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Palaeozoic palaeogeography: A North Atlantic viewpoint

TROND HELGE TORSVIK

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Abstract: Palaeozoic palaeogeography, highlighting the North Atlantic Caledonian evolution and the destruction of the Iapetus Ocean and the Tornquist Sea, is recapitulated with reconstruction maps from Early Ordovician to Mid-Devonian times. In the Early Ordovician (Tremadoc–Arenig), Laurentia, Siberia, and the North China Block were positioned in equatorial latitudes, Baltica was located at intermediate southerly latitudes, whilst Avalonia and the European Massifs were located together with the North African part of Gondwana in high southerly latitudes. During the Ordovician, Baltica drifted northwards and approached Siberia while undergoing counter-clockwise rotations. Avalonia rifted away from Gondwana during Arenig–Llanvirn time, and the Tornquist Sea, separating Avalonia and Baltica, narrowed gradually during the Ordovician followed by Late Ordovician ‘soft docking’ of Eastern Avalonia and Baltica prior to their joint collision with Laurentia. The main collisional event between Baltica and Laurentia occurred at c. 425 Ma and was marked by deep subduction of Baltican crust beneath Laurentia with concomitant eastward translation of nappes over the Baltican margin. Deep subduction was a function both of rapid motion of Baltica (8–10 cm/year) toward a stationary Laurentia and precedence of prolonged subduction of large volumes of cold lithosphere. Shortly after collision, in Emsian times, these rocks were exhumed by extensional collapse.

Keywords: Palaeozoic, North Atlantic, Caledonides, palaeogeography, palaeomagnetism.

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We have witnessed many changes and improvements in palaeogeographic modelling over the last two decades, and it is fair to state that Palaeozoic palaeogeographic models often have a short ‘shelf time’. New and better data invariably accumulate, but many classic papers (e.g. Cocks & Fortey 1982; Van der Voo 1988; Ziegler 1990; McKerrow et al. 1991), still hold as good first approximations. In this account I discuss Palaeozoic palaeogeography with a North Atlantic focus, highlighting Baltica and its interaction with Laurentia and Siberia in space and time. Palaeomagnetic data, if available, form the basis for the palaeogeographic reconstructions, complemented by faunal, facies, and petrotextonic data. The palaeogeographic scenarios depicted in Figs. 1–7 are based on data detailed in Torsvik et al. (1992, 1996), Hartz et al. (1997), and Smethurst et al. (1998a). Time-scales are adjusted to those of Tucker & McKerrow (1995) and Tucker et al. (1998).

The main players

The Early Palaeozoic continental plates comprised the independ-

ent plates of Laurentia, Baltica, Siberia, and North China, as well as the Gondwana ‘associates’ which were fully assembled by Late Precambrian (c. 550 Ma) times (Meert & Van der Voo 1997). The Laurentian plate includes North America, Greenland, and the ‘European’ elements of Scotland–North England and North Ireland, all of which ultimately collided with Baltica and Avalonia during Silurian times (Figs. 1–5).

Baltica broadly includes Eastern Europe (west of the present-day Urals) and Scandinavia; on most palaeogeographic maps, the NE margin of Baltica includes Novaya Zemlya. Other maps have depicted the northern and central parts of Taimyr as part of Baltica during the Palaeozoic (Ziegler 1990; Pickering & Smith 1995; Nikishin et al. 1996) or alternatively, as a separate micro-continent which ultimately collided with Siberia in Late Permian–early Triassic times and became an extension of the polar Urals. However, recent evidence may indicate that Baltica actually extended NE from Novaya Zemlya through to and including Taimyr in the Early Palaeozoic (Fig. 1): the identification of Bai-kalian(Baltica)-age deformation (620–575 Ma) in parts of Taimyr (Gee 1996) and documented compatibility between Late Ordovician (mid-Ashgill) fauna from central Taimyr and Baltica (Cocks & Modzalevskaya 1997) may suggest links between Baltica and north-central Taimyr from Late Precambrian time onward.

Other, smaller continental fragments also participated in the Palaeozoic chorus of the North Atlantic and are presently dispersed about the Tornquist margin of Baltica; these include Avalonia (including England) and the European massifs of Armorica, Bohemia, and Iberia. The Tornquist margin presently records Late Ordovician amalgamation and Devonian–Carboniferous collisions between Baltica and the massifs that are now constituents of Variscan Europe (Ziegler 1990; Franke 1989; Matte 1991). Palaeomagnetic data from the European massifs are sparse and therefore inadequate for constructing robust APWP’s for the Palaeozoic; however, palaeomagnetic palaeo-latitude estimates, fauna and facies data show that the European massifs and Avalonia bordered the northern areas of Gondwana during the Early Ordovician (Fig. 1).

Avalonia separated first from Gondwana (Fig. 2) and was eventually welded along the southern Baltic and eastern Laurentian margins. The Armorican, Iberian, Central, and Bohemian Massifs were probably peripheral to Gondwana during lower to mid-Ordovician times (Figs. 1–3). Palaeomagnetic data for Bohemia (Tait et al. 1995) demonstrate rifting away from Gondwana by Caradoc–Ashgill times (Fig. 3), whilst existing, but old, data indicate that the Armorican and Iberian Massifs had close affinities to Gondwana throughout the Ordovician.

Palaeogeographic synopsis

Early Ordovician

In Early Ordovician times, Laurentia, Siberia, and the North China Block occupied equatorial latitudes (Fig. 1) dominated

Early Ordovician (Late Tremadoc–Early Arenig, c. 480–490 Ma)

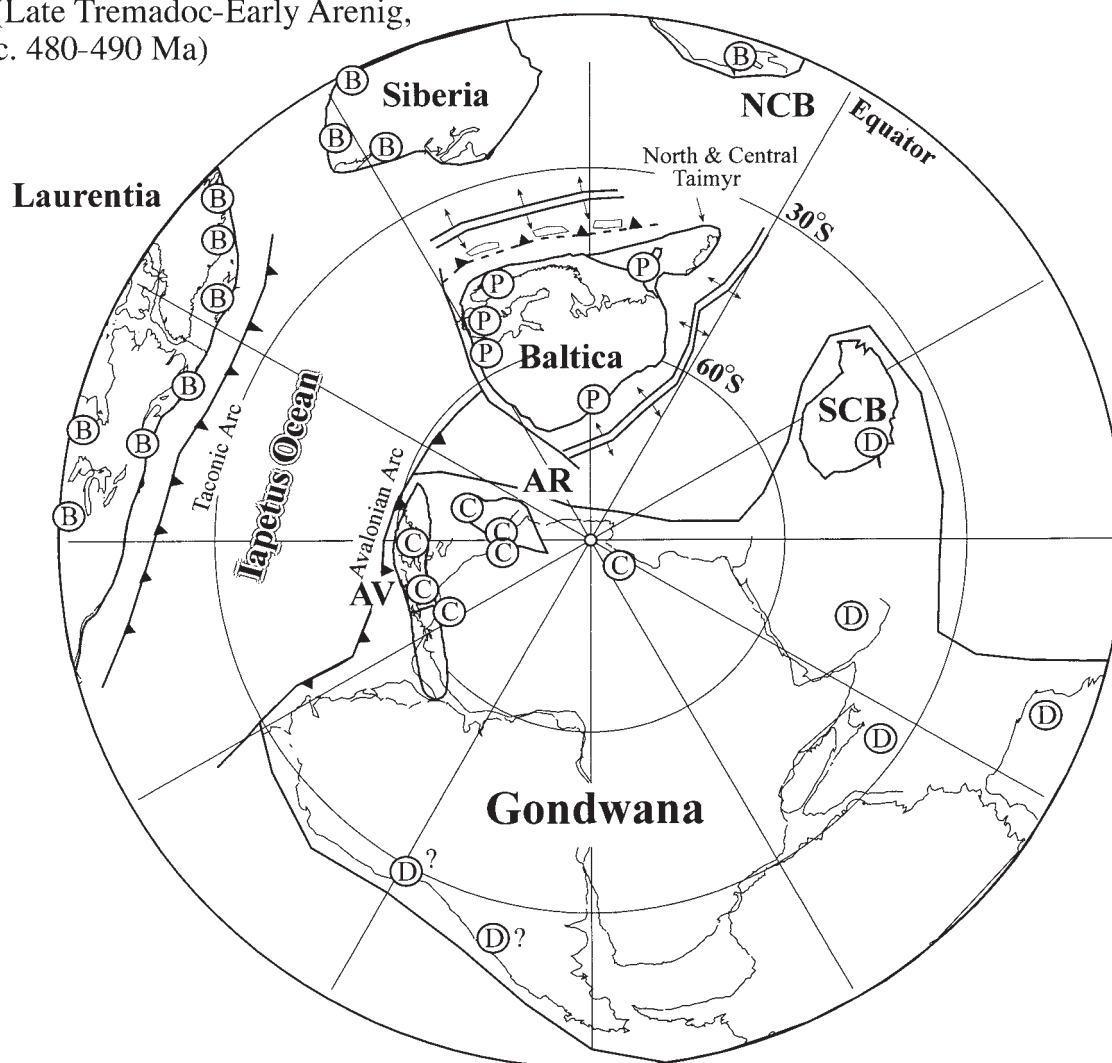


Fig. 1. Early Ordovician, Late Tremadoc–Early Arenig (c. 480–490 Ma), reconstruction (cf. Text). Arenig–Llanvirn platform trilobites (Cocks & Fortey 1990): B=Bathyurid, P=Ptychopygine/Megalaspid, C=Calymenacean, D=Dalmanitacean. NCB=North China Block, SCB=South China Block, AV=Avalonia, AR=European Massifs, including the Armorican, Iberian and Bohemian Massifs. Continents are reconstructed according to palaeomagnetic data which yield palaeolatitude and palaeorotation information; absolute palaeolongitude is unconstrained from palaeomagnetic data and we use the archetypal view (Torsvik et al. 1995b) in positioning continents in relative palaeolongitudes (for alternatives see Dalla Salda et al. 1992, Dalziel 1997).

by warm-water carbonates. Siberia was geographically inverted and the present-day Taimyr perimeter faced the strongly overturned Caledonian margin of Baltica. The passive or transform Torn-quist margin of Baltica faced the Avalonia–European Massifs–Northwest Gondwana conglomerate in high southerly latitudes ($>60^{\circ}\text{S}$). Arenig–Llanvirn platform trilobites (Fig. 1) generally indicate the existence of a separation between the low-latitude continents Laurentia, Siberia, and the North China Block [Bathyurid], intermediate-latitude Baltica [Ptychopygine/Megalaspid], and the high-latitude areas of NW Gondwana/Avalonia/Armorica [Calymenacean–Dalmanitacean] (Cocks & Fortey 1990). This faunal provincialism probably indicates maximum continental dispersal after break-up of the postulated Neo-proterozoic Rodinia Supercontinent (Dalziel 1992, 1997). Compared to an earlier Ordovician reconstruction (Torsvik et al. 1996), Siberia is slightly more displaced from Baltica at the Tremadoc–Arenig boundary (partly due to upgrading the time-scale of Harland et al. 1989 with that of Tucker & McKerrow 1995). However, converging palaeolatitudes during the Arenig (compare Figs. 1 and 2) suggest ‘closure’ of an intervening oceanic

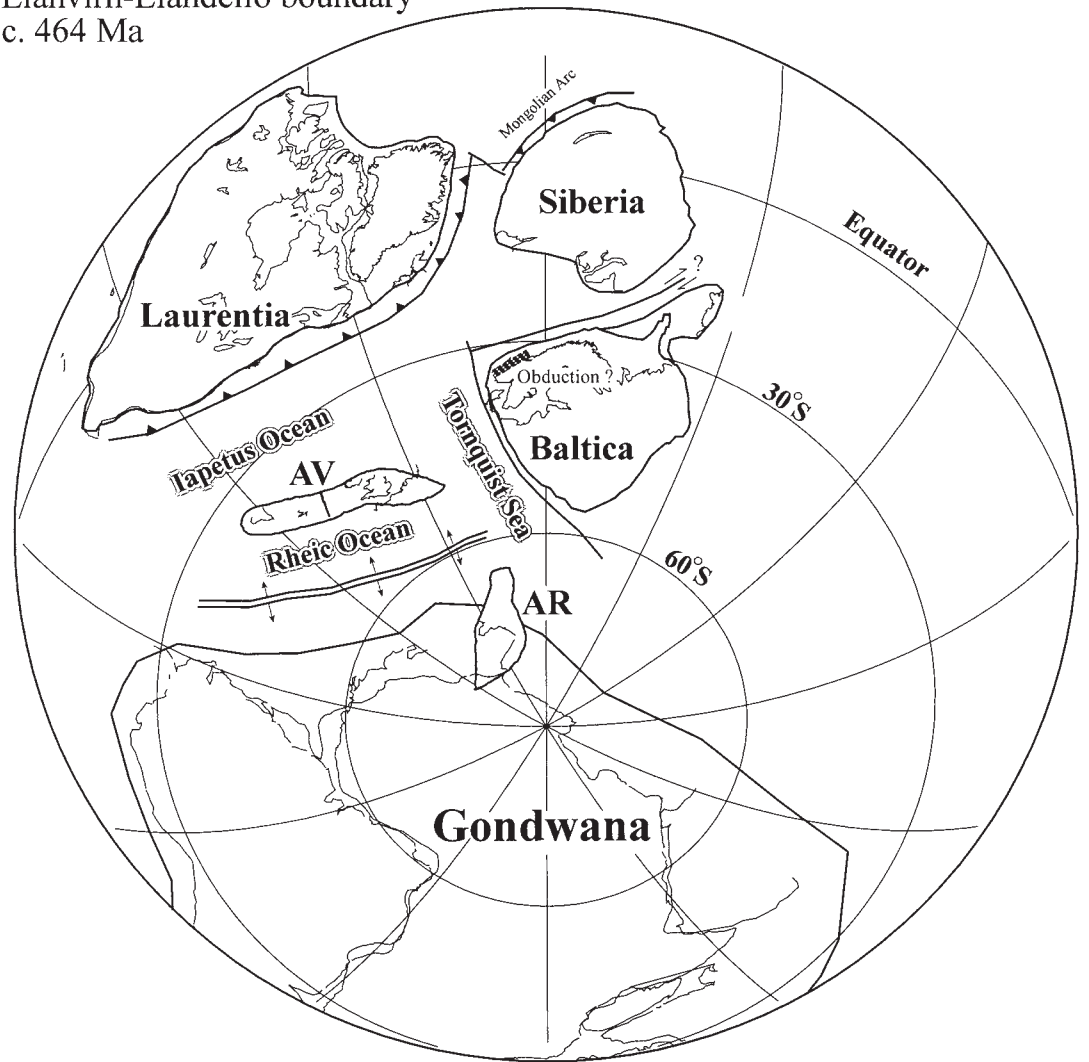
domain with palaeo-northward subduction of Baltic continental crust in an ocean between Baltica and Siberia. This subduction event, with local arc development, was later followed by uplift and retrograde metamorphism of the eclogites and obduction of Early Ordovician ophiolites (Sturt & Roberts 1991) across what is now the western margin of Baltica (Torsvik et al. 1995b). The c. 2000 km wide Tremadocian Ocean between Baltica and Siberia (Fig. 1) was considerably narrowed at the Llanvirn–Llandeilo boundary (Fig. 2). A narrow oceanic separation between Baltica and Siberia may explain the local occurrences of Siberia–Laurentian-type Bathyurid trilobite faunas (Arenig–Llanvirn) in the Central Norwegian Caledonian nappes (Torsvik et al. 1996).

Mid-Ordovician

Avalonia rifted away from Gondwana’s NW margin during Arenig times (Fig. 2) and this resulted in reduction of the width of the Iapetus Ocean across the British sector from 5000 to 3000 km (Torsvik & Trench 1991). An Early Ordovician Avalonian arc-subduction zone (Fig. 1) may have been shut down as

Fig. 2. Mid-Ordovician reconstruction (see text).

Llanvirn-Llandeilo boundary
c. 464 Ma



Avalonia rifted away from NW Gondwana; northward movement of Avalonia was facilitated and enhanced by development of a spreading regime between Gondwana and Avalonia (Fig. 2). A NW-directed subduction zone(s), along or adjacent to the Laurentian margin, is likely to have been established sometime during the Ordovician (Coakley & Gurnis 1995), although the polarity of subduction along Laurentia during the Ordovician remains contentious (see Bock et al. 1996). A southward-dipping subducted margin (Pickering & Smith 1995) along Laurentia during the Early Ordovician (Fig. 1) would require a polarity 'flip' to the NW-dipping configuration envisioned at mid-Ordovician time (Fig. 2).

Late Ordovician

As Avalonia drifted northwards and opened the Rheic Ocean (Figs. 2 and 3), Baltica continued to move northward with simultaneous counter-clockwise rotation; the latter vorticity peaked at c. 2 deg/Ma in Caradoc times (Fig. 3). Closure of the Tornquist Sea between Baltica and Avalonia is indicated by subduction

of oceanic crust (Fig. 3) beneath Eastern Avalonia (Noble et al. 1993) and faunal mixing between Avalonia and Baltica (Cocks & Fortey 1982, 1990; McKerrow et al. 1991). The Tornquist Sea had closed sufficiently to form 'Balonia' (Baltica + Eastern Avalonia) by latest Ordovician (Fig. 4) or earliest Silurian times (Torsvik et al. 1993). Elimination of the Tornquist Sea and production of the North German Polish Caledonides involved a strong component of palaeo-East-West closure and was probably dominated by dextral amalgamation of the two continents (Torsvik & Trench 1991). The timing of this closure may correspond to the early Ashgill Shelveian Orogeny in Britain (Toghill 1992). It is noteworthy that Caledonian Nappes in western Norway (excepting the Jotun Nappe), emplaced on Baltica during Mid-Silurian times, primarily record late Ordovician to early Silurian cooling ages (Andersen et al. 1998) that peak at 450–440 Ma (Fig. 6A, D; Torsvik & Eide 1998). These cooling ages are broadly similar to Taconic (c. 450 Ma) deformation on the Laurentian margin and the age of magmatic-arc activity in Eastern Avalonia (Fig. 3).

Balonia was situated at low latitudes by the end of the Or-

Caradoc (c. 450 Ma)

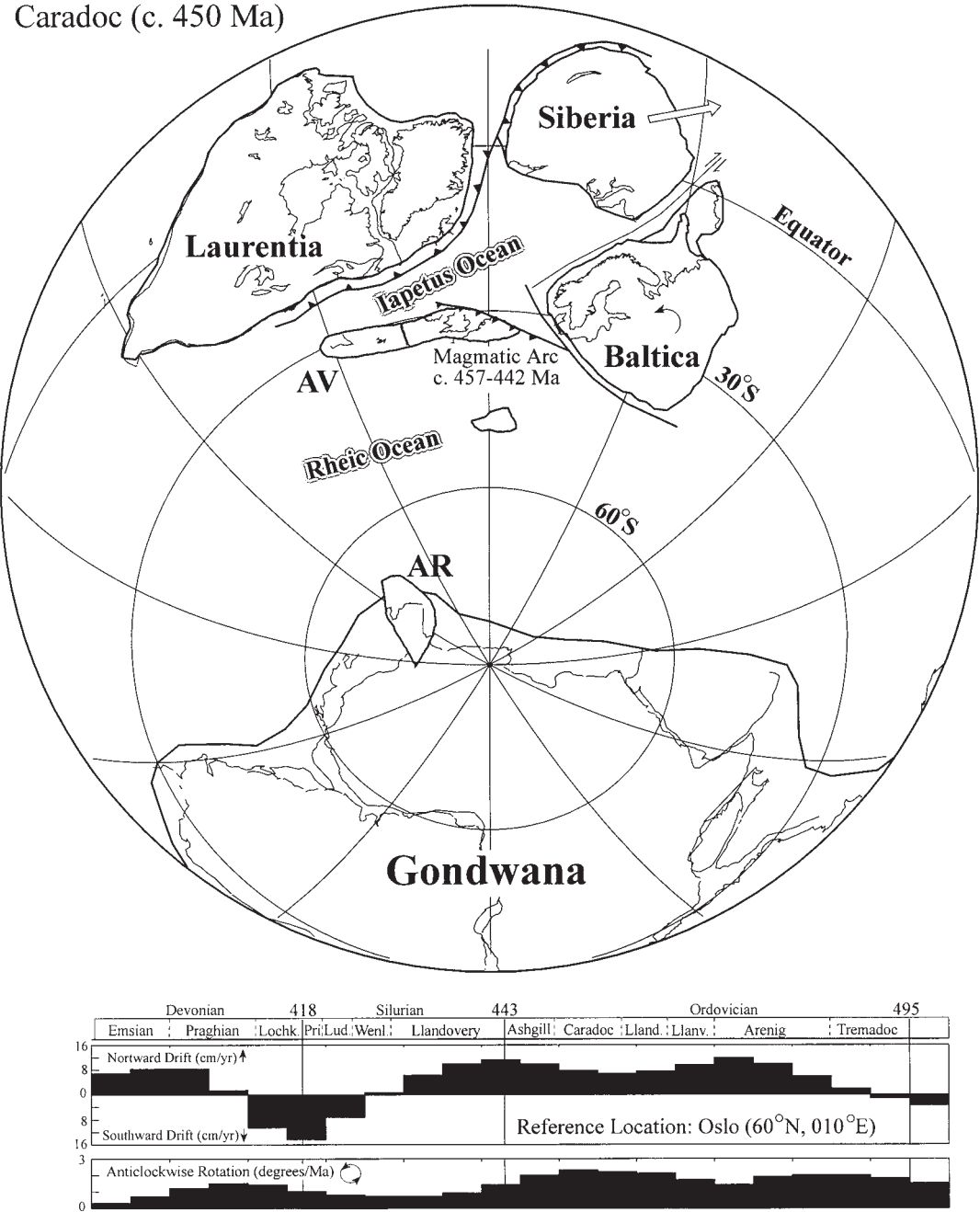


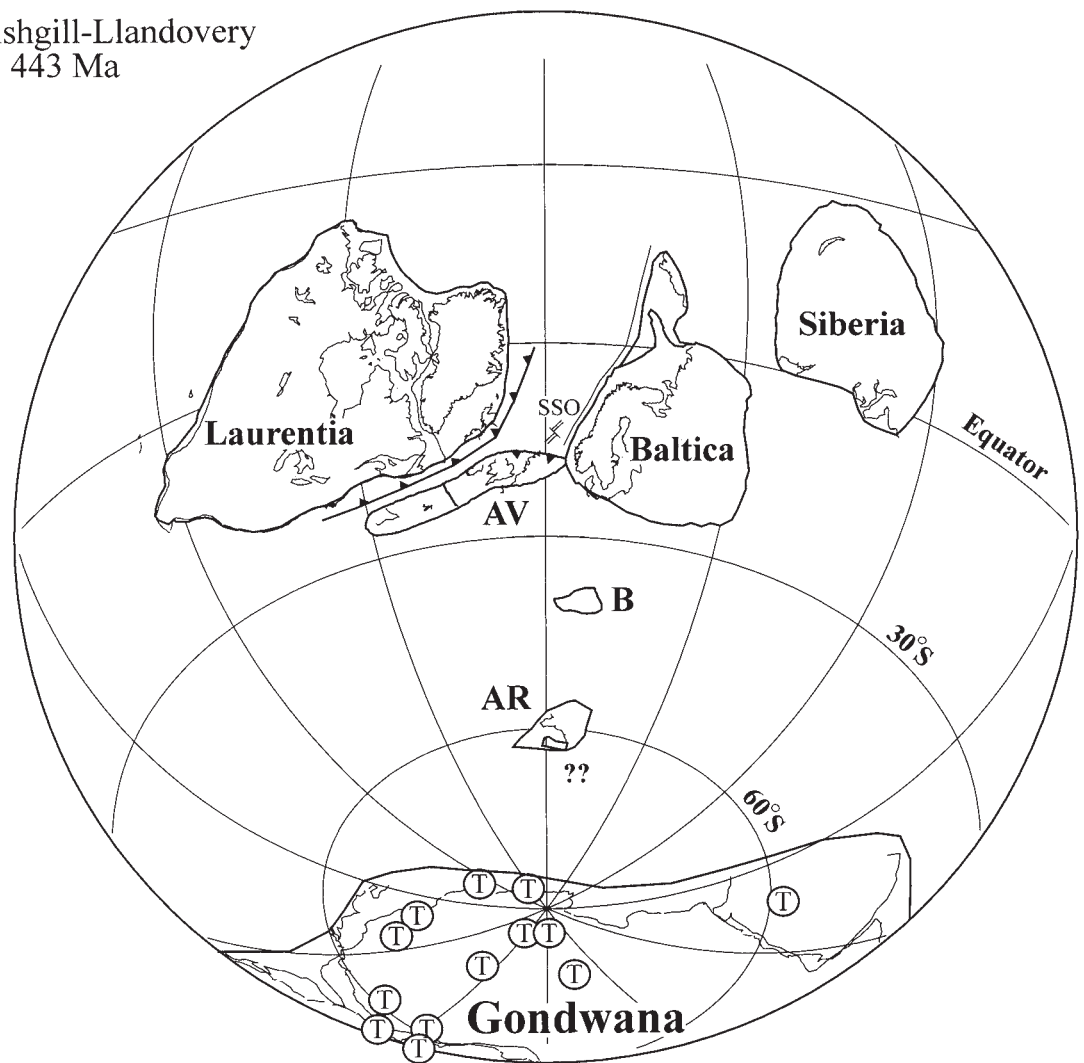
Fig. 3. Late Ordovician, Caradoc (c. 450 Ma) reconstruction. Bottom diagram: Latitudinal drift (cm/year) and angular rotation rates (degrees/Ma) for Baltica (reference location: Oslo, c. 60°N, 10°E) during Ordovician to Devonian times. Time-scale after Tucker & McKerrow (1995) and Tucker et al. (1998). AR as in Fig. 1 except Bohemian Massif (B=Bohemian Massif).

dovician (Fig. 4); this latitudinal shift was marked by the first appearance of warm-water Bahamian-type reefs in Late Ordovician and Mid-Silurian times, respectively, on Baltica and Eastern Avalonia. Conversely, parts of Gondwana were glaciated in the Late Ordovician (Scotese & Barrett 1990; Fig. 4). The Late Ordovician–Earliest Silurian reconstruction (Fig. 4) shows a significant change with respect to the position of Siberia. At this time interval, McKerrow et al. (1991) and Torsvik et al. (1992, 1996) place Siberia north of, but in close connection with, Baltica. The palaeomagnetic data for Siberia at this time are relatively poor, but the newest APW analysis of Smethurst et al. (1998a) appears to indicate a somewhat lower latitude for Siberia (Fig. 4) than previously considered. At this proposed

lower latitude, not enough space exists between Laurentia and Baltica to accommodate Siberia; hence, Siberia must be shifted eastward with respect to Baltica either during or shortly after the Caradoc. During Ordovician to Early Silurian times (Figs. 2–4), Baltica rotated counter-clockwise (vorticity peak during the Caradoc; Fig. 3) as it moved northward. This rotation-translation probably gave rise to a deep-seated, strike-slip regime in the narrowing oceanic tract between Baltica and Siberia (Torsvik et al. 1995b). The strike-slip origin postulated for the extensive allochthonous tracts of Late Ordovician (Ashgill) granites in Mid-Norway (Nordgulen 1993) may have originated in this type of mega-strike-slip regime.

Fig. 4. Late Ordovician–Early Silurian, Ashgill–Llandovery (c. 443 Ma) reconstruction. T=Tillites (after Scotese & Barrett 1990). SSO=Solund-Stavfjord Ophiolite; the SSO is probably related to back-arc spreading and demonstrates that Iapetus oceanic crust formed adjacent to western Norway as late as the Late Ordovician.

Ashgill-Llandovery c. 443 Ma



Silurian–Devonian

The 420–430 Ma palaeomagnetic poles from Baltica, Scotland, and North America (Torsvik et al. 1993, 1996) are virtually identical in a Bullard et al. (1965) fit and indicate that Baltica collided, probably obliquely, with Laurentia and caused the Scandian Orogeny in western Norway during Mid–Late Silurian times (Fig. 5). In Western Norway (Sunnfjord), the continental collision can locally be dated by the stratigraphic and deformational history (Andersen et al. 1990). In this area, the Solund-Stavfjord Ophiolite (443±3 Ma, Dunning & Pedersen 1988) was obducted above continental margin deposits of Wenlock age (428–424 Ma; Fig. 6D). The Wenlock deposits overlie Precambrian rocks which record an earlier ‘Taconian-aged’ (446–449 Ma) cooling event. These cooling ages are marginally older or overlap with the Solund-Stavfjord Ophiolite, a preserved remnant of the Iapetus oceanic lithosphere (Fig. 5), which probably evolved in a Caledonian marginal basin (Furnes et al. 1990).

Prior to their Silurian collision, Laurentia was nearly stationary at the equator whereas Baltica had a rapid northward-directed latitudinal velocity component of up to 8–10 cm/yr (Figs. 5 and 6C). Whole-scale palaeo-westward subduction of Baltic

continental crust gave rise to extreme crustal thickening in the Caledonian Belt, exemplified by the preserved high-pressure terranes in western Norway (Andersen et al. 1991; Dewey et al. 1993; Eide & Torsvik 1996). Sinistral transpressive deformation prevailed (Hutton 1987), probably due to oblique NW–SE collision, and Scandian thrust-related orogenesis continued into Devonian times in northern areas of Norway. The Scandian event was followed by Emsian extensional collapse at least in the southwestern parts of Norway, but from central Scotland to New York compressional events continued in the form of the Emsian/Eifelian Acadian Orogeny (McKerrow 1988). The extensional collapse in western Norway is recorded by uplift-cooling ages from the Western Gneiss Region (lower plate), that peak between 390 and 400 Ma (Fig. 6B). The age of Late Caledonian eclogite metamorphism in the lower plate has often been cited to c. 425 Ma; the high-pressure metamorphism is interpreted to signify the ‘main’ collision between Baltica-Laurentia. An analysis of the most reliable metamorphic ages (Torsvik & Eide 1998), however, shows a large metamorphic age spread between 400 and 450 Ma (Fig. 6B). Moreover, eclogite ages from the upper plate (allochthonous rocks on the Western Gneiss Region) yield a gen-

Wenlock
c. 425

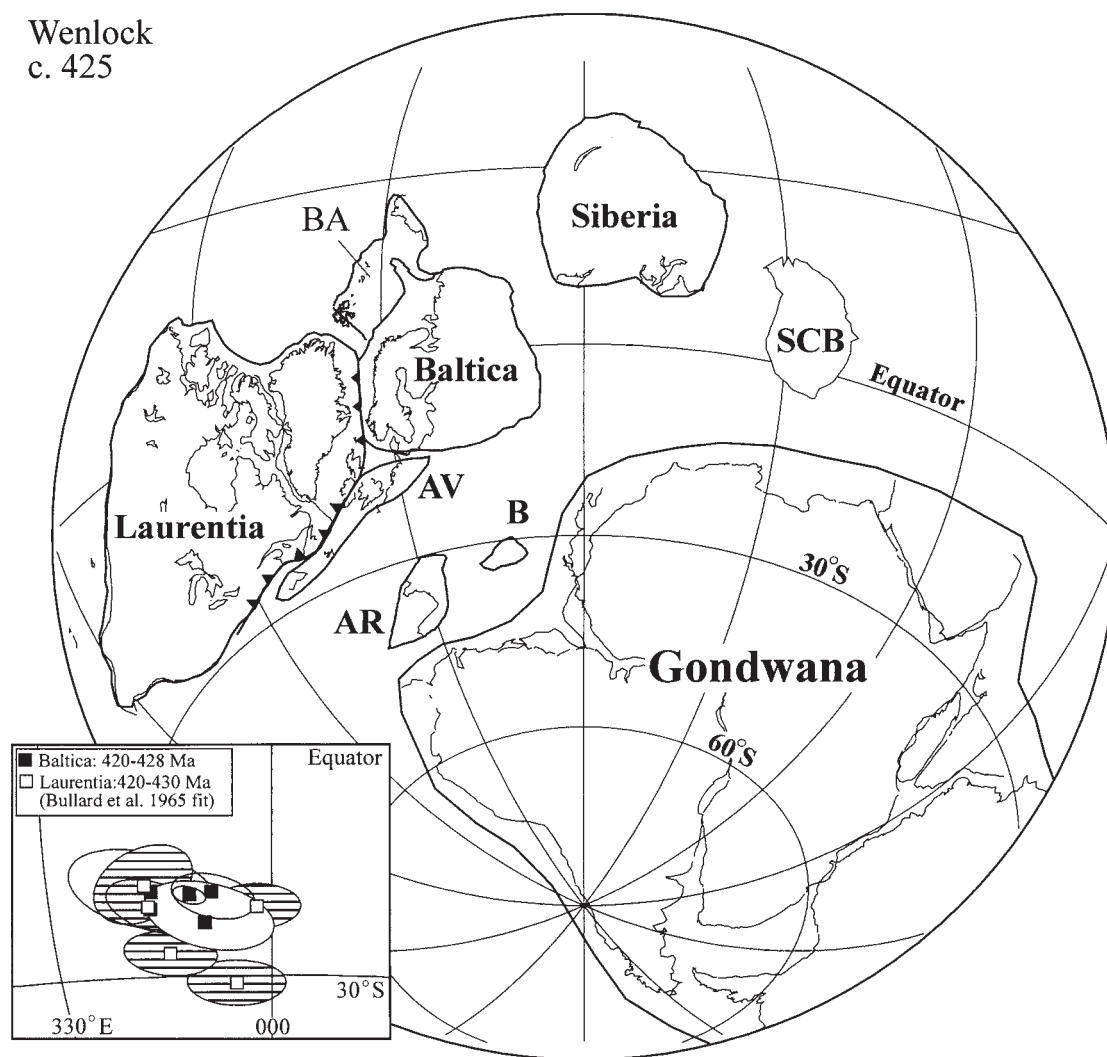


Fig. 5. Mid-Silurian, Wenlock (c. 425 Ma) reconstruction. Inset: 420–430 Ma palaeomagnetic poles from Baltica and Laurentia (North America and Scotland) in a Bullard et al. (1965) fit. Notice the overlap which demonstrates that Iapetus is closed or is so narrow as to be below the resolution power of palaeomagnetic data. BA=Barentsia: reliable pre-Devonian palaeomagnetic data for Barentsia (NE Svalbard and Barents Shelf) are non-existent, hence this palaeocontinent with strong Laurentian affinities (Gee 1996) is typically ignored in most reconstructions. Barentsia is likely to have collided with Greenland at the end of the Llandovery (McKerrow et al. 1991), and is therefore included in the mid-Silurian and Mid-Devonian reconstructions (Fig. 7).

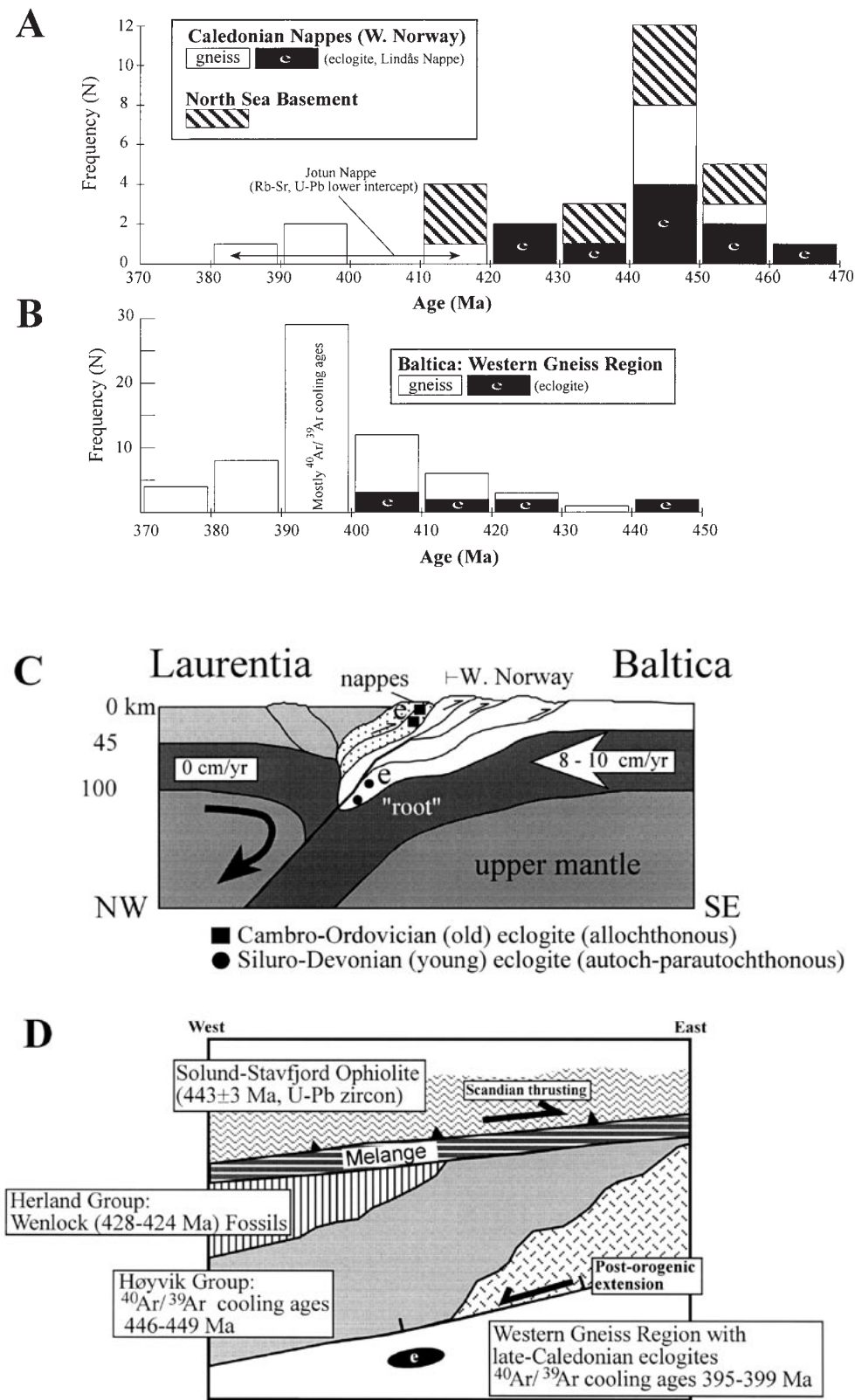
erally higher range of ages (420–470 Ma; Fig. 6A). Thus, data from both plates demonstrate variable ages of metamorphism, probably indicative both of subduction-collision diachroneity (early metamorphism of nappe-eclogites and later metamorphism of Western Gneiss Region eclogites) and of their differential exhumation and final emplacement (Fig. 6C). These data also imply that the oft-quoted '425 Ma' collision-metamorphism event necessarily oversimplifies the operative tectonic processes of the times.

In Mid-Silurian to Early Devonian times, Laurussia (probably comprising Laurentia, Avalonia, Baltica, and Barentsia) rotated counter-clockwise while undergoing southward-directed movement that probably narrowed the oceanic separation from the European Massifs and Gondwana. In Mid-Devonian times (Fig. 7) Euramerica stretched from low northerly latitudes (Taimyr-Barentsia) to intermediate high southerly latitudes (North America). Siberia was still geographically inverted while Kazakhstan probably approached the Baltic margin of Eur-america (Fig. 7). The exact positions, however, for Kazakhstan, the European massifs, and Gondwana are as yet uncertain. Siberia essentially stayed northeast of Baltica until their terminal collision in Late Permian–Early Triassic times.

Conclusion

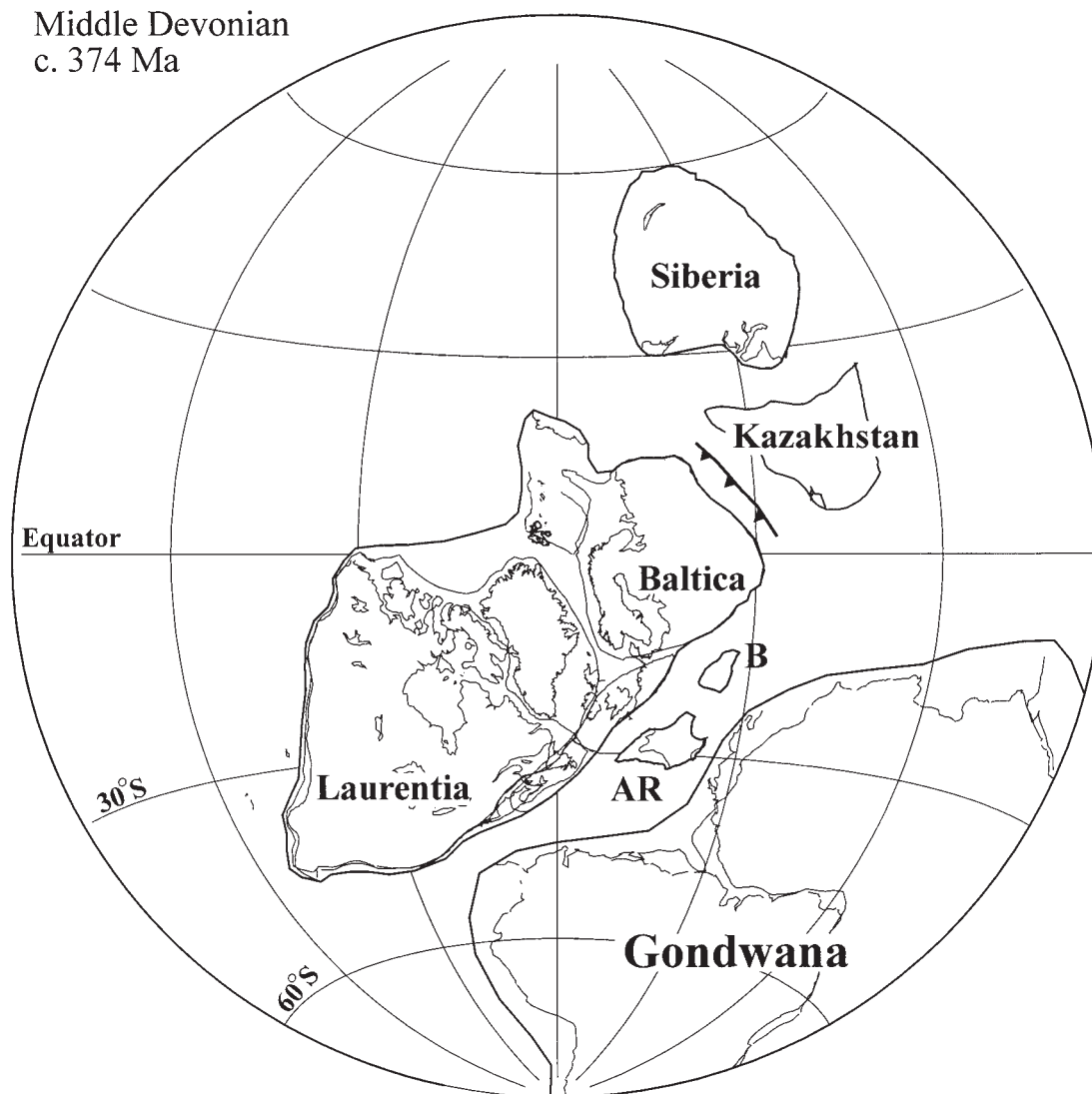
The palaeogeographic snapshots (Figs. 1–7) are fundamentally derived from an archetypal North Atlantic triple-suture approach (Cocks & Fortey 1982; Torsvik & Trench 1991). However, the overall picture is clearly more dynamic than that suture model and is also challenged by models which place Laurentia as a conjugate margin to South America during the Ordovician (Dalla Salda et al. 1992). Fundamentally, rotations of large continental plates further complicate the palaeogeographic syntheses. As an example, the Scandinavian Caledonides (Baltica) probably faced Siberia during the Early–Mid Ordovician (Figs. 1 and 2), whilst the same Baltican margin collided with a different continent (Laurentia) in Mid-Silurian times (Fig. 5) due to counter-clockwise rotation of Baltica in the intervening period. The Baltica rotation-story is essentially derived from Swedish Ordovician palaeomagnetic data which are of premier quality and are part of a stratigraphically linked reversal pattern (Fig. 8A). A new Lower Ordovician (Arenig) pole from Russia (Smethurst et al. 1998b) supports the Swedish data (Fig. 8A) and it is therefore an unavoidable conclusion that Baltica underwent almost 90° of rotation during the Ordovician (Figs. 1–5). Large-scale rota-

Fig. 6. **A.** Isotope ages from Caledonian Nappes in Western Norway and North Sea Basement (probably allochthonous) which show a similar age range. Eclogite ages marked with 'e' (Torsvik & Eide 1998). **B.** Isotope ages from the Western Gneiss Region (Baltica). Shortly after collision between Baltica and Laurentia (Fig. 5), geochronologic and structural evidence indicate the rocks were being exhumed by extensional collapse (main event c. 390–400 Ma); the welded continents moved southward at this time (compare Figs. 5 and 7) as the subducted cold lithospheric slab (Fig. 6C) began to delaminate. **C.** Schematic cross sections for the collision-exhumation-detachment sequence for Baltica and Laurentia in mid-Silurian times (modified from Eide & Torsvik 1996). White horizontal arrows indicate the direction and speed of the plates. Black dots and squares in the Baltican crust represent probable levels of formation and subsequent exhumation of eclogites found in western Norway; 'root' refers to the entire lithospheric slab underlying the oceanic and continental crust. The main collisional event between Baltica and Laurentia was marked by deep subduction (up to 120 km) of Baltican crust beneath Laurentia with concomitant eastward translation of nappes over the Baltican margin. Deep subduction was a function both of rapid motion of Baltica toward stationary Laurentia and precedence of prolonged subduction of large volumes of cold lithosphere. **D.** Schematic tectono-stratigraphy (not to scale) in the Sunnfjord region, western Norway (after Andersen et al. 1990, Torsvik et al. 1997).



Middle Devonian
c. 374 Ma

Fig. 7. Mid-Devonian reconstruction (see text).



tions of this sort are presently not well-constrained for the other major players; delimiting this component of plate motion in the future will certainly modify our conceptions of Palaeozoic plate amalgamation.

Rotations may partly result from 'in situ' local rotations dependent on the plate boundary conditions (oblique convergence/asymmetric rifting), but a controlling pattern of low- or intermediate-latitude euler-poles (Fig. 8C) may have been the principal mechanism for Baltica rotations during the lower Palaeozoic (Torsvik 1995). Iapetus (Figs. 1–5) probably had a controlling palaeo-North–South closure history, and while Laurentia was located in an equatorial position during most of Ordovician times, Iapetus closed by converging Laurentia with high-latitude and mobile terranes and plates such as Baltica and Avalonia. Palaeolongitudes cannot, of course, be determined from palaeomagnetic data, but by incorporating the constraints offered by geologic (stratigraphic and palaeontologic) data and geodynamic principles, we can accept the dominant north–south (NW–SE) closure-history between Baltica and Laurentia. Prior to collision, Laurentia was essentially flooded and stranded at the equator

while Baltica was clearly undergoing rapid plate motion; thus, the *dominant* polarity of Iapetus subduction(s) must have been north or northwest beneath Laurentia since slab-pull is the governing plate-tectonic driving force.

Acknowledgements. – This contribution is dedicated to Professor David G. Gee in commemoration of his 60th birthday and his enduring dedication to the Scandinavian Caledonides. My own interest in the Caledonides and Palaeozoic palaeogeography stems from the early 1980s when I first met David. At that time, I took great pleasure from the many sizzling discussions on Scandinavian geology between David and Professor Brian A. Sturt. More recently, I have had the pleasure to be involved in David's visions of a European interdisciplinary project that unites geologists from East and West through the EUROPROBE programme.

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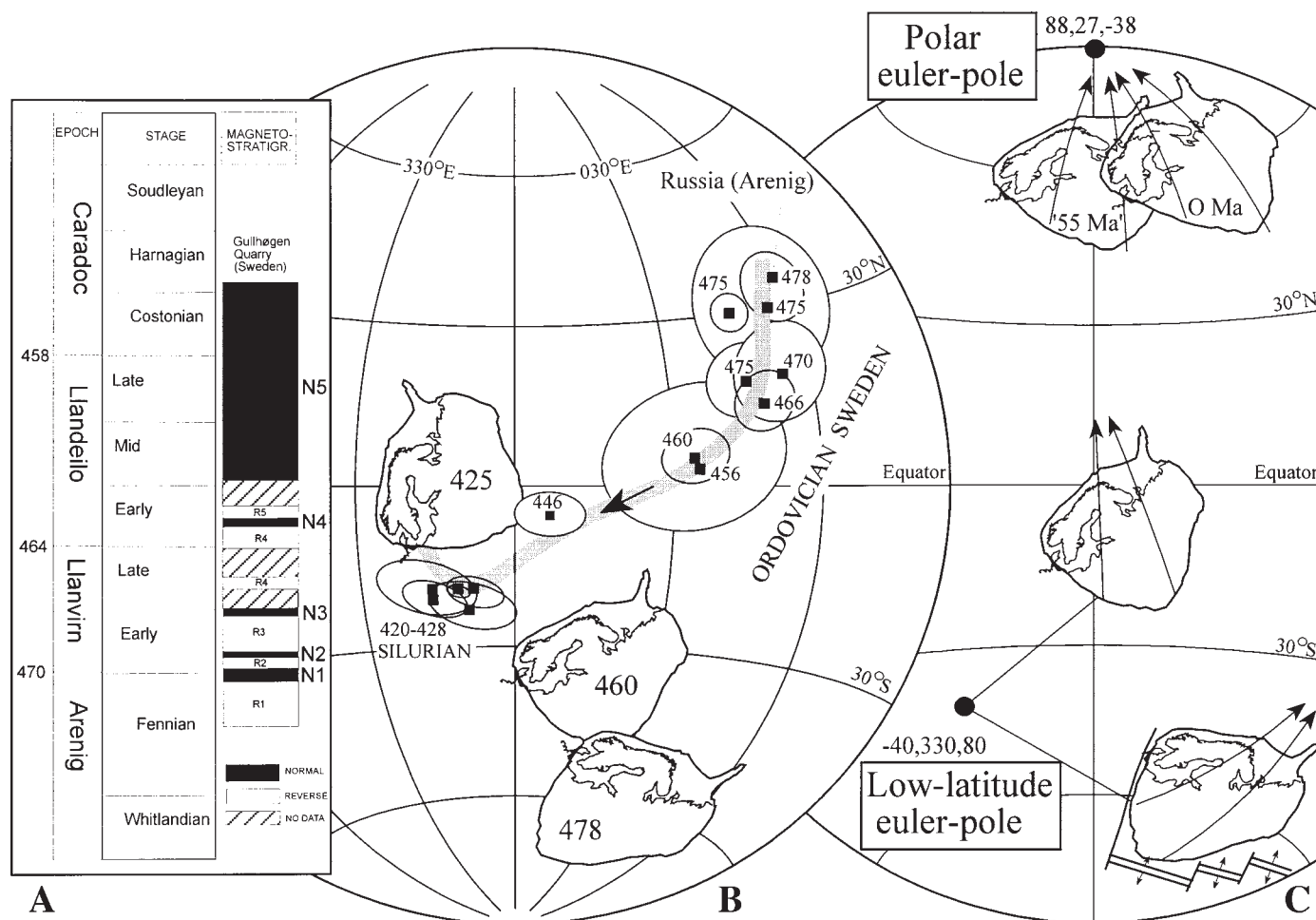


Fig. 8. **A.** Magnetostratigraphy from the Gullhögen Quarry section (Sweden) and geological stages and epochs (Torsvik et al. 1995a). **B.** Ordovician and Silurian poles from Scandinavia and Russia (from Torsvik et al. 1996, Smethurst et al. 1998b), a smooth apparent polar wander path (APWP), and selected reconstructions of Baltica (derived from the smooth APWP) which demonstrate the large counter-clockwise rotations of Baltica. **C.** Example of angular rotation (rotation of a palaeo-North-South meridian) with low- and high-latitude euler-pole geometries. The low-latitude example (euler pole 40°S, 330°E; euler rotation=80°) aims to explain Baltica's approach for low latitudes during the Ordovician while undergoing large counter-clockwise rotations prior to its collision with Laurentia in Mid-Silurian times (c. 425 Ma; Fig. 5). The high latitude euler-pole example (euler pole=88°N, 27°E; euler angle=-38°) illustrates the lack of rotation of the palaeo-North-South meridian for Baltica while keeping Laurentia fixed.

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