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BASEMENT EVOLUTION IN THE NORTHERN HESPERIAN MASSIF. A PRELIMINARY SURVEY OF RESULTS OBTAINED BY THE LEIDEN RESEARCH GROUP

BY

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ABSTRACT

Historical notes on Galician geology, and on the work of the Leiden University petrology team in particular, are first provided. This is followed by an introduction to the geology of Galicia with emphasis on its crystalline basement and upper mantle inliers.

Six lithotectonic units are distinguished: 1) the Variscan granitic rocks and migmatites, 2) the Palaeozoic supracrustal rocks and dismembered meta-ophiolites, 3) the blastomylonitic graben between Malpica and Tuy, 4) the Lalín and Forcarey Units, 5) the Ordenes basin and its meso-catazonal peripheral belt, 6) the predominantly mafic-ultramafic catazonal complex at Cabo Ortegal.

The supracrustal history of western Galicia in late Precambrian and early Palaeozoic times, as inferred from neighbouring areas, is briefly outlined and is compared with the igneous, tectonic and metamorphic evolution of the upper mantle and lower crustal rocks contained in the polymetamorphic basement complexes (1–4), which have sustained high-pressure and high-temperature metamorphism under a flow-folding regime prior to the Variscan orogeny. Several models proposed for the development of the basement complexes in the northern Hesperian Massif are briefly discussed. It is considered most likely that an early Palaeozoic rift system caused by mantle plume diapirism, and accompanied by deepseated thermal metamorphism, lower crustal recycling, updoming of the crust and incipient sea floor spreading, was closely followed by Variscan low-pressure metamorphism, migmatization and granite emplacement under an intermittently compressive and dilatational tectonic regime. Finally, the probability of a Precambrian orogenic crust in western Galicia is briefly explored.

CONTENTS

1. HISTORICAL NOTES

Schulz (1835) was the first geologist to mention the presence of a 'primitive terrain' (read: Precambrian basement) in Galicia in which he defined e.g. the 'formacion de Lage'. This primitive terrain was subdivided by Ch. Barrois (1882) in eastern, and by J. McPherson (1881, 1883) in western Galicia to comprise the following formations: 1) granitic and augen-gneisses, 2) green rocks, chlorite- and talc-schists, and 3) micaschists of Villalba. McPherson distinguished garnet-bearing gneisses and amphibolites, granulites, eclogites, kinzigites and serpentinites at Cabo Ortegal, and what he called glaucophane-bearing syenitic gneisses in the vicinity of Vigo. He inferred the activity of an Archaean orogeny to explain the nature and setting of these rocks. A porphyroid formation of infra-Cambrian age, locally known as 'Ollo de Sapo', was first described by Sampelayo (1922). From 1929 onward extensive contributions to the geology of Galicia were made by Dr. I. Parga Pondal. This eminent geologist produced six map sheets of western Galicia on a scale of 1:50,000, a 1:200,000 map of the Province of La Coruña, and a 1:500,000 map of the NW Iberian Peninsula. He also (re-) defined the following rock units: Formacion de Lage, Ollo de Sapo, Complejo Antiguo (ancient rock complex between Malpica and Tuy), Esquistos de Ordenes (schists around Ordenes), Lopolito de Rocas Basicas (lopolith of basic rocks around the Ordenes basin), and the eastern granite and schist terrain.

In 1955 the Department of Structural Geology in the State

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University at Leiden commenced detailed mapping in the ancient complex under the direction of L. U. de Sitter, followed in 1957 by W. P. de Roever, with graduate students of the Petrology Department in that university, at Cabo Ortegal, and on the peralkaline gneisses near Vigo. The present author succeeded de Roever in 1959 and took over the direction of the Galician research group at Leiden. Systematic mapping of western Galicia on a scale of 1:25,000 was initiated in that year. Geochronological work by the Z.W.O. Laboratory for Isotope Geology at Amsterdam was initiated in 1961 under the direction of H. N. A. Priem. Gravity surveys of key areas were carried out since 1968 by the Department of Geophysics and Hydrogeology in the State University at Leiden directed by J. G. Hagedoorn, while structural and geochemical investigations were occasionally performed in collaboration with H. J. Zwart and C. J. L. Wilson of the Department of Tectonics in the State University at Leiden, and with H. A. Das of the Energy Research Centre of the Netherlands at Petten respectively.

Since 1955 over a hundred unpublished M. Sc. theses* and ten published Ph. D. theses have appeared on areas or problems concerning western Galician geology. A close collaboration with the Laboratorio Geologico de Lage of Dr. Parga Pondal was maintained throughout. The mapping campaign was terminated in 1973 and a geological synthesis is now in preparation. Eight map sheets of western Galicia on a scale of 1:100,000 are being published by the Galician research group. An E–W cross section on the same scale has been prepared for the 1977 Meeting at Göttingen of the studygroup 'Variscan Orogeny in Europe' within Working Group 9 of the Inter-Union Geodynamics Project. In 1977 the Galician research group organized the Fifth Reunion on the Geology of the western Iberian Peninsula with the mafic/ultramafic rocks of western Galicia as main theme (Arps et al., 1977).

2. GEOLOGICAL INTRODUCTION

A broad orogenic belt of predominantly Variscan age, known as the Hesperian Massif, occupies the western perimeter of the Iberian Peninsula (Fig. 1). Its northern extremity is situated in the former kingdom Galicia in NW Spain. Western Galicia, with the provinces Pontevedra and La Coruña and parts of Lugo and Orense, constitutes the axial zone. It consists of a geanticlinal ridge flanked on either side by the geosynclinal troughs of eastern Galicia and SW Portugal, in which thick accumulations of Upper Proterozoic and Palaeozoic sediments and volcanics have been preserved. An (infra-) Cambrian volcanodetrital molasse deposit forms an antiformal belt of outcrops between the NE geosynclinal and the axial zone in western Galicia and northern Portugal (Parga Pondal et al., 1964; Parga & Vegas, 1971; Bard et al., 1972; Fontboté & Julivert, 1974). It indicates substantial uplift and erosion of a Precambrian granitic crust in what was to become the axial zone of the Variscan orogen. The geanticlinal character of this zone is further substantiated by its bimodal volcanic content,

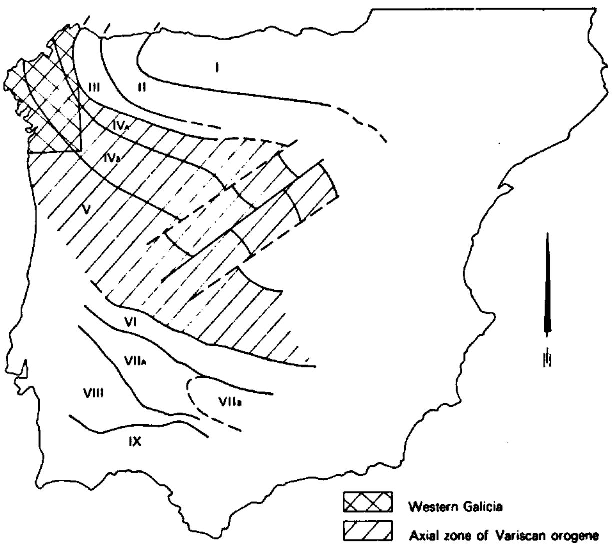

Fig. 1. Locality map of the Hesperian Massif showing its division in palaeogeographic zones. After Bard et al. (1972).

by strongly reduced thicknesses of Lower Palaeozoic sequences, and by the complete absence of Upper Palaeozoic supracrustal rocks in western Galicia (Fig. 2).

3. SUPRACRUSTAL HISTORY OF NW SPAIN

Comprehensive cross-sections through eastern Galicia, Asturias and Cantabria compiled by Matte (1968), Julivert et al. (1972) and van der Meer Mohr (1975) indicate the presence of extensive shallow seas in late Proterozoic and early Cambrian times, followed by the development first of an important clastic wedge on a westward dipping slope during the late Cambrian and early Ordovician, then by euxinic and turbiditic conditions during the middle and late Ordovician, and terminated by the return of extensive shallow seas in the Silurian (van der Meer Mohr, 1975, and pers. comm., 1977) (Fig. 3). Sedimentation gaps, locally accompanied by slight

Fig. 2. Geological map of the NW Iberian Peninsula. After Carte géologique du Nord Ouest de la Peninsule Ibérique au 500.000 me. From Engels (1972).

Legend: 1–7: Variscan rocks, 1: gabbro, 2–3 calcalkaline granite series (2: postkinematic biotite granite, 3: interkinematic biotite granodiorite), 4–7 alkaline granite series (4: postkinematic two-mica granites, 5: interkinematic two-mica granites, 6: inhomogeneous migmatic granites, 7: migmatites), 8–12: Upper Precambrian and Lower Palaeozoic (meta-)sediments (8: Ordovician younger than Armorican quartzite – and Silurian, 9: Cambrian, Ordovician up to Armorican quartzite inclusive (Spain), Complexo Xisto-grauvaquico ante-ordovicico (Portugal), 10: Upper Precambrian (fine-grained facies), 11: Upper Precambrian (Ollo de Sapo facies), 12: undifferentiated metasediments), 13: coarse-grained augengneiss, 14: probably younger Precambrian metasediments and late Ordovician orthogneiss (undifferentiated), 15: polymetamorphic metasediments, 16: metabasic rocks (partly polymetamorphic), 17: ultramafic rocks (partly polymetamorphic).

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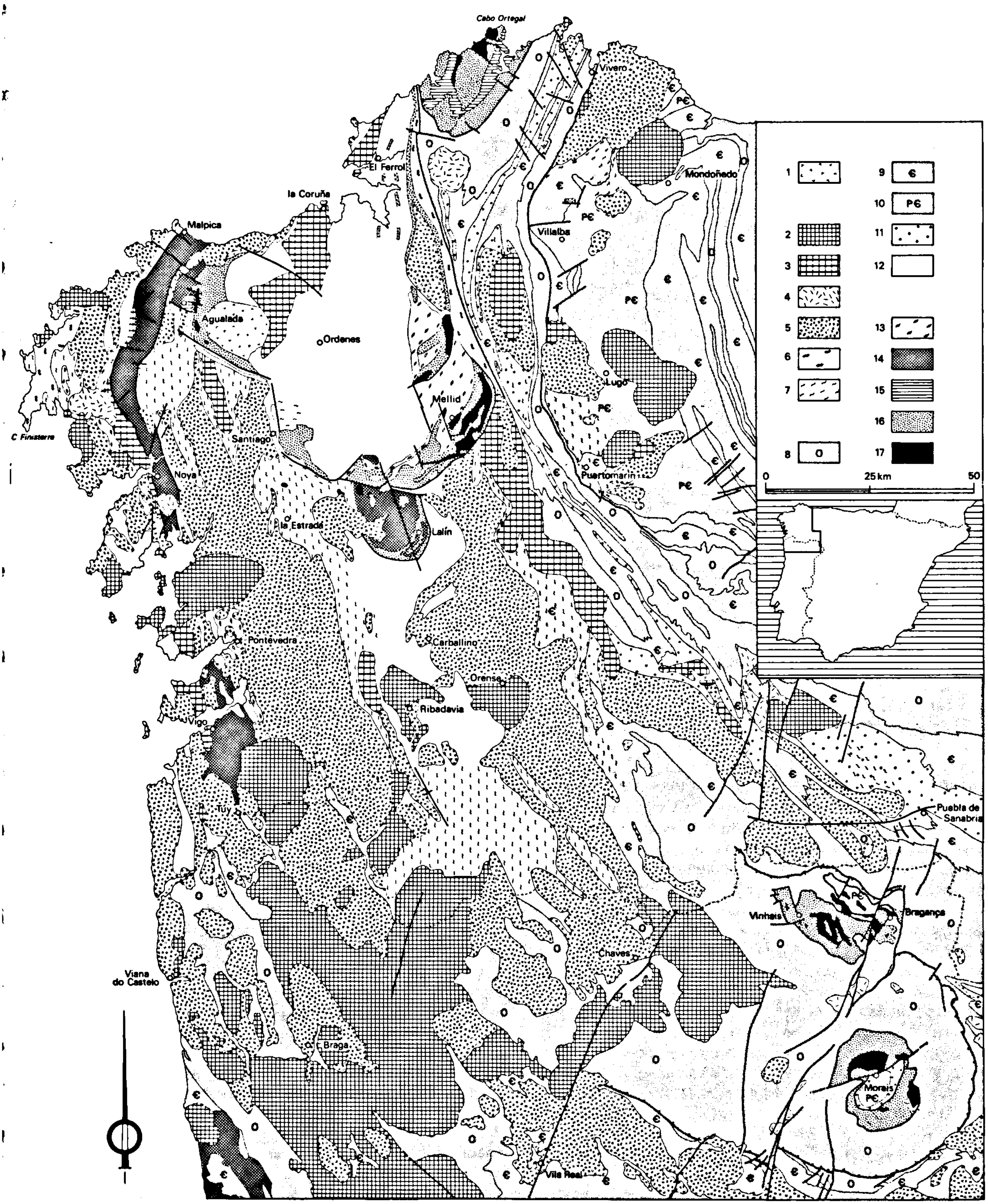
* The M. Sc. theses are written in Dutch. They may be consulted at the National Museum of Geology and Mineralogy, Garenmarkt 1b, Leiden, or may be obtained in photocopy at the expense of the applicant.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Vivero
El Ferrol
Mondoñedo
la Coruña
Malpica
Villalba
Agualada
Ordenes
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C Finisterre
Santiago
Noya
Puertomarin
la Estrada
Lalín
Pontevedra
Carballino
Orense
Ribadavia
Vigo
Tuy
Puebla de Sanabria
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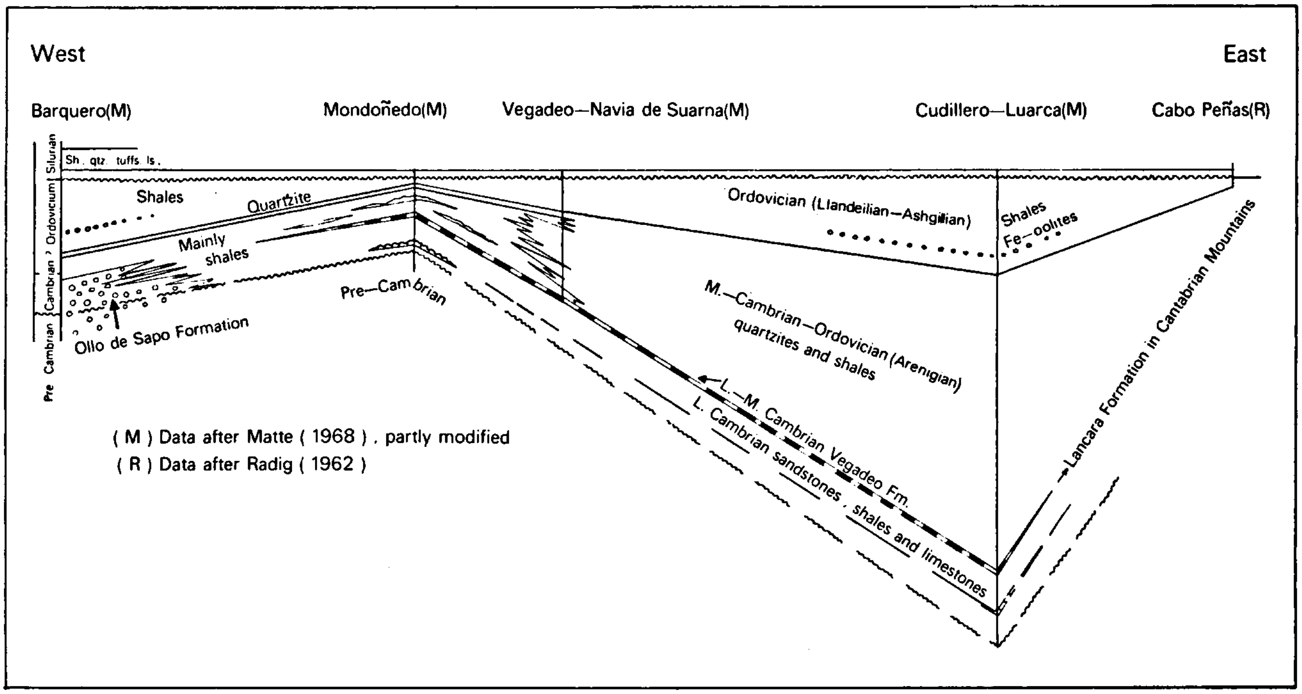

Fig.3. Stratigraphic cross-section of the Lower Palaeozoic strata between Cabo de Peñas and the antiform of Barquero, just E of the Cabo Ortegal Complex. From van der Meer Mohr (1975).

angular unconformities, predominantly monomictic conglomerates, and felsic volcanics, have been reported from the Upper Cambrian and from the Ordovician/Silurian transition zone. The latter hiatus is widespread and may extend from the Arenig to the lowermost Devonian. Near San Vitero, in the province of Zamora, it is terminated by polymictic conglomerate horizons containing deformed and metamorphic pebbles derived from Lower Ordovician and older formations (Martinez Garcia, 1972; Aldaya et al., 1976). Although it is clear that penetrative deformation and regional metamorphism of intermediate pressure type must have occurred in early Palaeozoic time (see also Capdevila, 1965; Aldaya et al., 1973), Martinez Garcia's implication of a Caledonian orogenic cycle in NW Spain is unwarranted, since evidence of large-scale compressive tectonics and uplift of a mountain range of that age is lacking. In our opinion the early Palaeozoic geography of NW Spain is rather reminiscent of a segment of continental crust with marine incursions owing to taphrogenic movements like block-faulting and flexuring.

The axial zone of the northern Hesperian Massif contains numerous inliers of upper mantle and lower to middle crustal material in polyphase tectonic and poly-metamorphic facies suggesting high pressures and temperatures of formation and subsequent retrogradation. They are arranged in more or less linear belts tectonically juxtaposed with non- or monometamorphic Upper Proterozoic and Palaeozoic sediments, volcanics, migmatites and granites (Fig. 4).

4. LITHOTECTONIC UNITS

Six lithotectonic units may be distinguished in western Galicia, four of which are polyphase tectonic and polymetamorphic basement inliers. Two are mono- or non-metamorphic. The summary starts with the latter, placing more emphasis on the basement inliers later on.

4.1. The Variscan granitic rocks and migmatites

In Galicia and northern Portugal two main types of Variscan granitic rocks have been recognized: 1) predominantly biotite-bearing calcalkaline granites and granodiorites with a subcalcic plagioclase (An_{10-40}), and 2) predominantly two-mica-bearing alkaline granites carrying albite or albite-oligoclase (An_{0-20}) (Fig. 5).

The first type is rarely associated with granitic migmatites, pegmatites, quartz veins and ore mineralizations of any kind. In Galicia its intrusion may be either inter- or post-kinematic in relation to the two main phases of Variscan deformation. The inter-kinematic type is locally associated with leucocratic microgranites and with tourmaline-, garnet- or beryl-bearing aplites.

The second main type of granite frequently grades into granitic migmatites and is abundantly associated with pegmatites, quartz veins and Sn-, W- and Li-mineralizations (Ypma, 1966; Hensen, 1967; Hilgen, 1970). It is almost exclusively interkinematic, i.e. emplaced between the first and second phase of Variscan deformation (Capdevila & Floor, 1970; Floor, 1970; Floor, Kisch & Oen Ing Soen, 1970; Capdevila, Corretge & Floor, 1973) (Fig. 6).

Rb-Sr whole rock isochron ages have been determined at 316 ± 10 Ma for the interkinematic alkaline and calcalkaline granites, and at 297 ± 11 Ma for the post-second phase calcalkaline granites (Priem et al., 1970; van Calsteren et al., 1979).

Variscan granitic rocks are distributed widely throughout

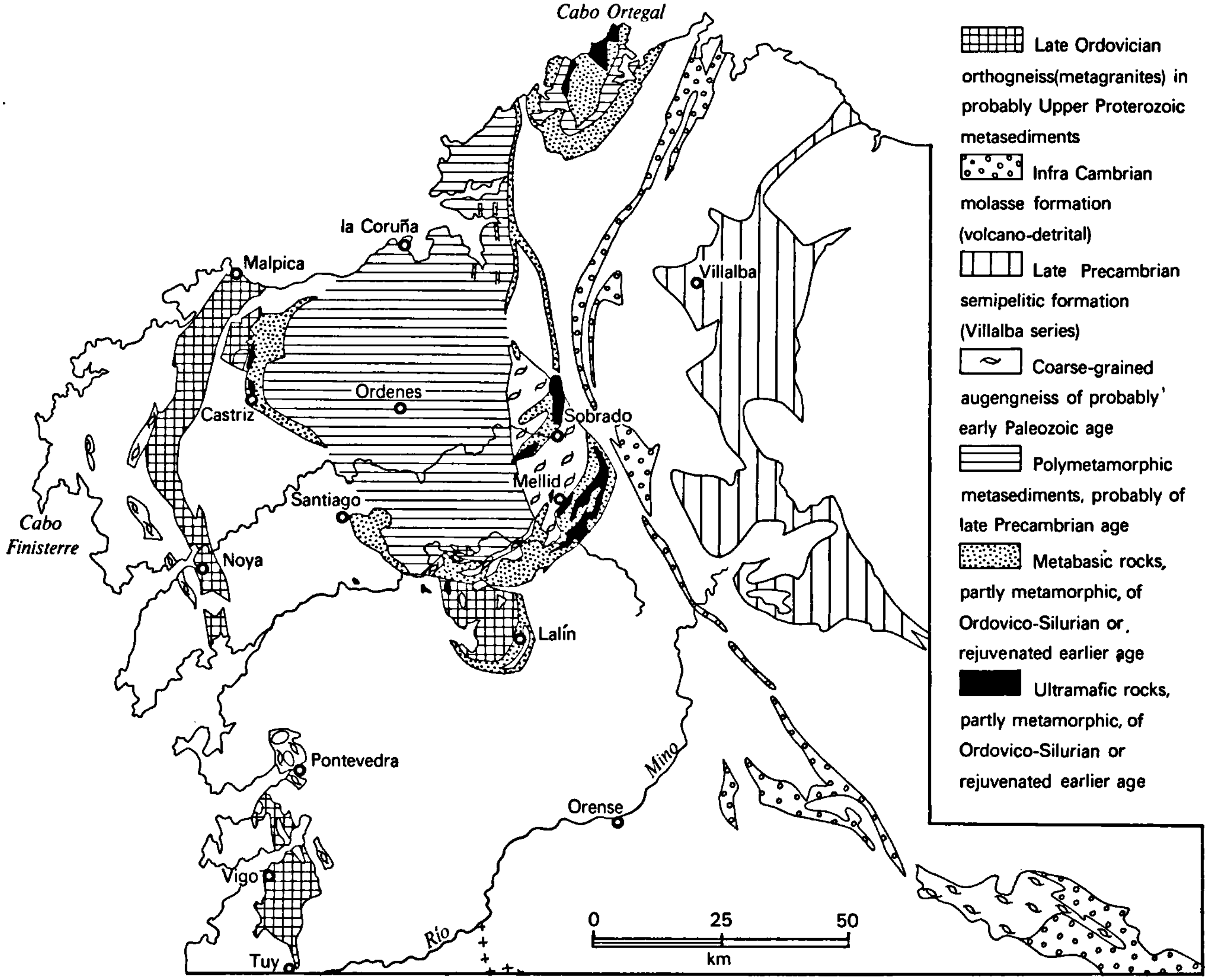

Fig. 4. Map showing the distribution of polymetamorphic basement inliers, of molasse and flyschoid deposits of Upper Precambrian age, and of Ordovico-Silurian orthogneisses set in probably Upper Precambrian metasediments. From Den Tex (1976). Data after Den Tex & Floor (1967) and Bard et al. (1972).

the axial zone of the northern Hesperian Massif, but they occur rarely within the polymetamorphic basement inliers mentioned below. A distinct preference for fundamental faults, such as the boundary faults of the blastomylonitic graben is displayed by the interkinematic calcalkaline granites (Den Tex, 1974), while the postkinematic granites frequently form composite bodies of subcircular or concentrical outcrop.

4.2. The Palaeozoic supracrustal rocks and dismembered meta-ophiolites

In westernmost Galicia (Fig. 7) the presence of Palaeozoic supracrustal rocks is based on lithostratigraphic correlations only, no identifiable fossils having been found in them. Monometamorphic (semi-) pelitic schists with quartzose or feldspathic laminae, white and black quartzites, anthracite schists, amphibolites, calcsilicate rocks and iron-rich horizons occur mainly south of the Ria de Muros y Noya in a submeridional belt near the Atlantic coast. This belt continues into NW Portugal where A. Ribeiro (pers. comm., 1972; 1974) has reported fossil ages ranging from the Cambrian to the Silurian for the various formations involved. Similar but rather less variable rock types are found in the central Galician schist area between Forcarey, Lalín, Carballino and Avion. A low-pressure plurifacial metamorphism has affected these rocks giving rise to chlorite, biotite I & II, garnet, staurolite, and andalusite I & II in pelitic rock types. This took place mainly before the second tectonic phase in a stratigraphic sequence previously disturbed by the first and main phase of Variscan deformation (Hilgen, 1971; van Meerbeke et al., 1973; Aldaya et al., 1973; Minnigh, 1975).

Further to the NE anchi- to low-grade metamorphic supracrustals of Ordovician and Silurian ages have been identified in the northwestern limb of the Barquero antiform (Matte, 1968). The sediments occurring here are rather similar to those found in the areas mentioned above, but they are interstratified with and overlain by arkoses, crinoidal lime-

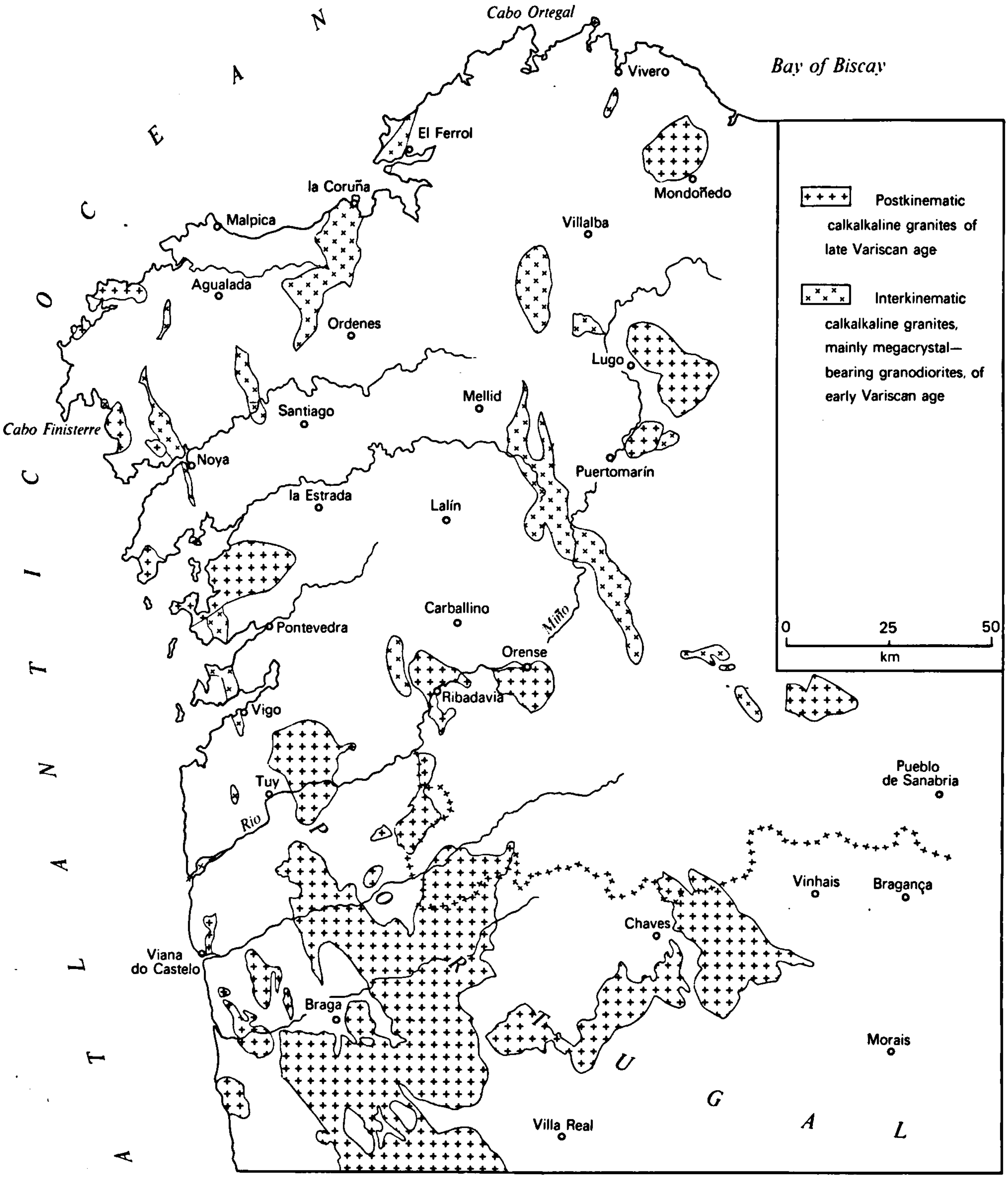

Fig. 5. Distribution map of the calcalkaline biotite granites and granodiorites in the NW Iberian Peninsula. From Den Tex (1977). Data after Carte Géol. du NO de la Péninsule Ibérique au 500.000 me. by I. Parga Pondal et al. (1967).

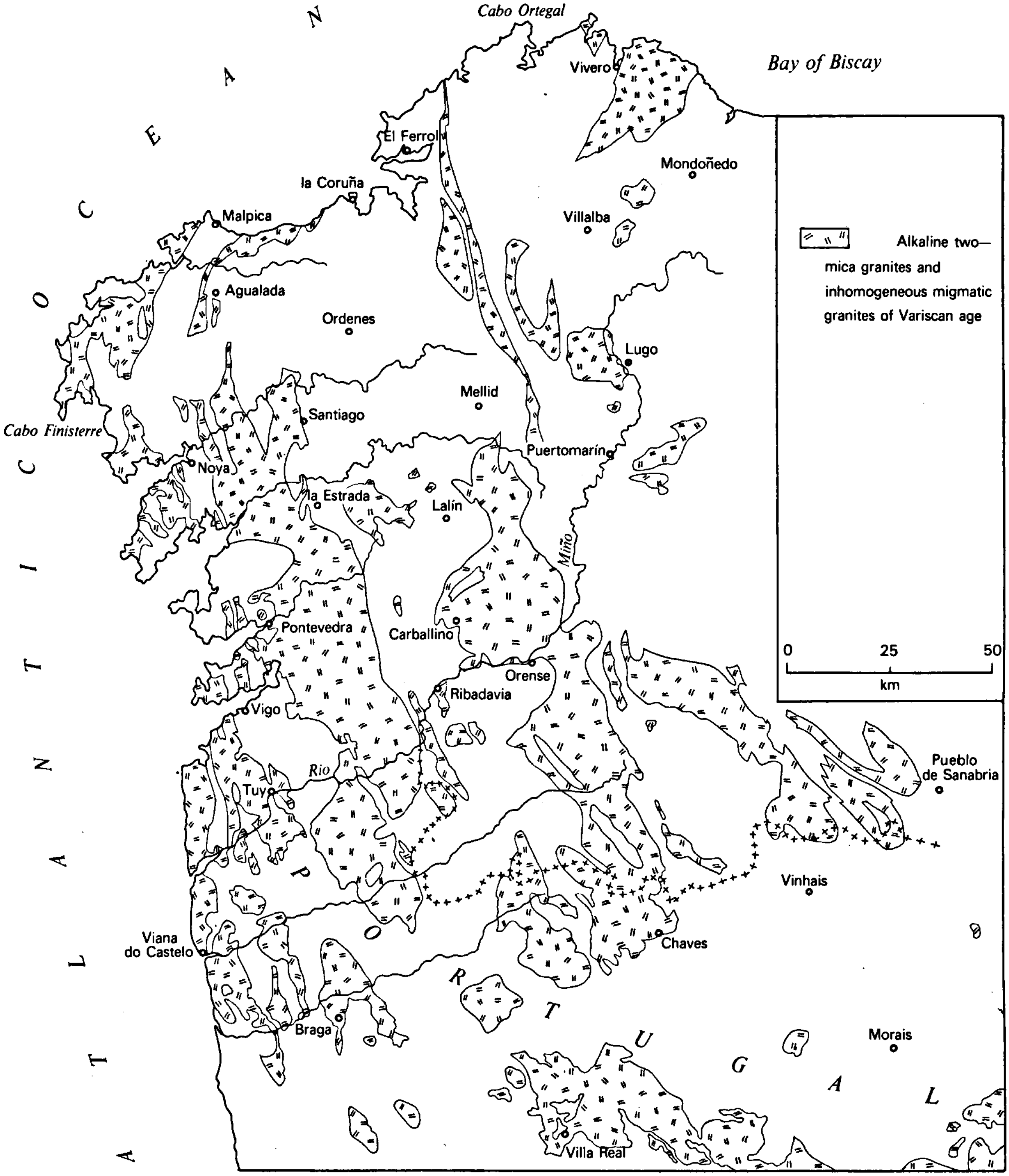

Fig. 6. Distribution map of the alkaline two mica granites in the NW Iberian Peninsula. From Den Tex (1977). Data after same source as Fig. 5.

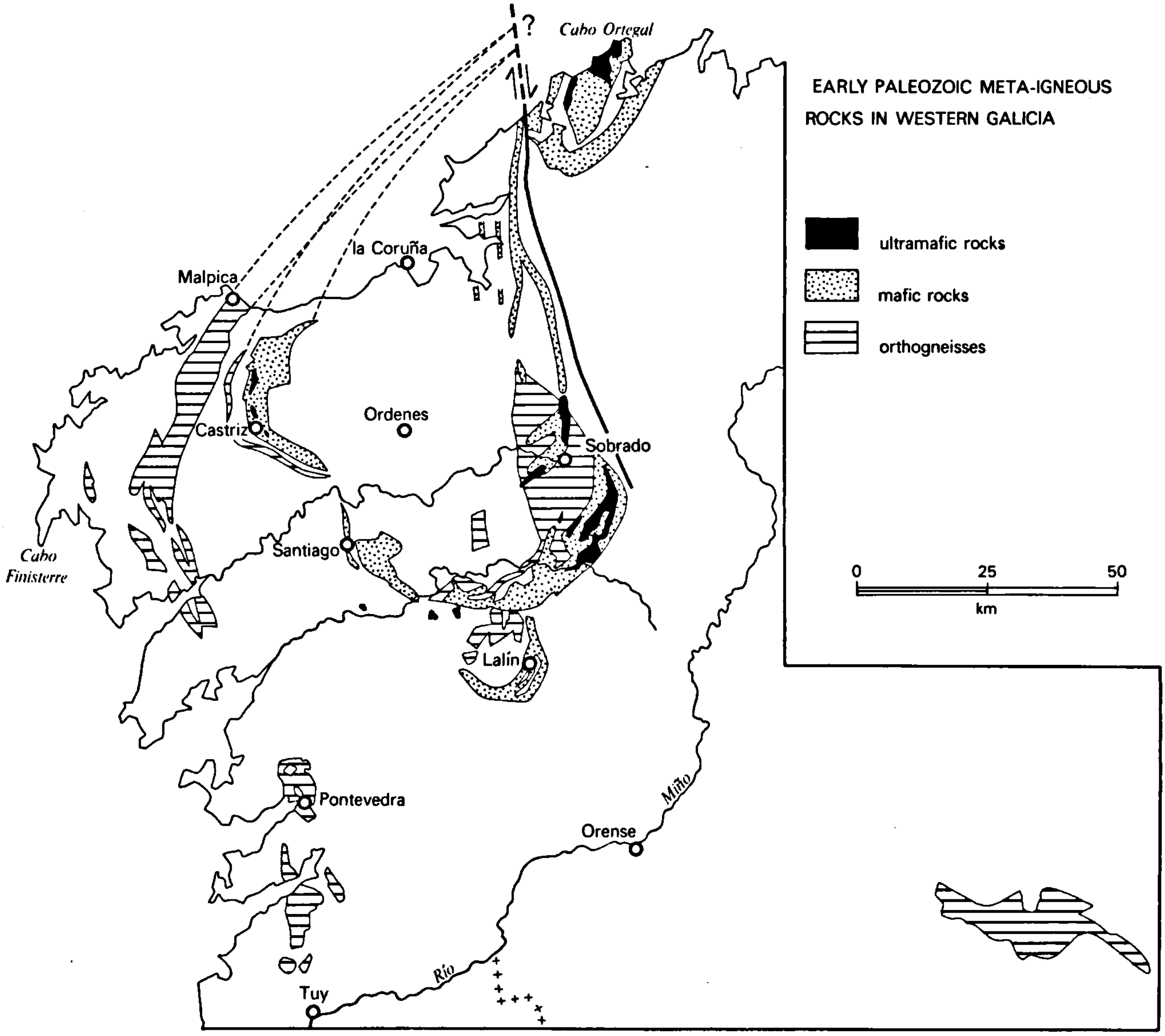

Fig. 7. Distribution map of Ordovico-Silurian orthogneisses and early Palaeozoic mafic and ultramafic rocks in Western Galicia. From Den Tex (1979).

stones, coarse quartzites, (micro-) conglomerates, and rhyolitic tuffs indicating epicontinental deposition in a shallow sea, and eventually penecontemporaneous erosion. Their fossil age may range from Upper Llandovery (Matte, 1968) to Upper Wenlock (Fernandez Pompa et al., 1976). This assemblage is followed by a monotonous sequence of interstratified arkoses, graywackes and phyllites indicating rapid subsidence and deposition in probably Upper Silurian times (Fernandez Pompa et al., 1976). The top of this sequence is formed by the greenschistfacies volcano-sedimentary Moeche Group consisting mainly of mafic metavolcanics, meta-keratophyres, flaser-metagabbros and serpentinites with subordinate variegated (quartz-) phyllites, metacherts and crinoidal limestone-lenses. The Group also includes volcano-sedimentary and tectonic breccias containing fragments not only of all coeval rock types but also of the polymetamorphic basement rocks exposed in the adjoining Cabo Ortegal complex. The Moeche Group may be described as a Wildflysch formation or a melange rather than an olistostrome (Hsü, 1974; Martinez Garcia et al., 1975), suggesting deposition in a deep furrow localized between an exhumed basement complex and a continental platform, locally involving more or less coeval tectonization. Its depositional age ranges from the Upper Silurian to the Devonian according to lithostratigraphic and fossil evidence (van der Meer Mohr, 1975; Fernandez Pompa et al., 1976). It compares rather well with the Upper Devonian flysch reported by Ribeiro & Ribeiro (1974) from the vicinity of the polymetamorphic catazonal Bragança complex in NE Portugal.

Rock suites rather similar to the Moeche Group have been

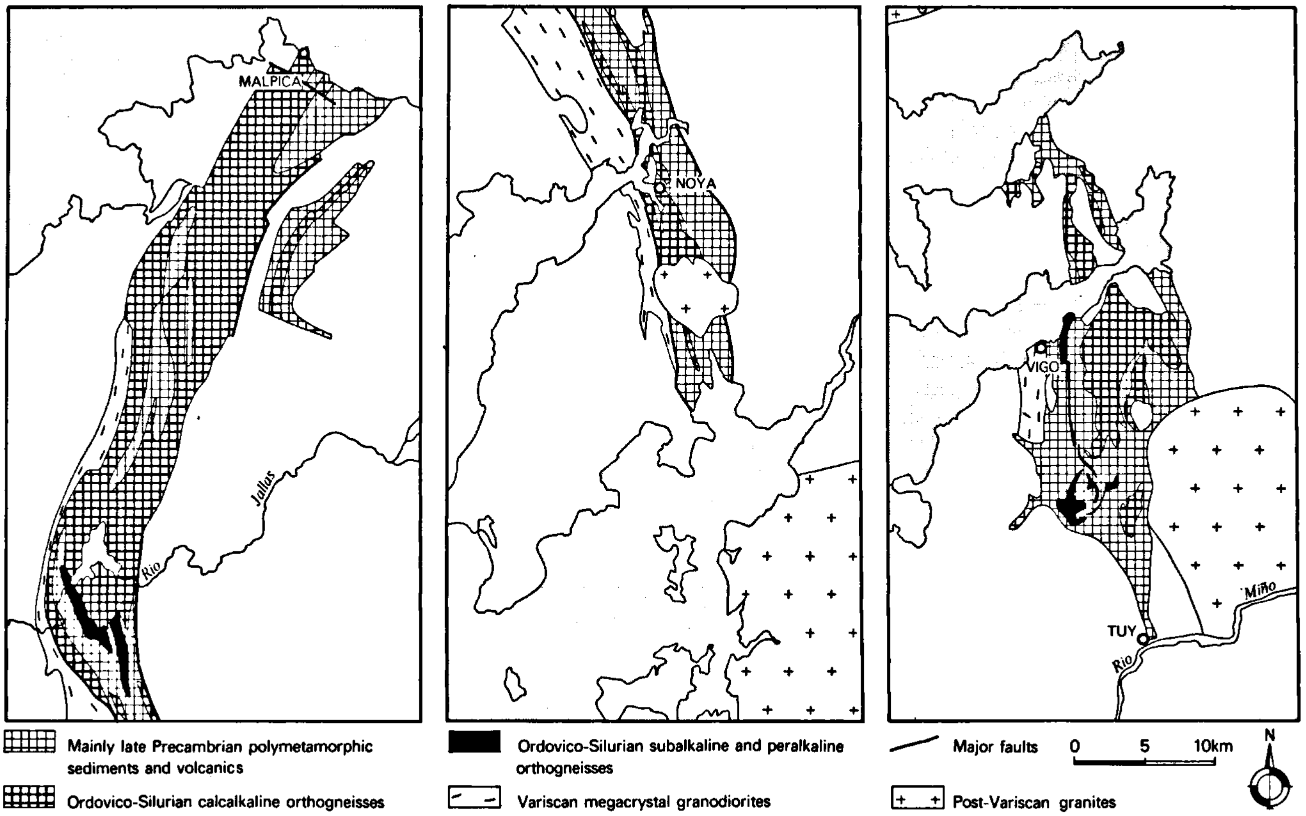

Fig. 8. Geological sketch map of the blastomylonitic graben between Malpica and Tuy in W. Galicia, divided in three segments (northernmost on left, southernmost on righthand side). From Den Tex (1979). Data after Geological map of Western Galicia 1:100,000, sheets Vigo-La Guardia, Pontevedra, Finisterre-Santiago and Mugia-Carballo, publ. by the Research Group Galicia of the Dept. of Petrology, Mineralogy and Crystallography, State University at Leiden.

reported from the eastern, southern and western perimeter of the Ordenes basin peripheral belt near Mellid, Villa de Cruces, Silleda and the Monte Castelo. Koning (1966) was the first to distinguish these monometamorphic greenschist- and amphibolite-facies rocks from the polymetamorphic amphibolite- and granulite-facies mafic and ultramafic rocks with which they are frequently associated in the field. The conspicuous banding of the polymetamorphic peridotites is completely absent in the monometamorphic serpentinites. The amphibolites and metagabbros have characteristic fabrics ranging from flaser- to laminar textures of highly variable orientation. More or less massive metagabbros and meta-porphyrite dykes are seen to cut across these foliated rocks and to enclose them. Around the Ordenes basin peripheral belt the dominant rock types in the greenschistfacies terrain are serpentinites and flaser-amphibolites, whereas meta-volcanic greenschists dominate around the Cabo Ortegal complex. In both areas the prevailing rock types are comparable with the constituents of an ophiolite suite but they never occur in the sequence required by recent definitions of the term ophiolite (Anonymous, 1972). They may qualify as dismembered or non-sequence ophiolites (Miyashiro, 1973) in a distinctly tectonized and metamorphic state, i.e. as a metamorphic melange.

4.3. The blastomylonitic and polymetamorphic graben

A zone of repeatedly tectonized, polymetamorphic but non-migmatic rocks trends parallel to the Variscan grain and to the Atlantic coast of western Galicia over a distance of 150 km from Malpica in the north to Tuy on the Portuguese border. It was first recognized as a pre-Variscan unit by Parga Pondal (1956) who gave it the name of Ancient Complex on the grounds of its abundant granitic gneisses and polymetamorphic paragneisses. Den Tex (1961) and Den Tex & Floor (1967) inferred the presence of a fossil graben structure in the Ancient Complex which they prefer to call the blastomylonitic and polymetamorphic graben. This inference was mainly based on the abundance within the complex of high-level granites, some of which are distinctly peralkaline, and on its steeply inward dipping boundary faults which may locally have acted as channelways for the emplacement of early Variscan granodiorites and biotite granites (Fig. 8). In recent years the evidence for the fossil graben has steadily accumulated (cf. Floor, 1966; Arps, 1970). Its sedimentary and volcanic content resembles Upper Proterozoic and possibly some Lower Palaeozoic strata in eastern Galicia and N Portugal. They were mainly greywackes, (semi-)pelites, sandstones, cherts, calcareous or dolomitic marls, and mafic lavas or tuffs. A regional metamorphism in the high- to intermediate pressure facies series has first affected these rocks giving rise to biotite and garnet in the schists and paragneisses, while the mafic rocks were converted to amphibolites which may contain garnet. In the northernmost segment of the graben lenses with eclogitic (type C) parageneses have been found. All these metamorphic rocks were intruded by calcalkaline, subalkaline and peralkaline granites. The latter, containing riebeckite, aegirine, lepidomelane and astrophyllite, are distinctly concentrated in the southern half of the graben. Some of these granites have caused hornfelses to develop in country rocks of non- or low-grade regional metamorphism. Minor occurrences of gabbro and of hybrid rocks between gabbro and granite occur in the southernmost segment of the graben, while a basic dyke swarm is seen to intrude the sub- and calcalkaline but not the peralkaline granites, suggesting a significant time interval between their emplacement and a genetic link between the basic and felsic magmas (Floor, 1966).

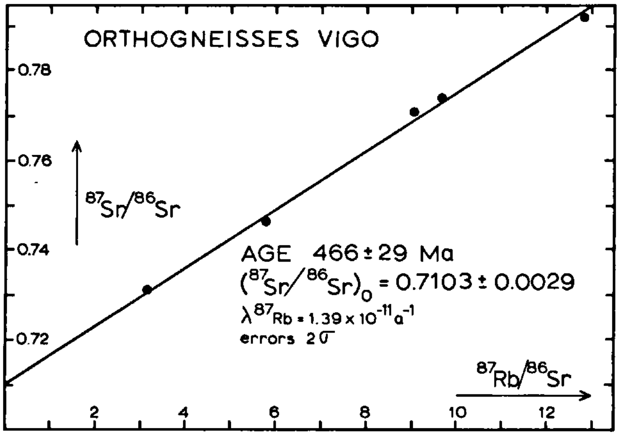

Fig. 9. Rb/Sr whole-rock data plots near Vigo in the blastomylonitic graben. From van Calsteren et al. (1979).

Rb/Sr isochrons of granitic gneisses (Priem et al., 1970; van Calsteren et al., 1979) from the graben indicate a middle to late Ordovician age for their first crystallization (Fig. 9). The morphology of their zircon crystals supports the contention that these gneisses were emplaced as high-level magmatic granites (Arps, 1970).

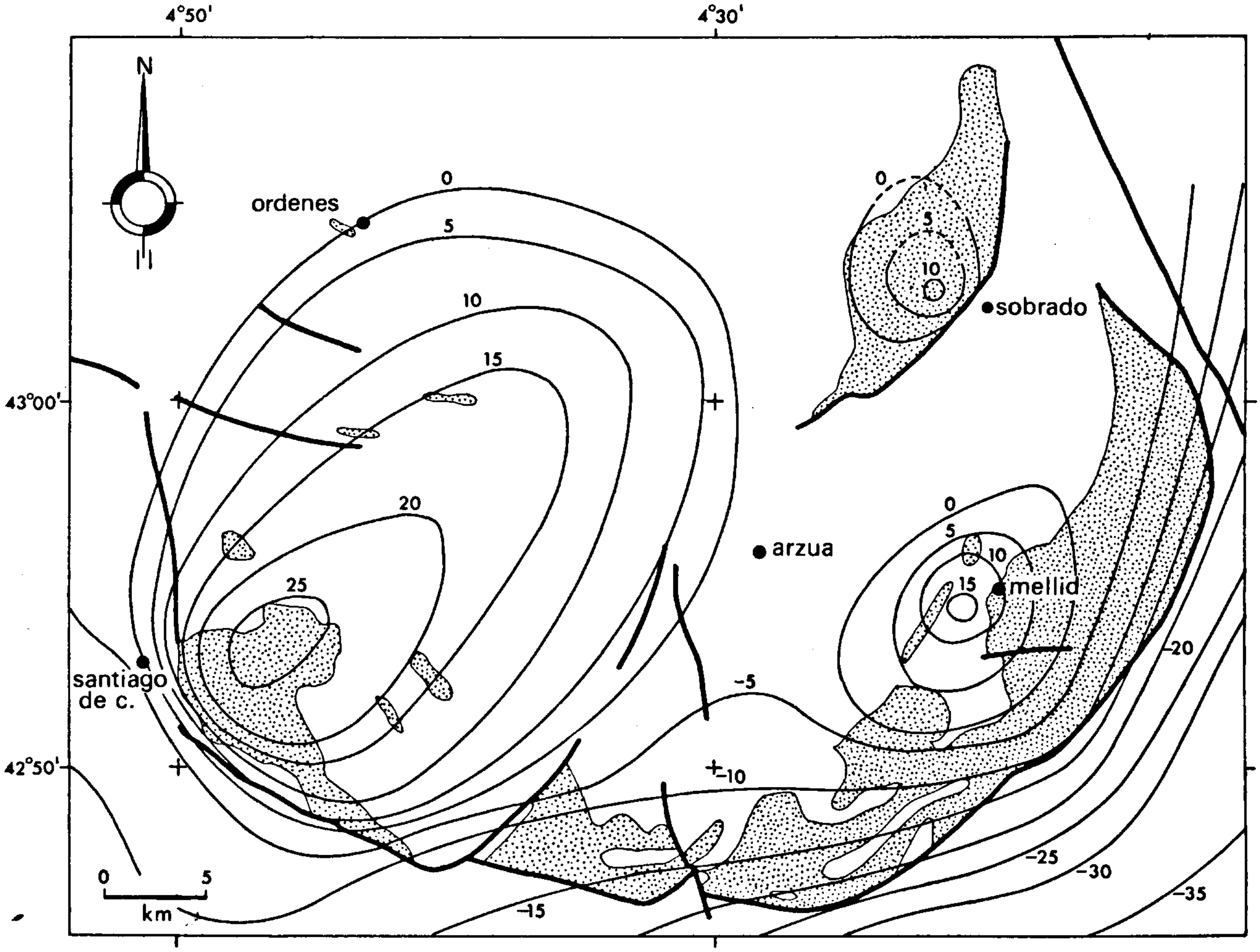

Fig. 10. Simplified geological and Bouguer anomaly map of the southern portion of the Ordenes complex. Isogals drawn at 5 mGal intervals. Stippled areas are outcrops of mafic and ultramafic rocks (heavy unit). From Keasberry et al. (1976).

During the ensuing Variscan orogeny this assemblage of rocks was first isoclinally folded or flattened on subhorizontal N–S trending axes, and metamorphosed (but not migmatized) in the cordierite-amphibolite facies (Winkler, 1967). Later they were refolded on subvertical N–S trending axial planes and partially retrograded in the greenschist facies. In this process the granitic rocks first developed a blastomylonitic texture and a foliation, marked by biotite ± garnet or riebeckite ± aegirine, which was subsequently folded and recrystallized under low-grade amphibolite or greenschist-facies conditions. Rare intrusions of postkinematic biotite granite constitute the termination of the Variscan cycle within the graben structure. A multi-stage graben model is considered most attractive: After a pre-Variscan stage of subsidence and magmatic intrusion the graben was compressed and metamorphosed. Subsequently it subsided again whereby mineralized quartz veins of the interkinematic Variscan granite suite were offset. Such a sequence of events is compatible with the concentration within the graben of the high-level Ordovico-Silurian granites, with their polyphase deformation and metamorphism, and with the generally lower grade of Variscan metamorphism and absence of migmatites within the graben as compared to the rocks outside.

It certainly represents the outcrop of the highest level among the pre-Variscan basement inliers in western Galicia.

4.4. The Ordenes basin and its peripheral belt

A grossly basin-shaped structure, open-ended to the north is centred on the township of Ordenes in the Province of La Coruña. It is filled with predominantly marine metasediments (the Ordenes schists of Parga Pondal, 1956) and metabasic rocks of similar lithology as those encountered in the blastomylonitic graben. Its constituent strata have repeatedly been folded and have been intruded, especially towards the peripheral closure, by high-level calcalkaline and subalkaline granites, an association highly reminiscent of the blastomylonitic and polymetamorphic graben although the configuration is different. To the W, S and E the basin is surrounded by a more or less inward dipping peripheral belt consisting predominantly of lower crustal and upper mantle materials. To the E, SE and W from Sobrado via Mellid to Ledesma and from Bazar to N of Carballo, it is accompanied by a mixed zone of mainly mafic metavolcanics, keratophyres, serpentinites and metasediments in greenschistfacies. The peripheral belt is made up essentially of individual central complexes of quasi-circular plan such as the Agualada (Balli, 1965) and Castriz/Bazar complexes (Warnaars, 1967), the complex east of Santiago (van Zuuren, 1969), the Mellid complex (Hubregtse, 1973a, b) and the Sobrado/Teijeiro complex (Keasberry et al., 1976; Kuijper, 1979). Some of these complexes (e.g. Mellid) incorporate subhorizontal slices of spinel-lherzolite with (garnet-) pyroxenite veins, while nearly all of them contain bodies or zones of metagabbro, and mafic to felsic high-pressure granulite, amphibolite or paragneiss. The Mellid and Sobrado/Teijeiro complexes are also characterized by the presence of large bodies of augen- and orthogneiss, the blastomylonitic border zones of which grade into felsic and intermediate granulites and paragneisses that show evidence of having been subject to partial fusion. The granitic gneisses and their immediate context contain globuliths (Berthelsen, 1970) of more or less hybridized garnet-bearing gabbro or diorite (Hubregtse, 1973a). Subsequent blockfaulting in this area has juxtaposed high- and low-level portions of these gneissose and locally garnetiferous granites which may have been formed by anatexis of lower crustal material under the thermal action of the spinel-lherzolite bodies and their pyroxenitic and gabbroic products of partial melting. A comparison between the peripheral Ordenes belt and the fossil graben reveals that both have been subject to a pre-Variscan regional metamorphism. In the Ordenes belt this metamorphism is of the high- rather than the intermediate-pressure type, and it is clearly associated with upper mantle rock complexes. A gravity survey by Keasberry et al. (1976) over the southern and southeastern segments of the peripheral belt suggests the subsurface presence of three high-density rock bodies (av. $d = 2.89 \text{ g cm}^{-3}$) causing positive Bouguer anomalies of amplitudes: 25 mGal (E of Santiago), 15 mGal (at Mellid) and 10 mGal (near Sobrado) (Fig. 10). Depending on the density contrast chosen these bodies may reach depths between 4 and 11 km. Zones of progressive metamorphism (biotite, garnet, staurolite, kyanite) can be identified in semipelites belonging to the Ordenes schists at the inner fringe of the peripheral belt roughly parallel to the outlines of the central complexes NE of Santiago and SE of Arzua. The high-level orthogneisses of Mellid and Sobrado compare well with those of the fossil graben, while the adjoining, high-grade garnetiferous augengneisses fit the deepseated context of lower crustal and upper mantle materials so characteristic of the peripheral Ordenes belt in general. A Rb/Sr whole rock isochron of six granitic augengneisses near Mellid reveals a Silurian age (409 ± 26 Ma) for their crystallization (van Calsteren et al., 1979). The 50 Ma difference with granitic gneisses of Ordovician age in the blastomylonitic graben might be due to slower cooling and crystallization of the deeper seated garnet-bearing gneisses near Mellid or to a younger intrusion age.

4.5. The Lalín and Forcarey Units

Structurally and lithologically the Lalín Unit is a small size replica of the Ordenes basin. Hilgen (1971) defined the Lalín Unit as a basin structure, open-ended to the N, where it is separated from the Ordenes basin peripheral belt by an intermediate zone of E–W trending metabasic and metapelitic rocks similar in composition to those of the Lalín Unit and the Ordenes basin proper, and by a slice of the Palaeozoic volcano-sedimentary formation (Moeche Group cf. § 4.2). The Lalín Unit contains polymetamorphic meta-graywackes (with two generations of garnet), garnetiferous amphibolites, and orthogneisses closely resembling those of the blastomylonitic graben. The amphibolites are intimately interstratified with the meta-graywacke and concentrated in a belt along the southern perimeter of the Unit, but unlike the Ordenes basin peripheral belt it contains no ultramafic rocks and lacks evidence of granulite- or eclogite-facies metamorphic conditions (Fig. 11). Gravity surveys have shown that the Lalín Unit does not coincide with an appreciable Bouguer gravity anomaly (Keasberry et al., 1976) (Fig. 10). The unit has been thrust over monometamorphic Lower Palaeozoic sediments of the central Galician schist belt to the south. The contact is

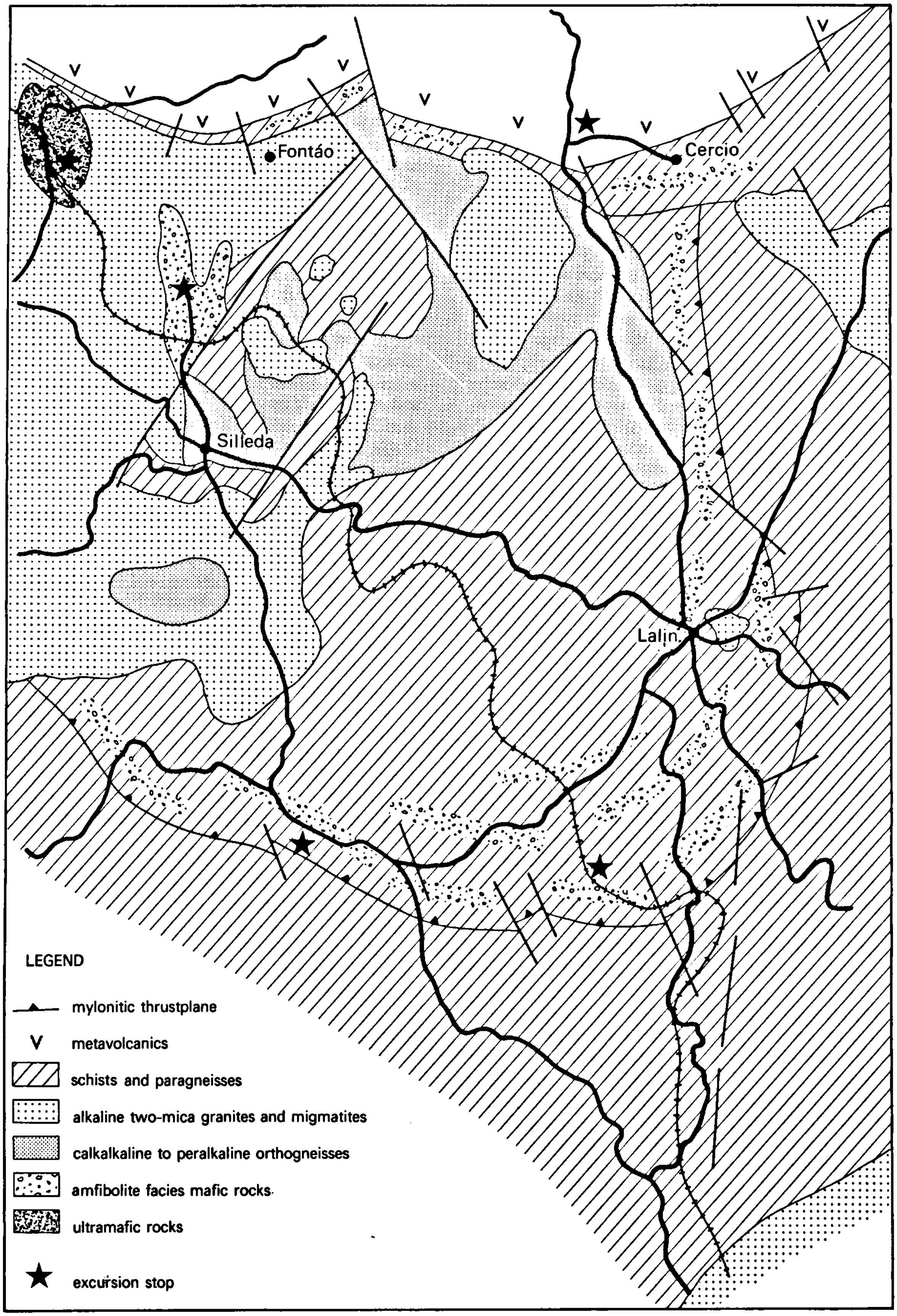

Fig. 11. Geological sketch map of the Lalín Unit and surrounding areas. From Arps et al. (1977).

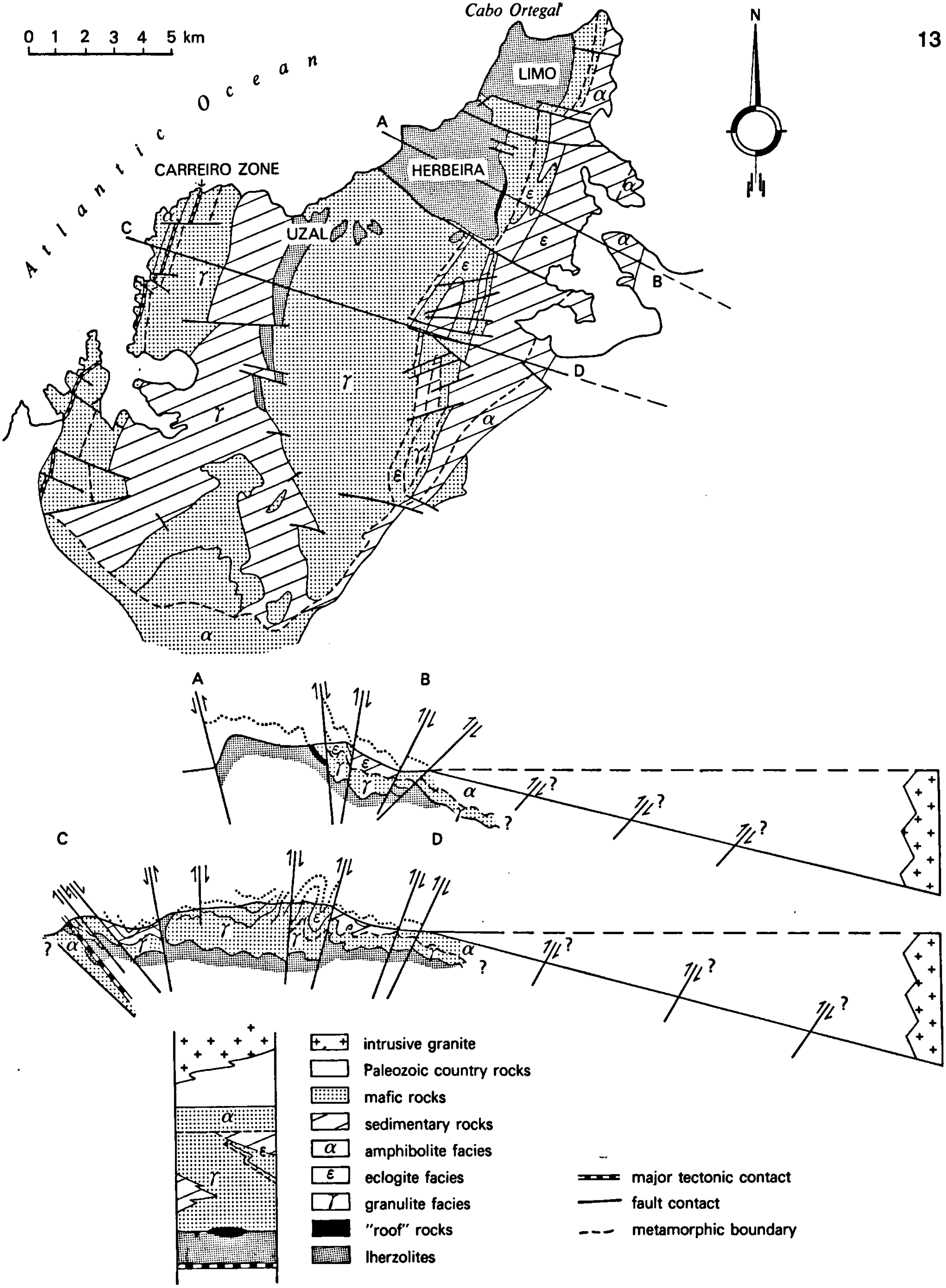

Fig. 12. Geological sketch map and cross-sections of the Cabo Ortegal complex (relief 2.5 times exaggerated). From van Calsteren (1977a).

situated in a white quartzite horizon that shows evidence of mylonitization. The Variscan isograds pass undisturbed from the schist belt through the tectonic contact into the Lalín Unit indicating that its emplacement occurred before the main phase of Variscan metamorphism. It is folded by the second phase of Variscan deformation and intruded by late-Variscan granites. The Forcarey Unit lies south of the Lalín Unit and is similar to it in many respects (van Meerbeke et al., 1973; Minnigh, 1975; J. D. Hilgen, pers. comm., 1979).

4.6. The catazonal central complex at Cabo Ortegal

Around Cabo Ortegal the largest of the central complexes of lower crustal and upper mantle rocks in western Galicia is well exposed by the Atlantic Ocean and the Bay of Biscay, and their rias. The terrestrial outcrop of 20 × 30 km is semi-elliptical with the long axis trending NNE. It is likely to extend northward below sealevel. The complex has been studied in great detail as regards its petrology, mineralogy, chemistry and geochronology (Den Tex & Vogel, 1962; Vogel, 1967; Maaskant, 1970; Den Tex et al., 1972; van Calsteren 1977a, b, 1978; van Calsteren et al., 1979) as well as its stratigraphy, structure and geophysics (Engels, 1972; Martinez Garcia et al., 1975; van der Meer Mohr, 1975; van Overmeeren, 1975).

Mafic and ultramafic rocks make up about 75% of its surface area (Fig. 12). The core consists of spinel-lherzolite with spinelfree websterite, wehrlite, (garnet-) pyroxenite and pargasite/phlogopite-bearing layers and veins. Their mineralogical and chemical data reflect an upper mantle origin as garnet- or aluminous pyroxene-pyrolite producing small amounts of picritic or pyroxenitic liquid and leaving a spinel-lherzolite as solid residue during its rise through the upper mantle into the lower crust (Maaskant, 1970). Subsequently the ultramafic core has suffered the same tectonic and metamorphic history as the mafic and felsic granulites, eclogites, amphibolites and garnet-kyanite-biotite gneisses of its immediate context (Fig. 13). Further out to the E, S and W the catazonal complex is surrounded by low-grade metamorphic, locally ferruginous, slates, quartzites, cherts, and limestones of Siluro-Devonian age (van der Meer Mohr, 1975; Martinez Garcia et al., 1975) intermingled with greenschist-facies variolites, keratophyres, serpentinites and volcanic breccias or melanges containing catazonal fragments (Arps et al., 1977). These peripheral associations indicate that the catazonal complex became exposed in Siluro-Devonian time, shedding debris around itself along with incipient seafloor spreading in the immediate vicinity. Engels (1972) demonstrated polyphase deformation of the complex. It started in pre-Variscan times with N–S trending fold axes in eclogites, followed by recumbent folds on E–W and N–S axes in all catazonal rocks and the development of peripheral blastomylonite zones. During the Variscan orogeny the complex was refolded on steep NNE trending axial planes. Its catazonal core was locally retrograded to greenschistfacies assemblages, accompanied by chevron folding and upthrusting into juxtaposition with the low-grade seafloor associations of Siluro-Devonian age.

A gravity survey was carried out by van Overmeeren (1975). A positive Bouguer anomaly of 38 mGal amplitude was found centred on the complex (Fig. 14). This suggests the presence of a high-density body reaching dephts between 3 and 6 km depending on the density contrast chosen. The SW contact surface dips steeply inward and the SE contact gently outward. The three-dimensional model preferred by van Overmeeren is a tilted mushroom-shaped dome or a tilted monocline overturned to the SW (Fig. 15). Van Calsteren (1978) studied the geochronology and geochemistry of suitable rocks and minerals from the complex. He found a Rb/Sr whole rock age of 487 ± 122 Ma for the lherzolites and 354 ± 17 Ma for the mafic granulites, while the eclogite plots do not allow a linear correlation on the Nicolaysen diagram. K-Ar mineral ages from the catazonal rocks show a peak in the frequency histogram at 390 Ma (Fig. 16). This indicates that the lherzolite whole rock systems closed first (in Cambro-Silurian times) followed by the constituent minerals of lherzolites and their immediate country rocks, while the thermal event terminated with the closure of the hornblende granulites at the end of the Devonian.

The distribution of major and trace elements led van Calsteren to distinguish between continental quartz-normative tholeiites, as represented by mafic granulites and eclogites from the lherzolite context, and olivine-normative tholeiites of oceanic island or mantle plume type, as represented by the early Palaeozoic gabbros, pyroxenites and amphibolites derived from the lherzolite by partial melting. Van Calsteren (1977a, b) developed a two-stage melting model for the Cabo Ortegal ultramafics on the basis of their chondrite-normalized La/Sm and K/Rb ratios:

1) A spinel-lherzolite melt fraction from a deep mantle plume,
2) A pargasite-peridotite residual fraction yielding partial melts of pyroxenite, pargasitite, phlogopite-rock and gabbro.

His mantle plume model for the basement inliers of the NW Iberian peninsula as a whole will be discussed in paragraph 5.5.

5. MODELS FOR THE DEVELOPMENT OF THE BASEMENT INLIERS IN W GALICIA

In recent years several attempts have been made to explain the development of the western Galician basement inliers. These models will be discussed and evaluated in the following group sequence:

5.1. A Caledonian orogenic cycle

Ferragne (1972), Martinez Garcia (1973) and Aldaya et al. (1973) picked up a thread left by Staub (1926) and Carrington da Costa (1952) who inferred the activity of a Caledonian orogenic cycle in the Hesperian Massif. In the context of this model the meso- to catazonal complexes and their partial envelopes of early Palaeozoic metasediments, metavolcanics and serpentinites may be interpreted as Caledonian basement inliers imbricated with early Palaeozoic ophiolites and associated marine sediments. The evidence for a Caledonian orogenic cycle to have occurred here is summarized in §3 and 4. However, little evidence has so far been produced for the presence of 'Caledonian' age (1) high P–low T metamorphism, (2) thrusting and compressive folding, (3) calcalkaline or potassic volcanism, (4) large-scale uplift, and (5) molasse-type erosion and deposition. I am therefore inclined to adhere to Stille's (1927) and Lotze's (1945) view that the NW Iberian

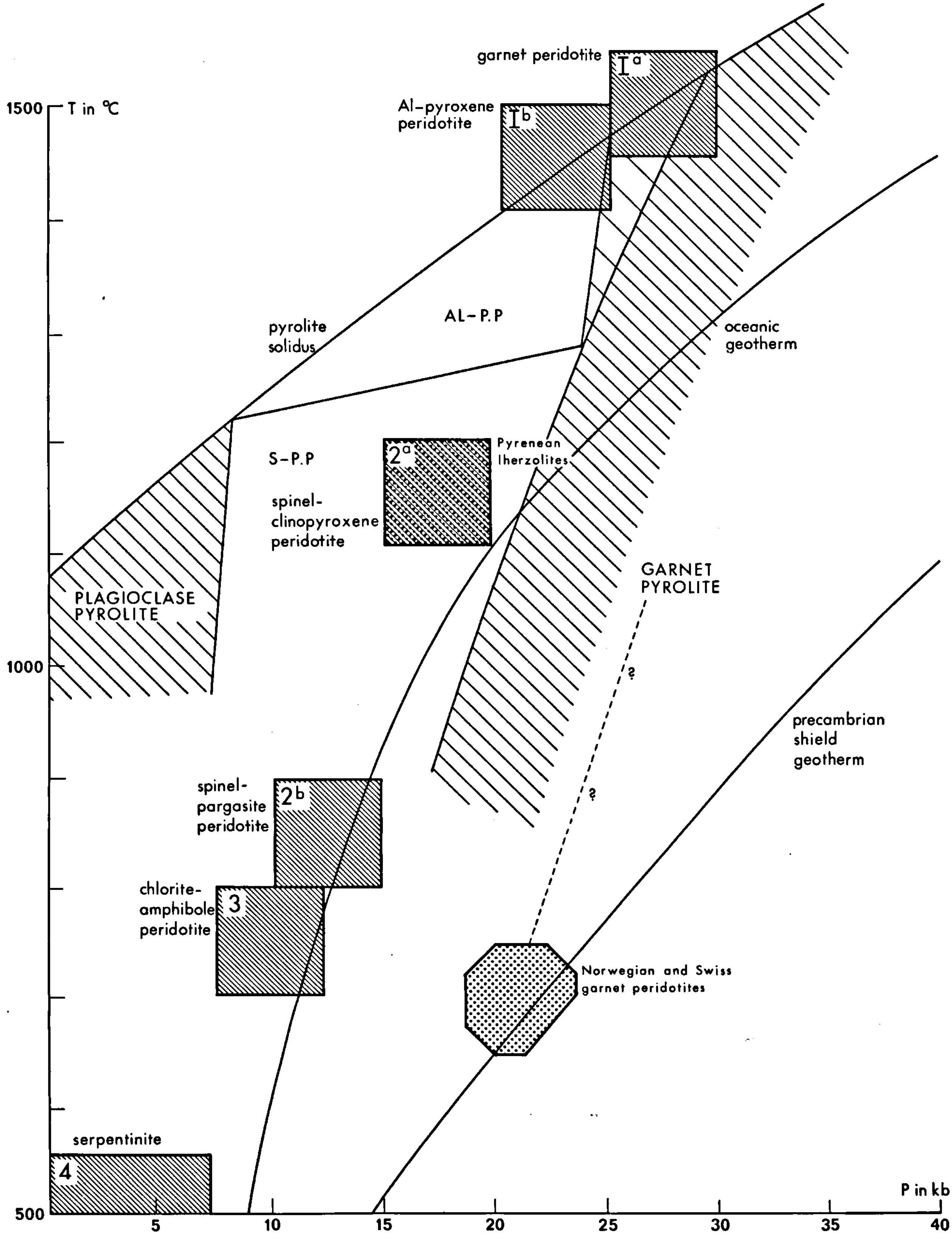

Fig. 13. Evolutionary path of the Cabo Ortegal peridotite in the pyrolite PT-diagram. Al-P.P. = aluminous pyroxene pyrolite, S-P.P. = spinel pyroxene pyrolite. After Maaskant (1970).

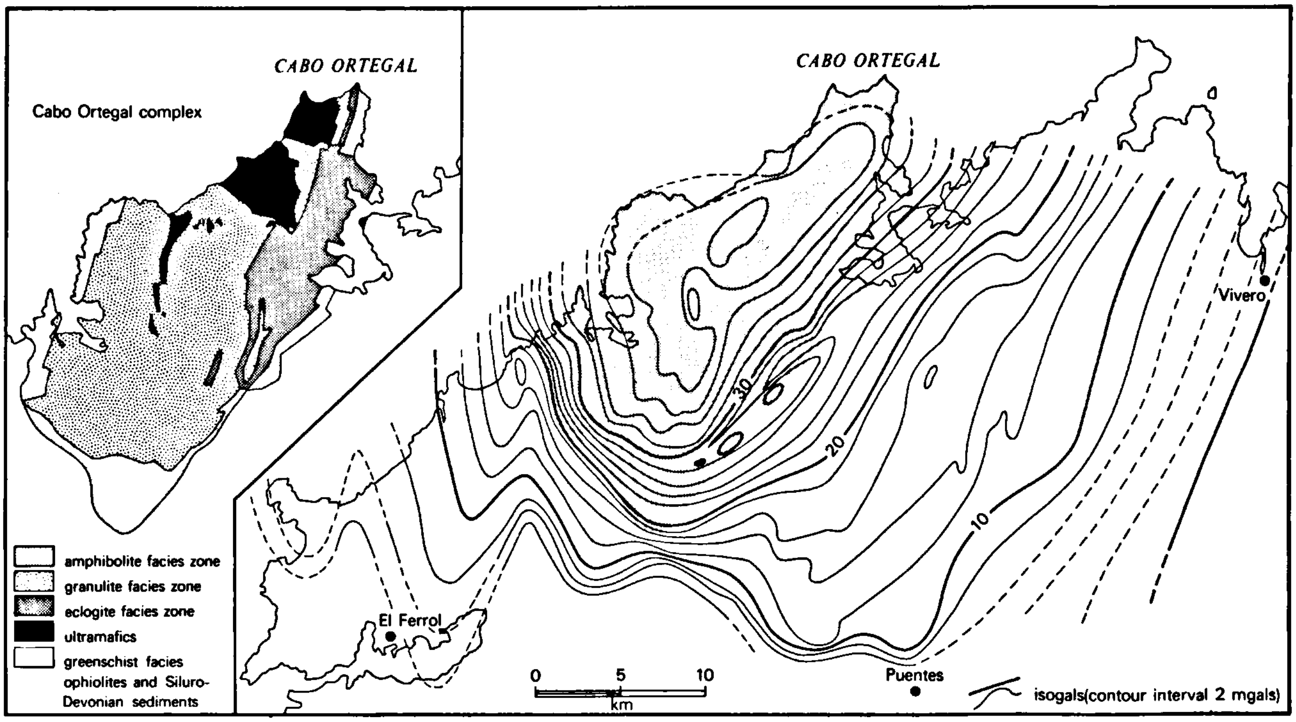

Fig. 14. Maps of the Bouguer anomalies and metamorphic facies (inset) in the Cabo Ortegal area. After van Overmeeren (1975) and Engels (1972).

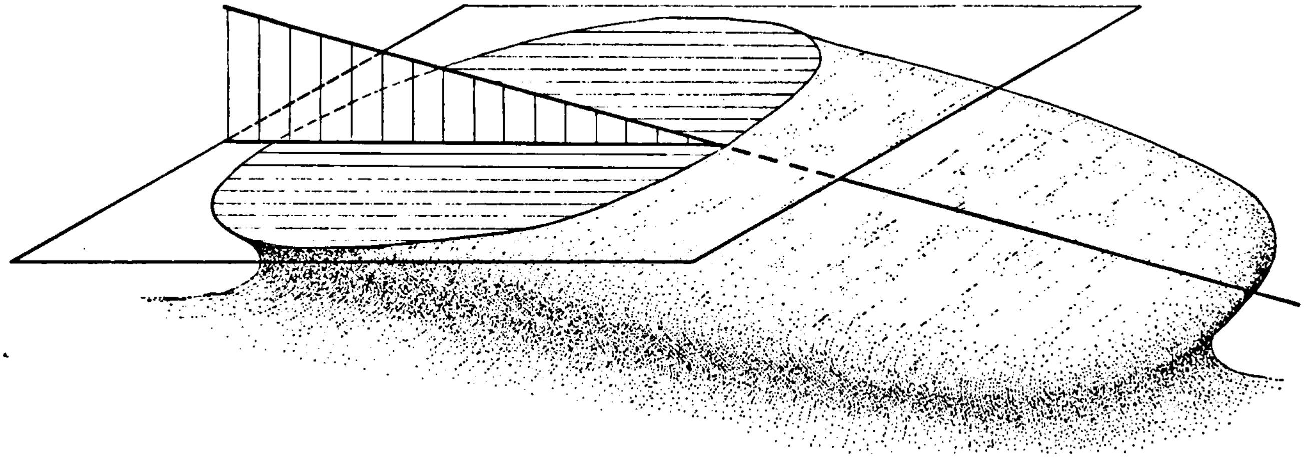

Fig. 15. Gravity model of the Cabo Ortegal complex. A tilted mushroom-shaped dome of dense material obliquely cut by the erosion surface. From van Overmeeren (1975).

peninsula has not been affected by a complete orogenic cycle of Caledonian age.

5.2. *Variscan basement nappes of Penninic style*

Anthonioz (1969) and Ries & Shackleton (1971) advanced the idea that the basement inliers represent the klippen of eroded basement nappes produced by the Variscan orogeny. The Morais-Lagoa and Bragança-Vinhais complexes in NE Portugal were inferred by Anthonioz (op. cit.) to have slid down from the Mid-Galician Cordillera to the SW as parts of an extensive gravity nappe. On the other hand Ries and Shackleton (op. cit.) maintain that all of the NW Iberian basement inliers are remnants of a Variscan thrust-plate rooted to the West, either in the blastomylonitic graben, or in the Porto-Viseu-Guarda Zone of NW Portugal, or even further W, in the Atlantic Ocean. Both views are based essentially on the tectonic superposition of the high-grade polymetamorphic basement complexes on low-grade monometamorphic sediments and volcanics of early to middle Palaeozoic age, separated by more or less gently inward dipping blastomylo-

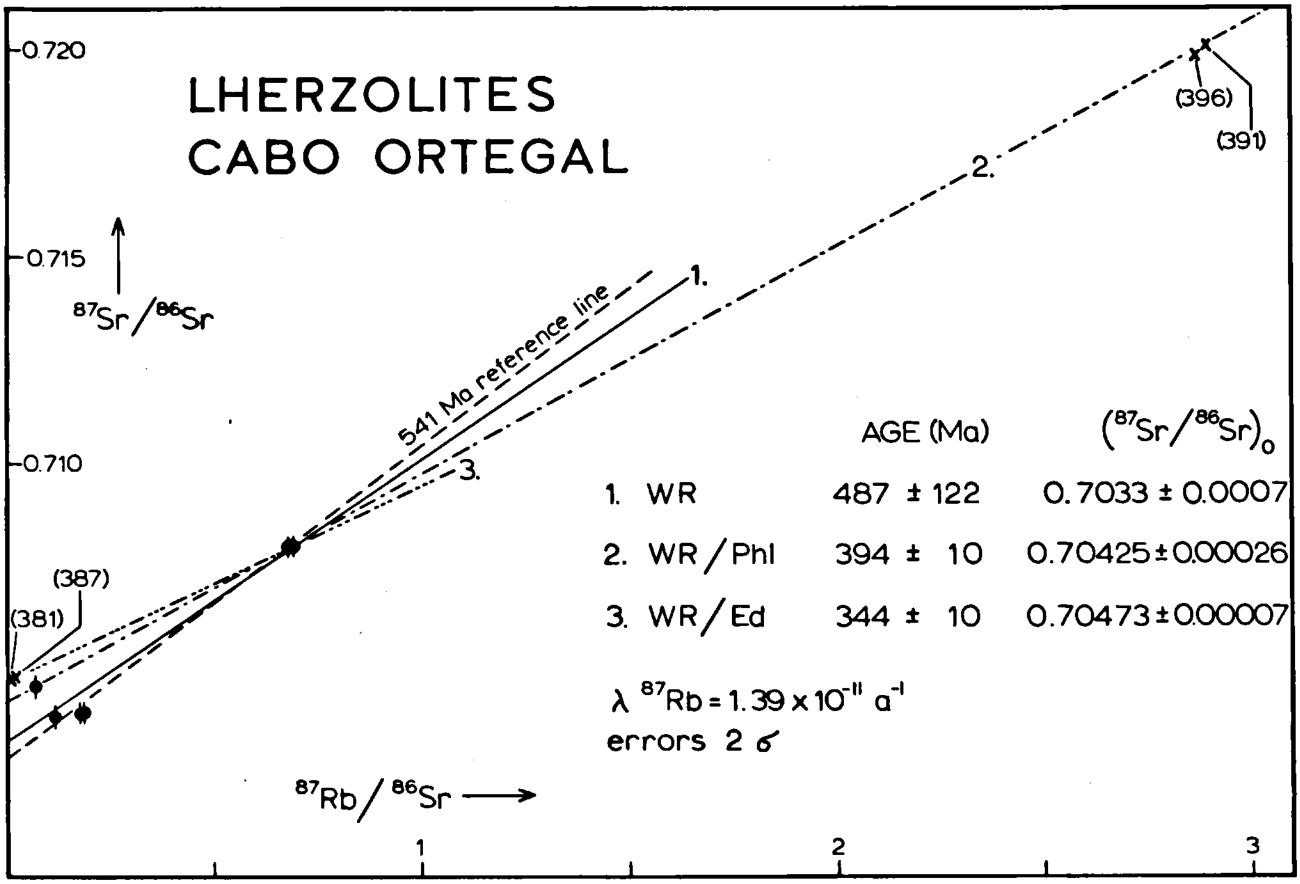

Fig. 16. Rb/Sr plot of whole rocks (with error bars), two edenites (crosses, with low Rb/Sr ratios), and two phlogopites (crosses, with high Rb/Sr ratios) from lherzolites in the Cabo Ortegal complex. Isochron 1 is calculated using all six whole-rock points. The reference line is obtained by omitting one slightly deviating point (the sample with the lowest Rb/Sr ratio). Isochrons 2 and 3 are calculated from two whole-rocks and separated phlogopites and edenites, respectively. Between brackets the K-Ar dates of the minerals are given.

nitic soles, thrust planes and tectonic melanges. Synformal structures and locally inverted metamorphic zones in the basement complexes are also quoted in support of the Variscan nappe model. But the following negative evidence may be adduced: 1) the blastomylonitic soles are of pre-Variscan age (cf. § 4.4 and 4.6), 2) the contact planes, though dipping inward, do so at angles up to 80°, 3) the internal structures are both synformal and antiformal but always bilaterally or radially symmetrical in a statistical sense, 4) the main phase Variscan fold axes are deflected around the basement inliers, 5) positive Bouguer anomalies of up to 38 mGal amplitude are centred on some of the complexes indicating deeply rooted rock masses of high density, 6) the abnormally iron-rich facies ('lie-de-vin') of the Silurian phyllites surrounding certain catazonal complexes (Morais and Bragança, cf. Ribeiro, 1974) imply in situ erosion of the (ultra-) mafic rocks concerned in a shallow Silurian sea, 7) the postulated root zones are composed of more superficial rock types (orthogneisses, paragneisses, amphibolites, etc.) than the presumed klippen (ultramafics, eclogites, granulites, etc.).

The sense of movement in the basement inliers is radially or bilaterally outward, which is incompatible with the movement picture that operates in thrust-plates or gravity-nappes. Moreover, it is difficult to see where the homeland of such a nappe could have been situated.

5.3. Suture zone of a Variscan collision-type orogen

In the wake of the bandwagon of plate tectonics almost any tract of country containing mafic volcanics has lately been proclaimed a suture zone of continental collision. As a result the network of 'suture zones' has ramified considerably and continents are being split into ever smaller 'microcontinents'. The Hesperian Massif has been no exception to this trend, the Galician-Castilian zone having been cited e.g. as a suture zone between a North American/northern European continent and a northern Spanish microcontinent by Riding (1974), and as a leading edge of an Iberian microcontinent by Badham & Halls (1975). Some of the objections made against model 5.1 are equally valid v.a.v. 5.3, such as absence of high P–low T metamorphism and of fully developed ophiolites of Variscan age. Calcalkaline volcanism of that age is also absent in the NW Hesperian Massif, although chemically somewhat similar Permo-Carboniferous plutonism is widespread in that area (cf. § 4.1), accompanied by thrusting and compressive folding. In summary the evidence for obducted or subducted oceanic lithosphere in the Variscan orogen of NW Spain is too tenuous to be seriously considered.

5.4. Back-arc-basins of a Variscan island arc

Bard et al. (1973) and Ribeiro (1974) presented more sophisticated models of a collision-type orogen for the Hesperian Massif as a whole. In their perspective the Galician-Castilian zone (including Mid-Galicia and Trás-os-Montes in Portugal) was once a back-arc-basin that developed behind an island arc, remnants of which are situated in the Ossa-Morena zone of the SW Iberian Peninsula. An oceanic plate, subducted from the SW underneath the Iberian continent, is invoked to explain the presence of the presumed island arc at the collision front in the Ossa-Morena zone. A back-arc-basin is then supposed to have formed owing to mantle diapirism from the subducted oceanic lithosphere, and later to have closed by collision and subduction of island-arc and continental crust from the SW and the NE respectively, accompanied by crustal diapirism. Although this model appears to fit the observed distension tectonics in the Mid-Galician/Trás-os-Montes zone, admitting mantle diapirism and incipient seafloor spreading in an euxinic basin, it encounters grave objections where time-space-rock relations are involved. Firstly, the presumed back-arc-basin in the Mid-Galician/Trás-os-Montes region is situated some 500 km NNE of the postulated trench and outer island arc and shows early Palaeozoic (Ordovico-Silurian) mantle-crust diapirism and incipient seafloor spreading. Assuming a dip of 30–45° for the subducted plate, a depth of 300–500 km should have been reached by its lowermost tip. During subduction to these depths, glaucophane-schist or eclogite facies metamorphism should have occurred followed by calcalkaline and potassic volcanism along with Cu-Zn-Pb mineralization as characteristic features of a mature island arc (Stanton, 1972 and pers. comm., 1977). However only pumpellyite- and greenschist facies metamorphism of later Palaeozoic age (Devono-Carboniferous) is found in the Ossa-Morena zone accompanied by non-ophiolitic spilite-keratophyre volcanism and pyrite-jasper-manganese mineralization in the so-called Pyrite Belt of the SW Iberian Peninsula. These features could reflect a eugeosynclinal setting or an incipient stage of island arc formation only (Schermerhorn, 1975a, b). For the western portion of the Hesperian Massif the model of a fully developed island arc and back-arc-basin is therefore rejected.

5.5. Mantle plume–rift system model

Within the Galician research group at Leiden continental rift- and mantle plume models have been under discussion during the last decade. Recently Den Tex (1977), van Calsteren (1977a, b, 1978; van Calsteren et al., 1979) and van Calsteren & Den Tex (1978) developed these models in more detail.

In 1961 the present author ventured the idea that the ancient complex of Parga Pondal (1956) is a fossil graben (cf. § 4.3). It was then believed to be an essentially Precambrian feature, but isotope-geochronological work (Priem et al., 1966, 1970; van Calsteren et al., 1979) has since shown that the accompanying epeirogenic granites and associated basic dyke swarms are of early Palaeozoic (Ordovico-Silurian) age. In the light of the supracrustal history of adjoining areas (cf. § 3) it became clear that Mid-Galicia and Trás-os-Montes had been the site of long-lived epeirogenic movements and bimodal magmatic activities from the late Precambrian right up to the Variscan orogenic climax. In a general way it was mainly uplift that this zone had then suffered but subordinate subsidence, concentrated in graben-like structures, was an essential corollary. These observations led to the concept of a rifted basement dome, deformed, metamorphosed and granitized by the Variscan orogeny (Den Tex, 1977, 1979; van Calsteren & Den Tex, 1978). The occurrence of dismembered meta-ophiolites, volcanics and melanges of Siluro-Devonian age, closely associated with some of the catazonal complexes, was interpreted as evidence of incipient seafloor spreading upon drifting asunder of the continental crust along preferred branches of the rift system (Fig. 17).

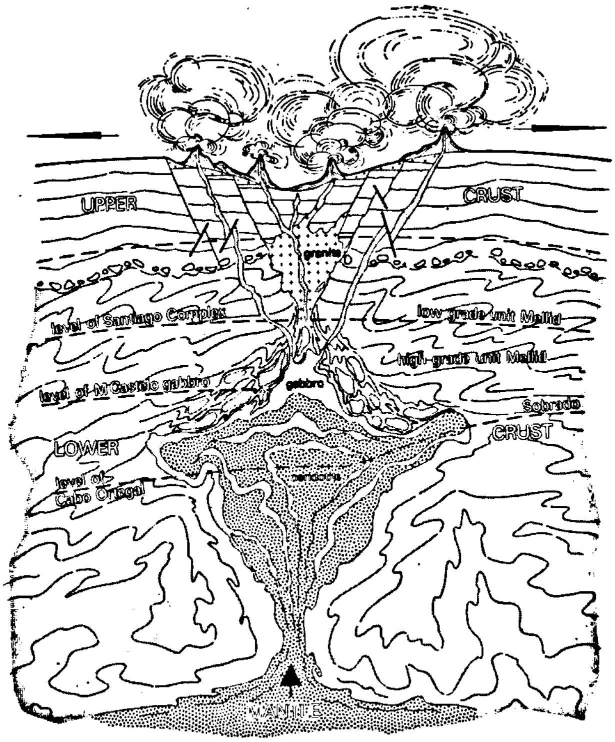

Fig. 17. Diagram illustrating the rift system model for the early Palaeozoic geological evolution of Western Galicia.

The results of geochronological, geochemical and geophysical work on the catazonal complexes at Cabo Ortegal and in the peripheral belt of the Ordenes basin led van Calsteren (1977a, b, 1978; van Calsteren et al., 1979) to assume the presence of an early Palaeozoic mantle plume beneath the continental crust of the NW Hesperian Massif (cf. § 4.5). The spinel-pargasite lherzolite at Cabo Ortegal was shown by him to be a possible melt fraction from a pyrolitic parent material in the deep mantle, and to be a probable residual counterpart of its own mafic associates at a later stage of partial melting in a second-order diapiric body (Fig. 18). According to van Calsteren the mantle plume and its diapiric off-shoots caused not only the inferred doming, rifting and thinning of the continental crust, but also the two phases of granulite facies metamorphism as well as the granitic anatexis and palingenesis that occurred concomitantly with the latter phase. In this part of the model, mass movement of hot rock and magma is used to explain both the mechanical and the thermal events that are recorded in the early Palaeozoic rocks and structures concerned. Its relation to the later Palaeozoic features of the Variscan orogeny proper cannot yet be resolved, but the virtual overlap of radiometric dates from the Variscan granites and the granulites around the mantle plume diapir at Cabo Ortegal is suggestive of a fairly close link (van Calsteren, 1977a). The presence of a lower continental crust, that was crystalline before the Cambro-Ordovician onset of mantle diapirism, is implicit in the model outlined above (see also § 4.5). Results of radiometric dating on zircons from some of the crustal rocks in Galicia confirm the assumption of a Precambrian orogenic basement to the Northern Hesperian Massif (Kuijper, 1979).

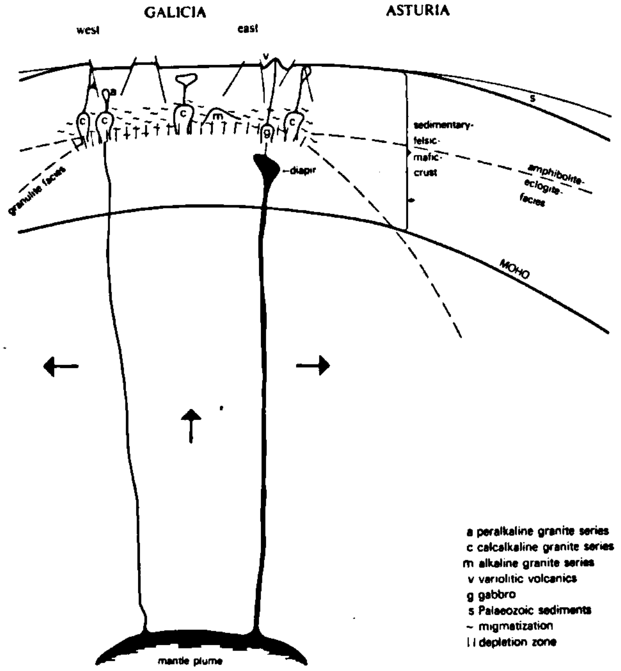

Fig. 18. Diagram illustrating the mantle plume model for the early Palaeozoic geological evolution of Galicia. From van Calsteren (1977a).

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