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MAFIC AND RELATED COMPLEXES IN GALICIA: AN EXCURSION GUIDE

BY

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ABSTRACT

In Galicia occur several polymetamorphic complexes that contain mafic and ultramafic rocks. Mafic volcanics and gabbros are situated in or near the complexes. An episode of metamorphism and granitization encompassed the generation of the volcanics and gabbros. Gravity surveys revealed the existence of deep roots below polymetamorphic complexes. Geochronological investigations yielded Palaeozoic ages from about 500 Ma for the generation of ultramafic rocks and calcalkaline granite series, till ages of around 300 Ma for post-kinematic alkaline and calcalkaline granites. A model involving mantle-plume diapirism and rejuvenation of the lower crust is proposed for the Early Palaeozoic evolution of the continental lithosphere of Galicia.

An excursion route is given, leading along 22 exposures of mostly mafic and ultramafic rocks, to be visited in 4½ days.

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CHAPTER I

INTRODUCTION

Galicia is situated in the northwestern part of the Iberian Peninsula. It comprises four provinces, named after their capital cities La Coruña, Pontevedra, Orense and Lugo. Other important cities are Vigo, El Ferrol and Santiago de Compostela. The latter two will be visited during the excursion.

Topographical maps, scale 1: 50.000 and 1: 25.000, have been published by the 'Instituto Geográfico y Catastral, Madrid'. Road maps are available e.g. from 'Michelin' (no. 990, scale 1: 1.000.000) and 'Firestone Hispania' (no. 1, scale 1: 500.000). A tourist map of the Rias Gallegas, scale 1: 200.000 is published also by 'Firestone Hispania'. The road network of Galicia is increasing in density and quality every year. The mentioned maps are not always revised with respect to the actual situation.

Hotel facilities in Galicia are poor except in the coastal area and in Santiago de Compostela.

The climate of Galicia is humid. Stable fair weather episodes are comparatively short and confined to the summer.

SYNOPSIS OF GEOLOGICAL RESEARCH

Scientific geological work started with the researches of

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G. Schulz in 1835 when he published the first geological map of the then existing 'Kingdom of Galicia'. In the last decades of the 19th century J. MacPherson published extensively on Galician geology.

More intensive and detailed geological investigations started with the work of I. Parga-Pondal. His subdivision of Galicia in major tectonic units and his tentative chronological classification of Galician granites still constitute the basis of recent work. One of his outstanding achievements is the publication, in 1963, of a structural and petrographic map of Galicia.

In 1955, L. U. de Sitter who then occupied the chair of Structural and Applied Geology in the State University at Leiden, initiated the Dutch investigations in western Galicia. A year later the Petrology Department under the direction of W. P. de Roever followed, and soon afterwards the supervision of the Galician work was taken over by E. Den Tex and has continued to date.

It resulted in over sixty mainly unpublished M. Sc. theses and nine Ph. D. theses, viz. P. Floor (1966): dealing with the area south of Vigo; F. W. Warnaars (1967): an area NW of Santiago de Compostela; A. van Zuuren (1969): the area around Santiago de Compostela; C. E. S. Arps (1970): the area around Noya, and J. J. M. W. Hubregtse (1973): the Mellid complex. J. D. Hilgen is preparing a thesis on the Lalín region.

The Cabo Ortegal complex was the subject of four theses: D. E. Vogel (1967): concerning the petrology and mineralogy; P. Maaskant (1970): on the chemical petrology of its ultramafic rocks, also including other occurrences in Galicia; J. P. Engels (1972): dealing with the structural petrology, and P. W. C. van Calsteren (1977): with the geochemistry and the geochronology, also with respect to other older parts of Galicia. R. P. Kuijper is preparing a thesis on the geochronology of the Mellid area and the Blastomylonitic graben of western Galicia.

In 1967, a geological map (1: 500.000) of the northwestern part of the Iberian Peninsula was published under the direction of I. Parga-Pondal, compiling the work of Spanish, Portuguese, French and Dutch geologists. In 1977 and 1978, seven geological maps (1: 100.000) will be published which summarize the mapping activities of the research group 'Galicia' of Leiden University. The map of Fig. 2 is based on these maps.

Recently, the Instituto Geológico y Minero de España, has started a new mapping campaign on a 1: 50.000 scale of which the first results concerning Galicia have already been published.

ACKNOWLEDGEMENTS

This excursion guide leans on the mapping work of some 30 members of the research-group 'Galicia' of the Petrology, Mineralogy and Crystallography Department in the State University at Leiden. We benefitted from the discussions in the field on a pre-excursion in spring 1977, with Prof. Dr. F. Aldaya Valverde and Mr. J. R. Martinez Catalán. Dr. J. Ayala of Rio Tinto-Patiño provided us the data on the Arinteiro copper deposits. For permission to visit their properties we thank: Canteras y Materiales de Silleda, S. A., Pontevedra; Arias Hermanos Construcciones, S. A., La Coruña, and Rio Tinto-Patiño, S.A., Santiago de Compostela. Financial support from the Geological and Mineralogical Institute, and the National Museum of Geology and Mineralogy, both of the State University at Leiden, the University of Salamanca, and the Molengraaff Fonds are gratefully acknowledged.

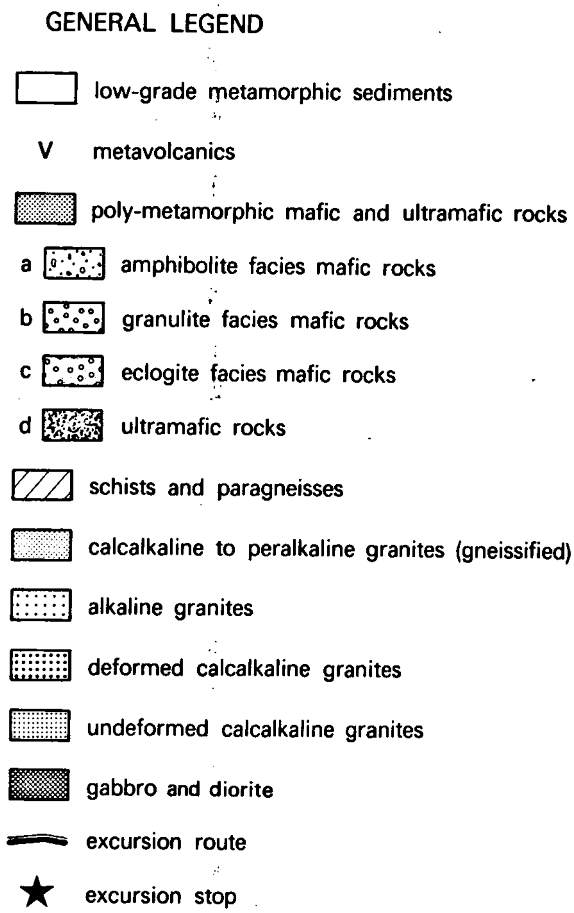

Fig. 1. General legend to the maps of Figs. 2, 7, 8, 9, 12, 13.

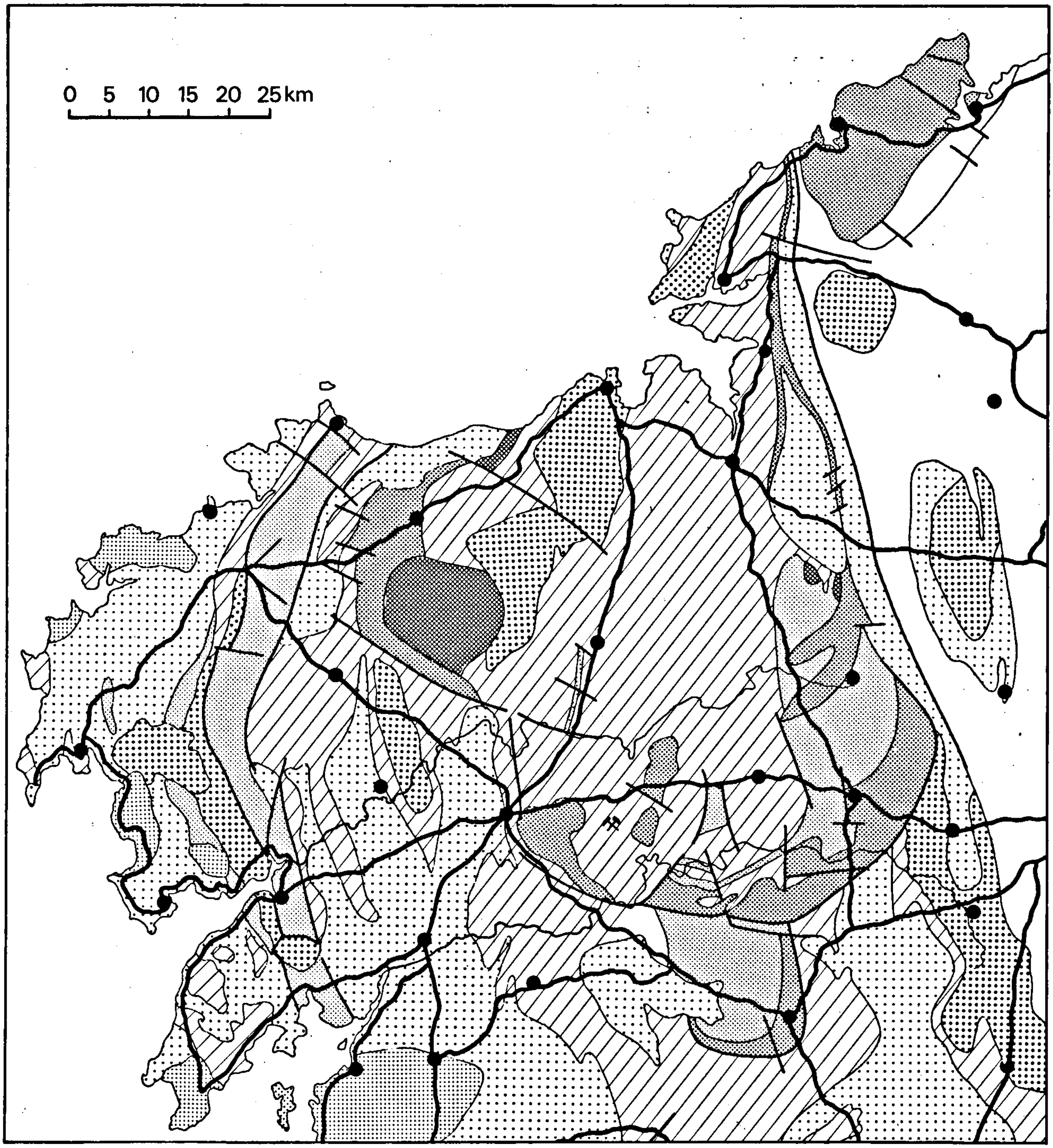

Fig. 2. Geological sketchmap of northwestern Galicia.

CHAPTER II

GEOLOGICAL SETTING

The majority of mafic rocks of the Hesperian Massif is confined to Galicia and northeastern Portugal (near the townships of Bragança and Morais). The mafic and ultramafic rocks can be divided into two groups, 1. low-grade or non-metamorphic gabbros, diorites and mafic volcanics, and 2. higher-grade metamorphics confined to polymetamorphic complexes.

THE POLYMETAMORPHIC COMPLEXES

The polymetamorphic complexes in Galicia are mainly restricted to three areas, viz. south of Cabo Ortegal, in a belt around the township of Ordenes, and in a narrow zone between Malpica and Túy close to the Atlantic coast. The complexes contain variable amounts of paragneisses, metagraywackes, mafic rocks in amphibolite, granulite or eclogite facies, ultramafic rocks (mainly lherzolites), and calcalkaline to peralkaline granite gneisses.

The semi-elliptical Cabo Ortegal complex contains more eclogite and less orthogneiss than the other complexes. The Ordenes complex, also known as Ordenes 'basin', is partially enclosed by a belt of individual polymetamorphic complexes. They are referred to under the names of the local townships, viz. Sobrado, Mellid, Santiago, Bazar-Castriz, and Agualada. South of this belt another polymetamorphic complex is situated near Lalín.

The narrow unit, extending from Malpica to Túy, was named 'Complejo Antiguo' by Parga-Pondal (1953). It has been redefined as Blastomylonitic graben by Den Tex & Floor (1967). This complex contains the largest amount of calcalkaline and peralkaline granite gneisses.

All the complexes are wholly to partially fault-bounded. They are set in a context of pelitic schists, migmatites and deformed or undeformed alkaline and calcalkaline granites. To these rocks Palaeozoic ages are assigned (see Chapter III). The sedimentary sequences in western Galicia are reduced in thickness as compared with similar sequences in eastern Galicia, northern Portugal and Asturias. In the latter areas the sedimentary column spans an episode from the Riphean to the Upper Carboniferous. Unconformities are found below the Wenlock and in the Carboniferous (van Adrichem Boogaert, 1967).

THE GABBROS AND VOLCANICS

The gabbros and volcanics occur exclusively in the vicinity of, or within the polymetamorphic complexes. Their low-grade metamorphic imprint excludes their primary incorporation in the high-grade complexes.

Gabbros occur in a number of places in Galicia. The largest occurrence, the Monte Castelo Gabbro, is situated north of Santiago de Compostela. Petrological investigations have indicated that this gabbro complex was formed by successive intrusions of mainly eastward-dipping sills, within which differentiation took place during crystallization. In many places the gabbro is strongly epidioritized. It was suggested by Warnaars (1967) that the intrusion took place shortly after the main phase of Hercynian deformation (F_4) and regional metamorphism (M_3) but before the (calcalkaline) granitic rocks were emplaced. Near Playa de Barañan some 12 km southwest of La Coruña, a mafic intrusion is situated at the northwestern margin of the Ordenes basin, surrounded by migmatites and metasediments. The rocks are of dioritic to tonalitic composition and almost undeformed. A few smaller occurrences of diorite have been encountered in the neighbourhood.

Other gabbros with more or less the same characteristics as mentioned above occur near Teijeiro. Moreover, in many places in Galicia, small gabbro to diorite bodies with dimensions up to 200 m are present.

Although the majority of mafic rocks in Galicia is confined to the polymetamorphic complexes and to a few larger intrusive bodies, it should also be mentioned that para- and ortho-amphibolites of Early Palaeozoic age, as well as scattered mafic intrusions (dolerites, and lamprophyres), most of which are post-kinematic and post-metamorphic, have been encountered outside these areas.

Predominantly mafic volcanic rocks crop out around the Cabo Ortegal complex and around the southeastern part of the Ordenes basin. Several varieties of volcanic rocks are found, ranging in composition from mafic to felsic. They are mostly associated with sedimentary rocks, and in some places the volcanic rocks themselves show evidence of sedimentary redeposition.

To the metavolcanics occurring east of the Cabo Ortegal complex, a Silurian or Devonian age is assigned (Matte, 1968; van der Meer Mohr, 1975).

HERCYNIAN METAMORPHISM AND GRANITIZATION

Apart from the older tectonic elements present in the Hesperian Massif, the Galician basement is mainly composed of pelitic schists and a large variety of migmatic, anatectic and intrusive rocks of granitic composition. Remnants of (migmatized) coarse-grained augengneisses are also frequently met with.

The age of the metasedimentary sequences outside the polymetamorphic complexes is inferred to be Early Palaeozoic, and they were subject to the Hercynian diastrophic event, i. e. three phases of deformation, and a (intermediate) low-pressure type of plurifacial metamorphism (Arps, 1970; Hilgen, 1971; Buiskool Toxopeus et al., 1977) that started after the first Hercynian deformation and continued during and after the second deformation phase.

All the pre-existing rocks suffered a metamorphism that culminated in places in an anatectic melting of parts of the crust, giving rise to the generation of a variety of migmatic rocks and ultimately of more or less homogeneous anatectic granites. Locally the new-formed granite magmas intruded into the surrounding basement and formed stocks and batholiths, e.g. the Espenuca granite (see Chapter IV). With respect to their petrographic character, the above-mentioned granite types were denominated 'alkaline granites' (Capdevila & Floor, 1970). In places, these two-mica granites have been penetratively deformed by the second Hercynian deformation giving rise to a typical phyllonitic fabric. The latest members of the alkaline granite series are megacrystal-bearing and were emplaced as relatively small oval-shaped bodies.

In addition to the alkaline granites a series of megacrystal-bearing biotite (muscovite) granodiorites intruded to higher levels. The latter granitic rocks have been indicated as 'calcalkaline' granites. Two separate groups can be distinguished within this series, an older group, often moderately to strongly deformed, and a younger group of biotite (hornblende) granodiorites. The megacrystal-bearing granodiorites may be associated with dioritic to tonalitic cognate inclusions, with a more leucocratic muscovite-biotite granodiorite variety, and with a relatively younger muscovite (biotite) granite differentiate, e.g. the La Coruña granodiorite series. The younger group of granodiorites are either homogeneous bodies, or are composed of several differentiates displaying zoned or more complicated intrusive relations. Similar Late-Hercynian granitic intrusions are also well-known from the southwestern margin of the axial zone of the Hesperian Massif in northern Portugal (Floor et al., 1970; Oen Ing Soen, 1970).

It is evident that the calcalkaline granites were generated at deep crustal levels. The intrusion of the older group of granodiorites took place along deep-reaching faults subparallel to the regional foliation, during a phase of crustal tension just before the great bulk of intrusive alkaline two-mica granites appeared. The emplacement of the younger group of granodiorites was facilitated by cross-cutting fault systems.

Scattered occurrences of granite porphyry dikes are the latest representatives of granite activity in Galicia.

CHAPTER III

A PETROGENETIC MODEL FOR WESTERN GALICIA

RESULTS OF GRAVITY SURVEYS

Gravity surveys were carried out in parts of western Galicia; they have revealed the existence of four separate positive Bouguer anomalies, as compared with the regional value, one of 38 mGal in the Cabo Ortegal complex (Fig. 3), another of 25 mGal around Santiago de Compostela, and two further ones of 15 mGal around Mellid and 10 mGal around Sobrado (Fig. 4). No anomaly was found in the Lalín area. A preliminary survey in the Monte Castelo area indicates the presence of an anomaly. The rather high anomalies prove the existence of deeply rooted high-density structures below these four complexes. These structures can be interpreted as more or less tilted mushroom-shaped domes or diapirs (van Overmeeren, 1975; Keasberry et al., 1976).

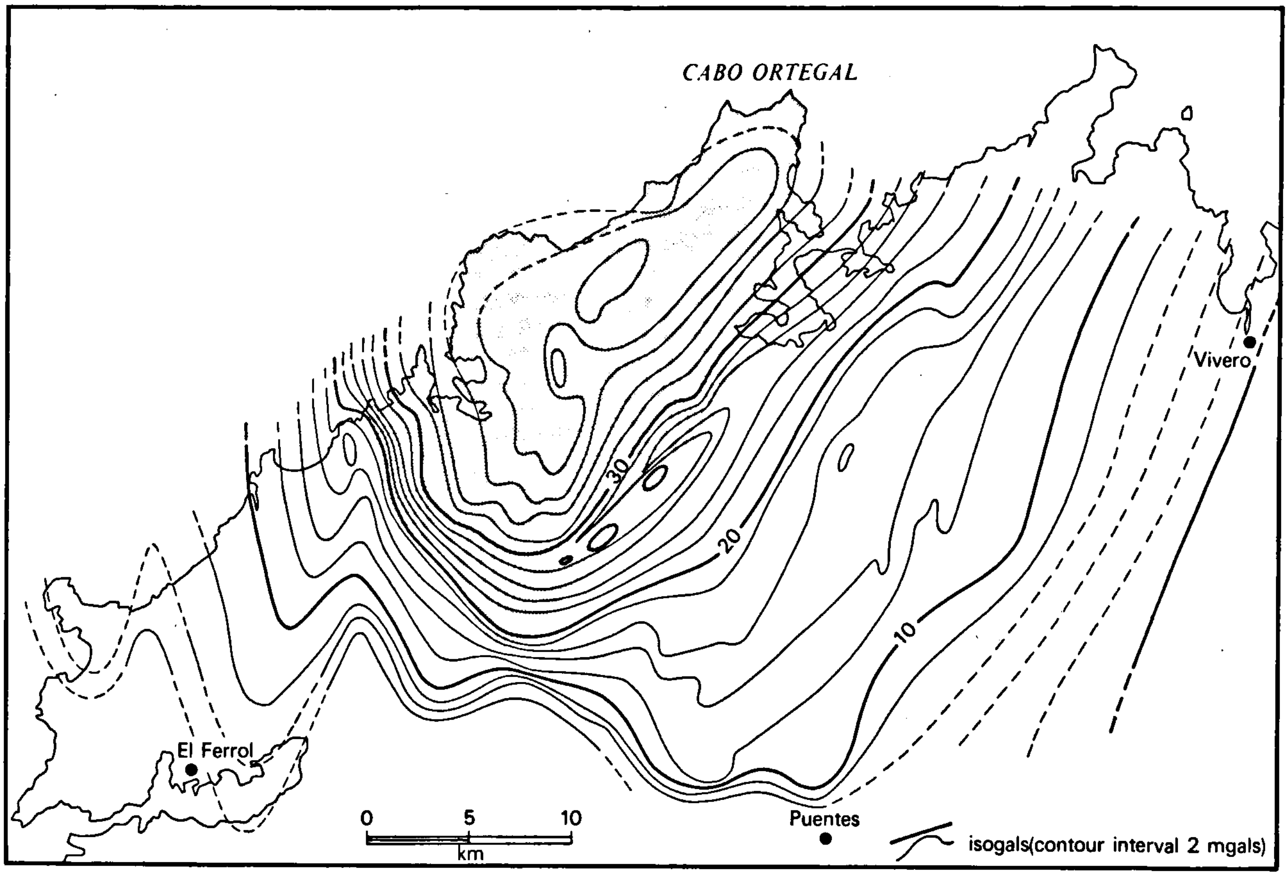

Fig. 3. Bouguer anomaly map of the Cabo Ortegal area, from van Overmeeren (1975).

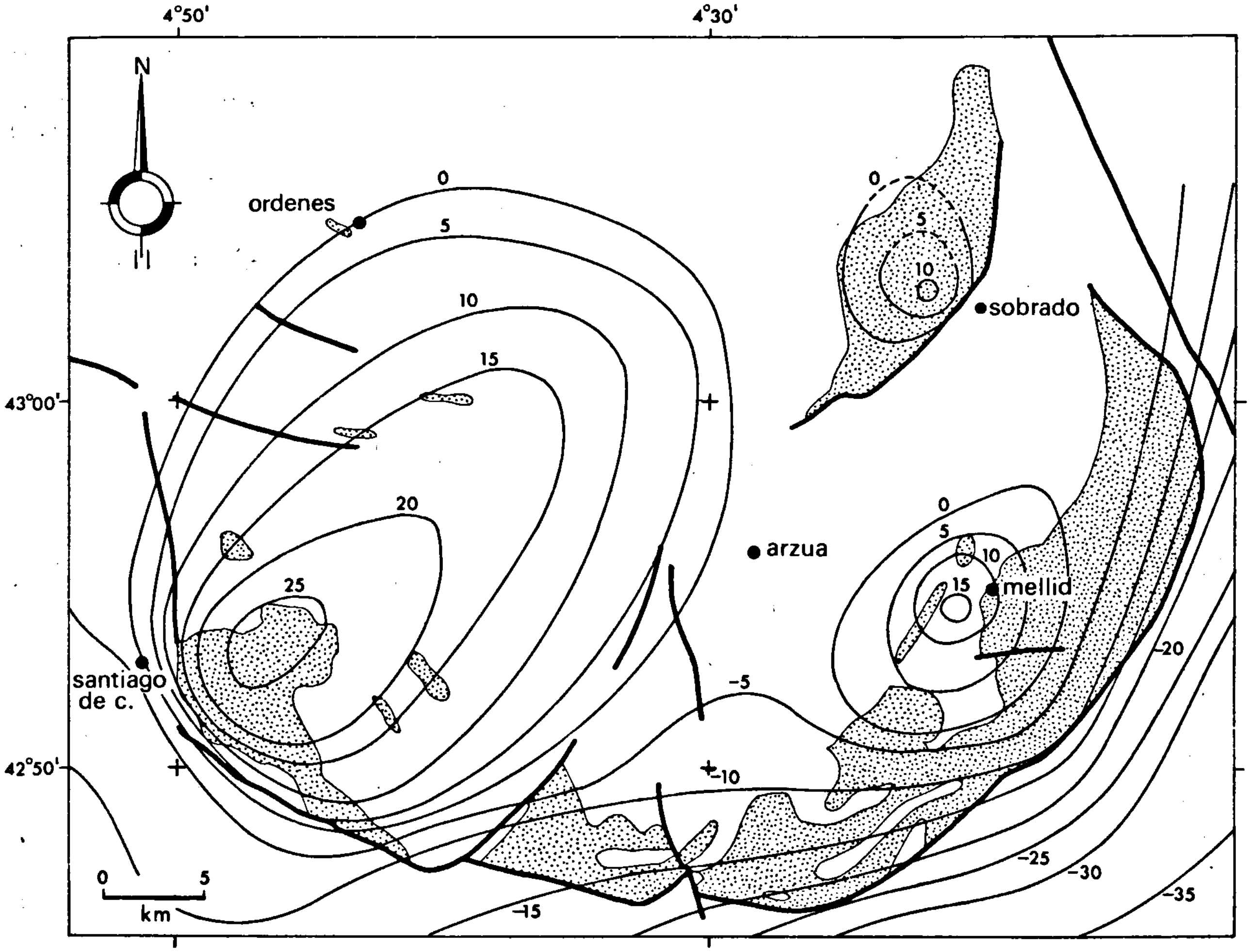

Fig. 4. Bouguer anomaly map of the Ordenes basin, from Keasberry et al. (1976).

GEOCHRONOLOGY

Geochronological data on Galician rocks have been reported by Priem et al. (1970) and by van Calsteren et al. (1977). Their results can be summarized as follows. In the Cabo Ortegal complex an isochron age of 487 ± 122 Ma was obtained for the intrusion of the lherzolites. Various Rb-Sr and K-Ar mineral dates cluster around 390 Ma. This age is regarded as the end of the granulite facies metamorphism. The Rb-Sr isochron age of 354 ± 17 Ma for some granulites together with a Rb-Sr mineral age of 344 ± 10 Ma are interpreted as the closing date of the hornblende granulite facies metamorphism. The extrusion age of the mafic eclogites and granulites has not been established. It could very well be a Precambrian age.

Rb-Sr and K-Ar ages of paragonite and phengite from an eclogite-lens in the Blastomylonitic graben also cluster around 350 Ma. This indicates that high-grade metamorphism ended at about the same time in both complexes.

A metamorphosed and strongly tectonized augengneiss from an area near Mellid, revealed a Rb-Sr whole-rock isochron age of 409 ± 24 Ma, while similar rocks from the Blastomylonitic graben yielded Rb-Sr whole-rock ages of 466 ± 29 Ma and around 462 Ma.

These ages are interpreted as reflecting an episode of felsic magmatism between 470 Ma and 400 Ma, apparently contemporaneous with the intrusion of the Cabo Ortegal lherzolite. A genetic relationship between these types of magmatism seems obvious.

In the area around La Guardia in southwestern Galicia, alkaline two-mica granites occur that originated before the second Hercynian deformation phase. These granites are genetically related to the regional migmatization episode in western Galicia (Buiskool Toxopeus et al., 1977). The Rb-Sr whole-rock isochron age of these granites is 318 ± 21 Ma. The time interval between the end of the high-grade metamorphism in the high-grade and polymetamorphic complexes, and the emplacement of these granites, is thus comparatively short, and therefore a genetic relationship between these two episodes cannot be excluded.

Deformed calcalkaline granites have yielded a Rb-Sr whole-rock age of 316 Ma, and similar but undeformed granites have revealed an age of 297 Ma. Minerals separated from various granites give ages of around 280 Ma.

It can be concluded, that the last major deformation episode took place around 310 Ma, and that metamorphism lasted until 280 Ma.

TENTATIVE CORRELATION OF GALICIAN GEOLOGICAL PHENOMENA

DEFORMATION (1)	METAMORPHISM (1)	INTRUSIONS: ALKALINE SERIES	INTRUSIONS: CALCALKALINE SERIES	INTRUSIONS: MAFIC SERIES	SEDIMENTS	
normal faulting F 5 local chevron folding		porphyries		dolerites lamprophyres		
	M 4 greenschist facies		stocks biotite- 297 Ma			
F 4 N-S isoclinal folding vertical axial plane	M 3 amphibolite facies migmatization	stocks mega X- 2-mica 318 Ma	mega X- 316 Ma	stocks (4)		
F 3 N-S horizontal axial plane	M 2 hbl-granulite	gneissification	gneissification peralkaline series (3)	basalts	carboniferous devonian silurian	carbonates pelites quartzites (1, Asturias)
F 2 E-W horizontal axial plane	facies 350 Ma migmatization	(2, 6)	409 Ma 462 Ma 466 Ma (2, 3. 5)	dolerites		
F 1 N-S horizontal axial plane	M 1 granulite eclogite amphibolite facies } old			gabbros (1 + 5) ultramafic (1) rocks 500 Ma basalts ? (1)	ordovician cambrian	arenaceous to pelitic with conglomerates (2, N. Portugal) greywackes and pelites (1)

(1) Cabo Ortegal area (2) La Guardia area (3) Vigo area (4) Monte Castelo area (5) Mellid area (6) Noya area

Table 1. Tentative correlation of Galician geological phenomena.

TENTATIVE CORRELATION OF GALICIAN GEOLOGICAL PHENOMENA

In Table 1 an effort was made to correlate a wide variety of geological phenomena such as sedimentation, metamorphism and intrusion. The lack of marker horizons and of extensive stratigraphic sections, the intensity of late faulting, and the poor degree of exposure, hamper the establishing of such a correlation. The present table is based on comparatively small episodes of similar evolution trends in different places, and on lithological correlations. Only the geochronological data can be regarded as unambiguous. The figures between brackets refer to the specific areas where the observations were made.

The columns 'deformation' and 'metamorphism' are slightly modified from the work of Vogel (1967) and Engels (1972). The sequence is deduced from mineral relations and from the relative age of blastesis with respect to deformation. Although relations between deformation and metamorphism may differ from place to place, the presented scheme provides a satisfactory framework.

In Galicia three series of granitic magmatism occur: an alkaline series, a calcalkaline series and a peralkaline series. The first two series intruded over a considerable time-span. The oldest counterparts have been strongly tectonized to linear and planolinear blastomylonitic orthogneisses, and to augengneisses. The peralkaline granites intruded after the oldest granites, separated in time by the intrusion of a mafic dike swarm. Their generation lasted only a short episode (Floor, 1966; Arps, 1970). The largest amounts of alkaline granites are associated with a regional migmatization (Arps, 1970; Buiskool Toxopeus et al., 1977); they have been deformed during the Hercynian. Few younger granites are megacrystal-bearing while post-tectonic granite porphyries also belong to the alkaline series. Hercynian deformed calcalkaline-type granitic rocks are also megacrystal-bearing, and the youngest representatives are completely undeformed.

At least two main episodes of mafic magmatism occurred in Galicia. The oldest series is now present as high-grade (amphibolite, granulite and eclogite facies) metamorphic rocks. The younger series might be associated with the ultramafic rocks. It comprises large gabbro stocks as well as small intrusive bodies. The mafic volcanics can be regarded as belonging to this series, as well as the swarms of post-tectonic dolerites and lamprophyres.

The sedimentary sequences in southwestern Galicia can be correlated with similar sequences in northern Portugal, to which Early Palaeozoic ages have been assigned (Buiskool Toxopeus et al., 1977). The sedimentary strata near Moeche also have Palaeozoic ages based on graptolites (Matte, 1968) and on crinoids and corals (van der Meer Mohr, 1975).

THE MANTLE-PLUME MODEL

The starting point of this model is a normal continental crust consisting of igneous mafic and sedimentary rocks with a metamorphic grade ranging up into the eclogite facies. It is assumed that in the Early Palaeozoic a mantle-plume developed under the crust. A short explanation of the phenomenon 'mantle-plume' seems appropriate here (see Fig. 5).

At some level in the mantle, perhaps at a depth of several hundreds of kilometers, a comparatively thin layer originates with a density lower than the density of the overlying mantle material. Such a density inversion can be caused by an anomalous composition of the mantle (mantle heterogeneity), or by a rising heat current from the lower mantle. At certain places on the interface between low- and high-density material, (Raleigh-Taylor instability), the lighter material will tend to rise. The viscosity ratio between the rising material and the wall rock determines the style of the diapirism. If the wall rock is more viscous, rim synclines will develop and the diapir becomes mushroom-shaped. If the material of the diapir is more viscous, there will be no rim synclines, and the diameter of the diapir at its top is less than at its base. A first order diapir can have a diameter of about 100 to 200 km depending on the thickness of the low density source layer (Whitehead & Luther, 1975). In the proposed model, a first order diapir, for the sake of convenience called 'mantle-plume', is situated in the mantle below western Galicia. In this mantle-plume the diapir production process is duplicated on a smaller scale. Second order diapirs of lherzolitic composition developed, which intruded the lower crust. Within the crust the density inversion ceases to exist and the diapir looses its buoyancy. Some lateral extension might accompany the process.

The lherzolite of the Cabo Ortegal complex is regarded as representing one of the second order diapirs, and its proposed evolution will be discussed. The lherzolites were the melt fraction of the mantle-plume at great depth. During the diapiric rise the lherzolite solidified. At a depth of about 100 km, in the asthenosphere, partial melting started again, leading to a liquid of tholeiitic composition (cf. Green & Ringwood, 1963) that was able to leave the diapir and to intrude the lower crust.

The group of metagabbros and amphibolites in the Cabo Ortegal complex may be regarded as representing this magma. Heat given off by the lherzolite diapir induced granulite facies metamorphism in the already medium- to high-grade metamorphic crust. The mafic eclogites and granulites may be regarded as part of this older crust.

The regional temperature increase caused by the mantle-plume induced anatexis in the deeper parts of the crust, leading to the generation of calcalkaline granitic magmas. These magmas intruded higher parts of the crust, mainly along deep-reaching faults, sometimes causing contact metamorphic aureoles. The oldest representatives of these granite series are now orthogneisses. Some of the calcalkaline magmas were enriched in juvenile material, derived from the mantle-plume or its diapirs, and differentiated to peralkaline granite magmas (Bailey, 1974) which also intruded higher crustal levels. Heat from the mantle-plume also caused migmatization at higher levels of the crust, and the generation of an alkaline two-mica granite series. The relatively low-grade metamorphism of penecontemporaneous sediments in the upper crust shows a rough spatial relationship with the younger granites (van Meerbeke et al., 1973).

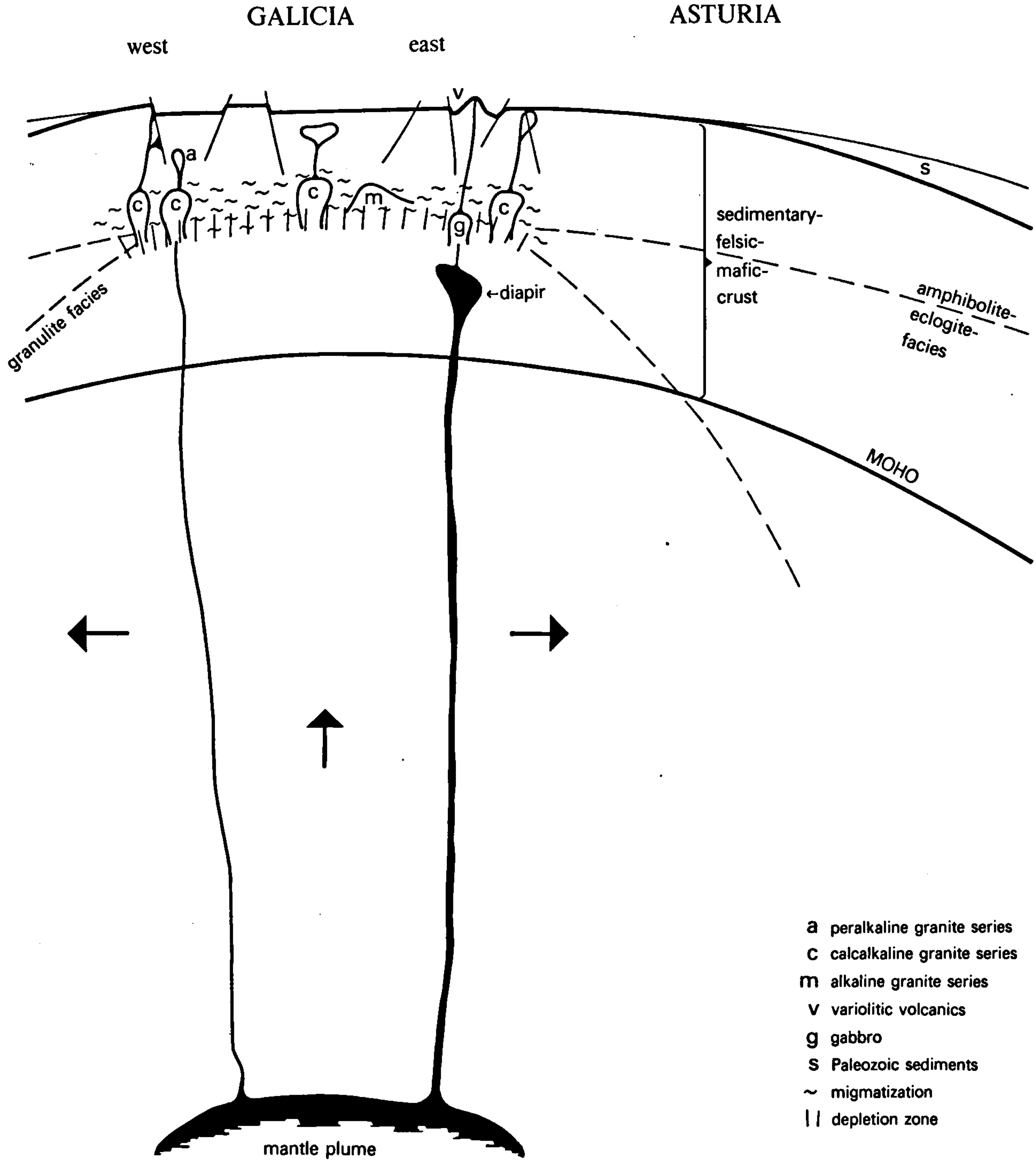

Fig. 5. Diagram illustrating the proposed mantle-plume model, from van Calsteren (1977b).

The mantle-plume caused deformation of the crust. The regional updoming induced deep-reaching faults along which vertical movements took place, causing horst and graben tectonics as exemplified by the Blastomylonitic graben between Malpica and Túy.

Blastomylonitic zones, varying in thickness from a few centimeters to a few hundreds of meters are concentrated near the borders of the high-grade complexes. These zones were formed during the mainly vertical movements that brought the complexes into their present position, mostly surrounded by low-grade, weakly deformed Palaeozoic sediments. The horizontal schistosity planes occurring in rocks from originally deep parts of the crust might have been caused by the pressure of the diapir, or by lateral spreading of the diapiric hats.

CHAPTER IV

EXCURSION GUIDE

THE LALIN REGION

The Lalín region is situated in the easternmost part of the province of Pontevedra (Fig. 6). It can be divided into four units, each characterized by different structural, lithological and metamorphic features and separated fro. each other by tectonic contacts:

1) The peripheral belt of the Ordenes basin, a tectonic unit defined by Den Tex (1966).

2) The Intermediate zone. Structurally, the rocks of this

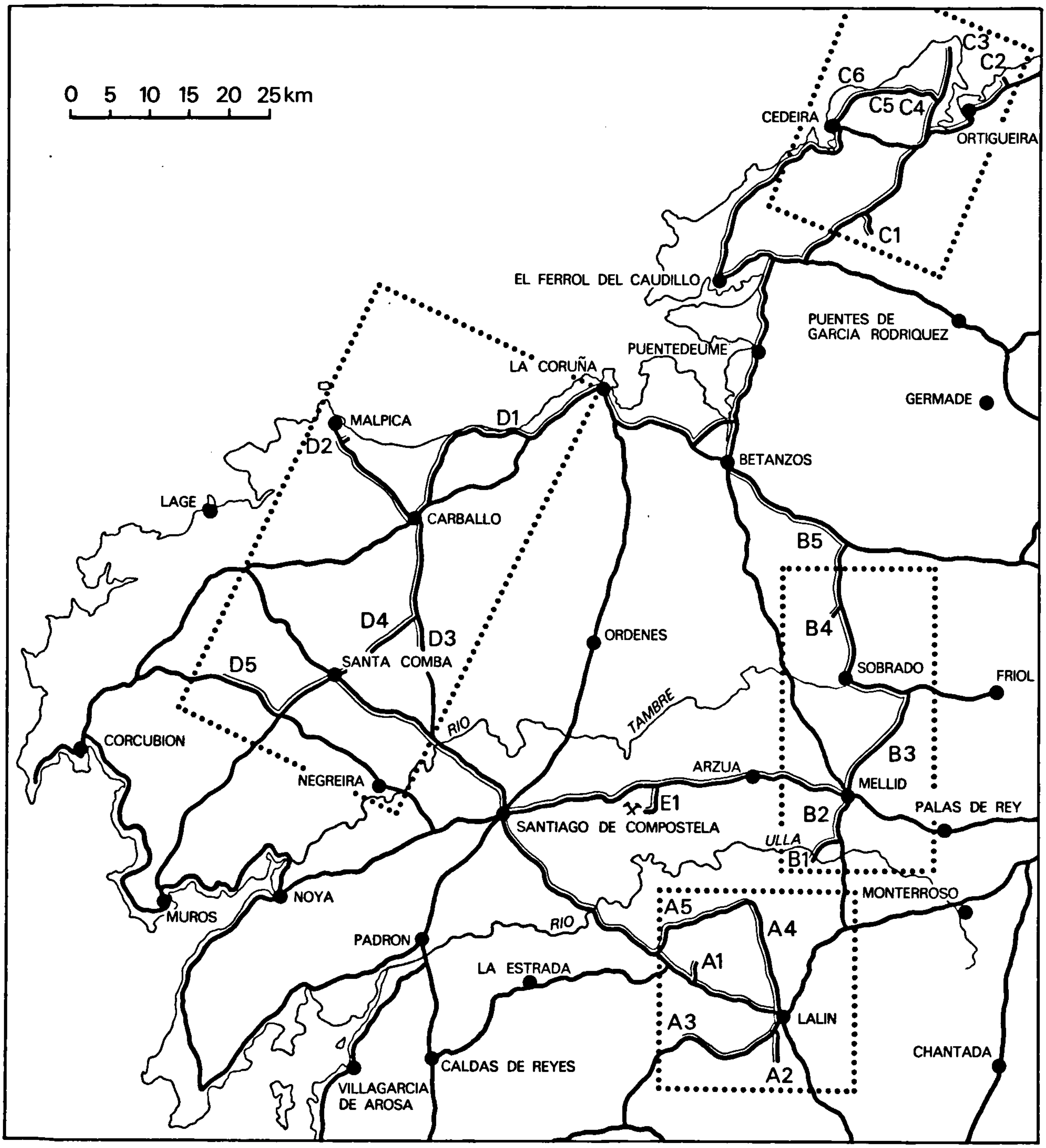

Fig. 6. Excursion route map, within rectangles the areas of Figs. 7, 8, 9 and 12.

zone correspond to the Ordenes basin, but considering its lithology and grade of metamorphism, an association with the Lalín unit seems to be appropriate.
3) The Lalín unit. A curved belt of mainly mafic rocks and paragneisses with thin layers of peralkaline orthogneiss.
4) The Schist complex. The northern part of the central Galician schistzone (van Meerbeke et al., 1973), is mainly constituted of locally strongly folded and metamorphosed pelitic schists, probably of Palaeozoic age.

Late Hercynian intrusive granites and migmatites, cutting off many of the older structures, are abundant, particularly in the northern and western parts of the region (see Fig. 7).

The southern part of *the peripheral belt of the Ordenes basin* is a melange of metavolcanics, metasediments, amphibolites and serpentinites. A Palaeozoic age has been attached to a comparable melange around the Cabo Ortegal complex.

The melange zone forms an arcuate zone outside the high-grade complexes of the Ordenes basin. The most important rock types exposed in this area are mafic and felsic metavolcanics alternating with metasediments. The original mafic rocks have been completely converted into greenschists, the metasediments are now present as porphyroblastic albite schists. The metamorphic grade of the rocks in this part of the Ordenes basin is of intermediate-pressure greenschist facies. The structure is rather complex. An E–W trend of the schistosity with a northern dip is recognizable, which has obviously been overprinted by later Hercynian N–S structures.

In the west the *Intermediate zone* has been intruded by Hercynian alkaline granites and migmatites. In the eastern part of the Lalín region the Intermediate zone becomes more important, showing large-scale interstratification of meta-mafic rocks and pelitic schists. The grade of metamorphism in this area is higher (amphibolite facies) than in the adjacent rocks of the Ordenes basin and corresponds with that of the Lalín unit. Within the Intermediate zone an older northward dipping E–W structure is overprinted by the steeply dipping Hercynian N–S trend. The contacts between the rocks of the Intermediate zone and those of the Lalín unit are tectonic but locally obliterated by Hercynian granites such as the porphyritic biotite granite of Fontao (Hilgen, 1970).

The main rock type of the *Lalín unit* is a compact paragneiss of graywacke composition with two micas, garnet, staurolite, andalusite, and sometimes sillimanite. In some places plagioclase blasts can be distinguished macroscopically. The garnets are hypidiomorphic, small, zoned, turbid, resorbed, and display an anomalous birefringence (Plate 1.1). They occur within oligoclase, andalusite and staurolite metablasts, as well as within biotite and quartz. A similar type of garnet is well known from the metasediments of the Blastomylonitic and polymetamorphic graben in western Galicia (Floor, 1966; Den Tex & Floor, 1967; Arps , 1970), and is considered to represent relics of a pre-Hercynian metamorphic episode.

Pre-Hercynian mafic and felsic intrusions are now represented by many intercalations of amphibolites, and by some peralkaline orthogneisses (locally with aegirine and riebeckite). South of the village of Lalín in the section of the railway Orense–Santiago de Compostela, the mafic intercalations reach their largest magnitude. The predominant trend of the arc is E–W to NE–SW, sometimes clearly overprinted by the Hercynian structure (F_4) with a predominant NNW–SSE trend in this area.

The central part of the Lalín unit is mainly composed of a large alkaline orthogneiss-massif of pre-Hercynian age, which has been intruded by numerous small late-Hercynian granites.

The existence of a mylonitic thrust zone surrounding the arcuate Lalín unit demonstrates that this complex does not occur in its original stratigraphic position. The thrust plane is associated with a zone of white quartzite, less than 1 m in thickness, that contains some feldspar, alternating with tiny bands of mica. Locally the quartz crystals or aggregates are eye-shaped (Plate 1.2). The southern front of the gently north-dipping thrust zone is folded on Hercynian NNW–SSE axes (F_4). At both flanks, the trends of the quartz-mylonite zone and the Hercynian (F_4) coincide. Here the thrust zone has been strongly folded together with the adjacent schists and paragneisses. Post-Hercynian block faulting has displaced the thrust zone several times.

The *Schist complex* consists of pelitic quartz-rich schists, and continues further south as the crystalline schist zone of central Galicia. The schists are strongly folded in accordance with the Hercynian NNW–SSE direction (F_4). They underwent plurifacial epi- to mesozonal Hercynian metamorphism. Roughly from south to north this complex shows an increasing grade of metamorphism. Near the border of the provinces of Pontevedra and Orense, low-grade schists occur with a greenschist facies metamorphism. Northward the increasing grade of metamorphism is demonstrated by the appearance of biotite, almandine-rich garnet, and staurolite porphyroblasts, successively. In some specimens of this schist complex, three S-planes (S_0, S_1 and S_2) can be recognized in thin section (van Meerbeke et al., 1973). Porphyroblastesis has started between F_3 and F_4, corresponding with S_1 and S_2. The growth of garnet and staurolite stopped shortly before F_4, while the growth of a second generation of cross-muscovite, cross-biotite and andalusite has continued after this phase (Hilgen, 1976). The isograds between the different zones of progressive Hercynian metamorphism are slightly folded (F_4). The isograds pass without any disturbance the mylonitic thrust zone from the Schist complex into the Lalín unit. This indicates that the emplacement of this unit in its present position took place before the main phase of Hercynian metamorphism (M_3).

Excursion program

Visits will be made to mafic rock associations characteristic of the several units in the Lalín region. The amphibolite association near Ocastro north of Silleda will be visited, the alternation of mafic rocks and metagraywackes of the Lalín unit in the railway section south of Lalín, the mylonitic thrust plane of the Lalín unit, the metavolcanics of the peripheral belt of the Ordenes basin, and partially serpentinized lherzolites in contact with Hercynian granites and migmatites north of Bandeira.

Stop A 1

Road N 525 from Santiago de Compostela to Silleda, in

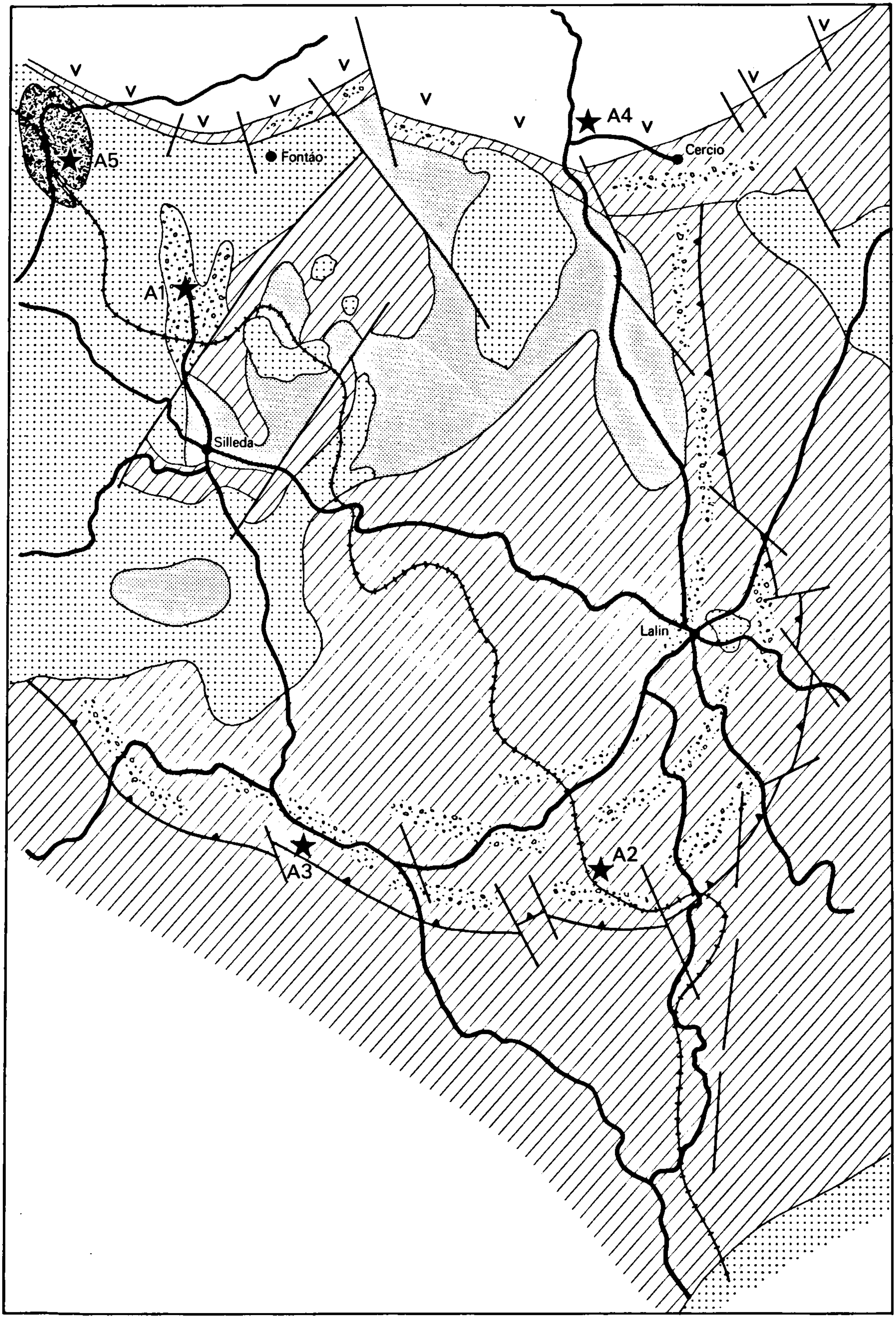

Fig. 7. Geological sketchmap of the Lalín region.

Silleda, direction Ocastro.

Near the village of Castro a small quarry in flaser amphibolite and outcrops of dark massive amphibolites with tiny bands of flaser amphibolites are encountered. The light-coloured minerals form lenses, clusters and patches, which give this rock its typical appearance. Microscopically the lenses consist of a zoned plagioclase (40–80% An), surrounded by clusters of a bluish-green amphibole with cores of clinopyroxene. Other constituents are pargasitic hornblende, (clino)zoisite-epidote, rutile and sphene.

The plagioclase of the dark massive amphibolite is recrystallized, less zoned, and consists of andesine (30–40% An); pyroxene is lacking.

From Silleda the N 525 is followed to Lalín.

Stop A 2

From Lalín N 640 is taken to the railway station. Then direction Mouriscade. Here a small part of the section along the railway will be visited.

The rocks of the Lalín unit exposed in this section show an alternation of garnet- and staurolite-bearing schists, paragneisses of graywacke composition and layers of amphibolite, sometimes with garnet and pyrrhotite. The garnet is considered to represent a relic of a pre-Hercynian metamorphism.

From the Lalín station the N 640 is followed to the bridge over the Asneiro (Puente da Veiga).

Stop A 3

Near Puente da Veiga, situated within the Lalín unit, the thrust plane and associated rocks are visited during a walk. Outcrops of paragneisses and amphibolites of the Lalín unit are encountered before reaching the white quartzite and mylonitic paragneisses and schists of the thrust plane. Staurolite- and garnet-bearing intermediate-grade schists of the Schist complex are also present. Microscopically the rocks of the thrust zone show a nearly granulitic texture (Plate 2.1). The individual crystals are flattened, show an undulose extinction, and possess sometimes mortar rims. The quartz is often slightly biaxial, some crystals show deformation lamellae.

From Puente da Veiga back to Lalín following the northward leading local road to Cruces. On the way the large blastomylonitic orthogneiss massif, forming the central part of the Lalín unit, and the Intermediate zone are passed.

Stop A 4

North of La Goleta (km 12) a local road to Santiago de Cercio is taken. After a hundred meters a quarry is visited with rocks of the peripheral belt of the Ordenes basin. In the quarry a melange of greenschists and mafic volcanics with some felsic intercalations, is exposed.

The local road to Cruces is followed, from here the road to Merza and Bandeira is taken leading through the melange zone of the Ordenes basin.

Stop A 5

At km 3 a quarry will be visited in the serpentinite body of Bandeira. The body is oval-shaped, probably without extension in depth (Diephuis, oral comm.), consisting mainly of a serpentinized lherzolite with dikes of dolerite and granite. Small zones of asbestos and talc are present. In thin section, fresh specimens consist of olivine, enstatite, amphibole, spinel, serpentine, talc and chlorite with opaque minerals (chromite, magnetite).

In Bandeira the N 525 is taken back to Santiago de Compostela.

THE MELLID, SOBRADO AND TEIJEIRO AREAS

The eastern border of the Ordenes basin (Fig. 2) is formed by the two comparable complexes of Mellid and Sobrado. Both consist of a central unit of serpentinized peridotites, surrounded by mafic granulites and high-grade paragneisses. Coarse-grained granitic and granodioritic augengneisses occur between the two complexes and northwest of the Sobrado complex, in both cases separating the high-grade rocks from the low- to intermediate-grade metasediments of the central part of the Ordenes complex.

The complex of Mellid (Fig. 8) consists of a central unit of ultramafics, (partly) surrounded by mafic granulites and kyanite-bearing paragneisses. The high-grade rocks are surrounded by granitic and granodioritic orthogneisses, showing augen- and cataclastic textures, and by low-grade mafic and ultramafic rocks. Most of the rock contacts are faults. The low-grade rocks are serpentinites, showing few relics of chlorite-amphibole peridotite, and amphibolites. The ultramafic rocks show no evidence of high-grade parageneses.

The orthogneisses can be divided into two units. The granodioritic gneisses of intermediate-grade display a characteristic augentexture and a second generation of garnet developed at the expense of biotite. The low-grade granitic gneisses show cataclastic textures, while only muscovite is recrystallized. A Rb-Sr whole-rock age of 409 ± 24 Ma has recently been obtained on orthogneisses of the intermediate-grade unit (see Chapter III).

Fine- to medium-grained kyanite-bearing paragneisses with planar and planolinear textures are mainly restricted to the western part of the complex. During granulite facies metamorphism (M_2), a coarse- to medium-grained assemblage of kyanite, garnet, biotite, plagioclase, orthoclase, quartz and rutile was formed. The minor gabbroic intrusions in the gneisses show a high-pressure paragenesis of garnet, clinopyroxene, plagioclase, amphibole and rutile. Ophitic textures are sometimes visible. As a result of these intrusions, the paragneisses in the immediate surroundings of the gabbros, show evidence of incipient partial melting, and have been reconstituted into layered migmatic gneisses in which quartzo-feldspathic streaks enclose dark restites, consisting of garnet, biotite, rutile and amphibole. As a result of assimilation, a complete range of metagabbros via assimilated paragneisses to unaffected kyanite-garnet-biotite gneisses occurs.

The first metamorphic phase (M_1) in the mafic rocks took place under conditions of the clinopyroxene-almandine subfacies. During a second phase (M_2), recrystallization of the original mineral assemblage, accompanied by growth of hornblende occurred under conditions of the hornblende-

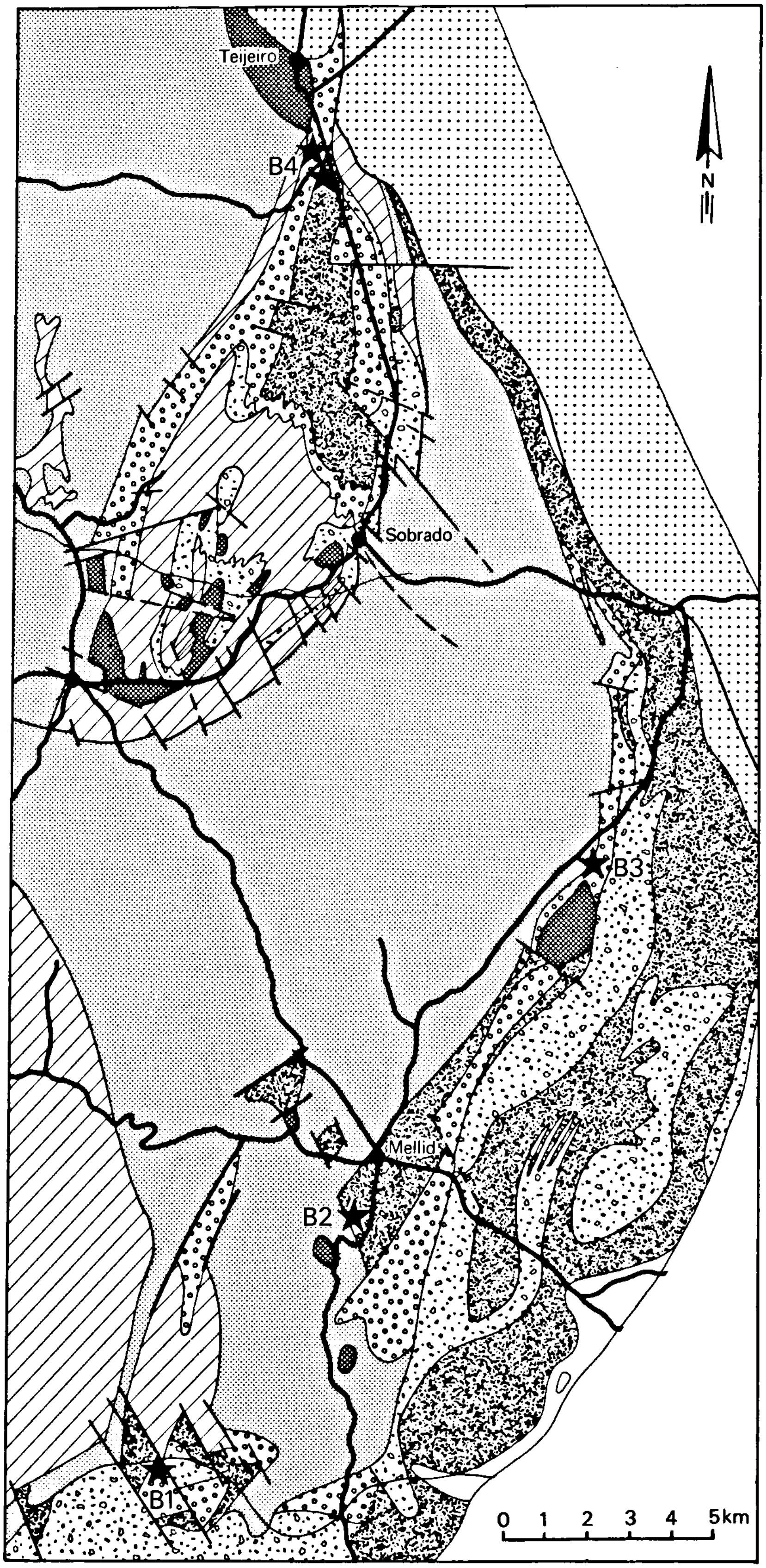

Fig. 8. Geological sketchmap of the Mellid/Sobrado area.

clinopyroxene-almandine subfacies. Later retrogradations occurred under amphibolite (M_3) and greenschist (M_4) facies conditions. Concentrations of garnet, clinopyroxene, amphibole, scapolite, epidote-group minerals and sphene occur as augen-like inclusions with sharp, tectonic boundaries, and as streaks parallel to the foliation. The chemical composition of the metamafics is similar to that of continental tholeiites, while some samples display alkali-olivine basaltic affinities.

The ultramafic rocks in the centre of the complex are foliated, partially serpentinized, spinel-pargasite peridotites with subordinate amounts of clinopyroxene and green spinel. Garnet + pyroxene ± amphibole occurs as boudins and lenses parallel to the planar texture of the host peridotite. Relics indicate that the rocks are retrograded lherzolites. P-T conditions were estimated by Maaskant (1970) to be 800–900°C and 10–15 kb.

Excursion program

Stop B 1

'Camiño de Santiago' (C 547) to Mellid. The road C 540 to Serantes is followed, then to the right to Novela, Belmil and the Rio Ulla.

Near the bridge across the Rio Ulla, an outcrop of flaser amphibolites is encountered. Plagioclase and zoisite form lenses and patches, which give this metagabbroic rock its typical macroscopic appearance, and result in a lighter colour than the dark amphibolites which surround them. Microscopically the plagioclase lenses turn out to consist of albite, crowded with numerous zoisite inclusions, surrounded by bluish-green amphibole. Other constituents are zoisite-epidote, colourless chlorite, rutile and sphene.

Return to the road C 540 and proceed in direction Mellid.

Stop B 2

Along the road C 540, some 1.5 km south of Mellid, a quarry is situated at the left hand side of the road.

In the quarry, peridotites with garnet + pyroxene ± amphibole boudins and lenses are exposed in a recumbent EW-fold. In the peridotite, olivine, amphibole and orthopyroxene occur as large anhedral grains, usually strained and bent, in a fine-grained recrystallized groundmass of olivine, amphibole, orthopyroxene, spinel, clinopyroxene, carbonate and opaque minerals. Garnet occurs in lenses as large, somewhat rounded, anhedral grains. Reaction relationships between garnet and orthopyroxene, and between garnet and olivine, are sometimes microscopically visible by the development of kelyphytic rims.

Mafic granulites are present 200 m south of the quarry. Macroscopically the rocks are dark, foliated hornblende granulites in which clinopyroxene, garnet, amphibole and plagioclase are visible. Retrogradation and deformation gave rise to the formation of blastomylonitic granulites and garnet amphibolites. Locally epidote-amphibolite inclusions are present in which microscopically several textural types, due to different degrees of retrogradation and deformation, can be distinguished.

North of Mellid the catazonal complex is sandwiched between orthogneisses in the west and low-grade mafics and ultramafics in the east. A narrow zone, consisting of granulites, retrograded granulites and garnet-amphibolites, containing lenses of highly serpentinized spinel-pargasite peridotite, is separated from the coarse-grained augengneisses by a discontinuous zone of fine- to medium-grained planar to planolinear, dark-coloured gneisses, with small feldspar augen. Macroscopically these rocks resemble mylonitic parts in the orthogneisses, which makes distinction of the two rock types difficult, especially in areas where strong tectonization has occurred. From field, textural and mineral relationships it is apparent that the possibly metasedimentary gneisses underwent high-grade metamorphism, during which they were transformed into granulites.

Stop B 3

Local road from Mellid northwards to Toques. Some 2 km north of Toques a path leads to Paradela. Just before the village a path leads to the left.

Along this path coarse-grained augengneisses are juxtaposed to layered mafic granulites, with a zone of blastomylonitic augengneisses in between. The coarse-grained gneisses contain large augen of K-feldspar. Plagioclase is usually only present in the groundmass, together with quartz, biotite, muscovite and garnet. The blastomylonites are fine-grained, rather dark-coloured, planolinear gneisses, containing small augen and streaks of K-feldspar. Garnet is macroscopically visible. Microscopically a blastomylonitic texture is apparent. K-feldspar, plagioclase and biotite are the major constituents, while muscovite, garnet, sphene, epidote-group minerals, zircon and opaques occur as minor components and accessories.

Follow the road till the intersection with the road Sobrado-Friol, turn left to Sobrado.

North of Mellid another fault-bounded complex is situated in the neighbourhood of Sobrado de los Monjes and Teijeiro. This complex consists of a central unit of peridotites, surrounded by mafic granulites, catazonal paragneisses, amphibolites and orthogneisses, comparable to the Mellid complex. The peridotites, in some places containing relics of olivine, clinopyroxene and brown amphibole, are highly serpentinized. Talc schists occur as bands and lenses along the borders of the peridotite.

The mafic catazonal rocks underwent strong retrogradation, ultimately resulting in the formation of amphibolites. Some differences with the Mellid complex are apparent. The proportion of granofelsic rocks, composed of a polygonal granoblastic assemblage of garnet, clinopyroxene, plagioclase, brown amphibole and sometimes scapolite, is greater, but the major difference is the occurrence of eclogites and granofelses and mafic granulites with eclogitic affinities (symplectic intergrowths of clinopyroxene and plagioclase which indicates that originally a jadeite-rich clinopyroxene was present). From these occurrences it can be concluded that the first phase of catazonal metamorphism took place under higher pressure than in the Mellid area. Blastomylonitic textures are a common feature in the metamafics.

Throughout the complex small gabbroic stocks occur.

Reaction rims around pyroxenes and olivines indicate retrogradation.

The paragneisses, consisting predominantly of biotite, K-feldspar, quartz and minor garnet and muscovite, are sometimes kyanite-bearing. The concentration of K-feldspar and quartz in augen and streaks is attributed to incipient mobilization.

Stop B 4

Local road northwards from Sobrado to Teijeiro. On the intersection with the road to Curtis, outcrops of mafic granulites, garnet amphibolites and serpentinites are encountered.

The granulites, layered and foliated in some places, show relics of a granoblastic polygonal fabric, consisting of garnet, clinopyroxene, plagioclase and minor brown hornblende. A first phase of retrogradation under amphibolite facies conditions resulted in the formation of green hornblende at the expense of pyroxene and garnet. Growth of chlorites, epidote, clinozoisite and hornblende, at the expense of garnet, pyroxene and older hornblende, is a result of further retrogradation under greenschist facies conditions.

About hundred meters to the south a small quarry has been opened in talcschists in which relics of serpentinite are preserved.

Stop B 5

North of Teijeiro both Early and Late Hercynian granitic rocks occur. They intruded along the eastern border of the Ordenes basin.

Local road from Teijeiro to La Castellana. Then main road N Vl westwards in the direction of Betanzos. At Montesalgueiro a quarry in an alkaline two-mica granite is situated. The medium- to coarse-grained Espenuca granite, named after a hill near Betanzos, is one of the younger Hercynian granites in Galicia.

K-feldspar, plagioclase, quartz, muscovite and biotite are the major components, while apatite, zircon, garnet and sphene occur as accessories. A weak alignment of feldspar-phenocrysts and micas, due to flow and later deformation respectively, is visible. In the quarry several pegmatitic and aplitic veins are present.

THE CABO ORTEGAL AREA

The Cabo Ortegal complex (Fig. 9) consists of three major rock types, 1) peridotitic or ultramafic rocks, 2) rocks of mafic character, and 3) rocks of sedimentary origin. All these rocks have been subject to high-grade metamorphism ranging from the amphibolite and high-pressure granulite to the eclogite facies, and suffered from successive retrogradations (Vogel, 1967; Engels, 1972).

Sedimentary rocks are considered to be one unit, and have been converted into paragneisses, calcsilicate rocks and garnet-biotite gneisses. In a few places in the amphibolite facies rocks, compositional layering and graded bedding can be recognized. In the granulite facies paragneisses, glandular and blastomylonitic textures are common, and in a few places incipient anatexis is visible. The paragneisses in eclogite facies are banded, and display textures that are comparable to the textures of the granulite facies paragneisses.

The mafic rocks recrystallized to eclogites, granulites and amphibolites. The mafic eclogites form three roughly parallel NNE–SSW running ridges in the eastern part of the complex, and numerous lenses in the banded paragneisses; they show a steeply inclined foliation. The mafic granulites occupy the central part of the complex. They are massive rocks devoid of foliation. A foliation has been developed during M_2/F_2 (Table 1) retrogradation. Locally migmatization occurs and barren pegmatoid veins are found. The amphibolite facies mafic rocks are divided into two units by a major thrust zone, the Carreiro zone of tectonic movement, trending in a NNE–SSW direction near the western margin of the complex. The amphibolites to the east of the thrust zone belong to the same group as the mafic eclogites and granulites. The amphibolites to the west are homogeneous nematoblastic almandine amphibolites. Probably the latter are genetically related to the intrusive metagabbros outcropping in the extreme east of the complex. These metagabbros are the youngest rocks of the Cabo Ortegal complex.

Ultramafic rocks in the complex crop out in three major (Limo, Herbeira and Uzal) and some 40 smaller occurrences. The dominant rock type is a partly serpentinized spinel-pargasite peridotite. From relics it can be deduced that it is a retrograde lherzolite. In the lherzolite occur several other ultramafic rock types, i.e. websterite layers, wehrlite layers, garnet-spinel pyroxenite layers and microfolded veins, edenite-phlogopite veins and lenses.

In the areas surrounding the complex occur greenschist facies metasediments with metavolcanics, and serpentinites associated with fossil-bearing limestones. The metasediments comprise rather clean quartzites, gradually changing to phyllites. The metavolcanic rocks are variolites, spilites, and keratophyres, sometimes agglomeratic. The serpentinites are associated with marbles, and sometimes on mm scale interlayered with crinoid- and coral-bearing limestones (Plate 2.2). Based on these and other fossils (graptolites, Matte, 1968), a Palaeozoic age is assigned to these rocks (Fig. 10) (van der Meer Mohr, 1975).

A gravity survey was carried out over the Cabo Ortegal area. The results show that the Cabo Ortegal complex itself is part of a much larger structure extending at least some tens of km to the east and southeast with a gently (10°–16°) SE–dipping boundary-plane. The southwestern boundary is much steeper (30°–90° NE). The magnitude of the Bouguer anomaly of +38 mGal shows that the structure is deeply rooted (van Overmeeren, 1975).

Geochemical investigations were made of mafic and ultramafic rocks from the Cabo Ortegal complex. The results show that the mafic rocks in granulite and eclogite facies belong to one group of quartz-normative tholeiites, enriched in incompatible elements, and with $(La/Sm)_N$ and K/Rb ratios of 3.25 and 284, respectively. This group has great similarities with continental tholeiites such as the Columbia River Plateau basalts and the Deccan Traps. Metagabbros and amphibolites that occur west of the Carreiro zone of tectonic movement are also one group,

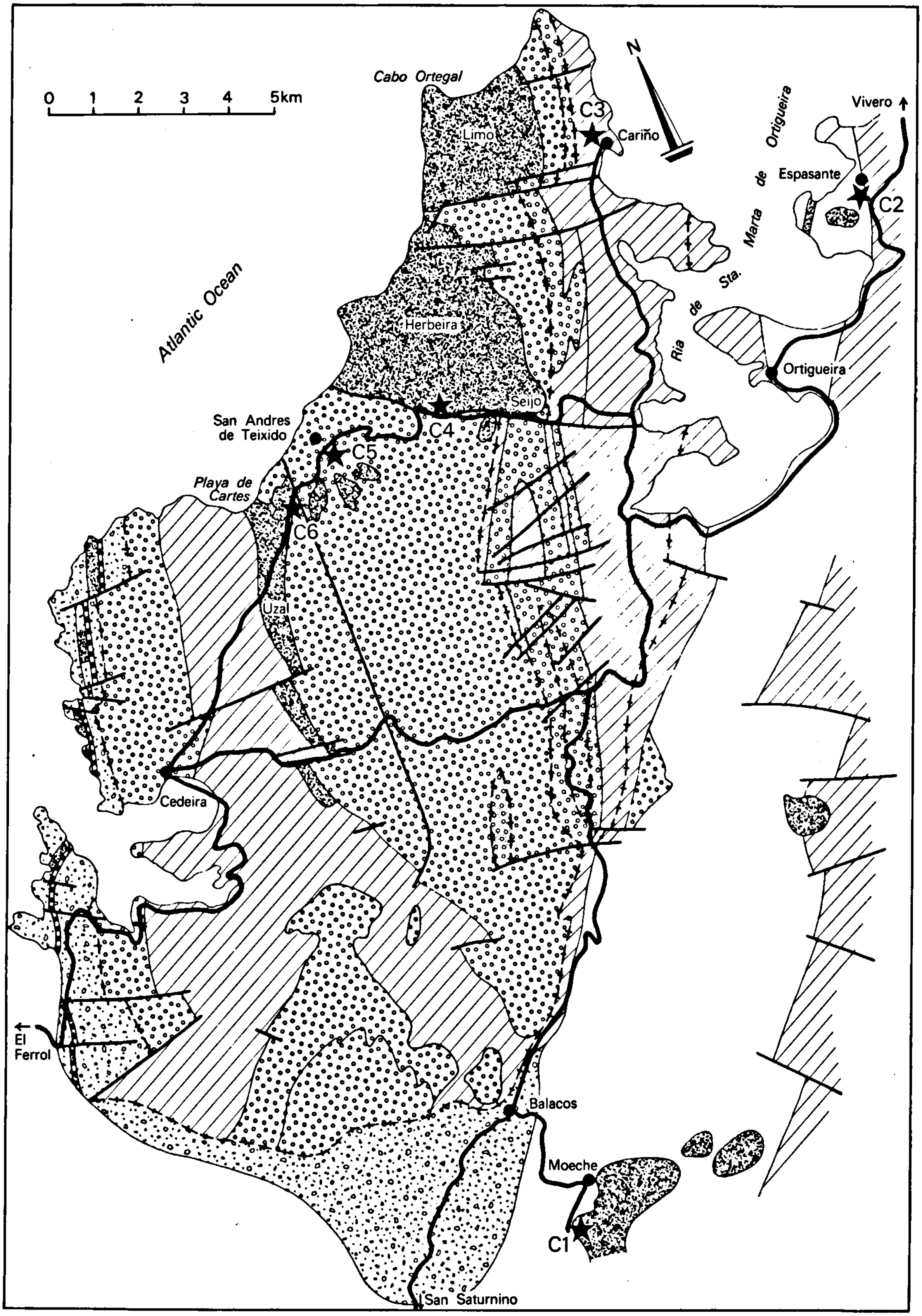

Fig. 9. Geological sketchmap of the Cabo Ortegal area.

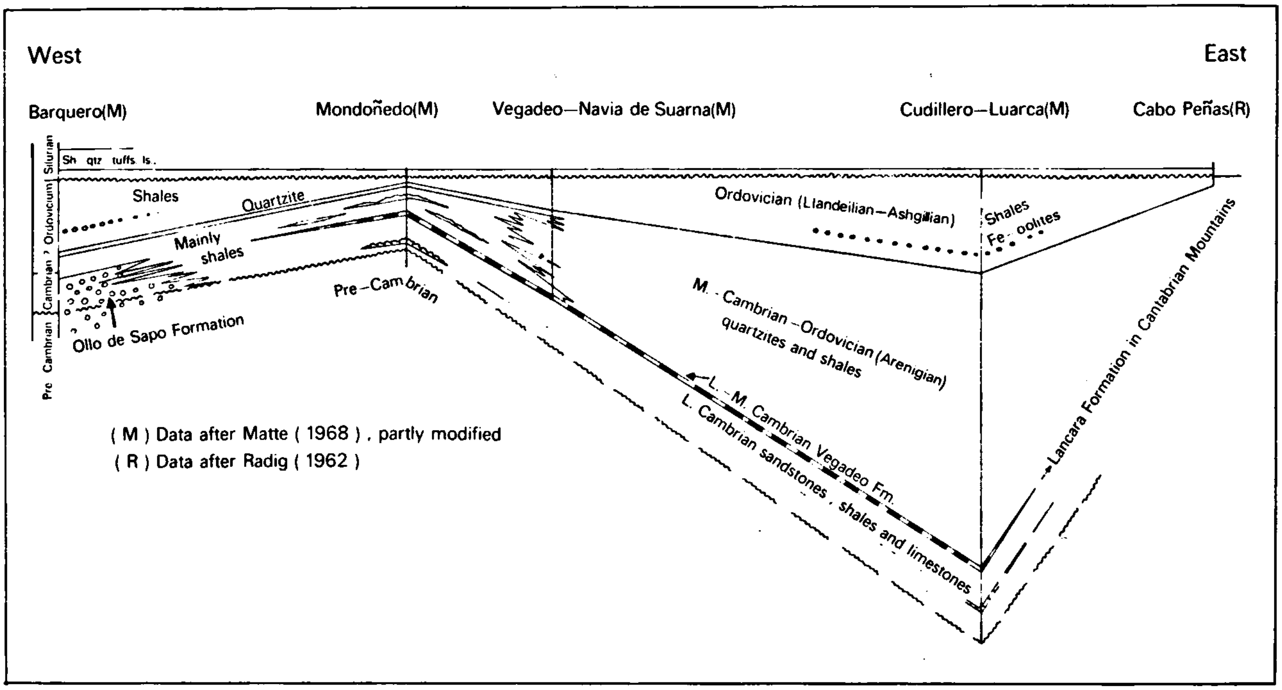

Fig. 10. Stratigraphic cross-section of the Lower Palaeozoic strata between Cabo de Peñas and the anticline of Barquero close to the Cabo Ortegal complex, from van der Meer Mohr (1975).

but this time of olivine-normative tholeiites .This group of rocks is depleted in incompatible elements, and has $(La/Sm)_N$ and K/Rb ratios of about unity and 319, respectively. They are comparable to oceanic island tholeiites such as occur on Iceland and on Hawaii. The lherzolites are depleted in incompatible elements; this implicates that they were the residual phase in a melting event. A similar behaviour is inferred for the high-temperature peridotites of the Lizard and Tinaquillo. However the high $(La/Sm)_N$ and K/Rb ratios of around 9 and 747, respectively, lead to the conclusion that the lherzolites themselves were the melt fraction in some melting event. This points to a two-phase evolution for the lherzolites (van Calsteren, 1978). The Cabo Ortegal complex can be interpreted as part of a diapiric structure (see Chapter III). The diapir originated in the Early Palaeozoic from a much larger mantle-plume and intruded the pre-existing crust. The ultramafic rocks from the complex are regarded to present material from the diapir.

Heat from the diapir induced granulite facies metamorphism in the high-grade rocks from the pre-existing crust. The complex was brought to its present position, surrounded by low-grade rocks, by vertical movements caused by the mantle-plume (van Calsteren, 1977b).

Excursion program

Visits will be made to the serpentinite fossiliferous limestone association and some metavolcanic rocks in the envelope of the complex, the spinel-pargasite peridotites of Herbeira in fault contact with granulites, to an inverted contact between these two, to folded migmatized granulites, and to retrograde eclogites.

Stop C 1

Road C 641, in Vista Alegre C 642, direction San Saturnino to Moeche (Fig.9). From Somazas through greenschist facies, Silurian quartzites and phyllites interlayered with volcanic rocks. Visit to a quarry in serpentinites, south of Moeche.

The serpentinite is a greyish-green rock composed of fine-grained chrysotile and lizardite, fine-grained picotite, and dispersed grains and crystals of calcite. Associated with the serpentinites are lightgreen and well-stratified limestones. In thin section they turn out to consist of a mass of microsparite with about 5–10% bioclasts, mainly crinoid and coral fragments. Sedimentary structures are visible, in some places coarse-grained chrysotile asbestos is found. The rocks are cut by calcite veins.

Stop C 2

Road C 642 to Ortigueira and Espasante through Silurian phyllites and metavolcanics. To the southwestern part of Playa de Espasante across the river.

Outcrops of a volcanic sedimentary melange (greenschists, conglomerates, metagraywackes, metaspilites, meta-andesites, metagabbros, diabases and serpentinites) and retrograded banded gneiss. The metavolcanic rocks have undergone greenschist facies metamorphism; they usually contain quartz, albite, chlorite, epidote, actinolite and accessoria. Amygdales and variolites are filled with albite and quartz.

Stop C 3

Road C 642 to Mera, from there through eclogite facies metasediments and banded gneisses to Cariño, in the village left to the quarry on Monte Castrillon. The quarry

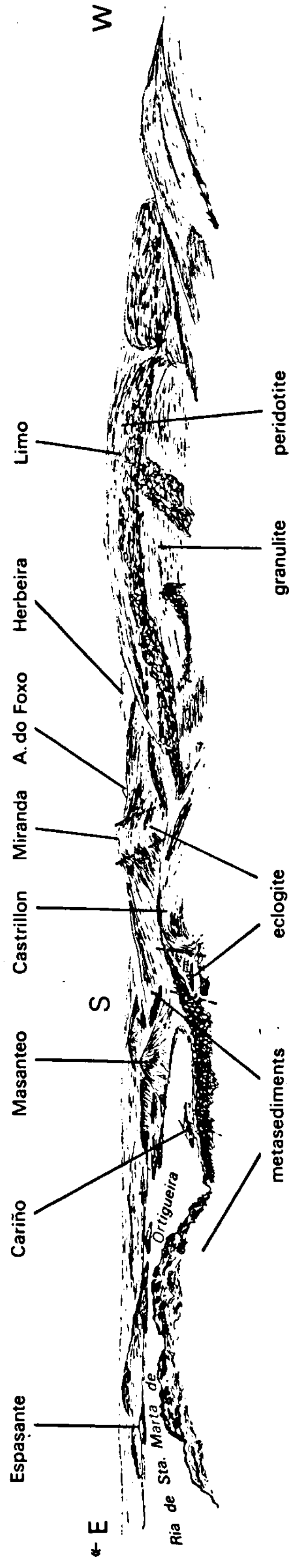

Fig. 11. Panoramic view of the Cabo Ortegal complex, looking south from Punta de Faroleiro.

provided the building stone for the breakwater of the harbour of Cariño.

The eclogite consists of garnet (up to cm size), clinopyroxene and α-zoisite (Plate 3.1). Grain-size varies from coarse to extremely fine, blastomylonitic textures are common. It is partly to wholly amphibolitized. Zoisite-bearing veins cut across the eclogite. Lenses of hornblende, quartz, plagioclase and phengite are late (M_2) phenomena. The quarry is visible on the panoramic view (Fig. 11) taken from Punta de Faroleiro, one km north of the quarry.

Stop C4

From Cariño direction Mera, after about 6 km to Seijo, then through peridotites to a small road-cut.

Partly serpentinized spinel-pargasite peridotite occurs in fault contact with granulites (not exposed). In the peridotite, orthopyroxenite layers occur, and seldom garnet-bearing veins (Plate 3.2). Lenses of pargasite or edenite are found. Close to the fault plane, slickensided serpentinites occur with minor talc and asbestos. The fault is over a considerable distance decorated with vein-quartz, especially near the village Seijo.

Stop C5

Same road direction Cedeira. After passing the bridge in the U-shaped curve (Fig. 9) through granulites. In the vicinity of San Andres de Teixelido in a road cut, migmatized and folded granulites are exposed. The granulites contain minor quartz, plagioclase, garnet, clinopyroxene (mostly amphibolized) and zoisite.

The migmatic layering is evident. After the migmatization, at least two phases of folding caused interference patterns (Plate 4.1). Greenschist facies retrogradation happened in small zones around veinlets.

Stop C6

Same road, direction Cedeira, from the saddle through peridotite up to a fire break to the west.

Along the corridor, Uzal spinel-pargasite peridotite is exposed. Tourmaline-bearing pegmatites are late phenomena. The fault contact with the Chimparra paragneisses is obscured but the gneiss itself is exposed nearby. It is migmatic with lenses of quartz and plagioclase alternating with streaks of mafic minerals. It contains mostly quartz, plagioclase, garnet, biotite, muscovite and kyanite. The texture is planar to planolinear and sometimes blastomylonitic.

A small track leads from the boundary serpentinite/paragneiss down to the Playa de Cartes. From this track there is a clear view of the contact serpentinite/granulite. If time and tide allow, a visit can be made to the Playa itself, some 200 m down. At the beach the following rocks and their contacts are exposed, from west to east 1) Chimparragneiss with lenses of granulite with amphibolized rims, 2) serpentinite, 3) an intrusive granodiorite, and 4) granulites.

Same road to Cedeira, first through peridotite, then through granulite facies metasediments, and after the junction with the road to Chimparra, through amphibolites.

THE AMPHIBOLITE COMPLEX OF BAZAR

West of the Ordenes basin a curved polymetamorphic amphibolite complex is exposed, extending from about 15 km NNW of Santiago de Compostela to 10 km northeast of Carballo. This body is bordered by pelitic and migmatic schists, the Gabbro complex of Monte Castelo, and by the polymetamorphic Ordenes schists and gneisses (Fig. 12). The southwestern contact with the schists is an important thrust fault, along which the amphibolites are strongly foliated and mylonitized.

The Amphibolite complex of Bazar (Warnaars, 1967) is characterized by a wide variety of amphibole-rich metamorphic rocks with a pronounced foliation, and the presence of several relatively large ultramafic bodies in the neighbourhood of the village of Castriz.

The majority of the amphibolites are dark green, fine- to medium-grained rocks with a linear or banded texture. Paler green flaser amphibolites – coarse-grained feldsparrich rocks with a patchy texture – occur closely associated with the ultramafic rocks. Along the western margin of the complex, the amphibolites are locally garnet-bearing, resulting from contamination at the contact with pelitic rocks. Garnetiferous paragneiss and schist lenses are present at or near the eastern border. The presence of numerous metagabbroic relics within the amphibolites indicates an igneous origin of the complex; the flaser amphibolites were derived from coarse-grained leucogabbros. Chemically the metagabbros have tholeiitic affinities. After their emplacement the originally gabbroic rocks were subjected to a progressive high-grade regional metamorphism up to the hornblende-granulite facies.

Warnaars (1967) concluded that just before the culmination of the metamorphism, sills of mafic and ultramafic composition intruded into the complex. Mineral reactions indicate a slight increase in pressure due to consolidation. The majority of the peridotites are wehrlites; lherzolites and other ultramafics also occur. Locally the peridotites are layered.

Retrograde metamorphism (M_3/M_4) transformed the ultramafic rocks and granulite facies metagabbros on a large scale into amphibolites and greenschists.

THE MONTE CASTELÒ AND BARAÑAN MAFIC INTRUSIONS

North of Santiago de Compostela on the northwestern periphery of the Ordenes basin, several intrusive bodies are exposed, viz. a large circular body of gabbroic composition, south of Carballo, and some smaller ones of dioritic composition, the largest of which is situated 12 km northeast of Carballo.

The gabbroic intrusion, which has been called the *Gabbro complex of Monte Castelo* (Warnaars, 1967), is surrounded by the Amphibolite complex of Bazar, polymetamorphic schists and gneisses, and the megacrystal-bearing La Coruña granodiorite (Fig. 12).

The gabbro complex is composed of different sills, probably due to a multiple injection. The differentation in each sill resulted in a decrease of the anorthite percentage of plagioclase, and of the olivine content from bottom to top. Xenoliths occur on the sill-margins, contaminating the gabbros, resulting in the growth of biotite and garnet, the disappearance of clinopyroxene, and an abundance of orthopyroxene adjacent to the xenoliths. In the southern part some ultramafic xenoliths, with high-pressure characteristics, occur. Dolerite dikes, probably representing a late phase of intrusive activity of the mafic magma, cut across the gabbro complex and the adjacent amphibolites and schists in the north. Late-stage epidioritization which locally obliterated the original sill layering, is visible throughout the complex.

The gabbros are massive, fine- to medium-grained, gray-coloured rocks with some pegmatoid parts. The main constituents are clinopyroxene, orthopyroxene and plagioclase. Olivine and brown hornblende are present as accessories. The texture is commonly ophitic, being more pronounced at the bottom than near the top of the sill. A preferred orientation of plagioclase may occur. Deformation (F_4) of varying intensity took place, resulting in the formation of flaser epidiorites, amphibolites with or without palimpsest gabbroic texture, and ultimately mylonites.

Chemical analyses suggest that the original magma was of tholeiitic affinity, while different degrees of contamination by Al_2O_3 and probably alkalies resulted in transitions towards high-alumina basalt affinities. Within the pelitic xenoliths that changed into gneisses or hornfelses, biotite, quartz and garnet are macroscopically visible. Amphibolitic xenoliths are restricted to the western part of the complex.

Mineral associations and mineral chemistry in both gabbros and xenoliths suggest that solidification took place at pressures of about 6 kb and at temperatures between 750 and 650°C.

The *Barañan mafic intrusion* is bordered by polymetamorphic Ordenes schists and gneisses, and by migmatic rocks (Fig. 12).

The main rock type of the Barañan intrusion is a diorite of variable grain-size. In the southern part of the body and along the borders the rocks have a hornblende-biotite tonalite composition. The diorite is undeformed except near the margin. In the diorite, three hornblende varieties occur, an igneous brown hornblende, and a fibrous very pale pargasitic variety; both types have generally rims of bluish-green hornblende (Plate 4.2). Primary biotite occurs as a main constituent in the tonalites. Bluish-green hornblende rims also formed around primary biotite. The plagioclase of the diorites is usually zoned with labradoritic cores and rims of andesine. The plagioclases of the tonalites are slightly more acid.

Within the intrusion, lenses of biotite(-garnet)(-hornblende) gneisses have been encountered. Diorite dikes also intruded the host rocks. At the contacts with the diorites, cordierite and garnet may have developed in the pelitic Ordenes schists, while in other places biotite-hornblende-garnet gneiss and biotite-hornblende felses occur (Rijks, internal report).

The intrusions of the diorites were facilitated by fundamental faults. After their emplacement the diorites were subjected to a retrograde metamorphism (M_4: blue-green hornblende, chlorite, epidote), that also seems to have affected the Monte Castelo Gabbro. The intrusion of the Barañan Diorite is probably more or less coeval with the intrusion of the Monte Castelo Gabbro. Both rock types may be regarded as differentiates of a similar mafic magma source.

THE BLASTOMYLONITIC GRABEN

Near the Atlantic coast of western Galicia, the central part of the axial zone of the Hesperian Massif is exposed. The regional direction of the Hercynian orogenic trend curves from NW-SE in the south to NE-SW in the north (Figs. 2 and 12). Almost parallel with the Hercynian regional trend an older system of fundamental faults has been active, facilitating two series of deep-seated magmas to intrude into higher crustal levels, before the onset of the Hercynian orogenesis. One series is represented by alkaline coarse-grained megacrystal-bearing granites, while the other series can be divided with respect to composition and relative age, into two intrusive groups interrupted by the intrusion of a mafic dike swarm. The rocks of the older group were mainly biotite granodiorites with calcalkaline affinities, and those of the younger group consist of ferrohastingsite(-biotite) granites, and peralkaline astrophyllite-bearing aegirine riebeckite granites. The emplacement of the two main granitic series took place along separate zones, no intrusive relations have yet been encountered in the field.

The first Hercynian deformation (F_3) transformed the granitic rocks to mylonitic augengneisses and planolinear gneisses. The subsequent metamorphism caused a metablastic recrystallization of the granitic gneisses and the surrounding paragneisses and para-amphibolites. The mafic dikes became amphibolite lenses, that sometimes retained relics of an ophitic texture (Plate 5.1) (Floor, 1966; Arps, 1970). Hercynian metamorphism culminated in a large-scale anatexis of deeper parts of the crust, and the generation of anatectic granites. Coeval with metamorphism, a phase of crustal dilatation facilitated large-scale intrusion of granitic rocks, viz. the calcalkaline megacrystal-bearing granodiorite series. Probably simultaneously, the dilatation caused the subsidence of a narrow part of the axial zone (average width 8 km) between the townships of Malpica in the north and Túy at the Portuguese border. Thus the graben developed, which, in contrast to the adjacent basement area, contains crystalline rocks, that have not been affected by the migmatic front. Some ultimate products of migmatization, however, i. e. intrusive alkaline granites, intruded into these higher levels.

The second Hercynian deformation (F_4), soon following the period of crustal tension, acted upon the existing rocks and parts of the consolidating granites as a result of an E–W directed compression. In few places, it can still be discerned that sub-horizontal F_3-folds and foliations have been deformed by F_4, causing an open folding with sub-vertical axial-plane cleavages. F_4 is responsible for a generally well-developed regional schistosity that within the graben almost completely obliterated the first Hercynian foliation.

A third Hercynian deformation (F_5) was the result of a revival of the E–W compression. Phyllonitization and mylonitization of strongly variable intensity clearly acted upon many granitic rocks. Also the displacement of parts of the basement rocks by a complementary set of wrench faults is allocated to this deformation phase (Fig. 12).

Based upon the presence of fine-grained, corroded, and skeletal remnants of turbid garnets enclosed within plagioclase metablasts, it has been suggested that part of the metasedimentary rocks of the graben have a polymetamorphic origin (Floor, 1966; Den Tex & Floor, 1967; Arps, 1970). Clear indications of polymetamorphism have been encountered in the northern part of the graben. Here, on the eastern side of the graben, a series of rather mesocratic gneisses crop out, consisting of a high-pressure paragenesis (garnet, clinopyroxene, a phengitic mica and zoisite) and a Hercynian mineral assemblage (albite, blue-green hornblende and epidote). Another interesting aspect of these gneisses is the presence of medium- to fine-grained eclogite lenses, partly retrograded into garnet amphibolites. Chemically, the eclogite facies mafic rocks display a resemblance with series of oceanic ridge basalts. The eclogites according to van der Wegen (in prep.) are group C eclogites. Metamorphism took place under temperatures of 585–625 °C and pressures of 13–16 kb.

The Hercynian metamorphism started after F_3, and continued until after F_4. The resulting metamorphic mineral assemblage of many rocks in the graben as well as non-migmatic metasediments outside the graben, is characterized by one or more of the minerals chloritoid, biotite, staurolite, andalusite, cordierite, garnet and sillimanite for the metapelites and metagraywackes, and of biotite, blue-green hornblende, cummingtonite, diopside and garnet within the amphibolites and calc-silicate lenses (Avé Lallemant, 1965; Floor, 1966; Arps, 1970).

The Hercynian metamorphic facies series in Galicia indicate relatively low-pressures. From mineral relations a slight pressure decrease and temperature increase can be deduced, as andalusite and sillimanite are relatively younger than staurolite and cummingtonite with respect to blue-green hornblende.

Excursion program

Main road N IV from El Ferrol via Miño to Bergondo and La Coruña. Up to the bridge over the Rio Mero, low-grade metasedimentary rocks belonging to the northern part of the Ordenes basin are traversed. In the area around La Coruña, various outcrops of the La Coruña megacrystal-bearing biotite-granodiorite can be seen. Road C 552 from La Coruña to Arteijo. The hills on the left are composed of a muscovite-biotite granodiorite belonging to the same calcalkaline intrusive series as the younger aplogranitic rocks that constitute the hill-tops on the right.

From Arteijo the local road to Cayon.

Stop D 1

Beside the road along the coast on the eastern side of the

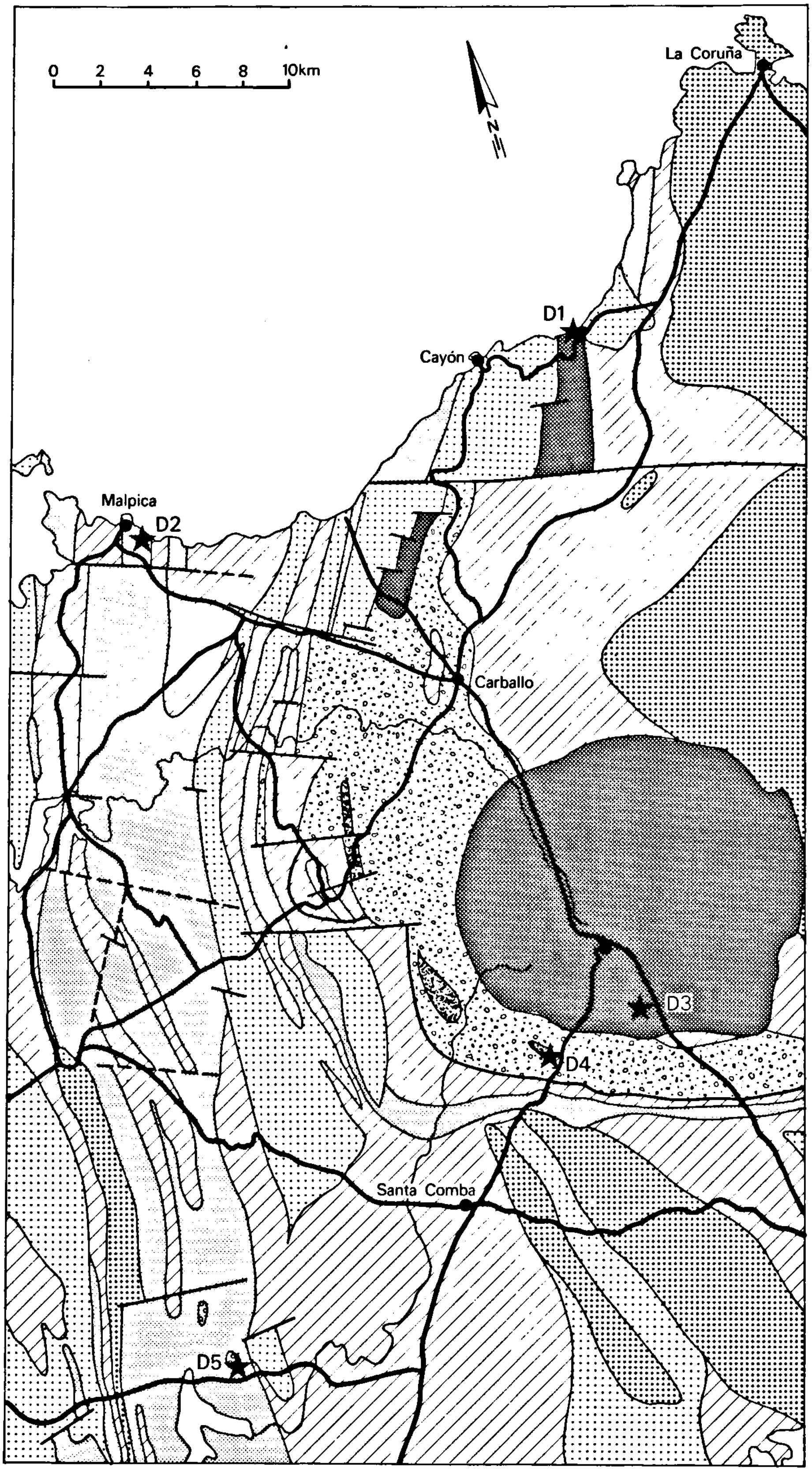

Fig. 12. Geological sketchmap of the area close to the Atlantic coast.

Playa de Barañan, a large quarry is in exploitation in the northeastern part of the Barañan mafic intrusion.

The main rock type is a dark-coloured diorite with a variable fabric and grain-size. Small comagmatic pegmatitic veinlets and a few larger (zoned) pegmatites of late-Hercynian age cut through the rocks. The dioritic rock consists of hornblende, biotite and plagioclase as main constituents. In addition to an igneous brown hornblende, a colourless amphibole occurs, which in some instances seems to be relatively older. Both amphiboles are often twinned. They have either rims of blue-green hornblende, or have more or less completely retrograded into this mineral. The transformation of brown hornblende has caused the exsolution of numerous opaque minerals. Plagioclase is mostly twinned and normally or irregularly zoned, with anorthite compositions varying between 34% (rim) and 53% (core).

Within the dioritic host rock, many melanocratic paragneiss inclusions are present, containing beside biotite and quartz a variable amount of colourless or blue-green hornblende, and sometimes relatively large pophyroblasts of garnet and plagioclase (andesine).

From Playa de Barañan the local road via Cayon to Carballo is followed, first passing migmatic rocks, and south of Playa de Baldayo, polymetamorphic Ordenes paragneisses and the northeastern part of the Amphibolite complex of Bazar. From Carballo to Malpica through amphibolites, phyllonitic (alkaline) muscovite-biotite granite, paragneisses and mesocratic polymetamorphic gneisses belonging to the blastomylonitic graben.

From about km 15, 1.5 km south of Malpica, by foot to the coast to Punta Palerón.

Stop D 2

Close to the coast-line the Palerón eclogite body occurs. It is enclosed by the polymetamorphic mesocratic gneisses carrying a.o. garnet, phengitic mica, biotite, and epidote. About 300 m to the east a relatively resistant coarse-grained variety of this gneiss crops out.

The eclogite is a homogeneous fine-grained rock consisting of clinopyroxene, garnet, kyanite, pale bluish barroisitic hornblende (van der Wegen, in prep.), pale greenish phengitic mica, little zoisite, a relatively large amount of quartz and accessories, a.o. rutile. Clinopyroxene and garnet are both weakly zoned, the clinopyroxene displaying a very pale greenish core and colourless rims with fibrous outlines, the pink garnets having inclusion-rich cores and clear rims with idiomorphic outlines. Two generations of rutile can be distinguished, the older consisting of very small grains is enclosed within clinopyroxene. Along the border of the eclogite body the rock has strongly been subjected to Hercynian deformation and retrogradation. The original rock has been transformed into a garnet-bearing epidote amphibolite, carrying almost colourless hornblende metablasts with bluish-green rims. The garnets are corroded and rutile is still present.

From Palerón back to Carballo, and then southwards to Santiago de Compostela through amphibolites and paragneisses, and after ca. 5 km the Monte Castelo Gabbro is entered.

Stop D 3

In the valley of the Rio Dubra, 17 km from Carballo, in a quarry at the righthand side of the road, the gabbro is exposed.

The gabbros vary from fine- to coarse-grained, with some pegmatoid parts. Assimilated, mostly laminated, xenoliths, containing large garnet porphyroblasts and contaminated gabbros, are present throughout the quarry. Different degrees of retrogradation are macroscopically visible by the disappearance of pyroxenes in the gabbro. Deformation is hardly apparent in the outcrop. No preferred orientation can be seen in the gabbros, although foliated and sometimes folded xenoliths were found in the tailings.

Microscopically, all gradations between non- to slightly-altered gabbro and completely epidioritized gabbro can be seen (Plate 5.2). The non-altered gabbros clearly show an ophitic texture, and consist of pyroxene with exsolution phenomena, mostly surrounded by a narrow rim of amphibole and plagioclase. Dense aggregates of fibrous amphibole developed at the expense of pyroxene in the altered gabbro, ultimately leading to an assemblage of amphibole and plagioclase in which an ophitic texture is still visible. All plagioclase crystals show strong deformation twinning, and are surrounded by a narrow mortar rim. Undulose extinction and kinking of the pyroxenes are frequent. All xenoliths contain garnet, sometimes as cm-large porphyroblasts, amphiboles possess a preferred orientation.

Back north some 4 km, then southwest to Santa Comba, after 6 km stop at the village of Bazar.

Stop D 4

Short walk westward of the village where numerous blocks of variable composition and structure can be examined in the open field. The main rock types are peridotites, serpentinites, hornblendites, epidiorites, epidote amphibolites, hornblende epidosites and flaser amphibolites. Hercynian amphibolitization of the metagabbroic rocks is generally almost complete. Albite and clinozoisite-epidote are associated in crystal aggregates and girdles.

From Bazar to Santa Comba. After leaving the amphibolite complex, paragneisses, orthogneisses, megacrystal-bearing granodiorites, two-mica granites and migmatites are passed successively. At the road-intersection 7 km southwest of Santa Comba, direction west to Mugia.

Stop D 5

Between the villages Brandomil and Baiñas, the La Pioza eclogite, the largest body within the graben, is exposed.

The eclogite is enclosed by strongly weathered polymetamorphic gneisses. A large blastomylonitic peralkaline riebeckite orthogneiss ridge is morphologically conspicuous in the terrain. The high-pressure mineral association of the eclogite can again be subdivided into two generations: clinopyroxene-garnet-kyanite, and garnet-xenoblastic barroisitic hornblende-phengitic mica-zoisite (Plate 6.1). Between these two metamorphic episodes relatively large amounts of quartz must have entered the rock.

In the eclogite body a subhorizontal layering, slightly dipping to the east, can be discerned due to variable amounts

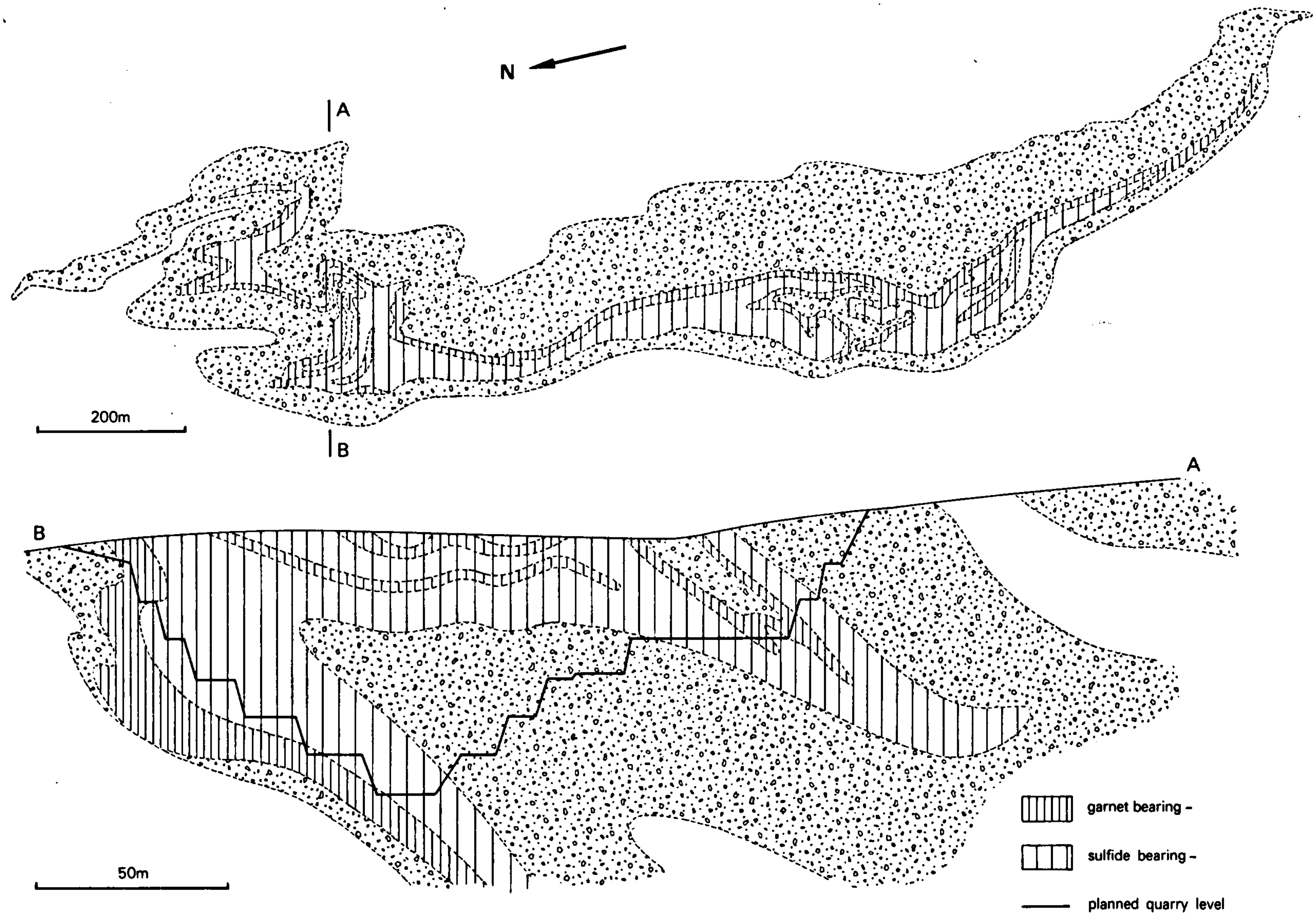

Fig. 13. Geological map of the Arinteiro amphibolite lens.

of kyanite, phengite, zoisite and quartz. Retrogradation started during F_3 with uralitization of clinopyroxene, quartz injection, and the forming of magnetite and ilmenite. Later, along zones of weakness and rims of boudin-like structures, the greenschist facies (M_4) paragenesis of epidote, albite and blue-green hornblende has been formed. The growth of a.o. chlorite and adularia is connected with F_5 (van der Wegen, in prep.).

THE AMPHIBOLITES EAST OF SANTIAGO DE COMPOSTELA

The polymetamorphic Ordenes complex east of Santiago de Compostela (Fig. 2) is separated from the low- to intermediate-grade complex of Santiago (van Zuuren, 1969) by an important curved thrust zone into which quartz dikes intruded (Pico Sagro).

Beside intermediate-grade metasedimentary rocks, graphite- and amphibole-bearing schists, and calc-silicate rocks, the Ordenes basin also comprises several metamafic bodies. The largest one is situated southeast of Santiago de Compostela. The main rock type is an amphibolite, in many places containing garnet, and along the borders epidote. The amphibolites are according to van Zuuren (1969) retrograde hornblende-granulite facies mafic rocks (M_2). In one place a (hornblende-spinel) peridotite has been encountered. Effects of Hercynian deformations ($F_3/F_4/F_5$) and retrogradations (M_3/M_4) to amphibolite facies and lower-greenschist facies conditions are widespread.

Further east between Santiago and Mellid, various other mafic and ultramafic rocks occur within the complex. They include peridotites, serpentinites, metavolcanics, and amphibolites, the latter often carrying high-grade relics of garnet and clinopyroxene.

The garnet-bearing amphibolites are of particular economic interest, because they are locally mineralized, e. g. Fornás, 5 km southeast, and Arinteiro, 20 km east of Santiago de Compostela.

Stop E 1: The Arinteiro copper deposits

The Arinteiro amphibolite, situated on the eastern flank of an anticlinorium, consists of three zones. The outer zone varies in magnitude from 20 to 150 m and consists of fine-grained amphibolite. The middle zone is discontinuous and 10 m thick; here the amphibolites carry small garnets. The central part of the folded body is a 20 to 80 m thick zone of garnetiferous amphibolites and garnet-amphibole gneisses. The large garnet porphyroblasts accompany sulfide minerals such as chalcopyrite, pyrite and pyrrhotite (Plate 6.2).

The sulfides are in some places segregated in veins and veinlets, in other places disseminated or concentrated in specks. At least three folding phases can be traced (Fig. 13). The most important one with N–S directed axial planes is caused by F_4. The schistosity planes and the stratification are parallel with the contacts.

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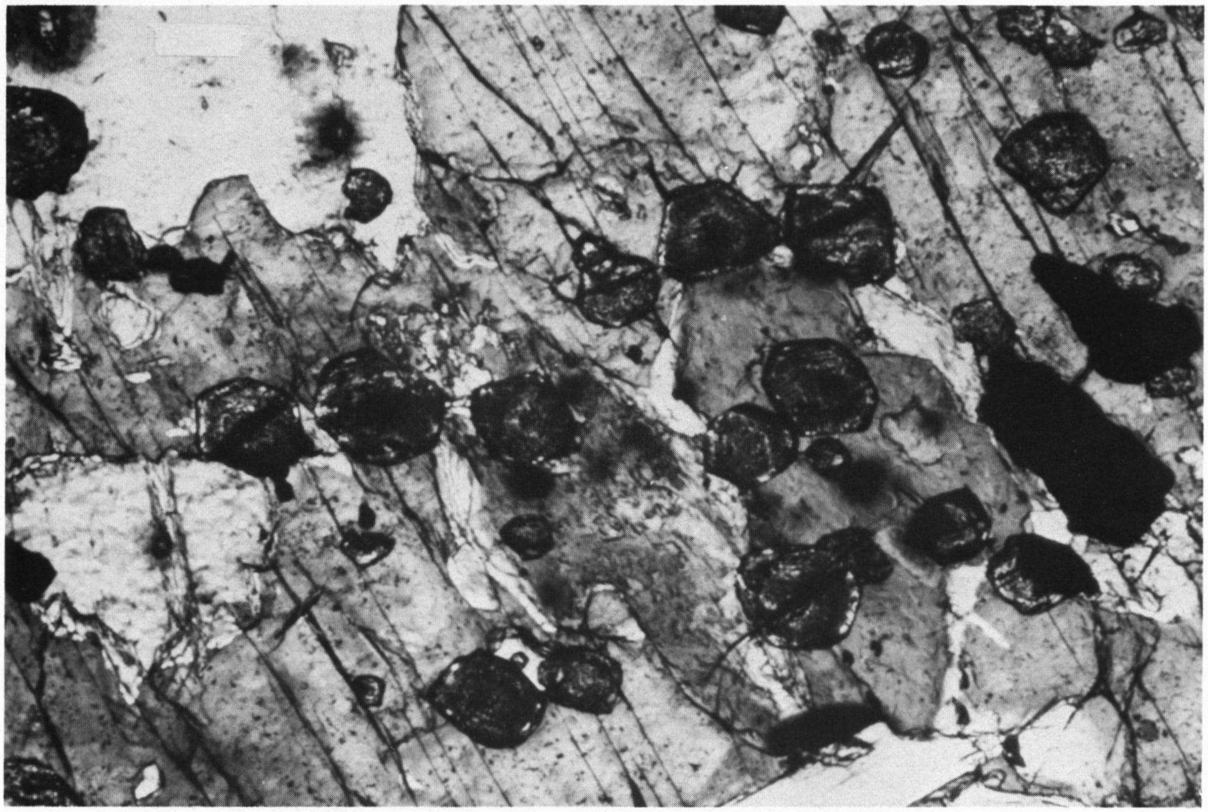

Plate 1.1. Pre-Hercynian paragneiss with resorbed garnets and mica in andalusite porphyroblasts (magn. 8 ×). Lalín unit.

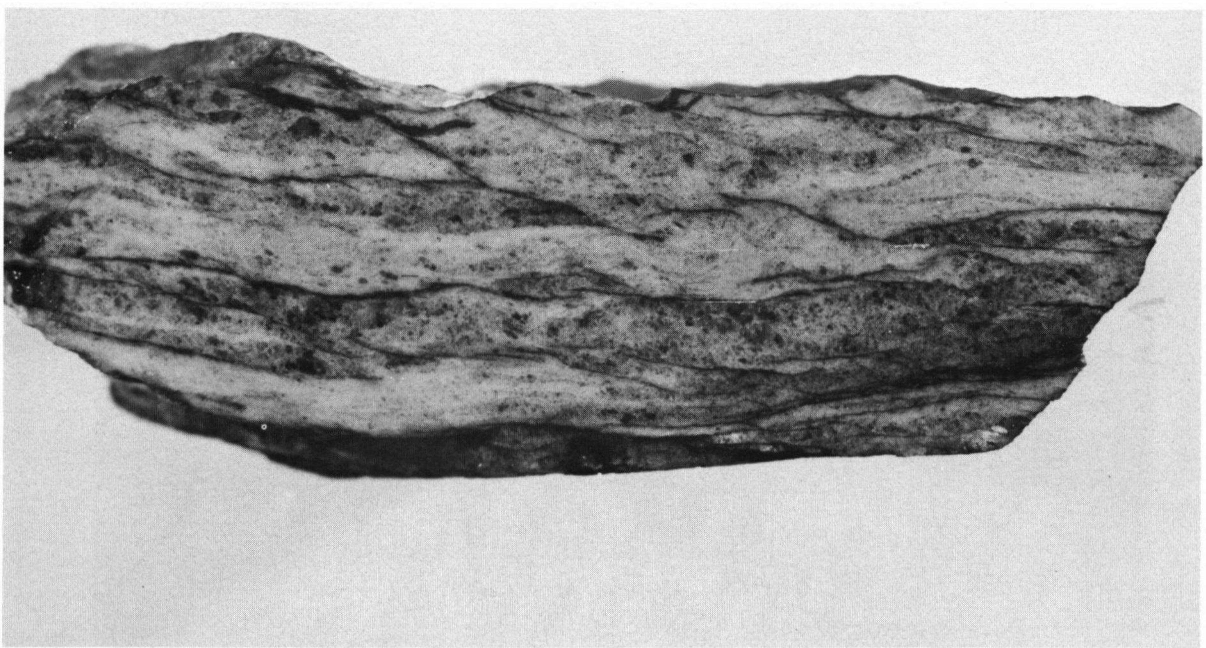

Plate 1.2. Elongated quartz aggregates of the mylonitic thrust plane of the Lalín unit (magn. 1.2 ×).

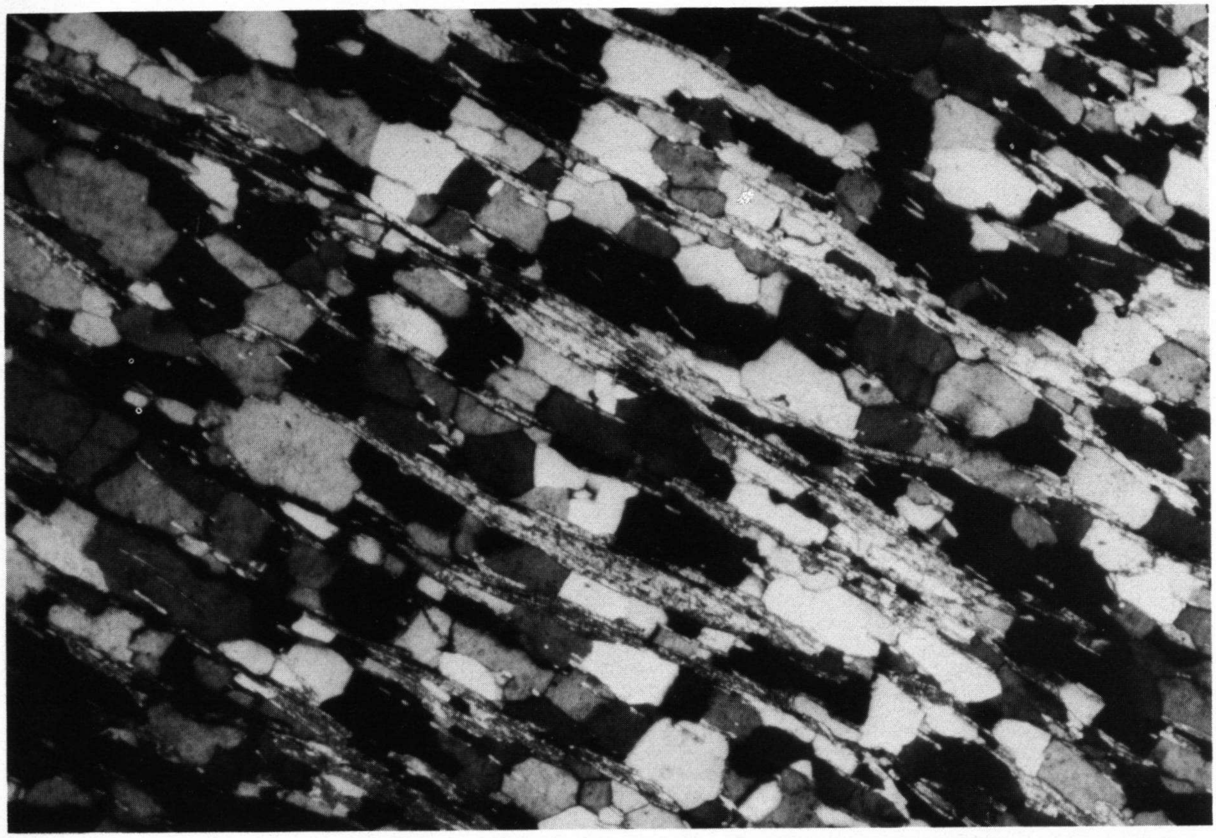

Plate 2.1. Elongated sections of quartz crystals in a mylonite from the thrust plane of the Lalín unit (magn. 40×).

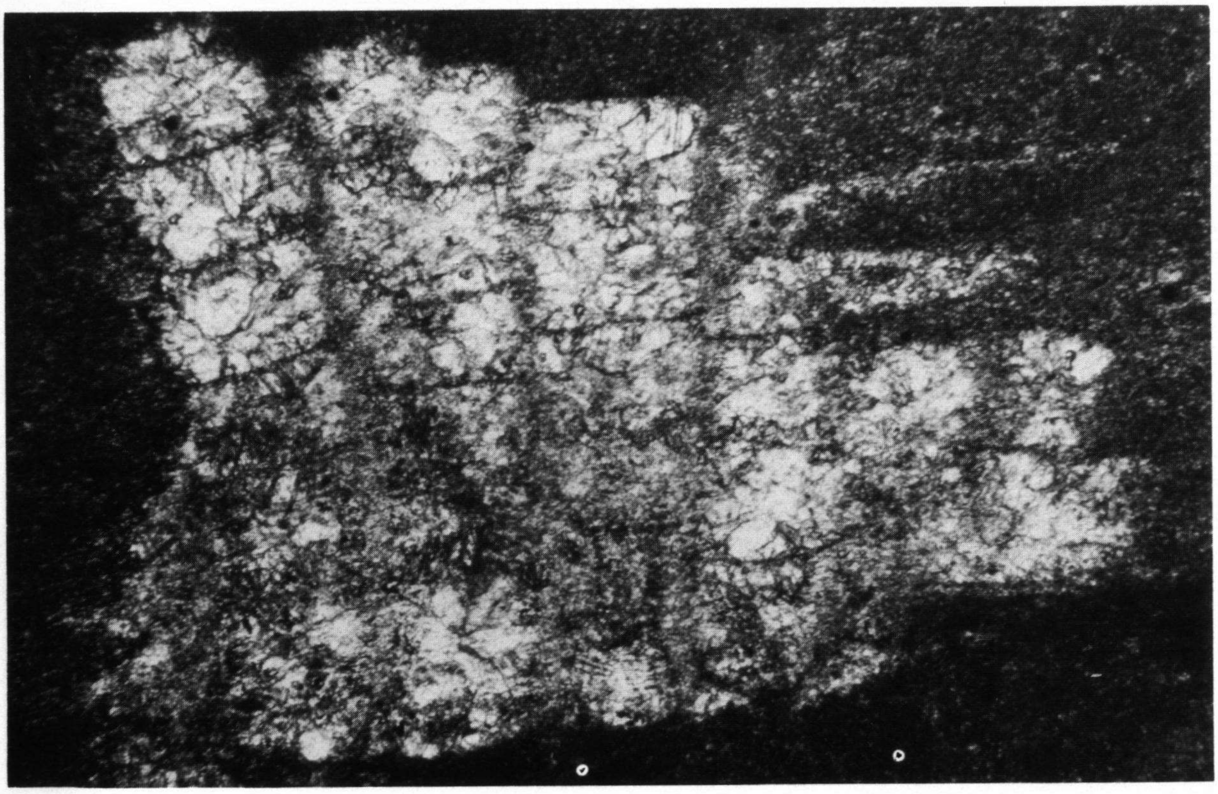

Plate 2.2. Coral fragments from a serpentinite/limestone association at Peña Grande (magn. 80×). Cabo Ortegal.

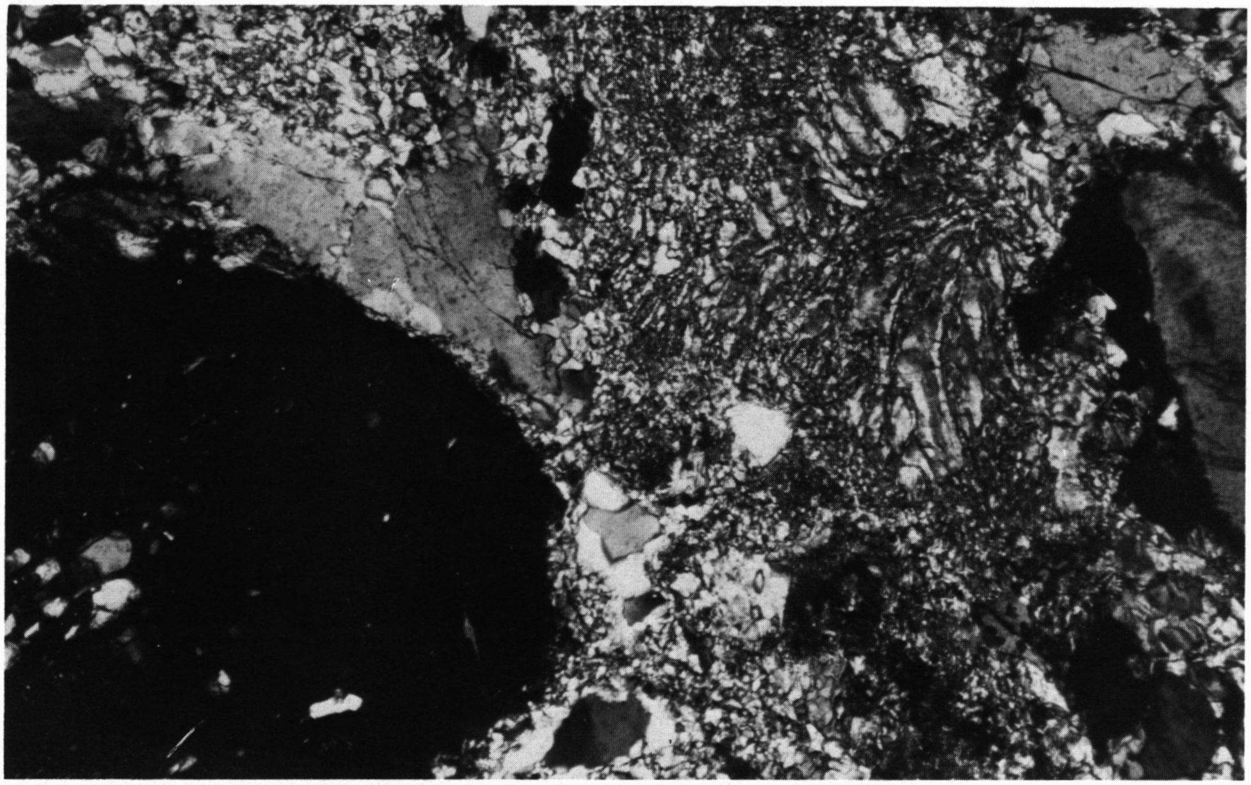

Plate 3.1. Retrograde α-zoisite eclogite (magn. 80×). Cabo Ortegal.

Plate 3.2. Clinopyroxene-garnet vein in lherzolite (magn. 12×). Cabo Ortegal.

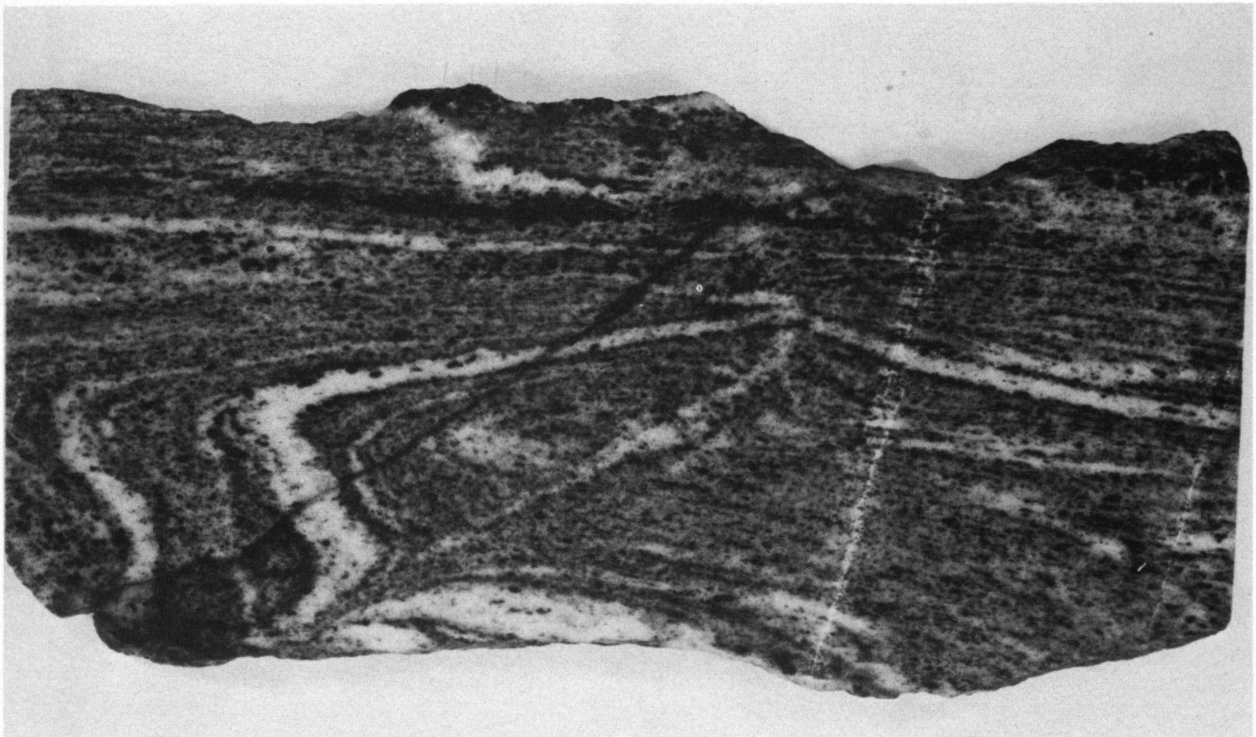

Plate 4.1. Mushroom-shaped interference fold in migmatic granulites (magn. 0.7×). Cabo Ortegal.

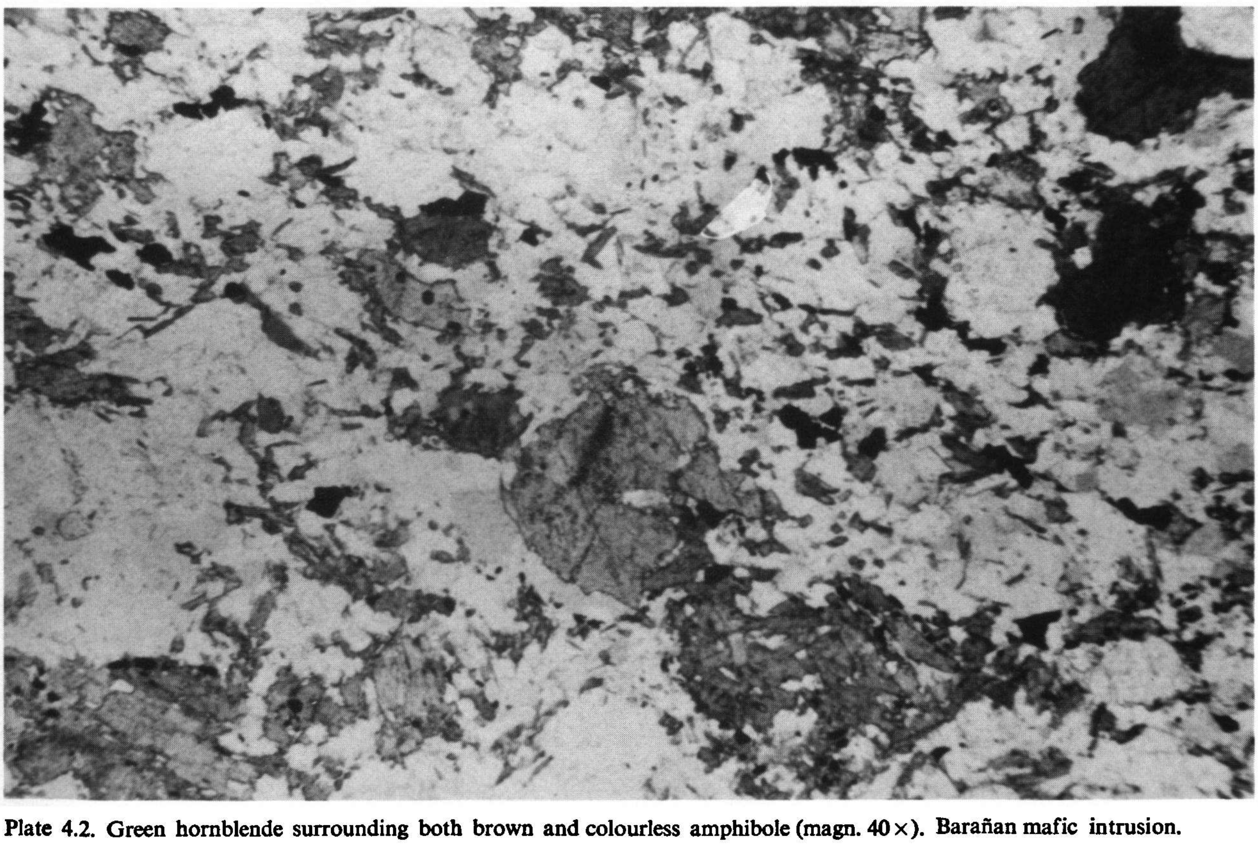

Plate 4.2. Green hornblende surrounding both brown and colourless amphibole (magn. 40×). Barañan mafic intrusion.

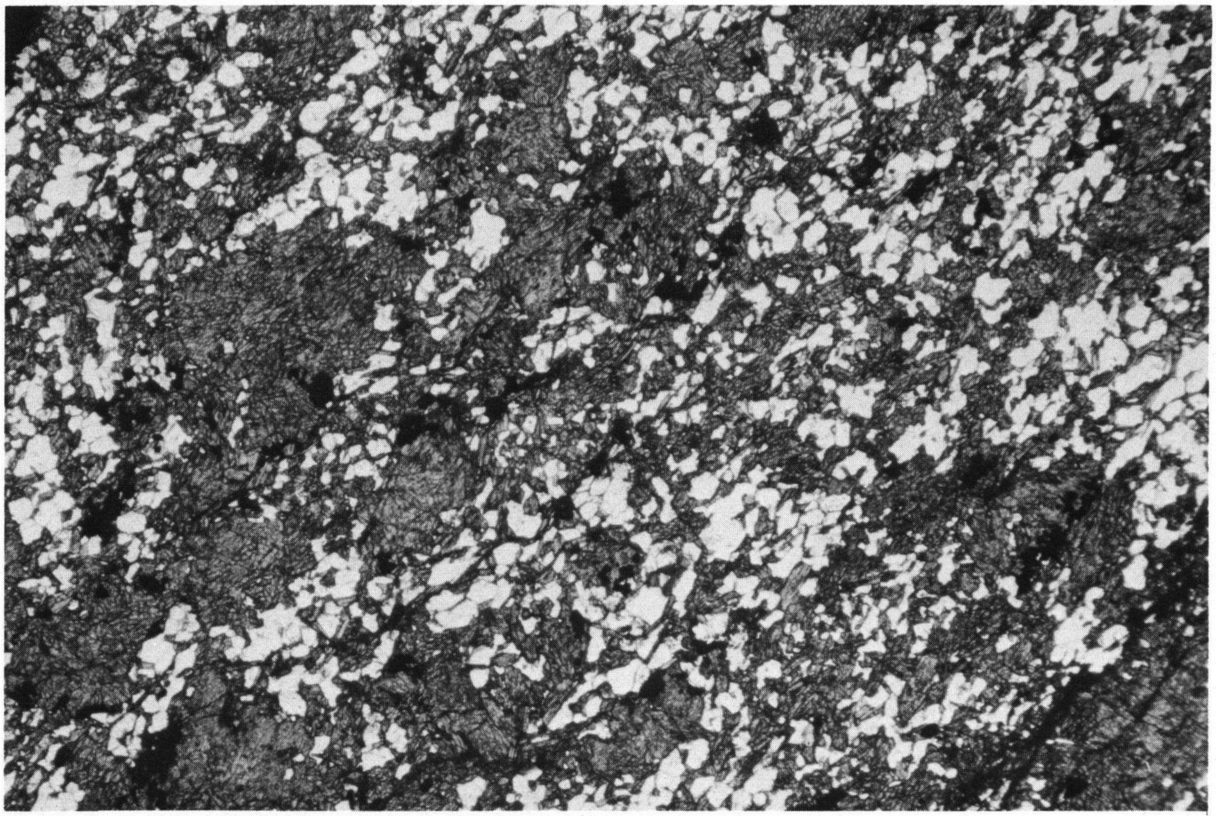

Plate 5.1. Relics of an ophitic texture in an amphibolite (magn. 30 ×). Blastomylonitic graben.

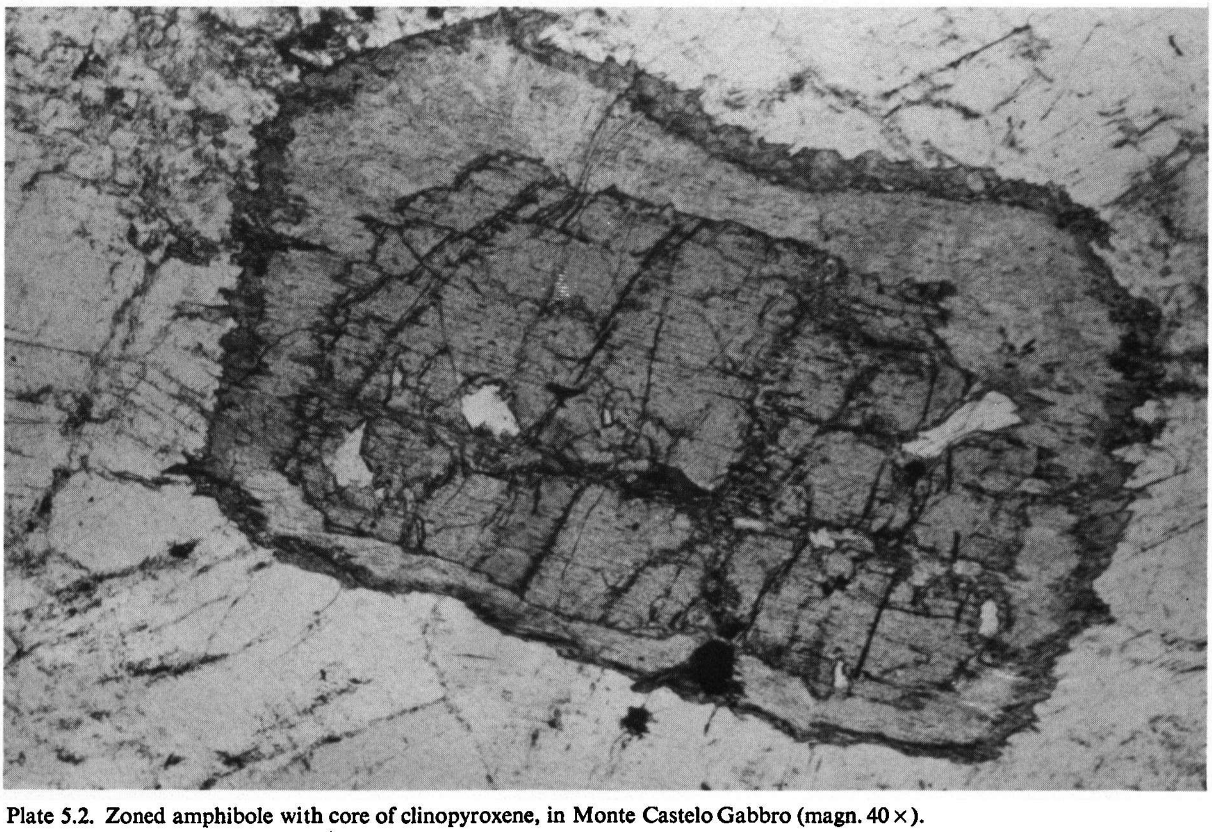

Plate 5.2. Zoned amphibole with core of clinopyroxene, in Monte Castelo Gabbro (magn. 40 ×).

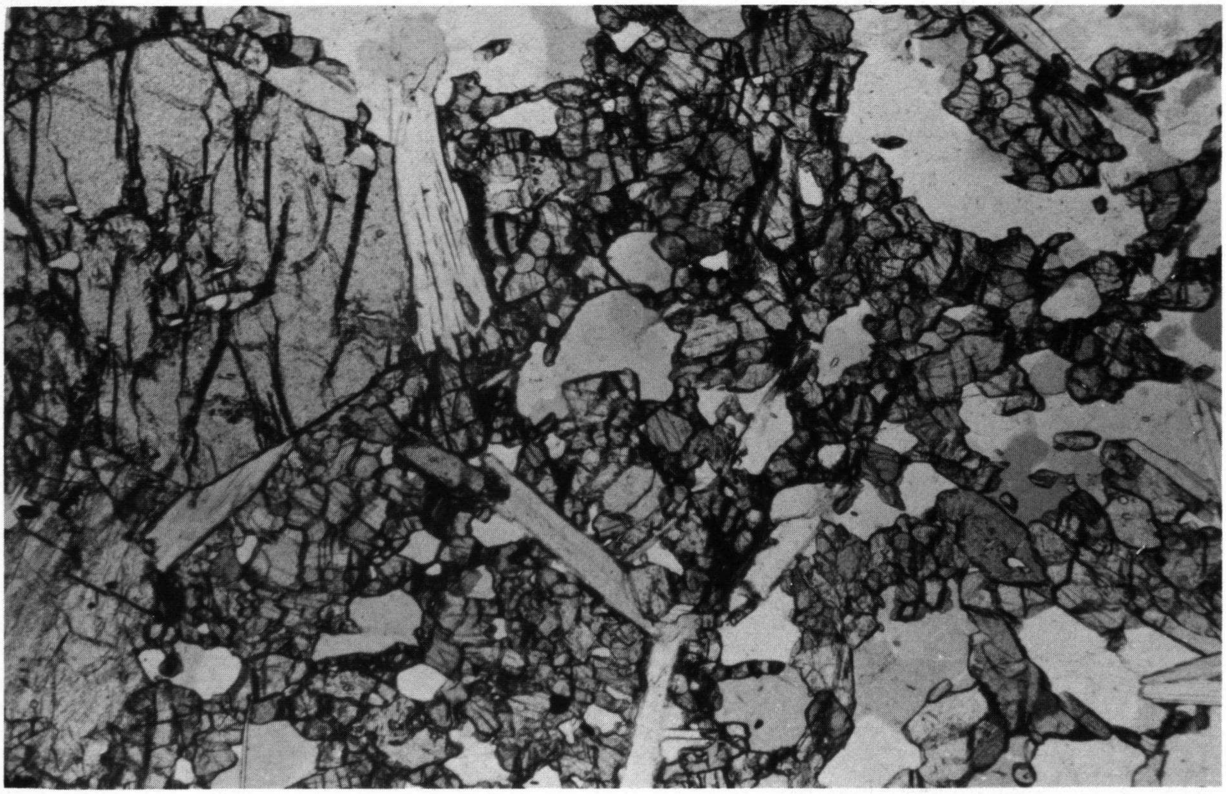

Plate 6.1. Mica eclogite from La Pioza (magn. 40×). Blastomylonitic graben.

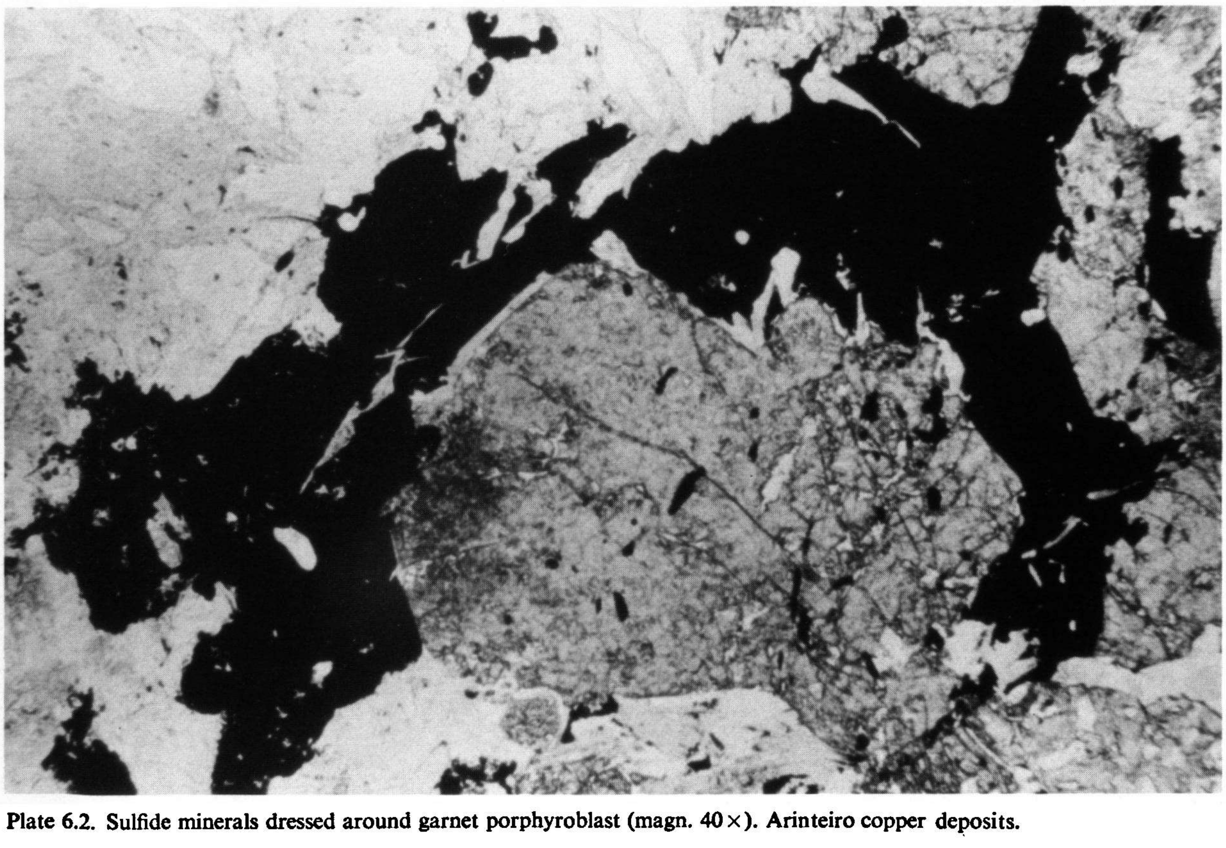

Plate 6.2. Sulfide minerals dressed around garnet porphyroblast (magn. 40×). Arinteiro copper deposits.