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THE RELATION BETWEEN GEOSYNCLINAL FOLDING PHASES AND FORELAND MOVEMENTS IN NORTHWEST SPAIN

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Summary.—The Palaeozoic in NW Spain is discussed in terms of palaeogeographic zones as distinguished by Lotze (1945). These are from west to east: the Galician-Castilian Zone, the West Asturian-Leonese Zone, and the Cantabrian Zone. The latter represents a foreland spur around which successive folds have been molded in an arcuate structure. The first two zones mentioned represent the internal parts of a geosynclinal complex which terminates and fuses in the western part of the Iberian Peninsula and which strikes eastwards under the Mesozoic and Tertiary cover.

The evidence is examined for tectonic movements in different parts of the orogen, and it is concluded that these occurred in seven major phases which can be correlated from one part of the orogen to another, although the intensity differs in the different areas. The older tectonic phases deformed strongly the more internal parts of the geosynclinal complex, while producing uplift on the foreland. Later phases hardly affected the cratonised internal parts but folded quite strongly the tardigeosynclinal basins which became established on the former foreland area.

Resumen.—El Paleozoico del NW de España se divide en zonas paleogeográficas descritas por Lotze (1945). Son, de oeste a este: Zona Galaico-Castellana, Zona de Asturias Occidental-Leonesa, Zona Cantábrica. Esta última representa la terminación occidental de un antepaís al que se amoldaron los haces de pliegues sucesivos en una estructura general arqueada. Las dos zonas primeramente mencionadas representan la parte terminal y unión de los geosinclinales de rumbo W-E que lindan con el antepaís y pasan por debajo de la cobertera mesozoica y terciaria hacia el este.

Examinando los datos sobre los movimientos tectónicos más importantes en las diferentes zonas del orógeno, se llega a la conclusión de que tuvieron lugar en siete fases cuyos efectos se hicieron notar en todo el NW de España, aunque en grado diferente en las distintas zonas. Las fases más antiguas deformaron intensamente la parte interna del complejo geosinclinal, mientras que su efecto se limitó a levantamientos en la zona del antepaís. Las fases más modernas no tuvieron mucha influencia sobre las zonas internas, cratonizadas, sino que deformaron los sedimentos depositados en las cuencas tardigeosinclinales establecidas sobre el área del antiguo antepaís.

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INTRODUCTION

The area under consideration in the present paper comprises most of NW Spain and impinges a little upon northern Portugal. It extends from eastern Asturias in the Cantabrian Cordillera to the Atlantic Ocean west of Galicia, all in the north-western part of the Iberian Peninsula. It has been the subject of numerous recent studies, in particular by geologists from the universities of Amsterdam, Leiden, Montpellier, Münster, Oviedo, Salamanca and Sheffield. Several general tectonic interpretations of this area have been made, some of the most recent being those of BARD *et al.* (1971, 1973) and MARTÍNEZ-GARCÍA (1973).

Three different major palaeogeographic regions have been recognised after LOTZE (1945). These are, from east to west (Figs. 1-2): Cantabrian Zone, West-Asturian/Leonese Zone, and Galician/Castilian Zone. The first one is characterised by an incomplete sequence of Lower Palaeozoic strata, showing a large stratigraphic gap after the Lower Ordovician (Armorican Quartzite), which is followed by Upper Silurian and Devonian deposits. The Lower Carboniferous is condensed and somewhat incomplete, but the Upper Carboniferous shows the greatest thickness of deposits in this area, containing, as it does, several basin fill successions separated by angular unconformities related to folding phases. The Cantabrian Zone is further characterised by high level tectonics, a general lack of metamorphic rocks and the absence of cleavage, despite the fact that the rocks have been closely compressed and great thicknesses are represented. It also has an abundance of well preserved fossils allowing the accurate dating of tectonic events.

The West-Asturian/Leonese Zone is separated from the Cantabrian Zone by the so-called Narcea Anticlinorium, an area of Precambrian slates and volcanics. In the West-Asturian/Leonese Zone there is a full succession of Lower Palaeozoic strata, consisting of slates and quartzites with subordinate limestones and abundant vulcanites. These terrigenous clastics are developed in great thickness, and the sequence is both more complete and vastly thicker than that found in the Cantabrian Zone. Beyond the Wenlockian no undisputable record of the stratigraphic sequence exists in this area until a practically unfolded succession of unconformable late Stephanian strata is reached. The Lower Palaeozoics of the West-Asturian/Leonese Zone are cleaved and folded into large, highly compressed structures.

The Galician/Castilian Zone is rather similar to the adjacent West-Asturian/Leonese Zone in regard to the sedimentary sequence, but it is much more metamorphic and contains extensive igneous intrusions which are mainly of silicic character. There are also several basic complexes of a very particular nature that have been explained in various ways.

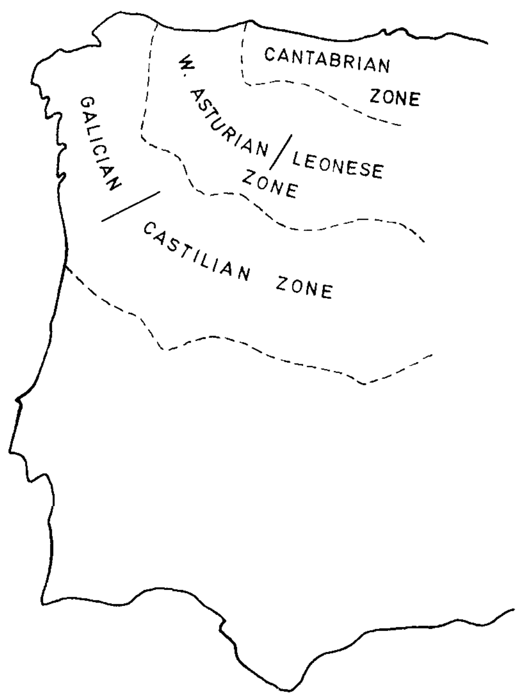

Fig. 1

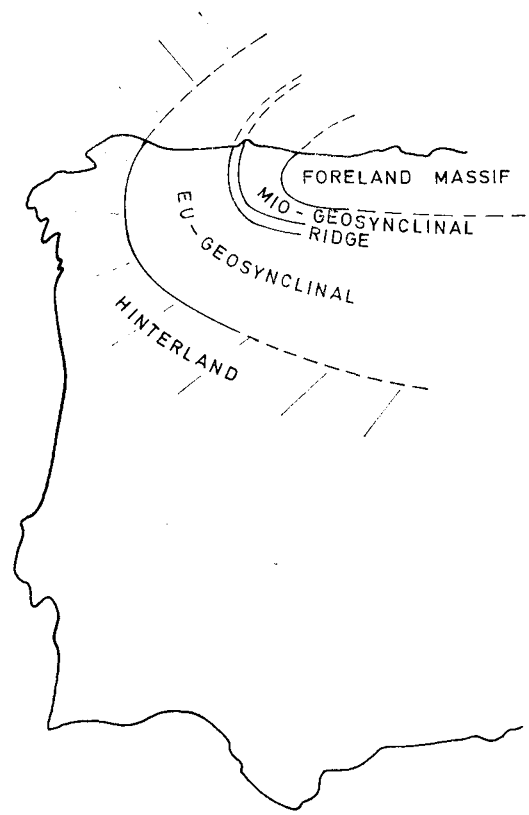

Fig. 2

FIG. 1. *General palaeogeographic zones in the Palaeozoic rocks of NW Spain (after* LOTZE *1945).*

FIG. 2. *Interpretation of the palaeogeographic units in the geosynclinal complex of NW Spain. The situation depicted is mainly that corresponding to Cambrian to Lower Carboniferous times. During the later stages in the development of this region, in Upper Carboniferous and Permian times, the foreland area was encroached upon by the miogeosyncline and tardi-geosynclinal basins, and the hinterland area also advanced in this direction. In detail, the situation was a good deal more complex.*

These three palaeogeographic zones are presently disposed as arcuate belts of folded rocks verging towards the central part of the Cantabrian Zone which appears to have been a tectonic foreland massif during most of its Palaeozoic history. The general disposition may be explained in terms of a conventional geosynclinal couple as described by AUBOUIN (1965). The miogeosynclinal and foreland areas would coincide with the Cantabrian Zone, east of the Narcea Anticlinorium. West of this anticlinorium a Lower Palaeozoic eugeosynclinal belt would be found in the West-Asturian/Leonese Zone which borders onto the Galician/Castilian Zone, coincident with the internal part of the eugeosyncline and partly geanticlinal. The arcuate eugeosynclinal region swings eastwards both south and north of the Cantabrian Zone which can only be explained as representing the western termination of a foreland extending eastwards into an area which is presently covered by unrelated Mesozoic and Tertiary rocks of the mountains of Santander and the Basque country. It is possible that this foreland area re-emerges in the western and central Pyrenees where the stratigraphic sequence resembles that of the central Cantabrian Mountains and where a rather incomplete and relatively thin succession of Devonian and Carboniferous rocks is recorded. This area may well be interpreted as an intermediate foreland *sensu* AUBOUIN, and this means that E-W striking geosynclinal areas existed both north and south of this foreland. The West-Asturian/Leonese Zone, as exposed at present, would merely represent the coalesced terminal part of both geosynclines in their area of union, and the general N-S strike in this zone would be due to the general termination of the E-W striking geosynclinal complex together with the western end of the intermediate foreland massif (Fig. 2).

Within the coalesced geosynclinal area of a general N-S strike it may be that the Narcea Anticlinorium represented the miogeanticlinal ridge, as suggested by PARGA (1970), and there is little doubt that the eugeosynclinal development is found west of this ridge in the West-Asturian/Leonese Zone and in part of the Galician/Castilian Zone. The eugeanticlinal ridge probably lay to the west and coincided, at least partly, with western Galicia. This geanticline apparently extended south-eastwards into central Spain, and separated the geosynclinal complex of northern Spain from that of the southwest. There has been a certain amount of speculation about its links across the Atlantic, but the position is by no means clear.

In the following chapters we will describe the main features associated with the successive folding phases observed in the different palaeogeographic areas discussed. There appears to be a direct relationship between diastrophic events in the early Palaeozoic eugeosynclinal region (West-Asturian/Leonese Zone and part of the Galician/Castilian Zone) and uplifts of the contemporaneous foreland area (Cantabrian Zone). Later on, during the late Palaeozoic, the foreland was encroached upon by the miogeosyncline and a number of relatively small tardigeosynclinal successor basins became established in the Cantabrian Zone which became folded and thrust during Upper Carboniferous and Permian times.

FIG. 3. *Diagrammatic sections for the different palaeogeographic units in NW Spain. Data for the Galician/Castilian Zone from* MARTÍNEZ-GARCÍA *(1973) and* WALTER *(1965), for the West-Asturian/Leonese Zone from* WALTER *(1965),* MARCOS *(1970),* MATTE *(1968) and* MARTÍNEZ-GARCÍA *(1971), for the Cantabrian Zone from many sources (see References) compiled by* WAGNER. *The Lower Ordovician 'Armorican Quartzite' has been used as a correlatable horizon across the different zones, and this is probably justified in consideration of the large scale of the diagram* →

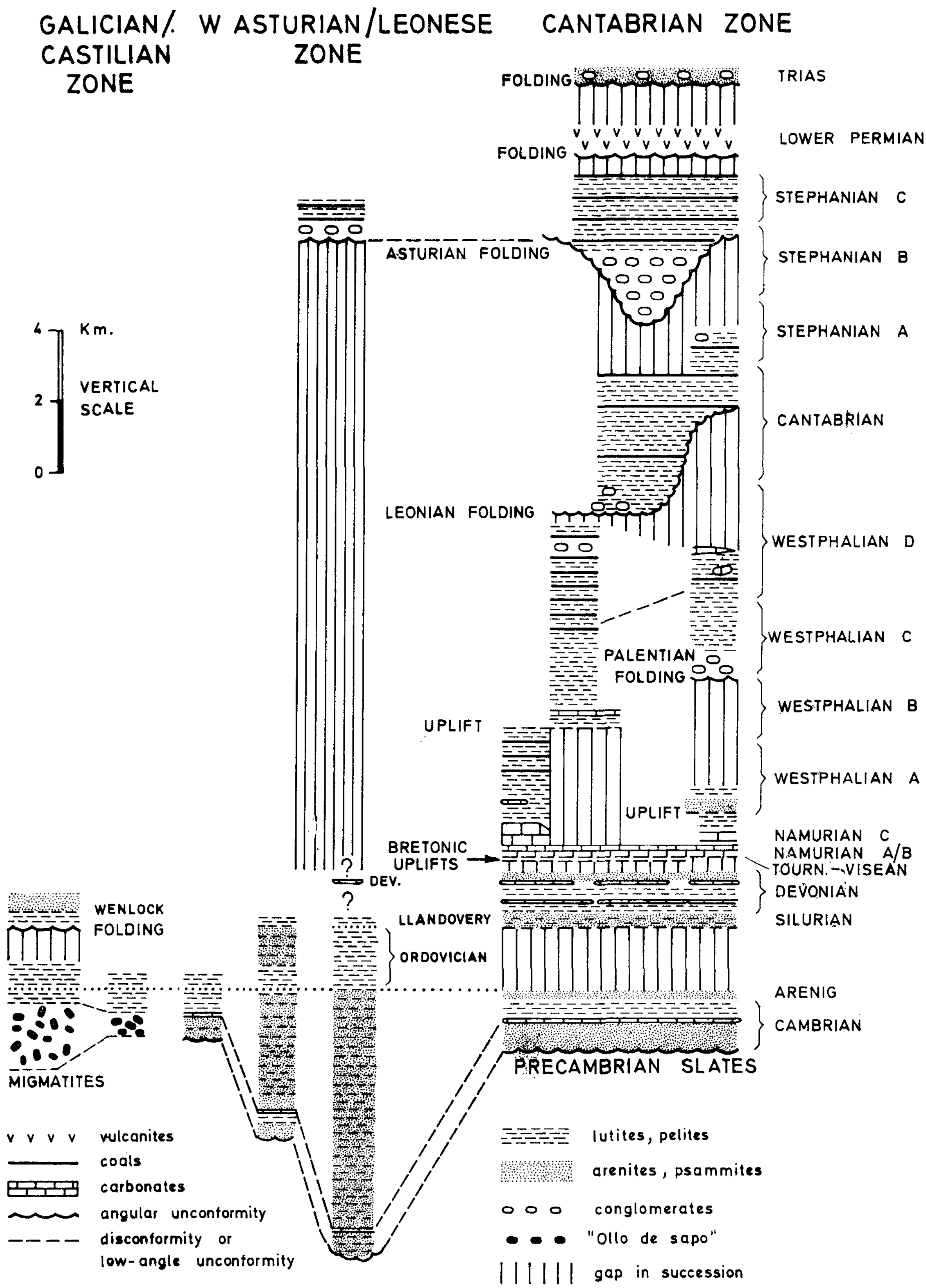
GALICIAN/ CASTILIAN ZONE
W ASTURIAN/LEONESE ZONE
CANTABRIAN ZONE
FOLDING
TRIAS
FOLDING
LOWER PERMIAN
STEPHANIAN C
ASTURIAN FOLDING
STEPHANIAN B
4
2
0
Km.
VERTICAL SCALE
STEPHANIAN A
CANTABRIAN
LEONIAN FOLDING
WESTPHALIAN D
WESTPHALIAN C
PALENTIAN FOLDING
WESTPHALIAN B
UPLIFT
WESTPHALIAN A
UPLIFT
NAMURIAN C
NAMURIAN A/B
BRETONIC UPLIFTS
TOURN.-VISEAN
DEV.
DEVONIAN
WENLOCK FOLDING
LLANDOVERY
SILURIAN
ORDOVICIAN
ARENIG
CAMBRIAN
MIGMATITES
PRECAMBRIAN SLATES
v v v v vulcanites
coals
carbonates
angular unconformity
disconformity or low-angle unconformity
lutites, pelites
arenites, psammites
conglomerates
"Ollo de sapo"
gap in succession

FIG. 3

FIRST FOLDING PHASE: WENLOCKIAN

A continuous sequence of Cambrian and Ordovician strata has been recorded for the West-Asturian/Leonese Zone as well as for the Cantabrian Zone (Fig. 3). The difference between these two zones is found in the much thicker succession developed in the former, i.e. at least 4,000 m according to MARCOS (1970) and perhaps even as much as 12,000 m (BARD *et al.* 1971), as against some 1,600 m in the latter (COMTE 1959). This is an appreciable difference which is accompanied by a different development of facies. The West-Asturian/Leonese Zone contains a large development of turbidites (MATTE 1968) which are conspicuously absent in the Cantabrian Zone. These turbidites are common in the basal part of the Cambrian sequence and in the higher Ordovician (MARCOS 1970). The highest strata recorded in the continuous succession of Lower Palaeozoic rocks in the West-Asturian/Leonese Zone belong to the Llandoverian (WALTER 1965), Wenlockian (NOLLAU 1968) or Caradocian (MARCOS 1970). This may be compared with the Llanvirnian recorded by PELLO & PHILIPPOT (1966) and the Llanvirnian with Llandeilian found by JULIVERT, MARCOS, PHILIPPOT & HENRY (1968) below an important disconformity of pre-Valentian (Llandoverian/Wenlockian) age recorded in the Cantabrian Zone (compare RADIG 1962). This disconformity, due to a major uplift of the foreland, may be compared with the important pre- upper Wenlockian unconformity found in north-western Zamora by MARTÍNEZ-GARCÍA (1971, 1972, 1973). In this area tectonised, rather poorly dated Ordovician rocks are overlain with a strongly angular unconformity by graptolite-bearing upper Wenlockian strata. It is noted that the latest pre-tectonic deposits of the continuous sequence of Lower Palaeozoic rocks in the West-Asturian/Leonese Zone are not much earlier in age than the unconformable upper Wenlockian strata in Zamora. The movements of uplift in the Cantabrian Zone are somewhat in advance of tectonism in the West-Asturian/Leonese Zone, since the earliest disconformable Silurian rocks of the foreland area have been dated as late Llandoverian by COMTE (1959) and middle Llandoverian by VILAS (1971).

With regard to the Galician/Castilian Zone, the existence of the pre-upper Wenlockian folding phase recorded by MARTÍNEZ-GARCÍA (1971-1973) shows that an important tectonic phase preceded the movements of MATTE's Phase 1 (MATTE 1968), of a later age (Fig. 4). The Wenlockian phase is characterised by strongly isoclinal folds with N-S to NNE-SSW trending axes (Fig. 5). The associated axial plane cleavage has been almost obliterated by the second phase cleavage and can usually be recognised only in thin section. Nevertheless, there are instances in which this first phase schistosity has been preserved in the outcrop and can be seen to have been penetrated and transposed by the main, second phase cleavage.

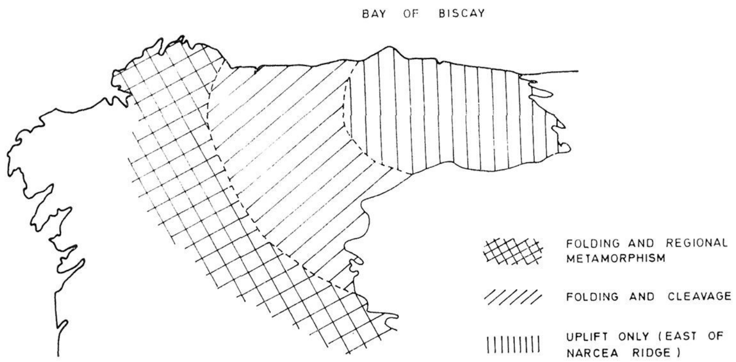

FIG. 4

Wenlockian tectonic phase: different effects of this first tectonic phase in the different palaeogeographic units

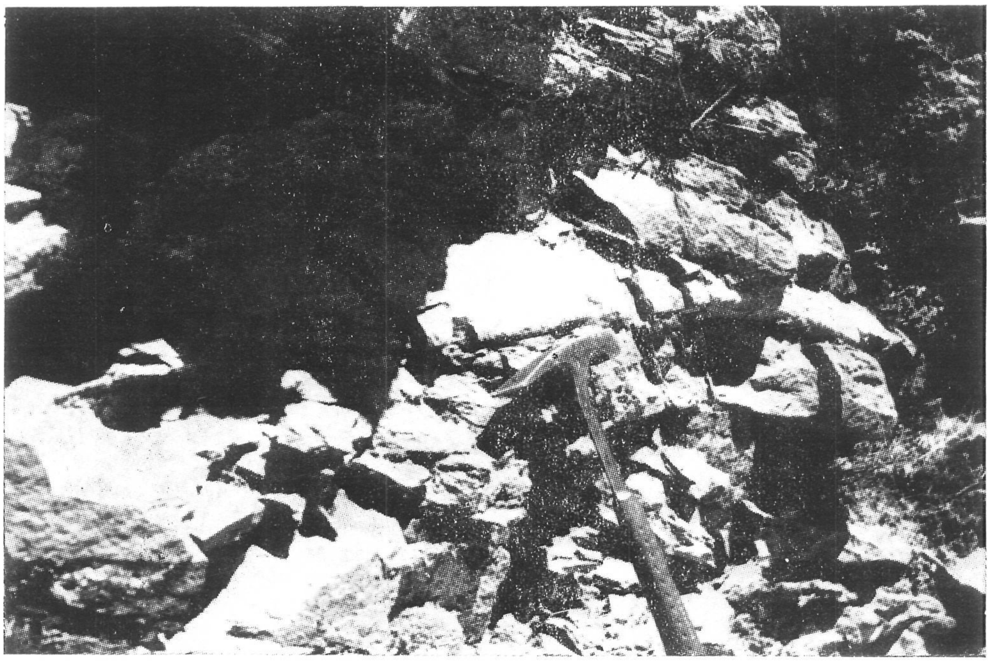

FIG. 5

Example of a first phase fold (of Wenlockian age) with a N-S trending axis; Sanabria region of the Galician/Castilian Zone

There are also criteria based on the growth of metamorphic minerals which contribute to the reconstruction of the features engendered by the first phase of deformation. Amongst these is the growth of the big feldspar megacrystals in the Ollo de Sapo Formation, taking place before the second phase schistosity. The fact that these large feldspar crystals were formed before the first folding phase of MATTE (1968) gave rise to the idea that they would have been inherited from eroded, pre-existing porphyroid granites, which remained undiscovered (e.g. MATTE 1968, CAPDEVILA 1969). This idea, supported by several authors, does no longer seem to be acceptable.

Some relics of relatively high pressure metamorphism have been discovered in relation to the first tectonic phase (MARTÍNEZ-GARCÍA & CORRETGÉ 1970). Such minerals as kyanite and chloritoid are mainly found in supposedly Palaeozoic rocks, together with strong evidence of retrometamorphism by the second phase metamorphism in the Ollo de Sapo Formation.

One is reminded that only uplift took place during the late Silurian in the Cantabrian Zone which was clearly a foreland massif at this time. However, the dating of these first movements interrupting a continuous sequence of Lower Palaeozoic strata (from Lower Cambrian upwards - see LOTZE 1961) is so strikingly coincident with that established for the first diastrophic phase in the Galician-Castilian Zone (and probably also in the West Asturian - Leonese Zone), that a direct link is suspected. Apparently, the foreland massif was uplifted at approximately the same time as the eugeosyncline was being compressed.

SECOND FOLDING PHASE: LATE FAMENNIAN

In the West-Asturian/Leonese Zone, any conclusion to be drawn from the stratigraphic succession is necessarily hampered by the incompleteness of the sequence found in this area (Fig. 3). Apart from the unconformable late Stephanian, it does not reach beyond some Devonian strata which were recorded by DROT & MATTE (1967) from a succession reported to contain also the immediately preceding Wenlockian and ¿Ludlovian strata. The latter are separated by a stratigraphic (and tectonic?) break from the earlier Silurian and Ordovician rocks. Since this is the only find of Devonian strata in the West-Asturian/Leonese Zone, the stratigraphic record is very incomplete indeed in this area.

On the contrary, in the Cantabrian Zone the record is continuous from the upper Silurian onwards into the Devonian which is almost completely developed (Fig. 3). The first break in this area is at the level of the upper Famennian. In late Famennian times the central part of the Cantabrian Zone was uplifted to the extent of removing the entire Devonian and Silurian succession, with a probable (estimated) thickness of *ca.* 3,000 m. The shape of the uplift shows a proper dome, the outline of which is marked by the progressively more complete sequence of upper Silurian and Devonian rocks being preserved on the flanks of this dome. The post-tectonic transgressive beds belong to the Ermita Formation of COMTE (1938, 1959), who was the first to describe the amount and extent of updoming. The facies of the transgressive Ermita Formation is littoral, with calcarenites and quartzarenites which may locally include conglomerates. This formation shows gradual onlap onto the dome which commenced to be transgressed in late Famennian times but which was not finally covered until the Tournaisian was in progress. The western and southern limits of this dome were traced fairly accurately by COMTE (1959), VAN DEN BOSCH (1969) and VILAS (1971), and there are a number of general reconstructions showing these limits. Eastwards, however, the sedimentation was continuous from the Middle Devonian into Upper Devonian and Lower Carboniferous (SCHINDEWOLF & KULLMANN 1958), and it appears that the doming effect was restricted to the western part of the central Cantabrian Zone. The exact shape of the uplifted regions may eventually prove to be more complex than the simple dome postulated by COMTE, but a discussion of these features would be both premature and outside the scope of the present paper. A crescent-shaped pattern as drawn by PARGA (1969) appears to be the most likely for the time being.

Extremely condensed deposits of Lower Carboniferous and early Namurian ages throughout the Cantabrian Zone mark this area as a submerged massif, the Cantabrian Block. The size of this block diminished during Namurian times as Namurian B flysch deposits came in from the south in the region of La Robla, on the southern edge of the Palaeozoic of northern León (WAGNER & FERNÁNDEZ-GARCÍA 1971). Carbonate deposits continued to be laid down on the block at the same time (WAGNER, WINKLER PRINS & RIDING 1971).

The almost complete disappearance of Devonian strata west of the Narcea Anticlinorium is probably due to tectonic causes, since both the facies of the fully developed Devonian of the Cantabrian Zone and the presence of some Devonian sediments in the area south-west of this anticlinorium (DROT & MATTE 1967) suggest that Devonian strata were probably deposited. The large scale eastward thrusting, which is known to have happened in this area, may well have been instrumental in bringing areas of different stratigraphic development in close proximity. Thus, a combination of folding and thrusting with relatively uplift may have produced the general absence of Devonian strata in the West-Asturian/Leonese Zone (west of the Narcea Anticlinorium) whereas, on the other hand, *ca.* 1,500 m of Devonian sediments were deposited in the Cantabrian Zone south of the uplifted dome (Fig. 6).

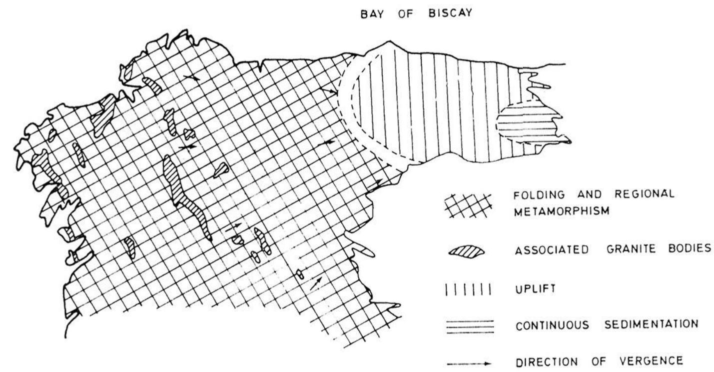

FIG. 6

Late Famennian tectonic phase: different effects of this second tectonic phase in different parts of NW Spain

In the Galician/Castilian Zone, a Bretonic folding phase has been described by MATTE (1968) but this record cannot be maintained since the attribution was based on a tentative dating of plant-bearing strata as Carboniferous whereas, in fact, these rocks proved to be Silurian in age (MARTÍNEZ-GARCÍA 1972).

The second phase of folding in the Galician/Castilian Zone is characterised by isoclinal folds trending NW-SE, and which are at an angle of some 45° to 60° to the earlier, first phase folds which are also isoclinal. The second phase folds possess a strong axial plane cleavage which penetrates and almost obliterates that of the earlier fold structures. The folds verge to the north-east (Fig. 7). Sometimes, the inverted limbs of some of the more recumbent folds (e.g. that of the Sierra del Caurel) are several kilometres wide. These second phase folds and the associated cleavage show up clearly in the upper Wenlockian sediments which are free from the transposition of an earlier foliation as found in the rocks deformed by the first, Silurian folding phase. At the end of the second folding phase some important overthrusts to the north-east were produced, and these show an associated blastomilonitisation of metamorphic rocks. There is also an associated regional metamorphism of the intermediate high pressure type, which produced chlorite, andalusite, garnet, staurolite and sillimanite. Some regional migmatisation also occurred and several granitic intrusions happened near the end or immediately after the tectonic phase. These consist of early diorites and later granodiorites.

The structures of the second folding phase are intruded by the Friol Granite which, according to CAPDEVILA & VIALETTE (1970), dates as middle Westphalian. This indicates, at the latest, an early Westphalian age for these second phase structures.

In the West-Asturian/Leonese Zone, this phase (phase I of MATTE 1968) produced mainly folds with an eastward vergence and some associated thrust faults.

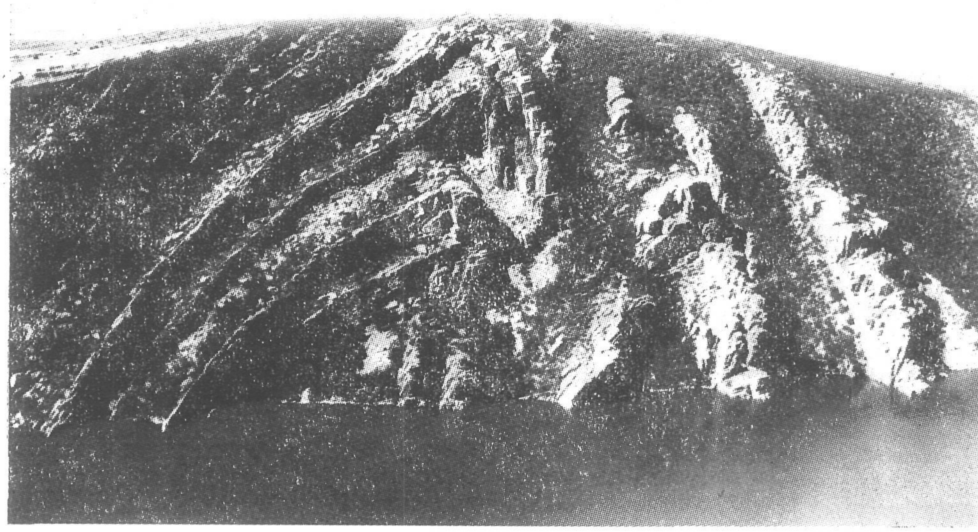

FIG. 7

A recumbent fold of the second tectonic phase (of late Famennian age) folded by a third phase fold (province of Zamora) (after MARTÍNEZ-GARCÍA *1973)*

THIRD FOLDING PHASE: LOWER TO MIDDLE WESTPHALIAN

In south-eastern Galicia this phase has been described by MARTÍNEZ-GARCÍA (1973) as a relatively strong folding phase without associated cleavage (Fig. 8), and with SE dipping axial planes which become shallower with increasing depth. This phase affected some of the granitic bodies intruded at the end of the migmatisation process which took place at the end of the second phase (Fig. 9).

In the Cantabrian Zone there is a strongly marked angular unconformity between folded Lower Palaeozoic, Devonian and early Carboniferous rocks (including Bashkirian-Westphalian A? deposits) and post-tectonic conglomeratic strata which have been dated as lower? and middle Westphalian. This unconformity is well developed in the province of Palencia, in the south-eastern part of the Cantabrian Cordillera, and the corresponding tectonic phase has been named the Palentian Phase (Fig. 9). Post-tectonic conglomeratic strata, at least 500 m thick, have yielded upper Westphalian B floras. Earlier conglomerates also occur, and these are associated with a probable Westphalian A flora, but the main unconformity appears to be below the

FIG. 8

Example of folding due to the third tectonic phase (of early to middle Westphalian age) (province of Orense)

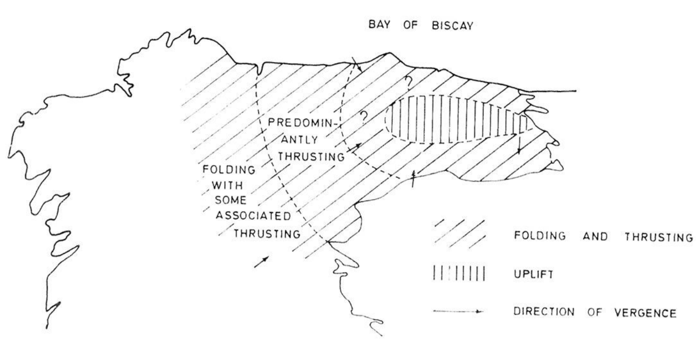

FIG. 9

Early to middle Westphalian (Palentian) tectonic phase: different effects of this third tectonic phase in different areas of NW Spain

upper Westphalian B deposits. The presence of either one or two early Westphalian folding phases in northern Palencia is subject to discussion. However, it is clear that there was at least one strongly diastrophic tectonic phase at some time during the first half of the Westphalian in the south-eastern part of the Cantabrian Zone. The area affected by the Palentian folding phase extends some 120 km eastwards into the Sierra de la Demanda (Burgos/Logroño) where a strongly angular unconformity has been recorded between conglomeratic lower Westphalian C strata and Lower Palaeozoic rocks which were strongly folded (COLCHEN 1971). The movements of the Palentian Phase may also have extended westwards from Palencia into northern León, where the fold structures are apparently continuous. Northwestwards, however, in the Asturias and in part of northern León, there is only a stratigraphic gap with disconformity at the level of Westphalian A. Westphalian B and C strata were deposited here in a continuous sequence. In the region of Villamanín, in northern León, this disconformity has been dated accurately as lying between basal Westphalian A and basal Westphalian B deposits (MOORE *et al.* 1971). On the other hand, the region east of the central Asturian coalfield shows a more important stratigraphic gap which includes the higher Namurian and the Westphalian A (VAN GINKEL 1965, SJERP 1967). It may well be that part of the central Cantabrian Zone which was doming upwards in late Famennian times, moved again in the same way during the Westphalian A.

It is interesting to observe that the important fold movements of the Palentian Phase in northern Palencia and in the Sierra de la Demanda found their counterpart in the uplift of an area in the centre of the Cantabrian Zone. Thus, the important hinterland movements were apparently accompanied by uplift in the foreland area. During Namurian and early Westphalian times the hinterland apparently moved more closely towards the Cantabrian Zone. The area of uplift is fairly closely circumscribed and its western boundary, in particular, has been clearly delimited in northern León where the Villamanín region shows the Westphalian A to have been eliminated by uplift whereas the San Emiliano region, only some 60 km westwards, shows an apparently continuous succession of Namurian and lower Westphalian strata (VAN DEN BOSCH 1969).

There is generally no cleavage associated with the Palentian fold structures in the Cantabrian Zone, despite the fact that the deformation was fairly intensive. Isoclinal and recumbent folds as well as some small nappe structures were formed in northern Palencia. Apparently, the Cantabrian Zone, obtaining its first fold structures in early to middle Westphalian times, retained some foreland characteristics in the absence of a cleavage and in the lack of intrusive activity associated with this folding phase. On the other hand, there was diminished tectonic activity in the Galician/Castilian Zone which may have served as an area of runoff for the increasingly important amount of deposition taking place in the Cantabrian Zone during Namurian and early Westphalian times (and this includes turbiditic deposits in the southernmost exposures of the Cantabrian Chain - e.g. near La Robla).

With regard to the West Asturian/Leonese Zone, this tectonic phase produced, according to MARCOS (1971), overthrusts with associated crenulation. These structures show verging to the east.

FOURTH FOLDING PHASE: LATE WESTPHALIAN D

In south-eastern Galicia this phase is more important than the preceding one (MARTÍNEZ-GARCÍA 1973), as it produced a crenulation of the main (second phase) cleavage with an associated strain-slip cleavage (Fig. 10), the latter being sometimes very well developed with continuous S-surfaces dipping NE-wards. This feature separates the effects of the fourth tectonic phase from those of the third phase, since the folds formed by both phases are characterised by nearly vertical axial planes. Furthermore, the axial planes of the fourth phase folds also diminish their steepness of dip with increasing depth in the north-western part of the Galician/Castilian Zone. The fourth folding phase seems to have given birth to the largest fold structures found in the Galician/Castilian Zone. These are comparable (though not necessarily correlatable) to the huge antiforms and synforms in the Ordovician quartzites (i.e. the so-called Armorican Quartzite) elsewhere in the Iberian Peninsula.

The fourth folding phase, as defined here, has been described as a second folding phase by MATTE (1968), CAPDEVILA (1969) and others working in the same area. Its age has been ascertained through the study of the Friol Granite

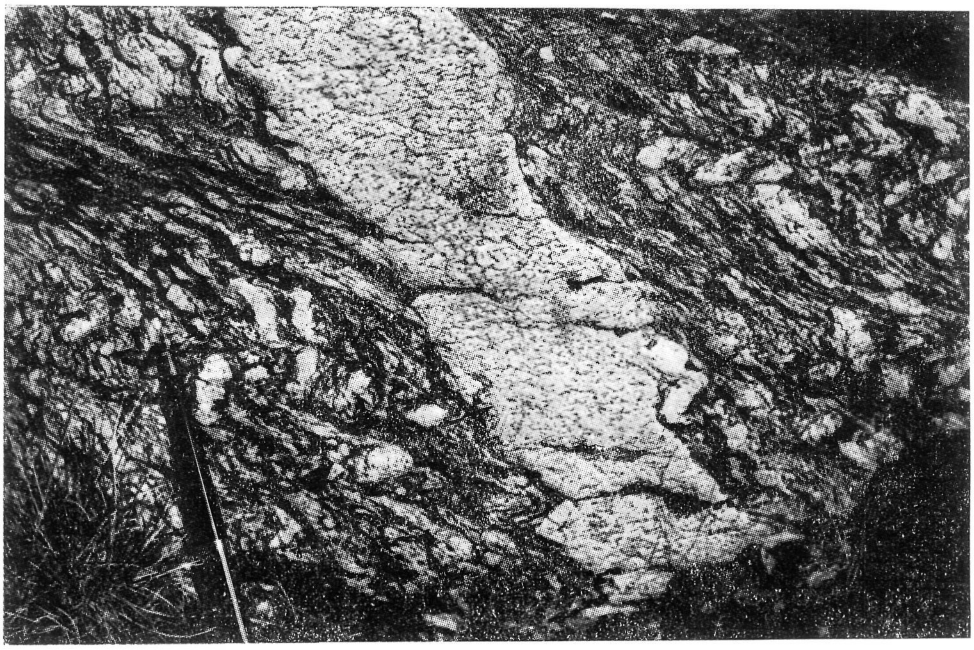

FIG. 10

Strain-slip cleavage associated with the fourth tectonic phase (of late Westphalian D age) in the Galician/Castilian Zone; see the orientation produced in an aplite vein (province of Orense)

(CAPDEVILA & VIALETTE 1970). This middle Westphalian granite was found to have been affected by the strain-slip cleavage which characterises the fourth folding phase. The Friol Granite was dated by means of the rubidium-strontium method, giving a total age of *ca.* 310 m. y.

In the West-Asturian/Leonese Zone, this folding phase (which is the third one of MARCOS 1971) caused open W verging folds with an associated crenulation cleavage.

In may be that the fourth folding phase of the Galician/Castilian Zone is represented by the late Westphalian D movements of the Leonian Phase in the Cantabrian Zone (Fig. 11). This tectonic phase may well have affected the total area of the Cantabrian Zone, producing cross-folds on earlier structures in northern León (Fig. 12), and being most likely responsible for the first folding of strata of Westphalian C and D ages in and around the central Asturian coalfield. This coalfield occupies a central position in the Cantabrian Zone. It corresponds to an area which was only subject to uplift during the earlier movements, corresponding to the Westphalian A. In Palencia the Leonian Phase produced no folding but a widespread disconformity which corresponds to a short-lived uplift and erosion within the Westphalian D sequence. The uplift was combined with some normal faulting which lasted throughout late Westphalian D and early Cantabrian times and which produced a syn-sedimentary fault separating the basin from a stable platform in the eastern part of the area. It is likely that this platform was the remnant of the Cantabrian Block which, at an earlier time of the geological history of the Cantabrian Mountains, occupied most of the Cantabrian Zone. This platform retreated further eastwards at a later stage in the development of the post-Leonian basin, when the syn-sedimentary fault at the western boundary of the platform ceased to be active, and the tilted platform was gradually transgressed by early Stephanian (Cantabrian) deposits.

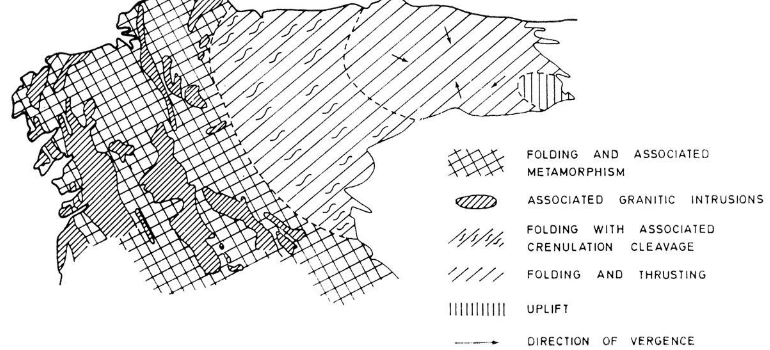

FIG. 11

Late Westphalian D (Leonian) tectonic phase: different effects of this fourth tectonic phase in different areas of NW Spain

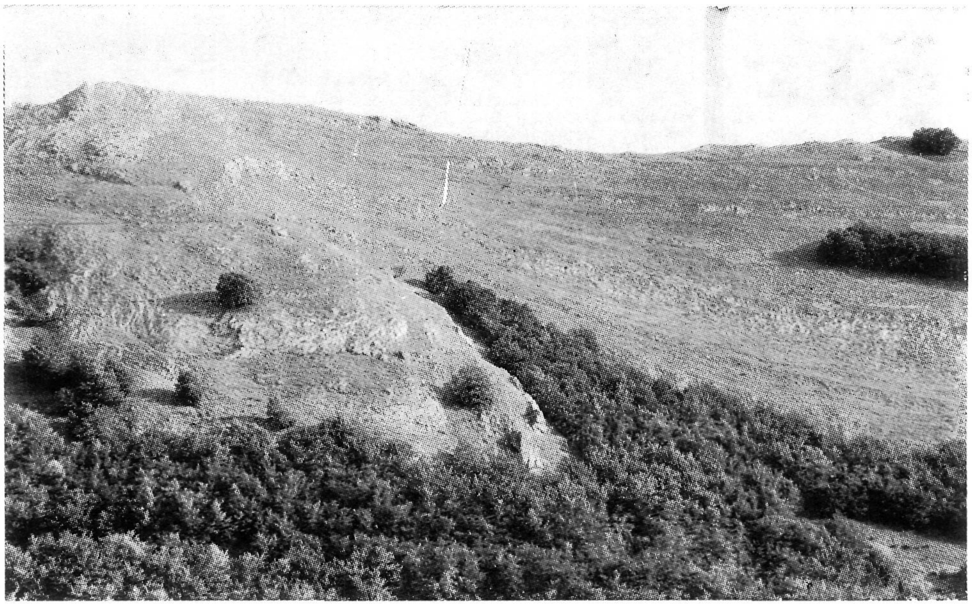

FIG. 12

Cross-fold of the Leonian phase superimposed on the flank of a much larger isoclinal fold produced by the earlier Palentian phase; Cantabrian Zone. The cross-fold is in Devonian limestone of the Santa Lucía Formation south-east of La Vid, in northern León. Cross-fold trending NW-SE, as against an E-W trend of the earlier, isoclinal fold

The Leonian Phase movements mainly affected northern León and central Asturias (Fig. 11). The style of folding in these regions is similar to that produced by the earlier Palentian Phase in northern Palencia. It is characterised by large isoclinal folds in the areas not affected by the Palentian folding, and by rather small cross-folds where there is a superposition of Leonian structures on the Palentian folds. The cross-folding pattern is particularly clear in north-eastern León where the Leonian Phase movements were very active and where there is a strongly angular unconformity associated with these movements. The immediately post-orogenic deposits in north-eastern León are valley fills fossilising a mountainous relief of some 150 to 300 metres depth (WAGNER 1970, pl. I, p. 440).

Although the Leonian Phase is clearly separated in time from the earlier Palentian fold movements, its effects can only be separated satisfactorily where Leonian cross-folds are superimposed on the Palentian structures (Fig. 12). In other pars of the Cantabrian Zone, where the two folding phases are not clearly superimposed, similar structures were formed at different times. They show identical trends which are adapted to the so-called Asturian arc or kneefold formed as the result of verging towards the foreland termination (i.e. the Cantabrian Block of RADIG 1962).

The general style of folding of the Leonian structures is that of thrust isoclines, without cleavage. Thrusting is quite intensive and an imbricate structure of rather steeply inclined thrust sheets is commonly developed. Some of the more important overthrusts can be followed along the strike over distances of 60 to 80 km. Their displacement cannot always be calculated but it is not likely to have been in excess of a few kilometres in most cases. In a few instances, however, a displacement of some ten kilometres across the strike has been recorded (RUPKE 1965). JULIVERT (1971), following DE SITTER (1962), regarded these thrust isoclines developing into thrust sheets as nappe structures, but although small nappes are undoubtedly present in the Cantabrian Cordillera (WAGNER 1971), there appears to be no need to invoke large scale nappe structures. Lateral transitions from relatively undisturbed isoclinal synclines and anticlines to thrust isoclines forming imbricate structures can be observed, and it is significant that there is no apparent disruption of the relative position of facies belts. This seems to preclude the existence of large scale movements. JULIVERT (1971) further interpreted these structures as having been provoked by large scale decollements from the basement, but the latter is never apparent and where local decollements have been observed they are rather small in extent and do not involve the basement. The presence of a preferred horizon of thrusting at the level of incompetent Middle Cambrian strata occurring between two major quartzite formations, has been observed and stressed by both DE SITTER and JULIVERT, but there are also numerous instances of thrusting having taken place at different horizons in the stratigraphic succession.

FIFTH FOLDING PHASE: STEPHANIAN A

In the Sanabria region of the Galician/Castilian Zone this tectonic phase is represented by intermediate concentric-kink folds of small amplitude and with axial planes dipping some 30° to 40° NE.

A late phase of kinking is also described by MATTE (1968) in the West-Asturian/Leonese Zone (Fig. 13).

In the Cantabrian Zone the Leonian Phase movements were succeeded by the formation of a basin collecting well over 5,000 m of marine and continental strata (WAGNER & VARKER 1971, BOUROZ *et al.* 1972). This post-Leonian basin extended from north-eastern León into northern Palencia and was apparently *ca.* 60 km wide in the early stages of its existence when its eastern limit was determined by a syn-sedimentary fault contact with a platform to the east. The latter was slowly transgressed eastwards at a later stage in the development of the basin. The position and history of the post-

Leonian basin shows clearly the much reduced character of the foreland massif (Cantabrian Block) which retreated eastwards while a substantial part of the Cantabrian Zone became subject to subsidence and accumulated a thick pile of sediments. Although the thickness of this sedimentary sequence is quite considerable, the areal extent of the basin was rather limited. Eastward onlap is also recorded for the post-Leonian basin in eastern Asturias (MARTÍNEZ-GARCÍA & WAGNER 1971), where the sedimentary sequence appears to be much thinner. This area may or may not have been in direct communication with the more important basin in north-eastern León and Palencia. These small basins are tardi-geosynclinal in AUBOUIN's terminology and occupy a position near the foreland.

The post-Leonian deposits in the area of maximum sedimentation were folded into steep isoclines and large asymmetrical folds verging south- and south-westwards (Fig. 13). They trend E-W in northern León and in north-western Palencia, and NW-SE in north-eastern Palencia (Fig. 14). The folding has been dated as either late Stephanian A or early Stephanian B in northern Palencia where late Stephanian B deposits overlie Stephanian A with an almost right-angle unconformity (Fig. 15). This is the Asturian Folding Phase of STILLE (1920) which is generally marked by an important angular unconformity throughout the Cantabrian Cordillera, with Stephanian B and C coal-measures lying as an independent sequence on top of previously folded earlier Carboniferous, Devonian and Lower Palaeozoic strata. The widespread nature of this unconformity has given rise to the often expressed belief that the Asturian Folding Phase would represent the most important tectonic event in the Cantabrian Cordillera. However, this is not necessarily so, and may even be regarded as unlikely.

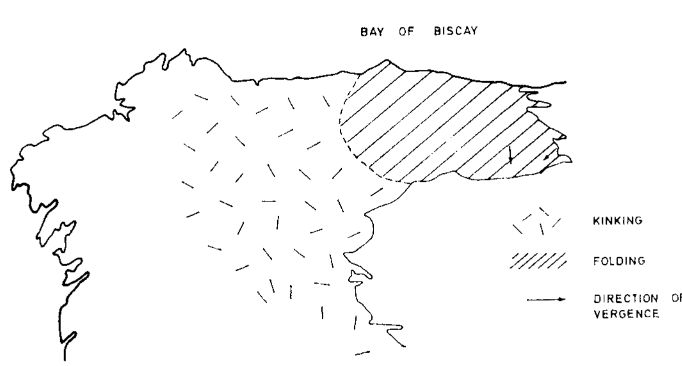

FIG. 13

Late Stephanian A (Asturian) tectonic phase: different effects of this fifth tectonic phase in different areas of NW Spain

FIG. 14

One of the smaller isoclinal folds formed by the Asturian phase in northern Palencia; Cantabrian Zone. This is the NW-SE trending Celada Syncline in upper Moscovian (Westphalian D) limestones

Although its effects are widespread, it is not clear that the Asturian Phase was active in eastern Asturias. In the Sierra de la Demanda, south-east of the Cantabrian Chain, its effects are marked only by a disconformity, as are those of the Leonian Phase (COLCHEN 1971).

In fact, the area of influence of the Asturian Phase is not clearly delimited and it is quite possible that only the eastern part of the Cantabrian Zone was affected by the isoclinal style of folding recorded for this tectonic phase in northern Palencia.

SIXTH FOLDING PHASE: LATE STEPHANIAN C OR EARLY PERMIAN

A late episode of kink bands occurred in the Sanabria region of the Galician/Castilian Zone. These show vertical planes and a N-S trend.

In the Cantabrian Zone the post-Asturian basin commenced to be formed in late Stephanian A times in the Sabero region of northern León, and it extended from this region both north-westwards and north-eastwards, with a gradual onlap. The basal deposits of the post-Asturian succession do in fact vary in age from late Stephanian A in Sabero to early Stephanian C

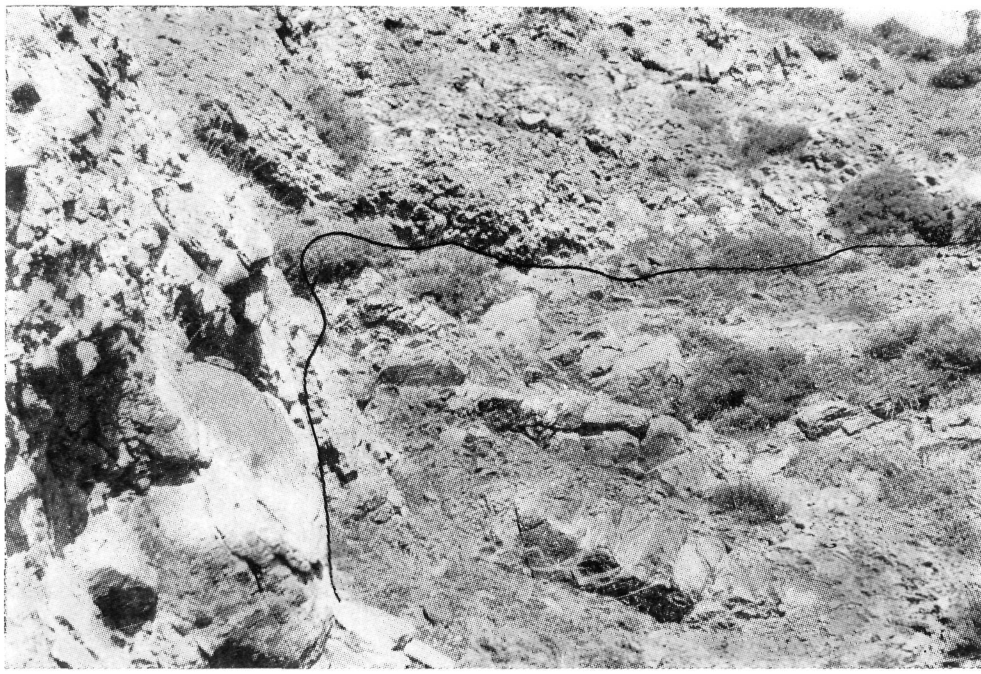

FIG. 15

Outcrop of the Asturian unconformity in the mountains north-west of Barruelo de Santullán in the province of Palencia; Cantabrian Zone. The drawn line marks the base of post-orogenic conglomerates of Stephanian B age which form a small anticlinal structure. They are strongly unconformable to steeply dipping earlier Upper Carboniferous rocks participating in an isoclinal structure which also contains strata of Stephanian A age. The boulders in the unconformable conglomerate are commonly up to 10 or even 15 cm in diameter

in Cangas del Narcea and Tineo (Asturias), and the onlap is therefore clearly expressed. The latest post-Asturian strata extended into the West-Asturian/Leonese Zone. They are widely developed in the region of El Bierzo, south-west of the Narcea Anticlinorium.

The total sequence of post-Asturian sediments reached a thickness of *ca.* 4,500 m but the full succession was only developed where the basin commenced, i.e. in the Sabero area, and here the top part of the sequence is taken off by erosion. Away from the initial basin the sequence is gradually less as the sedimentation started at later times with the onlap in NW and NE directions. The shape of the post-Asturian basin appears to have been unrelated to the pattern of the earlier geosynclinal and tardi-geosynclinal basins in NW Spain. On the other hand, the subsequent folding, either late Stephanian C or early Permian in age, produced folds and thrusts similar in trend and style to those formed by the earlier folding phases in the Cantabrian Zone. These structures of Permian (?) age are adapted again to the Asturian arc or kneefold, and although there is no sign of the old foreland massif in the shape of the post-Asturian basin, it must have reasserted itself again when the folding took place. The late Stephanian C or early Permian folds are asymmetrical, with steeply dipping axial planes. In some cases, they become nearly isoclinal. Small thrusts are associated and these verge towards the central part of the Cantabrian Zone, similarly to those formed in earlier tectonic phases. It is likely that this folding phase produced the refolding found in the area of thrust slices east of the central Asturian coalfield (JULIVERT 1971).

The dating of this folding phase is somewhat ambiguous, since there is no direct unconformable contact between Stephanian B and C strata in the post-Asturian coalfields and the sporadic Lower Permian (Autunian) deposits which are poorly represented in NW Spain. However, there is one undisputable record of Autunian strata near Pola de Siero, in the Asturias (PATAC 1920), and this small sequence is quite different in facies to the known Stephanian C rocks of Tineo and Villablino. Within the confines of the central Asturian coalfield, near Mieres, there is a succession of strata which are apparently unconformable on steeply dipping upper Westphalian coal-measures and which have recently yielded a flora of either late Stephanian C or Autunian age (unpublished investigation made in collaboration with J. P. LAVEINE). These strata, which are being studied by M. GERVILLA (pers. comm.), are strongly influenced by volcanics (ALMELA & RÍOS 1962). A strongly angular unconformity is also recorded below some probable lower Permian strata in northern Palencia (MAAS in DE JONG 1971) where they overlie folded Moscovian sediments (Fig. 17). The latter were deformed during the Asturian Phase. The unconformable Lower Permian (?) strata of northern Palencia are separated by a low angle unconformity from Triassic strata which are overlapping to the extent that they rest immeditely upon highly unconformable Stephanian B rocks a few kilometres further along the strike. This appears to date the movements connected with the angular unconformity as either late Stephanian or, more likely, early Permian.

The area affected by this early Permian (?) folding phase is apparently limited to the Cantabrian Zone (Fig. 16), because the Stephanian C of the El Bierzo region, in the West-Asturian/Leonese Zone, is essentially unfolded, although affected by faulting.

SEVENTH FOLDING PHASE: PERMIAN

The Autunian strata of Pola de Siero are steeply folded and covered unconformably by Cretaceous rocks. On the other hand, MAAS (in DE JONG 1971), in Palencia and Santander (Fig. 17), only records a low angle unconformity with little angularity between the lower Permian (?) deposits and the overlying Triassic. The effect of the corresponding tectonic phase was therefore rather limited in area, in as far as folding is involved. On the other hand, it is quite likely that this phase of movements produced some of the large strike-slip faults in the Cantabrian Cordillera, e.g. the León Fault of De Sitter (compare Marcos 1968) and the Cantabrian Fault of Martínez Alvarez (1968).

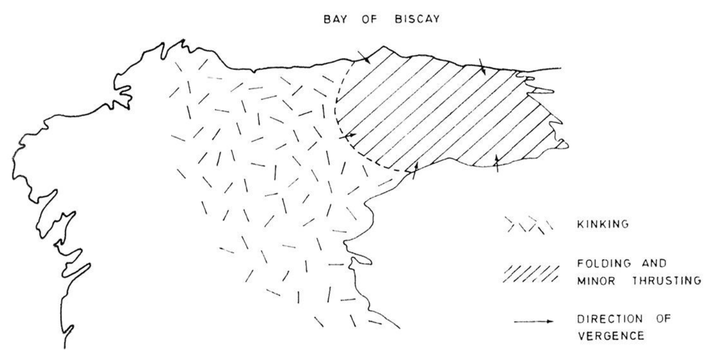

Fig. 16

Late Stephanian C or early Permian tectonic phase: different effects of this sixth tectonic phase which folded the Stephanian B and C coal-measures in the Cantabrian Zone

Fig. 17

Early Permian and Triassic strata, mutually separated by a low-angle unconformity, and together forming a strikingly unconformable sequence with regard to underlying limestones and mudstones of the upper Moscovian. The mountain scarp in predominantly Triassic strata (conglomerates and sandstones) is that of Peña Labra on the boundary of the provinces of Palencia and Santander; Cantabrian Zone

In the Galician/Castilian Zone there are fractures with E-W and NNE-SSW trends, found in southern Galicia, and which may be ascribed to this late tectonic phase.

After this phase, the post-geosynclinal basin of Burgos and Santander developed during the full length of Mesozoic time. The general palaeogeographic configuration became rather different and the eventual tectonic structure of these Mesozoic strata also shows little relation to that of the Palaeozoic rocks in the Cantabrian Cordillera and in the Sierra de la Demanda. They apparently represent a different part of the geological history of northern Spain.

CONCLUSIONS

Despite the different palaeogeographic units, with a different tectonic, igneous, metamorphic and sedimentary development, the Palaeozoic geology of NW Spain shows an overall pattern which indicates the fundamental unity of this area. The palaeogeographic units distinguished by LOTZE (1945) have stood the test of time, and appear to correspond to different parts of a geosynclinal complex which lasted from the early Cambrian (or late Precambrian) into the Permian. The main geanticline may have corresponded to the western part of the Galician/Castilian Zone, and the early Palaeozoic eugeosyncline to the eastern part of this zone and to the adjacent West-Asturian/Leonese Zone. The latter was apparently separated from the miogeosyncline and foreland by a miogeanticline corresponding to the Narcea Anticlinorium of Precambrian rocks in northern León and Asturias. The Cantabrian Zone, corresponding generally to the Cantabrian Cordillera of the present day, mainly represents a foreland area which was progressively encroached upon by the miogeosyncline. This foreland massif terminated westwards and also shows southern and northern borders which were emphasized further by the successive folding phases which moved tectonic structures onto the massif. These structures are perfectly adapted to the western termination of this foreland massif (the Cantabrian Block of RADIG 1962), and this produced the so-called Asturian arc or kneefold structure. The foreland present in the Cantabrian Zone was probably an intermediate foreland *sensu* AUBOUIN (1965), with geosynclinal areas both south and north of the massif. These geosynclinal areas, with a general E-W trend, coalesced west of the intermediate foreland spur in the Cantabrian Cordillera, and thus formed a single geosynclinal unit with a general N-S trend in the West-Asturian/Leonese Zone. The eastern continuation of the foreland spur, representing the main development of the intermediate foreland, may well coincide with the area of the western and central Pyrenees.

Both the sedimentary and the tectonic history of the Palaeozoic rocks in NW Spain fit a general pattern which is recognisably similar until the tardi- and post-geosynclinal basins became established in late Carboniferous and Permian times. It is the writers' contention that the sedimentary history of the geosynclinal complex of NW Spain was interrupted at certain, fairly short-lived intervals by tectonic phases which acted with different degrees of intensity upon the different palaeogeographic zones, but which were discernible throughout the entire area.

The earliest of these tectonic phases produced folding and cleavage in the internal part of the geosyncline in the Galician/Castilian and West-Asturian/Leonese zones during Wenlockian times. It is likely that these movements were provoked by the hinterland which may have been situated in the western part of the Galician/Castilian Zone. In the foreland area of the Cantabrian Zone, the Wenlockian movements produced an extensive uplift, recognisable throughout the Cantabrian Cordillera, which eliminated upper Ordovician and lower Silurian strata in the area east of the Narcea Anticlinorium. Similarly, a later tectonic phase, of late Famennian age, produced a further uplift in the central part of the Cantabrian Zone, but it is noted that the latter uplift was apparently more restricted in area than the Silurian one. This uplift may have occurred at approximately the same time as the second folding phase recorded in the eastern part of the Galician/Castilian Zone.

The sedimentary development of the foreland area with the adjoining miogeosyncline shows a general and progressive restriction of the foreland region, i.e. of the Cantabrian Block. The whole of the Cantabrian Zone was situated within the foreland region during Lower Palaeozoic and Devonian times, and including the Lower Carboniferous which is characterised by condensed sediments laid down on a platform far from the land. Flysch deposits reached the Cantabrian Zone during middle Namurian times and this marked the first occasion when the Cantabrian Block did not wholly coincide with the present-day mountains of the Cordillera Cantábrica. Folding of the miogeosyncline occurred in early to middle Westphalian times, but this folding phase affected only a part of the Cantabrian Zone. The block, in the central part of this zone, reacted again by uplifting. This tectonic phase is also detected in the earlier geosynclinal area of the Galician/Castilian Zone which, at this time, may well have become incorporated partly with the geanticlinal hinterland. It was also subjected to granitic intrusions (e.g. the Friol Granite which was dated as being of approximate middle Westphalian age).

Late Westphalian D movements extended further onto those parts of the old foreland massif which had become incorporated with the miogeosyncline form middle Westphalian times onwards and which had accumulated an important load of upper Westphalian sediments (as represented, particularly, in the central Asturian coalfield). The folds formed during this Leonian Phase complement those of the earlier Palentian Phase (early to middle Westphalian) and are difficult to distinguish in those areas where there is no superposition of fold structures.

After the Leonian Phase only small tardi-geosynclinal basins became established. The Cantabrian Block was further reduced in size and was clearly retreating eastwards as the post-Leonian basin advanced upon its foreland which was tilted at its margin and which temporarily became a supplier of sediment.

The later, Asturian Phase of folding, of late Stephanian A age, produced the same style of folds and attendant overthrusts as the earlier tectonic phases, but in some areas the vergence was different. The post-Asturian basin may also be classed as tardi-geosynclinal, but its shape was no longer conforming the earlier palaeogeographic configuration. However, the subsequent folding, of either late Stephanian or early Permian age, closely followed the lines established by the earlier fold phases and its structures molded themselves clearly around the old Cantabrian Block which reasserted its role as a foreland massif, albeit for the last time.

The Palentian, Leonian and Asturian phases had a steadily diminishing effect on the area of the earlier eugeosyncline of the Lower Palaeozoic (West-Asturian/Leonese Zone, primarily), and it appears that this area became progressively cratonised from late Devonian times onwards. The upper Stephanian deposits, which were fairly strongly compressed in the Cantabrian Zone, remained practically unfolded in the West-Asturian/Leonese Zone west of the Narcea Anticlinorium.

Finally, the Permian movements which occurred prior to the establishment of the Mesozoic basin of Burgos and Santander, east of the Cantabrian Cordillera, produced some late wrench faulting and other fractures in the now fully cratonised geosynclinal complex of NW Spain.

The general shift in area which is reflected by the different intensity of tectonic movements of the same phases in different palaeogeographic zones, can also be observed in the distribution of thickness of sedimentary sequence. The eugeosynclinal area of the West-Asturian/Leonese Zone (and the eastern part of the Galician/Castilian Zone) accumulated a great thickness of Lower Palaeozoic strata, which is vastly in excess of that deposited on the foreland massif in the Cantabrian Zone. The latter became subjected to increasingly important subsidence during the late Palaeozoic when the miogeosyncline encroached progressively upon the foreland. Upper Carboniferous tardi-geosynclinal basins in the Cantabrian Zone accumulated vast thicknesses of sediment, of the order of 5,000 m for each post-orogenic sequence, but the areas of sedimentation had become much more restricted. The changing role of the Cantabrian Zone is reflected most markedly in the Upper Carboniferous successions which show gradually increasing thicknesses of sediment for similar lengths of time in the same general area. This explains the vast development of Stephanian rocks in the Cantabrian Chain, with a cumulative thickness of up to 8,000 m of sediments, which is more than anywhere else in the world.

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