

THE TECTONIC FRAMEWORK OF CENTRAL AND WESTERN EUROPEH. J. ZWART¹ & U. F. DORNSIEPEN¹**ABSTRACT**

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The complexity of the structure of Central and Western Europe is for a large part due to the rapid succession of four important orogenic events each belonging to a major orogenic period: the Cadomian, Caledonian, Variscan and Alpine orogenies. The four successive mountain chains have partly occupied the same space, resulting in an intricate pattern of rocks formed or deformed during each orogeny. Due to this multiple orogenesis the presence of older Precambrian rocks is difficult to demonstrate.

Low grade Proterozoic sediments and volcanics are known from the Armorican and Bohemian Massifs and from the Iberian peninsula. Crystalline basement rocks predating these supracrustals have been reported only from the Armorican and Bohemian Massifs. Other signs of Precambrian events are zircon ages of more than 2000 Ma.

The Cadomian orogeny has been demonstrated in England, the Armorican Massif, the Bohemian Massif, the Pyrenees and in the Iberian peninsula either by the unconformity of Cambrian on folded basement, or by geochronological methods. The folding is accompanied by regional metamorphism of varying grade up to granulite facies. Postorogenic Cadomian granitic magmatism occurs in the Armorican and Bohemian Massifs.

The Caledonian orogeny occurs besides the main belt in Scandinavia, Scotland, Ireland and Wales, in the Ardennes and a zone from northern Germany towards Poland and Rumania. South of this zone no Caledonian folding based on geological evidence as unconformities can be ascertained, although numerous radiometric dates on metamorphic and igneous rocks indicate a thermal event during the period corresponding to the Caledonian orogeny.

The Variscan orogeny is much better known although many problems still remain unsolved. Folding, metamorphism and granitic activity started in the Devonian, but the most widespread and intense folding, low P/T type metamorphism and granitic intrusion is of Late Carboniferous age.

The pre-Cadomian basement and the Caledonian event are discussed in some detail.

A pre-Mesozoic drift reconstruction shows the relationships of the Cadomian, Caledonian and Variscan belt on either side of the Atlantic Ocean. A large Y-shaped pattern of orogenic belts appears, where intermittent folding, metamorphism and granite intrusion has taken place at least from the end of the Precambrian to Permian times. Central and Western Europe lying on the intersection of these belts has been a high heatflow region during that time, for which a mantle origin is proposed. Spreading and contracting movements at different places and different times are thought to be responsible for the orogenies. However, the presence of oceans other than the Proto-Atlantic or Iapetus is as yet to be proved. It is suggested that they were of minor size or that spreading did not go beyond the rift stage.

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INTRODUCTION

In this paper that part of Europe will be discussed, lying to the SW of the Tornquist line, which separates the Precambrian of Fennosarmatia from the younger part of Europe; to the south of the main Caledonian belt of northern Europe, and to the north and west of the Alpine belt. Most of this region has been influenced by the Variscan orogeny, which has caused strong folding, usually accompanied by the formation of cleavages or schistosity, low- and high-grade metamorphism and the intrusion of many large bodies of granite. The effect of this orogeny has laid a veil over this part of Europe, through which it is difficult to see older events. This effect has been intensified in the Alpine belt by the Alpine orogeny, where it is even more difficult to see the older history.

At least two more orogenies prior to the Variscan are responsible for the shaping of this part of Europe, the Cadomian and Caledonian orogenic periods. Remnants of older rocks, that is of Grenvillian, Svecofennian or early Proterozoic and Archaean age, are extremely rare.

THE PRE-CADOMIAN BASEMENT

Geological evidence for such an older basement is only found in the northern part of the Armorican Massif, where COGNÉ (1976) described an unconformity of the Brioverian on a crystalline basement, the Pentevrian. Furthermore BERNARDOVA & CHAB (1968) have reported pebbles of metamorphic rocks from the Upper Proterozoic greywackes of the Barandian. The origin and the age of these pebbles is not known.

Also geochronological evidence is available. The pre-Cadomian age of the northern Armorican basement complex, the Pentevrian, is confirmed by Rb-Sr data, yielding whole rock ages between 1900 and 2600 Ma (ADAMS, 1967, 1976; LEUTWEIN ET AL., 1973) and mineral ages (Rb-Sr, K-Ar) between 800 and 1100 Ma (LEUTWEIN, 1968). Dates between 1400 and 3400 Ma have been found on granulites occurring offshore on the Banc Le Danois north of Spain (CAPDEVILA & VIDAL, in prep.). The wide range of these ages is due to scattering of data points in the Rb-Sr diagrams, which does not allow to define an isochron and a precise age. This indicates, that the Rb-Sr systems of these old rocks have been opened by later orogenic events (VIDAL, 1977). Recently SCHARBERT (1977) has published a late Grenvillian age of 800 Ma from a granodioritic orthogneiss in the southern part of the Bohemian Massif.

Some more information about a pre-Cadomian basement has been obtained from U-Pb ages on zircons from orthogneisses, paragneisses and schists in the Bohemian Massif and the Alps (GRAUERT ET AL., 1973), in the Armorican Massif (Calvez unpubl.: see VIDAL, 1977), in the Montagne Noire (GEBAUER & GRÜNENFELDER, 1976), in the Black Forest (TODT,

1977) and in the northern part of the Iberian peninsula (Kuiper, pers. comm.) (Fig. 1). Most of the zircon ages have one feature in common: they are discordant, and have an upper intercept between 2000 and 2500 Ma and a lower one between 300 and 600 Ma in the U-Pb diagram. Except for the late Grenvillian granodiorite reported by SCHARBERT (1977), and some mineral ages from the northern part of the Armorican Massif (LEUTWEIN, 1968), there is no radiometric evidence for either a Grenville or a Svecofennian orogeny in Central and Western Europe.

As the 2000 – 2500 Ma old zircons may be derived from a Precambrian basement, for example the Fennosarmatian shield, far away from the place of sedimentation, they do not prove the existence of a pre-Cadomian continental crust in the whole of Central and Western Europe. Therefore the nature of the basement, on which the late Proterozoic sediments (600 – 800 Ma) were deposited, remains uncertain. There are two alternatives for such a basement:

- (1) it is a pre-Cadomian continental crust, older than 800 Ma;
- (2) it is an oceanic crust of late Proterozoic age (700 – 800 Ma).

Although the first alternative is in good agreement with the geological evidence, some geochronologists favour the interpretation of a late Proterozoic oceanic crust in Central and Western Europe (JÄGER, 1977; VIDAL, 1977). This problem will be discussed in a later section of this paper.

THE CADOMIAN OROGENY

The Cadomian orogeny (synonymous with the Assyntian and Baikalian orogeny) took place at the end of the Precambrian – the beginning of the Phanerozoic, about 550 – 650 Ma ago, and is to a large extent contemporaneous with the Pan-African event. It is well dated by unconformities in the Armorican, Bohemian and Iberian Massifs, and by geochronological methods. In all cases the Cadomian orogeny has folded and metamorphosed sedimentary and volcanic rocks of Upper Proterozoic age.

Armorican Massif

In the Armorican Massif the Proterozoic sequence of rocks is called the Brioverian and consists mainly of greywackes, slates, and mafic and felsic volcanics (COGNÉ, 1976). At a few places the Brioverian lies unconformably on the Pentevrian crystalline basement, which occurs at some localities in northern Brittany and on the Channel islands (Fig. 1). The unconformable Brioverian starts with coarse detrital arkoses and conglomerates, followed by volcanic rocks of spilitic and keratophyric composition. The Middle and Upper Brioverian consists of greywackes, shales and sandstones with minor limestones and tillites. Mafic and felsic volcanics are important constituents but are much less abundant than in the Lower

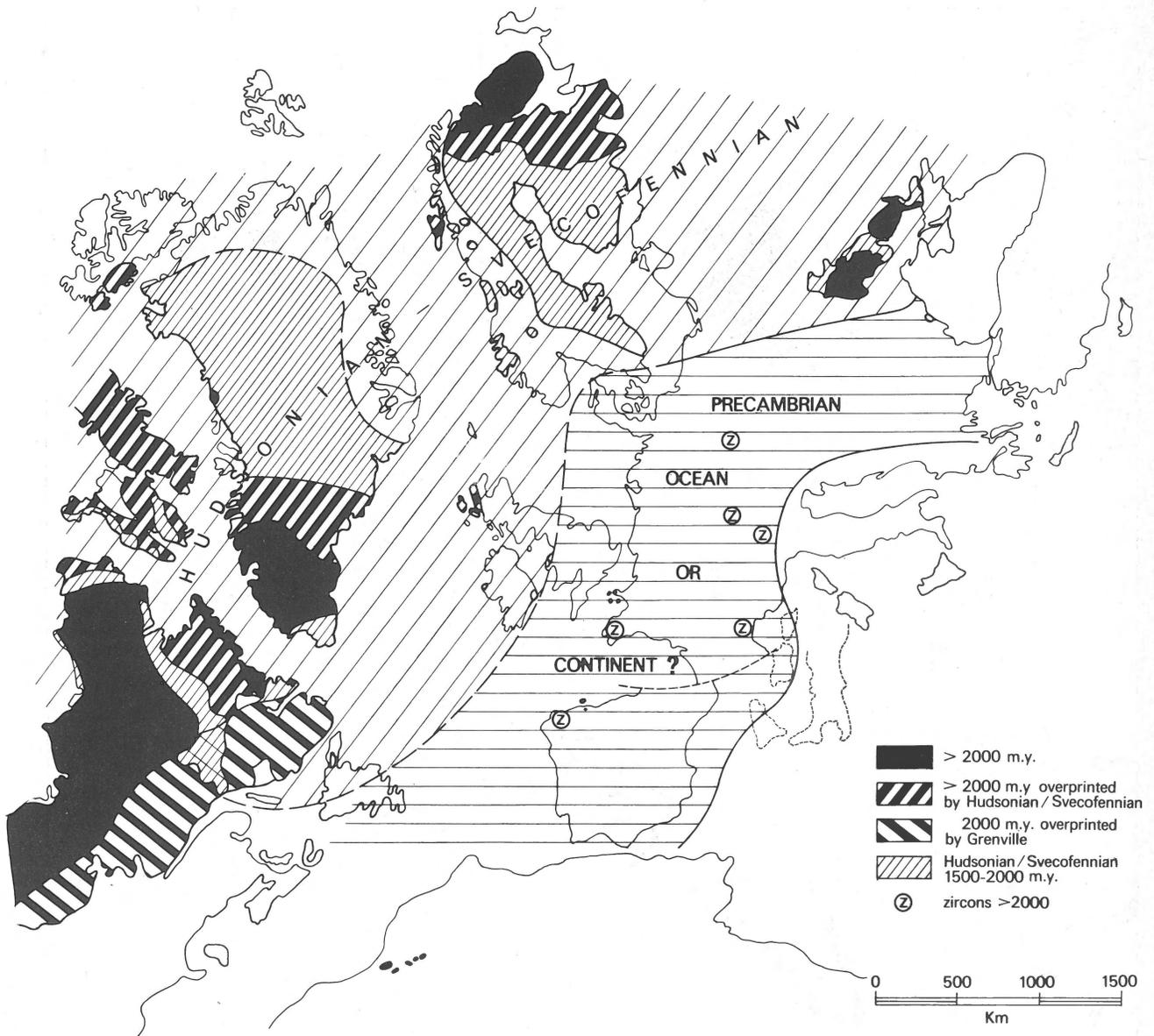


Fig. 1
Transatlantic correlation showing the distribution of pre-Cadomian rocks (fit of continents after Le Pichon et al., 1977).

Brioverian. Towards the south the Brioverian becomes thicker and its base is no longer exposed. The same rocktypes as those in northern Brittany are common.

At several places in Normandy and Brittany the folded Brioverian is unconformably overlain by Cambrian, thus clearly establishing the Cadomian orogeny. Apparently the Cadomian chain was not deeply eroded at that time, as the Cambrian always rests on Brioverian not higher in grade than the greenschist facies. Folds in low-grade Brioverian are tight to isoclinal and at some places recumbent. Nappe structures are very scarce, while superposed folding is common. In northern Brittany (Domnonean Province) the Brioverian is metamorphosed to a high degree (Fig. 2). The St. Malo mig-

matites are developed in a complex folded area. They belong to a low pressure facies series with sillimanite and cordierite (BRUN, 1977). In the Baie of St. Brieuc area and in the northern coastal area between Brest and Treguier, micaschists and gneisses occur together with metamorphosed mafic rocks (amphibolites, metadiorites) and locally ultramafics. Due to Variscan overprint and lack of diagnostic minerals it is difficult to ascertain the characteristics of this metamorphism. In the southern part of the Armorican Massif (Anticline of Cornouaille, Ligerian Province) it is difficult to prove a Cadomian metamorphism, but there are indications, that the intermediate P/T-type granulite-facies metamorphism is of Cadomian age (FORESTIER, 1977). Late orogenic granites have

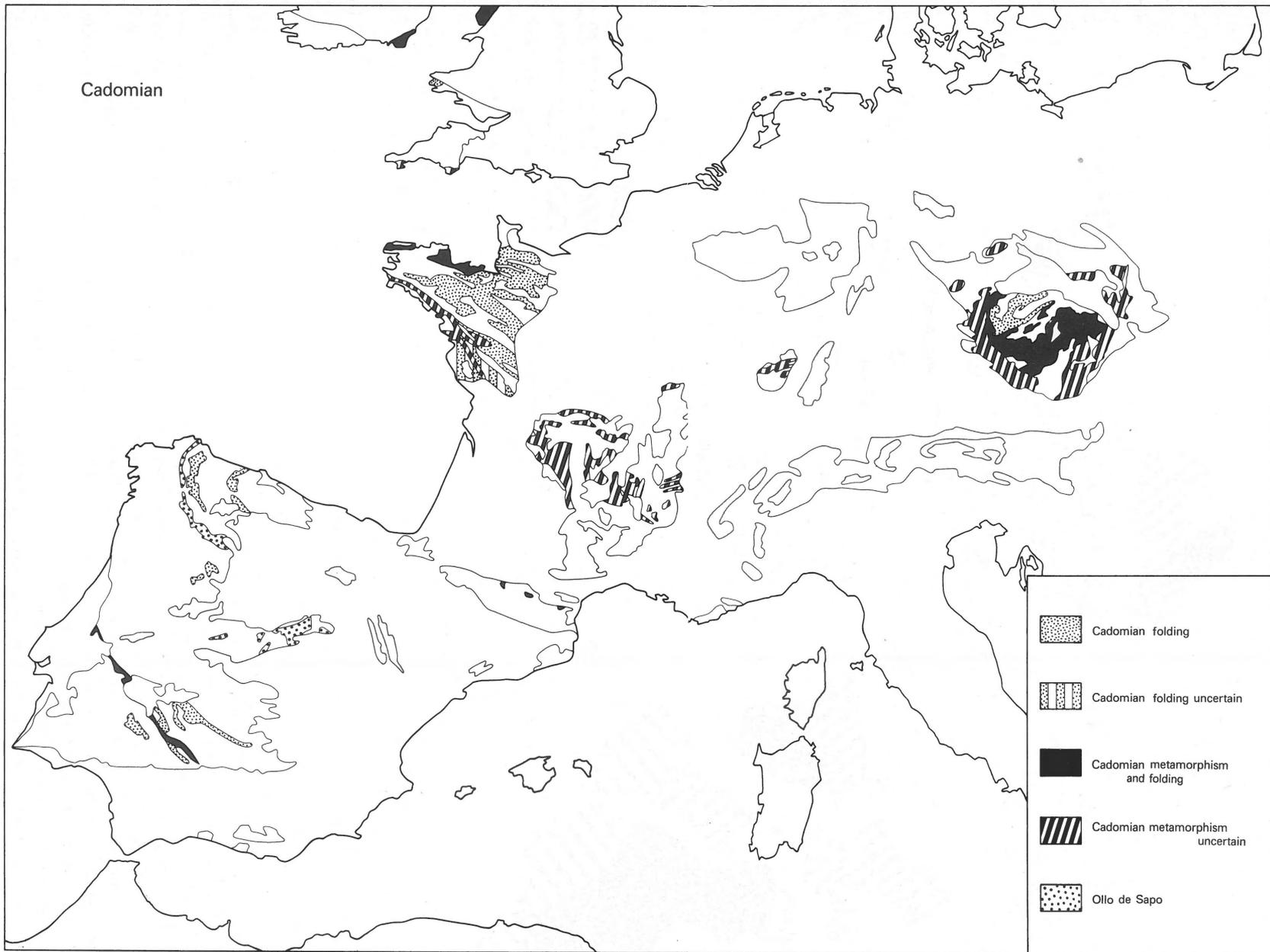


Fig. 2
Map of Central and Western Europe showing Cadomian events.

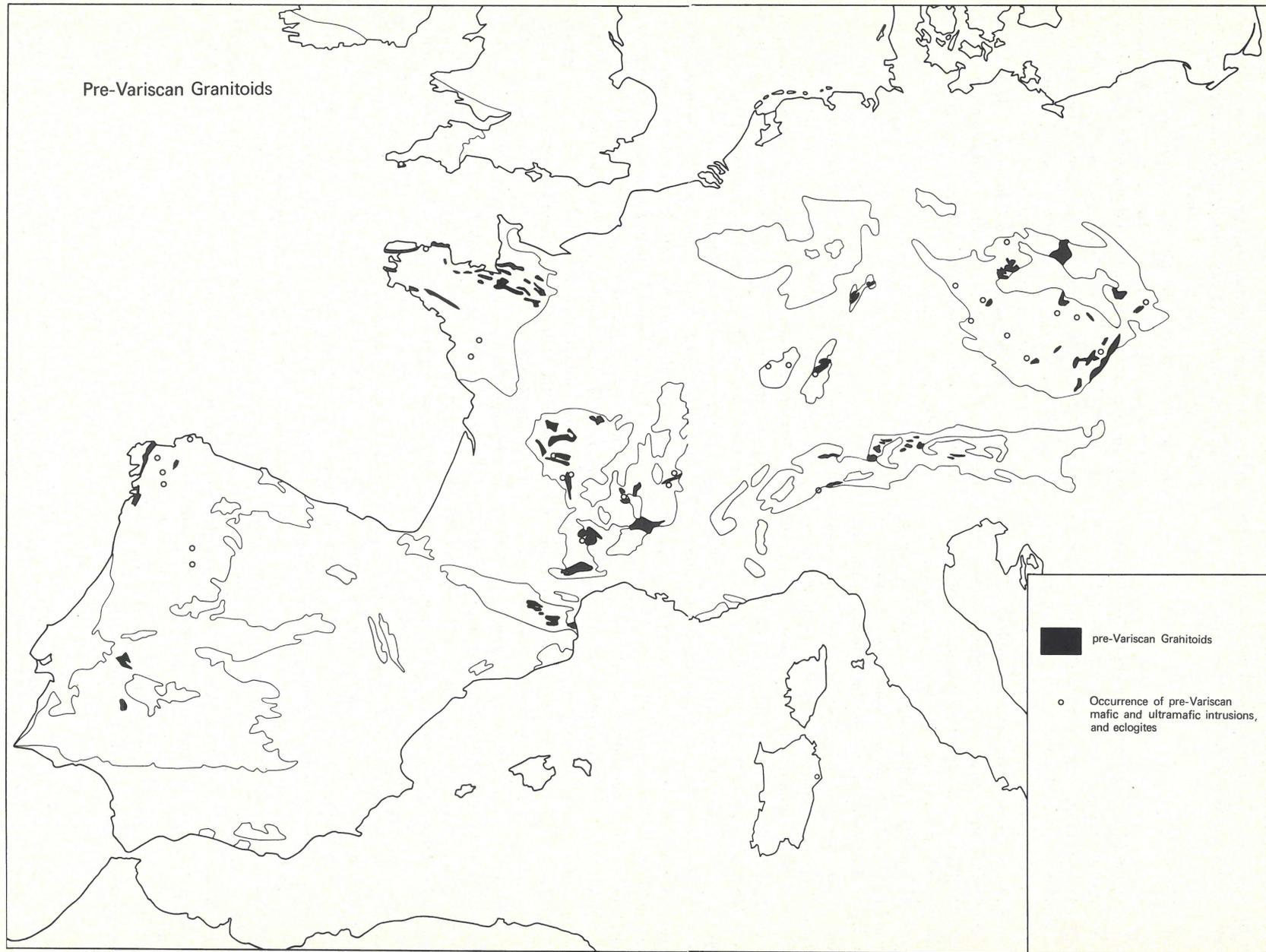


Fig. 3
Map of Central and Western Europe showing pre-Variscan granitoids.

intruded the Brioverian at various places, mainly in the Man-cellian Province (Fig. 3). The age of these granites ranges from 600 – 500 Ma (JONIN & VIDAL, 1975).

Bohemian Massif

In the Bohemian Massif the general situation is more complex. An unconformity between Upper Proterozoic sediments and the Lower Ordovician or Middle Cambrian exists in the Barrandian near Prague. The grade of metamorphism, where the unconformity occurs, is very low as in Brittany. In the Železné Hory (Iron Mountains), SE of Prague, Cambro-Silurian rocks lie unconformably on garnet micaschists. The Proterozoic consists of greywackes, shales and sandstones, with intercalated mafic and felsic volcanics, mainly in the lower part of the sequence, which has a thickness of about 7 km. The rocks are strongly folded and contain one or more cleavages. Away from the unconformable Palaeozoic, north- and westwards, the Proterozoic grades into greenschist facies and then, in the Tepla Highlands, into intermediate pressure amphibolite facies with kyanite and staurolite. It is likely that these rocks grade southwards into the so-called Moldanubian, but a strong high temperature-low pressure Variscan overprint makes the distinction between Cadomian and Variscan metamorphism difficult. However, various remnants of granulitic rocks containing kyanite, and eclogite bodies point to a similar intermediate P/T type, pre-Variscan metamorphism. According to ZOUBEK (1965) it concerns an older, early Proterozoic metamorphism, but we agree with DUDEK & SUK (1965), LOSERT (1967) and VEJNAR (1971), that one is probably dealing with a Cadomian event. The same may apply to the rocks of the granulite massif in Saxony and the Münchberg gneiss massif in Bavaria. The basement gneisses in the Sudetes are also considered to be Cadomian (CHAB & SUK, 1978). There is, however, conflicting geochronological evidence, as many whole-rock Rb-Sr analyses yield Caledonian ages. Nevertheless, on geological grounds it seems likely that the Cadomian caused widespread metamorphism varying in grade from prehnite-pumpellyite facies to granulite facies (Fig. 2). The rocks mainly belong to an intermediate- to high-pressure facies series (Saxonian type: HIETANEN, 1967). Except for metamorphic pebbles in the Proterozoic sediments (BERNADOVA & CHAB, 1968), there are very few arguments to support an older Precambrian metamorphism. Numerous orthogneisses in the Bohemian Massif and the Sudetes represent an intense pre-Variscan magmatism, which is Cadomian and late-Cadomian. The Cambrian volcanics in the Barrandian are also considered to belong to the late-Cadomian magmatic activity.

Iberian peninsula

In the Iberian peninsula the occurrence of the Cadomian orogeny is witnessed by unconformities in Cantabria, Galicia,

in SW Spain and Portugal (BARD ET AL., 1972). The Upper Proterozoic near the unconformity is of very low grade. Only in SW Spain and in the Elvas-Cordoba belt of Portugal is the Cadomian folding strong and accompanied by an intermediate-pressure metamorphism up to amphibolite facies, again with Variscan overprint. High-grade rocks with mafic and ultramafic rocks, eclogites and granulites occur in some massifs in Galicia (Cabo Ortegal, Ordenes Basin) and in N Portugal (Bragança, Morais). The relationship between these rocks and the low-grade Precambrian is not known. They may be metamorphic equivalents of Upper Proterozoic rocks, metamorphosed during the Cadomian cycle, but often they are considered to be older Precambrian. Again geochronological measurements indicate younger ages (VAN CALSTEREN ET AL., 1978).

Other regions

In the Black Forest, Vosges and Central Massif in France, pre-Variscan metamorphic rocks similar to those in Bohemia, namely granulites and eclogites, are exposed. It is possible that they belong to the Cadomian regional metamorphism. However, there is no definite proof, and geochronology in this case also gives younger ages.

In the Pyrenees granulite-facies rocks have been described from the North Pyrenean massifs (ZWART, 1954; ROUX, 1977). They are kyanite-bearing and can be assigned to the intermediate P/T type. Radiometric ages indicate that these rocks belong to the Cadomian cycle (VITRAC-MICHARD & ALLÈGRE, 1975). Other remnants of the Cadomian chain occur in Great Britain on the island of Anglesey, where strongly folded, low-grade phyllites and local glaucophane-schists occur, and at various places in Wales and in SE Ireland.

In conclusion, we can state that the Cadomian orogeny is widespread within Central and Western Europe. It involves Upper Proterozoic sediments and volcanics, unconformably overlain by the Lower Palaeozoic. Metamorphism grades from anchizone to granulite facies and is mostly of intermediate P/T type. Cadomian and post-Cadomian granites and Cambrian volcanics occur in the Armorican and Bohemian Massifs, in the Massif Central and in the Pyrenees. In the Iberian Massif the post-Cadomian magmatic activity is documented by the volcano-detrital series 'Ollo de Sapo' with local granite intrusions. The Cadomian rocks are almost everywhere overprinted by Variscan structures and metamorphism.

THE CALEDONIAN CYCLE

The geological history of the time span from Cambrian to Silurian is one of the most controversial issues in middle European geology. Rb-Sr and U-Pb data on high-grade rocks, which geologists generally thought to be either of Variscan or Precambrian age, yield Caledonian ages. At present

geochronological data indicate an almost continuous magmatic and metamorphic activity of a duration of 300 Ma, from 600 to 300 Ma ago (SCHMIDT, 1976; DORNSIEPEN, 1979).

Caledonian folding has been known for a long time from the northern border of the Variscan belt in southern Ireland, S Wales and in the Ardennes (DUNNING, 1977). The deformation in S Wales and in southern Ireland is relatively mild, mainly without metamorphism or with anchimetamorphism. The precise southeastern limit of the British Caledonides is difficult to draw. In southern Ireland and SW Wales it is obscured by the Variscan fold belt. In S Wales the intensity of folding gradually decreases towards the southeast. In the middle of England the Caledonides are bordered by the Central England Precambrian Craton of probable Cadomian age (DUNNING, 1977).

The Caledonian deformation in the Brabant Massif and the Ardennes is more intense than in S Wales, resulting in strong folding, the development of cleavage and a greenschist-facies metamorphism. The extension of this folded area is not very well known. It probably extends to S England (DUNNING, 1977). Furthermore new data from drill holes indicate the existence of a narrow Caledonian fold belt at the southwest border of the east European platform running from the North Sea over Denmark and north-eastern Germany to Poland. It may continue into the Carpathian fore-deep and from there to the Dobrugea at the Black Sea (ZIEGLER, 1975; TESCHKE, 1975). The deformation varies from block faulting and gentle folding to strong compression with the development of cleavage. The metamorphism is usually very low or absent, but may locally reach greenschist-facies conditions. The connection and the relationships between this Caledonian fold zone and the Scandinavian Caledonides are not known. Some similarities between the low grade zones suggest that the S Wales – middle England Caledonides continue into the North Sea – Poland zone rather than bearing a relation to the high-grade metamorphic belt of Scotland and Scandinavia.

There may also be a connection between the Caledonides of the Brabant Massif and the North Sea – Poland area, hidden by younger sediments in N Germany (ZIEGLER, 1975), or obscured by Variscan structures in the northernmost part of the Rheinische Schiefergebirge, while a direct continuation into the S Wales area is difficult to establish (Fig. 4).

Besides the local occurrence of unconformities in the Upper Cambrian and Lower Ordovician (Sardic phase) in the southern part of the Iberian Massif and in SW Sardinia, no evidence for Caledonian deformation can be found in Lower Palaeozoic rocks in Central and Western Europe. Although the Cambro-Devonian sequence is not always complete in some areas, strong angular unconformities are absent. Conformable sequences occur in Saxony and Thuringia, Bohemia, the Alps, Brittany, Montagne Noire, the Pyrenees, Asturias and southern Portugal (Fig. 4). On geological grounds, therefore, no Caledonian orogeny is present in Central and

Western Europe south of the above mentioned Caledonian fold belt.

It is therefore most surprising that numerous radiometric dates on metamorphic rocks have given Caledonian ages. The ages are obtained from three types of rocks:

- (1) high-grade kyanite-bearing gneisses and granulites, which in many places are overprinted by low to intermediate P/T type metamorphism in the cordierite-sillimanite zone (e.g. Bohemia, Saxony, Vosges, Massif Central;
- (2) Eocambrian-Ordovician rocks, which are metamorphosed and migmatized in a low P/T type facies series (e.g. Bavarian Forest, Black Forest, Montagne Noire);
- (3) metagranites and orthogneisses.

From the geological point of view, it seems more likely to us that the kyanite-bearing gneisses and granulites are formed during the Cadomian orogeny (perhaps some of the granulites are even older), while the overprinting of these rocks and the metamorphism of the Eocambrian-Ordovician strata is considered to be Variscan (ZWART, 1976). However, if the Caledonian ages on metamorphic rocks, established by geochronology, represent a real event, a fundamental problem arises: is it possible that high-grade regional metamorphism occurs without the existence of a clearly defined orogenic belt and without regional deformation and folding? Structural geologists would be inclined to answer this question in a negative way, because in all well known orogenic belts there is a clear connection between regional metamorphism in high- and low-grade rocks and deformation, which in its turn is usually documented by unconformities. What then is the meaning of these radiometric data? We shall discuss this point in a later section of this paper.

As far as the magmatic activity is concerned the following remarks can be made: whole-rock ages on metagranites and orthogneisses are mostly interpreted as the age of emplacement of a granitoid body or the extrusion of a volcanic rock. Intrusion of granitic bodies has taken place almost continuously at various localities in Central and Western Europe from the Cambrian until the late Silurian or even early Devonian time (Fig. 3). In the Mancellian province of the Armorican Massif JONIN & VIDAL (1975) have shown that granites, intrusive into the Brioverian, have a Cambrian to Early Ordovician age. These post-kinematic granites are the last expressions of the Cadomian cycle. Likewise in other regions such as the Bohemian Massif, the Massif Central and the Pyrenees granites of the same age are considered to be late orogenic Cadomian granites. However, in some of these regions like the Montagne Noire and the Pyrenees, these granites intrude Lower Palaeozoic rocks.

In the regions as mentioned above, and also in Saxony, the Alps, the Black Forest, the German Crystalline Rise and in the Iberian Massif dates of orthogneisses indicate an intense magmatic activity in Ordovician and Silurian time, which cannot be considered to belong to the Cadomian cycle (Fig. 3). The chemical composition of these orthogneisses is quite variable. Besides granites and granodiorites, syenites (PRIEM

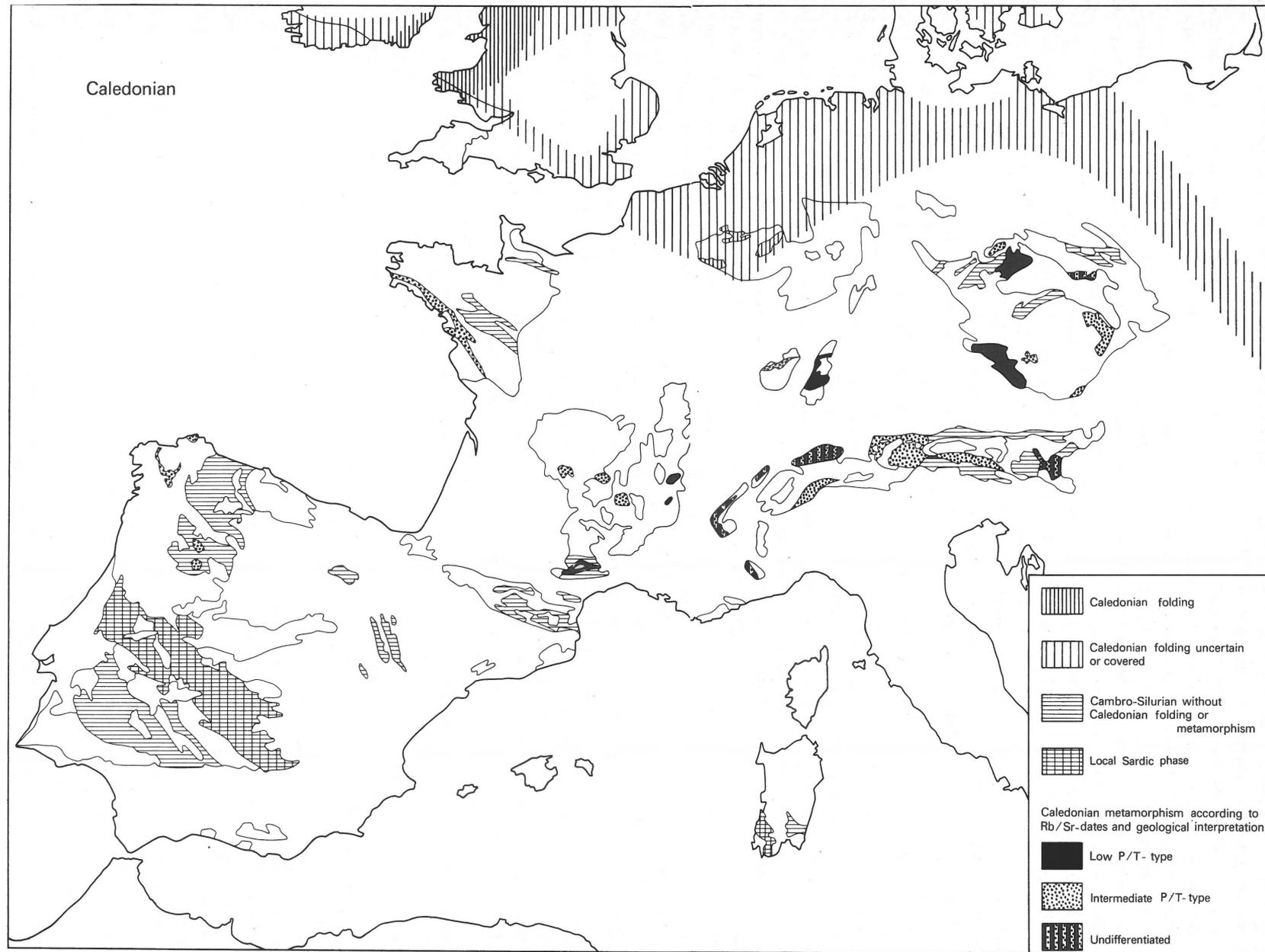


Fig. 4
Map of Central and Western Europe showing Caledonian events.

ET AL., 1970), alkali-granites (FLOOR, 1966) and trondjemites (BARRIÈRE ET AL., 1971) have been reported. The origin of these anorogenic granitoids is not well known.

In the southern part of the Armorican Massif (Moëlan-Lanvaux area: VIDAL, 1972) and in the Massif Central (Limousin: AUTRAN & GUILLOT, 1977) they are situated in the same areas as the Cambrian ones. Elsewhere they occur contemporaneously with and in, or close to, the same area as the Ordovician and Silurian volcanics (Saxony, Bohemian Massif, Alps, southern part of the Armorican Massif, Limousin). So far no unambiguous cogenetic relationship between the granitoids and the volcanics has been proved, although some of the orthogneisses may be derived from felsic volcanic rocks. The strong deformation and intense metamorphism of these rocks do not always allow a determination of their original character, but most of them are rather megacrinites than metarhyolites. Some orthogneisses are associated with ultramafic and mafic bodies which can be, according to radiometric dates, of early Palaeozoic age (VAN CALSTEREN ET AL., 1978). DEN TEX (1979) supposes a genetic relationship between the ultramafics and the alkaligranites in northern Spain and interprets this situation as a relict of a Palaeozoic continental rift system. Some of the granitoids, according to their chemistry and low Sr^{87}/Sr^{86} initial ratio, may originate from mantle material (BARRIÈRE ET AL., 1971). LEFORT (1977) explains the distribution and the chemistry of the Cambro-Ordovician granites in the northern part of the Armorican Massif with the aid of a southeasterly dipping subduction zone with a suture in the British Channel. Summarizing we can state that there still remains a great deal of uncertainty about the origin of the Ordovician-Silurian magmatic activity.

THE VARISCAN OROGENY

Although much is known about the Variscan orogeny (see for example 'Franz Kossmat symposion': Karl Marxstadt, 1976; and 'La chaîne varisque d'Europe moyenne et occidentale': Rennes, 1977), there still remain a number of problems, especially with regard to early Variscan events. Variscan events of Carboniferous age, coinciding roughly with the Sudetic phase between Lower and Upper Carboniferous, and the Asturian phase within the Upper Carboniferous are quite well known. Fold structures, simple and complicated, metamorphism, low- and high-grade, and granite intrusion have been described from many regions within the Variscan chain. Also the well known Kossmat-zonation is mainly based on these events. However, there is increasing evidence that the Variscan orogeny already started in the Devonian (Acadian and Bretonic phases), but due to later overprinting effects this is more difficult to substantiate. The Variscan orogeny was active in almost all Central and Western Europe. It affects the Cadomian and a small part of the Caledonian basement, and a more or less complete Pa-

laeozoic sequence from Cambrian to Devonian or Carboniferous.

In the Armorican and Bohemian Massifs partly continental Cambrian molasse-type sediments, with intercalation of felsic and basic volcanics, are found. Elsewhere marine deposits consist of shales, sandstones and abundant limestones. The Cambrian does not always rest unconformably on Cadomian folded rocks, as in some areas like Saxony, the southern part of the French Massif Central and in some parts of the Iberian Massif it is conformably underlain by sediments, which are supposed to be Uppermost Proterozoic (Eocambrian). The Ordovician consists mainly of sandstones with intercalated shales and numerous basic volcanics. The equivalents of the characteristic Armorican quartzite also occur in the Bohemian and Iberian Massifs and in the Saxothuringian. The Cambrian and Ordovician together in general reach a thickness of 2000–6000 m, but occasionally it is more than 10,000 m thick as in northern Spain. The Silurian, usually less than 500 m thick, is characterized by black shales, which can be found in nearly the whole of Central and Western Europe. At some places limestones and sandstones occur. The Ordovician volcanic activity mostly continues into the Silurian, but with less intensity. In the Devonian the following two types of sedimentary basins are present.

(1) Filled with a clastic sequence (sandstones and shales) and intercalated basic volcanics, characterized by rapid and drastic changes in thickness from some hundred metres to several thousand metres. These basins occur in the external parts of the Variscan belt in southwest England, Germany and Moravia and also in the central parts of the Armorican and Iberian Massifs.

(2) Filled with carbonates interlayered with some shales and sandstones with a thickness of 500–1000 m. Volcanism is absent. These basins are found in the Bohemian Massif, Montagne Noire, the Pyrenees and Cantabria. The Carboniferous is characterized, besides by shales and cherts, by flysch sedimentation, olistoliths and turbidites and also rapid changes of thickness from some hundred metres up to 5000 m. The reworking of the Caledonian basement at the northern border of the Variscan belt is weak because the intensity of the Variscan deformation decreases towards the north. The reworking of the Cadomian basement in the internal zones of the Variscan belt is very intense. The strong deformation, together with a high-grade metamorphism, has obliterated many traces of pre-Variscan structures and metamorphism. It should be emphasized that the high-grade Variscan metamorphism in the Moldanubian zone coincides with high-grade pre-Variscan metamorphism.

At many places in the Variscan belt the folding is autochthonous as in most of the Rhenohercynian and Saxothuringian zones and does not involve nappe structures. In general folding in unmetamorphosed and low-grade regions is relatively simple, usually with only one cleavage, and in the more internal parts often with two cleavages. Nappe structures in low-grade rocks occur in the Harz mountains, the southern

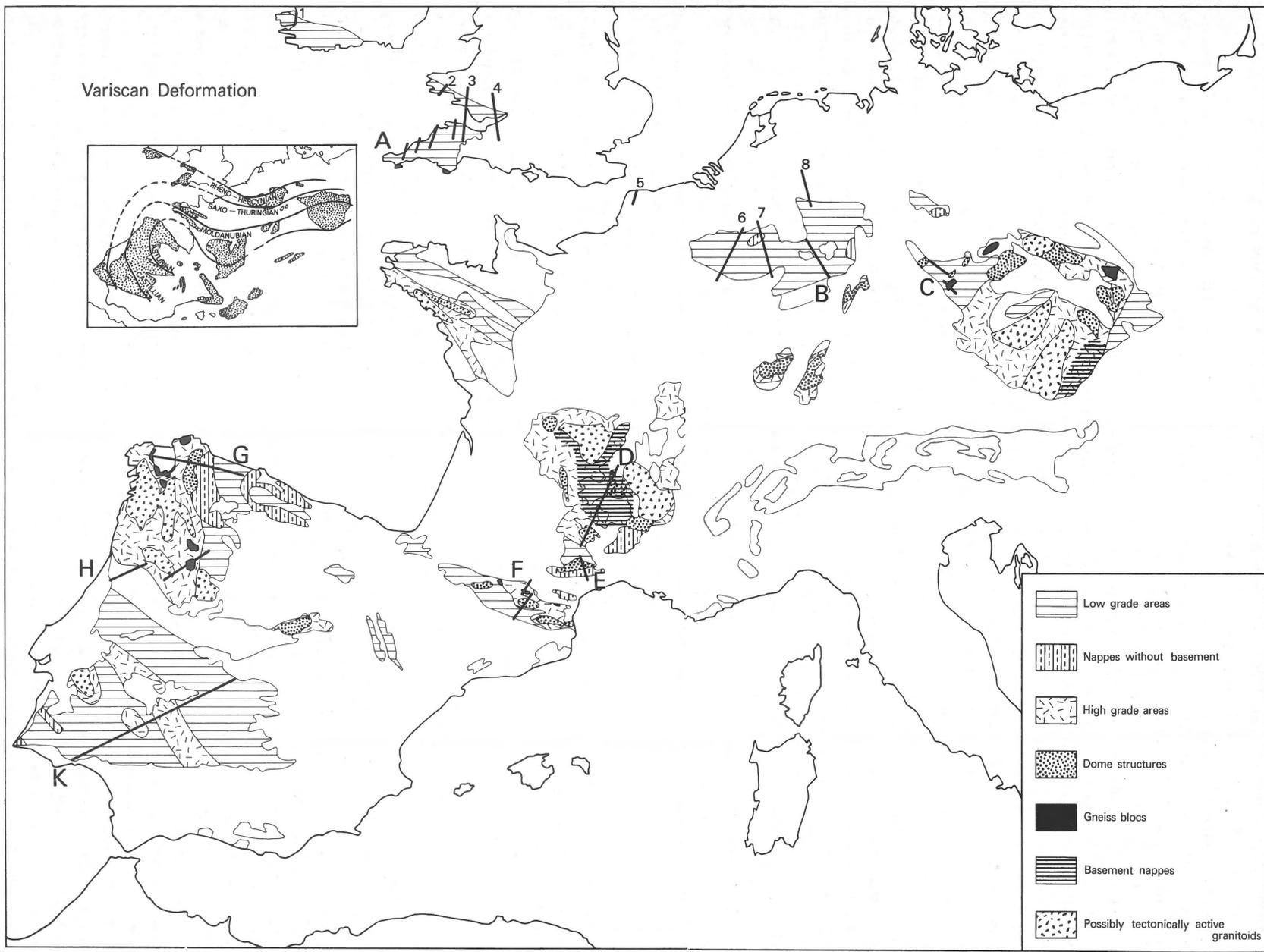


Fig. 5
Map of Central and Western Europe showing Variscan structural type regions; 1-8 and A-K: locations of profiles of figures 6, 7 and 8.

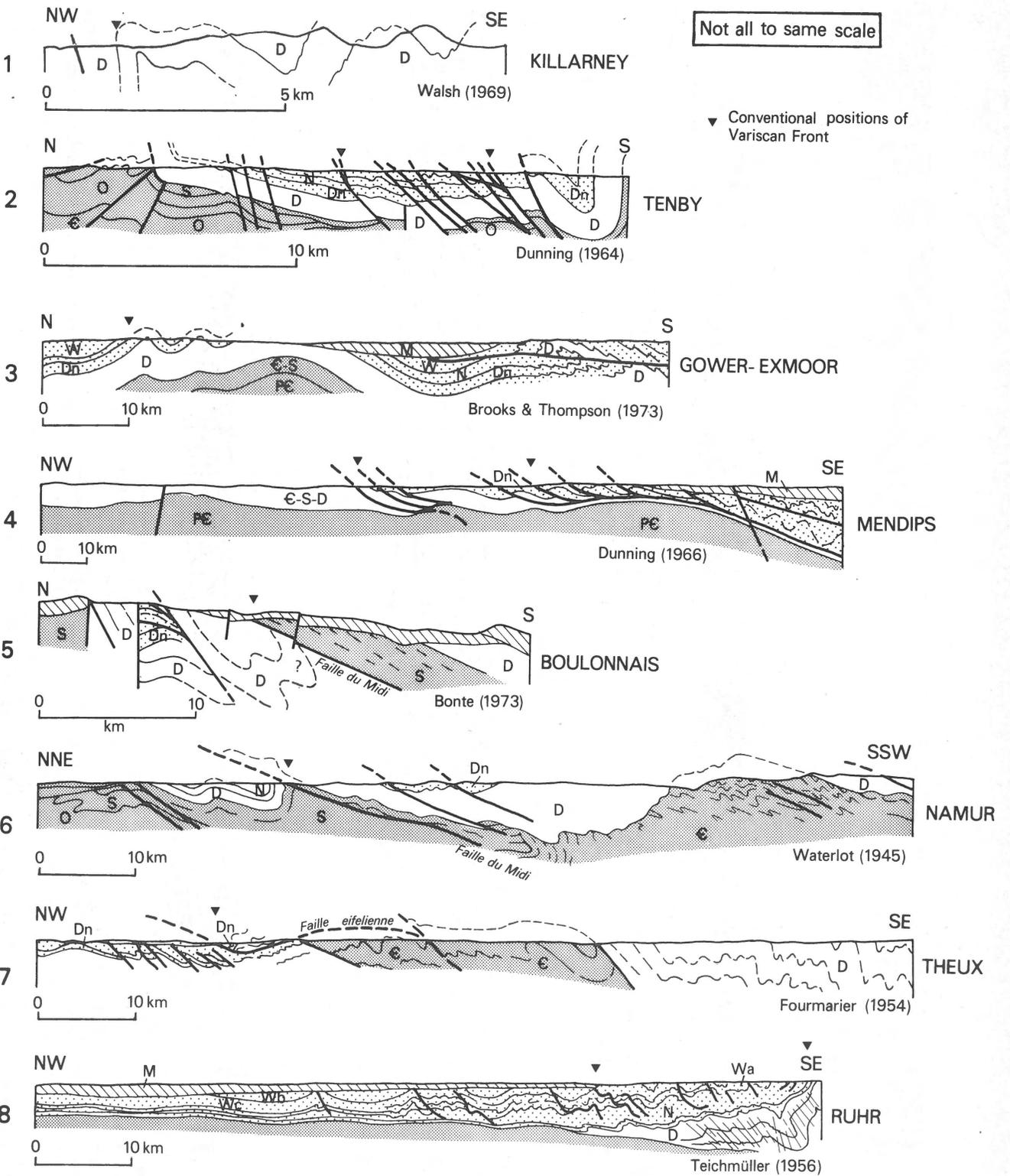


Fig. 6 Profiles through the northern Variscan front (after Dunning, 1977).

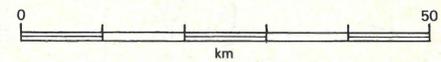
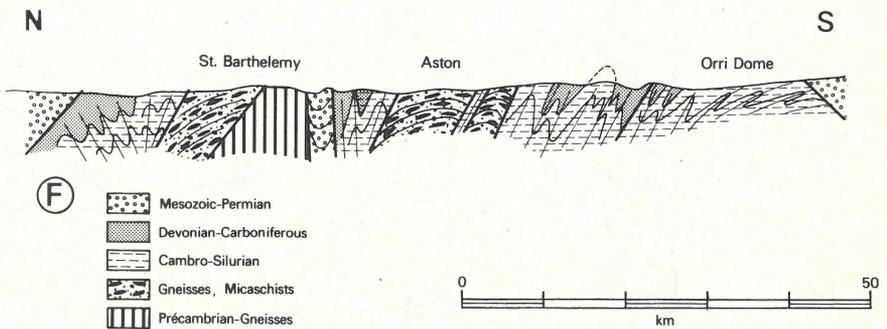
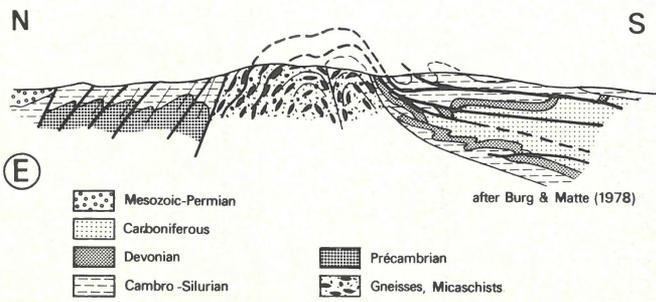
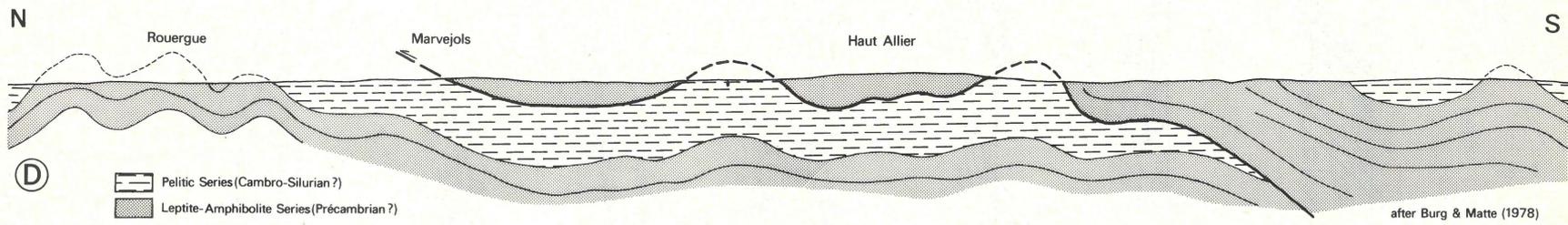
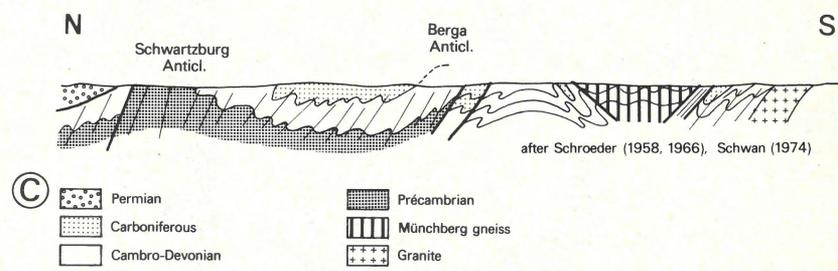
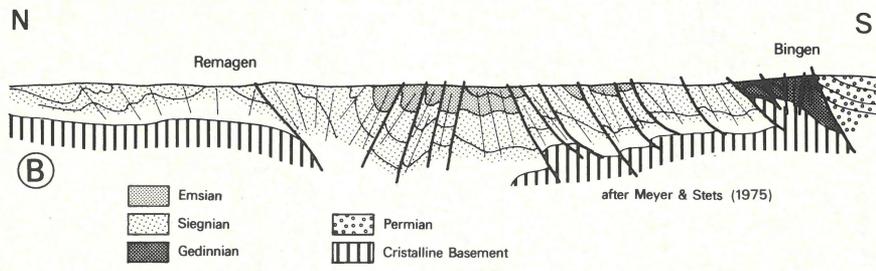
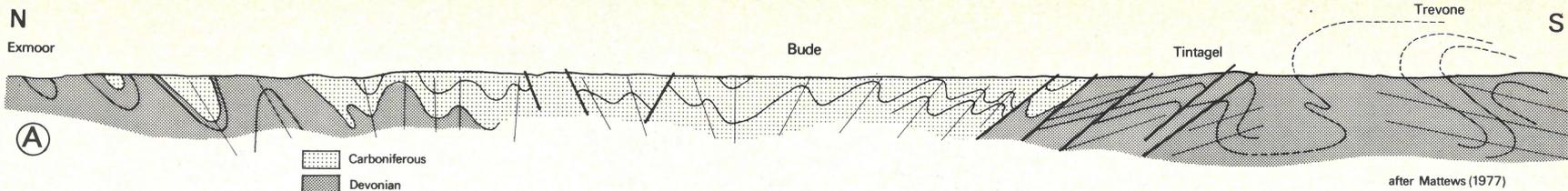


Fig. 7 Profiles through different parts of the Variscan belt (vertical scale exaggerated about two times).

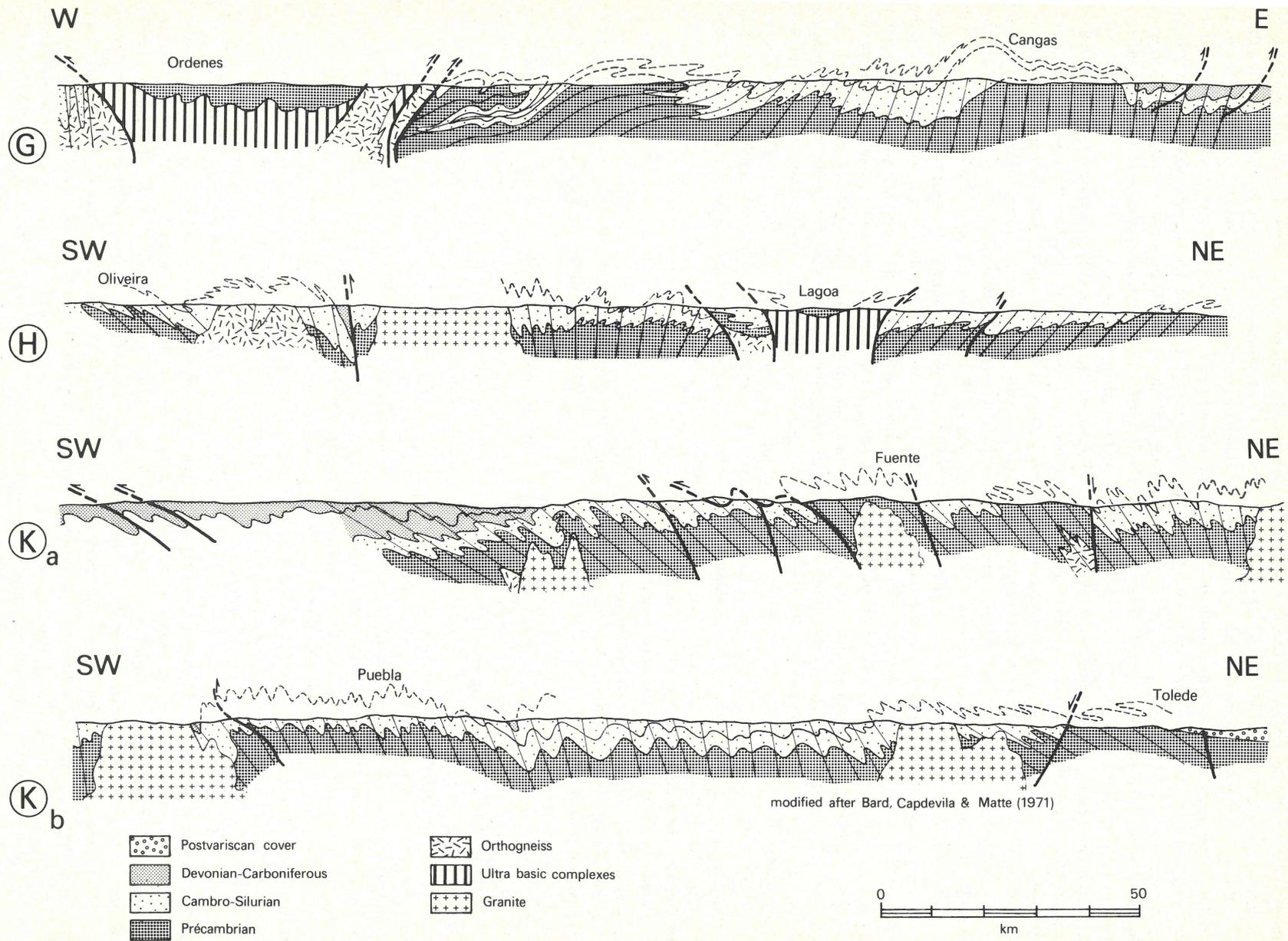


Fig. 8
Profiles through the Iberian Massif.

part of the Rheinische Schiefergebirge, Montagne Noire, Cevennes, Cantabria and E Galicia (Fig. 5). In high-grade regions, as in the Moldanubian zone, folding is more complex often with three or more fold generations. Another difference is that low-grade rocks have steep axial planes whereas in higher-grade regions they are recumbent on a small or large scale. In these regions the occurrence of dome structures often in migmatic or gneissose rocks, often in tectonic contact with the surrounding rocks, is characteristic. A number of synoptical profiles through the Variscan chain is given in figures 6, 7 and 8. Variscan metamorphism has been dealt with by ZWART (1976). The late Variscan metamorphism is almost everywhere of low pressure – high temperature type (Abukuma, Bosost). Locally Variscan kyanite has been recorded for example from Spain, the Bohemian Massif and the Alps. In the French Massif Central the Variscan kyanite-metamorphism has a larger regional distribution (Fig. 9), but belongs to an early Variscan event. Variscan granites make up an integral part of the Variscan chain. Most of the granites are syn- to late-tectonic and have yielded ages in the range of 400 – 260 Ma, with a maximum at about 340 – 300 Ma, that is Upper Carboniferous.

Older events in the Variscan orogeny are dated with geochronological, but also with geological methods. The Bretonic phase, for example, at the Devonian-Carboniferous boundary has already been known for a long time although the type locality in Brittany is not the most convincing occurrence. But there is radiometric evidence for an intra-Devonian tectonometamorphic event in the southern part of the Armorican Massif (COGNÉ, 1977).

Recent work of AUTRAN & GUILLOT (1977) and BERNARD-GRIFFITH ET AL. (1977) in the western part of the French Massif Central (Limousin) has established a number of folding and metamorphic phases in the Devonian followed by the intrusion of granites. The rocks involved are Upper Proterozoic and Cambro-Silurian sediments and volcanics. There are four folding phases of which the first two in the higher-grade rocks result in the formation of a foliation and isoclinal major recumbent folds. The last two phases generally have steep axial planes and are more open. Intermediate P/T type metamorphism took place during the first two folding phases, whereas the last two phases are essentially post-crystalline. With the aid of radiometric methods the first two phases are dated between 400 – 360 Ma. That is early Devonian or in terms of Stille's folding phases, Acadian.

The last events around 320 – 300 Ma belong to the Sudetic phase. There are several generations of granites in the area, early ones predating the Acadian phase and transformed to orthogneisses, and late ones postdating that phase and of uppermost Devonian and Carboniferous age. The results of the Limousin area may be extended to the central part of the Massif Central, where unconformable Upper Devonian and Carboniferous rests on folded and metamorphosed older rocks (BURG & MATTE, 1978). The metamorphic zonation is partly inverse and is interpreted by BURG & MATTE (1978) as a

large south-vergent nappe structure involving granulite-facies rocks of probable pre-Variscan age. There are three folding phases; the nappe formation is supposed to be due to the second phase. The granulites are overprinted by an intermediate P/T type metamorphism, which is contemporaneous with the second folding phase, and is early Variscan. The last deformation caused gentle open folds and the formation of dome structures.

Folding in the Devonian is also known from Spain, where BARD ET AL. (1973) have reported pre-Visean folding, producing large recumbent folds. Also the radiometric dates indicate an early Devonian metamorphism in the Cabo Ortegal complex in Galicia (VAN CALSTEREN ET AL., 1978). In the Vosges and the Black Forest the early Variscan granites are of Upper Devonian age (BREWER & LIPPOLT, 1974). Early Variscan events have been described by VON RAUMER (1976) in the autochthonous massifs of the western Alps. In the Bohemian Massif indications for an intra-Devonian deformation and metamorphism can also be found (CHAB & SUK, 1978).

In conclusion it can be stated, that the Acadian-Bretonic folding and metamorphism have occurred in the central parts of the Variscan chain (see Fig. 16). The later Carboniferous events have folded and metamorphosed the outer parts of the Variscan belt as well as the earlier formed more internal zones.

THE PRE-CADOMIAN BASEMENT AND THE CALEDONIAN EVENT: A DISCUSSION

We have pointed out in the previous chapters that there are two controversial issues in Central and Western Europe between geochronologists and geologists:

- (1) the nature of the pre-Cadomian basement;
- (2) the Caledonian event.

The pre-Cadomian basement

According to JÄGER (1977) and VIDAL (1977), interpretation of Rb-Sr and U-Pb dates leads to the conclusion that the pre-Cadomian basement consists of young Proterozoic oceanic crust. The Sr-evolution diagrams on metamorphic rocks indicate that the parent rocks cannot be older than 600 to 700 Ma (JÄGER, 1977). Also the $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratios of magmatic rocks show that no continental crust older than 700 Ma is involved in the formation of those magmas (VIDAL, 1977). According to JÄGER (1977) the U-Pb dates on zircons exclude a metamorphism between 700 and 1500 Ma. Zircons older than 2000 Ma can be interpreted as detrital grains originating from the Precambrian platform of NE Europe.

From the arguments given by Jäger and Vidal, the following succession of events for the evolution of Central and Western Europe can be derived. A clastic sequence with a thickness of 5,000 – 10,000 m is deposited on an Upper Pro-

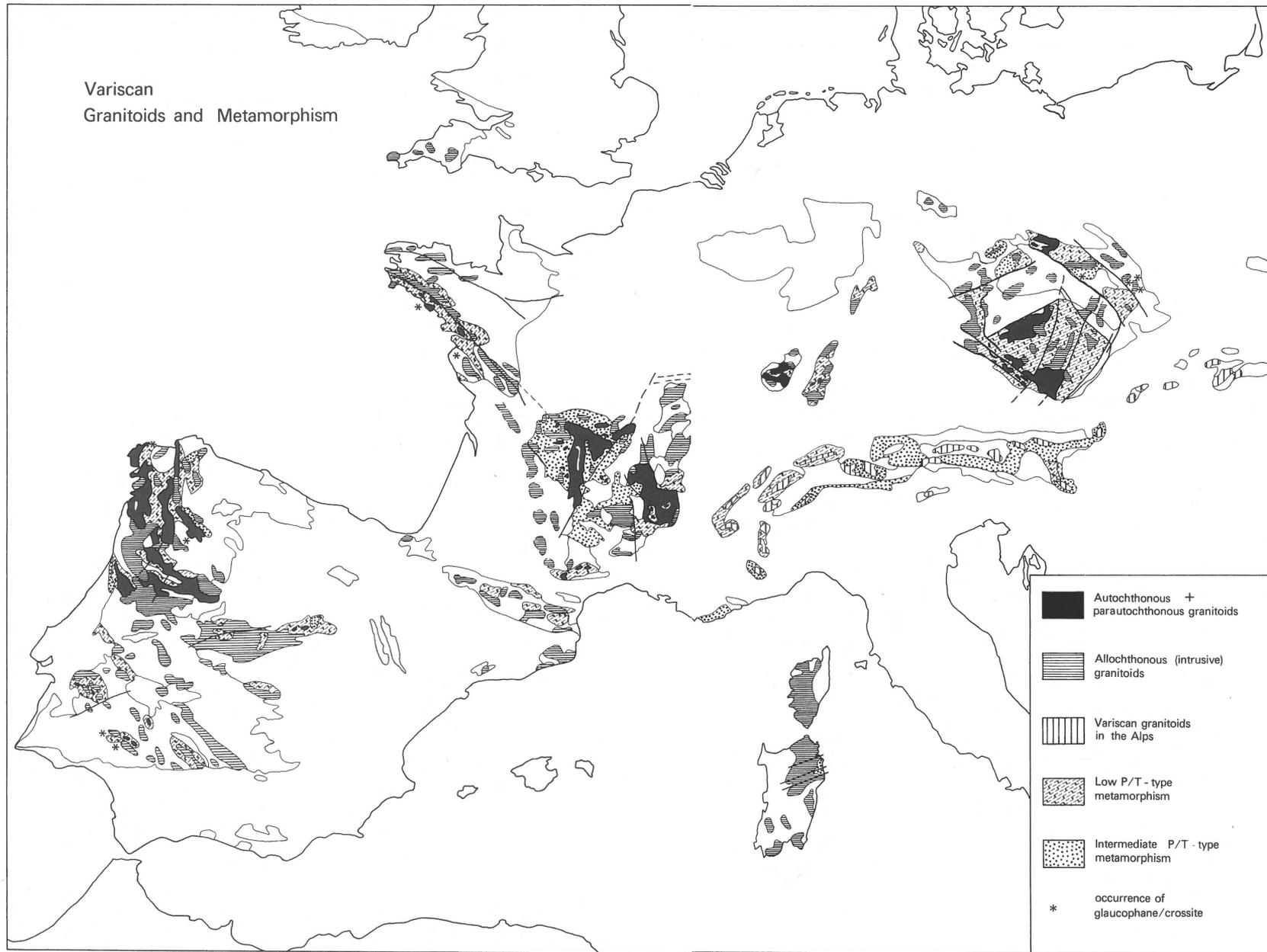


Fig. 9
Map of Central and Western Europe showing Variscan granites and metamorphism (granites after Perekalina, 1978).

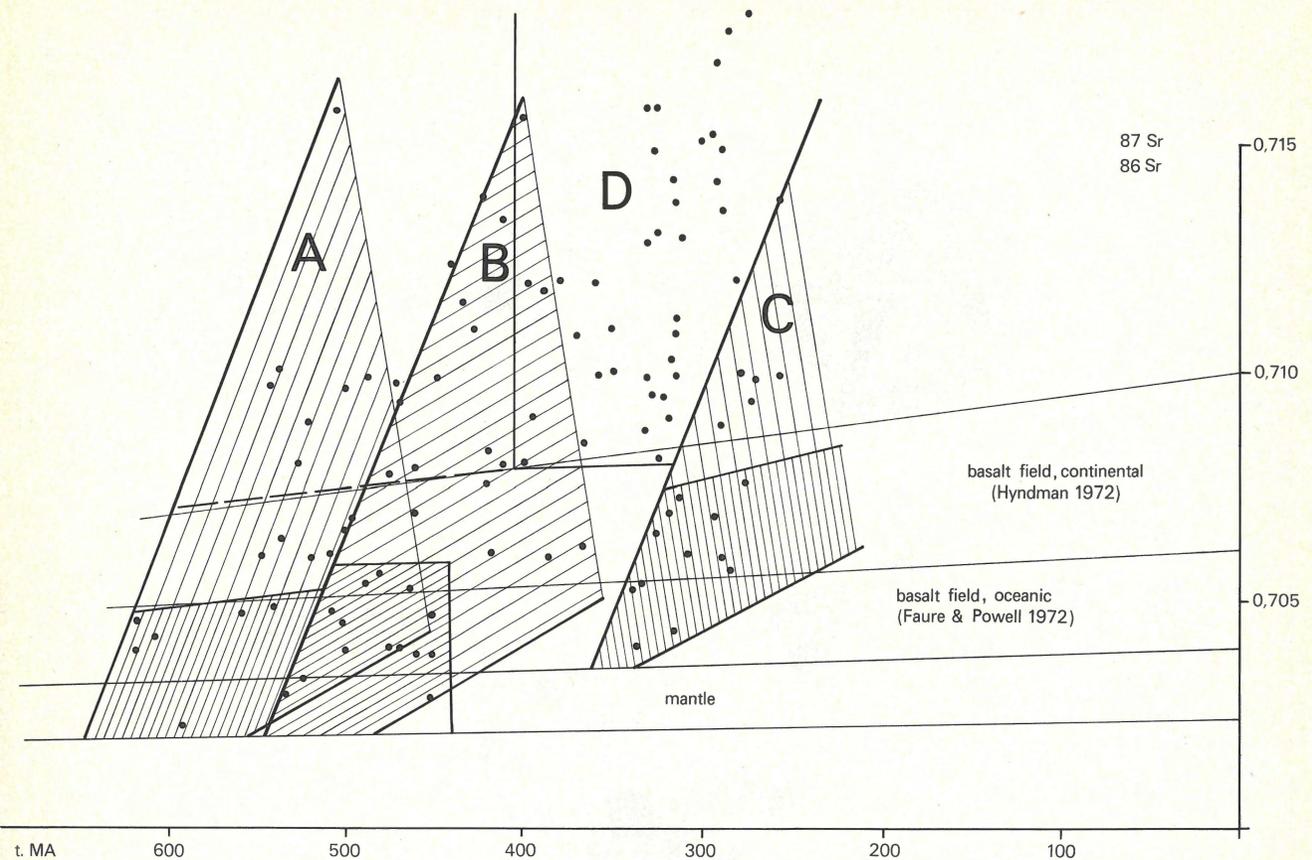


Fig. 10
 Sr^{87}/Sr^{86} initial ratios - time diagram (modified after Vidal, 1977).

terozoic oceanic crust in the time span from 800 – 600 Ma ago. This sequence is folded and metamorphosed during the Cadomian orogeny around 630 – 570 Ma ago, producing a continental crust in Central and Western Europe. From 550 – 400 Ma ago there is an almost continuous magmatic and metamorphic activity. The latter reaches grades as high as the granulite facies, including migmatization within different facies series. In Devonian and Carboniferous time the Variscan orogeny affects the whole of Central and Western Europe with folding, metamorphism and the production of a large amount of granitoids.

It is difficult to design a model based on plate tectonics for the formation of the continental crust in Central and Western Europe on the basis of the above mentioned sequence of events. If the Cadomian orogeny is of the collision type the pre-Cadomian ocean would have closed, thus joining two older pre-Cadomian crustal segments. However, according to Jäger and Vidal, such older crust does not exist in the region under discussion. Also an Andean type orogeny would imply the existence of an older continental crust at least on one side. Another possibility is that the Cadomian is of the Pacific island arc type, leaving a large part of the pre-Cadomian ocean unaffected, which would then be the Palaeozoic Mid European ocean (BURRETT, 1972). In a later

phase during the Variscan orogeny this ocean could have been closed completely, so that there is only a piece of Cadomian continental crust between the two Precambrian continental blocks on either side. However, a Pacific type orogeny would produce only a narrow zone (200 – 300 km) of continental crust of at least 30 km thickness as can be seen around the Pacific, and not a broad zone of more than 1000 km, which is the observed width of the Cadomian chain (Fig. 2). In this model it would also be difficult to explain the Caledonian metamorphism in granulite facies.

A number of other points against the arguments of Jäger and Vidal can be raised. The Sr-evolution diagrams, on which the interpretation of JÄGER (1977) is based, are only valid if the Rb-Sr system was closed since the time of deposition. This can be doubted for some rocks, as intermediate-pressure granulite-facies metamorphism can change the Rb/Sr ratio of a rock (HEIER, 1970). Also the intense polymetamorphic history of some rocks, including metasomatic changes, has an influence on the Rb-Sr system.

There is also an explanation for the fact that no pre-Cadomian continental crust is involved in the formation of magma. From the diagram given by VIDAL (1977), and modified by us (Fig. 10), it appears that some of the magmatic bodies with low Sr^{87}/Sr^{86} initial ratios may originate from the

mantle. It is possible to interpret granite suites in Cadomian (A), Caledonian (B) and late Variscan (C) time, which have their origin in the mantle and which developed higher Rb/Sr ratios and higher Sr^{87}/Sr^{86} initial ratios by differentiation, and contamination with crustal material. Although not all Cadomian and Caledonian granitoids are necessarily formed in this way, the available data allow such an interpretation. Most of the Variscan granitoids seem to be of crustal origin (Fig. 10 D). The abundance of migmatites and their close relation to granites (PEREKALINA, 1978) indicate that anatexis of crustal material was largely responsible for the formation of the magmas. The P/T conditions for the low-pressure migmatites suggest that their formation took place between 10 and 20 km depth. At that depth we can only expect to find Upper Proterozoic and Lower Palaeozoic strata. Most of the dry granulite-facies basement rocks do not melt there because the melting curve for dry granitic rocks is reached only at the base of the crust (Fig. 11). Moreover the deeper part of the crust consists of more mafic rocks with even higher melting temperatures. This makes it less likely that basement rocks are involved in the crustal anatexis processes. This hypothesis is in good agreement with geological observation, as relicts of granulite bodies in migmatite areas are quite common. The Upper Proterozoic and Lower Palaeozoic rocks involved in the formation of magmas consist of clastic sediments, derived in part from a continental basement, and of intercalated basic volcanics with low Sr^{87}/Sr^{86} initial ratios indicating a mantle origin. The Sr^{87}/Sr^{86} initial ratios resulting from the anatexis of these rocks is a mixture of crustal and mantle initial ratios. Therefore the Variscan granites cannot be used to define the nature of the crust, and do not deny the presence of an older continental crust.

The zircon ages of 2000 – 2500 Ma suggest a provenance from an old basement. This source area could be the Fennosarmatian shield. However, this shield is for a large part built up by the Svecofennian and Dalslandian orogens with ages of 1600 – 1800 Ma and 1000 – 1200 Ma respectively, and only for a smaller part of older rocks (>2000 Ma) (Figs. 1, 13). It is therefore surprising that no zircon ages of 1000 or 1800 Ma have been found, and for this reason the provenance of sedimentary zircons in Central and Western Europe from Fennosarmatia is improbable. Furthermore there is no geological evidence for the presence of an oceanic crust in the Proterozoic and, although mafic and ultramafic rocks do occur in these sequences, they do not seem to be part of an ophiolite suite.

In conclusion, we can state that it is unlikely that up to 800 Ma ago there was an oceanic crust in Central and Western Europe. It seems impossible to create a continental crust of a thickness of 30 km over such a large area in a time span of only 400 Ma from 700 – 300 Ma ago, as at the end of the Variscan orogeny the crust already had its present thickness. Moreover there is no evidence that a large part of this crust is derived by erosion from the surrounding Precambrian, as indicated by the zircon ages. We are therefore of the opinion

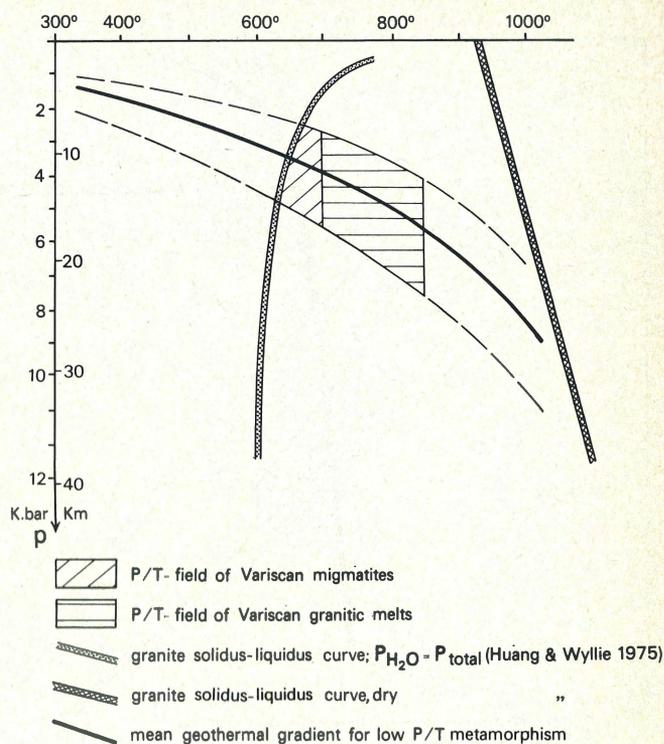


Fig. 11
P/T grid for formation of migmatites and granites in the Variscan belt.

that the crust of this part of Europe was already sialic before the late Proterozoic. In this case two possibilities exist:

- the crust was older than 2000 Ma as indicated by zircon ages;
- the crust consisted of rocks of Svecofennian and Dalslandian age and formed the continuation of the Canadian-Fennosarmatian shield. There is no evidence for the latter alternative, so, for the time being, we prefer the first one.

The Caledonian event

The following facts are relevant to the discussion of this point:

- (1) whole-rock ages on metamorphics are between 400 – 550 Ma (SCHMIDT, 1976; DORNSIEPEN, 1979) and interpreted as the age of a 'Caledonian' metamorphism (JÄGER, 1977);
- (2) many granitic rocks give the same ages;
- (3) minerals of the same rocks give Variscan ages;
- (4) the rocks belong to different facies series (Fig. 12):
 - (4a) kyanite-bearing granulite facies rocks with P/T condition of 10 – 12 Kbar and 700 – 800°C corresponding to a geothermal gradient of 20°/km (Bohemian Massif, Saxony, Vosges, French Massif Central);
 - (4b) micaschists and gneisses of an intermediate P/T type facies series with P/T conditions for the high grade rocks of 7 – 8 Kbar and 600 – 700°C corresponding to a geothermal gradient of 30°/km (French Massif Central, Alps);

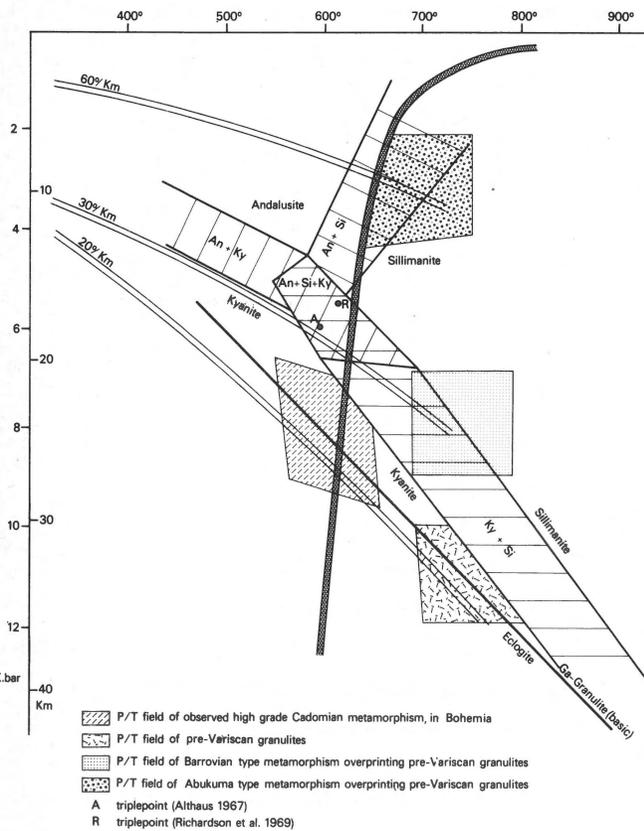


Fig. 12
P/T grid for pre-Variscan granulites and Variscan overprinting (eclogite - garnet-granulite transition after Green & Ringwood, 1967).

(4c) micaschists and migmatites of a low P/T type facies series with P/T conditions for the migmatites of 2 – 4 Kbar and 600 – 700° corresponding to a geothermal gradient of 60°/km (Bavarian Forest, Black Forest, Montagne Noire).

There is, of course, no objection to the intrusion of granites during the Ordovician and Silurian, despite the fact that apparently no folding took place, and they could be called anorogenic. However, the occurrence of high-grade metamorphics of the same age poses severe problems for us because of the absence of contemporaneous folding. These Caledonian metamorphics possess structures and fabrics, but in most if not all cases it can be shown that these structures are of Variscan age. Some more objections against a high-grade Caledonian metamorphism can be made:

- (1) The thickness of the Cambro-Silurian sediments is not large enough to produce the pressure needed for the granulites and there is no folding to thicken the sedimentary pile;
- (2) it seems impossible that the Abukuma or Barrovian facies series lead to the kyanite-bearing granulite-facies rocks in a progressive metamorphic sequence, because both end in the sillimanite field (Fig. 12);
- (3) if granulites and low to intermediate P/T type meta-

morphics both giving Caledonian ages occur in the same area, the granulites are always overprinted by the lower pressure metamorphism and are hence older, and could not be contemporaneous, as indicated by geochronology (Fig. 12);

(4) an important concept in metamorphic petrology is the development of a facies series during regional metamorphism. Up till now such a facies series of doubtless Caledonian age dated by radiometric methods has not been described.

Several attempts have been made to solve this problem, of which the following deserve mention:

(1) A Caledonian thermal event (SCHMIDT, 1976): the abundance of granitic and volcanic rocks at this time, and peridotites and gabbros possibly of Palaeozoic age occurring in the granulite terrains, indicate a thermal activity. This thermal event could have its origin in a mantle plume caused by an abnormally hot mantle (VAN CALSTEREN, 1977). It is possible that the metamorphic rocks yielding Caledonian ages and occurring near the intrusive bodies have been influenced by the latter and that their ages are reset. Consequently they do not date the time of regional metamorphism but the time of heating by the intrusion of granites and gabbros. This interpretation is favoured by many geologists. However, there remains the problem of whether it is possible to have a homogenisation of the Sr isotopes on whole-rock scale in dry granulite-facies rocks by static heating only.

(2) The subfluence model (BEHR, 1978): this model means a restricted subduction in a small area which does not involve the whole lithosphere but affects only crustal segments, which are underplating each other. The downgoing slab is migmatized and transformed to granulites, while in the overriding segment earlier formed granulites are excavated. These processes were active from late Proterozoic to Carboniferous. In his article Behr uses this model to explain some special features of the geology in Central Europe and the controversy between radiometric and geological evidence. Although it is a very interesting attempt to solve the problem, some objections can be made:

- (a) there is no source for the heatflow needed for the migmatization at shallow depth corresponding to a pressure of 2 – 4 Kbar. To the contrary, a downgoing crustal segment will tend to decrease the geothermal gradient as can be deduced from known subduction zones.
- (b) the model does not explain why strong folding activity only occurs in Cadomian and Variscan time, that is to say at the beginning and at the end of the processes, neither does it explain folding at depth only, and not in the higher level of the crust.
- (3) The radiometric dates have no real meaning due to rejuvenation. As described above, whole-rock samples yielding Caledonian dates give Variscan mineral ages. The Variscan overprinting took place under high-grade conditions and under the presence of a fluid phase. The possibility cannot be

excluded that the Rb-Sr system has been opened during the overprinting event, dated by the mineral ages, and that the whole rock ages are meaningless with respect to a geological event. However, the opening of the Rb-Sr system usually results in the scattering of data points in the Rb-Sr diagrams and no isochron is obtained in that case. Yet the possibility of 'pseudo-isochrons' or 'inherited isochrons' which has been discussed by MATSUDA (1974) and RODDICK & COMPSTON (1977) may be applicable for the Caledonian ages.

In conclusion it can be stated that the problems about the 'Caledonian' event in Central and Western Europe are far from being solved. According to the present authors there is no doubt about the existence of a high heatflow regime during the Ordovician and Silurian, resulting in large-scale granite formation and volcanism. The 'Caledonian' regional metamorphism remains an enigma, as it is uncertain whether there was regional metamorphism at all, or whether genetic relationships between this thermal event and the metamorphism exist. More geological investigations, and studies on the behaviour of Rb-Sr systems under high-grade metamorphism are necessary.

TRANSATLANTIC CORRELATION

In 1970 WYNNE-EDWARDS & ZIA-UL HASAN published a review of the 'Intersecting orogenic belts across the North Atlantic'. Since that time numerous new dates have become available.

Early Proterozoic

The relationships between early Proterozoic orogenies (Hudsonian – Svecofennian and older) in North America, Greenland and Northeastern Europe are well known and confirmed by numerous radiometric dates and similarities in structure and metamorphism (WYNNE-EDWARDS & ZIA-UL HASAN, 1970; BRIDGEWATER ET AL., 1973) (Fig. 1).

Grenville – Dalslandian (Fig. 13)

The timing of orogenic events, the similarities in metamorphic rocks (low- to intermediate-pressure granulite and amphibolite facies) and intrusives (anorthosites) indicate a close connection between the Grenville province in Canada and the Dalslandian in SW Scandinavia. At first the reconstruction of a continuous belt across the British Isles was uncertain (WATSON, 1975). However, in the last few years Grenvillian ages have been obtained on rocks from the Rockall Bank (MILLER ET AL., 1973), from the Annagh Gneiss complex in Ireland (VAN BREEMEN ET AL., 1976) and from various gneisses in Scotland (BROOK ET AL., 1976, 1977), indicating continuation of the Grenville belt across the British Isles. Ages of 950 – 1150 Ma from the central metamorphic

complex in the Caledonides of East Greenland probably date intensive deformation and regional metamorphism with migmatization and granitization in Grenvillian time (HENRIKSEN & HIGGINS, 1976). In 1961 HALLER described a pre-Caledonian orogeny (the Carolinian) in the northern part of the Greenland Caledonides which perhaps is also of Grenvillian age. Recent work on the central part of the Seve-Köli nappe complex in the Scandinavian Caledonides has shown that the high-grade metamorphism in the Seve nappe is pre-Caledonian (ZWART, 1978). Rb-Sr dates indicate a Grenvillian age for this metamorphism (REYMER ET AL., in prep.). Radiometric investigations on basement complexes within the Scandinavian Caledonides in the Jotunheim area (SW Norway) (BRUECKNER ET AL., 1968; PRIEM ET AL., 1973; BRUECKNER, 1973) and in the Lofoten-Vesterålen area (N Norway) (HEIER & COMPSTON, 1969, WILSON & NICHOLSON, 1973) also show the possible influence of a Grenvillian event on Svecofennian gneisses. K-Ar dates on minerals from Precambrian rock in Rumania gave ages of about 850 Ma (KRÄUTNER ET AL., 1976) which can be interpreted as cooling ages after a Grenvillian event. Also the 800 Ma date obtained from an orthogneiss in the southern part of the Bohemian Massif (SCHARBERT, 1977) may be a last witness of a Grenvillian granitic activity.

In conclusion, it can be stated that there is good evidence that the Grenville belt crosses the British Isles and is linked to the Dalslandian in S Norway and S Sweden. From there it continues to the north to the Caledonides of Greenland and Scandinavia, as suggested by STURT ET AL. (1975) and confirmed by REYMER ET AL. (in prep.). The link between SW Scandinavia and SE Europe is hidden by younger rocks. The southern boundary of the Grenville – Dalslandian belt is difficult to find, as the supposed occurrences of Grenvillian rocks in Germany, Brittany, northern Spain and Portugal (WYNNE-EDWARDS & ZIA-UL HASAN, 1970) are obscured by overprinting in later orogenies. Therefore the reconstruction of the Grenville – Dalslandian belt (Fig. 13) must remain conjectural until more results of geochronological, petrological and structural research become available.

Cadomian (Fig. 14)

The Cadomian orogeny is well established within Europe. It reaches to the north as far as the Irish Sea geanticline (DUNNING, 1977) (it is uncertain whether the Moravian event (700 – 750 Ma) in Scotland and Ireland (JOHNSON, 1975) is related either to the Grenvillian or Cadomian, or whether it forms part of an independent orogeny). The southern border of the Cadomian is not known due to the reworking in the Alpine orogeny and to the uncertainty about the Caledonian radiometric dates. The Cadomian orogenic belt in Europe has its counterpart in the Avalonian orogeny in the easternmost parts of the Appalachian belt (RODGERS, 1970) and the Avalonian platform can be considered as a small relict of the late Precambrian European continent (Fig. 14).

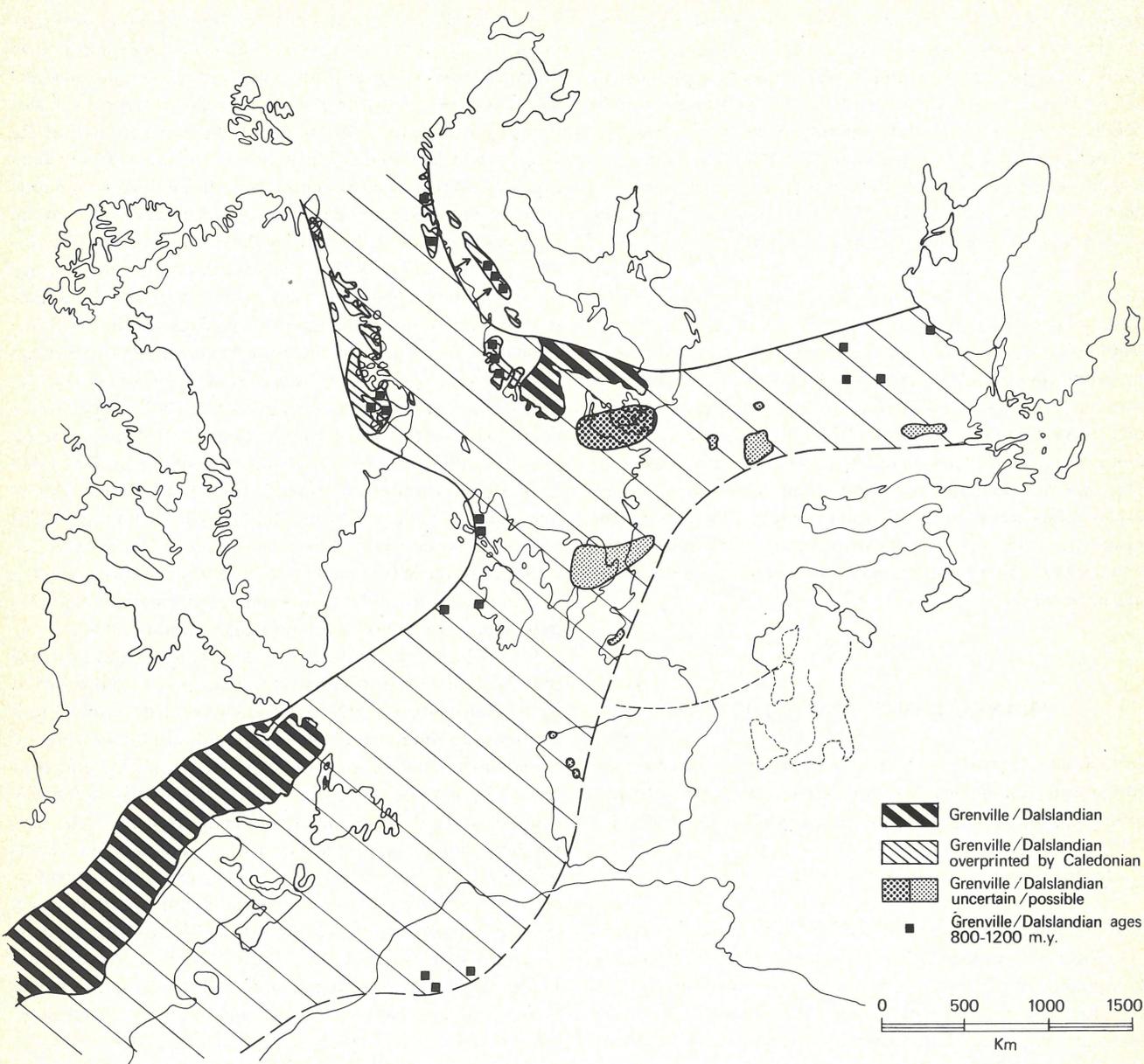


Fig. 13
Transatlantic correlation of the Grenville orogeny.

Phanerozoic (Figs. 15,16)

The Caledonian and Variscan belts, which except for a small part in the British Isles do not interfere in Europe, join in North America. There is little doubt about the continuation of the Appalachian belts into the British and Scandinavian Caledonides on the one hand and to the European Variscides on the other. This idea has been expressed since the beginning of the century by numerous geologists (see RODGERS, 1970). Nevertheless there are difficulties in relating the tectonometamorphic events over the whole belt. The event which occurs on both sides of the Atlantic is the Grampian

(Dalradian) event in Scotland, Ireland and probably in N Norway in the Upper Cambrian to Lower Ordovician time. It can be correlated with a comparable event in Newfoundland. The Appalachian Taconic event in Middle Ordovician time with high-grade metamorphism and strong deformation and thrusting has no equivalents in the British Caledonides nor in Greenland and Scandinavia. There is evidence for a pre-Silurian event (Grampian or Taconic) in the Scandinavian Caledonides (STURT & THON, 1976; NATERSTADT, 1976; GEE & WILSON, 1976), but the nature and extent of this event is still uncertain. The main tectonic event in the Scandinavian – Greenland branch of the Caledonides took place in the Silu-

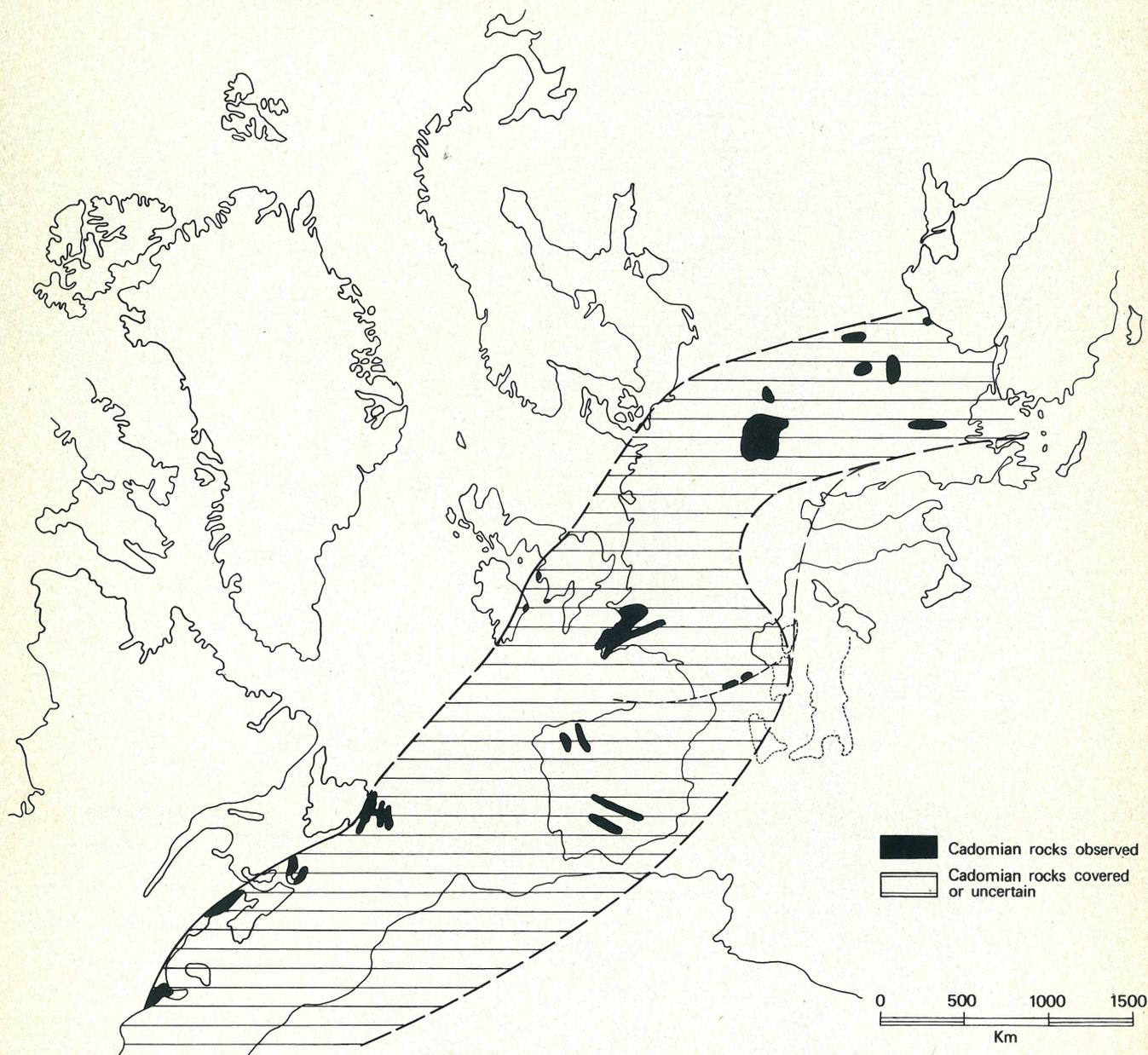


Fig. 14
Transatlantic correlation of the Cadomian orogeny.

rian. This event is probably not connected with the late Silurian folding in England, Wales and S Ireland and is not found in North America (Fig. 15).

The Acadian event in Devonian time is not only known from the Appalachians, but also from the Inuitian belt in Northern Greenland and from the central parts of the Mid-European Variscides in the Iberian peninsula, France, Germany, Poland and Czechoslovakia (Fig. 16). The direct continuation of the Acadian belt from Newfoundland to Brittany is doubtful, because most European geologists prefer to connect the Armorican with the Iberian Massif in a large arc, which then cannot be linked to North America. Furthermore

the later orogenic events in the two belts are not equivalent. In the Appalachians the Alleghenian event took place in the Permian, while the Sudetic and Asturian events in Europe are of Carboniferous age. RAST & GRANT (1973) suggest certain similarities in the Variscan structure of the British Isles and New Brunswick in Canada and it is possible that the folding in the northern part of the Appalachian belt started in the Upper Carboniferous. During the Permian, Central and Western Europe was only affected by intense faulting and very weak folding. However, radiometric dates indicate a Permian metamorphism in the Western Alps. It is possible that the main Variscan folding in SE Europe and Turkey is of Permian age (Fig. 16).

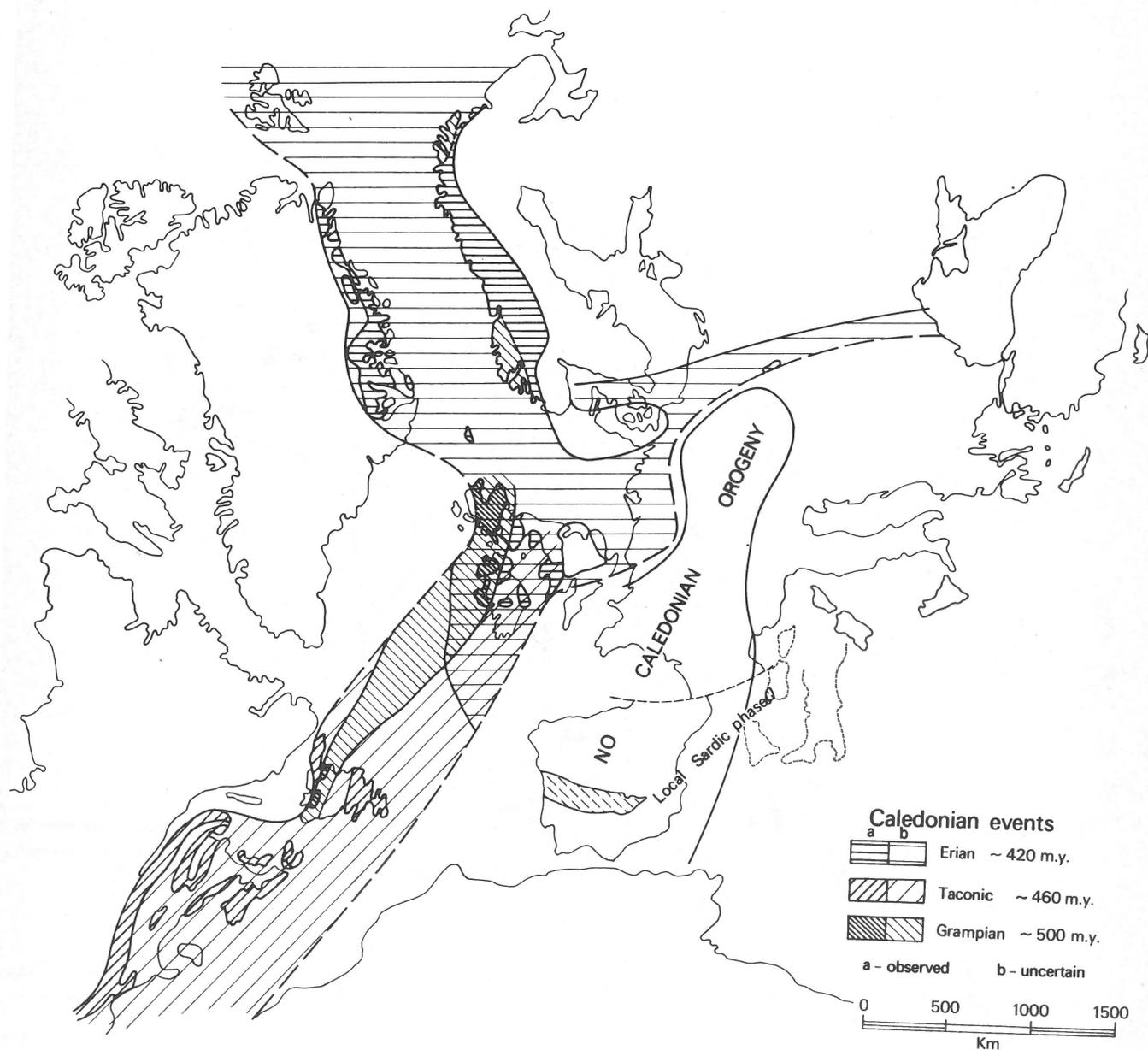


Fig. 15
Transatlantic correlation of the Caledonian orogeny.

THE TECTONIC EVOLUTION OF CENTRAL AND WESTERN EUROPE: A TENTATIVE MODEL

During the last six years several attempts to interpret the Variscan orogen in terms of plate tectonics have been made. All of these mainly try to explain the Carboniferous events, and only few take earlier occurrences into account, although none goes back beyond the Silurian. Several of these publications are rather hypothetical and based on few facts. It is therefore not surprising that several different interpretations exist. The hypotheses can be categorized in a few groups.

One group assumes the presence of a Mid-European ocean somewhere between the Rhenohercynian and Saxothuringian zones (BURRET, 1972; LAURENT, 1972; JOHNSON, 1973; DEWEY & BURKE, 1973). In this hypothesis the Variscan orogen should be due to continental collision and the closing of the Mid-European ocean in Upper Carboniferous time. The arguments for the existence of this ocean are of a palaeontological nature and rest upon different trilobite faunas in northern Europe and southern Europe-Africa. We reject this hypothesis, mainly because there is little real evidence for this ocean, or for a suture in that region. The absence of

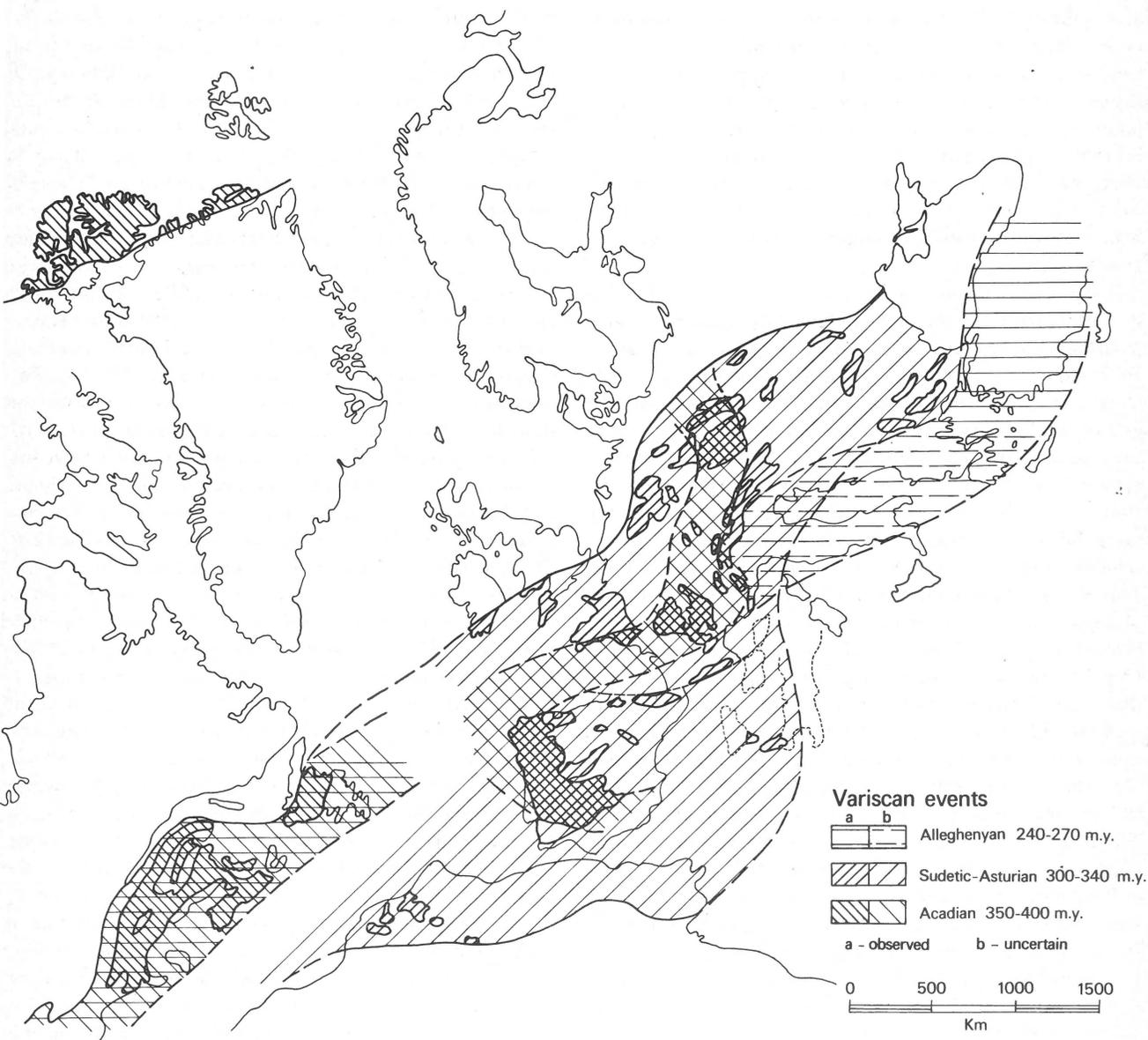


Fig. 16
Transatlantic correlation of the Variscan orogeny.

ophiolites and high-pressure metamorphism makes subduction and the closing of an ocean in this region very unlikely (the Lizard complex may be a relict of an ophiolite suite, but its age is quite uncertain). Another hypothesis, proposed by NICOLAS (1972), suggests the Variscan orogeny to be of the Andean type, the ocean being the proto-Tethys, and subduction should have taken place in southern Europe; the suture is now concealed by the Alpine chain. BARD ET AL. (1973) proposed a collision model for the Iberian massif. More complex sequences of events, also taking older events into consideration, are treated by MCKERROW & ZIEGLER (1972),

HURLEY (1974), RIDING (1974), BADHAM & HALLS (1975) and LORENZ (1976), invoking several successive stages of subduction, involving the Caledonian, Appalachian and Variscan belts, and the movement of a number of microplates. These hypotheses also consider the presence of an ocean and subduction within Europe or between Europe and Africa.

None of the above mentioned authors have taken the pre-Caledonian events into account. We feel that for any explanation of the Palaeozoic tectogenesis this earlier history has to be considered. The main difficulty in a reconstruction is that the supposed oceans have left almost no traces (see

also SCHMIDT, 1977). Furthermore there is little palaeomagnetic evidence for a pre-Mesozoic reassembly of Europe. A very wide ocean between northern Europe and southern Europe-Africa, existing during the Devonian, has been proposed by IRVING (1977), but on his reconstruction little detail is visible, and moreover he stated that the presence of such 'Hercynian' ocean is doubtful. Therefore in a reassembly one has to rely almost solely on the products of subduction, as high pressure or paired metamorphic belts, volcanism and granitic activity.

If figures 14, 15 and 16 are compared, the most striking feature is that the same region, namely the Caledonian-Appalachian-Variscan belt with the shape of a large Y (SCHMIDT, 1977; BARD ET AL., 1971) has been the scene of activity, beginning at least in late Precambrian time and lasting until the end of the Palaeozoic or even up to the present time. It is even possible that the Grenville orogeny also belongs to this system (Fig. 13) and that the tectonometamorphic processes started more than 1000 Ma ago. However, the data about the Grenvillian in Central and Western Europe are as yet not reliable enough to be certain about the Y-shape at that time. This Y-shaped configuration clearly establishes the presence of three major Precambrian blocks: the North American-Greenland shield, Fennoscandia and the S Europe-African block. Obviously the intervening mobile belts between these three large Precambrian plates form a major triple point in Central and West Europe. The movements of these plates must be responsible for the formation of the different orogenic belts, but the difficulties arise apparently from several microplates within the mobile zones which seem to have moved independently, and from the overprinting of two or more belts, resulting in an extremely complicated pattern.

If we propose the following tentative model, it is based on a number of facts and some assumptions. The main facts are the occurrence of Cadomian intermediate to high-pressure metamorphism (granulites, eclogites) and granitic magmatism, widespread Ordovician and Silurian granitic and volcanic activity, early Variscan intermediate to high-pressure metamorphism, and late Variscan low-pressure metamorphism with abundant granites. Assumptions are that the 'Caledonian' high-grade metamorphism is in fact of Cadomian age and that the crust of Central and Western Europe in the Proterozoic was of continental nature. On this crust late Proterozoic sediments and volcanics were laid down from 800-600 Ma ago in a number of basins. Some of these basins were due to rifting, incipient seafloor spreading and perhaps due to the formation of a narrow ocean with a maximum width of 200-500 km comparable to the Red Sea, in the area which is now occupied by the Moldanubian zone. This may be the first sign of a large hot spot under Central and Western Europe which seems to be responsible for the ensuing events. Although the formation of rifts and aulacogens with a thin continental crust in the Proterozoic is fairly well established, a real late Proterozoic ocean within Europe is hypothetical. Subduction and closing of such an ocean, or

of a rift with thinned crust—which seems to us more likely—started towards the end of the Precambrian, producing the Cadomian orogen. The best evidence for subduction is the high- and intermediate-pressure metamorphism in the present Moldanubian zone. Especially the granulites and eclogites were formed under high P/T conditions and may be comparable with blueschist belts in recent orogens. The relationships of the Cadomian granites to the subduction zone are not clear. A suture is no longer discernable due to later tectonic, magmatic and metamorphic events of Variscan age. It is suggested here that the compression due to the Cadomian orogeny was caused, or in any case related to, the opening of the Iapetus between Europe and North America-Greenland, where sedimentation started in the late Precambrian (DEWEY & KIDD, 1974). This proto-Atlantic was short-lived as it began to close in Late Cambrian and Ordovician time, producing the Grampian event in Newfoundland, Ireland and Scotland, the Taconic event in the Appalachians, and the Erian event in the northern Caledonides. The best evidence for the Iapetus is the occurrence of ophiolite belts. Contrasted to the Cadomian and Variscan orogenies, relatively few granites were produced in the Caledonian chain on both sides of the Atlantic, whereas there is abundant granitic plutonism in Central and Western Europe at the same time. The repercussion of these contracting movements in the Caledonian-Appalachian belt has been extension in Central and Western Europe, producing rift structures accompanied by alkaline and calcalkaline granitic activity and mafic volcanism. An example of such a rift has been described by DEN TEX & FLOOR (1967) as the so-called blastomylonitic graben in NW Spain in which Ordovician granites, in part alkaline, have intruded. This graben may continue in Brittany as the 'axe granitique de Moëlan-Lanvaux' and the 'sillon de St. Georges sur Loire' (COGNÉ, 1977), which are accompanied by mafic and ultramafic rocks, and alkaline intrusions. Another example is perhaps the basin in NW Spain filled with about 10,000 m Cambro-Ordovician. Also the Saxothuringian and Barrandian may be due to incipient rifting. The abundantly occurring Ordovician and Silurian granites (Fig. 3) are in our opinion due to partial melting in the mantle and contamination with crustal material under a high heatflow regime, followed by intrusion in a tensional stress field. In this way the 'Caledonian' thermal event in Central and Western Europe is not due to orogeny or subduction but to mantle activity and rifting. It is difficult to get a good idea about the overall rift structure as a result of the strong Variscan overprint. It is still uncertain whether this stage of rifting led to basins with an oceanic floor, as again ophiolites are virtually absent in the Variscan belt. Also palaeomagnetic evidence for such an ocean is not conclusive (IRVING, 1977). If such ocean did exist, it was not of Devonian-Carboniferous, but of Ordovician-Silurian age, and not lying at the site of the Mid-European ocean of Burrett, Laurent, Johnson and others, but on the southern side of the Moldanubian zone, along the southern border of the Armorican massif and in the Massif Central. Its

eastern continuation is uncertain. If this region was not underlain by oceanic crust, it must have been a zone of considerable crustal thinning, which made it possible to develop a subduction zone with a northerly dipping Benioff plane (COGNÉ, 1977; BURG & MATTE, 1978).

Evidence for it is the high to intermediate P/T belt (Ile de Groix, Vendée, some localities in the Bohemian massif with glaucophane schists; early Variscan kyanite metamorphism see Fig. 9), with granitic and volcanic activity mainly to the north of it. Also large nappe structures described from the Armorican massif by Cogné, and from the Massif Central by BURG & MATTE (1978) with a southward vergence, fits well with such hypothesis. This subduction is an early Variscan event and took place in the Devonian. During this time troughs were formed in SW England, the Rhenic slate belt, the Harz, the south of the Bohemian massif and in S Portugal, filled with thick Devonian sediments with or without volcanics, and indicating extension in these regions (ZIEGLER, this issue). By the end of the Devonian the ocean or rift was closed, although compression continued, or was renewed during Upper Carboniferous times, giving rise to the main fold belt with its low-pressure metamorphism and abundant granites. Although some of these granites may have been generated in the subducting plate, most granites are due to melting of crustal material in a large region with high heatflow. We suggest this because the supposed subduction zone shows no spatial relationship to the distribution of the granites. They occur on both sides of it. The situation can perhaps be compared to the Alps. During the Upper Cretaceous the Piemonte oceanic basin, which must have been quite narrow, closed and subducted oceanic and sialic material, producing a high-pressure belt. Subduction apparently ceased at the beginning of the Tertiary, but a new important tectonic phase took place in the Oligocene accompanied by intermediate P/T metamorphism (the Lepontine phase), which, however, cannot directly be connected with subduction of oceanic crust.

Although at the end of the Palaeozoic the large-scale thermal activity decreased considerably, the crust and upper mantle in Europe had not come to rest, as in the Mesozoic again small oceans were created. One is the Piemonte trough in the Alps formed in Jurassic-Early Cretaceous times, and another the Bay of Biscay which opened in the Late Cretaceous. The opening of the latter was compensated by the closing of the Piemonte trough with a subduction zone, now characterized by ophiolites and high-pressure metamorphism in the Alps, and possibly a subduction zone in the northern Pyrenees (BOILLOT & CAPDEVILA, 1977). Again we are dealing with short-lived oceans of minor size, as seems to have been the case with the hypothetical Cadomian and Hercynian oceans. There is, however, one major difference with the Variscan cycle. As the high heatflow regime had stopped there is no longer granitic activity in the Alps, except for a few small bodies like the Bergell granite, and no more low-pressure metamorphism, but to the contrary, a well preserv-

ed high-pressure/low-temperature belt.

In a previous publication, one of us (ZWART, 1967) has drawn the attention to the contrast between the Alpine and Variscan chains of Europe in which especially the differences in type of metamorphism, and the occurrence of granites and ophiolites were emphasized. As it stands now, it seems that both orogens are due to collision and the closing of minor oceans or rifts, but the Variscan took place in a high heatflow environment, and the Alps under a low heatflow regime. There are, after all, also similarities. The Alpine orogeny lasted about 100 Ma from the first subduction phase in the Cretaceous, to strong compression in the Oligocene and Miocene, to recent, still continuing uplift. The earliest metamorphism is of the high P/T type, the later Lepontine metamorphism of intermediate P/T type. It clearly reflects decrease of pressure and increase of temperature during the whole orogenic period. The Variscan orogeny also took about 100 Ma, from 370–270 Ma ago, starting with collision and subduction with intermediate and some high P/T metamorphism, and ending with a compressive phase under low P/T conditions and the formation of much granite. Also here a decrease in pressure and an increase in temperature in the course of the orogeny took place. The main difference then amounts to processes in a high and in a low heatflow regime.

As has been said already, this high heatflow lasted about 300 Ma. Its cause must lie in a major mantle plume under Central and Western Europe on the triple junction of the Palaeozoic mobile belts (BURKE & DEWEY, 1973).

DEWEY & BURKE (1973) ascribe the great amount of granites in the Variscan belt to thickening of the crust as a result of continental collision. There is, however, no evidence that the crust during the Carboniferous was considerably thicker than it is now. The level of erosion in the major part of the Variscan belt is not deep, and can be estimated between a few up to perhaps 15 km. This is, among others, witnessed by the ubiquitous occurrence of low-pressure metamorphics which were formed at depths from 5 to 15 km. This stands in contrast to the Alps where the Moho lies at a maximum depth of 50–60 km. Nevertheless, the heatflow in the Alps is not very high and it did not result in granite formation of any significance. Moreover, in the Variscan chain the granite activity started much earlier, before collision had taken place. Therefore we think that many particularities of the Variscan chain are due to an underlying abnormally hot mantle.

KREBS & WACHENDORF (1973, 1974) have explained the Variscan orogeny as being due to large-scale introduction of heat from below, causing melting of the crust and the diapiric rise of granite plutons, which in their turn are supposed to be responsible for the folding. We agree with the first part of their interpretation, but we do not believe that the tectonics of the Variscan chain can be explained without any horizontal movement of larger blocks or plates.

In conclusion, we can state that in our opinion the tectogenesis of Central and Western Europe has to be explained by a more or less continuous movement of three major plates,

involving the opening of small, and occasionally large, oceans or rifts due to spreading, and to simultaneous closing of other basins with oceanic floor or rifts, giving rise to compression and folding. This process went on at different places at different times in the large Y-shaped mobile belts between the large plates. The mechanism of closing and collision may be the now classical theory of subduction with the large-scale consumption of the floor of a major ocean, like the Iapetus and producing the Caledonian-Appalachian belt, or on a small scale with the consumption of only minor oceans or rifts with a thin continental crust, as in the Variscan and possibly the Cadomian. This process is driven by heat, originating from a major mantle plume under the triple junction in Central and Western Europe. Before this mantle plume started to be active, the three plates may have formed one continent during part of the Proterozoic, and split apart towards the end of the Precambrian by the rising mantle plume. It ceased to be active at the end of the Palaeozoic, or it shifted position and is now lying under the Mid-Atlantic ridge or partly in the Mediterranean, and in that case is also responsible for the Alpine orogeny.

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