappes and the axial trace of the arched and radial sets of folds. The more conspicuous domes and basins in the zone are also indicated. These are the result of cross folding and/or anomalous thickening of the stratigraphic succession due to tectonic overlapping.

Characteristics of the different provinces of the Cantabrian zone

The fold and nappe province is characterized stratigraphically by the presence of Silurian and Devonian rocks and the lack of the Ordovician younger than the Arenigian. Cambrian and Early Ordovician as well as Carboniferous rocks are found in all zones and will only be mentioned where they present some peculiarity. Two exceptions to the above stratigraphic characterization are: the existence of a complete Ordovician succession in the capes Peñas and Vidrias (RADIG, 1978; JULIVERT & TRUYOLS, 1972) neighbouring the Narcea antiform, and the lack of Silurian and Devonian rocks in the eastern extreme of the Sobia-Bodon unit, neighbouring the Ponga nappe (see Figs. 4 and 5); both exceptions are due to the existence of a certain obliquity between palaeogeographic and tectonic trends.

From the structural point of view the chief feature of the fold and nappe province is the existence of two décollement nappes (DE SITTER, 1962; JULIVERT ET AL. 1968; MARCOS, 1968): the Somiedo-Correcilla unit whose eastern extreme is called the Esla nappe (DE SITTER, 1959; RUPKE, 1965; ARBOLEYA, 1978), and the Sobia-Bodon unit. These units exibit some differences in their stratigraphic sequences. The most striking is that the Somiedo-Correcilla unit has a complete Devonian sequence while in the Sobia-Bodon the Devonian is incomplete and locally Silurian and Devonian are absent. In addition, there are facies differences in some formations between some of the units (ZAMARREÑO, 1972; MENDEZ-BEDIA, 1976; BASTIDA ET AL., 1976). East of the Sobia-Bodon unit, in its northern part, between this unit and the central coal basin, occurs a folded area still considered to be a part of the fold and nappe province, but it is also related to the central coal basin.

The décollement thrust units were folded subsequent to their emplacement. In addition, in the fold and nappe province there is a change from décollement nappes in the southeast to a folded area to the northwest (JULIVERT, 1971, 1976). The western boundary of the province is formed by the Narcea antiform, separating the Cantabrian and the West-Asturian-Leonese zones.

The central coal basin is a big, crescent-shaped, depressed area, in which, except in its western thrust border (Laviana thrust sheet), only Carboniferous rocks outcrop. The Carboniferous succession has a thickness of some 5800 m, and the Westphalian shows the typical paralic development, peculiar of the Asturian province (GARCIA-LOYGORRI ET AL., 1971; JULIVERT, 1978). The pre-Carboniferous stratigraphic sequence in the Laviana thrust sheet is the same as in the Ponga nappe, which will be described later. The central coal basin has a synclinorial structure with a complicated cross-fold pattern (JULIVERT & MARCOS, 1973).

The Ponga nappe province (JULIVERT, 1965, 1967-a, 1967-b; SJERP, 1967) is formed by the Ponga nappe and several other minor décollement sheets, more or less related to the Ponga nappe and showing the same type of stratigraphic succession. The chief stratigraphic feature of this province is the lack of Silurian and Devonian sediments, except for some late Famennian sandstones. As normal in the Cantabrian zone, the Ponga nappe shows subsequent folding.

The Picos de Europa province is formed by a huge accumulation of limestones, overridden by the Ponga nappe and overriding the Pisuerga-Carrion province. From the stratigraphical point of view, the most striking characteristic is that the whole Carboniferous succession is developed in carbonate facies (MAAS, 1974; MARQUINEZ, 1978). The structure of the Picos de Europa also shows décollement and subsequent folding, but the décollement surface is at the level of the Visean condensed sequence, higher than the generalized décollement in the rest of the Cantabrian zone.

The Pisuerga-Carrion province is characterized by its peculiar facies, different from those of the rest of the Cantabrian zone. The Devonian and the Westphalian show the most striking differences of facies; the Devonian is found in pelagic Palentian facies (KULLMANN, 1963; BROUWER, 1964, 1968; VAN VEEN, 1965, LOBATO, 1977). The province also has an abundance of olistostromes and big limestone olistoliths in the Namurian and Westphalian. The structure shows a weak development of cleavage (SAVAGE, 1967; LOBATO, 1975).

Folds

Folds of several different trends and generations can be seen in the Cantabrian zone. In a somewhat schematic way, three kinds of folds can be considered (JULIVERT & MARCOS, 1973; JULIVERT, 1976).

(1) Folds facing towards the core of the Asturian arc (facing southeast), syngenetic with the décollement tangential structures. These folds are not widespread throughout the Cantabrian zone, but they are bounded to the northwestern part of the fold and nappe province, where the structure of décollement sheets change to a fold structure. They are asymmetrical or even recumbent folds, and in the area near the Narcea antiform they develop a slight cleavage. These folds correspond to the first folds and form the most relevant structures in the zones to the west.

(2) A set of folds trending more or less parallel to the outcrop traces of thrust and nappe surfaces, and facing in opposite direction, that is towards the convex part of the arc. These folds deform the nappes and thrust sheets, and in the northwestern part of the fold and nappe province, they deform the above-mentioned southeast facing folds (JULIVERT, 1976). In the areas near the Narcea antiform or in tight structures, a poorly developed cleavage (or a crenulation cleavage where a prior slaty cleavage exists) can be found. The position and shape of these folds is in some way controlled by the accumulation of anomalous thicknesses of sediments due to tectonic subsidence produced during nappe emplacement.

(3) A radial set of folds crossing the arched set and the outcrop traces of thrust and nappe surfaces roughly perpendicularly (except in the limbs of the arc). These folds show vertical axial surfaces and are generally less compressed than folds of the arched set. They are rather open parallel folds, only very locally showing a poorly developed cleavage. The crossing of both sets of folds gives way to many interference patterns (JULIVERT & MARCOS, 1973). Although age relationships between folds of both sets are not simple, the arched set predominated at the beginning of folding. As folding progressed, radial folds predominated. The arched set is most apparent in the core of the arc and vanishes towards the Narcea antiform; as a consequence, radial folds are predominant in the Ponga nappe, the Picos de Europa and the Pisuerga-Carrión provinces.

Late structures

Folding continued until very late in the Cantabrian zone, as shown by more or less intensively folded Stephanian B-C rocks. But the very late structures chiefly affect elongated zones, and are related to strike-slip movements. A very varied number of late structures exist, but the deformation did not effect the whole Cantabrian zone in a uniform way and a progressive change took place from fold to fault structures.

THE STRUCTURE OF THE WEST-ASTURIAN-LEONESE ZONE

Subdivision in provinces of the zone

The West-Asturian-Leonese zone is characterized by its regional metamorphism and by the general occurrence of cleavages. In most of the zone the rocks are in greenschist facies, although in the western part the sillimanite isograd is reached. In contrast to the Cantabrian zone, the West-Asturian-Leonese zone shows a more uniform lithology, with abundant pelitic sediments, but sequences of competent quartzitic layers alternating regularly with incompetent beds are very common. Differences in the stratigraphic succession as well as in the structure permit three provinces to be distinguished within the zone: the Navia province, the Mondonedo recumbent fold province and the Caurel-Truchas province (MARCOS, 1973). The eastern and western boundaries of the West-Asturian-Leonese zone are formed by two antiforms in whose cores Precambrian rocks outcrop: the Narcea and the 'Ollo de Sapo' antiforms.

The Navia province (MARCOS, 1973) is characterized by a very thick and complete Cambrian-Ordovician sequence. This province is the only one showing a complete Ordovician succession. The successions of the capes Peñas and Vidrias, although being located in the Cantabrian zone, represent the border of the depositional trough of the Navia province and are found in the Cantabrian zone due to the existence of an obliquity between structural and palaeogeographic trends. From the structural point of view, this province, like the whole West-Asturian-Leonese zone, differs from the Cantabrian zone by the development of cleavages, the flattened character of folds, and the absence of décollement structures. The folds in the Navia province are asymmetric eastfacing folds associated with an axial plane slaty cleavage (S_1), more or less modified by a new deformation (MARCOS, 1973) and associated with a steeply dipping crenulation cleavage (S_3).

The Mondoñedo and Caurel-Truchas provinces are characterized by their thinner and incomplete Ordovician succession. The Mondoñedo recumbent fold province is formed by several recumbent folds of different sizes (MATTE, 1964, 1967, 1968; WALTER, 1965, 1968; MARCOS, 1973; MARTINEZ-CATALAN ET AL., 1977; BASTIDA & PULGAR, 1978). An overthrust zone, the Oscos overthrust, forms the sole of this pile of folds (MARCOS, 1973), the more conspicuous of which is the Mondoñedo recumbent fold. This fold is the most westerly, and in consequence the highest of all the folds visible; its core is formed by Precambrian schists. To the west, a fault masks its relationships with the 'Ollo de Sapo' antiform.

The Caurel-Truchas province (RIEMER, 1965; MATTE, 1964, 1967, 1968; PEREZ-ESTAUN, 1978) is formed by the Caurel recumbent fold (MATTE, 1964) and its eastern extension, the Truchas area shows asymmetric folds (PEREZ-ESTAUN, 1978). The Mondoñedo and the Caurel recumbent folds exibit an *en echelon* arrangement and thus the two provinces characterized by these folds do not show a regular development along the arc.

Recumbent and asymmetric folds and east facing overthrusts

As in the Cantabrian zone the earlier tectonic phases of the West-Asturian-Leonese zone gave way to tangential structures. These are represented by recumbent and asymmetric folds and overthrusts facing eastwards.

The folds in the West-Asturian-Leonese zone are flattened flexural folds; at least those developed in the Cambrian-Early Ordovician sequence that consists of a regular alternation of competent and incompetent beds. These folds have been studied in the Mondoñedo recumbent fold province by BASTIDA & PULGAR (1978), where the interlimb angle can be as low as 10-30°. These folds are related to an axial-plane slaty cleavage (S_1), present in the West-Asturian-Leonese zone. The axial traces of the folds of this first generation describe the Asturian arch rather regularly. These folds are the first structures generated, and in consequence have been modified to varying extents by superposition of structures generated during later deformation phases: effects of later deformations chiefly affect the large folds. The tangential tectonics are represented not only by the folds referred to above, but also by important overthrusts facing towards the concave part of the Asturian arc (generally facing east). These overthrusts can be regarded as the last manifestation of the tangential tectonics, and are later than the east facing

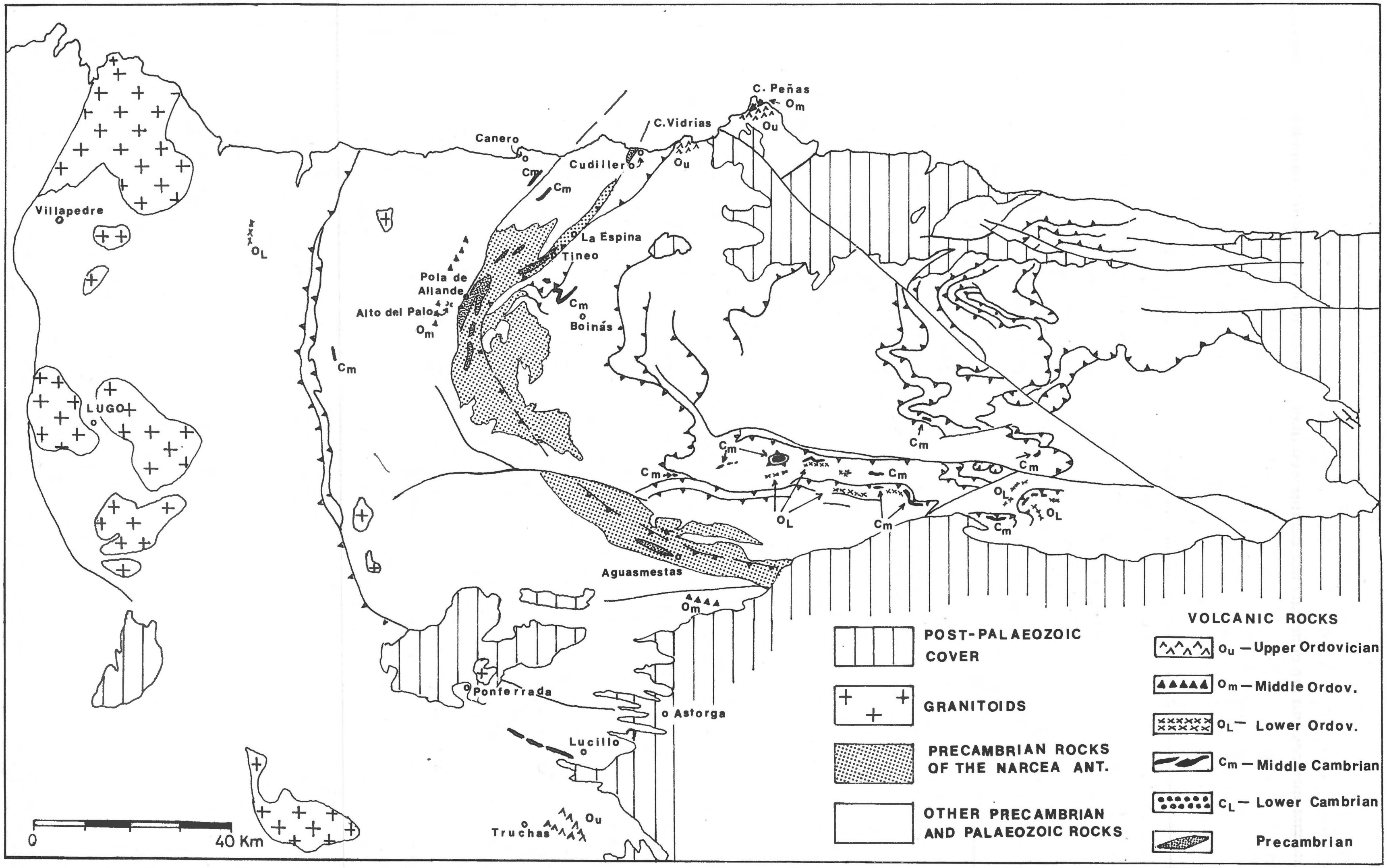


Fig. 9
Volcanism in the Cantabrian and West-Asturian-Leonese zones.

folds, although both events were probably not widely separated in time. Among the most important of these structures is the Mondoñedo basal thrust, forming the sole of the Mondoñedo recumbent fold. Another important overthrust is found along the Narcea antiform, giving rise to the overriding of the West-Asturian-Leonese zone over the Cantabrian zone and forming, strictly speaking, the boundary between both zones. Associated with these overthrusts, a second cleavage and asymmetric minor folds can be found. These structures are restricted to narrow zones along the thrusts and have been interpreted as generated in relation with shear zones (PEREZ-ESTAUN, 1978; BASTIDA & PULGAR, 1978).

Folds with steeply dipping axial planes and later structures

The tangential deformation phases were followed by a gentle folding of the zone. The new folds generated are nearly homo-axial with the first recumbent and asymmetric folds, and they have steep axial planes, generally facing westwards. A widespread crenulation cleavage (S_3) is related to these folds. This cleavage is very irregularly distributed, being very strong in some areas and very weak or nearly lacking in others. Kink bands are also very abundant in the West-Asturian-Leonese zone. Kink bands and crenulations are found alternately in parallel stripes throughout the zone, and although some differences can exist between them concerning the time of formation, all these structures seem to be closely related. Radial structures are less apparent in the West-Asturian-Leonese than in the Cantabrian zone, and no-large-scale cross-folding is found, although some axial plunges can be explained by transversal open folding. The most prominent radial structures are close joints, and in some areas vertical kink bands and even crenulations transverse to the general trend of the structures.

The latest structures found resulted from brittle deformation. Structures affecting Stephanian B-C rocks, present in some areas such as the surroundings of Ponferrada, are much less important and variable than in the Cantabrian zone.

MAGMATISM AND METAMORPHISM

Pre-orogenic volcanism was not very important in the West-Asturian-Leonese and the Cantabrian zones, although volcanic activity persisted from late Precambrian until Silurian times. Volcanic rocks are found in the following stratigraphic position and localities (Fig. 9):

(1) In the Precambrian of the Narcea antiform, in Aguasmestas, between Pola de Allande and Tineo, and in Cudillero, porphyroids occur resulting from the metamorphism of acid tuffs, and some rhyolites and rhyodacites (FARBER &JARITZ, 1964; VAN DEN BOSCH, 1969, p. 142; PEREZ-ESTAUN, 1973; PEREZ-ESTAUN & MARTINEZ, 1978). The 'Ollo de Sapo' porphyroidic formation, at the western boundary of the West-Asturian-Leonese zone is thought to originate partly from arkosic and partly from rhyolitic tuffaceous material (LOTZE, 1945-a, 1966; RIEMER, 1963; PAEGA ET AL., 1964).

(2) In the Middle Cambrian, in the lower part of the Oville Formation (DE SITTER, 1962, RUPKE, 1965; EVERS, 1967; MARCOS, 1968; etc.), especially in the fold and nappe province (Cantabrian zone), a suite embracing intermediate (traquites; GARCIA DE FIGUEROLA & PARGA-PONDAL, 1964) to basic rocks (olivine basalts) has been found; the most important occurrence of these rocks is found between Boinas and Tineo (GARCIA DE FIGUEROLA & PARGA-PONDAL, 1964; JULIVERT ET AL., 1977). Similar rocks, in similar stratigraphic positions, have been recorded in the western limb of the Narcea antiform, between la Espina and Canero (JULIVERT ET AL., 1977) and in the West-Asturian-Leonese zone, west of Astorga (NOLLAU, 1968).

(3) In the Lower Ordovician, in several localities of the fold and nappe province (COMTE, 1959; DE SITTER, 1962; RUPKE, 1965; EVERS, 1967; etc.), the same types of rocks (basic sills and effusive rocks and tuffs) occur interbedded in the Barrios quartzite.

(4) In the Llanvirn-early Llandeilian black slates (Luarca slates), basic igneous sills and/or flows have been observed in the Cantabrian zone, in the Cape Peñas (JULIVERT & TRUYOLS 1972) and in the West-Asturian-Leonese zone, along the western limb of the Narcea antiform (near the Alto del Palo and in its southeastern end (PEREZ-ESTAUN, 1968).

(5) In the Upper Ordovocian in the capes Peñas and Vidrias, a thick succession (500 m in Peñas and 150 m in Vidrias) is found, including lava flows in its upper part (JULIVERT & TRUYOLS, 1976; JULIVERT ET AL., 1973), as well as in the Truchas syncline (MATTE, 1964; PEREZ-ESTAUN, 1974-b), and in the West-Asturian-Leonese zone, although the latter is perhaps a little older.

(6) Volcanic rocks have also been found in the Silurian, in the Formigoso shales (MARCOS, 1968), and in the Furada-San Pedro Formation, as minor components in the sandstones (COMTE, 1959), and in some localities of the West-Asturian-Leonese zone (CAPDEVILA, 1969). The Silurian volcanism is of little importance in the zones considered, but becomes much more important towards the west and southwest.

The plutonism in the Cantabrian and West-Asturian-Leonese zones is also of minor extension (Fig. 10). Only to the west, in the Mondoñedo recumbent fold province has it some importance. East of this province several little stocks occur in the Navia province (LLOPIS-LLADO, 1961; SUAREZ, 1971-a) and one in the core of the Narcea antiform (SUAREZ, 1971-b). Further east, a few very small bodies are found in the fold and nappe province, between Belmonte and Salas (CORRETGE,

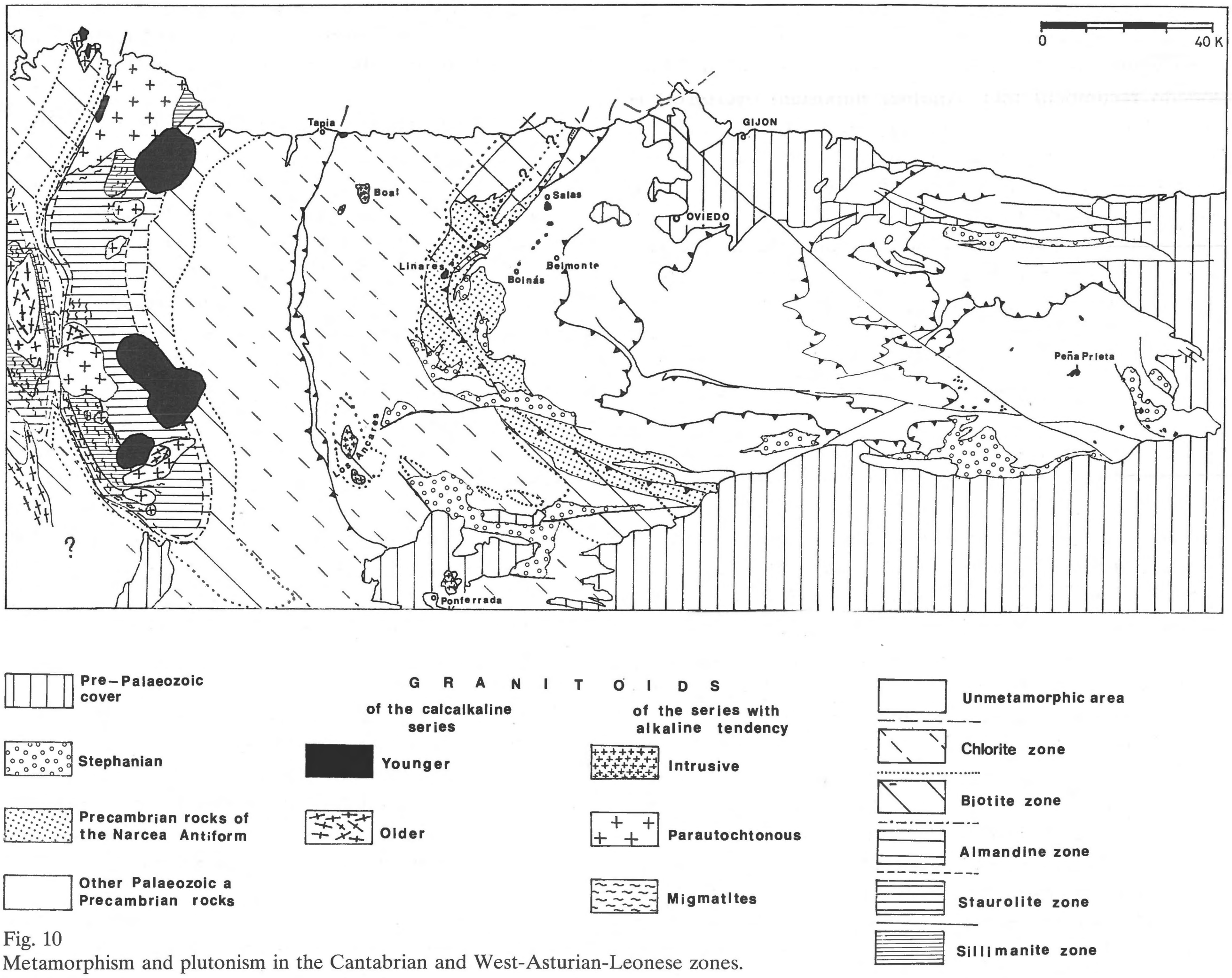


Fig. 10
Metamorphism and plutonism in the Cantabrian and West-Asturian-Leonese zones.

1969; CORRETGE ET AL., 1970) and in the Pisuerga-Carrion province (DE SITTER, 1962) as in Peña Prieta where a number of dykes connected with it exist. Granitoid rocks in the northern part of the Iberian Peninsula have been divided into two series (CAPDEVILA & FLOOR, 1970; CAPDEVILLA ET AL., 1973; MARTINEZ, 1974), a calcalkaline series and a series with an alkaline tendency. In the first series an older (generally intrusive in high-grade metamorphic zones) and a late intrusion (posttectonic granodiorites, with induced metamorphism in the host rock) can be distinguished. The series with alkaline tendency is closely related to the regional metamorphism and is formed by different types of granites (from autochthonous to intrusive bodies), showing different relationships with the deformation.

Although the great development of granitoids is to be found more to the west and to the south, in the Galician-Castilian subzone, in the Mondoñedo recumbent fold province and in the 'Ollo de Sapo' anticline the two series of granitoids occur.

The granitoids of the series with alkaline tendency are related to the migmatisation. The migmatite front is found near the sillimanite isograd and migmatites occur in several areas, but anatectic autochthonous granites are not observed (CAPDEVILA, 1969). The granites of this series are present as parautochthonous bodies in the Mondoñedo recumbent fold area and in the 'Ollo de Sapo' antiform. Intrusive bodies exist in the same areas (CAPDEVILA, 1969) and more to the east form the small stocks of Ponferrada, Campo de Agua, Ancares and Boal (SUAREZ, 1970, 1971-b); these granites are often associated to mineralisation of Sn and W.

The granitoids of the calcalkaline series can be divided into older and younger granodiorites. The first form only a few bodies in the Mondoñedo recumbent fold area and in the 'Ollo de Sapo' antiform (CAPDEVILA, 1969), although they are more abundant in the Galician-Castilian subzone. The younger granodiorites in the Mondoñedo recumbent fold area form several round shaped bodies, with a diameter of some 15-20 km. More to the east, little stocks of more or less similar rocks are found in the surroundings of Tapia de Casariego (hypersthene-granodiorites and gabbros): SUAREZ & SUAREZ, 1970), in the Narcea antiform, in Linares (SUAREZ, 1971-a), and between Belmonte and Salas, which form several very small outcrops of hypersthene-gabbro, diorite and granodiorite (CORRETGE, 1969; CORRETGE & LUQUE, 1970). Finally, the small bodies of the Pisuerga-Carrion province are also of the granodioritic type.

The metamorphism is plurifacial and ranges in grade from intermediate to low pressure. It has been studied in Galicia by Den Tex and coworkers (see DEN TEX, 1966; DEN TEX & FLOOR, 1971). In the West-Asturian-Leonese zone it has been studied by CAPDEVILA (1969). Considering the Cantabrian and West-Asturian-Leonese zone a general increase in metamorphism from east to west is observed: the Cantabrian zone locks significant metamorphism (chloritoid is found in the Pisuerga-Carrion province) and the West-Asturian-Leonese zone shows metamorphism in greenschist and low-grade amphibolite facies, except in its western part (Mondoñedo recumbent fold) where the sillimanite isograd is reached. Nevertheless, if the whole northern part of the Iberian massif is considered it can be seen that although an increase of metamorphism exists from the external (Cantabrian) towards the internal (Galician-Castilian) zones of the chain, the zones of high-grade metamorphism form several elliptic areas, indicating several thermal domes. The metamorphic area of the Mondoñedo recumbent fold has these characteristics also.

AGE OF DEFORMATION AND GEOLOGICAL HISTORY

Carboniferous rocks are widespread in the Cantabrian zone and the Carboniferous system is virtually complete; in consequence, the age of deformation can be determined from unconformities. From the study of the Carboniferous facies and unconformities in the Cantabrian zone, the following conclusions can be reached.

(1) The first record of instability in the basin is provided by the Namurian turbidites and olistostromes. These probably reflect deformation in more internal areas.

(2) The Palaeozoic succession is conformable throughout the Cantabrian zone until the Namurian (or the Westphalian A). The first unconformity is found below the Upper Westphalian B, in the Pisuerga-Carrion area.

(3) The nappes were emplaced and folded before the late Westphalian D, as shown in the Esla nappe (RUPKE, 1965, ARBOLEYA, 1978).

(4) The structure of the chain was essentially built before late Westphalian D times. This is shown by the fact that late Westphalian D and Stephanian rocks occur throughout the different provinces of the Cantabrian zone and cross their boundaries, while in the older terrains the facies distribution coincides with the Cantabrian provinces.

(5) Stephanian rocks are also deformed, but deformation did not uniformly affect the whole zone, being chiefly concentrated along narrow zones, in relation with strike-slip faults. Stephanian B-C outcrops are chiefly found along strike-slip fault zones.

All this indicates that deformation in the Cantabrian zone took place during Westphalian times. Deformation started with décollement and nappe emplacement and changed progressively to folding, starting with the generation of the arched set of folds and followed by the generation of the radial cross-set. All these events, which affected the whole Cantabrian zone, were completed before late Westphalian D times; later , some deformation still took place, but this was concentrated chiefly along fault zones.

In more internal parts (West-Asturian-Leonese and Central-Iberian zones), the age of deformation is more uncertain, due to the lack of well dated Carboniferous rocks older than the Stephanian B-C. The Stephanian B-C, present in several localities, especially in the Ponferrada area, rests unconformably on older rocks and is nearly undeformed. This indicates that in the West-Asturian-Leonese zone, as in the Cantabrian, deformation is older than the Stephanian. Additional evidence on the age of deformation is provided by radiometric dating of granites (PRIEM ET AL., 1967, 1970). Posttectonic undeformed granitoids give an age coinciding with the Stephanian-Permian boundary, and more or less deformed granites give a Westphalian age (ages ranging from 296 ± 13 to 307 ± 3 Ma for granites of the series with alkaline tendency and ages from 307 ± 4 to 312 ± 7 Ma for the older granodiorites). This provides information for the later phases as they are always younger than the first phase, and indicate a Westphalian age, that is a similar deformation age as in the Cantabrian zone.

Nevertheless the beginning of deformation (first phase) in the internal zones of the chain was probably earlier than in the Cantabrian zone, perhaps during Early Carboniferous or Late Devonian times. Supporting this interpretation the existence in western Galicia of some granites giving ages between 330 and 369 Ma (average 349 ± 10 Ma) can be mentioned, together with the displacement during the Carboniferous of the turbiditic culm (flysch) facies from the internal zones towards the Cantabrian zone, indicating a migration of deformation.

Metamorphism started with the first deformation and reached its climax during the interphase 1-2, or during the beginning of the second phase (shear zones and overthrusts) (BASTIDA & PULGAR, 1978). As migmatisation and formation of autochthonous granites (found more to the west) coincide with the climax of the metamorphism (CAPDEVILLA, 1969), the same age must be assigned to the anatexis, although intrusive granites of the series with alkaline tendency can give later ages. For this reason the granites of this series show a different relationship with deformation.

CONCLUSIONS

The cross-section (Encl. I) described in this paper shows the disposition peculiar to linear fold belts, with an external part, containing carbonate and terrigenous varied platform facies without cleavage, metamorphism and plutonism, and an internal part with more monotonous and more pelitic facies and with widespread cleavage, metamorphism and plutonism.

On the basis of sedimentary facies, structural, metamorphic and magmatic characteristics, several zones and provinces can be distinguished, in a similar way to the well known Kossmat zonation of central Europe and Lotze's zonation of the Iberian Massif. The zones and provinces form elongated belts that can be followed for long distances; the first-order zones can even be extended to the neighbouring massifs. These zones are parallel to the trend of the Variscan structures and both describe an arc with its concavity towards the eastern, external part of the chain.

During the pre-Carboniferous Palaeozoic there is evidence of continued uplift towards the core of the arc (external part of the chain). There is also evidence of supply of terrigenous material from the core of the arc until the beginning of the Carboniferous times.

The nature of the Proterozoic crust in the Variscan domain of Europe is still controversial, as well as the collisional or Andean character of the chain, or even the validity of the plate-tectonic model for the Variscan Fold Belt (see discussion in ZWART & DORNSIEPEN, 1978). As the scope of this paper is to describe a particular section of the chain, only considerations strictly affecting the area have been dealt with. In this respect it is interesting to point out that the facies distribution in the Cantabrian zone indicates the existence towards the core of the Ibero-Armorican arc of an emerged continental area; this area might be of lesser microcontinental extent.

The structure is essentially linear in all the sections described, and this is observed in the trace of Variscan structures and in the trace of palaeogeographic units. Nevertheless, in detail there are many structures that to some extent obscure this linear arrangement. These are dome and basin structures that originated from tectonic overlapping and anomalous local thickening of the stratigraphic succession or from superimposition of cross folds (see Fig. 8).

The general disposition of metamorphism and plutonism is in accordance with the above conclusions; both show an increase from external to internal parts, and in addition the axis of high-grade metamorphic and abundant plutonism can be traced along the whole Variscan Fold Belt. Nevertheless, in detail high-grade metamorphic zones form elliptic areas showing the existence of different thermal dones. In the section described there is one such thermal dome, coinciding with a zone of tectonic stacking of recumbent folds.

In the geological history of the area, there is a break more or less coinciding with the Devonian-Carboniferous boundary. This is shown by the change of direction of terrigenous supply (coming from the internal zones of the chain during the Carboniferous), and by change from anorogenic to orogenic conditions, leading to folding and the development of the metamorphism and plutonism of Variscan age.

All this indicates a change in tectonic regime. Before the Carboniferous (or the Late Devonian) the evolution of the area could be explained by a tensional regime, giving way to synsedimentary volcanism, the peralkaline granites of Galicia and northern Portugal, and early Palaeozoic thermal events. The importance of thermal events and the importance and origin of early Palaeozoic granitoids is still uncertain (see discussion in ZWART & DORNSIEPEN, 1978). Since the beginning of the Carboniferous or the Late Devonian, the control of the geological evolution of the area is to be found in compressional orogenic processes.

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