CALEDONIAN EUROPE

by

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The North Atlantic Caledonides were broken up by continental drift or isolated by epeirogenic movements into several fragments in post-Devonian time. In the following series of articles, four of these fragments are described according to geotectonic premise, reconstructing concisely the sequence of structural and metamorphic events which formed the Caledonides in Ordovician and Silurian times.

Introduction

During the Upper Proterozoic (mainly Upper Riphean and Vendian time), a belt of sedimentation extended along the margin of the Laurentian continental plate, following the opening of the Iapetus Ocean. On the opposite side of the ocean, late-Precambrian (Cadomian) disturbances folded and block-faulted the equivalent sedimentary and volcanic rocks marginal to the Fennoscandian continent. In the Cambrian, a new belt of sedimentation and volcanic activity encroached on the eroded Cadomian fold-belt, while sedimentation persisted on the Laurentian shore of Iapetus.

Around the end of the Cambrian, the northern Laurentian belt underwent very intense alpinotype deformation and metamorphism - the Grampian orogeny - probably as a result of microcontinental collisions. Sedimentation continued elsewhere with relatively little interruption until the Silurian, when the continental collision between Laurentia and North Europe (already presaged by the merging of faunas in the late Ordovician) folded the Lower Palaeozoic sequences and, in a major outbreak of magmatism and vulcanism, brought the North Atlantic Caledonides into existence.

The Caledonides were subsequently broken up by continental drift or isolated by epeirogenic sinking into five separate fragments: East Greenland, Svalbard, Scandinavia, the British Isles and Newfoundland (Fig. 1). For geotectonic reasons, the alpine-type metamorphic Caledonides of Scotland, Ireland and Scandinavia are described as a unit (though they are not equivalent in age), followed by the non-metamorphic mediotype late Caledonides of Britain and Ireland, the Caledonides of Greenland and Svalbard, essential to the understanding of the North Atlantic Caledonides, and lastly, the enigmatic and problematic Caledonides of central Europe, which fit with the greatest difficulty into plate tectonic syntheses, and whose relationship to the North Atlantic Caledonides is obscure. Newfoundland is omitted purely for reasons of space.

Figure 1. Orogenic zones in North Atlantic region on a pre-Atlantic reconstruction. Dots are located on younger sides of boundaries of orogenic zones; the latter are broken where overlapped by younger belts. The track of the future Alpine zone is shown. Ar - Archaean, Pr₁ - Early Proterozoic (Svecofennic-Karelidic, Hudsonian, Nagssugtoqidian, Laxfordian) orogenic zones, Pr₂ - mid to late Proterozoic (Grenvillian, Sveco-Norwegian, Dalslandian) orogenic zones, Pr₃ - Late Proterozoic (Moravian) orogenic zone in the Scottish Caledonides, CA³ - Cadomian-Avalonian orogenic zone, C - Caledonian, NAC - North Atlantic Caledonides, Ta - Taconic belt, Ac - Acadian belt, R-PC - Rügen-Pomeranian Caledonides, NF - Norddeutsches Festland (median massif), Bm - Brabant massif, V - Variscan/Hercynian/Appalachian orogenic zones, A - Alpine zone.

Orthotectonic Caledonides of the British Isles and Scandinavia

by

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The Caledonian metamorphic rocks of Scandinavia and the British Isles form the orthotectonic section of the northeastern European Caledonides. Though separated only by the North Sea, they show interesting and fundamental differences in character and evolution. In recent years, our understanding of large segments of this orthotectonic section has been augmented by various studies, many of which are summarized in Tozer and Schenk (1978).

The traditional view was that the Moine thrust belt of Scotland and the Scandinavian thrust-front represented respectively the northwestern and southeastern margins of the Caledonian orogenic belt. However, it is now thought that the major translations on the Moine Thrust took place in

early to middle Ordovician times, whereas along most of the Scandinavian thrust-front, translation of nappes took place in late Silurian to earliest Devonian times.

The Moine Thrust represents the frontal thrust translations related to the Grampian orogenic phase (late Cambrian/early Ordovician) which can be correlated in time with the Finnmarkian (Sturt et al., 1978) of northern Norway. In both the Grampian and Finnmarkian, the major movements appear to have been in the early Ordovician, though later reactivation probably occurred in both cases.

It is now known that the development of the Caledonian orthotectonic zone in Britain and Ireland was essentially

View toward north shore of Loch Glencoul showing part of the Caledonian Moine thrust zone. From left to right Lewisian gneiss (metamorphosed between 2800-2700 Ma), bedded Cambrian quartzites, the Glencoul Thrust overlain by Lewisian. The Moine Thrust is thought to have developed in four phases between post Cambrian and early Devonian times, with major translations in early to middle Ordovician time. (Photo courtesy W.C. Morgan).

completed during the Grampian. This is in marked contrast to the Scandinavian orthotectonic zone, where the structural/metamorphic development occurred in two distinct cycles: the Finnmarkian and the Main Scandinavian (late Silurian). Thus the two segments had different geotectonic evolutionary patterns, particularly during post-Finnmarkian/Grampian development.

The British Isles' Segment

This orthotectonic segment represents the heartland of Caledonia, where many concepts concerning Caledonian orogenic evolution were formulated, based on studies made in "classic" terrains. In recent years, however, new discoveries and re-assessments, focussing on internal relationships and possible tectonic evolutionary models, have been made which will eventually lead to a major revision of the significance of this orthotectonic segment.

The orthotectonic belt of Britain and Ireland has a clearly defined NNE/SSW trending thrust-front and consists essentially of two major lithostratigraphic units referred to as the Moine (best developed NW of the Great Glen fault, Scotland) and the Dalradian (SE of the fault; see Fig. 2).

Figure 2. Caledonides of the British Isles.

The Moine, long regarded as a sub-Dalradian continental prism sequence of Late Precambrian age, and probably the time-equivalent of the Torridonian clastic sequence of the foreland, is now known to be an extremely complex tectono-stratigraphic unit. In addition to the long-recognized "Lewisian inliers", the Moine is now considered to contain at least two major sequences which display different patterns of orogenic development. Evidence indicates widespread presence of metasediments and gneisses, initially deformed and metamorphosed during the Grenville Orogeny around 1000-1100 Ma ago.

Some have also claimed the existence of a later Precambrian orogenic phase (the Morarian) at around 700-800 Ma ago, though evidence for this is more tenuous (van Breeman et al., 1978). Rocks unaffected by these events (that is, the younger Moines or Grampian Group), are now considered to be a cover sequence to older metamorphic rocks, passing vertically upwards into the more varied shallow-water sequence of the Dalradian.

Glencoul Thrust of the Moine thrust zone showing Lewisian gneiss of Archean age, separated from the underlying Cambrian (Durness) limestone by a mylonite zone. (Photo courtesy W.C. Morgan)

In early plate-tectonic models, the Dalradian, which spans the Precambrian-Cambrian boundary and possibly extends into the lowermost Ordovician, was regarded as a continental rise prism built out from the edge of a developing Atlantic-type continental margin onto oceanic crust to the south (Dewey and Pankhurst, 1970). This is now considered unlikely, since sediments of the Upper Dalradian require a provenance area in continental crust lying to the south of the depositional basin (Harris et al., 1978).

The latter postulate has been enhanced by the discovery of high-grade basement-type metamorphics as inclusions in the Carboniferous volcanic vents of the Midland Valley of Scotland and in Central Ireland, and by evidence from the LISPB seismic experiment (Bamford et al., 1977), where the presence of high-velocity continental crust can be inferred at fairly shallow levels beneath the Midland Valley. An important recent article (Harris et al., 1978) interprets Dalradian sedimentation as having occurred in an ensialic, fault-controlled marginal basin; sedimentation has been

analyzed as a record of several large-scale, basin-deepening and shallowing sequences which indicate a progressive upward increase in tectonic instability.

Metamorphism affecting the Dalradian is essentially of the classical Barrovian type, with a local development in NE Scotland of lower pressure Buchan type metamorphism. The age of metamorphism and attendant deformation is generally placed in earliest Ordovician times, based on a plethora of radiometric age determinations. Williams (1978), however, points to a number of possible ambiguities in this interpretation, while Phillips et al. (1976) suggest that deformation may have been diachronous.

The structure of the Dalradian of Scotland and Ireland is dominated by alpine-type nappe tectonics with associated thrusts. In a recent proposal, the rocks of the Banff Division of NE Scotland are regarded as part of a major thrust nappe separated from the main Dalradian by Precambrian gneisses (Ramsay and Sturt, 1979). That the internal relations in the Dalradian are not simple is indicated by the recognition of Precambrian gneiss units within the sequence - in NW Mayo (Max and Sonet, 1979), the Ox Mountains (Pankhurst et al., 1976) and NE Scotland (Ramsay and Sturt, 1979).

Various attempts have been made to fit the orthotectonic segment of the British Isles into a general geotectonic evolutionary model which embraces also the paratectonic zone (as, for example, by Phillips et al., 1976). There are still many uncertainties in such reconstructions, some of which will only be resolved when palaeomagnetic data, showing a reasonably precise positioning for the British Isles during the Lower Palaeozoic, are available.

The Scandinavian Segment

The Scandinavian Caledonides have a clearly defined south-eastern foreland, with a thin autochthonous sedimentary sequence overlying the crystalline rocks of the Baltic Shield. This sequence is generally of Late Precambrian to Cambrian age, extending locally upwards into the Upper Ordovician in Central Jämtland.

The orthotectonic section of Scandinavia is dominated by extensive nappes thrust great distances, probably in excess of 600 km (Gee, 1978). Large basement windows are exposed in a series of great culminations arching the nappe piles. It has

been shown (in Tozer and Schenk, 1978) that the nappe sequences are complex, and contain, in addition to Caledonian metamorphics, Precambrian sialic gneisses and probably metasediments as well. In addition, it was recently established that considerable fragments of obducted oceanic crust in the form of ophiolites occur within the nappe sequence (Furnes et al., 1979).

The orthotectonic evolution of the Scandinavian Caledonides occurred in two major orogenic cycles: the Finnmarkian and the Main Scandinavian. The Finnmarkian has its type area in northernmost Norway (Sturt et al., 1978) where it impinges directly on the autochthon and is truncated by later nappes belonging to the Main Scandinavian cycle. It involved the emplacement of a series of nappes containing distinctive basement-cover couplets. Orogenic metamorphism was entirely of the medium pressure Barrovian type, with a general increase in grade upwards through the nappe pile; it took place during Late Cambrian and Early Ordovician times. Basement gneiss shows evidence of variable degrees of Caledonian reworking, although local stratigraphic unconformities with the overlying Caledonian sediments are preserved.

The highly unusual synorogenic magmatism of the Seiland Province is found in West Finnmark and includes a large number of layered gabbro plutons (derived from varied parent magmas), ultramafic plutons and alkaline complexes. The Finnmarkian complex is truncated by nappes of the Main Scandinavian phase in the Lyngen district (Zwaan and Roberts, 1979); further south it was incorporated as a basement element during the Main Scandinavian cycle.

Recent interpretations suggest that there was extensive involvement of oceanic crust in the framework of the Scandinavian Caledonides (Furnes et al., 1979). Large fragments of what is probably oceanic crust are located along the western part of Scandinavia from Karmøy in the south to the Lyngen peninsula in the north. These include the virtually complete ophiolites of Karmøy (Sturt et al., 1979) and Leka (Prestvik, 1979), and a large number of less complete fragments. Stratigraphic evidence from the Storen Ophiolite of the Trondheim region suggests that ophiolite obduction occurred in pre-Middle Arenig time, though, with lack of faunal control, the obduction of other fragments cannot be dated more precisely than sometime prior to the Middle/Upper Ordovician.

The implications of this are profound and point to major ophiolite obduction being more or less contemporaneous with the thrusting, folding and metamorphism of the Finnmarkian continental prism. This pattern appears to correlate well with the major ophiolite obduction in western Newfoundland and the deformation and metamorphism of the Fleur de Lys continental prism (Williams, 1978).

A significant feature in the western part of the orthotectonic zone is the widespread evidence for a major tectono-metamorphic hiatus marked by uplift, deep-seated erosion and deposition of transgressive continental or shallow marine deposits in the Ordovician. Except for parts of the Trondheim region, there is no precise stratigraphic evidence for dating the hiatus more accurately than Pre-Upper Ordovician, and the need for obtaining precise stratigraphic data for the transgression in different regions is obvious.

Following Finnmarkian orogenesis and ophiolite obduction, erosion products accumulated in continental and shallow water marine deposits, and in thick, deep-marine infill of major sedimentary basins. The evolution of the volcanic island arc and marginal back-arc basin (which developed in early to mid-Ordovician times in Iapetus), is particularly well illustrated in the Trondheim region (Furnes et al., 1979). No clear evidence is yet available to indicate ophiolite obduction during the Main Scandinavian orogenic phase.

The major thrusting, accounting for the present-day distribution of the major post-Finnmarkian nappes, occurred mainly in late Silurian time, though evidence suggests that it continued through into post-Lludlow or even post-Downtonian

Folding in Silurian sandstones and quartzites, Rannasen, Jämtland, central Sweden. (Photo courtesy National Museum of Wales).

times (Gee, 1978). Metamorphism is again essentially of the medium pressure Barrovian type with local areas of low pressure Abukuma type occurring in the southern part of the Trondheim region (Guezou, 1977). The timing of the peak of orogenic metamorphism, based on reasonable stratigraphic and geochronological control, is Wenlockian in age and essentially prior to final nappe emplacement.

One of the great unresolved problems regarding nappes of the Main Scandinavian lies in identifying the provenance of great crystalline sheets high in the nappe sequence in southwestern Norway, such as the Jotunheim and Hardanger-Ryfylke nappe systems. This is of obvious importance to formulation of an evolutionary geotectonic model, especially when it has been shown that nappe units high in sequence in the East Greenland Caledonides bear similar high grade Precambrian gneisses (Higgins, 1976).

Lower Ordovician Venna volcanic conglomerate with intercalated volcanics, Hølanda area, Norway. (Photo courtesy W.H. Poole)

Comparing the Segments

Looking at the differences in the evolutionary pattern of the British/Irish and the Scandinavian orthotectonic belts, one notes the similarity of timing of the Grampian and Finnmarkian orogenic episodes. The Dalradian, however, was deposited in a marginal basin, whereas the time equivalent sequences of Scandinavia developed as a continental prism along the margin of a major ocean, followed by substantial obduction of oceanic crust onto the Scandinavian margin in early Ordovician times.

During the Ordovician, the metamorphic Caledonides of Britain and Ireland ceased to be an orthotectonic belt; subsequent tectonics were dominated by vertical uplift. In the western part of the Scandinavian orthotectonic belt, major transgression occurred in the Ordovician and new basinal sequences were deposited on the eroded relics of the Finnmarkian belt, with evidence for island arc development and back arc spreading.

The orogenic activity of the Main Scandinavian phase with its extensive southeasterly nappe translations, folding and metamorphism and local basement reactivation is not represented in the orthotectonic belt of Britain/Ireland. This leads one to point to the enigmatic position of Caledonian nappe sequences of Shetland, which lies north of the British orthotectonic zone. Shetland includes, in part, a sequence of nappes containing a possible major ophiolite slab which Flinn (1959) has likened to the Bergen-Jotun section. It is of interest also that these crucial relations in Shetland have been ignored in almost all geotectonic reconstructions for both the British Isles and Scandinavia, and represent an important area for further study.

Considerable work must be done before meaningful models can be formulated to successfully integrate the patterns of geotectonic evolution of the NE Atlantic Caledonides. There is need for carefully designed paleomagnetic studies to enable precise palaeogeographic positioning of the various segments of the British Isles and Scandinavia during Lower Palaeozoic evolution.

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Non-Metamorphic Caledonides of Great Britain

by

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As outlined below, six geotectonic zones of general NE trend can be recognized in the paratectonic Caledonides of Britain (Fig. 2).

Midland Valley

This is a post-Caledonian graben bounded to the NW by the Highland Border Fault which is traditionally taken as the southern limit of the orthotectonic Caledonides. Recent deep seismic investigations (Bamford et al., 1978) and studies of basement xenolith suites in Carboniferous volcanic necks (Graham and Upton, 1978), have shown that Lewisian-type basement of granulite-facies exists beneath the Midland Valley and possibly represents the southward Lewisian extension of the Hebridean Craton. The basement is probably overlain by a southerly thinning wedge of low grade but intensely deformed Dalradian metasediments, mantled by a weakly deformed cover of mainly marine Silurian and continental early Devonian clastics.

The Southern Uplands Fault is the southern boundary of this graben; most exposures are late Palaeozoic (Devonian, Carboniferous and Permian), although small outcrops of Ordovician and Silurian shale and graywacke occur close to the southern boundary. In addition, there are exposures of the early Ordovician ophiolite-amphibolite-olistostrome complex (at Ballantrae near Girvan), disrupted by NW-directed thrusting which figures prominently in plate tectonic reconstructions of the Caledonides.

Southern Uplands

This area is inferred to be underlain by continental basement, nowhere exposed but characterized by seismic velocities more representative of the 'Pentevrian-type' deep basement of northern England than of the Lewisian-type basement to the north. The exposed cover consists of late Ordovician-early Silurian deep water (perhaps oceanic) Moffat Shales overlain by thick Silurian flysch.

Recent structural re-interpretation of the area between the Southern Uplands Fault and the Ettrick Valley Fault (Weir, 1979) indicates imbricate stacking of the cover sequence on a series of listric faults, propagated sequentially towards the SE during later Ordovician and Silurian time. South of the Ettrick Valley Fault (thought to represent a fundamental

plane of décollement), the Silurian rocks show intense multi-phase folding (though little cleavage) associated with strike-slip faulting.

Lake District - Isle of Man

The north of England is apparently floored by 'Pentevrian-Cadomian-type' deep basement, below which the Moho, at about 30 km, is particularly shallow. The exposed succession starts with about 4 km of late Cambrian-early Ordovician turbidites, the Manx and Skiddaw Slates. Recent work has shown that vulcanicity (previously thought to have been confined essentially to Llandeilo time) occurred throughout the Ordovician. Submarine, tholeiitic lavas were extruded at first, followed by an accumulation of thick calc-alkali subaerial piles, weakly deformed and partially eroded by Ashgill time. Thin transgressive carbonate and clastic sequences of late Ordovician age were followed by several kilometres of Silurian turbidites.

The major deformation took place abruptly near the end of Silurian time, when polyphase folding and associated cleavage occurred within an arcuate slate belt convex to the NW. Granite plutons, emplaced at about this time, coalesced with subvolcanic intrusions of Ordovician age to form the granitic foundation of the Lake District. The density contrast between these intrusions and their country rocks has controlled in large part the subsequent tectonic and sedimentary history of the whole region.

Irish Sea Horst

Pre-Caledonian metasediments and basement gneisses of the Mona Complex are thought to have formed a positive region trending SW through Anglesey in early Palaeozoic time. The principal evidence for this - absence of Cambrian rocks in Anglesey in contrast to their thick development on the mainland and the north-westerly Arenig overstep of Cambrian and earlier formations - has now been weakened. A major part of the Mona 'Bedded Series' (including the Gwna olistostromes) is now known to be of Cambrian age (Muir et al., 1979), and structural re-evaluations show that much of the multiphase deformation and metamorphism previously assigned to the Cadomian is Caledonian (Barber and Max, 1979).

Welsh Basin

Long regarded as a classical geosyncline, this area is still seen to comprise an ensialic basin filled by a thick sequence of dominantly shallow marine clastic and volcanic rocks of latest Precambrian (Arvonian) to Silurian age. Although strain studies have indicated that the sequence is thinner in certain areas than previously supposed, it is probably in excess of 10 km where bolstered by volcanic piles. The volcanics are dominated by acid, often ignimbritic volcanoclastics, and range in age from latest Precambrian (Arfon) through Arenig-Llanvirn (Cader Idris) to Caradoc (Snowdon). The volcanic outbursts were preceded by crustal updoming, followed by erosional overstep and accumulation of a thick Silurian flysch, later converted into a slate belt.

The tectonic pattern is more complex than that of the Lake District, and the strain diminishes markedly toward the SE margin where, in the Welsh Borders, there is a sedimentary transition upward into continental Devonian. As in the Lake District, the main deformation appears to have taken place close to the end of the Silurian or in the early Devonian. Recent suggestions (Davies and Cave, 1976) that the cleavage is an early diagenetic feature associated with primary dewatering of sediments have not met with acceptance. In contrast with the Lake District and Southern Uplands, no

Hutton's unconformity, Siccar Point, near Berwick on Tweed, England. The section shows near-vertical Silurian rocks overlain with gross unconformity by almost horizontal Old Red Sandstone strata; it is the locality at which James Hutton first appreciated the significance of unconformities. (Photo courtesy National Museum of Wales)

Cliff section SW of Rhoscolyn, Anglesey, North Wales, showing folded metamorphosed turbidites of the South Stack Formation, part of the Monian Supergroup. The latter was deposited in late Precambrian times, and may represent an early Caledonian geosynclinal basin fill. (Photo courtesy National Museum of Wales)

major Caledonian granites are found in this region at the present level of exposure, although subvolcanic and hypabyssal intrusions are widespread.

Midland Craton

The Welsh Basin is flanked to the SE by an apparently isolated cratonic area which is characterized by thin, 'shelf' sequences of weakly deformed Lower Palaeozoic strata. The accessible sub-Cambrian rocks comprise altered gneiss remnants, probably of late Proterozoic age, and a varied cover sequence dominated by coarse clastics and acid volcanics, considerably deformed and faulted with minimal metamorphism in latest Precambrian time.

Pillow lavas of the Fishguard Volcanic Group, South Wales, U.K. - products of an episode of igneous activity during early Ordovician times. Average diameter of the long axis of pillow is about 75cm. (Photo courtesy National Museum of Wales)

Plate Tectonic Interpretation

It is widely accepted that a plate tectonic hypothesis which involves the creation and destruction of a major ocean (Iapetus) provides the only adequate uniformitarian interpretation of the Caledonide orogen. Evidence for the existence of Iapetus is provided by the provinciality of Cambrian and early Ordovician shelly faunas. Few surviving fragments of oceanic lithosphere have been identified with certainty, and the palaeomagnetic data from the opposing plates are insuff-

ficiently precise to define the width of the ancient ocean.

The strongly contrasting physical nature and age of stabilization of the deep basement to the north and south of the Southern Uplands, places the boundary between the Laurentian and Afro-Asian plates somewhere in that region. The tectonic style and aeromagnetic 'grain' change abruptly at the Solway Line (Fig.2), and this is now regarded as the most likely site of the Iapetus suture (Phillips et al., 1976). The climactic tectonism that affected the non-metamorphic Caledonides at the close of the Silurian can only be seen as a massive conversion of kinetic energy into work: collision-type orogeny.

Beyond these basic points, the details are far from clear. In particular, the geometry and timing of subduction are matters of continuing speculation because the evidence is generally scant and/or ambiguous. The multitude of hypotheses put forward over the last decade cannot be reviewed here, but some consensus views are emerging.

It is widely agreed that

- . northerly subduction occurred in Ordovician time along a line close to the Southern Uplands Fault;
- . the imbricate structure of the central Southern Uplands results from the accretion of a flysch wedge onto the northern continental margin;
- . the Ballantrae complex represents oceanic lithosphere obducted northwards; and that
- . southerly subduction took place in the Ordovician beneath the Lake District.

An earlier phase of northward subduction has been invoked to account for the Grampian Orogeny in the metamorphic Caledonides, and southward subduction at the Solway Line to explain the distribution of volcanicity, not only in the Lake District, but in Wales. Both are acceptable working hypotheses. The recently proposed ideas that the end of subduction is marked by the cessation of volcanicity is less acceptable: it implies that no significant subduction occurred in the Silurian. The corollary - that the cessation of volcanicity indicates the moment of collision - is refuted by evidence from the Lake District where volcanicity terminated in the Ashgill, to be followed by a period of quiescence in the early Silurian. Even wilder speculations - for example, the proposed 960-km wrench displacement on the Solway Line (Phillips et al., 1976) - have no foundation. Nonetheless, collision, in the general case, is likely to have been diachronous and oblique, and to have generated non-coaxial strains and wrench displacements.

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Non-Metamorphic Lower Palaeozoic Rocks of Ireland

by

P.M. Bruck

The Lower Palaeozoic sequence on the northwestern side of the Solway Line (Iapetus Suture) in Ireland (Phillips et al., 1976) is essentially an extension of the Scottish Southern Uplands. Its main developments are in Longford-Down, Tyrone, Mayo, Galway and the northern central inliers.

The oldest rocks occur in the north and comprise, at the base, a thick succession of lower and middle Ordovician volcanics. These are overlain by upper Ordovician turbidites with cherts, slates and volcanics exposed chiefly in the region of Longford-Down. In Mayo and Galway, Silurian shelf rocks and turbidites rest unconformably on older strata. In Longford-Down, however, the Silurian is thick, conformable, and turbiditic; the structure is complex and similar to that of the Scottish Southern Uplands.

The succession SE of the Iapetus Suture is comparable with that in the Lake District. At Leinster, the rocks range upwards in thick, continuous and discontinuous sequences, from Lower Cambrian to Llandovery, and in Slievenamon from Upper Cambrian to Wenlock. In the eastern inliers, both Ordovician and Silurian sequences occur, while the western Lower Palaeozoics are entirely Silurian. Sandstone and siltstone turbidites dominate all the successions.

There are also important volcanics, particularly of upper Ordovician age in Leinster, lower-upper Ordovician age in the eastern inliers, and Wenlock in Dingle in the southwest. The structure is defined by major and minor upward facing folds with a variably developed cleavage, generally dipping steeply to the southeast.

Reference

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Late Lower Silurian (Upper Llandovery) red siltstone, slate, graywacke in an anticline of Caledonian age, Clogher Head, Leinster zone, Co. Louth, Ireland. (Photo courtesy W.H. Poole)

Caledonides of East and North Greenland and Svalbard

by

N.J. Soper

East Greenland

The East Greenland Caledonian orogen underlies a 50-200 km-wide tract between the coast and inland ice from 70°N to 82°N. The tectonic trend is roughly N-S and the western margin is overthrust. Much of the belt is composed of gneiss complexes. In the south, the Flyverfjord infracrustal complex has yielded Archaean isotopic ages (ca 3000-2300 Ma) and is overlain by a cover sequence (the Krummedal supracrustals) which underwent orogenic deformation in mid-Proterozoic time (ca 1245-1000 Ma).

Between 72°N and 74°N, gneisses form involuted domes and mushroom shapes mantled by metasediments which, in the classic interpretations of Backlund, Wegmann and Haller, were regarded as Caledonian migmatite fronts. Recent research (Higgins, 1976) favours an origin in the multiphase interfolding of basement gneiss and later cover, and this is supported by the early Proterozoic (ca 2000-1700 Ma) isotopic ages on the gneisses. The region was evidently the site of an extensive early Proterozoic mobile belt. An obvious comparison can be drawn between the three pre-Caledonian orogenic cycles of East Greenland and the Scourian, Laxfordian and Grenville-Moravian of northwestern Scotland.

Between 76°N and 81°N, a thick sedimentary sequence previously referred to as the Thule Group (from an assumed

correlation with the Thule Group *sensu stricto* of NW Greenland - now not accepted) is affected by Proterozoic open folding assigned to the Carolinide orogeny. Gneisses between 76°N and 78°N were thought to result from a Carolinian phase of crustal reworking, although a sample from these gneisses, yielding an Archaean age, has thrown doubt on the orogenic status of the Carolinides.

Late Proterozoic sedimentation was widespread. In the north, the Hagen Fjord Group attains 5 km in thickness. South of the fold belt, the Eleonore Bay Group comprises a lower 8 km sequence of deltaic and fluvial quartzites and shales (reminiscent of the Grampian Group of the Scottish Dalradian), and an upper 4 km containing stromatolitic carbonates; the latter extends into the late Riphean and has similarities with the Appin Group of Scotland. The whole sequence is non-flyschoid; previous reports of an ophiolite complex near the base are erroneous.

The Eleonore Bay Group is overlain unconformably by the Tillite Group (< 1 km) of Vendian age, which can reasonably be associated with other late Proterozoic tillite sequences in the North Atlantic region. About 3 km of Lower Cambrian to Middle Ordovician platform carbonates with a Pacific fauna follow; Skolithos quartzite is known from erratics. These Palaeozoic sediments bear a close similarity to shelf succes-

sions of Durness, Scotland and Western Newfoundland. Flyschoid basinal sequences of this age are unknown in East Greenland.

Caledonian deformation is less intense than previously supposed and generally takes the form of open N-S folds in the cover, with large scale westerly-directed thrusts in the basement gneisses and along the western margin. Metamorphism of the cover is only significant in the lower part of the Eleonore Bay Group, but reaches amphibolite-facies in the pre-Caledonian basement gneisses where it is often sufficiently intense to reset Rb-Sr mineral, but not whole rock, systems. Mineral ages suggest stabilization in the interval from late Ordovician to early Devonian in different areas. Granitic intrusives, mainly confined to the southern half of the fold belt have, in the few examples dated, given Ordovician ages. There are very thick late orogenic intermontane molasse deposits of Middle and Upper Devonian age.

North Greenland

An E-W trending Caledonian fold belt occupies northernmost Greenland (N of 83°N) and continues into the Canadian Arctic Archipelago as the Franklinian mobile belt. South of the fold belt in Greenland, an undeformed platform sequence consists essentially of late Proterozoic-'Eocambrian' siliciclastic sediments, Lower Cambrian-Silurian shelf carbonates and late Silurian flysch. The platform carbonates pass rapidly northward into basinal arkosic and calcareous turbidites. The shelf edge was defined by E-W syn-sedimentary faults which migrated progressively southward through early Palaeozoic time.

The fold belt coincides approximately with the flysch basin, and its southern margin is quite abrupt but unthrust. Multi-phase folds verge northward and intensify in that direction, accompanied by an increase in metamorphic grade to amphibolite-facies on the north coast. The fold belt is terminated in the north by a Tertiary thrust zone with greenschist mylonization which transported the metamorphics over late Palaeozoic sediments and late Mesozoic volcanics (Kap Washington Group).

The major tectonic evolution of the fold belt is believed to be Caledonian. The oldest cover rocks recorded are Upper Carboniferous or Permian; no Devonian cover has been identified in the region. Basement gneiss is not involved in the fold belt at the level exposed, but amphibolite-facies gneiss xenoliths are recorded from volcanic necks. There are no Caledonian plutonic rocks.

Svalbard

Although pre-Atlantic reconstructions place Svalbard (Spitsbergen) in juxtaposition with the Wandel Sea shelf, where the projected trends of the East and North Greenland fold belts meet, the geology of Svalbard throws little light on the inter-relationship of these belts. Perhaps, if Harland's (1978) hypothesis is accepted, this is because Svalbard would appear to comprise three distinctive Caledonian provinces, originally widely separated and brought into juxtaposition by major, late Devonian wrench displacements.

The eastern province includes the Ny Friesland peninsula, type locality of the well-known Hecla Hoek succession, which has Cambro-Ordovician carbonates with Pacific faunas at the top, and ranges down through tillites and carbonates into an enormously thick, largely volcanogenic clastic sequence whose metamorphic grade increases with depth. The upper part has similarities with upper Eleonore Bay and later sediments of East Greenland; in both the eastern and central provinces, the main tectogenesis (the Ny Friesland Orogeny) took place in mid-Silurian time.

The successions in the western province are characterized, at least in the upper parts, by turbidites of the Høltedahl Geosyncline, subjected to easterly directed thrusting and folding in late Silurian or Devonian time. Affinity with the North Greenland-Franklinian mobile belt is evident.

According to Harland's hypothesis, in early Palaeozoic time the western province was much closer to North Greenland while the eastern province was closer to East Greenland. This idea awaits a definitive test, which could perhaps be provided by palaeomagnetic studies.

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Caledonian Fold Zones Peripheral to the North Atlantic Caledonides

by

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The extent and degree of Caledonian folding on the continent of Europe SE of the North Atlantic Caledonides and SW of the East European platform are not easily determined, mainly because early Palaeozoic strata are not commonly exposed or are difficult to recognize within areas of Hercynian and/or Alpine folding.

There are some unequivocal Caledonian fold-zones such as the Brabant massif, the Ardennes massifs, and the Rügen-Pomeranian belt under the North German-Polish plain. There are regions such as the Sudeten in which the existence of Caledonian orogenesis has been vigorously disputed and even discounted. There are also those parts of the Bohemian massif, the Alpine massifs and crystalline nappes, the

Schwarzwald, Vosges and Massif Central which have given abundant Rb-Sr isochron ages in the Caledonian range 350-500 Ma, reputedly dating high-grade metamorphic and magmatic events (Jager, 1977).

Autran and Guillot (1977, Fig. 4) have devised a pre-Atlantic reconstruction showing a Caledonian (essentially Acadian) metamorphic belt extending from the Massif Central through Newfoundland into the Appalachians. The same belt presumably spreads out eastward to the Bohemian massif and the Alpine zone, as shown in Figure 1. If this is a real Caledonian orogenic belt - and good stratigraphical evidence for this seems to exist only in the northwestern Massif Central, at Limousin - it must constitute some sort of 'Pan African'-type

internides to all the external Caledonian fold-zones to the north, that is, Brabant, Ardennes and Rügen-Pomerania.

On evidence available at present, it is not possible to connect the Brabant-Ardennes fold-zone across north Germany to the Rügen-Pomeranian Caledonides. In fact, the clear discordance between the strongly folded Lower Palaeozoic and the Devonian (Gedinnian) in the Ardennes massifs cannot be traced eastward into the Rheinische Schiefergebirge; neither can the discordance between folded Silurian and Givetian in the Brabant massif be traced westward beyond the Région du Nord in NE France.

The Brabant massif apparently extends under the Mesozoic cover into SW England in the region north and south of the Thames Estuary. But it is difficult to establish a connection with the NW British Caledonides on land, via the East Midlands Caledonian aulacogen of Evans (1979), or off the coast of East Anglia via the Mid-North Sea geosyncline of Wills (1978) on the scant borehole evidence.

The Rügen-Pomeranian Caledonides situated on the SW boundary of the East European platform (as proposed by Tornquist) comprise an 8-10 km-thick Ordovician-Silurian miogeosynclinal sequence (Dadlez, 1974) strongly overfolded toward the platform. Under the name of "Danisch-Polnische Tafelrandsenke" (Franke, 1977), it may underlie northern Denmark. The big question then, is whether or not it crosses the North Sea to connect with the non-metamorphic Caledonides in Britain. This latter geotectonic unit, comprising thick volcanic and flyschoidal formations characterized by mediotype folding, is unrepresented in Scandinavia.

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Curator of London's Geological Museum, a part of the Institute of Geological Sciences, U.K., **Frederick W. Dunning**, O.B.E., joined the Geological Survey of Great Britain in 1950 after graduating from the University of Wales at Cardiff. Author of the Tectonic Maps of Great Britain, he has served on three CGMW subcommissions, participating in several international map projects since 1959. He is perhaps best known for his 'marathon' lectures on the geological structure of the British Isles, and for the popular geological exhibit "Story of the Earth" conceived and produced in the early 1970's.

Dr. N.J. Soper has been on staff at the University of Sheffield in England since 1964. His original research on the granitic intrusions of Rogart in the Scottish Highlands was followed by work on the Lake District and the Moine Thrust. He participated in the British Joint Services Expedition to North Greenland in 1969 and has since made several visits to East and North Greenland. An editor of the *Journal of the Geological Society* from 1977 to 1979, he was awarded the Society's Lyell Fund in 1979.

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