The Sveconorwegian tectonic cycle reviewed

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The Mesoproterozoic supercontinent

Piper (1982, 1983) depicted the Mid-Proterozoic supercontinent, recently designated Midgardia (Johansson 1999), as a landmass encompassing Baltica, Laurentia, Africa, South America, India, Antarctica, Australia, and several smaller continental blocks. It was characterised by widespread bimodal anorogenic magmatism (e.g. Hoffman 1989; Windley 1995), that is also recognised in western Baltica (cf. Åhäll and Connelly 1998 and references therein). Well-defined and precisely dated palaeomagnetic poles for Laurentia and Baltica at 1.27 Ga are consistent with reconstructions in which Baltica is located adjacent to the present-day eastern Greenland coast (Buchan *et al.* 1999). This sets the base for the Sveconorwegian tectonic cycle.

A short (thus incomplete) review is given below starting with the break-up of Midgardia to the assembly and finial fragmentation of Rodinia. The Sveconorwegian orogen and its units are shown in Figure 1.

Geons 14-13

Metamorphic overprinting of Paleo-Proterozoic and early Meso-Proterozoic rocks of southern Baltica are dated at 1.4 and 0.9 Ga. In SW Sweden high-grade metamorphism affected large areas at 1.4 Ga. This event is manifest in A-type, granitoid plutonism, gabbro intrusions and mafic dyking (Hageskov and Pedersen 1985; Lundqvist 1996 and references in therein), indicating extensional tectonics in southern Baltica. Granitoids were also formed in NW Ireland (c. 1.35 Ga) that were later affected by the Grenvillian-Sveconorwegian orogeny (Menuge and Daly 1990). In addition, the c. 1.4±0.1 Ga period (Jotnian) is characterised by deposition of extensive red beds in central Baltica. Magmatism is also known to have occurred in Labrador at this time (Gower *et al.* 1990), a period characterised by rifting. Thus Gower and Tucker (1994) suggested that a failed rift arm developed between Baltica and east of Greenland.

Baltica – Laurentia separation

Weakly alkaline - transitional, olivine basaltic volcanism (Solyom *et al.* 1992) is recognised at c. 1225 Ma (Welin and Lundqvist 1975) in central Baltica (e.g. Gorbatschev *et al.* 1979) and at c. 1.26 Ga in Finland (Suominen 1991). This resulted in sheet and sill complexes with variable thickness (of less than 500 metres) of which the most prominent is the Ulvö dolerite complex of east central Sweden. These complexes are age equivalents to the Sudbury dyke swarm of Canada that is considered to be related to a spreading zone, and show similar chemical signatures (e.g. Baragar 1977). Intrusion of gabbroic rocks in south Norway also characterises this period (1.25-1.22 Ga; Starmer 1993).

In southern Sweden scattered occurrences of granitoids have similar (c. 1.2 Ga) ages. Thus quartz monzonites, granites, and syenites are recognised related to the Sveconorwegian shear zone; the Protogine Zone (Johansson 1990) of south central Sweden, but are found also to the west of this. Slightly younger (c. 1.18 Ga), alkaline, N-S trending dolerites are also found along the Protogine Zone (Solyom *et al.* 1992 and references therin). Extensional tectonism in SW Norway, suggesting decompression partial melting before 1.16 Ga, is reported by Falkum (1998) and explains the 1.19-1.13 Ga granitoids and gabbro that intruded SW Norway (Åhäll and Connelly 1998 and references therein). Coeval dykes intruded the Sveconorwegian province in southeast Norway (Starmer (1985) and in northern Finland (Gorbatschev *et al.* 1987). In Canada the (c. 1.14 Ga) Abitibi dyke swarm likely represents failed Kewenaawan rifting (Fahrig 1987).

It is believed that the 1.22 Ga magmatism marks the incipient break-up of Baltica from the Mid-Proterozoic supercontinent Midgardia (cf. Park 1992). The following alkaline dyke related magmatism at c. 1.18 Ga represents a more advanced stage of rifting and is here considered as the onset of the Sveconorwegian tectonic cycle.

Postulated break-up, relative rotation and re-amalgamation of Laurentia and Baltica are difficult to confirm from the existing palaeomagnetic record since the age control is poor (Buchan *et al.* 1999).

In southwestern Sweden the volcano-sedimentary Dal Group of Early Sveconorwegian age is preserved because of basement faulting. It likely represents deposits on a shelf along a marine basin (Kumpulainen 1996) related to the Sveconorwegian rift stage. Contemporaneous, similar deposits are also known from the Telemark terrane of south Norway.

The Sveconorwegian orogeny

Tectonics:

A series of Sveconorwegian shear zones are identified in southern Baltica (e.g. Berthelsen 1980; Hageskov 1985; Park *et al.* 1991). These trend roughly N-S trending, and some are delineating terranes and lithostratigraphic units. Of these "the Mylonite Zone" of west Sweden (Stephens *et al.* 1996; Berglund 1997) probably was activated by Sveconorwegian crustal thickening (cf. Page *et al.* 1996). In addition, small nappe complexes are recognised west of Lake Vänern in Sweden (Gorbatschev 1988) indicating eastwards thrusting.

In S. Norway thrusting took place at 1.13 Ga in the Kristiansand-Porsgrund fault zone, while strike slip movements are recorded in the Mandal line further west at 1.05 Ga, succeeded by faulting at 0.93 Ga representing extensional tectonics (Bingen and van Breeman 1998). A minimum age for Sveconorwegian contractional tectonics in SW Norway is also provided by the 0.93–0.92 Ga Rogaland AMCG complex (Schärer *et al.* 1996). Romer and Smeds (1996) argued that Sveconorwegian thrusting had ceased by 984 Ma.

Magmatism:

Sveconorwegian, synkinematic, calc-alkaline magmatism has been recognised only in the southwestern part of the Sveconorwegian Province (Bingen *et al.* 1993). This magmatism dated at 1.04 Ga takes the form of relatively potassium rich augen gneisses. In south Norway, numerous, post-tectonic, granitic, anorthositic and charnokitic plutons intruded at c. 0.95- 0.88 Ga. This interval overlaps the period of extension (0.93-0.92 Ga) in the southwestern part of the Sveconorwegian Province (Bingen et al. 1998).

Further east, in westernmost Sweden, a few similar granite plutons (e.g. Eliasson and Schöberg 1991), a norite-anorthosite complex, and related hybrid rocks are recognised (Åhäll and Schöberg 1999 and references therein). The post-tectonic magmatism is generally considered to have marked the end of tectonic displacement along this sector of the Baltica margin (Park 1992).

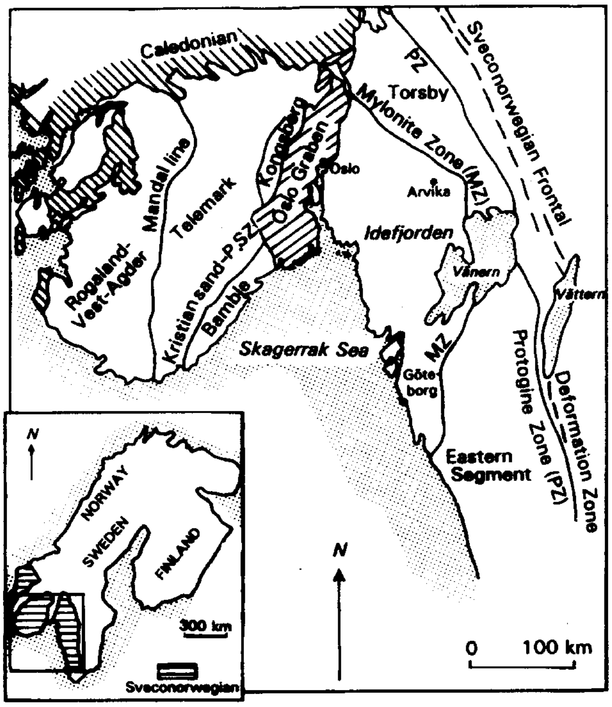

Fig.1. Sketch-map of the Sveconorwegian Province of S. Norway and W. Sweden showing units and tectonic zones mentioned in the text. Inset map: The Baltic Shield and the Sveconorwegian Province.

However, Sveconorwegian pegmatites east of these intrusions are somewhat older (c. 1.06 to 0.98 Ga), and were interpreted by Romer and Smeds (1996) to represent melts generated at thermal peaks related to eastward thrusting.
Late-Grenvillian intracrustal melts also formed granitic pegmatites at c. 1.0 Ga in the Erris Complex of NW Ireland post dating synkinematic granites injected between 1.07 and 1.0 Ga (Winchester and Max 1990). In northernmost Baltica, swarms of c. 1.0 Ga, N-S to NE-SW trending mafic dykes are known from the Kola peninsula in Russia and are also represented by the Laanila dyke (c. 985 Ma) in Finland (Gorbatschev *et al.* 1987).

Metamorphism :
The Sveconorwegian metamorphic overprinting in western Baltica is heterogeneous with metamorphic grade spanning from greenschist to granulite facies. In SW Sweden, the latter is dated at c. 0.92 Ga (Johansson *et al.* 1991). Veining and gneissification of older rocks characterises the Sveconorwegian overprinting in large areas of western Sweden (west of the Protogine Zone), although localised low grade areas are also found. The granulite terrain in SW Sweden represents overthickened Sveconorwegian crust related to orogenic deformation. Ar-Ar dating of hornblende in the eastern part of the Sveconorwegian Province in Sweden yield ages of 1.0- 0.97 Ga and 0.93-0.92 Ga (Page *et al.* 1996), and metamorphic zircon growth at 0.97-0.96 Ga (Johansson *et al.* 1998 and references therein). In SW Baltica Ar/Ar hornblende ages yield cooling in the Bamble Sector, in Norway at c. 1091 Ma and extensional tectonics at 0.93 Ga (Bingen *et al.* 1998b). However, granulite facies metamorphism took place earlier, at c. 1145 Ma in SW Norway (Cosca *et al.* 1998) and at c. 1105 Ma in the Kongsberg-Bamble sector (Kullerud and Dahlgren 1998). A second Sveconorwegian metamorphic event in southern Norway was dated by Bingen et al. (1998b) at 0.93 to 0.92 Ga. In Ireland Grenvillian-Sveconorwegian regional metamorphism is recognised at 1.07-1.0 Ga (Winchester and Max 1990).

Orogenic collapse and Rodinia Break up
Early manifestations of rifting are recognised by the N-S trending Blekinge-Dalarna dolerite swarm (c. 0.93 Ga) in southern Baltica, that is parallel to the prominent Sveconorwegian shear zone; the Protogine Zone. Ar-Ar dating of muscovite (c. 0.93–0.91 Ga; Page et al. 1996) reveals that the Protogine Zone of south central Baltica was active during late Sveconorwegian uplift of southwest Sweden. The activation of this shear zone was related to exhumation of the overthickened Sveconorwegian crust of west Sweden (corresponding to titanite ages of 0.95-0.93 Ga; Connelly *et al.* 1996; Wang 1996), and subsequent deposition of erosion products in a Sveconorwegian foreland basin. Fission track annealing ages (Larson *et al.* 1999), and remnants of the sedimentary cover today trace these deposits. A late Riphean age was suggested for the deposition of one of these; the Visingsö Group of south central Sweden (Vidal *et al.* 1995 and references therin). A similar age is likely for the Almesåkra Group, south Sweden, since these sediments were unconsolidated (Berg-Lembke 1970) when intruded by the Blekinge-Dalarna dolerites.
The Mylonite Zone also exhibits extensional features (Berglund 1997) related to the gravitational collapse and the rapid exhumation that began after 0.97 Ga (Johansson et al. 1998).
Phases of rifting are also traced by the basin formation in south central Sweden at c. 0.8 Ga (Andreasson 1994), magmatism in north Norway (Reginiussen *et al.* 1995) and formation of aulacogens in the East European Platform (Vidal and Moczydlowska 1995; Nikishin *et al.* 1996).
Initial Laurentia and East Gondwana break up from Rodinia before c. 725 Ma was followed by rifting of the Laurentia and Baltica margin. It was completed at c. 0.65 Ga (Dalziel 1997; Torsvik *et al.* 1996) and ceased before the Phanerozoic. Dyke swarms and sheeted dyke complexes from this period are common within the Scandinavian Caledonides (e.g. Andreasson *et al.* 1998 and references therein). Rift related magmatism is also recognised in the Proterozoic basement of the Caledonian foreland as exemplified by the 616±3 Ma Egersund dyke swarm in south Norway (Bingen *et al.* 1998a, 1999; cf. Torsvik *et al.* 1996). Final magmatism of basalts appeared in Poland, Belarus and Ukraine (Nikishin *et al.* 1996) marking the opening of the Tornquist basin (Compston *et al.* 1995; Vidal and Moczydlowska 1995).

Conclusion
The precise date for the Baltica separation from Laurentia is not constrained although it is assumed that this took place at c. 1.18 Ga. The subsequent plate collision caused syn-kinematic magmatism at c. 1.07-0.98 Ga (mostly in the western part) and metamorphic growth of zircons at 0.97-0.96 Ga in the eastern part of the Sveconorwegian Province, although substantial calc-alkaline magmatism is missing. Crustal thickening caused metamorphism that locally was high-grade.
There is a need for precisely dated coeval rocks in Laurentia - Baltica in order to constrain the plate configurations during the Mesoproterozoic.

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