Chapter 1
Late Caledonian Tectonic Framework (Latest Silurian–Earliest Devonian)

INTRODUCTION

The late Caledonian megatectonic framework of the Arctic–North Atlantic area and its borderlands is summarized in Plate 1.

The Caledonian orogenic cycle spanned Late Cambrian to earliest Devonian times. It embraced the Late Cambrian to Early Ordovician Grampian/Finnmarkian, the mid- to Late Ordovician Taconic, and the Late Silurian to early Gedinnian Main Scandinavian or late Caledonian orogenies (Gee and Sturt, 1986; Fig. 1).

The late Caledonian evolution of the Arctic–North Atlantic domain involved the convergence of four plates. The Late Ordovician and Silurian sinistral oblique collision of the continental Laurentia–Greenland and Fennosarmatian plates was preceded by the progressive subduction of the oceanic Iapetus plate and culminated in their Late Silurian–Early Devonian suturing along the Arctic–North Atlantic Caledonides. With this the Laurussian Megacontinent, also referred to as the North Continent, was formed (Wilson, 1966; Phillips et al., 1976; Roberts and Gale 1978; Soper and Hutton, 1984).

At the same time, the oceanic Proto-Tethys plate converged northward with the colliding Laurentia–Greenland and Fennosarmatian plates (Fig. 2). Northward subduction of the Proto-Tethys plate at an arc-trench system marking the southeastern margin of Laurentia and the southwestern margin of Fennosarmatia was accompanied by the northward rafting of a number of continental fragments that were rifted off the northern margin of Gondwana during the Cambro-Ordovician and Early Silurian. Some of these micro-continents (allochthonous terranes) became accreted during the Caledonian orogenic cycle to the southern margin of the newly forming North Continent (Laurussia). These continental fragments are enclosed by the North German-Polish, Mid-European, and Ligerian–Moldanubian Caledonian fold belts. In view of the contemporaneous sinistral-oblique convergence of Fennosarmatia and Laurentia–Greenland (Soper and Hutton, 1984), the consolidation of these fold belts involved presumably major sinistral translations (Ziegler 1982a, 1984, 1986; Brochwicz-Lewinski et al., 1984).

In the Arctic domain, the continental Siberian plate converged southward, toward the northern margin of Laurentia–Greenland. This involved the closure of the Proto-Arctic Ocean along a presumably south-dipping subduction system that was associated with the Innuitian fold belt. This fold belt became consolidated, however, only during the latest Devonian to earliest Carboniferous (Chapter 2).

LATE CALEDONIAN CONTINENT ASSEMBLY ($\pm$ 410 Ma)

Compared with the classical "Bullard Fit" (Bullard et al., 1965), the continent assembly given in Plate 1 shows a dextral offset of some 1500 km between Laurentia–Greenland and Fennosarmatia–Baltica. Such an offset, which is a minimum value, is suggested by paleomagnetic data (Morris, 1976; van der Voo et al., 1980; Kent, 1982; van der Voo, 1983; Perroud et al., 1984). Although there is considerable uncertainty about the magnitude of this offset, the available paleomagnetic data suggest that a continent assembly comparable to the Bullard Fit was only achieved during the Early Carboniferous as a result of intra-Devonian and earliest Carboniferous sinistral translations between Laurentia–Greenland and Fennosarmatia–Baltica along a fault system transecting the Arctic–North Atlantic Caledonides (Keppie et al., 1985; Chapter 2).

In Plate 1, the northern Scottish Highlands, the Hebrides, Orkney, and Shetland Isles are shown as being dextrally offset across the Great Glen Fault by some 400 km relative to the Southern Highlands of Scotland (compare with Fig. 12). Such an offset is indicated by paleomagnetic data that support a commensurate intra-Devonian rotation of the northern Highlands along the curvilinear Great Glen Fault (Storedvedt, 1987) but that challenge the 2000 km offset across this fault postulated by van der Voo and Scotese (1981) (Tørsvik et al., 1983, Storedvedt and Tørsvik, 1983). On the other hand, Briden et al. (1984) question even a 400 km offset across the Great Glen Fault and prefer to reduce it to 100–200 km which, according to these authors, is "more in line with the conventional Scottish geological wisdom."

This implies that the bulk of the Late Silurian–Early Devonian offset between Laurentia–Greenland and Fennosarmatia–Baltica had to be taken up by a hypothetical fault system located to the west of the Hebrides Isles.

Plate 1 shows, in accordance with Harland et al. (1984), western Svalbard as forming part of the Greenland Craton, Eastern Svalbard as forming part of Fennosarmatia, and Central Svalbard as taking in an intermediate position. This postulate requires, however, further support by paleomagnetic analyses (see Løvlie et al., 1984).

CALEDONIAN FOLD BELTS AND ALLOCHTHONOUS TERRANES

The Arctic–North Atlantic Caledonides, corresponding to the Iapetus megasuture, became consolidated during the late Caledonian orogeny (Fig. 1; Gee and Sturt, 1986; Dallmeyer and Gee, 1986). They embrace the Caledonide fold belts of Eastern Greenland, Svalbard, Norway, Sweden, and the northern British Isles. Although the trace of the Caledonian deformation front in the Barents Sea is uncertain, it is questionable whether a branch of the Scandinavian Caledonides extended from northernmost Norway in a northeastern direction, across the Barents Shelf, into the area between Novaya Zemlya and Severnaya Zemlya (North Islands) as suggested by Gortunov et al. (1984) and Khain (1985).

The structural style of the Scandinavian and East Greenland Caledonides is characterized by major basement-involving nappes (Haller, 1971; Roberts and Gales, 1978; Sturt et al., 1978; Hossack, 1985; Hossack et al., 1986). In combination with an extensive high-grade metamorphism and a widespread syn- and late-orogenic plutonism (Gee and Sturt, 1986), this indicates that the evolution of the Arctic–North Atlantic Caledonides was accompanied by major crustal delaminations and the subduction and anatectic remobilization of lower crustal and upper mantle material. The Late Ordovician closure of the Iapetus Ocean and the ensuing Himalaya-type collision of Laurentia–Greenland and Fennosarmatia–Baltica, giving rise to the late Caledonian orogeny, is thought to have been accompanied by important sinistral translations (Mitchell, 1981; Leggett et al., 1983; Soper and Hutton, 1984; Dallmeyer and Gee, 1986).

To the northwest, the Arctic–North Atlantic Caledonides grade into the Innuitian fold belt of northernmost Greenland

and the Canadian Arctic Island and, to the northeast, possibly into the hypothetical Lomonosov fold belt, which is though to have fringed the leading edge of the Siberian Craton. The Innuitian and possibly also the Lomonosov fold belt became finally consolidated during the latest Devonian–Early Carboniferous Ellesmerian orogeny (see Chapter 2). The evolution of the Innuitian fold belt, involving the Mid-Ordovician M'Clintock, the Late Silurian Vølvedal, and the Devonian–earliest Carboniferous Ellesmerian orogenies (Fig. 1), probably reflects the gradual closure of the Proto-Arctic Ocean and the collision of the Siberian Craton with Laurentia-Greenland (Trettin and Balkwill, 1979; Kerr, 1981a; Trettin, 1987). In such a scenario, the hypothetical Lomonosov fold belt may have been associated, at least during the Ordovician and Silurian, with the essentially transform margin of the Siberian block facing the Ural and Lomonosov oceans.

To the south, in the North Sea area, the Arctic–North Atlantic Caledonides bifurcate into the Scottish-Irish Caledonides, which find their continuation in the Appalachian geosynclinal system and into the North German–Polish Caledonides.

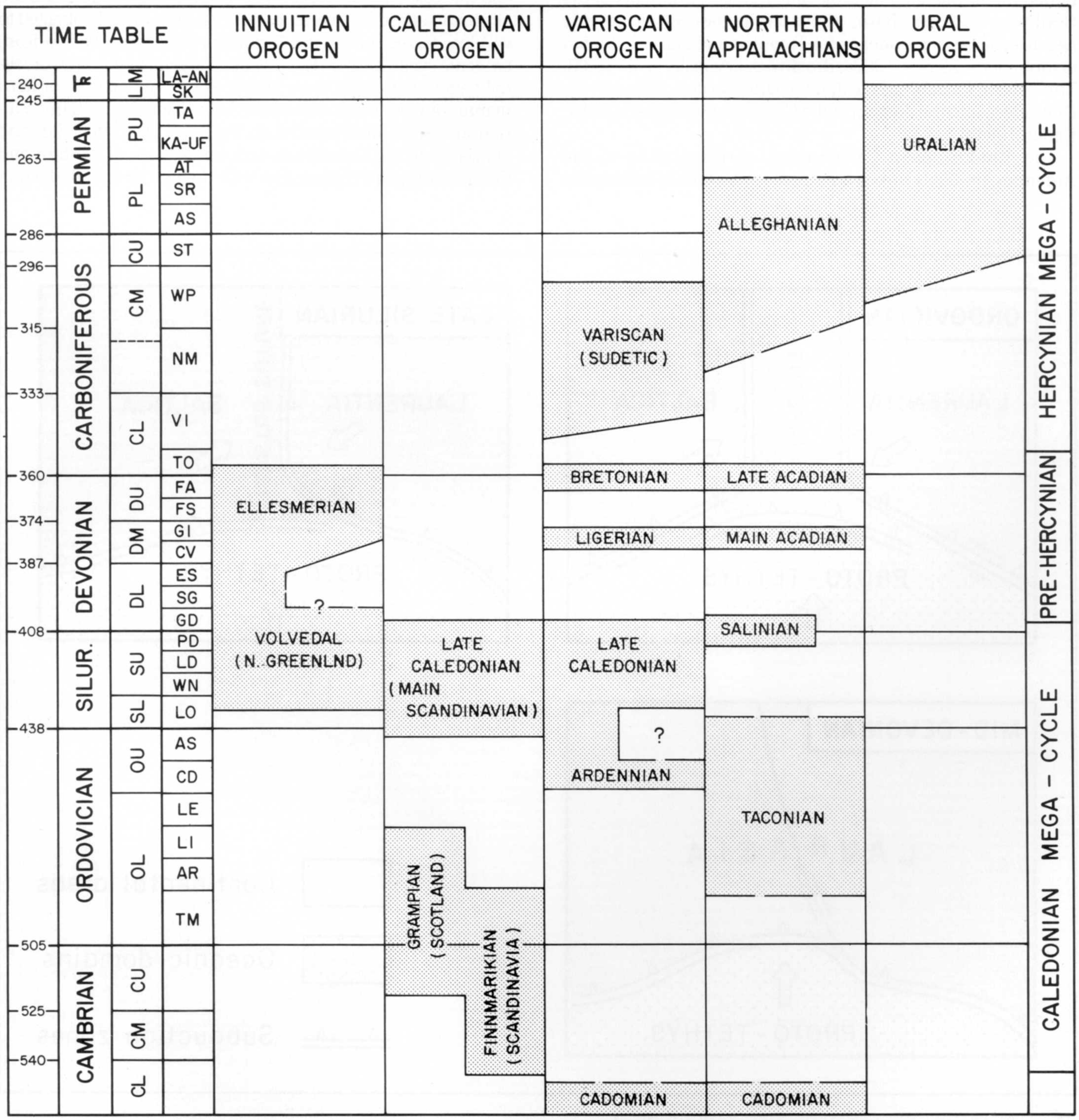

Figure 1—Correlation of Paleozoic orogenic cycles.

In the Appalachian domain, the main phase of the Caledonian orogenic cycle corresponds to the Taconian orogeny that terminated during the latest Ordovician–Early Silurian with the accumulation of a thick clastic wedge in the foredeep flanking the rising orogen (Fig. 1; Cook and Bally, 1975). The less pervasive Salinian disturbance, corresponding to the late Caledonian diastrophism, was accompanied by important plutonism in northern Maine and New Brunswick (Poole, 1977; Williams and Hatcher, 1983; Hatcher, 1985; Spariosu and Kent, 1983; Hubacher and Lux, 1987).

The North German–Polish Caledonides, which are deeply buried under the late Paleozoic and younger sediments of the Northwest European Basin, show on the basis of radiometric age determinations evidence for Taconian and late Caledonian deformations (Ziegler, 1982a; Brochwicz-Lewinsky et al., 1984). The Polish Caledonides extend southeastward through the Dobrudgea into the domain of the Caucasus (Sandulescu, 1984; Khain, 1984b).

The Mid-European Caledonides, corresponding to the Ardennes, probably linked the Appalachian area of incomplete Caledonian consolidation with the North German–Polish Caledonian fold belt via the Mid-German High. The Ardennes, which show evidence for Late Ordovician deformation, became consolidated during the latest Silurian–earliest Devonian late Caledonian diastrophism (Waterlot, 1974; André et al., 1986).

On the basis of limited data, it is assumed that the Ligerian-Moldanubian Cordillera developed during the late Caledonian orogeny.

These fold belts enclose the Gondwana-derived cratonic blocks of the Irish Sea Horst, the London–Brabant Massif, the Central Armorican, Saxothuringian, and Barrandian blocks, and the East Silesian Massif. These allochthonous terranes are all characterized by a continental crust that was consolidated to varying degree during the Cadomian (Baikalian, Pan-African) orogenic cycle (Ziegler, 1984, 1986). Paleomagnetic and/or faunal data indicate that these blocks were rifted off the northern margin of Gondwana during the Late Cambrian to Early Silurian and were incorporated during the Late Ordovician and Silurian into the Caledonian orogenic system of Western and Central Europe in conjunction with the northward subduction

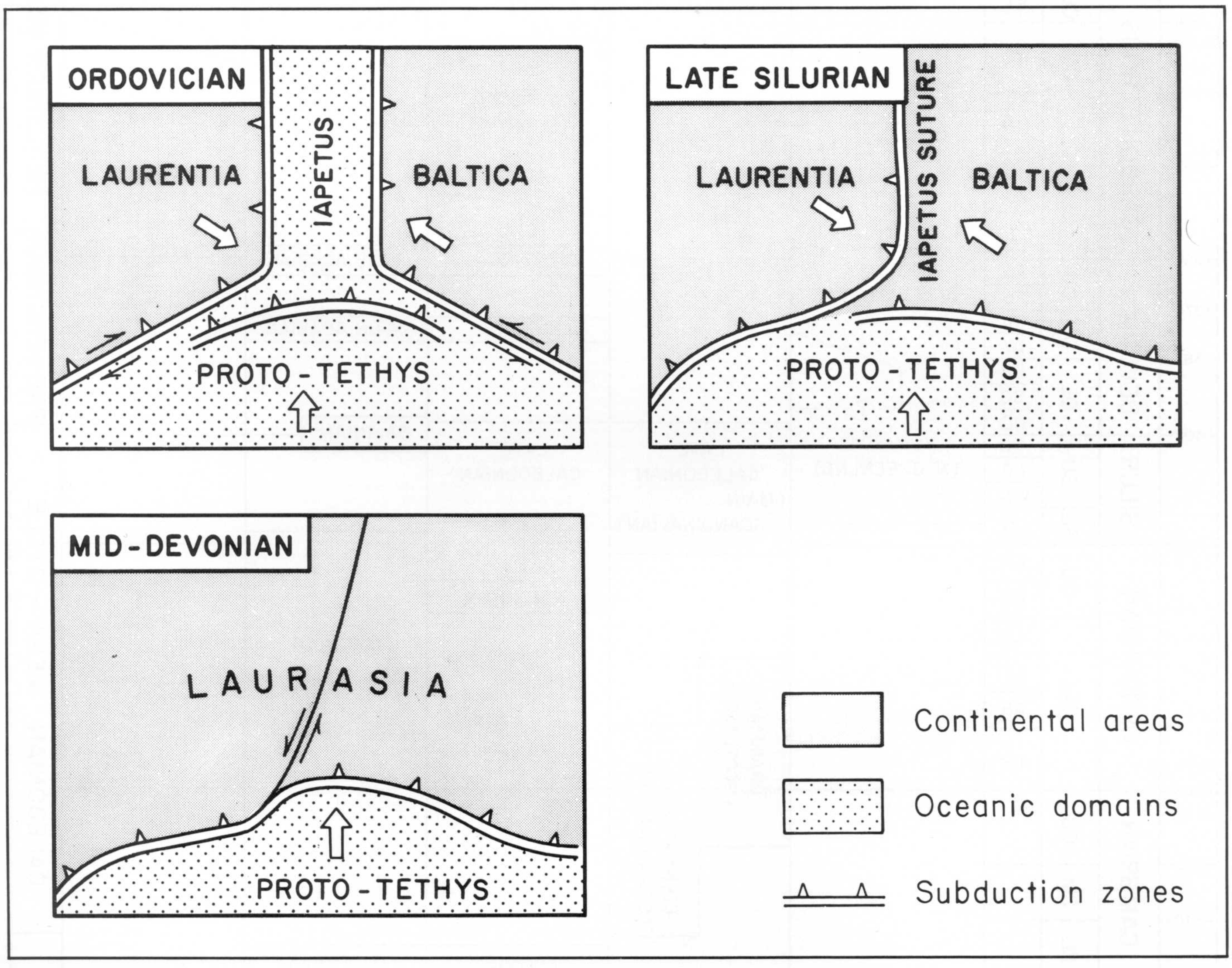

Figure 2—Changes in plate configuration in Arctic–North Atlantic realm during Ordovician and Early Devonian time.

of the oceanic Proto-Tethys plate (Perroud and Bonhommet, 1981; Spjeldnaes, 1981; Cocks and Fortney, 1982; Krs, 1982; Séguin, 1983; van der Voo, 1983; Perroud et al., 1984; Bonhommet and Perroud, 1986; McKerrow and Cocks, 1986). Furthermore, preliminary paleomagnetic data also indicate that the Malopolska Massif (Holy Cross Mountains), which forms an important element of the Polish Caledonides, corresponds to a Gondwana-derived terrane (Brochwicz-Lewinski, personal communication, 1986; Lewandowsky, 1987). The occurrence of Ashgillian glaciomarine series in the Armorican Massif (Lardeux et al., 1977; Doré, 1981) and in the Saxothuringian–Barrandian domain (Katzung, 1961; Steiner and Falk, 1981) stress the Late Ordovician Gondwana affinity of these terranes (see also Brenchley and Newall, 1984). Moreover there is widespread evidence for a rift-related Cambro-Ordovician alkaline to peralkaline magmatism in the Central Armorican and Saxothuringian–Barrandian blocks (Weber, 1984; Matte, 1986). This rifting activity presumably preceded their detachment from Gondwana.

Most of these allochthonous terranes were little affected by the Late Caledonian diastrophism; some were, however, intruded by Caledonian granitoids (e.g., Irish Sea Horst, London–Brabant Massif).

In view of the limited control available on the North German–Polish and the Mid-European Caledonides, as well as on the Ligerian–Moldanubian Cordillera, little can be said about their structural style. Moreover, the definitions of these fold belts is hampered in part by their deep burial under younger sediments and in part also by their overprinting during the Acadian–Ligerian, Bretonian, Variscan,* and Alpine orogenic cycles (Fig. 1).

At present, there are insufficient geophysical data on which a palinspastic restoration of the Variscan fold belt could be based. Consequently, areas south of the Variscan deformation front, shown on Plate 1 by a dotted line, are distorted by an unquantifiable amount of post-Caledonian crustal shortening. For want of a palinspastic restoration of these areas, it is difficult to understand the spatial relationship between the various allochthonous terranes and their enclosing Caledonian fold belts. For instance, it is debatable whether the Armorican Craton, underlying the Central Armorican Basin, and the Bohemian Craton, underlying the Saxothuringian and Barrandian basins, formed part of one structural unit, as postulated by Ellenberger and Tamain (1980), or whether they are formed by two or more separate entities as proposed by Behr et al. (1984).

Owing to these constraints and often limited data sets, the stepwise accretion history of the individual continental fragments enclosed by the Caledonian fold belts of Europe is still difficult to resolve.

Furthermore, the controversy is still ongoing whether by the end of the late Caledonian orogeny Europe was occupied by coherent fold belts and intervening successor basins, floored by continental crust, as suggested by Plate 1, or whether a significant oceanic basin (Rheic or Tornquist Sea) was preserved in the area of the Mid-European Caledonides (Rhenohercynian zone) as postulated by McKerrow and Ziegler (1972), Johnson (1976), Scotese et al.(1979), Lorenz and Nicholls (1984), and Behr et al. (1984).

Paleomagnetic data suggest, however, that during the Early Devonian a major ocean separated Laurasia and Gondwana (Morel and Irving, 1978; van der Voo et al., 1980) with more recent data favoring its location to the south of the Ligerian–Moldanubian Cordillera as indicated on Plate 1 (Briden and Duff, 1981; van der Voo, 1983; Séguin, 1983; Perroud and van der Voo, 1983; Perroud et al., 1984; Bonhommet and Perroud, 1986). The width of oceanic domains separating during the latest Silurian–Early Devonian the Gondwana-derived Avalon–Meguma composite terrane and the Aquitaine–Cantabrian–Intra-Alpine (composite?) microcontinent(s) from the Appalachian and Ligerian–Moldanubian arc-trench systems is, however, uncertain and is therefore only schematically depicted on Plate 1 (see Keppie et al., 1985; Ziegler, 1984, 1986; Johnson and van der Voo, 1985).

CALEDONIAN FOREDEEP BASINS

Geodynamic considerations suggest that the Caledonian fold belts of the Arctic–North Atlantic domain and those marking the southern margin of Laurasia were associated with extensive foredeep basins. Large parts of these basins were, however, destroyed during post-Caledonian tectonic events or are now obscured by younger sediments.

The foredeep basin of the Caucasus–Dobrugea–Polish Caledonides is only partly preserved (Rizun and Senkovskiy, 1973; Foose and Manheim, 1975; Gluschko et al., 1976; Wjalow and Medwedew, 1977; Pozaryski et al., 1982; Vinsjakov et al., 1984). In southeastern Poland and in the Dobrugea, deposition of the Caledonian Molasse series began during the Siegenian (Plate 24). In the Eastern Baltic, late Early Devonian continental clastics, overlaying conformably marine Silurian strata, may represent a remnant of the distal part of the Caledonian foredeep basin.

The foredeep basin of the North German and the Scandinavian Caledonides has been largely destroyed by post-Caledonian tectonic and erosional events (Ziegler, 1982a). Only in the Oslo Graben is a remnant of this basin preserved owing to latest Carboniferous–Early Permian downfaulting. In it, Upper Silurian marine strata grade upward into Downtonian red molasse series (Holtedahl, 1960; Nilsen, 1973), which became deformed by décollement folding and thrusting during the Gedinnian–Siegenan(?) (Roberts, 1983). On the basis of regional considerations, it can be assumed that much of the Fennoscandian Shield was originally covered by lower Paleozoic open marine platform sediments. These presumably graded upward into lower Silurian to uppermost Devonian continental red beds that accumulated in the foredeep basin paralleling the thrust front of the North German–Scandinavian–Svalbard Caledonides. Whether part of this foredeep is preserved in the Barents Sea is unknown.

The foredeep basin of the Innuitian fold belt is partly preserved in the area of Parry Island fold belt, outcropping along the southern margin of the Sverdrup Basin and, to a lesser extent, in Northern Greenland (Plate 22). In this basin, Late Silurian turbiditic sands were transported along the basin axis in a westward direction, indicating a major clastic source area in northeastern Greenland (Trettin and Balkwill, 1979; Hurst et

*The terms, *Hercynian* or *Hercynides*, as used in this paper, refer to the late Paleozoic 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.

al., 1983; Hurst and Surlyk, 1984; Surlyk and Hurst, 1984). This suggests that in the East Greenland foredeep basin, clastics were transported northward along its axis and were deflected at its northern end in northeastern Greenland into the east–west-trending incipient Innuitian foredeep (Franklinian Basin). Ice cover, however, impedes the recognition of a possible foredeep basin paralleling the deformation front of the East Greenland Caledonides. On trend to the south, a remnant of this foredeep basin is preserved in western Newfoundland (Poole et al., 1970). The West Newfoundland Basin was presumably connected with the Appalachian foredeep basin. Scattered outcrops of early Paleozoic and Devonian sediments in Eastern Canada and in Hudson Bay suggest that much of the Laurentia–Greenland Shield was originally covered by Siluro-Ordovician and possibly Early Devonian marine strata (Cook and Bally, 1975).

CALEDONIAN SUCCESSOR BASINS

In the framework of the Caledonian fold belts of Western and Central Europe, the Central Armorican Basin and the composite Saxothuringian–Barrandian Basin, which are superimposed on the Cadomian consolidated Armorican and Bohemian cratons, can be considered as successor basins (Fig. 3; Ziegler, 1984). These basins are characterized by nearly continuous marine sedimentary sequences that extend from the Cambro-Ordovician into the Devonian and in part even into the Early Carboniferous (Plate 25; Svoboda, 1966; Watznauer et al., 1976; Lardeux et al., 1977; Guillocheau and Rolet, 1982). Eastward, this complex system of successor basins extended into the Sudetic Basin and into the Harz area (Alberti et al., 1977; Walliser and Alberti, 1983). These basins are located to the east and to the north of the Mid-German High. This high represents the easternmost parts of the Mid-European Caledonides (Ziegler, 1982a, 1984; Plate 1).

It is assumed that the Central Armorican–Saxothuringian successor basin was connected to the west with the Proto-Tethys Ocean but was separated from the South Polish–Dobrugea foredeep by the Polish Caledonides. In the area of the London–Brabant and the East Silesian massifs, a major hiatus separates lower and upper Paleozoic sediments (Plates 23, 24).

EASTERN MARGIN OF FENNOSARMATIA

According to Zonenshain et al. (1984), the eastern margin of Fennosarmatia–Baltica was tectonically inactive during the Late Silurian and Early Devonian and displayed the characteris-

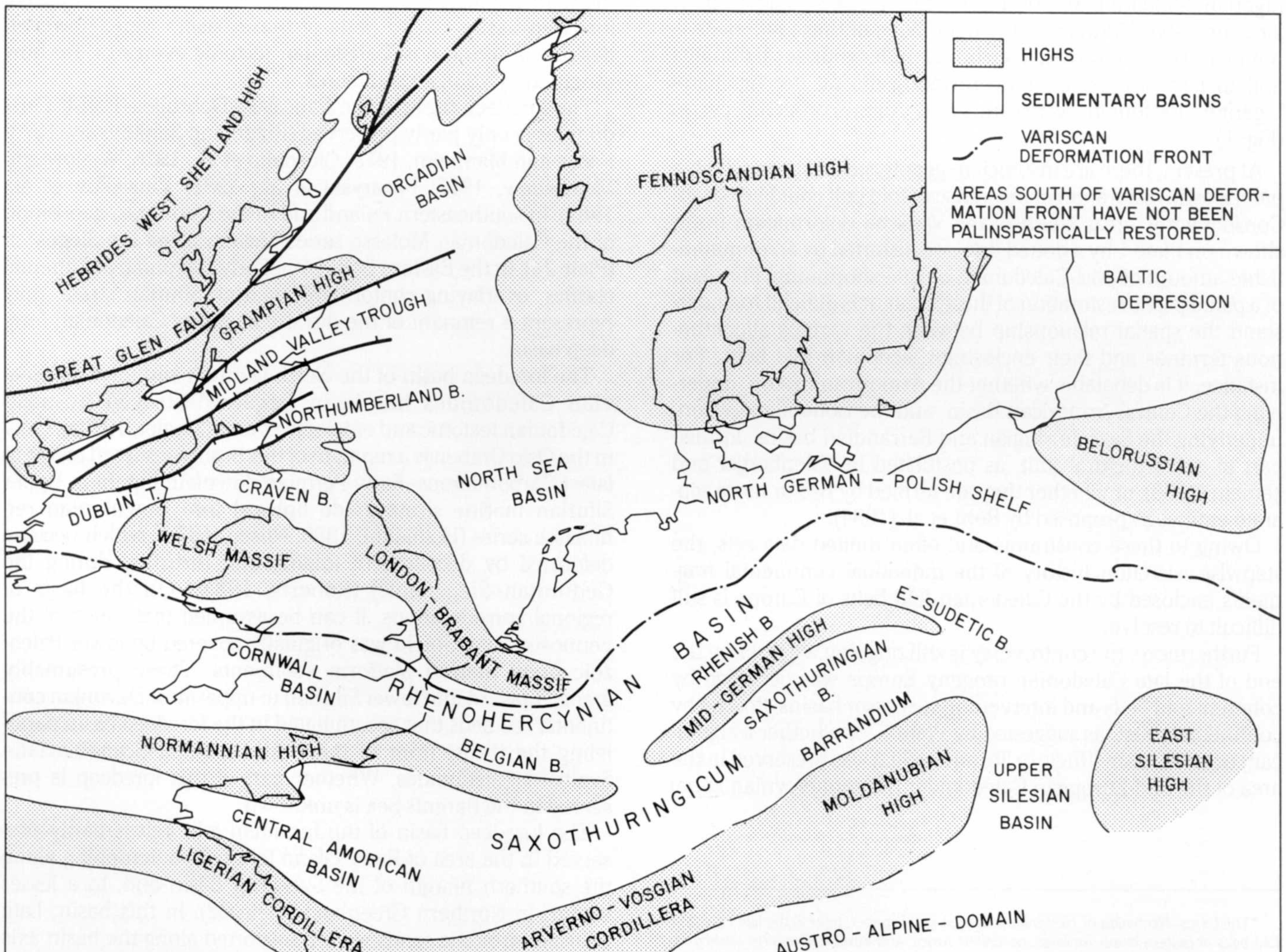

Figure 3—Main structural elements of the Variscan Geosynclinal System.

tics of an Atlantic-type passive margin. It faced the Sakmarian Ocean, which was separated from the Ural Ocean by the Sakmarian arc-trench system. This subduction system, which was associated with a west-dipping Benioff zone, came into evidence during the late Early Silurian. Its development is therefore contemporaneous with the onset of the Main-Scandinavian phase of the Caledonian orogeny that involved the continued convergence of the already collided Laurentia-Greenland and Fennosarmatia-Baltica cratons and the emplacement of major, basement-cored nappes (Sturt et al., 1978). This suggests that increasing constraints in the motion of the Fennoscandian-Baltica plate induced the development of the new Sakmarian arc-trench plate boundary within the Ural Ocean. During the Late Silurian, a back-arc compressive system developed within the oceanic Sakmarian Basin. Tectonic activity along the Sakmarian arc-trench system and the Sakmarian back-arc subduction zone apparently abated at the transition from the Silurian to the Devonian but resumed again during the late Early and early Middle Devonian. On the other hand, the subduction system associated with the Arctic-North Atlantic Caledonides became inactive with their final consolidation at the transition from the Silurian to the Devonian.

The existence of a Lomonosov ocean during the Siluro-Ordovician and Early Devonian, separating the northern margin of Fennoscandia-Baltica from the Lomonosov fold belt marking the margin of the cratonic Siberian Block, is hypothetical and is proposed here on geometrical grounds alone. Presumably, this oceanic basin became progressively closed in the course of the Devonian to earliest Carboniferous sinistral northward translation of Fennoscandia-Baltica relative to Laurentia-Greenland (see Plates 2–4 and Chapter 2).