The 616 Ma Old Egersund Basaltic Dike Swarm, SW Norway, and Late Neoproterozoic Opening of the Iapetus Ocean[1]

B. Bingen,[2] D. Demaiffe, and O. van Breemen[3]
Département des Sciences de la Terre et de l'Environnement, Université Libre de Bruxelles, 1050 Bruxelles, Belgium

ABSTRACT

The Egersund dike swarm of SW Norway is made up of 11 basaltic dikes trending ESE-WNW. Two groups are defined: porphyritic dikes with bytownite phenocrysts of tholeiitic affinity and aphyric dikes of tholeiitic to alkaline affinity. Baddeleyite in the most alkaline dike gives a U-Pb intrusive age of 616 ± 3 Ma. The swarm is parallel to the Neoproterozoic southwestern (present-day orientation) Tornquist margin of Baltica. It is coeval with the Long Range swarm of Labrador which is parallel to the southeastern proto-Appalachian margin of Laurentia. Both swarms are related to rifting that resulted in the opening of Iapetus ocean. Chronocorrelation of Neoproterozoic rift-related magmatic suites in western Baltica and eastern Laurentia suggests diachronic opening of Iapetan oceanic basins at ca. 610 Ma along the northwestern Baltoscandian margin of Baltica and at ca. 550 Ma along the proto-Appalachian margin of Laurentia and Tornquist margin of Baltica.

Introduction

After the Grenvillian orogeny (1.25–0.9 Ga), land masses worldwide were probably grouped in one supercontinent, Rodinia (McMenamin and Schulte McMenamin 1990). Break-up of this continent started at around 750 Ma and proceeded in several steps during the Neoproterozoic (reviews of Hoffman 1991; Torsvik et al. 1996; Dalziel 1997; Unrug 1997). Around 600 Ma, fragments of Rodinia collided together to form Gondwana, during the Pan-African-Brasiliano orogenic event (e.g., Trompette 1997). Closely related in time, the Iapetus Ocean (Roberts and Gale 1978) opened between Siberia, Baltica (Scandinavia + Russia + Ukraine), Laurentia (North America + Greenland + Scotland), Amazonia and the craton of Rio de la Plata. In detail, the reconstruction of Rodinia and the time frame of Iapetus formation are still highly speculative. Precise characterization and geochronology of geological events related to Iapetus formation are important to understand the global geodynamic and paleogeographic evolution of the Neoproterozoic.

Dike swarms represent direct evidence for magma generation and intrusion in extensional stress regimes. They are commonly associated with major rifting events and opening of oceanic basins in response to mantle plume activity (e.g., Ernst and Buchan 1997). The volumetrically minor Egersund dike swarm of SW Norway is pristine and unaffected by deformation. It has been interpreted as relating to rifting along the western (present-day orientation) margin of Baltica prior to opening of Iapetus (Torsvik et al. 1996). In order to evaluate this interpretation, geochemical, isotopic (Sr and Nd), and geochronological (U-Pb) data on this swarm were collected. This paper focuses on the geochronology and its tectonic implications.

Geological Setting and Petrography

The Egersund dike swarm intrudes the 0.93 Ga (Schärer et al. 1996) Rogaland Anorthosite Complex and the surrounding Sveconorwegian granulite-facies gneiss terrane. The swarm consists of 11 subvertical dikes trending at 110° to 120°, and numbered d1 to d11 from N to S (figure 1; Antun 1955). The largest dike (d1) is 60 km long and 30 m wide at maximum. The smallest dike (d11) is a few kilometers long and ca. 50 cm wide. At regional

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[1] Manuscript received October 21, 1997; accepted April 28, 1998.

[2] Present address: Geological Survey of Norway, P.B. 3006 Lade, 7002 Trondheim, Norway, e-mail: bernard.bingen@ngu.no.

[3] Continental Geosciences Division, Geological Survey of Canada, Ottawa, K1A 0E8 Canada.

[The Journal of Geology, 1998, volume 106, p. 565–574] 0022-1376/98/10605-0002$01.00

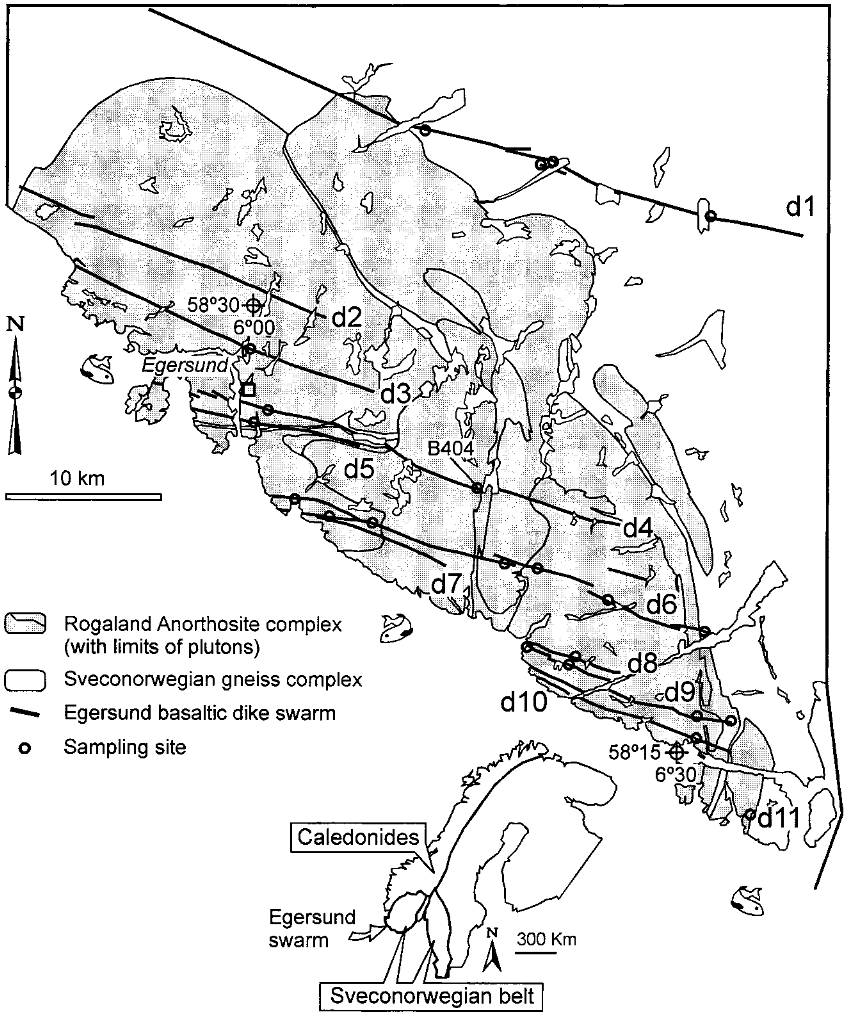

Figure 1. Geological sketch map of the Egersund dike swarm (adapted from Antun 1955). Individual dikes (d1 to d11) and sampling sites (dots) are indicated.

scale, the dikes are almost parallel and do not crosscut each other, suggesting that they are related to a single magmatic event. Contacts between the dikes and their wallrocks are sharp (<5 mm). Grain size increases up to ca. 1 mm toward the center of large dikes. A couple of centimeters wide fine-grained to glassy chilled margins are observed. Glass is locally a major constituent in chilled margins of apophyses of dikes 1, 4, and 5 (Antun 1955).

Two groups of dikes are defined on the basis of their texture: porphyritic (d3, d7–d11) and aphyric (d1–d2, d4–d6). Porphyritic dikes display zoned, up to 1 cm long, phenocrysts of bytownite. The matrix has a subophitic texture with plagioclase, augite, and olivine, and minor titano-magnetite and hemo-ilmenite. Interstitial brown biotite, quartz and K-feldspar are common. The aphyric dikes show a subophitic texture having plagioclase, augite, and some titano-magnetite and hemo-ilmenite. In dikes 1 and 6, olivine is common, but not ubiquitous, and in dikes 4 and 5, Fe-rich olivine is abundant. Interstitial biotite, apatite, quartz and K-feldspar are present. Acicular apatite is especially abundant in dikes 4 and 5.

Baddeleyite U-Pb Age

Baddeleyite was separated from a sample collected in the center of dike 4, which has the highest Zr content (295–301 ppm). Baddeleyite was purified by centrifugation in heavy liquids from several hundreds of grams of finely crushed material, followed by magnetic separation and hand picking. Recovered baddeleyite crystals were a few microns thick and 40–80 μm long. Four fractions were analyzed (table 1) following the procedure of Parrish et al. (1987). Errors on ages are quoted at the 2σ level and were propagated following the techniques of Roddick (1987). The largest fraction (fraction C: 20 μg) has 587 ppm U, is nearly concordant, and yields a ^{207}Pb/^{206}Pb age of 616 ± 2 Ma (figure 2). The analytical precision for fractions B and D is poorer but the estimated ^{207}Pb/^{206}Pb ages are similar. The smallest fraction, A (4 μg) is significantly more dis-

Table 1. Baddeleyite U-Pb Isotopic Data in Sample B404, Dike 4 (UTM Coordinate: 32V LK 401 763)

	Wt (µg)	U (ppm)	Pb_r^a (ppm)	$^{206}Pb^b/^{204}Pb$	Pb_c^c (pg)	$^{208}Pb^d$ (%)	$^{206}Pb^e/^{238}U$ ± 1σ (%)	$^{207}Pb^e/^{235}U$ ± 1σ (%)	$^{207}Pb^e/^{206}Pb$ ± 1σ (%)	R^f	Age^g ± 2σ (Ma)	$Disc^h$ (%)
A	4	646	60	1833	9	3.19	.097852 ± .10	.82186 ± 0.21	.060915 ± 0.18	.53	639 ± 9	5.7
B	7	112	10	481	11	1.19	.098780 ± .17	.82174 ± 0.52	.060334 ± 0.46	.49	616 ± 20	1.4
C	20	587	54	5371	14	1.47	.098745 ± .09	.82174 ± 0.11	.060355 ± 0.05	.88	616 ± 2	1.6
D	10	148	13	201	50	0.80	.097592 ± .40	.80877 ± 1.50	.060105 ± 1.37	.44	607 ± 60	1.2

[a] Radiogenic Pb.
[b] Measured ratio, corrected for spike and fractionation.
[c] Total common Pb in analysis.
[d] Mole % of ^{208}Pb in radiogenic Pb.
[e] Ratio corrected for blank Pb and U, and common Pb; estimated Pb blank: 5–9 pg; common Pb isotopic composition following Stacey and Kramers (1975) evolution curve.
[f] R = correlation coefficient of errors in isotopic ratios.
[g] $^{207}Pb/^{206}Pb$ model age.
[h] Disc = % discordance of the fraction from the concordia curve on a chord through the fraction and the origin.

cordant (5.7%) which together with its more thorogenic composition (table 1), points to an extraneous and older component; this fraction is thus not considered for regression analysis. Regression of fractions B, C, and D through the origin of the concordia diagram yields a weighted average $^{207}Pb/^{206}Pb$ age of 616 ± 3 Ma. This age, weighted heavily on fraction C, is considered the best estimate for the crystallization of the baddeleyite. Pb loss episodes have possibly occurred after crystallization, for instance during the low-grade Caledonian metamorphic overprint at ca. 400 Ma (Rb-Sr green biotite–whole rock age; Verschure et al. 1980), during the late Paleozoic to Mesozoic rifting in the North Sea Basin, or during the Cenozoic opening of the Atlantic ocean. Regression of fractions B, C and D through a forced lower intercept of 400 Ma yields an age of 631 Ma, which represents the oldest age limit compatible with the data and regional geological setting. Nevertheless, evidence for post-intrusion alteration linked to fluid activity or metamorphic re-crystallization are lacking in the dated sample, as magmatic minerals are perfectly preserved. In the absence of direct evidence for Pb loss, the $^{207}Pb/^{206}Pb$ age of 616 ± 3 Ma is preferred and considered as the crystallization age of dike 4 (figure 2), and, by extension, of the whole swarm. This age is significantly younger, but nevertheless overlaps with available Rb-Sr and Sm-Nd internal isochron ages on the swarm. These range from 668 ± 28 to 641 ± 25 Ma (unspecified sample locations; Miller et al. 1996).

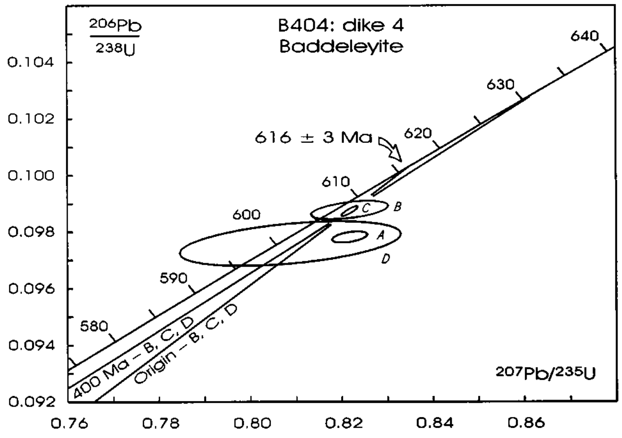

Figure 2. U-Pb concordia diagram for four baddeleyite fractions from dike 4.

Geochemical and Isotopic Signatures

Fifty-six whole rock samples collected in nine dikes were analyzed for major and trace elements. Fourteen samples were further selected for trace element analyses by INAA. Sr isotopic data were acquired for twenty-one samples and Nd isotopic data for seven of them. Geochemical and isotopic data will be presented elsewhere. A summary is given hereafter.

In a binary $Na_2O + K_2O - SiO_2$ diagram, porphyritic dikes plot in the field of subalkaline-tholeiitic basalts (figure 3). The most primitive, phenocryst-poor, samples of dikes 3 and 8 have Mg# [100*Mg/(Mg+Fe), atomic ratio] of 56 to 61, TiO_2 contents of 1.99 to 2.13% and SiO_2 contents of 46–47%. Porphyritic dikes are enriched in incompatible elements, enrichment factors being intermediate between typical values for E-MORB and OIB. In a ternary Th-Ta-Hf discrimination diagram (Wood 1980), they plot in the field of alkaline within-plate basalts (figure 4). Initial Sr isotopic ratios of porphyritic dikes, recalculated at 616 Ma, cluster between 0.7034 and 0.7039. Initial ϵ(Nd) are positive and range from +2.0 to +3.1.

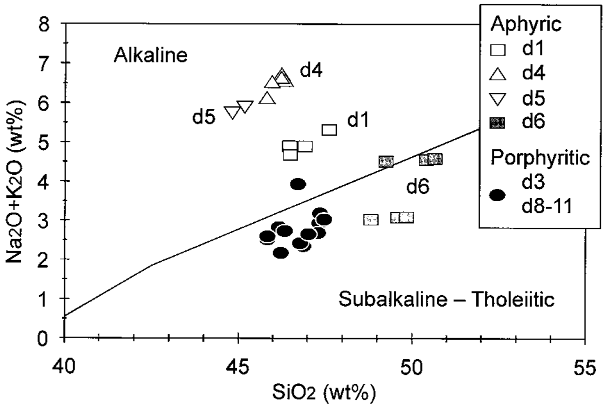

Figure 3. $Na_2O + K_2O - SiO_2$ diagram with whole rock analyses of the Egersund dike swarm.

The aphyric dikes are internally more homogeneous in composition than the porphyritic dikes, but the different dikes display variable and distinct Mg#, SiO_2, TiO_2 and P_2O_5 contents. For dike 6, the richest in SiO_2 (48.8–50.7 wt %) with a Mg# of 49–52, data points plot at the boundary between the tholeiitic and alkaline fields in the $Na_2O + K_2O - SiO_2$ diagram (figure 3). Dikes 1, 4, and 5 are alkaline and characterized by low SiO_2 contents (44.8–47.6 wt %), low Mg# (38–46), and high TiO_2 contents (2.8–3.5 wt %). Aphyric dikes are strongly enriched in incompatible elements: for dikes 1 and 6, enrichment factors are slightly below or overlapping typical values for OIB, whereas for dikes 4 and 5, they are higher. In a ternary Th-Hf-Ta discrimination diagram, dike 6 plots at the boundary between within-plate tholeiite and alkaline within-plate basalts whereas dikes 1, 4, and 5 plot in the center of the field of alkaline within-plate basalts (figure 4). Aphyric dikes have significantly more radiogenic initial Sr isotopic composition than porphyritic dikes. Dike 1 has an average $(^{87}Sr/^{86}Sr)_i$ of 0.7046, while dikes 4, 5 and 6 have higher values, in the range 0.7054–0.7062. Initial $\epsilon(Nd)$ for the aphyric dikes range from +0.6 to +1.3.

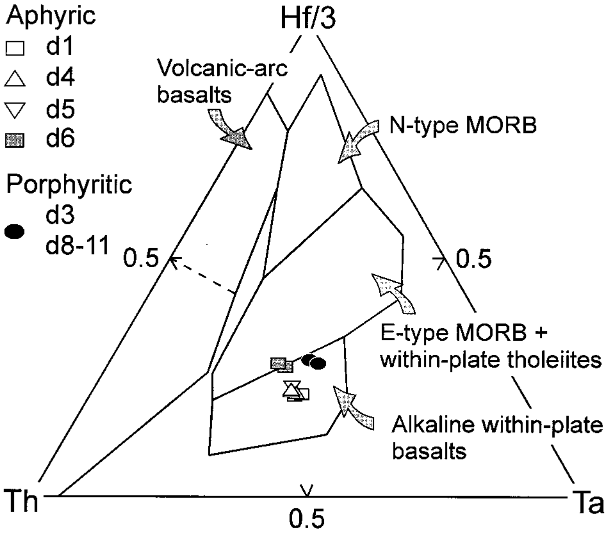

Figure 4. Hf-Th-Ta discrimination diagram (Wood 1980).

The Egersund dike swarm consists of two types of basaltic dikes of discrete petrologic, geochemical and isotopic signatures. Porphyritic dikes display common characteristics and were presumably derived from a common parent magma. By contrast, aphyric dikes display significantly more evolved Mg# and distinct ratios of incompatible elements; moreover each dike has a distinct composition. This suggests that aphyric dikes, especially the most alkaline ones, cannot be derived from the magma of the porphyritic dike by a simple fractional crystallization process in a crustal magma chamber. At least two mantle sources have to be invoked to account for the diversity of geochemical signatures of the swarm.

Neoproterozoic Rifting in Western Baltica

Following the Sveconorwegian orogeny, the Fennoscandian Shield entered a period of extensional tectonic regime. Intracratonic sedimentary basins developed during the Upper Riphean and Vendian in rifts and aulacogens (Roberts and Gale 1978; Kumpulainen and Nystuen 1985; Vidal and Moczydlowska 1995). These include the Vättern graben (SW Sweden), the Tanafjorden-Varangerfjorden basin on the Varanger peninsula (N Norway), the Lublin slope (E Poland), the Volhyn basin (Belarus and Ukraine) and several basins now situated within the Caledonian Allochthons. These transported basins contain stratigraphic successions, locally thicker than 9 km, attributed to the Neoproterozoic northwestern Baltoscandian margin of Baltica. Tillites associated with the Varanger Ice Age (653 ± 7 Ma; Rb-Sr age from shale horizons; Pringle 1973) are used as marker horizons for correlation between groups of the different basins. Early Cambrian is characterized by marine transgression in all basins.

A review of Neoproterozoic igneous activity in the western part of the Fennoscandian Shield is offered by Andréasson (1994). In S Sweden, the NNE-SSW-trending dikes from the Blekinge-Dalarna dolerite swarm, yield Sm-Nd internal isochron ages ranging from 935 ± 36 Ma to 844 ± 82 Ma. The youngest dikes may be associated with the formation of the Vättern basin. They display within-plate tholeiitic affinity with $\epsilon(Nd)_i$ of −2.7 and $(^{87}Sr/^{86}Sr)_i$ of 0.7045.

In SW Norway, the late Sveconorwegian regional cooling is constrained by $^{40}Ar/^{39}Ar$ data on hornblende ranging from 930 to 855 Ma and by Rb-Sr brown biotite-whole rock ages ranging from 895 to 850 Ma (data and compilation in Bingen et al. 1998). The 616 ± 3 Ma age obtained for the Egersund swarm is much younger. It indicates that the swarm is not linked to post-orogenic relaxation but represents indisputable evidence for Vendian magma intrusion in extensional stress regime in western Baltica. The swarm displays within-plate geochemical signature with pronounced enrichment in incompatible elements and $\epsilon(Nd)_i$ values characteristic of a slightly depleted mantle. This signature is compatible with magmatic activity linked to continental rifting. As the dikes are not deformed and have not been transported after intrusion, the direction of the swarm is significant and points to a component of crustal extension perpendicular to its ESE-WNW direction during intrusion. This direction is parallel to the southwestern Tornquist margin of Baltica (figure 5*a*). The intrusion of the swarm is thus probably related to a phase of rifting, which eventually led to the opening of the Iapetus Ocean and its Tornquist arm during the Vendian.

Basaltic dike swarms are common and locally voluminous in Neoproterozoic sediments of the Baltoscandian margin of Baltica (Andréasson 1994). They are now found within Caledonian nappes of the Middle and Upper Allochthons. The main swarms are the Ottfjället swarm in the Särv Nappe Complex dated at ca. 665 Ma ($^{40}Ar/^{39}Ar$ method; Claesson and Roddick 1983) but probably younger as it cuts Varanger Ice Age deposits of 653 ± 7 Ma (Pringle 1973), the Sarek sheeted dike complex in the Sarektjåkkå Nappe (Seve Nappe Complex) dated at 573 ± 74 Ma (Sm-Nd internal isochron) or 608 ± 1 Ma (zircon U-Pb age; Svenningsen 1994, 1996), and a dike swarm in the Corrovarre Nappe (Kalak Nappe Complex; Zwaan and Van Roermund 1990) dated at 582 ± 30 Ma (Sm-Nd internal isochron). These swarms generally have homogeneous composition and display E-MORB to T-MORB geochemical signature, with positive $\epsilon(Nd)_i$ values (+4.8 to +6.6), indicating a depleted mantle source. The setting and geochemical signature of these dikes point to a transition between continental rifting and seafloor spreading (rift-to-drift transition; Svenningsen 1994). If the zircon U-Pb age of 608 ± 1 Ma for the Sarek swarm is selected as representative of the opening of Iapetus along the Baltoscandian margin, this event is tightly constrained and occurred only shortly (ca. 8 m.y.) after the intrusion of the Egersund swarm.

Two carbonatite complexes intrude Baltica at ca. 580 Ma: the Fen complex and associated alkaline dikes in SE Norway (578 ± 24 Ma; Rb-Sr isochron; Dahlgren 1994), and the Alnö carbonatite complex of E Sweden (584 ± 13 Ma; Pb-Pb whole-rock isochron; Andersen 1996). The intrusion of these two complexes is compatible with an extensional tectonic regime, at least locally, toward the center of Baltica after the initial opening of Iapetus.

In Poland, Belarus, and Ukraine, basalts occupy a large subsurface area along the southwestern Tornquist margin of Baltica (Nikishin et al. 1996). The Volhyn basalts have a maximum thickness of 500 m and are covered by transgressive marine sediments. They are possibly correlated with the volcanites of the Slawatycze formation (E Poland), emplaced at 551 ± 4 Ma (zircon U-Pb age of tuffs in the upper section of the formation; Compston et al. 1995). These basalts are interpreted as evidence for the final phase of rifting leading to the opening of the Tornquist basin (Compston et al. 1995; Vidal and Moczydlowska 1995; Nikishin et al. 1996).

In the Barents Sea basin (Caledonian Parautochthon of N Norway), the ENE-WSW Hamningberg dike yields a zircon U-Pb age of 567 +30/−23 Ma (Roberts and Walker 1997). This dike is attributed to a relaxation stage following the Baikalian orogeny occurring farther east along the northeastern to eastern margin of Baltica at ca. 580–560 Ma (Nikishin et al. 1996; Roberts and Walker 1997).

Neoproterozoic Rifting in Eastern Laurentia

It is a traditional view to correlate the Sveconorwegian belt of Baltica with the Grenvillian belt of Laurentia; Baltica is generally placed to the east of Laurentia after the Grenvillian event, so that western Baltica is facing eastern Laurentia. It is thus relevant to compare Neoproterozoic suites along both margins.

Neoproterozoic sedimentary sequences preceding the opening of Iapetus occur all along the eastern margin of Laurentia from Svalbard and NE Greenland to Georgia (Rankin et al. 1989; Soper 1994). They include the thick Eleonore Bay Supergroup of E Greenland, Dalradian Supergroup of Scotland, and Ocoee Supergroup of Tennessee. Stratigraphic analysis in the Appalachians indicate a change from synrift clastic sequences to open marine sequences at the base of the Cambrian, suggesting that the rift-to-drift transition along the southeastern margin of Laurentia occurred at ca. 545 Ma (Williams and Hiscott 1987; Thomas 1991).

Neoproterozoic rift-related magmatic activity is documented in eastern Laurentia between 760 and 550 Ma. In the British Iles, the Tayvallich Volcanics (595 ± 4 Ma; zircon U-Pb age; Halliday et al. 1989) and the Mam sill (625 ± 47 Ma; Sm-Nd inter-

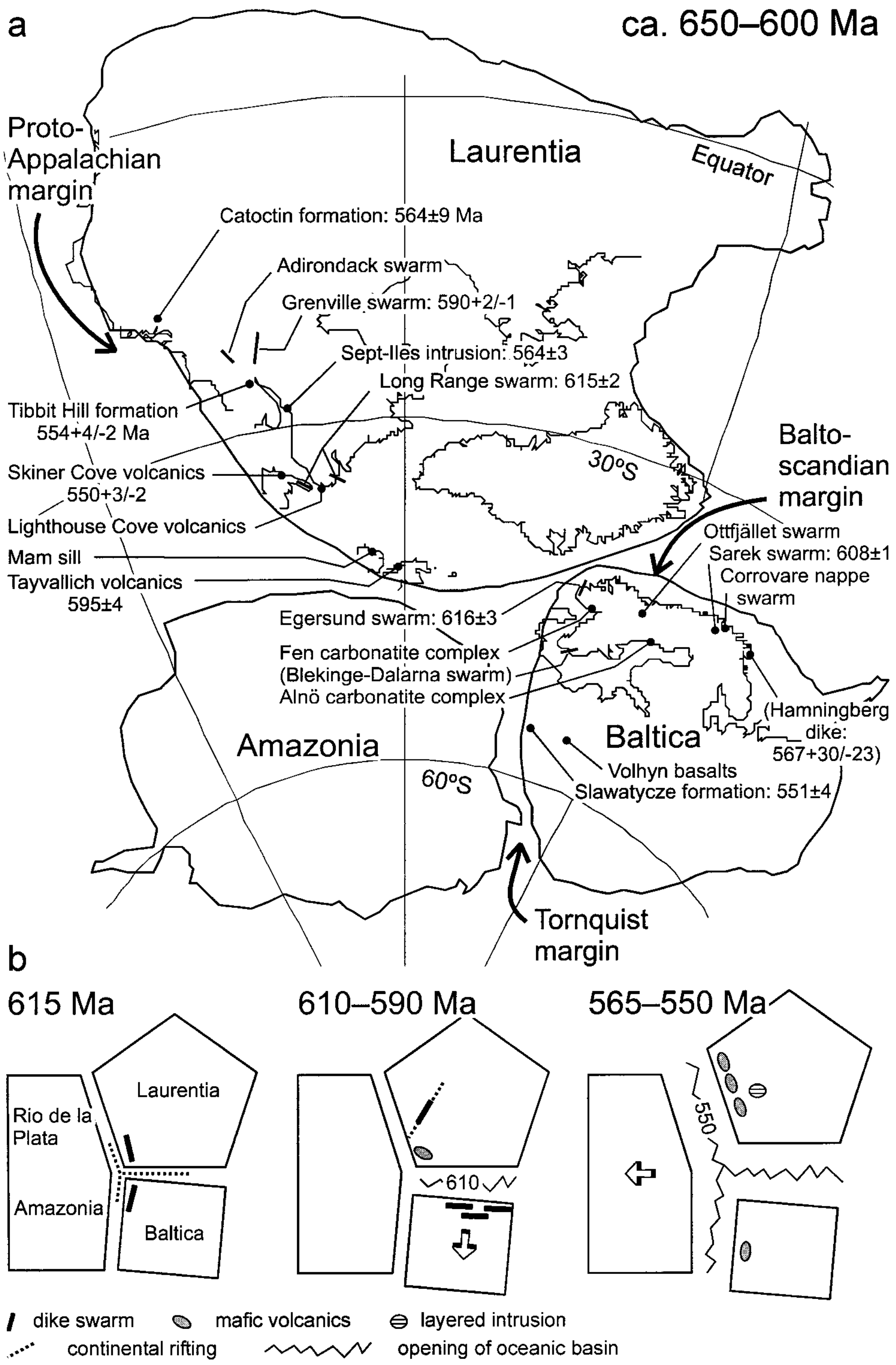

Figure 5. (*a*) Plate reconstruction at ca. 650–600 Ma according to Torsvik et al. (1996) with location of Laurentia, Baltica, and Amazonia. Neoproterozoic mafic magmatic suites related to opening of Iapetus are located with zircon or baddeleyite U-Pb intrusive ages (references in text). Two suites having no direct relationship with Iapetus opening are shown between brackets. (*b*) Interpretative sketch map showing possible relationships between Baltica, Laurentia, and Amazonia in the interval 615–550 Ma based on time correlation of magmatic suites (relative orientations as in 5*a*). Diachronic opening of Iapetus oceanic basins is suggested.

nal isochron; Kirwan et al. 1989) are interlayered in the Dalradian Supergroup; they display tholeiitic affinity with $\epsilon(\mathrm{Nd})_i$ ranging from +2 to +4.

In the St. Lawrence region, two large dike swarms intrude the Grenvillian basement: the NE-SW trending Long Range swarm of NW Newfoundland and Labrador dated at 615 ± 2 Ma (zircon and baddeleyite U-Pb age; Kamo et al. 1989; Kamo and Gower 1994) and the E-W-trending Grenville swarm of Quebec and Ontario dated at 590 +2/−1 Ma (zircon and baddeleyite U-Pb age; Kamo et al. 1995). The Grenville swarm is parallel to the Ottawa graben, interpreted as a failed arm of Iapetus. It is probably coeval with NE-trending mafic dikes in the Adirondack mountains (New York; Coish and Sinton 1992). Geochemically, the Long Range swarm is tholeiitic to mildly alkaline (Strong 1974; Murthy et al. 1992). The Grenville swarm is tholeiitic, whereas the Adirondack dikes are mildly alkaline (Coish and Sinton 1992; St. Seymour and Kumarapeli 1995). The intrusions of the dike swarms is followed by a pulse of alkaline to carbonatitic plutonism associated with the formation of the St. Lawrence rift (compilation in Higgins and van Breemen 1998), and the intrusion of a large layered intrusion—the Sept-Iles intrusion—dated at 564 ± 3 Ma (zircon U-Pb age, Higgins and van Breemen 1998).

In the Appalachians, Neoproterozoic, predominantly mafic volcanites interlayered in clastic sedimentary sequences are widespread. In the Blue Ridge (Pennsylvania and Virginia), rhyolite flows and hypabyssal felsic dikes associated with mafic volcanites define a bimodal age distribution at 760–700 Ma and 570–560 Ma (Aleinikoff et al. 1995), pointing to two pulses of rifting. The second pulse, corresponding to the Catoctin formation (zircon U-Pb age of 564 ± 9 Ma), resulted in continental break-up. In Quebec, the voluminous Tibbit Hill volcanic formation yields a zircon U-Pb age of 554 +4/−2 Ma (Kumarapeli et al. 1989). In Newfoundland, bimodal volcanites, including the Lighthouse Cove Formation and the Skinner Cove Volcanics, are observed in sedimentary sequences almost up to the Precambrian-Cambrian boundary, i.e., up to 550 Ma (McCausland et al. 1997; Williams and Hiscott 1987).

Vendian Opening of Iapetus Ocean

Different paleogeographic reconstructions of Rodinia (at ca. 750 Ma) have been proposed recently. According to Torsvik et al. (1996) and Dalziel (1997), the Baltoscandian margin of Baltica was facing E Greenland (figure 5*a*). Amazonia was the conjugate margin of the Tornquist margin of Baltica, in such a way that a triple junction was located close to Scotland and the Rockall Plateau; the proto-Appalachian margin of Laurentia was facing Amazonia and the Rio de la Plata Craton. The opening of Iapetus was possibly associated with relative rotation of Laurentia (anticlockwise) and Baltica (clockwise) (Torsvik et al. 1996). Other fits of continents have been proposed: in the model of Hoffman (1991), the Baltoscandian margin of Baltica is facing the proto-Appalachian margin of Laurentia on the southwestern side of the Scotland promontory; in the model of Soper (1994), the Tornquist margin of Baltica is facing E Greenland. The uncertainty in the relative latitude and orientation of the three continental blocks stems from (1) the small number of reliable paleomagnetic data for Baltica and Amazonia in the Neoproterozoic (Torsvik et al. 1996); (2) the lack of a global understanding of the Grenvillian orogen, and (3) the lack of precise correlations between Neoproterozoic rift-related magmatic suites and sedimentary sequences that preceded the opening of Iapetus. As both northwestern Baltica and eastern Laurentia were reworked during the Phanerozoic Caledonian-Appalachian orogeny, and as rifting itself may be asymmetric, correlations are difficult to establish.

The summary of geochronological data presented above brings two possible correlations to light. (1) The Egersund swarm of SW Norway (616 ± 3 Ma), parallel to the Tornquist margin of Baltica, is coeval to the Long Range swarm of Labrador (615 ± 2 Ma), parallel to the proto-Appalachian margin of Laurentia. Both swarms intrude the Grenvillian (=Sveconorwegian) basement. Available major and trace elements geochemical data on the Long Range swarm (Strong 1974; Murthy et al. 1992) overlap the compositional ranges of the Egersund swarm. This compositional similarity suggests that the two swarms may correspond to a single large magmatic event related to continental rifting. (2) The Slawatycze volcanic formation of E Poland (551 ± 4 Ma; possibly correlated to the Volhyn basalts of Belarus and Ukraine), situated along the Tornquist margin of Baltica, is coeval to several volcanic formations located along the proto-Appalachian margin of Laurentia: the Tibbit Hill formation (554 +4/−2 Ma), the Skinner Cove volcanics (550 +3/−2 Ma) and the Catoctin formation (564 ± 9 Ma). On both continents, these basaltic suites, interlayered with clastic sediments, are interpreted as rift-related magmatic products, emplaced shortly before opening of Iapetus. The chronocorrelation of these magmatic suites at 615 Ma and 570–550 Ma underscores the similarity of tectonic setting of the Tornquist and the proto-Appalachian margins in the Neoproterozoic. It gives support to the plate geometry proposed by Torsvik et al. (1996) and Dalziel (1997), in which these margins are aligned (figure 5*a*).

Magmatic suites directly related to the opening of Iapetus range in age from ca. 620 to 550 Ma in Baltica and Laurentia, which represents a 70 m.y. timespan. From studies of Phanerozoic geologic systems for which plate dispositions are well understood, it is generally accepted that magma generation, associated with the opening of oceanic basins, is typically of short duration, for example 12 m.y. for the Cenozoic opening of the North Atlantic basin (Saunders et al. 1997). The Vendian opening of Iapetus may thus be regarded either as a slow process or as a polyphase process involving diachronic development of more than one oceanic basin. The estimates of the timing of rift-to-drift transitions along the different continental margins favor the second interpretation. Along the Baltoscandian margin of Baltica, the rift-to-drift transition occurred at ca. 610 Ma (intrusion of the Sarek swarm), whereas along the Tornquist margin of Baltica and the proto-Appalachian margin of Laurentia, it is close to 550 Ma (intrusion of basaltic volcanites in the range 565–550 Ma). If the plate geometry of Torsvik et al. (1996) and Dalziel (1997) is selected (figure 5*a*), this time frame suggests that an ocean basin opened between northwestern Baltica and northern Laurentia (E Greenland) at ca. 610 Ma, and another ocean between Laurentia, Baltica, and Amazonia at 550 Ma (figure 5*b*). This diachronic opening of Iapetus implies a large component of strike-slip movement along the Tornquist margin and/or the proto-Appalachian margin between 610 and 550 Ma. In this model, the Egersund and Long Range swarms represent magmatic manifestations related to continental rifting on both sides of the triple junction between these plates. The Tayvallich volcanics of Scotland (595 ± 5 Ma) would have been emplaced close to the triple junction, shortly after the initial opening (<15 m.y.). The thick accumulation of sediments, i.e., the Dalradian Supergroup, in the vicinity of this junction fits the model (Soper 1994). Intrusion of the Grenville swarm (590 +2/−1 Ma) arrests to continuing rifting oblique to the proto-Appalachian margin of Laurentia, after opening of the first basin.

The new age obtained for the Egersund swarm and its correlation with the Long Range swarm give an opportunity for precise paleomagnetic determination of the relative paleolatitudes of Laurentia and Baltica at 616 Ma and will possibly permit further testing of existing plate tectonic models for the Neoproterozoic.

ACKNOWLEDGEMENT

B. Bingen was "Chargé de recherches du Fonds National de la Recherche Scientifique de Belgique" and was funded by a NATO research fellowship for a one year stay at the Geological Survey of Canada. Thanks are due to D. Bellerive, J. Macrae, and K. Santowsky for analytical work or analytical assistance. T. Torsvik provided the framework for figure 5*a.* We acknowledge K. Buchan, R. Ernst, D. Roberts and T. Torsvik for reading the manuscript. Constructive critical reviews were provided by I. Dalziel and two anonymous reviewers. This is Geological Survey of Canada contribution no. 1997 190.

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