

## CALEDONIAN AND HERCYNIAN CRUSTAL CONSOLIDATION OF WESTERN AND CENTRAL EUROPE – A WORKING HYPOTHESIS<sup>1</sup>

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### ABSTRACT

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The crystalline basement of Western and Central Europe consists of a mosaic of crustal elements which were consolidated during pre-Grenvillian, the Grenvillian-Dalslandian, Morarian, Cadomian, Caledonian and Hercynian orogenic cycles. Contemporaneous with the Caledonian suturing of the Precambrian Laurentian-Greenland and Fennosarmatian shields a number of Gondwana-derived Cadomian micro-cratons were accreted to the southern margin of Laurasia. Following the Late Caledonian paroxysm, the Devonian and Early Carboniferous evolution of Europe was dominated by continued subduction of the Proto-Tethys plate at an arc-trench system parallelling the southern margin of Laurasia, the accretion of additional Gondwana-derived continental fragments, back-arc rifting, and a sinistral translation of major proportions between the Laurentian-Greenland and the Fennosarmatian sub-plates.

The Acadian and Bretonian orogenies were of the Pacific type. The Visean collision of Gondwana with Laurasia marked the onset of the Himalayan-type Variscan orogeny during which collision-related compressive stresses overpowered the Devonian-Early Carboniferous back-arc rift systems and caused the development of A-subduction zones. The Central Armorican-Saxothuringian successor basin became folded and destroyed during the latest Visean, whilst the Variscan foredeep became scooped out, in part by basement nappes, during the latest Westphalian.

Major crustal shortening during the Variscan diastrophism was accompanied by the anatectic remobilisation of subducted lithosphere and a widespread syn- and late orogenic magmatism.

The latest Carboniferous-Early Permian reorientation of the convergence direction between Gondwana and Laurasia induced the development of a complex wrench-fault system transecting the Variscan fold belt, and extensive post-orogenic volcanism.

The hypotheses summarised here require confirmation by further palaeomagnetic and radiometric data.

### INTRODUCTION

The crystalline basement of Western and Central Europe consists of a mosaic of crustal elements which were consolidated step-wise during pre-Grenvillian, the Grenvillian-Dalslandian, Morarian, Cadomian, Caledonian and Hercynian<sup>3</sup> orogenic cycles. In the process of this long and complex crustal evolution, earlier consolidated crustal elements became repeatedly remobilised during subsequent paroxysms. This accounts for the wide range of the radiometric age

determinations obtained from the various basement provinces which make up the crust of Western and Central Europe. These basement provinces are essentially defined by the youngest orogenic event that affected the corresponding crustal segment profoundly enough to give rise to widespread metamorphism, which may or may not have been accompanied by the intrusion of calcalkaline plutons.

In order to unravel the complexity of the crust of Western and Central Europe, its evolution has to be retraced in a plate-tectonic context. It is the objective of this paper to

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<sup>3</sup>The terms 'Hercynian' or 'Hercynides' are used here as referring to the Late Palaeozoic fold belts of Eastern North America, Northwest Africa, and Europe. The term 'Variscan' is used to refer to the Western and Central European segments of the Hercynian fold belt and specifically to the Late Visean to Westphalian diastrophism that resulted in their consolidation.

review, on an interdisciplinary basis, the Caledonian and Hercynian crustal evolution of Western and Central Europe.

### PRECAMBRIAN CRATONS

The forelands of the Caledonides of Western and Central Europe comprise, the Fennoscandian Shield and its extension beneath the Baltic Depression and Moscow Platform on the one hand and, on the other, the Laurentian-Greenland Shield, of which the Rockall-Faeroe plateau and the Hebridean craton form a part.

The age of crustal consolidation of these Precambrian cratons is summarised in Encl. 1, on which are given the range of radiometric age determinations for the major basement provinces. For a detailed discussion of the evolution for the Fennoscandian-Baltic craton the reader is referred to MAGNUSON (1965), POZARYSKI (1977), BERTHELSEN (1981) BOWES & GAAL (1981), GAAL (1982) and LINDH (1982). The Precambrian basement provinces distinguished in the northwestern British Isles are based on the works of VAN BREEMEN ET AL. (1978), BOWES (1978), HARRIS ET AL. (1975, 1981), PHILLIPS (1981), PIASECKI ET AL. (1981) and PIASECKI & VAN BREEMEN (1983).

On Encl. 1, principally three groups of basement provinces are distinguished in the Caledonian forelands, namely the areas of pre-Grenvillian (> 1100 Ma), Grenvillian-Dalslandian (850-1100 Ma) and Morarian or Knoydartian (690-780 Ma) crustal consolidation. Each of these provinces has undergone a long and complex evolution. This is evident from the wide range of the isochron ages that have been obtained from the intrusive and metamorphic rocks which make up these basement provinces.

The bulk of the Fennoscandian-Baltic craton was consolidated in pre-Grenvillian time, with isochron ages of metamorphic and intrusive rocks ranging between 2000 and 1280 Ma (Karelian-Gothian). Similarly the Hebridean craton yields radiometric ages of 2900 in 1300 Ma and it is speculated that the continental crust underlying the Faeroes and at least the northern parts of the Rockall-Hatton Bank was also consolidated during the Lewisian-Scourian-Laxfordian orogenic cycles (ROBERTS, 1975).

On the other hand, the crust of southern Sweden and Norway, which became consolidated during the Dalslandian-Grenvillian orogenic cycle, yields isochron ages ranging between 1800 Ma and 860 Ma (ANDERSEN & HEIER, 1975; BERTHELSEN, 1981; PRIEM & VERSCHURE, 1982). In northern Ireland and Scotland, evidence for the existence of a Grenvillian-Dalslandian and a Morarian basement complex comes

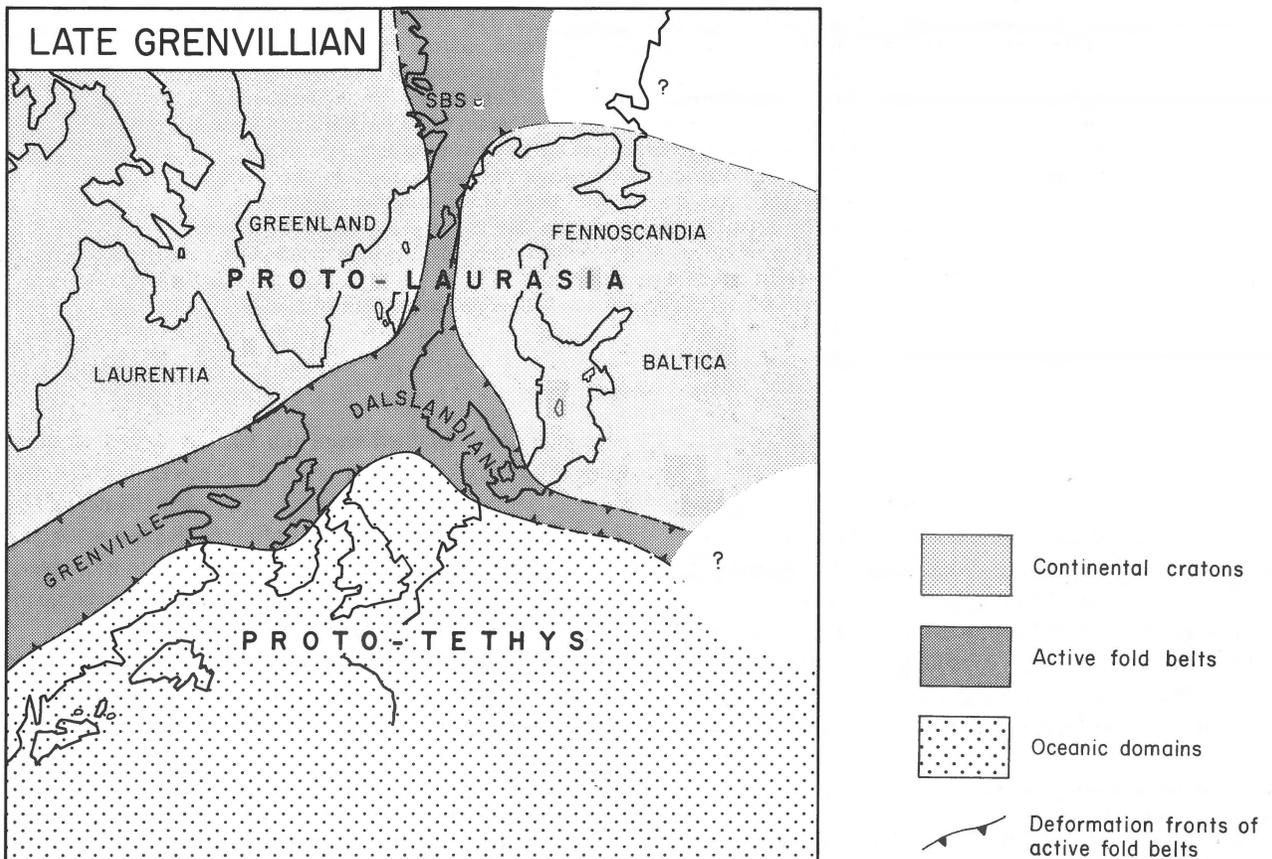


Fig. 1  
Tentative Grenvillian tectonic framework of the Arctic-North Atlantic domain. Continental fit does not take into account a palinspastic restoration of the Arctic-North Atlantic Caledonides. SBS-Scoresby Sound Area.

from areas that were overprinted by the Caledonian orogeny (VAN BREEMEN ET AL. 1978, PIASECKI ET AL., 1981, 1983). The existence of a Moravian basement province underlying large parts of Denmark is inferred from the few age determinations that are available from basement rocks encountered in boreholes drilled in southern Jutland (LARSEN, 1971).

Grenvillian age metamorphics have been reported from the basement involving nappes of the Norwegian Caledonides, the Lofoten-Vesteralen area and the Eastern Greenland Scoresby Sound Area (ZWART & DORNSIEPEN, 1978; HANSEN ET AL. 1974; HENDRIKSEN & HIGGINS, 1976). This indicates that a branch of the Grenvillian-Dalslandian folbelt extended northward through the Norwegian-Greenland Sea area.

It is still uncertain whether the area of the Barents Sea is underlain by a Grenvillian-age foldbelt that was subsequently overprinted by the Early Cambrian Timanides orogenic cycle. The latter can be considered as forming part of the global Cadomian-Baikalian-Pan Africa orogenic system, for which there is, however, little evidence in the immediate foreland of the Caledonides of Western and Central Europe.

Palaeomagnetic data indicate that, following the Grenvillian-Dalslandian orogenic cycle, Laurentia-Greenland and Fennoscandia-Baltica formed part of the same mega-continent, whereby a palinspastic assembly of the two blocks as shown in Fig. 1 is suggested (PATCHETT & BYLUND, 1977). From such a continental fit, it is concluded that the Grenvillian fold belt *sensu lato*, which extended through the Norwegian-Greenland Sea and which formed the suture between Laurentia-Greenland and Fennoscandia-Baltica, joined the Grenvillian and Dalslandian fold belts *sensu stricto* of eastern Canada and southwestern Scandinavia respectively. These now widely separated fold belts apparently formed part of a single fold belt which probably marked the southern margin of Proto-Laurasia. Traces of this fold belt occur within the Caledonides of Ireland and Scotland. There is, as yet, little evidence supporting a possible extension of the Dalslandian orogenic system into Poland as suggested in Fig. 1. Moreover, on the basis of the available data, it is difficult to map the extent of the areas that were affected by the Moravian diastrophism, and to assess the plate movements that were associated with it.

#### CALEDONIAN FOLD BELTS AND ALLOCHTHONOUS TERRAINS

The Caledonian orogenic cycle spans Late Cambrian to earliest Devonian time, and embraces the Late Cambrian to Early Ordovician Grampian/Finnmarkian, the Mid-to-Late Ordovician Taconic and the Mid-Silurian to Early Gedinian Main Scandinavian or Late Caledonian orogenies. The distribution of the Caledonian fold belts in Western and Central Europe, as summarised in Fig. 2 and Encl. 1, has recently been reviewed by ZIEGLER (1982). For a more detailed account, particularly of the outcropping parts of

these Caledonides, the reader is referred to GEE & STURT (in press).

The principal elements of the Caledonian orogenic system of Western and Central Europe are the Irish-Scottish-Norwegian Caledonides, which find their northern prolongation in those of Eastern Greenland and Svalbard, and the North German-Polish and the Mid-European Caledonides, and the Ligerian-Arverno-Vosgian Cordillera, which extends eastward into the Moldanubian Massif. These fold belts enclose the stable blocks of the Irish Sea Horst, the London Platform, the Armorican, Saxothuringian and East Sudetic basins and the East Silesian Massif. Most of these blocks were little affected by the Caledonian diastrophism; all are characterised by a continental crust that was consolidated to a varying degree during the Cadomian (Baikalian, Pan African) orogenic cycle, which spanned the time interval of 650 to 550 Ma. In the following, a summary is given of the radiometric age determinations obtained from intrusive and metamorphic rocks making up the crust of these stable blocks.

The relatively narrow Irish Sea Horst, which yields radiometric ages ranging between 2400 and 550 Ma (COGNÉ & WRIGHT, 1980; PHILLIPS, 1981; PIASECKI ET AL., 1981) is enclosed by the Caledonian Leinster-Lake District and the Welsh Basin fold belts, but was itself intruded by Caledonian granites (STILLMAN, 1981).

The London Platform, with its little deformed Early Palaeozoic sedimentary cover, is encircled by the Mid-European Caledonides, the Caledonides of Ireland and Scotland, and the Caledonian fold belt of the Central and Southern North Sea. Isochrons obtained from basement rocks forming the London Platform range from 530 Ma to 700 Ma. Moreover, there are indications that crustal elements as old as 800 to 1200 Ma had become remobilised during the 530-700 Ma orogenic events. Also, the London Platform was itself intruded by Caledonian granitoids (PATCHETT ET AL., 1981; PIASECKI ET AL., 1981; HAMPTON & TAYLOR, 1983).

The Mid-Palaeozoic Armorican Basin was framed to the north by the Mid-European Caledonides, and to the south by the Ligerian-Arverno-Vosgian Cordillera. This basin is characterised by a nearly continuous sequence of epicontinental Ordovician, Silurian and Devonian sediments, which overlay a basement complex that was consolidated during the Cadomian paroxysm. The metamorphic and intrusive rocks that form this Armorican craton yield radiometric ages ranging between 2600 Ma and 550 Ma. The complex crustal evolution of the Armorican craton has been reviewed by COGNÉ & WRIGHT (1980) (see also LAMEYRE & AUTRAN, 1980 and KORNPROBST, 1980). It is possible that the Armorican craton extends eastward into the northern parts of the Vosges and the Black Forest, from where metamorphics and intrusives have been reported that range in age from 630 to 520 Ma (FLUCK ET AL., 1980). A possible southeastward extension of the Armorican Craton into the northernmost parts of the Massif Central may be indicated by the occurrence of 560 Ma old intrusives in the latter (LAMEYRE & AUTRAN, 1980).

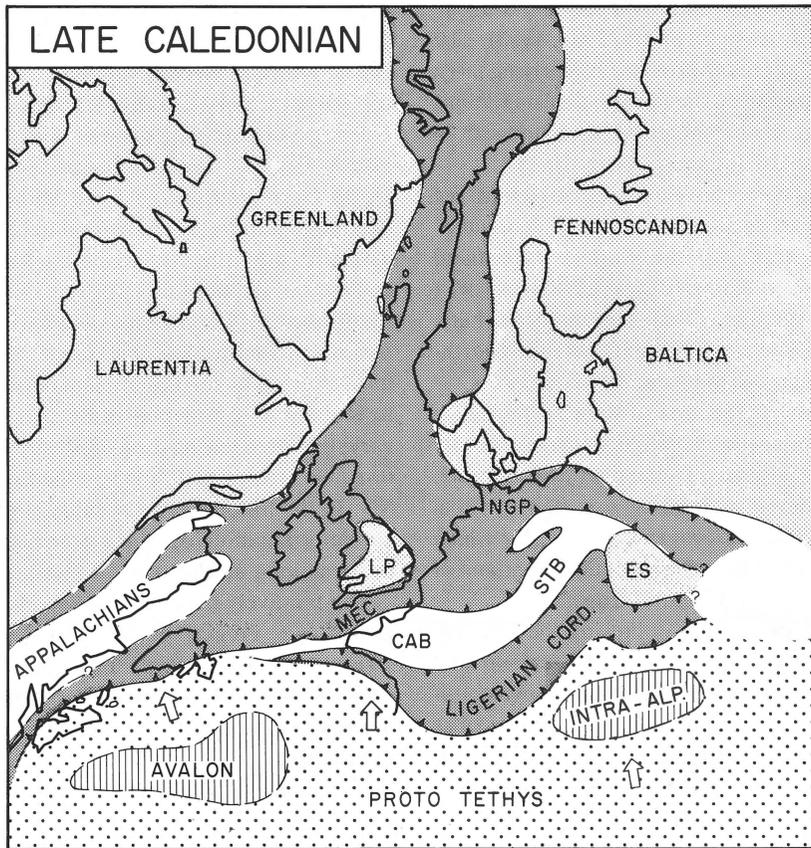


Fig. 2  
Tentative Late Caledonian tectonic framework of the Arctic North Atlantic domain showing a - (this page) basins of continuous Silurian-Early Devonian marine sedimentation; b - (facing page) intra-Caledonian allochthonous terrains.

CAB-Central Armorian Basin, ES-East Silesian Massif, LP-London Platform, MEC-Mid European Caledonides, NGP-North German-Polish Caledonides, SBS-Scoresby Sound Area; STB-Saxothuringian Basin.

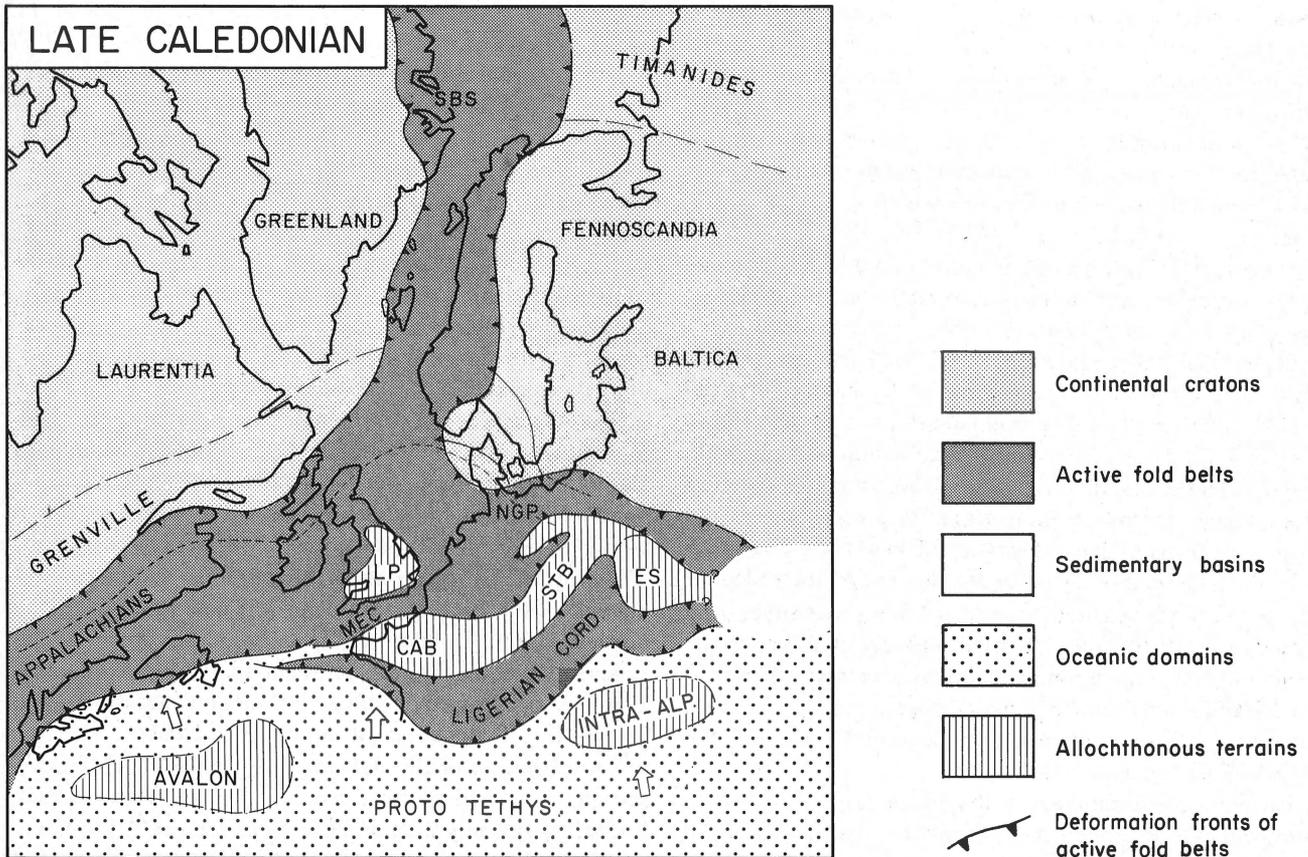
The Early Devonian Saxothuringian-Barrandian Basin was limited to the north by the Mid-German High and to the south by the Moldanubian Massif. Like the Central Armorian Basin, the Saxothuringian-Barrandian Basin is also characterised by a nearly continuous sequence of Ordovician, Silurian and Devonian marine sediments, which were deposited on a Cadomian basement complex here referred to as the Bohemian Craton. Radiometric age determinations carried out on its intrusive and metamorphic rocks indicate an age range of 550 Ma to 950 Ma (CHALOUPSKY, 1975; 1978). It is uncertain whether the Sudetic Basin and the unnamed basin located to the north of the Mid-German High, both of which are characterised by continuous Silurian-Devonian marine sedimentation, are also underlain by Cadomian continental crust. The interpretation for these areas, as given on Encl. 1, is therefore purely hypothetical.

Another Cadomian continental element is the East Silesian Massif, which is partly overlain by Lower Palaeozoic sediments that were not affected by the Caledonian folding phases. Radiometric age determinations on basement rocks from borehole cores yielded ages ranging from 526 to 1410 Ma (DUDEK & MELKOVA, 1975; DUDEK, 1980; POZARYSKI & KOTANSKI, 1978).

The East Silesian Massif is separated by the Caledonian Cracow fold belt (BUCKOWY & JURA, 1982) from the eastward adjacent Malopolska Massif, for which radiometric age determinations indicate an initial age of crustal consolidation of 625 to 706 Ma (POZARYSKI & KOTANSKI, 1978). The Malopolska Massif and the area of the Cracow fold belt became strongly deformed during the Grampian paroxysm but were only mildly affected by the Late Caledonian diastrophism (POZARYSKI, 1983 pers. comm.).

Whether further Cadomian or older micro-cratonic elements are enclosed in the broad belt of the North German-Polish Caledonides, or occur in the Southern and Central North Sea, is unknown due to the lack of sufficient borehole control. The wells Per-1 and B/4-1 in the Central North Sea indicate, however, that older basement complexes were severely overprinted by the Caledonian diastrophism in that area as well (ZIEGLER, 1982).

From the above, it is concluded that the consolidation of the cratonic elements enclosed in the Caledonian fold belts of Western and Central Europe, was highly complex and involved the repeated remobilisation of earlier consolidated crustal elements.



There are at present insufficient geophysical data to permit a palinspastic restoration of the Variscan fold belt. For want of such a restoration, it is difficult to understand the spatial relationship between the various cratonic blocks that are now enclosed in those parts of the Caledonian fold belts of Western and Central Europe that were later overprinted by the Variscan and, even more so, by the Alpine orogeny. For instance, it is generally accepted that the Armorican and the Bohemian cratons form part of one structural unit (ELLENBERGER & TAMAIN, 1980). This, however, requires confirmation by palaeomagnetic data.

For a long time it was uncertain whether the cratonic blocks which are enclosed in the Caledonian fold belts are fragments of the Fennoscandian-Baltic shield or are truly allochthonous terrains. During recent years, however, faunal analyses (BABIN ET AL., 1980; SPJELDNAES, 1981; COCKS & FORTEY, 1982) and palaeomagnetic data (VAN DER VOO ET AL., 1980; PERROUD & BONHOMMET, 1981; KRS, 1982; SEGUIN, 1983) have become available, and clearly indicate that at least the London Platform and the Armorican and the Bohemian cratons were derived from the northern margin of Gondwana and were incorporated during the Ordovician and Silurian into the Caledonian orogenic system of Western and Central Europe. The same probably applies for the Irish Sea Horst. For the East Silesian and Malopolska massifs, however, the available data sets are incomplete and do not permit an unequivocal determination of the origin of these continental fragments.

Based on faunal analyses alone, a derivation of the Dalslandian (?)-Grampian consolidated Malopolska Massif from Baltica is favoured (BROCHWICZ-LEWINSKY, 1983 pers. comm.; see also MILANOVSKA, in press). Similarly, Early Cambrian faunas obtained from the sedimentary cover of the East Silesian Massif display a clear Baltic affinity (ORLOWSKI, 1975).

This may be taken as an indication that the Malopolska and the E. Silesian massifs became partly or wholly detached from Baltica by transform faulting and/or rifting during the opening phase of the Iapetus but were welded again to Baltica during the Grampian orogenic cycle. On the other hand, the Irish Sea Horst, the London Platform and the Armorican-Bohemian craton represent truly allochthonous terrains. In the course of the Lower Palaeozoic, these terrains were rifted off the northern margin of Gondwana<sup>4</sup>, were transferred across the Proto-Tethys ocean as a result of its northward subduction and, during the Caledonian orogenic cycle, were docked against and accreted to the southern margin of the re-forming Laurasian megacontinent (ZIEGLER, 1982). This entailed the closure of oceanic domains separating these micro-continents from Fennoscandia-Baltica. These oceanic areas have been referred to by COCKS & FORTEY (1982) as the Tornquist Sea.

<sup>4</sup>In the case of the Armorican Craton, the rifting phase preceding its separation from Gondwana can be dated by alkaline intrusives as Cambrian to Early Ordovician (Lameyre & Autran, 1980).

These plate motions were contemporaneous with the Cambrian break-up of Proto-Laurasia, the opening of the Iapetus Ocean, and its closure during the Ordovician-Silurian Caledonian orogenic cycle. (WILSON, 1966; PHILLIPS ET AL., 1976). In this context it has to be pointed out that the plate movements responsible for the Late Cambrian-Early Ordovician Grampian diastrophism are still poorly understood (BROCHWICZ-LEWINSKI ET AL., 1981).

The structural style of the Scandinavian and East Greenland Caledonides is characterised by major basement-involving nappes (ROBERTS & GALE, 1978; HALLER, 1971). This indicates that the evolution of the Arctic-North Atlantic Caledonides was probably accompanied by major underplating. In addition, crustal consolidation in the domain of the Iapetus suture was associated with an extensive high-grade metamorphism and the widespread intrusion of syn- and late-orogenic plutons (GEE & STURT, in press). Due to the limited outcrop and subsurface control on the Mid-European and North German-Polish Caledonides and on the Caledonides of the North Sea area, little can be said about either their structural style or the intensity and distribution of the metamorphism that accompanied their development. Yet, it can be concluded from the post-Caledonian evolution of these areas that their crust became firmly consolidated during the Caledonian orogenic cycle.

Palaeomagnetic data suggest that by the Early Devonian, a continent assembly was achieved similar to that given in Fig. 2 (VAN DER VOO, 1983; VAN DER VOO ET AL., 1980; HARLAND, 1980). A comparison of this continental fit with the one proposed by PATCHET & BYLUND (1977) for the Late Grenvillian episode (Fig. 1) indicates that the Cambrian break-up of Proto-Laurasia and the Late Ordovician-Silurian closure of the Iapetus Ocean were associated with only minor net lateral translations between Laurentia-Greenland and Fennoscandia-Baltica.

#### ACADO-LIGERIAN AND BRETONIAN OROGENIC CYCLES

Following the Late Caledonian diastrophism, the megatectonic setting of Western and Central Europe underwent a fundamental change. Regional compression ceased essentially at the transition from the Silurian to the Devonian and gave way to regional extension. This is interpreted as relating to an Early Devonian plate reorganisation in the North Atlantic domain (ZIEGLER, 1982).

Whilst the Iapetus subduction zone became inactive during the earliest Devonian, the north-plunging Proto-Tethys subduction zone, which presumably paralleled the southern margin of the Ligerian-Moldanubian Cordillera, assumed a dominant rôle. At the same time convergence rates between the oceanic Proto-Tethys and the continental Laurasian plates apparently decreased. This gave rise to the development of an

extensive back-arc rift system, which affected much of Western and Central Europe (Fig. 3).

The main elements of this back-arc rift system are the Cornwall-Rhenish-East Sudetic Basin and the Central Armorican-Saxothuringian-Barrandian successor basins. Together, these basins form an important part of the geosynclinal system out of which the Variscan fold belt developed during the Late Carboniferous. The Devonian and Carboniferous evolution of this back-arc rift system was accompanied by an intra-continental alkaline, mafic-felsic, bimodal volcanism (ZIEGLER, 1982). Only locally may crustal extension have proceeded to crustal separation and the temporary opening of limited oceanic basins (e.g. Cornwall, BADHAM, 1982).

Back-arc rifting in the domain of the future Variscan foldbelt was apparently paralleled by a Middle Devonian to Early Carboniferous major translation between the Laurentian-Greenland and the Fennosarmatian subplates (VAN DER VOO, 1983; VAN DER VOO & SCOTSE, 1981; KENT, 1982).

During the Devonian and Carboniferous, continued subduction of the Proto-Tethys plate was accompanied by the northward rafting of further Gondwana-derived continental fragments such as the Avalon-Meguma, and the Aquitaine-Iberian blocks together with the ill-defined Austro-Alpine and the largely hypothetical Intra-Alpine blocks.

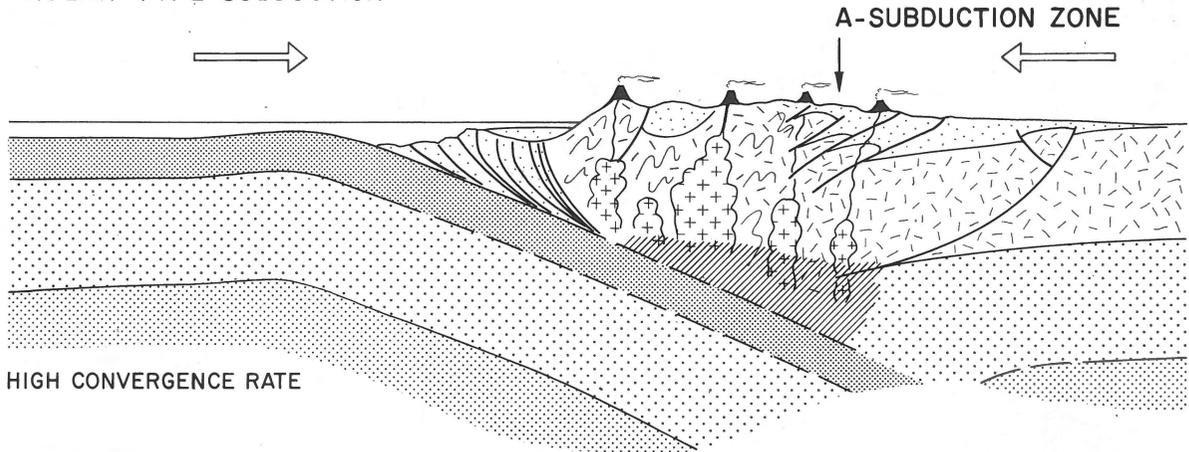
The definition of the individual suspected allochthonous terrains contained in the European part of the Hercynian foldbelt is severely hampered by their intense deformation during the Variscan and Alpine diastrophisms, by limited exposures of the Variscan basement complex and by incomplete data sets. It is likely that their number is actually greater, and their configuration and lateral relationship is more complex than suggested by the conceptual tectonic diagrams given in Figs 2, 4 and 5 (see also VAI, 1980a).

During the Middle Devonian the Avalon-Meguma microcontinent(s) collided with the Proto-Tethys subduction arc-trench system (Fig. 4). This, in combination with a possible temporary increase of the convergence rates between the Proto-Tethys and Laurasian plates, gave rise to the relatively short-lived Acadian-Ligerian orogeny. Whether in Europe the Acado-Ligerian diastrophism was also accompanied by the accretion of allochthonous terrains, such as the postulated Intra-Alpine block(s) is uncertain. (POOLE, 1977; SCHENK, 1978, 1981; AUTRAN & COGNÉ, 1980; BRADLEY, 1983; ZIEGLER, in press).

In the Canadian Maritime Provinces, the Acadian diastrophism was associated with intense deformation and an extensive Middle to Late Devonian plutonism and metamorphism (WILLIAMS & HATCHER, 1982). In the South Armorican Massif and the Massif Central, the Ligerian orogeny gave rise to high-pressure metamorphism and major plutonic activity that persisted into the Late Devonian. Moreover, the development of major south-verging nappes is reported from the southern parts of the Massif Central (BERNARD-GRIFFITHS ET AL., 1977; AUTRAN & COGNÉ, 1980; see also AUTRAN &

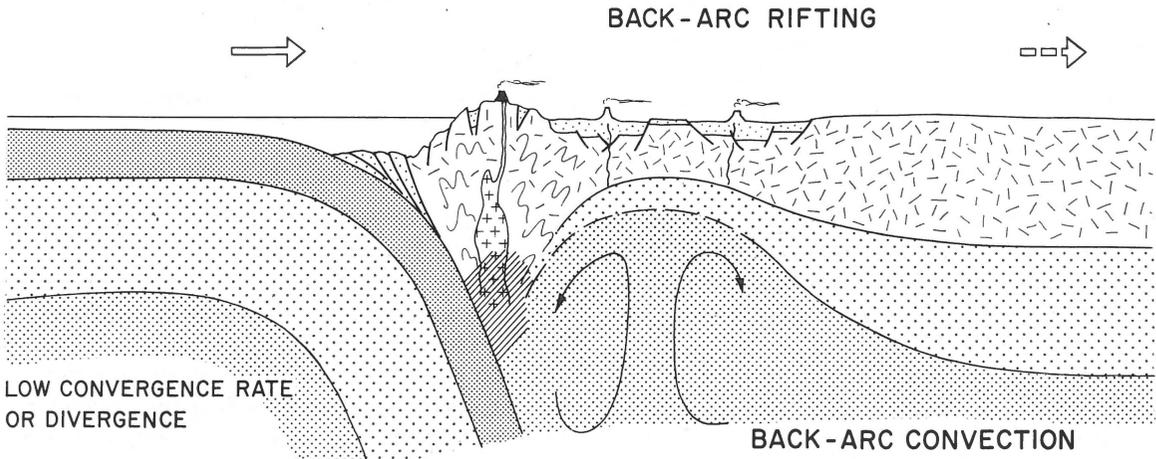
# BACK - ARC COMPRESSION

## ANDEAN-TYPE SUBDUCTION



# BACK - ARC EXTENSION

## MARIANA-TYPE SUBDUCTION



## SUBDUCTION MODELS

(not to scale)

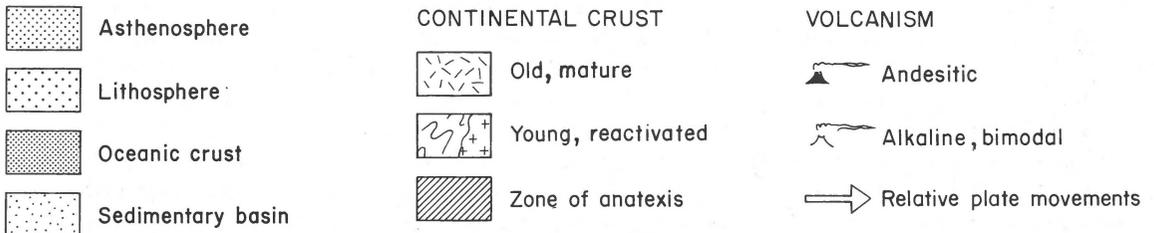


fig. 3  
 subduction models, modified after Uyeda, 1982 and Bally & Snelson 1980 (not to scale).

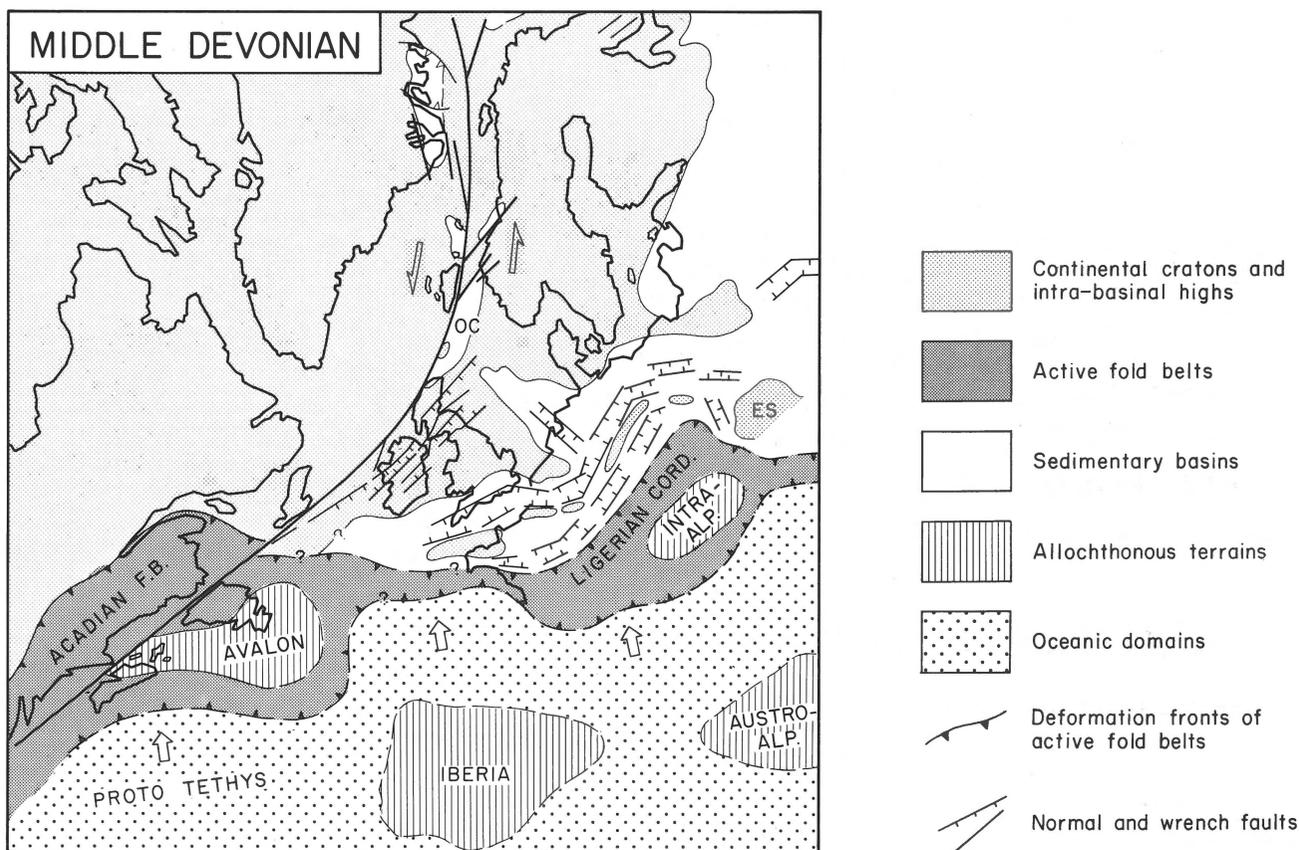


Fig. 4 Tentative Middle Devonian tectonic framework of the Arctic-North Atlantic domain. OC - Orcadian Basin, ES - East Silesian Massif.

DERCOURT, 1980). Although there is stratigraphic evidence that the Moldanubian Cordillera was also effected by the Ligerian diastrophism, there is only limited radiometric evidence for a Middle Devonian granitoid plutonism (BERNARD & KLOMINSKY, 1975).

The Ligerian-Moldanubian Cordillera is thought to mark the suture between the largely hypothetical Intra-Alpine micro-continent(s) and the Central European metastable craton (AUTRAN, 1978; AUTRAN & COGNÉ, 1980). Areas affected by the Acado-Ligerian diastrophism possibly extend from the Massif Central, the West Alpine External Massifs and the Vosges and the Bohemian Massif (AUTRAN & COGNÉ, 1980; LAMEYRE & AUTRAN, 1980; KORNPROBST, 1980) into the area that is now occupied by the autochthonous basement of the Alps and the basement of the Penninic and Lower and Middle Austro-Alpine nappes. The latter contain Siluro-Ordovician, Early and Middle Devonian sedimentary sequences and have yielded limited evidence for a Middle to Late Devonian plutonism (SCHÖNLAUB, 1979). Radiometric age determinations indicate, moreover, that the Variscan basement complex of the Central Alps contains Cadomian and older continental crustal elements that were apparently affected by a Caledonian distensional phase (GEBAUER & GRÜNENFELDER, 1982). This is essentially compatible with the hypothesis that these areas contain Gondwana derived conti-

ental fragments. However, more radiometric datings are needed to confirm this concept.

During the Acado-Ligerian diastrophism, compressive stresses temporarily overcame back-arc extension in the Central Armorican-Saxothuringian Basin, whilst the Middle Devonian evolution of the Cornwall-Rhenish-East Sudetic Basin continued to be governed by crustal extension. From this, it is concluded that during the Acado-Ligerian orogeny both the subducting Proto-Tethys and the overriding Fennoscandian plate were partly coupled at the B-subduction zone that paralleled the southern margin of the Ligerian-Moldanubian Cordillera. It is likely that in the course of the Acado-Ligerian diastrophism, new B-subduction zones developed along the southern margins of the Avalon-Meguma and the postulated Intra-Alpine blocks whilst those along their northern margins became inactive. By the end of the Acado-Ligerian paroxysm, both of these micro-cratons were presumably solidly welded to the southern margin of Laurasia.

It is uncertain whether the Aquitaine-Iberian micro-craton had already collided with the South Armorican arc-trench system during the Middle Devonian, as suggested by the available palaeomagnetic data (PERROUD & BONHOMMET, 1981) and as proposed by BRUN & BURG (1982). Middle Devonian compressional features as well as calcalkaline granitic intru-

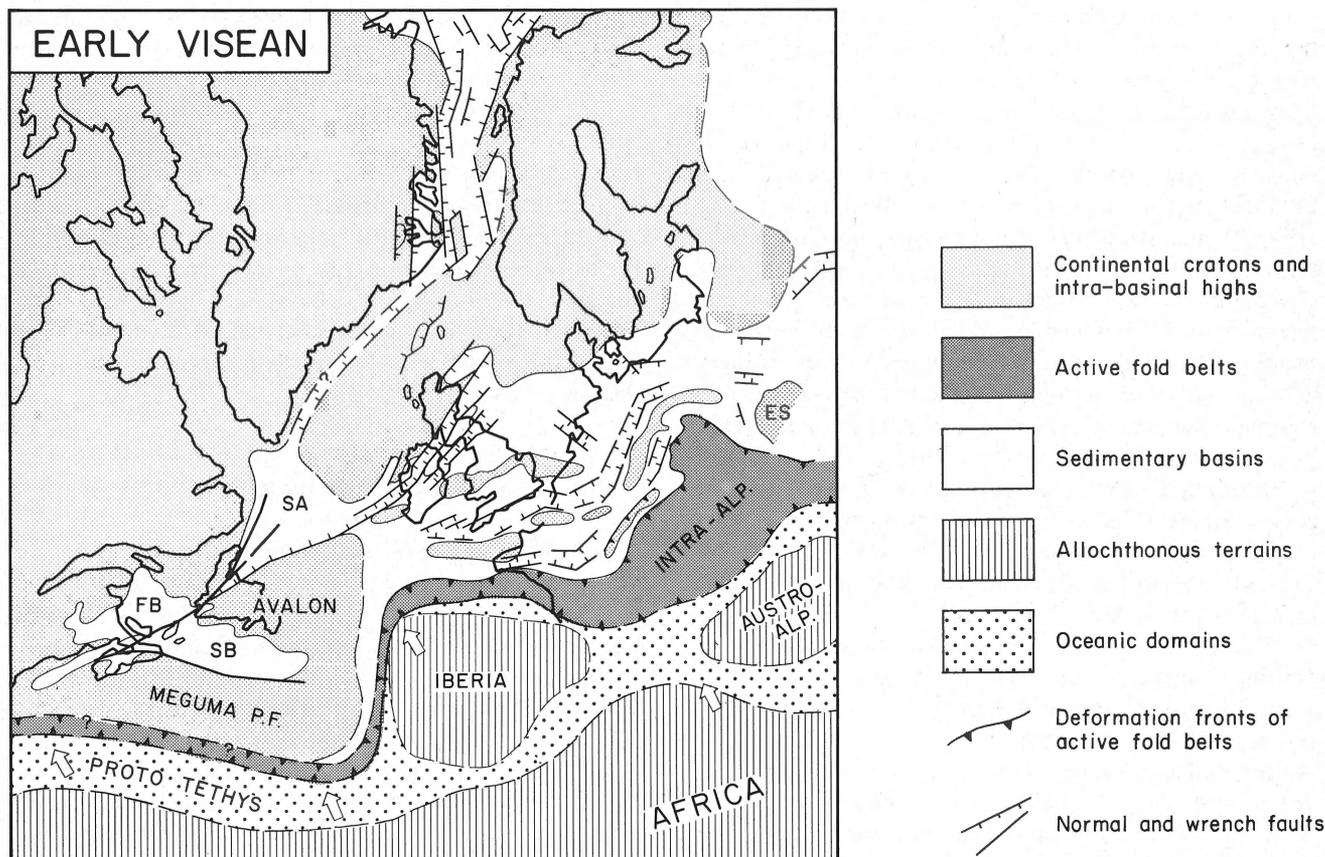


Fig. 5  
Tentative Early Visean tectonic framework of the Arctic-North Atlantic domain. FB – Fundy Basin, SA – St. Anthony Basin, SB – Sidney Basin, ES – East Silesian Massif.

sives are distinctly lacking in western Galicia as well as in the remainder of Iberia (PRIEM & DEN TEX, in press; TAMAIN, 1978). In fact, throughout the Devonian and earliest Carboniferous, much of Iberia remained in a tensional setting as is underlined by the repeated extrusion of alkaline, bimodal volcanics and the possible opening of small oceanic basins (RIBEIRO, 1980, 1981; ALVARADO, 1980; OLIVEIRA, 1982). This could be interpreted as being related either to hot-spot activity, transtensional faulting during the northward drift of the Aquitaine-Iberian microcontinent, or to back-arc extension behind an – as yet not documented – subduction zone that developed during the Middle Devonian along the southern margin of the Iberian micro-continent(s) (see RIBEIRO ET AL., 1983). This important mega-tectonic problem still requires clarification, particularly by detailed palaeomagnetic analyses.

Following the Acado-Ligerian diastrophism, back-arc extension resumed control of the subsidence of the Central Armorican-Saxothuringian Basin. This probably reflects a renewed decrease in the convergence rate (or even a gentle divergence) between the Proto-Tethys plate and the Fennosarmatian sub-plate, a commensurate steepening of the Proto-Tethys B-subduction zone, and at least a partial decoupling of the subducting and overriding plates. This

interpretation is in keeping with the postulated Middle Devonian to Early Carboniferous sinistral translation of Fennosarmatia and Laurentia-Greenland during which Fennosarmatia may actually have temporarily receded from the Proto-Tethys subduction zone. Whether back-arc extension also affected the Intra-Alpine domain has yet to be resolved.

The Bretonian orogenic pulse, straddling the Devonian-Carboniferous boundary, can be related to a second phase of increased convergence between the Fennosarmatian and Proto-Tethys plates. Renewed shallowing of the Proto-Tethys B-subduction zone and partial coupling of the subducting and the overriding plates resulted, once more, in the exertion of compressive stresses on the back-arc areas. Again, only the southern parts of the Central Armorican-Saxothuringian Basin were affected by compressive stresses, whilst back-arc extension persisted in the Cornwall-Rhenish-East Sudetic Basin. Latest Devonian-earliest Carboniferous granitoids and gneisses are documented by radiometric age determinations from the southern parts of the Armorican Massif, from the Massif Central (AUTRAN & LAMEYRE, 1980), the Moldanubian Massif (BERNARD & KLOMINSKY 1975) and also from the Intra-Alpine domain (SCHÖNLAUB, 1979; TRÜMPY, 1980; OBERLI ET AL. 1981).

On the Iberian Peninsula, evidence for a Bretonian compressive deformation phase appears to be lacking, except possibly in westernmost Galicia from where poorly dated latest Devonian-Early Carboniferous turbiditic clastics have been reported (TAMAIN, 1978; JULIVERT, 1979). Their accumulation is thought to be related to the emplacement of an ultrabasic nappe complex (BARD ET AL., 1980; FRANKENFELD, 1982). Contemporaneous granitoids are, however, lacking (PRIEM & DEN TEX, in press). The Late Devonian and Early Carboniferous megatectonic setting of the Aquitaine-Iberian micro-continent and possible additional continental fragments now forming the central and southern parts of Iberia, and the question of their potential involvement in the Bretonian orogenic cycle needs to be clarified (see JULIVERT ET AL., 1980; RIBEIRO, 1981; OLIVEIRA, 1982).

The stratigraphic record of the Gondwana-derived Austro-Alpine Block (Upper Austro-Alpine nappes) also lacks evidence for a compressive Bretonian deformation phase. The same applies for the South Alpine – Carnic – Dinaric domain which is also characterised by a nearly complete Gondwana – type Palaeozoic sedimentary sequence.<sup>5</sup> A Devonian separation between the Austro-Alpine and the Carnic-Dinaric blocks is indicated by faunal differences (SCHÖNLAUB, 1979; VAI, 1975, 1980b). This suggests that the Austro-Alpine block constitutes a separate microcontinent. Whether the Carnic-Dinaric block was still attached to the northern margin of Gondwana during the Devonian and Early Carboniferous is uncertain. Its tensional evolution, that persisted into the Westphalian is thought to be related to large scale dextral strike-slip movements preceding and accompanying the Carboniferous convergence of Gondwana and Laurasia (VAI, 1975, 1980a; VAI & SPALLETTA, 1982). Palaeomagnetic data may be able to shed further light on the Palaeozoic evolution of the Austro-Alpine and the Carnic-Dinaric blocks.

Following the Bretonian orogenic pulse back-arc extension dominated the Dinantian and Early Visean evolution of the Central Armorican-Saxothuringian and the Cornwall-Rhenish-East Sudetic basins and possibly also of the Intra-Alpine domain. This can be related to a renewed decrease in the convergence rate of the Proto-Tethys plate and the Fennoscandian sub-plate. Palaeomagnetic data indicate that by the Early Carboniferous the oceanic domains separating the Gondwana continent, the Aquitaine-Iberian micro-continent and Laurasia had been drastically reduced (PERROUD & BONHOMMET, 1981; VAN DER VOO & SCOTSESE, 1981; KENT, 1982). With this, the collision of Gondwana and Laurasia was imminent.

<sup>5</sup>Gondwana-type Palaeozoic sequences are characterised by Ordovician cold-water faunas. Caledonian compressional deformations are distinctly lacking. Sedimentation took place in a tensional setting that variably ranges from the Ordovician to the Silurian, Devonian or Early Carboniferous. The widespread Ordovician magmatism (Caledonian thermal event) is of an essentially anorogenic nature and is most likely related to a regional tensional phase that affected the northern margin of Gondwana.

From the above, it can be concluded that the intermittent Acado-Ligerian and Bretonian orogenic cycles of 'Hercynian Europe' are the result of the progressive subduction of the oceanic Proto-Tethys plate and the ensuing accretion of a number of Gondwana-derived allochthonous terrains against the southern margin of Laurasia. In view of their association with the Proto-Tethys subduction zone, both the Acado-Ligerian and the Bretonian fold belts can be regarded as 'Pacific-type' or 'Accretion type' orogens (UYEDA, 1982). The structural style of these fold belts is largely unknown, mostly because of their limited exposure, but partly due to their profound overprinting by younger orogenic events (ZIEGLER, 1982, in press).

## VARISCAN OROGENY

In the course of the Visean, the megatectonic setting of Western and Central Europe underwent again a fundamental change. In the Arctic-North Atlantic domain, large-scale wrench-movements gradually ceased during the Early Carboniferous and gave way to regional crustal extension and the development of a major rift system in the Norwegian-Greenland Sea area. The Carboniferous rifts of the Northern British Isles probably form an integral part of this rift system (Fig. 6). In the domain of the Variscan geosynclinal system, on the other hand, back-arc extension ceased at the transition from the Early to the Late Visean and gave way to regional compression. This can be related to a renewed acceleration of the convergence rate of the Proto-Tethys and Laurasian plates and the subsequent collision of the Gondwana and Laurasia mega-continent. This marked the onset of the Himalayan-type Variscan orogeny during which the Iberian, Austro-Alpine and Carnic-Dinaric and possibly additional, not yet identified micro-continent were also incorporated into the Hercynian fold belt of Europe and North Africa.

Closure of the Proto-Tethys ocean was probably not synchronous along the trace of the Variscan fold belt. During the final phase of convergence of Gondwana and Laurasia and their ultimate collision, multiple collisions of micro-continent and the commensurate subduction/obduction of intervening oceanic domains presumably took place (VAI, 1980 a and b). Correspondingly, the onset of the Variscan orogenic deformation phase varies in time and space in the different Mediterranean parts of the Variscan fold belt.

In the domain of the Aquitaine-Iberian microcontinent, the onset of the Variscan orogeny is reflected by the change-over from pelagic platform sedimentation to the accumulation of synorogenic deepwater clastics. The first Culm-flysch deposits are dated in the Montagne Noire as Late Visean (PELHÂTE & MIROUSE, 1980), and in the Central Pyrenees and in Cantabria as Early Namurian (MIROUSE ET AL., 1983; JULIVERT, 1978). In the West Asturian- Leonese zone, however, the earliest Culm-type turbidite sequences are probably of an Early Dinantian age (PEREZ-ESTAUN, 1974; JULIVERT, 1978). In

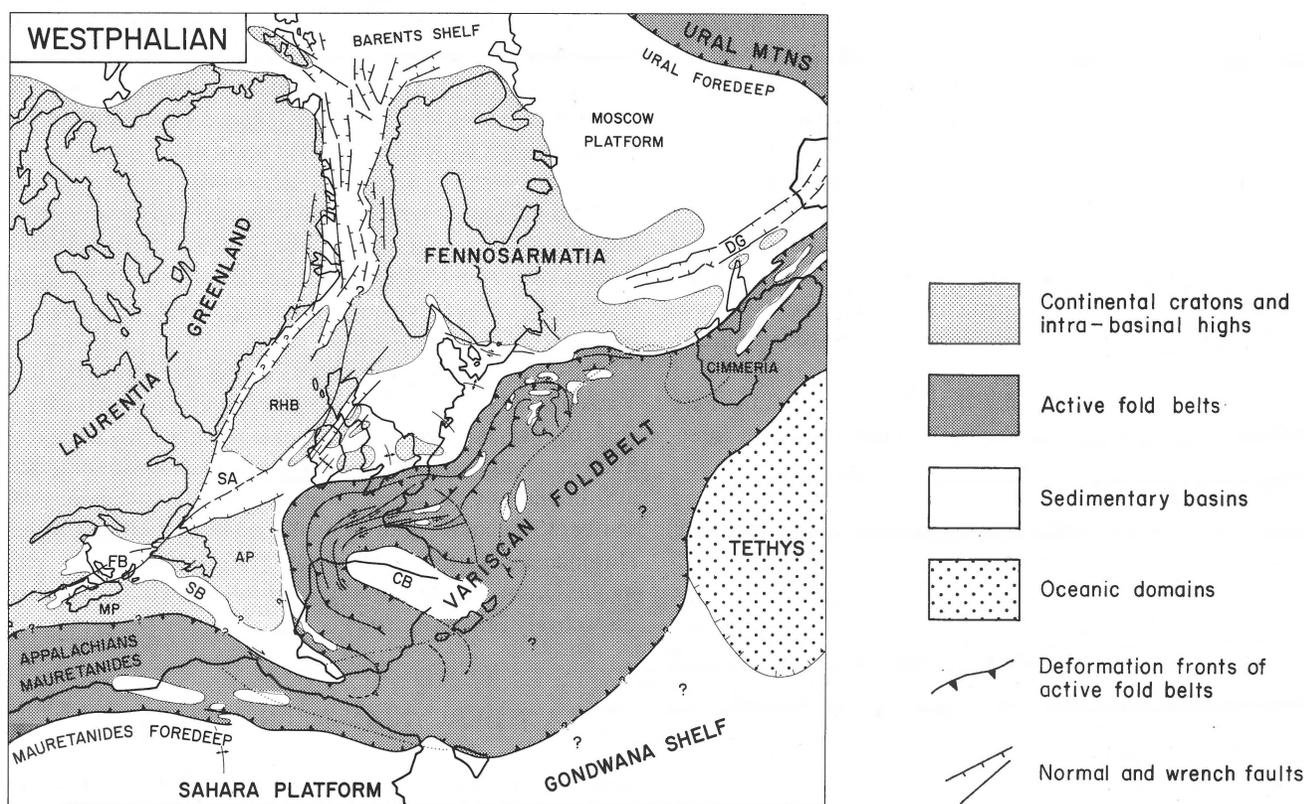


Fig. 6  
Tentative Westphalian tectonic framework of the Arctic-North Atlantic domain. AP – Avalon Platform, CB – Cantabrian Basin, DG – Dnepr-Donets Graben, FB – Fundy Basin, MP – Meguma Platform, RHB – Rockall-Halton Bank, SA – St. Anthony Basin, SB – Sidney Basin.

northern Iberia Westphalian-D and Stephanian-Autunian coal measures and redbeds form part of a neo-autochthonous, postorogenic series which was deposited in intramontane basins, and thus brackets the Variscan orogeny as Mid-Visean to Late Westphalian-C. Variscan granitoids range in age from 330 Ma to 280 Ma (Late Visean to Autunian; PRIEM & DEN TEX, in press).

In the South Portuguese zone, deposition of synorogenic Culm-type flysch set in during the Late Visean and Early Namurian (OLIVEIRO, 1982), whilst in southern Spain, on the Balearic Islands and in northern Algeria, the onset of Culm-flysch deposition dates the beginning of the Variscan diastrophism as Middle to Late Visean (BOURROUILH ET AL., 1980). This was followed by the Late Namurian to Westphalian inversion of Palaeozoic grabens on the Sahara Platform. Also in northern Sardinia, which is characterised by an almost continuous Gondwana-type Cambrian to Early Carboniferous sedimentary sequence, metamorphics related to the Variscan orogeny are dated as Mid-Visean (NAUD, 1980; CARMIGNANI ET AL., 1981).

Collision of the Austro-Alpine micro-continent with the Proto-Tethys arc-trench system is approximately dated as intra-Visean to Early Namurian by the accumulation of synorogenic clastics and by radiometric dating of granitoids (SCHÖNLAUB, 1979). On the other hand, the east-central parts of the South Alpine domain were affected by a synkinematic

metamorphism, radio-metrically dated as  $\pm 350$  Ma (Early Visean, VAI ET AL., in press), whilst the tensional setting of the Carnic-Dinaric domain came to a close only at the end of the Westphalian B. In the latter area the accumulation of a Namurian to Westphalian-A, flysch-like series was accompanied by a rift-related alkaline, bimodal volcanism. As Westphalian D series already form part of the neo-autochthonous sedimentary sequence, the climax of the Variscan diastrophism is dated in this area as Westphalian C (VAI, 1975; CASTELLARIN & VAI, 1981). This may indicate that oceanic domains separating the Austro-Alpine and Carnic-Dinaric blocks were only closed during the Late Westphalian.

North of the Carboniferous Proto-Tethys suture, in the Central Armorican-Saxothuringian Basin, back-arc extension and rift-related volcanism ceased at the transition from the Early to the Late Visean. Uplift of the Ligerian-Arverno-Vosgian-Moldanubian Cordillera, in response to the development (reactivation) of A-subduction zones along its northern and possibly also its southern margins, went hand-in-hand with the shedding of the massive synorogenic clastics into the Central Armorican and Saxothuringian basins (ZIEGLER, 1982; BEHR ET AL., 1982). Similarly, crustal extension and rift-related volcanism came to a halt in the Cornwall-Rhenish-East Sudetic Basin at the beginning of the Late Visean. Also in this basin, the beginning of the accumulation of massif synorogenic Culm flysch is probably related to the

development of an A-subduction zone along the northern margin of the Normanian-Mid German High (ENGEL & FRANKE, 1983). Tectonic loading of the foreland crust by the advancing nappe systems resulted in the rapid, asymmetric subsidence of the Cornwall-Rhenisch-East Sudetic Basin. With this, this longstanding tensional basin developed into the compression-dominated Variscan foredeep basin.

The Central Armorican-Saxothuringian Basin was folded and partly destroyed during the latest Visean-earliest Namurian Sudetic, or Variscan main orogenic phase (PFEIFFER, 1971; SCHMIDT & FRANKE, 1975). Subsequently, Namurian and Westphalian continental sequences accumulated in local intra-montane basins. These sediments form part of the Late Palaeozoic neo-autochthonous series of the Variscan Internides.

The Variscan foredeep basin, on the other hand, remained active until the Late Westphalian Asturian diastrophism, during which it became scooped out by, in part, thin-skinned thrust sheets. The resultant fold belt corresponds to the Variscan Externides.

The amount of crustal shortening accomplished during the Variscan paroxysm is difficult to assess. Major, in part basement involving, nappe structures occur in the Moldanubian area, the southern Massif Central, in Iberia, and also in the Variscan Externides (THIELE, 1977; BURG & MATTE, 1978; JULIVERT ET AL., 1977; MEISSNER ET AL., 1981; BEHR ET AL., 1982).

For the South Alpine segment of the Variscan fold belt, for instance, CASTELLARIN & VAI (1981) estimate a shortening factor of five, i.e. some 80 km. On the other hand, palaeomagnetic data show that post-Devonian crustal shortening between the Armorican Massif and the northern Variscan foreland does not exceed the palaeomagnetic margin of error, and thus cannot be larger than some 500 km (maximum shortening factor of 2.5; JONES ET AL., 1979). Low-pressure metamorphism and late to post-orogenic calcalkaline intrusives are widespread in the Variscan fold belt (ZWART & DORNSIEPEN, 1978). This is taken as indirect evidence that significant amounts of crustal shortening, accompanied by crustal delamination, subduction, and anatexis remobilisation of lower crustal and upper mantle material, had taken place during the Variscan orogeny.

In the domain of the Variscan Internides, older crustal complexes became overprinted by a low to high-grade, generally low-pressure metamorphism ranging in age from 290 to 330 Ma. (ZWART & DORNSIEPEN, 1978). In the Variscan Externides older basement complexes became overprinted in varying degrees by a low-pressure, low temperature metamorphism that ranges in age between 290-330 Ma. (AHRENDT ET AL., 1983; Encl. 2).

The occurrence of granitic intrusions in the Variscan Externides (e.g. Cornwall, Harz) indicates that the Benioff zone, along which lower crustal and upper mantle material was subducted, dipped northward from the Proto-Tethys suture(s) at a relatively gentle angle under the Variscan

Internides and possibly even under the Variscan Externides (SHACKLETON ET AL., 1982).

In the western part of the Variscides, the Proto-Tethys suture is to be sought between the Ligerian Cordillera and the Aquitaine-Iberian block and to the south of the latter. In the central and eastern parts of the Variscides the Proto-Tethys suture is difficult to locate owing to severe Alpine overprinting and limited outcrops of the Variscan complex and uncertainties in defining the outlines of potential allochthonous terrains such as the Austro-Alpine and the Carnic-Dinaric blocks.

Unlike the linear Appalachians and the Uralides, the Variscan fold belt is characterised by a complex arcuate shape (Fig. 6). This is partly the result of it being draped around a number of internal microcratons (e.g. Aquitaine-Iberia), but also because of the irregular geometry of its northern and southern forelands which were shaped by the pattern of the Devonian and Early Carboniferous back-arc rift systems and by the Ordovician to Carboniferous Gondwana rift systems respectively (ZIEGLER, 1982).

#### LATE HERCYNIAN WRENCH TECTONICS

Following the latest Westphalian-Early Stephanian consolidation of the Variscan fold belt, convergence between Gondwana and Laurasia apparently changed from an essentially northwest-southeast direction to one that was east-west oriented. Crustal shortening continued during Stephanian-Autunian time in the Urals and the Appalachian-Mauretides. This was accompanied by the development of a right-lateral transform fault system, which linked the southern Uralides and the northern Appalachians via Europe. Here, it caused the development of a complex pattern of conjugate shear faults and related pull-apart structures that transected the newly consolidated Variscan fold belt (ARTHAUD & MATTE, 1977; ZIEGLER, 1982). This fault-system, which also extended into the Variscan foreland, remained active until the late Early Permian consolidation of the Uralides during the Saalian orogenic phase, and of the Appalachian-Mauretides during the essentially contemporaneous Alleghenian diastrophism (Fig. 7). The latest Carboniferous and Early Permian evolution of the Arctic-North Atlantic domain, on the other hand, continued to be governed by crustal extension.

In Western and Central Europe, deep crustal fracturing induced by the Late Hercynian wrench deformations, triggered widespread extrusive and intrusive activity of a highly variable chemistry. For instance, extensive Late Carboniferous tholeiitic dykes and sills are reported from northern Britain (FRANCIS, 1982), whilst the latest Carboniferous and Permian igneous rocks of the Oslo Graben display a distinctly mafic-felsic bimodality and are highly alkaline (RAMBERG, 1976; OFTEDAHL, 1968). A similar alkaline bimodality characterised the Early Permian volcanics in the North Sea, whereas

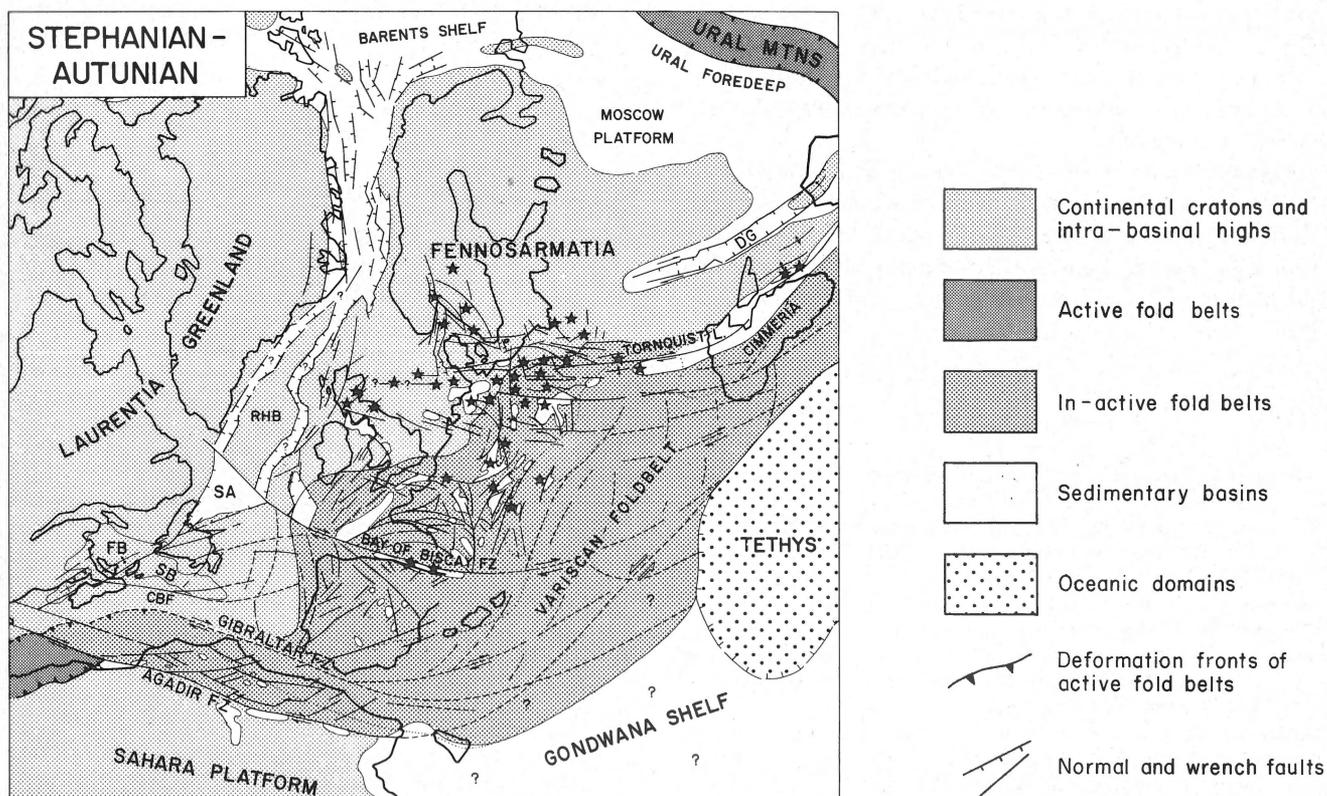


Fig. 7  
Tentative Stephanian-Autunian tectonic framework of the Arctic-North Atlantic domain. CBF – Chedabucto Fault, DG – Dnepr-Donets Graben, FB – Fundy Basin, SA – St. Anthony Basin, SB – Sidney Basin.

those in the immediate foreland of the Variscan fold belt are only mildly alkaline with mafic rocks predominating over felsic ones (DIXON ET AL., 1981; ECKHART, 1979). In the domain of the Variscan fold belt proper, Early Permian volcanics consist of rhyolites and andesites and display the typical calcalkaline composition of a late to post-orogenic volcanism (KRAMER, 1977; D'AMICO, 1979; DZIEDZIC, 1980).

The modification of plate movements during the terminal suturing phases of the Pangean mega-continent induced in Europe a phase of essentially anorogenic faulting which caused the fragmentation of the Variscan fold belt. The associated magmatic activity was widespread and not so much related to the final phase of consolidation of the Variscan fold belt as to the first phase of its disintegration.

The Late Hercynian fault-system became reactivated time and again, and played a major role during the Mesozoic opening of the Tethys and the North Atlantic.

## CONCLUSIONS

The basement provinces recognised in Western and Central Europe are summarised in Encl. 2. No attempt was made to extend the basement provinces of the Alpine foreland into the Alpine domain proper, where they were telescoped and overprinted to varying degrees by the Alpine diastrophism.

In the Alpine foreland, however, the definition of the individual basement provinces also has to contend with major uncertainties. Sedimentary basins occupy large parts of Western and Central Europe. In them, the top of the crystalline basement lies at depths of several kilometres and only cores from deep boreholes can provide spot control on its age and composition. Not all the basement cores obtained in boreholes drilled by the oil industry have been petrologically studied and radiometrically dated. This applies, for instance, to the eastern Molasse Basin from which considerable core material is available; its study could provide further insight into the extent and evolution of the Vosgian-Moldanubian Cordillera, for example.

There are still major uncertainties regarding the tectonic framework and the evolution of those parts of the Variscan fold belt that were overprinted by the Alpine orogeny. A basic requirement for the reconstruction of this part of the Variscides is a palimpsestic restoration of the Alpine fold belts, which is currently not available. Only in the framework of such a restoration can the major Variscan tectonic units of the Alpine foreland be related to those contained in the Alpine fold belts.

In order to assess the geodynamics of the Caledonian and Variscan fold belts, and in particular the dimensions of the crustal shortening that took place during the various phases of their consolidation, additional radiometric age-determina-

tions, palaeomagnetic data and faunal analyses are needed. This applies specifically to an analysis of the role played by the various, poorly defined, micro-continents that appear to be enclosed in the Caledonian and Variscan fold belts of Western and Central Europe.

Having attempted to construct a geodynamic model for the step-wise consolidation of the crust of Western and Central Europe, I am fully aware that such a model is but a working-hypothesis, and that further research, together with the pooling of knowledge, is required to evaluate its validity.

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