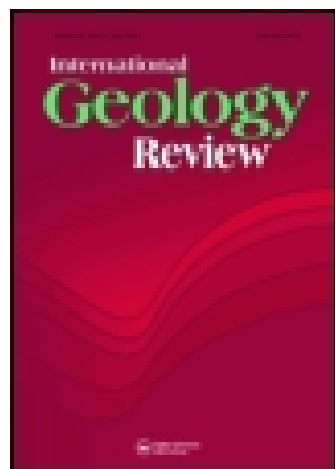




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Characterization of the Paleoproterozoic Mantle beneath the Fennoscandian Shield: Geochemistry and Isotope Geology (Nd, Sr) of ~ 1.8 Ga Mafic Plutonic Rocks from the Transscandinavian Igneous Belt in Southeast Sweden

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Characterization of the Paleoproterozoic Mantle beneath the Fennoscandian Shield: Geochemistry and Isotope Geology (Nd, Sr) of ~1.8 Ga Mafic Plutonic Rocks from the Transscandinavian Igneous Belt in Southeast Sweden

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Abstract

Geochemistry and Sr-Nd isotope geochemistry of ca. 1.8 Ga, mafic intrusions of the Transscandinavian Igneous Belt (TIB-1) in the Fennoscandian shield were studied in southeastern Sweden. These rocks show LILE-LREE-enriched, HFSE-depleted, calc-alkaline, continental arc signatures in the north, grading to slightly less enriched, oceanic affinities southward.

$\epsilon_{\text{Nd}}(1.80)$ values range from +2.0 to +0.7 and $^{87}\text{Sr}/^{86}\text{Sr}(1.80)$ from 0.7022 to 0.7029 (with one outlier at 0 and 0.7033), without correlation to fractionation (e.g., Mg#) or crustal contamination, indicating sources that are mildly depleted. The most depleted ratios occur in the south, trending with the geochemistry toward more enriched compositions northward. The sources represent depleted mantle wedge material that was subjected to enrichment not long before (T_{DM} ca. 2.0 Ga), i.e., during the preceding arc subduction (2.1–1.82 Ga), and/or during the TIB-1 magmatism itself, by hydrous fluids with a sediment and/or melt input increasing northward. The TIB-1 magmatism occurred above a south(west)ward-retreating subduction zone along the continental margin of the juvenile Svecofennian continent at 1.81–1.76 Ga.

Introduction

MAFIC ROCKS IN continental settings provide important information on the nature of the subcontinental mantle from which they were generated, and the particular geodynamic setting of which they were a part. For modern rocks, the setting is often apparent, but old rocks may have formed in various settings and from variable mantle types, and have been brought together by paleotectonic processes of plate convergence and orogeny. Thus, in Precambrian shield areas, the paleotectonic settings of mafic, not

least plutonic rocks, are not immediately apparent, but have to be deduced from structural studies, types of and relations to associated felsic rocks, and geochemical character. One way to approach this problem is by integrated studies of the geochemistry and isotopic character of mafic rocks that form part of crustal blocks that can be considered relatively coherent based on previous geological and geochronological studies.

Settings of modern mafic volcanic rocks are commonly subdivided into constructive margin (mid-ocean ridge basalts), ocean intra-plate (ocean island basalts), intra-continental (continental flood

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basalts), and destructive margin (island and continental arcs) (e.g., Wilson, 1989), each of which carry plutonic equivalents. In arcs, which are most relevant here, mafic rocks are typically tholeiitic to calc-alkaline, strongly depleted in high-field strength elements (HFSE), but enriched in large-ion lithophile elements (LILE) to variable degrees (e.g., Pearce, 1982). Continental arc rocks show normally stronger enrichment in LILE and light rare earth elements (LREE) compared with those in oceanic arcs (e.g., Pearce, 1983). Large volumes of andesites occur in continental arc settings and are well-studied (e.g., Gill, 1981; Thorpe, 1982), while the associated mafic plutonic rocks are more sparsely studied (e.g., Brown, 1982; Bateman, 1983; Weaver et al., 1990; Grissom et al., 1991).

In the Fennoscandian shield (Fig. 1) examples of comprehensive studies of mafic rocks include early Paleoproterozoic volcanics within the Archean craton or along its margin (e.g., Huhma et al., 1990; Puchtel et al., 1997, 2001), Svecofennian juvenile 1.91–1.87 Ga mafic volcanism (e.g., Kähkönen, 1989; Valbracht, 1991; Lawrie, 1992; Lahtinen, 1996), 1.8–1.7 Ga Dala volcanics (Nyström, 2004), and Mesozoic volcanic rocks in southernmost Sweden (e.g., Tappe, 2004). Different mafic dike generations have been studied by Laitakari (1969), Patchett (1978), Gorbatshev et al. (1979), Johansson and Johansson (1990), Rämö (1990), Risku-Norja (1992), and Söderlund et al. (2005). Petrogenesis of mafic plutonic rocks include studies of early Paleoproterozoic layered intrusions (e.g., Alapieti et al., 1990; Amelin and Semeonov, 1996; Mutanen, 1997; Hanski et al., 2005), Transscandinavian Igneous Belt (TIB) intrusions (Andersson, 1997a; Claeson, 2001), rapakivi-related mafic rocks (e.g., Savolahti, 1956; Rämö, 1991; Lindh et al., 2001a) and Sveconorwegian mafic complexes (Wilson et al., 1996; Duchesne, 2001; Årebäck, 2001).

In this study we attempt to systematize the spatial distribution of geochemical and isotopic characteristics of mafic plutonic rocks belonging to the TIB-1 episode (1.81–1.76 Ga) of magmatism within the Transscandinavian Igneous Belt in southeast Sweden, with implications for mantle source character and paleotectonic evolution in this part of the Fennoscandian shield at ca. 1.8 Ga. To this end we present new elemental and isotope geochemical (Sr and Nd) data, and propose a paleotectonic model of crustal growth for southern Sweden.

Geological Background

Regional Framework

The oldest, Archean (>2.5 Ga) rocks of the Fennoscandian shield form a cratonic nucleus in its northeastern part (Fig. 1). At 2.45–2.0 Ga the craton was subjected to rifting in the interior and along its margins (Park et al., 1984; Gaál and Gorbatshev, 1987; Huhma et al., 1990). Following this period of divergence, juvenile crust was generated in several arc systems with intervening basins outboard of the craton to the southwest during the period 2.1–1.93 Ga, of which only few remnants have been identified (Skiöld et al., 1993; Wasström, 1993, 1996; Lundqvist et al., 1998; Rutland et al., 2004). This early, “proto-Svecofennian” period (Andersson et al., 2004b, 2006b) has been suggested to have resulted in juvenile “microcontinents” in several places (Lahtinen et al., 2005), material that is abundantly present in detrital zircon populations (Claesson et al., 1993; Lahtinen et al., 2002; Andersson et al., 2004c, 2006b; Sultan et al., 2004; Rutland et al., 2004). During the main Svecofennian period, at 1.91–1.86 Ga, the ‘proto-Svecofennian’ crust was reworked and the major part of the juvenile Svecofennian crust was created and accreted to the Archean nucleus, thus forming what is now the Svecofennian domain (e.g., Gaál and Gorbatshev, 1987; Baker et al., 1988; Gaál, 1990; Nironen, 1997; Lahtinen et al., 2005, and references therein).

During the late Svecofennian period, at 1.85–1.75 Ga, the new crust was subjected to thorough reworking, resulting in numerous granitoid plutons within the Svecofennian domain, and the voluminous TIB (Andersson, 1991; Högdahl et al., 2004). Westward, the Fennoscandian shield continued to grow in the interval 1.7–1.55 Ga (Gothian), ending with a major reworking during the Sveconorwegian orogeny (1.2–0.9 Ga) (Lindh, 1987; Åhäll and Gower, 1997). Within the Svecofennian domain, the crust was further modified during 1.65–1.50 Ga extension-related rapakivi magmatism (Rämö and Haapala, 1995; Andersson, 1997b). A second period of alkali-rich granitoid plutonism is recorded in southernmost Fennoscandia at ca. 1.45 Ga (Åberg, 1988; Čechys et al., 2002).

Transscandinavian Igneous Belt

The TIB is more than 1500 km long in a N-S direction and up to a few hundred km wide E-W, and runs from southeast Sweden northward to north-central Norway. In Sweden it is normally subdivided into four main provinces that are partly separated by

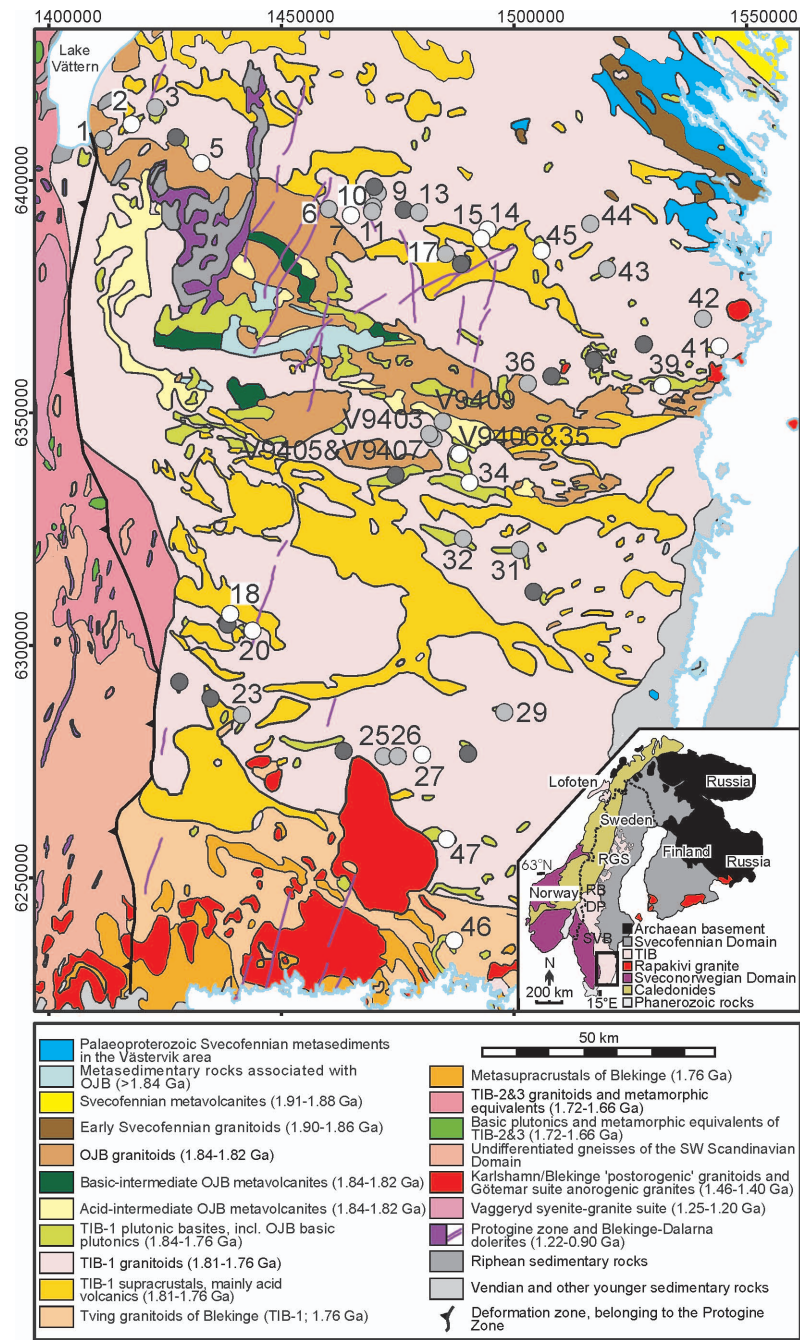


FIG. 1. Geological map of southeast Sweden (modified after Koistinen et al., 2001). Sampled mafic plutonic TIB-1 rocks are marked as circles on the map. Rocks that have been analyzed geochemically are numbered and marked with light-grey circles; the white ones have also been analysed for Nd and Sr isotopes. Localities, rock types, and coordinates of the respective intrusions are presented in Table 1. The frame in the inset map of the Fennoscandian shield (modified after Högdahl and Sjöström, 2001) marks the present study area. TIB is subdivided in the inset. Abbreviations: SVB = Småland-Värmland Belt; DP = Dala Province; RB = Rätan Batholith; RGS = Revsund granitoid suite; Lofoten = Lofoten Islands.

tectonic boundaries, namely from south to north: (1) the Småland-Värmland Belt (SVB); (2) the Dala Province (DP); (3) the Rätan Batholith (RB); and (4) the Revsund granitoid suite (RGS) (see Högdahl et al., 2004 for a review). North of the RGS, TIB continues as a part of the basement of the Caledonides to the Lofoten Islands in Norway (Corfu, 2004; inset in Fig. 1). Associated volcanic rocks dominate in the downfaulted DP and are common in the SVB, but unknown in the RB and RGS. Mafic and intermediate rocks are essential constituents in the whole TIB, not least in the SVB (Andersson et al., 2004a). The commonly undeformed TIB granitoids are characterized by dominant coarse K-feldspar porphyritic textures and alkali-calcic geochemistry, although transitions to both alkaline and calc-alkaline types occur (Gorbatshev, 2004; Andersson et al., 2004b). Mingling and mixing between mafic and felsic magmas are commonly reported from TIB rocks (Andersson, 1991, 1997a; Nyström, 2004).

The total age range of TIB rocks is normally considered to encompass 200 m.y. (1.85–1.65 Ga; Andersson and Wikström, 2001, 2004; Gorbatshev, 2004) and has a rather complex distribution. Larson and Berglund (1992) divided the TIB into three magmatic episodes; TIB-1: 1.81–1.76 Ga, TIB-2: 1.71–1.69, and TIB-3: 1.67–1.65 Ga. However, the earliest magmatic episode, the ~1.85–1.83 Ga “TIB-0” (Ahl et al., 2001), was not recognized until fairly recently (Persson and Wikström, 1993), and has been considered by some workers as not belonging to the TIB (Åhäll and Larson, 2000). It typically occurs along the margin of the Svecofennian domain in southern Sweden, and comprises both deformed and undeformed varieties that are otherwise chemically and texturally inseparable from other TIB rocks (Wikström and Andersson, 2004). TIB-1 is the major early magmatic episode that comprises essentially all of RGS (e.g., Claesson and Lundqvist, 1995), rocks in the Lofoten area of Norway (Corfu, 2004), a substantial part of the DP (Ahl et al., 1999; Lundqvist and Persson, 1999), and most of the eastern SVB in SE Sweden (Mansfeld, 1991; Andersson and Wikström, 2004). Separation of TIB-2 and TIB-3 has proven difficult to uphold, because they may represent a single episode of magmatism (Andersson and Wikström, 2001; Gorbatshev, 2004). Geographically, TIB-2 and 3 (1.71–1.65 Ga) rocks compose the entire RB (Ahl et al., 2004), major sections of DP (Lundqvist and Persson, 1999), and most of the western SVB (Söderlund et al., 1999; Åhäll and Larson, 2000; Gorbatshev, 2004).

The Småland-Värmland Belt in southeast Sweden

In southeast Sweden the SVB is separated into a northern and southern block by a WNW-ESE-trending belt of 1.84–1.82 Ga foliated calc-alkaline rocks running through central Småland (Fig. 1), called the Oskarshamn-Jönköping Belt (OJB; Mansfeld, 1996; Åhäll et al., 2002; Mansfeld et al., 2005). Rock types of the OJB are mainly granodioritic to tonalitic, and the associated volcanites basaltic to dacitic (Wik et al., 2003). Both Mansfeld (1996) and Åhäll et al. (2002) interpreted the OJB as a juvenile arc terrane separated in time and space from the early Svecofennian (>1.86 Ga) crust farther north. Further, Sundblad et al. (1997) reported MORB-type geochemistry for some basalts and gabbros inferred to be associated with the OJB.

The block north of the OJB, sometimes referred to as the Vimmerby batholith (Mansfeld, 2004), stretches all the way up to the margin of the Svecofennian domain. Along most of the Svecofennian margin the ~1.85 Ga TIB-0 rocks form an apparently discontinuous border zone (Wikström and Andersson, 2004) that passes into the TIB-1 rocks of the Vimmerby Batholith without any known contacts. Although the Vimmerby Batholith by some workers is characterized as homogenous and continuous (Henkel et al., 1990; Mansfeld, 2004), others have identified a pattern of WNW structural trends defined by individual intrusions (Gorbatshev, 1980, 2004; Lund et al., 2001). It consists mainly of red to greyish red coarse-grained granitoids associated with predominantly rhyolitic volcanites, the so-called Småland porphyries (e.g., Persson, 1974, 1985, 1989). The volcanic TIB-1 rocks essentially also follow the WNW-trend in the form of several extensive belts and smaller units within the granitoids (Fig. 1). Reliable U-Pb zircon ages of the rocks in the Vimmerby Batholith range between 1.81 and 1.79 Ga (Patchett et al., 1987; Jarl and Johansson, 1988; Mansfeld, 1991; Kornfält et al., 1997). Field evidence suggests a co-magmatic relationship between the intrusive and extrusive rocks (Persson, 1989, and references therein), although the analytically most reliable of the few available age estimates of rhyolites within the Vimmerby Batholith is slightly older, 1813 ± 3 Ma (Wikström, 1993).

South of the OJB the TIB-1 rocks are bordered more or less sharply in the west by TIB-2 and 3 rocks (Fig. 1) (Gorbatshev, 2004). The boundary is, however, obscured by deformation along the Protogine zone (e.g., Wikman, 1998). South of the OJB the geochemistry of the TIB-1 granitoids has

been reported to trend from alkali-calcic toward calc-alkalic southward, while the WNW-directed structural pattern is prevalent also here (Gorbatshev, 2001, 2004). The pattern of intrusive ages is more irregular in the south, but generally younger than north of the OJB. They range from 1.80 to 1.77 Ga (Patchett et al., 1987; Jarl and Johansson, 1988; Wikman, 1993; Kornfält and Vaasjoki, 1999). The cogenetic volcanic rocks are among the oldest (1.80–1.79 Ga; Wikman, 1993; Mansfeld, 1996).

In the south, the SVB is truncated and separated from the Blekinge Province by a major shear zone, the E-W-trending Småland-Blekinge deformation zone (SBDZ) (Lindh et al., 2001b). South of this border, the calc-alkaline ca. 1.77 Ga Tving suite of Blekinge (TSB; Fig. 1) dominates. The TSB comprises mostly deformed granites, granodiorites, and tonalites that are more calc-alkaline than their SVB counterparts in the north. They are commonly grey to reddish grey and carry microcline megacrysts. Small, mostly foliated massifs of mafic rocks and dikes, commonly amphibolites and metagabbros, are associated with the Tving granitoids (Kornfält, 1993, 2000; Rimša, 2002). The rocks of both the SVB and the TSB are deformed along the SBDZ, ranging from slightly foliated rocks to banded mylonites, and even pseudotachylites. Vertical displacement along the SBDZ caused uplift of the TSB relative to the SVB (Kornfält, 1993; Lindh et al., 2001b). Age determinations of the TSB span 1.77–1.75 Ga (Johansson and Larsen, 1989; Kornfält, 1993; Johansson et al., 2006), and most workers consider it as a more calc-alkaline, deep-seated variety of the TIB (Norin, 1936; Johansson and Larsen, 1989; Kornfält, 1993; Lindh et al., 2001b). In the west the TSB (and other rocks of the Blekinge Province) are overprinted by the N-S-oriented deformation along the Protogine zone, mainly Sveconorwegian in age.

Mafic rocks in the Småland-Värmland Belt

Previous work. A limited number of studies discussing mafic rocks of the SVB have been undertaken (excluding map descriptions). Larsson (1935) and Claeson and Andersson (2000) investigated the ~1.85 Ga Nygård norite pluton, while Andersson (1997a) reported on the mafic rocks from Tiveden (~1.85 Ga). Asklund (1925) studied the partly noritic Stavsjö pluton (probable TIB-0). Vinnefors (1985) described several mafic TIB-1 plutons in eastern Värmland, and Claeson (2001) and Claeson and Meurer (2004) conducted a detailed study of

one of them, the Eriksberg gabbro. Mafic rocks of the Tjällmo-Vättern zone (TVZ) and the Kårtoorp area of northern Östergötland have been discussed by Andersson (1997a) and Andersson et al. (2004a, 2006a).

Both in the Vimmerby Batholith and south of the OJB, comprehensive studies of mafic TIB-1 rocks are lacking, although such rocks are abundant (Fig. 1). Mansfeld (1995), Sundblad et al. (1997), and Mansfeld et al. (2005) studied mafic volcanic rocks related to the OJB. In the area in and around the OJB, the distinction between OJB- and SVB-related mafic plutonic rocks is difficult to make (e.g., Persson, 1989). Johansson and Larsen (1989) presented an isotopic study of a suite of rocks from the Blekinge Province and southern SVB, while Rimša (2002) conducted a comparative study of ~1.80–1.77 Ga metamafic plutonic rocks associated with SVB and TSB granitoids on both sides of the SBDZ. The only study so far of mafic rocks belonging to the younger SVB suite (TIB-2 and 3) was the detailed studies of Claeson (2001) and Claeson and Meurer (2004) on the 1.69 Ga Rymmen gabbro in central southern Sweden (not too far west of the present study area).

Numerous felsic (porphyries) and mafic (porphyrites) dikes that are associated with, and transect, the plutonic TIB-1 rocks in the southern SVB, have ages in the range 1805–1770 Ma (Nilsson and Wikman, 1997; Johansson, 1999). These dikes have been studied in detail by Nilsson (1992).

Samples: Field descriptions and petrography. For the present study, samples were collected from a large geographical area in southeast Sweden (Fig. 1, Table 1). They were chosen to give a regional reconnaissance picture of the mafic plutonic TIB-1 magmatism in the southern SVB and TSB, and taken from plutons and bodies considered by us or previous investigators, based on map or field relations, as related to their surrounding TIB-1 granitoids. The sampled bodies range in size from just a few hundred meters to tens of kilometers. Care was also taken to avoid areas with possible mafic OJB or TIB-2 and 3 plutonites. None of the sampled mafic intrusions have been dated, but contacts with the surrounding TIB-1 granitoids typically indicate magma mingling-mixing relations. This and the abundant occurrence of mafic enclaves and synplutonic mafic or composite dikes within the granitoids suggest the rock types to be coeval, with an age of ~1.80 Ga (e.g., Persson, 1985; Mansfeld, 2004). In a few instances, however, there are some uncertainties

TABLE 1. Localities, Coordinates, Rock Types, and Mineralogy of the Analyzed Mafic Plutonic TIB-1 Rocks in Southeast Sweden¹

Regions	No.	Locality/sample	Lat. N°	Long. E°	Rock type	ol	cpx	opx	amph	pl	bt	qtz	ox	Other
North of western OJB	1a	Hakarp 1a	640851	141132	fine-grained qtz hbl diorite				x	x		x	x	ti,ep,kfs
	2e	Jakobstorp 2b	641228	141739	gabbronorite		x	x	x	x	x		x	ap
	3c	Ylen 2b	641535	142268	hbl diorite				x	x	x	x	x	chl,ap,ti
	5a	Stenskar 1	640365	143260	pl porphyritic ol websterite	x	x	x	x	x	x	x	x	clinozo,ser,chl,biotit
	5d	Stenskar 3	640350	143340	lherzolite	x	x	x	x	x	x	x	x	chl, ser, ca
North of middle OJB	6b	Försjön 1b	639405	145967	ol cpx hbl gabbronorite	x	x	x	x	x		x	x	ser
	7a	Höganaskog a	639241	146527	ol cpx opx hornblendite	x	x	x	x	x			x	phl/bi,chl,kfs
	9b	Övrabo b	639758	147102	cpx hbl diorite		x		x	x	x	x	x	ap,ep,chl
	10a	Långsjö a	639535	146979	hbl norite			x	x	x	x	x	x	clinozo,phl/bi,chl
	11	Svartgölen	639374	146944	pl bearing cpx opx hornblendite		x	x	x	x	x	x	x	clinozo
	13	Bergshult	639332	147973	(qtz) opx hbl gabbro		x	x	x	x	x	x	x	clinozo,ep
	14	Pelarne	638921	149435	pl porphyritic cpx hbl diorite		x	x	x	x	x	x	x	ep,phl/bi,ti,ap,chl,zr
	15	Sevedstorp	638751	149299	pl porphyritic ol hbl norite	x		x	x	x			x	ser
	17	Fagerhult	638411	148502	coarse-grained leucodiorite			x		x			x	ep,ms,chl
	43a	Tuna a	638067	152041	cpx hbl diorite		x		x	x	x	x	x	ep,ap,chl
Most NE intrusions	44a	Sjämrevik a	639070	151672	qtz cpx opx hbl diorite		x		x	x	x	x	x	ap!,ms,ep,chl,zr
	45b	Ramshult 2	638524	150555	qtz cpx hbl diorite		x		x	x	x	x	x	ep,ap,ms el. bio/phl,chl
	36a	Morlunda a	635589	150254	amph megacrystic cpx opx hbl alkalidiorite		x		x	x			x	ep!,ti,clinozo
	39b	Skrikebo 2	635624	153299	cpx opx hbl diorite		x	x	x	x		x	x	phl/bi,ep,zr
	39c	Skrikebo 3	635603	153231	fine-grained cpx opx hbl diorite		x	x	x	x	x	x	x	ap
North of eastern OJB	41	Slåthult	636335	154384	cpx hbl norite		x	x	x	x	x	x	x	zr,ap
	42a	Plåtorp 1	636817	154185	qtz cpx hbl diorite		x		x	x	x	x	x	ep!,zr,phl/bi,ap,chl,clinozo
	31b	Kimramåla 2a	632055	150082	cpx (opx) hbl diorite		x	x	x	x	x	x	x	phl/bi,ap,ep,ms
	31d	Kimramåla 3	631990	149656	fine-grained hbl diorite			x	x	x	x	x	x	ep,ti,chl,clinozo
	32	Kräkenmåla	632249	148934	cpx hbl diorite		x		x		x	x	x	ap,ms,chl
South of OJB	34a	Fagerhult 1a	633658	148464	ophitic fine-grained gabbronorite		x	x		x	x	x	x	ms,ap,chl
	34c	Fagerhult 2	633491	149073	ophitic fine-grained gabbronorite		x	x	x	x	x	x	x	ap,ms,zr,chl
	35b	Skålsäck 2a	634103	148867	fine-grained cpx opx diorite		x	x	x	x	x	x	x	chl
	V9403	Sandåkra	634547	148180	serpentinite						x		x	ser
	V9405	NV BP-94	634455	148250	gabbro		x		x	x			x	chl
	V9406	Skålsäck	634142	148787	gabbro		x		x	x			x	chl
	V9407	NO BP-94	634460	148270	gabbro		x		x	x			x	chl
V9409		gravpkt 28	634815	148465	basic composite dyke			x	x	x			x	chl

Sample numbers correspond to those in Figure 1, Tables 2 and 3. Bold type denotes isotopically analyzed samples. Abbreviations: hbl = hornblende; ol = olivine; cpx = clinopyroxene; opx = orthopyroxene; amph = amphibole; pl = plagioclase; bt = biotite; qtz = quartz; ox = oxides; sp = spinel; ti = titanite; ep = epidote; kfs = K-feldspar; ap = apatite; zo = zoisite; chl = chlorite; ser = serpentine; ca = calcite; plh = phlogopite; ms = muscovite; zr = zircon; fl = fluorite.

To facilitate spatial comparisons, the samples were divided into geographical subgroups: north of western OJB, north of middle OJB, north of eastern OJB, the most northeastern intrusions, south of OJB, southernmost SVB, and TSB. Samples for whole rock geochemistry were selected to obtain optimal spread both in terms of geography and petrography. Based on the whole-rock geochemistry, samples for isotopic analysis were selected to obtain maximal variation in geochemical evolution (as reflected in Mg#, Ni, etc.), but avoiding crustal contamination as far as possible (e.g., considerable amounts of quartz or K-feldspar in thin section, and/or high K₂O, Rb, etc.).

The sampled rock types range from ultramafic to leucodioritic in composition (Table 1). Texturally, they vary from fine- to coarse-grained, some being plagioclase porphyritic. Sample #36 is special in the sense that it carries rounded amphibole megacrysts several centimeters in diameter. Generally the rocks are greenish black, but sample #17 is a leucodiorite consisting mainly of plagioclase and amphibole, with the plagioclase most abundant. In general, the texture is massive, but a few samples (samples #21 and #22, not geochemically analyzed) from the southwest underwent solid-state or ductile deformation in the same manner as the TIB-1 granitoids in the area (Sukotjo, 2005). Only sample #32, a monzogabbro, shows a weak magmatic foliation. Sample #47 demonstrates a weak deformation and metamorphism (Rimša, 2002).

Most of the rocks consist of varying proportions of plagioclase, amphibole, clinopyroxene, orthopyroxene, and biotite (Table 1). Plagioclase (locally strongly sericitized) is, in combination with pyroxenes and/or amphibole, the main mineral in most of the rocks. Amphibole typically shows evidence of alteration after pyroxene, either surrounding relict cores of pyroxene (mostly clinopyroxene) or in pseudomorphs where the pyroxene has been completely replaced by amphibole + quartz + oxides (partial replacement in Fig. 2). The absence,

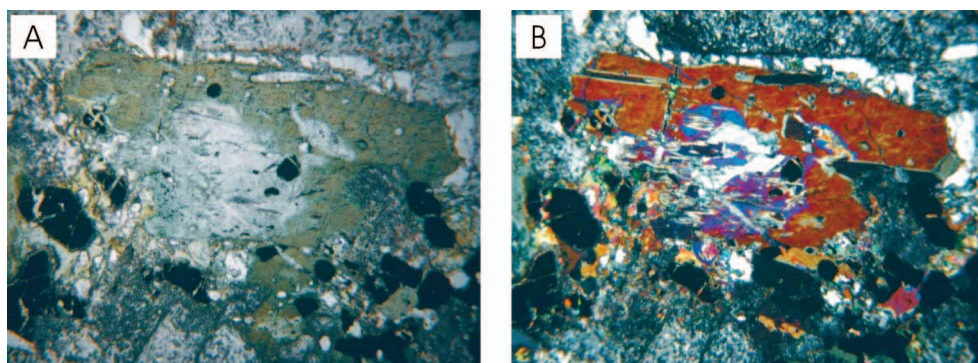


FIG. 2. Thin section in plane (A) and cross-polarized (B) light of sample #7a. Clinopyroxene (pale green and strongly colored, mainly in blue and red, in the respective pictures), mainly in the center of the pictures, is strongly replaced by amphibole (darker green and brown in the respective pictures), quartz (white in both pictures) and oxides (black in both pictures). Also sericitized plagioclase and titanite (pale yellow and brightly colored, mainly in green, red, and yellow, in the respective pictures) are present. Depicted area of the thin section is 1.3×1.4 mm.

or small amounts, of amphibole in rocks with fresh olivine and pyroxenes also indicates that it is mostly of secondary origin. In contrast, amphibole and quartz generally occur together in pyroxene-free samples (or samples with minor clinopyroxene) (Table 1).

Olivine is present only in a few samples north of the OJB, as well as in the sample from the TSB in the far south (sample #46). Olivine- and/or orthopyroxene-bearing samples mostly do not contain quartz. Inasmuch as quartz in these rocks is mainly present as an alteration product after pyroxene (together with amphibole and oxides), it is more common in rocks where the pyroxenes and olivine are lacking and have been replaced, particularly in the northeast and in the southernmost SVB. The olivines are also serpentinized to varying degrees, except for sample #7a. Sample #V9403 is a totally serpentinized dunite. Biotite is well preserved in most cases, even if chlorite is normally found. However, biotite can be strongly, or even totally, altered to chlorite.

Among accessory minerals, the most widespread are the Fe-Ti-oxides magnetite and ilmenite, absent only in sample #29. Spinel is present in a few rocks (samples #18a and #46). Apatite (particularly in sample #44a) and epidote-clinozoisite (particularly in samples #36 and #42) are also common accessories. Furthermore, phlogopite (or Fe-bearing phlogopite), titanite, K-feldspar, zircon, muscovite, chlorite, and serpentine occur in varying amounts, as well as calcite in sample #5d. Epidote-clino-

zoisite typically formed by breakdown of plagioclase + mafic minerals. To some extent K-feldspar may have formed as an alteration product after biotite. Mostly, however, K-feldspar appears to represent, together with quartz, silicic residual melts in the more evolved mafic rocks.

From a geographic perspective, the mineralogy can be summarized as: olivine-bearing rocks are present north of OJB and in #46 from TSB, whereas anhydrous mafic minerals are rare in the mafic intrusions from the southernmost SVB.

Analytical Techniques

Whole-rock geochemical analyses were performed by Acme Analytical Laboratories Ltd., Vancouver, Canada, on 35 of the samples (Table 2). The major elements, Ba, and Sc were determined by ICP-ES and the remaining trace elements by ICP-MS. Carbon and sulfur were analysed by Leco and fluorine by a specific ion electrode method. Whole rock powders were prepared using a soft-tempered steel swingmill, which may introduce some contamination for Fe, Cr, Ni, and Cu (cf. e.g., Johnson et al., 1999). However, contamination levels are probably insignificant in relation to the concentration of these elements in the samples. Moreover, Ni and Cr show clear correlation with Mg# (see below), which is not expected from a sample suite disturbed by contamination. Samples #46 and #47 were analysed for major elements at the chemical laboratory of the Ernst Moritz Arndt University, Greifswald

TABLE 2. Geochemistry and Normative Mineral (SIN) Contents of the Analyzed Mafic TIB-1 Intrusions in Southeast Sweden¹

Regions: Sample:	North of western OJB					North of middle OJB								
	1a	2e	3c	5a	5d	6b	7a	9b	10a	11	13	14	15	17
	wt%													
SiO ₂	51.08	51.28	47.54	43.70	39.85	46.11	45.49	43.88	45.06	46.64	45.10	46.65	42.93	45.13
TiO ₂	1.11	0.75	1.17	0.82	0.24	0.33	0.49	1.81	0.35	0.71	0.75	0.96	0.31	0.43
Al ₂ O ₃	17.75	17.02	17.52	8.82	3.57	17.36	8.77	14.29	22.00	12.76	15.64	15.89	18.44	24.12
Fe ₂ O ₃	10.84	10.73	10.58	15.23	13.47	6.52	10.30	15.32	7.12	10.48	9.59	10.70	10.12	4.61
FeO	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
MnO	0.15	0.15	0.11	0.19	0.17	0.08	0.14	0.14	0.08	0.13	0.11	0.15	0.11	0.07
MgO	4.25	8.02	5.89	13.50	26.72	10.07	18.72	8.10	9.37	12.32	11.25	8.09	14.19	5.74
CaO	7.01	7.83	10.10	15.25	8.67	14.66	11.62	10.81	10.91	12.04	13.77	10.89	9.45	12.23
Na ₂ O	3.72	2.35	2.65	0.46	0.13	1.09	1.05	1.76	1.46	1.57	1.23	2.60	1.43	1.86
K ₂ O	2.22	0.77	0.99	0.34	0.05	0.73	0.60	0.73	0.83	0.87	0.67	1.28	0.35	1.74
P ₂ O ₅	0.30	0.20	1.04	0.05	0.01	0.05	0.11	1.02	0.08	0.15	0.06	0.40	0.08	0.06
Cr ₂ O ₃	0.003	0.007	0.024	0.053	0.257	0.037	0.165	0.020	0.002	0.063	0.030	0.036	0.045	0.013
CO ₂	0.15	1.32	1.32	0.99	0.18	1.91	0.15	1.14	0.73	0.55	0.11	0.66	0.66	0.77
SO ₂	0.42	0.06	0.14	0.48	0.16	0.20	0.10	0.32	0.14	0.32	0.50	0.20	0.12	<0.02
LOI	1.10	0.90	2.40	1.20	6.50	3.00	2.00	1.90	2.40	1.80	1.70	2.10	2.40	3.30
Total	99.53	100.01	100.01	99.61	99.64	100.04	99.46	99.78	99.66	99.53	99.90	99.75	99.86	99.30
Mg#	47.8	63.5	56.5	67.4	82.2	78.3	80.9	55.2	75.4	73.3	73.2	63.8	76.6	74.4
	ppm													
F	990	n.a.	n.a.	160	30	120	320	n.a.	n.a.	n.a.	n.a.	n.a.	90	n.a.
Ba	567	325	501	113	20	304	259	395	365	255	236	470	193	418
Rb	103.5	22.0	31.1	13.3	2.0	29.7	19.6	22.9	23.7	23.8	19.6	45.4	8.1	84.5
Sr	965	566	1230	436	68	871	436	1078	1363	694	818	1118	1180	1311
Cs	1.9	1.2	2.4	0.8	<0.1	5.8	0.8	1.5	1.9	2.2	1.6	1.9	0.7	9.0
Ga	21.2	18.6	21.8	14.2	5.6	14.9	10.7	23.7	18.6	16.4	17.0	21.9	16.2	18.0
Ta	0.4	0.2	0.2	<0.1	<0.1	<0.1	<0.1	0.3	0.1	0.4	0.1	0.3	0.1	<0.1
Nb	5.9	3.7	4.3	1.0	<0.5	1.0	2.1	5.4	2.1	5.4	2.7	7.4	1.6	2.4
Hf	3.5	2.0	2.2	1.1	<0.5	0.7	1.2	2.5	0.9	2.0	1.7	2.5	0.6	1.3
Zr	111.0	77.3	87.8	29.2	9.7	21.8	38.5	82.7	29.4	55.8	42.0	81.8	22.7	41.5
Y	27.6	16.8	19.0	16.0	7.7	8.3	11.9	19.1	7.2	18.0	16.1	26.2	4.9	8.6
Th	6.5	2.4	2.4	0.7	0.2	0.9	1.6	1.5	0.6	2.2	1.9	1.8	0.5	0.6
U	3.0	0.5	0.5	0.2	<0.1	0.2	0.6	0.5	0.2	1.2	0.5	1.1	0.2	0.4
Ni	9.9	34.6	37.7	69.7	591.3	46.3	121.1	55.7	66.1	55.3	54.3	33.1	177.9	33.4
Co	32.5	43.5	34.3	72	109.2	39.3	69.9	60.3	50	53.8	57.4	37.4	72.3	23.8
Sc	19	26	24	74	42	47	52	31	8	45	59	33	8	10
V	191	117	248	426	112	119	162	354	63	177	204	213	55	77
Cu	60.1	52.3	68.0	203.6	93.7	202.3	35.3	117.5	26.4	102.9	448.9	95.8	14.2	2.1
Pb	4.1	1.5	2.0	1.2	1.1	2.1	1.6	2.3	3.4	2.6	2.6	2.3	1.5	1.8
Zn	71	24	41	25	66	16	33	66	30	23	29	46	49	23
W	4.4	9.6	9.0	9.1	0.6	9.6	2.7	7.6	6.7	6.8	2.3	6.7	6.3	8.2
Mo	0.8	0.9	1.0	1.0	0.1	0.8	0.4	0.9	0.6	0.9	0.3	0.8	0.7	0.8
La	33.2	13.6	29.8	6.1	1.7	5.3	9.6	26.6	9.1	16.6	9.6	30.3	6.9	8.2
Ce	74.6	29.1	66.9	17.1	5.1	12.0	20.8	59.2	19.7	39.4	23.1	77.2	16.0	20.2
Pr	9.80	3.78	8.63	2.65	0.87	1.74	2.87	7.69	2.55	5.18	3.32	10.61	1.99	2.62
Nd	43.5	15.8	39.6	14.3	5.1	8.2	12.2	33.8	11.1	23.9	16.2	47.2	8.2	12.7
Sm	9.4	3.7	7.1	3.9	1.6	2.1	3.1	6.4	2.3	4.9	4.2	10.1	1.7	2.5
Eu	2.46	1.07	1.78	0.83	0.37	0.62	0.85	1.56	0.71	1.16	1.09	2.38	0.61	0.76
Gd	7.37	3.26	5.57	3.59	1.69	1.80	2.82	5.10	1.99	4.06	3.64	7.57	1.06	1.97
Tb	0.95	0.49	0.71	0.53	0.29	0.26	0.39	0.69	0.25	0.61	0.54	1.03	0.16	0.31
Dy	4.91	2.71	3.62	3.10	1.49	1.54	2.13	3.47	1.24	3.21	3.11	5.06	0.94	1.69
Ho	0.97	0.58	0.64	0.60	0.29	0.28	0.45	0.66	0.26	0.60	0.60	0.94	0.17	0.29
Er	2.26	1.67	1.63	1.49	0.72	0.74	1.10	1.69	0.61	1.63	1.43	2.37	0.45	0.86
Tm	0.36	0.25	0.22	0.21	0.11	0.11	0.17	0.23	0.10	0.24	0.21	0.32	0.06	0.12
Yb	2.09	1.57	1.42	1.37	0.68	0.69	1.00	1.43	0.63	1.61	1.27	2.07	0.40	0.68
Lu	0.32	0.25	0.20	0.21	0.08	0.09	0.14	0.20	0.08	0.25	0.16	0.29	0.06	0.10
	SIN norms, %													
qtz	-	2.25	-	-	-	-	-	-	-	-	-	-	-	-
or	13.39	4.57	5.96	2.04	0.32	4.39	3.66	4.41	5.03	5.27	4.05	7.76	2.13	10.68
ab	32.03	19.94	22.81	1.50	1.19	8.94	9.11	15.19	12.65	13.60	7.65	18.10	12.16	9.11
an	25.67	33.75	33.61	21.33	9.77	40.93	18.01	29.54	52.34	25.82	35.96	28.60	44.05	54.25
ne	-	-	-	1.33	-	0.22	0.03	-	-	-	1.61	2.40	0.14	3.90
di	6.36	3.40	9.05	44.83	29.35	26.28	32.54	15.48	2.53	27.88	27.16	19.99	3.21	7.04
hy	8.73	29.46	13.49	-	0.01	-	-	9.87	5.22	1.49	-	-	-	-
ol	6.29	-	6.43	22.16	55.57	14.85	32.47	14.56	18.85	20.81	19.07	16.94	34.86	12.17
mt	3.83	3.32	2.38	3.42	2.52	1.46	2.35	3.45	1.61	2.37	2.17	2.42	1.79	1.06
il	2.15	1.43	2.26	1.58	0.49	0.64	0.96	3.51	0.68	1.38	1.45	1.87	0.60	0.85
ap	0.727	0.467	2.465	0.122	0.026	0.121	0.269	2.419	0.191	0.357	0.143	0.954	0.196	0.145
zr	0.022	0.015	0.017	0.006	0.002	0.004	0.008	0.016	0.006	0.011	0.008	0.016	0.005	0.008
fl	0.147	-	-	0.023	0.004	0.015	0.045	-	-	-	-	-	0.003	-
pyr	0.390	0.055	0.129	0.443	0.149	0.183	0.093	0.295	0.130	0.297	0.465	0.185	0.111	-
chr	0.046	0.035	0.088	0.168	0.400	0.079	0.277	0.105	0.017	0.130	0.088	0.098	0.078	0.036

Table continues

TABLE 2. *Continued*

Regions: Sample:	North of eastern OJB					Most northeastern intrusions				South of OJB				
	36a	39b	39c	41	42a	43a	44a	45b	31b	31d	32	34a	34c	35b
	wt%													
SiO ₂	40.10	45.14	43.97	44.59	48.21	46.66	50.42	48.92	48.45	47.99	49.15	48.48	48.32	48.55
TiO ₂	1.93	0.74	1.93	1.69	0.70	1.38	1.05	1.56	1.04	1.28	0.83	1.11	1.10	0.67
Al ₂ O ₃	11.28	17.55	15.62	16.71	17.77	16.73	16.72	16.05	17.06	18.61	19.78	15.73	16.09	16.15
Fe ₂ O ₃	20.81	10.01	14.88	15.83	8.52	11.71	9.30	11.44	10.00	11.56	10.50	11.55	11.46	9.89
FeO	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
MnO	0.16	0.13	0.14	0.13	0.11	0.11	0.12	0.13	0.14	0.17	0.18	0.14	0.14	0.14
MgO	8.28	9.20	5.96	5.70	7.05	6.36	6.79	6.53	6.49	4.29	3.83	7.79	7.99	9.04
CaO	12.37	11.31	10.59	11.48	10.27	11.58	7.62	8.26	10.65	8.07	8.39	9.71	9.73	10.53
Na ₂ O	1.48	2.04	2.57	1.45	2.42	2.23	2.56	2.85	3.17	4.05	4.13	2.76	2.67	2.35
K ₂ O	0.69	1.12	1.53	1.02	1.53	0.93	1.47	1.19	1.31	1.17	0.80	0.96	0.85	0.67
P ₂ O ₅	0.15	0.23	0.53	0.14	0.22	0.33	0.42	0.46	0.30	0.34	0.65	0.36	0.38	0.08
Cr ₂ O ₃	0.002	0.005	0.004	0.003	0.026	0.016	0.025	0.036	0.010	0.002	0.001	0.025	0.027	0.037
CO ₂	1.14	0.26	0.92	0.73	0.07	0.66	1.43	0.95	0.77	1.06	1.14	0.62	0.81	1.36
SO ₂	0.60	0.24	0.58	0.62	0.30	0.66	0.30	0.42	0.16	0.28	0.18	0.30	0.20	0.16
LOI	2.00	2.40	1.40	1.00	2.30	1.60	3.20	2.10	1.10	2.00	2.20	1.20	1.40	1.90
Total	99.25	99.88	99.12	99.74	99.13	99.64	99.70	99.53	99.72	99.53	100.44	99.82	100.16	100.01
Mg#	48.1	68.2	48.3	45.6	65.9	55.9	63.0	57.1	60.2	46.4	46.0	61.1	61.9	68.1
	ppm													
F	460	n.a.	n.a.	330	n.a.	n.a.	670	n.a.	1530	n.a.	n.a.	510	n.a.	n.a.
Ba	340	544	934	324	432	545	677	716	899	862	680	456	540	364
Rb	21.1	25.1	41.8	28.8	48.1	22.6	66.9	30.2	40.4	34.0	21.1	28.9	19.2	15.0
Sr	796	1259	1066	701	887	1615	814	1142	889	908	1134	580	619	557
Cs	0.3	1.1	1.1	1.4	1.6	1.3	2.4	1.5	1.2	0.9	0.5	1.6	0.7	1.0
Ga	22.7	19.2	25.3	24.2	19.7	23.1	20.1	22.9	20.9	25.9	22.2	18.9	19.0	17.8
Ta	0.2	0.2	0.5	0.2	0.3	0.3	0.5	0.4	0.3	0.5	0.2	0.2	0.2	<0.1
Nb	3.3	4.3	9.2	4.7	5.2	5.6	9.7	9.1	7.7	13.4	3.9	3.9	3.3	<0.5
Hf	2.3	2.0	2.9	1.7	2.2	2.6	3.7	3.1	1.8	1.6	1.3	2.2	2.3	0.8
Zr	54.7	55.0	100.0	56.7	62.7	83.9	139.7	111.8	43.0	35.2	33.5	75.1	67.2	18.4
Y	17.3	17.0	30.8	17.1	19.5	18.1	21.3	22.4	28.1	47.1	19.2	21.9	22.2	13.3
Th	1.1	0.4	1.4	2.0	2.1	1.9	2.8	1.8	1.0	0.5	0.6	2.5	1.2	<0.1
U	0.5	0.2	0.5	0.6	0.6	0.5	1.1	0.6	0.5	0.3	0.2	0.9	0.6	<0.1
Ni	7.8	40.5	36.0	13.2	47.7	71.0	76.8	107.5	21.7	3.3	2.4	79.5	83.8	72.8
Co	70.7	46.2	49.2	60	39.3	48.6	38.4	42.9	35.2	29.4	23.1	44.5	45.9	47.1
Se	52	26	32	38	31	29	20	18	30	24	10	32	29	34
V	686	152	409	463	163	267	132	197	204	242	171	225	200	168
Cu	172.7	67.6	91.5	103.5	81.6	117.1	45.5	67.5	93.3	38.2	34.5	93.9	86.3	72.4
Pb	4.1	1.3	1.7	3.3	3.4	2.4	4.4	2.1	1.4	1.7	0.8	1.6	2.8	0.7
Zn	67	37	76	65	38	50	64	87	45	82	69	39	42	30
W	7.8	2.1	7.6	8.2	2.2	9.0	6.9	8.9	7.3	8.1	8.4	8.8	7.8	9.5
Mo	0.9	0.3	1.0	1.0	0.4	0.8	1.0	0.9	0.8	1.0	1.0	1.2	1.0	0.7
La	14.3	17.9	34.1	14.3	22.7	26.2	34.5	27.4	26.9	35.3	28.9	17.9	16.6	5.7
Ce	36.0	41.2	80.7	32.5	49.1	59.7	72.3	62.9	62.6	87.5	61.3	39.6	35.8	12.2
Pr	5.35	5.56	10.94	4.46	5.79	7.37	8.19	7.97	8.28	11.63	7.34	5.11	4.81	1.81
Nd	25.9	25.7	49.8	19.6	25.8	34.3	36.5	38.1	36.9	52.5	30.9	21.6	22.6	8.6
Sm	6.2	5.3	9.8	4.4	5.2	6.3	6.4	7.7	7.7	11.3	5.5	5.0	4.7	2.2
Eu	1.57	1.51	2.22	1.17	1.57	1.77	1.89	2.14	1.80	2.06	1.75	1.39	1.52	1.10
Gd	5.12	4.55	7.99	3.95	4.76	5.20	5.68	6.14	6.41	9.33	4.09	4.52	4.50	2.59
Tb	0.71	0.62	1.12	0.58	0.63	0.70	0.75	0.82	0.92	1.44	0.61	0.67	0.68	0.41
Dy	3.65	3.33	5.98	3.28	3.48	3.59	4.02	4.50	5.14	8.17	3.27	3.81	4.06	2.46
Ho	0.68	0.63	1.21	0.65	0.65	0.60	0.70	0.76	0.96	1.59	0.67	0.80	0.80	0.53
Er	1.66	1.61	2.84	1.69	1.82	1.57	1.86	1.90	2.68	4.33	1.83	2.05	2.07	1.38
Tm	0.23	0.22	0.42	0.27	0.27	0.22	0.31	0.27	0.37	0.67	0.26	0.32	0.31	0.19
Yb	1.32	1.40	2.59	1.47	1.62	1.42	1.81	1.68	2.53	4.08	1.58	2.01	1.93	1.32
Lu	0.21	0.23	0.33	0.23	0.23	0.18	0.25	0.22	0.39	0.63	0.27	0.30	0.31	0.20
	SIN norms, %													
qtz	-	-	-	-	-	-	1.83	-	-	-	-	-	-	-
or	4.21	6.82	9.25	6.12	9.39	5.60	8.93	7.20	7.84	7.07	4.79	5.77	5.09	4.01
ab	1.82	12.86	13.88	12.44	21.22	19.19	22.20	24.65	23.15	32.12	35.36	23.69	22.85	20.13
an	22.78	36.49	27.18	36.60	34.35	33.53	30.60	28.16	28.79	29.80	33.54	28.11	29.79	31.95
ne	6.00	2.65	4.51	-	-	-	-	-	2.14	1.54	-	-	-	-
di	32.96	16.43	19.53	16.99	14.13	19.24	4.55	9.22	18.20	7.73	4.04	15.15	13.79	16.77
hy	-	-	-	7.94	4.16	3.61	24.00	18.19	-	-	3.70	7.98	9.50	9.94
ol	22.40	19.92	15.66	11.23	12.43	11.31	-	4.38	13.62	13.42	10.82	12.62	12.31	11.92
mt	3.70	2.28	3.36	3.55	1.95	2.63	2.94	2.59	2.23	3.63	3.27	2.59	2.56	2.21
il	3.78	1.45	3.74	3.25	1.38	2.67	2.05	3.03	2.00	2.48	1.60	2.14	2.11	1.29
ap	0.366	0.551	1.261	0.338	0.530	0.782	1.027	1.097	0.722	0.810	1.534	0.868	0.895	0.187
zr	0.011	0.011	0.020	0.011	0.013	0.017	0.028	0.022	0.009	0.007	0.007	0.015	0.013	0.004
fl	0.065	-	-	0.041	0.000	-	0.057	-	0.257	-	-	0.037	-	-
pyr	0.552	0.223	0.534	0.573	0.279	0.609	0.275	0.387	0.148	0.258	0.166	0.278	0.185	0.147
chr	0.150	0.040	0.094	0.104	0.073	0.081	0.064	0.095	0.058	0.055	0.038	0.085	0.082	0.090

Table continues

TABLE 2. *Continued*

Regions: Sample:	South of OJB					Southernmost SVB								TSB
	V9403	V9405	V9406	V9407	V9409	18a	20b	23	25a	26	27	29	47	46
wt%														
SiO ₂	38.10	49.30	49.30	45.30	46.30	42.21	40.02	44.92	52.96	42.13	52.25	52.80	53.67	45.04
TiO ₂	0.19	0.91	0.65	1.80	1.08	0.25	1.84	1.47	1.10	1.77	0.78	0.60	0.86	0.19
Al ₂ O ₃	3.63	17.30	17.30	14.30	16.90	17.80	15.71	14.84	16.68	18.75	14.90	13.86	18.62	18.59
Fe ₂ O ₃	13.60	9.07	8.56	16.80	12.10	10.17	16.78	17.01	10.68	14.40	9.32	8.80	n.a.	n.a.
FeO	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	8.27	9.92
MnO	0.21	0.15	0.15	0.20	0.21	0.14	0.19	0.17	0.14	0.15	0.14	0.22	0.13	0.14
MgO	32.10	7.76	8.10	7.00	8.26	14.45	6.16	6.25	3.93	5.62	8.22	8.39	3.99	12.38
CaO	1.14	9.08	12.20	11.30	9.76	10.39	12.09	10.97	7.68	11.30	9.18	7.54	7.38	11.29
Na ₂ O	0.31	2.79	2.68	2.38	2.32	1.09	1.89	1.83	3.84	2.49	2.44	3.58	4.43	1.39
K ₂ O	0.25	1.66	0.54	0.66	0.82	0.29	0.61	0.69	1.55	1.02	1.41	1.74	1.37	0.25
P ₂ O ₅	0.10	0.42	0.12	0.14	0.19	0.09	1.75	0.16	0.27	0.92	0.13	0.13	0.41	0.04
Cr ₂ O ₃	0.23	0.03	0.05	0.01	0.01	0.002	0.002	0.006	<0.001	0.001	0.056	0.045	n.a.	n.a.
CO ₂	n.a.	n.a.	n.a.	n.a.	n.a.	0.51	1.06	1.03	0.70	0.70	0.15	0.84	n.a.	n.a.
SO ₂	n.a.	n.a.	n.a.	n.a.	n.a.	0.04	0.62	1.02	0.08	0.44	0.16	<0.02	n.a.	n.a.
LOI	11.0	1.9	1.1	0.3	3.0	2.90	2.60	1.40	1.10	1.30	1.10	2.20	0.37	1.48
Total	100.85	100.37	100.75	100.19	100.95	99.78	99.64	99.72	99.93	99.85	99.93	99.91	99.50	100.71
Mg#	84.6	66.6	68.8	49.3	61.4	76.8	46.1	46.1	46.2	47.6	67.3	69.0	50.3	72.4
ppm														
F	n.a.	n.a.	n.a.	n.a.	n.a.	50	n.a.	210	n.a.	1110	n.a.	1750	n.a.	n.a.
Ba	89.2	630	419	384	368	137	332	227	615	386	542	743	991.0	183.0
Rb	4.06	46.2	15.2	13.9	59.4	10.9	11.9	24.6	83.7	27.9	41.3	63.4	26.1	7.2
Sr	80.6	987	624	925	492	866	1088	708	684	1423	477	449	1324	774
Cs	n.a.	n.a.	n.a.	n.a.	n.a.	2.7	0.6	2.4	2.8	1.5	0.7	2.0	0.9	0.9
Ga	<0.3	13.9	3.8	11.4	<0.3	13.3	22.5	19.8	22.5	19.9	16.6	17.6	27.3	14.2
Ta	<0.01	0.575	<0.01	0.381	<0.01	<0.1	0.2	0.1	0.3	0.2	0.3	0.7	0.3	<0.1
Nb	<0.3	7.93	<0.3	2.88	2.68	1.5	4.8	2.6	6.8	4.0	4.8	12.2	5.4	0.7
Hf	<0.03	5.86	<0.03	1.54	8.55	0.6	1.1	1.3	4.3	1.2	2.4	2.1	2.8	0.6
Zr	15.4	117.0	25.0	50.7	51.3	20.0	26.5	44.3	135.5	38.2	79.9	51.7	88.2	15.0
Y	6.72	21.9	12.4	18.9	30.2	5.4	38.3	11.8	21.5	19.7	15.7	38.9	17.0	4.4
Th	0.49	3.19	<0.01	0.92	1.86	0.5	0.2	0.9	3.2	1.2	1.8	5.7	1.6	0.4
U	<0.02	1.38	<0.02	0.449	0.77	0.4	0.1	0.5	1.1	0.5	0.9	2.1	0.7	0.1
Ni	525	102	112	45.6	105	52.5	0.2	18.9	3.4	0.5	71.3	51.9	14.0	144.0
Co	123	36.7	37.8	47.4	50.8	66.4	42.4	52.7	22.6	37.9	42.3	38.8	44.6	73.6
Sc	9.4	19.0	38.7	36.4	32.0	15	38	44	27	32	29	36	n.a.	n.a.
V	59.5	137	166	501	228	58	353	496	225	278	149	159	155	73
Cu	44.7	61.7	94.4	57.7	90.3	25.8	32.5	156.3	14.7	111.0	96.7	4.8	62.0	102.0
Pb	n.a.	n.a.	n.a.	n.a.	n.a.	3.3	1.4	1.4	1.9	1.6	1.4	2.9	<3.0	<3.0
Zn	71.2	90.5	58.2	139	104	24	67	41	51	41	38	83	47	14
W	<0.01	<0.01	<0.01	<0.01	0.90	1.6	8.6	11.1	8.8	7.3	4.9	8.0	115.0	45.0
Mo	<0.2	<0.2	<0.2	<0.2	<0.2	0.2	0.8	1.3	1.1	0.8	0.7	0.8	<1.0	<1.0
La	6.1	40.0	7.4	18.5	19.0	5.9	39.9	9.2	23.6	19.7	15.0	33.9	30.8	4.3
Ce	15.0	97.3	20.1	44.8	44.9	13.2	114.3	22.0	55.4	49.6	32.1	92.2	64.8	8.5
Pr	1.01	11.6	1.91	5.88	5.63	1.61	15.09	2.86	6.62	6.81	3.86	11.96	8.42	1.07
Nd	6.67	53.3	13.0	28.4	25.9	7.3	67.8	11.4	25.8	32.7	15.1	48.7	34.6	4.7
Sm	<0.006	6.88	<0.006	3.75	3.32	1.6	13.1	2.8	5.5	7.5	3.6	9.6	6.4	1.1
Eu	<0.006	1.31	0.657	1.48	1.52	0.53	3.06	0.86	1.52	2.15	1.00	2.20	1.89	0.59
Gd	1.22	8.45	3.62	6.12	5.89	1.19	10.55	2.83	4.46	6.41	3.30	7.66	4.42	1.09
Tb	0.50	1.29	0.69	0.97	1.7	0.21	1.48	0.38	0.69	0.86	0.48	1.10	0.58	0.14
Dy	0.45	4.63	2.02	3.04	6.30	0.93	7.89	2.26	3.70	4.22	2.83	6.48	3.30	0.88
Ho	<0.01	1.08	0.32	0.48	1.55	0.22	1.46	0.44	0.77	0.74	0.54	1.31	0.61	0.16
Er	<0.01	2.31	0.35	1.49	3.84	0.59	3.73	1.26	2.15	1.86	1.60	3.68	1.74	0.44
Tm	<0.01	0.23	0.06	0.19	0.58	0.11	0.50	0.19	0.31	0.24	0.25	0.61	0.23	0.06
Yb	<0.002	1.33	0.38	0.78	3.33	0.43	2.87	1.12	2.17	1.51	1.56	3.90	1.42	0.38
Lu	<0.01	0.16	0.03	<0.01	0.68	0.10	0.39	0.16	0.32	0.23	0.20	0.61	0.20	0.06
SIN norms, %														
qtz	—	—	—	—	—	—	—	—	1.39	—	0.97	—	—	—
or	1.66	10.04	3.25	3.94	4.98	1.78	3.72	4.15	9.29	6.13	8.48	10.50	8.13	1.49
ab	2.97	24.11	22.88	17.34	20.22	8.79	12.64	15.71	32.84	12.00	20.97	30.85	37.61	11.81
an	5.70	30.46	33.91	26.78	34.32	44.35	33.60	30.70	23.99	37.57	25.96	16.94	27.06	43.98
ne	—	—	—	1.66	—	0.41	2.08	—	—	5.08	—	—	—	—
di	—	10.76	21.65	24.51	11.88	6.99	14.08	19.75	10.88	11.31	15.94	15.70	6.37	9.98
ol	19.78	5.63	0.81	—	5.25	—	—	8.30	14.27	—	22.51	13.60	13.70	2.53
py	65.10	14.10	13.95	18.09	17.95	34.57	21.34	12.15	—	17.75	—	6.49	1.26	27.29
mt	2.64	2.05	1.91	3.76	2.76	1.81	2.98	3.82	3.75	3.23	2.92	3.11	3.20	2.45
il	0.40	1.77	1.25	3.46	2.11	0.49	3.60	2.83	2.11	3.41	1.51	1.16	1.64	0.36
ap	0.257	1.004	0.278	0.329	0.464	0.222	4.191	0.385	0.635	2.221	0.308	0.315	0.964	0.093
zr	0.003	0.023	0.005	0.010	0.010	0.004	0.005	0.009	0.027	0.008	0.016	0.010	0.018	0.003
fl	—	—	—	—	—	0.010	—	0.013	—	0.055	—	0.333	—	—
pyr	—	—	—	—	—	0.037	0.571	0.938	0.074	0.406	0.149	—	—	—
chr	0.354	0.077	0.104	0.124	0.058	0.016	0.079	0.115	0.049	0.061	0.114	0.100	0.034	0.016

¹Sample numbers correspond to those in Figure 1 and Tables 1 and 3. Bold type denotes isotopically analyzed samples. LOI = loss on ignition; Mg# = Mg number (100 x (MgO x 0.603 / 24.305) / ((MgO x 0.603 / 24.305) + (0.85 x FeOtotal) x 0.777 / 55.847)); n.a. = not analyzed. Normative minerals were calculated using the SINCLAS program of Verma et al., 2002, employing the Fe recalculation scheme by Middlemost, 1989.

(Germany) by XRF. The trace elements including REE were analysed at Acme Analytical Laboratories Ltd. by ICP-MS, except for Cu, Pb, Zn, and Ni, which were analyzed by ICP-ES (cf., Rimša, 2002). Samples #V9403, #V9405, #V9406, #V9407, and #V9409 were analyzed by ICP-AES (major elements, and Ba, Be, Co, Cr, Cu, Ni, Pb, Sc, Sr, V, Zn, and Zr) and ICP-MS (Ga, Hf, Mo, Nb, Rb, Sn, Ta, Th, U, W, Y, and the REE) at SGAB Analytica, Luleå, Sweden.

The Sr and Nd isotopic analyses (Table 3) were made at the Laboratory for Isotope Geology (LIG) at the Swedish Museum of Natural History in Stockholm. Nd and Sm concentrations were determined by isotope dilution, using a mixed ^{150}Nd - ^{147}Sm spike. Sm, Nd, and Sr were loaded on double Re filaments, and analysed as metal ions on a Finnigan MAT 261 thermal ionization mass spectrometer. The Nd and Sr isotopic compositions were measured in multidynamic, and Sm in static mode. Nd compositions were corrected for spike, Sm-interference, and fractionation to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. Sm-interference was monitored by measurements at mass 149. The Nd samples were measured during two sessions, separated in time by ~6 months. The measured $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of the La Jolla Nd-standard during the first session was 0.511844 ± 12 ($n = 11$; 2σ), and during the second session 0.511850 ± 20 ($n = 5$; 2σ). The differences are thus small, and the values sufficiently close to the preferred value of 0.511854, and no corrections were made.

Reported $^{87}\text{Rb}/^{86}\text{Sr}$ ratios were calculated from measured $^{87}\text{Sr}/^{86}\text{Sr}$ and the Rb and Sr analyses in Table 2. Precisions for Rb and Sr were reported by Acme at $\sim \pm 5\%$ (2σ). This would propagate to errors in $^{87}\text{Sr}/^{86}\text{Sr}$ (1.80) of <0.0005 ($<\pm 0.065\%$; 2σ) (Table 3). The Sr isotope ratios were corrected for Rb interference and normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. Measurements of the SRM 987 Sr standard during the time of the sample measurements yielded an average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.710232 ± 32 ($n = 12$; 2σ), which within error overlaps with the preferred value (0.710240; Gladney et al., 1990), and no correction was necessary. Details of the analytical procedures for isotope determinations are described in Andersson (1997a).

Major Elements

Table 2 reports the complete whole-rock geochemical data set of 42 samples of mafic plutonic TIB-1 rocks from the southern SVB and TSB.

Mg# variation diagrams (Fig. 3) show the wide variation in evolutionary level of the sample suite—from primitive compositions with Mg# around 85 to the most evolved around 45. The SiO_2 contents range between 38 and 54 wt%. Although the samples were derived from many, widely scattered intrusive complexes, some trends and cumulative characteristics can be detected. For example, some of the most primitive samples have very high MgO contents, 32.1, 26.7, and 18.7 wt%, respectively, whereas two slightly less primitive (lower Mg#) have Al_2O_3 contents above 20 wt% (Table 2). A few of the less evolved samples are characterized by CaO contents above 12 wt%, and some of the intermediately evolved rocks are enriched in K_2O (>1.5 wt%). A group of the most evolved samples are high in SiO_2 , Na_2O , and K_2O , whereas another group shows elevated contents, particularly of TiO_2 , Fe_2O_3 , and P_2O_5 . A broad evolutionary trend is observed from primitive compositions between Mg# 70 and 80 to ~57–58, where a division between mainly cumulative and liquid trends are apparent. Also above Mg# 60, earlier effects of cumulation and contamination are recorded. Detailed interpretations of the geochemical evolution are given in the discussion.

When plotted in the R1-R2 diagram (Fig. 4), the geochemistry indicates a compositional spread from peridotite/pyroxenite to syenogabbro/monzogabbro. SIN (Standard Igneous Norm) normative mineral contents have been calculated, using the SINCLAS software of Verma et al. (2002), and are reported in Table 2 and plotted in Figure 5. Iron was recalculated according to the procedures of Middlemost (1989). Four samples are quartz normative and 15 are nepheline normative, whereas the remaining are hypersthene and olivine normative. The sample suite thus spans the entire range from alkali basalts to quartz tholeiites, where the most primitive rocks (high Mg#) generally plot close to the olivine-diopside line, partly on the undersaturated side (together with some oxide-rich, cumulate rocks), and more evolved rocks extend towards the quartz-saturated field.

In the AFM diagram (e.g., Irvine and Baragar, 1971) the sample suite trends from primitive tholeiitic compositions into the calc-alkaline field, while some evolved oxide-rich rocks also plot within the tholeiitic field (Fig. 6). In the K_2O - Na_2O diagram, following Turner et al. (1996), most of the rocks plot in the calc-alkaline field, particularly those in the south, whereas rocks mainly north of OJB tend to plot in the shoshonitic field (Fig. 7A). In the K_2O - SiO_2

TABLE 3. Sm-Nd and Rb-Sr Isotope Data of Mafic Plutonic TIB-1 Intrusions in Southeast Sweden¹

Sample no.	Sm, ppm ²	Nd, ppm ²	$^{147}\text{Sm}/^{144}\text{Nd}$ ²	$^{143}\text{Nd}/^{144}\text{Nd} \pm 2\sigma_{\text{m}}$ ³	ϵ_{Nd}^4 1.80 Ga	T_{DM}^5 Ga	$^{87}\text{Rb}/^{86}\text{Sr}$ ⁶	$^{87}\text{Sr}/^{86}\text{Sr} \pm 2\sigma_{\text{m}}$ ³	$^{87}\text{Sr}/^{86}\text{Sr}$ 1.80 Ga	ϵ_{Sr}^7 1.80 Ga
2e	3.30	15.64	0.1274	0.511852 ± 10	0.7	2.11	0.1124	0.705700 ± 19	0.7028	6.1
5d	1.58	5.11	0.1872	0.512578 ± 8	1.0	2.74	0.0851	0.704804 ± 10	0.7026	3.4
7a	2.99	12.94	0.1399	0.512042 ± 7	1.5	2.07	0.1300	0.705850 ± 17	0.7025	1.8
14	9.87	47.35	0.1260	0.511904 ± 12	2.0	1.98	0.1175	0.705656 ± 18	0.7026	3.6
15	1.51	8.00	0.1143	0.511737 ± 11	1.5	2.00	0.0199	0.703306 ± 15	0.7028	6.1
18a	1.46	6.78	0.1303	0.511941 ± 5	1.7	2.01	0.0364	0.703231 ± 9	0.7023	-1.0
20b	13.60	69.93	0.1175	0.511800 ± 9	2.0	1.97	0.0316	0.703286 ± 11	0.7025	1.6
27	3.38	15.93	0.1283	0.511930 ± 6	2.0	1.99	0.2507	0.708720 ± 7	0.7022	-1.9
34c	4.50	20.94	0.1298	0.511950 ± 6	2.0	1.99	0.0898	0.704742 ± 11	0.7024	0.8
35b	2.25	8.79	0.1551	0.512249 ± 8	2.0	2.06	0.0778	0.704218 ± 13	0.7022	-2.2
39c	9.48	46.23	0.1240	0.511829 ± 12	1.0	2.06	0.1135	0.705833 ± 7	0.7029	7.6
41	4.16	19.04	0.1319	0.511869 ± 5	0.0	2.19	0.1188	0.706376 ± 10	0.7033	13.4
45b	7.01	34.54	0.1228	0.511823 ± 4	1.2	2.05	0.0765	0.704756 ± 13	0.7028	5.9
46	1.05	4.62	0.1373	0.512011 ± 6	1.5	2.06	0.0269	0.703317 ± 7	0.7026	3.7
47	5.65	31.18	0.1095	0.511692 ± 5	1.7	1.98	0.0570	0.703711 ± 9	0.7022	-1.8

¹Sample numbers correspond to those in Figure 1, and Tables 1 and 2.

²Sm and Nd concentrations and $^{147}\text{Sm}/^{144}\text{Nd}$ ratio from isotope dilution. Estimated analytical uncertainty of $^{147}\text{Sm}/^{144}\text{Nd}$ ratio is $\leq \pm 0.5\%$.

³Error given as 2σ of the mean from the mass spectrometer run in the last digits.

⁴Initial ϵ_{Nd} value calculated according to Jacobsen and Wasserburg (1984): present-day chondritic $^{147}\text{Sm}/^{144}\text{Nd}$ ratio = 0.1967, present-day chondritic $^{143}\text{Nd}/^{144}\text{Nd}$ ratio = 0.512638.

⁵Model age calculated relative to the depleted mantle curve (DM) of DePaolo (1981).

⁶Calculated from ICP-MS data (Table 2) and measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratio.

⁷ ϵ_{Sr} value calculated using the UR values of McCulloch and Chappell (1982): present-day $^{87}\text{Rb}/^{86}\text{Sr} = 0.0827$; present-day $^{87}\text{Rb}/^{86}\text{Sr} = 0.7045$.

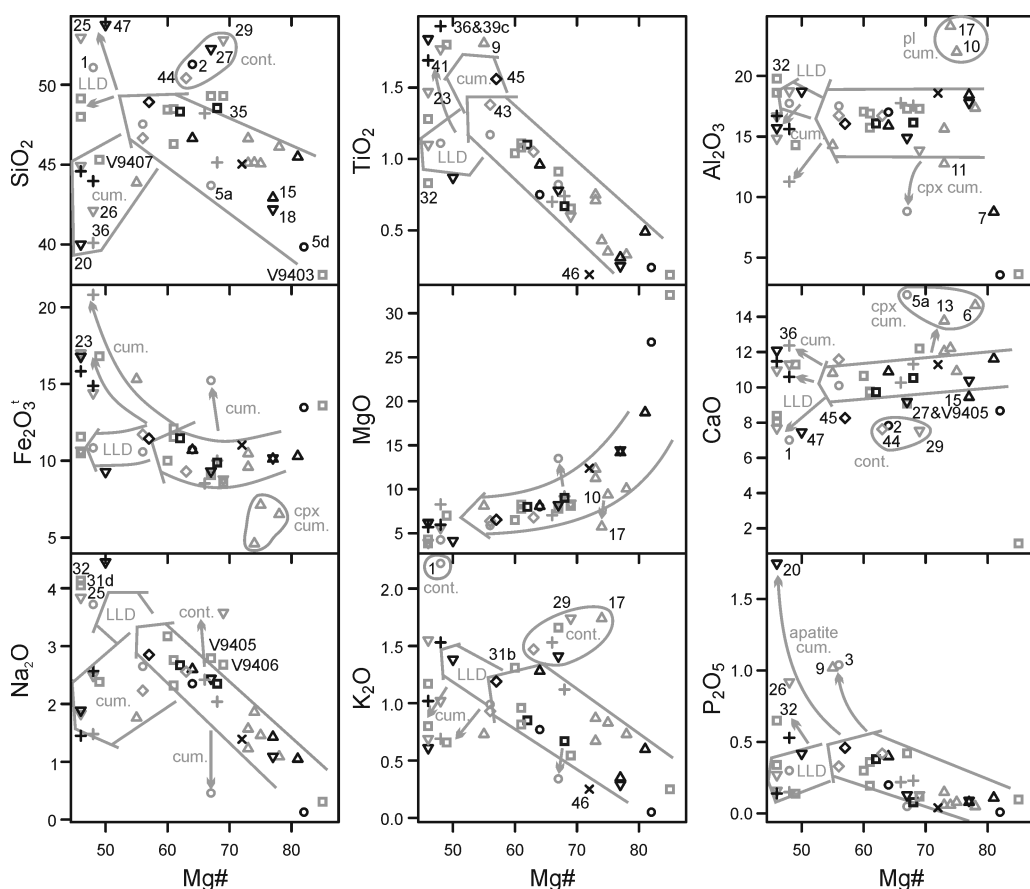


FIG. 3. Mg# variation diagrams of major elements. Abbreviations: LLD = liquid line of descent; cont. = contamination; cum. = cumulation; pl = plagioclase; cpx = clinopyroxene. The arrows mark evolution directions. The symbols are the same as those in Figure 4, except that black symbols represent samples that are isotopically analyzed. Sample numbers correspond to Figure 1 and the tables.

diagram (Fig. 7B), after Peccerillo and Taylor (1976) and modified after Rickwood (1989), only a few rocks plot outside the calc-alkaline field.

Trace Elements

Selected trace elements are plotted in variation diagrams against Mg# in Figure 8. Similar evolutionary trends as for the major elements are evident for many trace elements. For example Ba, Rb, Nb, Zr, Y, V, and the REEs (incl. Eu) show trends of increase with decreasing Mg# to about Mg# 57, where trends diverge. In contrast, Cr, Ni, and Sc decrease with decreasing Mg#. Some elements show more scatter and uncommon high values (e.g., Rb, Nb, Ce, Sr, and Sc), indicating contamination and/or

cumulative processes (see discussion). Ag and Au for all samples are below 0.3 and 0.008 ppm, respectively.

In a Ce/Yb vs. Ta/Yb plot (Fig. 9), the analyses indicate mainly a shoshonitic character, partly transitional into the calc-alkaline field, which tends to be most pronounced for rocks in the south. In the La/10-Nb/8-Y/15 diagram (Fig. 10), they plot in the field of calc-alkali volcanic-arc rocks, with one exception that is more tholeiitic. No MORB or intra-plate signatures are evident for any samples.

Figure 11 shows a combination of spider diagrams and REE patterns for the TIB intrusions separated into different geographical areas in order to detect spatial variations in elemental characteristics. All rocks show enrichment in large-ion litho-

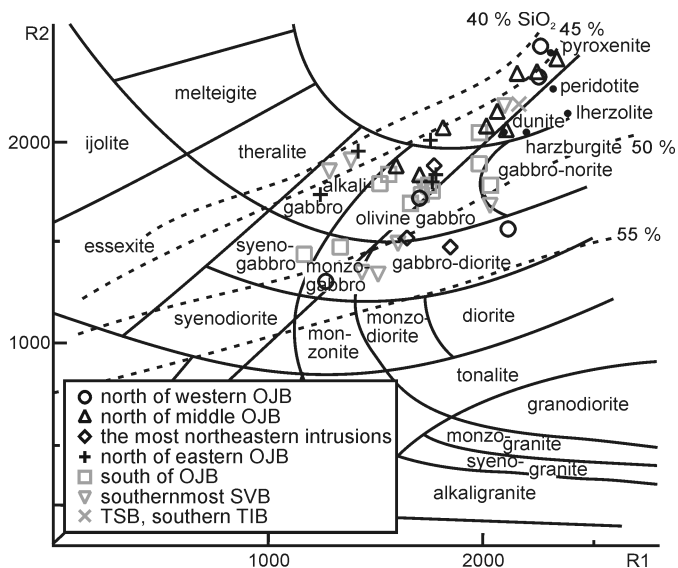


FIG. 4. R1-R2 diagram after De la Roche et al. (1980). $R1 = 4Si - 11(Na + K) - 2(Fe + Ti)$; $R2 = 6Ca + 2Mg + Al$. The dashed lines mark the levels of SiO_2 concentrations. Black and grey symbols mark mafic plutonic rocks north and south, respectively, of the OJB.

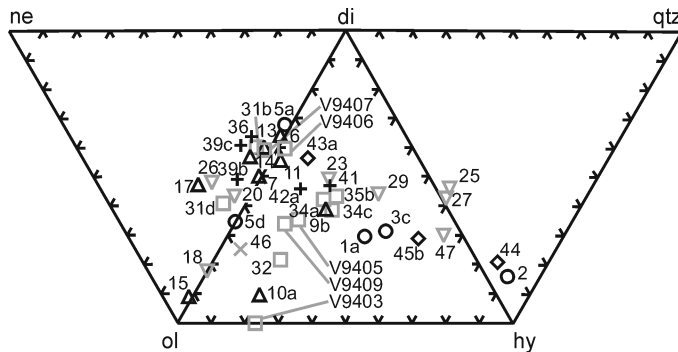


FIG. 5. Classification diagram after Thompson (1984). The SIN normative mineral compositions are calculated using the SINCLAS computer program of Verma et al. (2002), and are reported in Table 2. Iron was recalculated according to the procedures of Middlemost (1989). Abbreviations: di = diopside (clinopyroxene); ne = nepheline; ol = olivine; hy = hypersthene (orthopyroxene); qtz = quartz. Symbols are the same as in Figure 4. Sample numbers correspond to Figure 1 and the tables.

phile (LILE) and light rare earth (LREE) elements, relative to N-MORB, in most cases combined with a depletion in heavy rare earth (HREE) and high-field-strength (HFSE) elements, particularly Nb and Ta (Figs. 11A–11D and 11I–11K), which is characteristic of arc rocks (e.g., Rollinson, 1993; Pearce, 1996). In detail, however, enrichment levels vary both locally and regionally. In general, the concen-

trations of the elements are significantly higher for almost all intrusions than for tholeiitic to calc-alkaline island (oceanic) arc rocks, with a tendency for less strong enrichments in the south. In the REE diagrams (Figs. 11E–11H and 11L–11N), most samples, except for #5a and #5d, show pronounced LREE enrichments (La_N/Yb_N in the range of 5.4–15.6). The two exceptions show convex upward REE

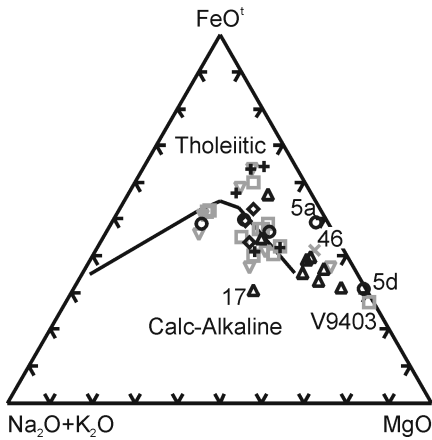


FIG. 6. AFM diagram after Irvine and Baragar (1971). Symbols are the same as those used in Figure 4. Sample numbers correspond to Figure 1 and the tables.

patterns (Fig. 11E) with a relative depletion in the LREE, reminiscent of N-MORB. Most samples show insignificant Eu anomalies, but both negative and positive anomalies occur.

Nd Isotopes

Fifteen samples were selected for Nd and Sr isotopic characterization from the geochemical sample suite. They were chosen to yield both geographical spread (Fig. 1) and as large variation as possible in geochemistry, however avoiding indications of crustal contamination and/or alteration (Table 3, highlighted in Tables 1 and 2). Hence, the Sm and

Nd contents show wide ranges, from 1.1 to 13.6 ppm Sm, and 4.6 to 69.9 ppm Nd.

¹⁴⁷Sm/¹⁴⁴Nd values show a relatively wide range, from ~0.11 to 0.19. The latter approaches the chondritic value of 0.1967 (Jacobsen and Wasserburg, 1984).

Measured ¹⁴³Nd/¹⁴⁴Nd ratios for the samples range between 0.511692 and 0.512578, where the highest value is close to the present-day chondritic uniform reservoir (CHUR) value (0.512638; Wasserburg et al., 1981). This is the same ultramafic sample that has the highest ¹⁴⁷Sm/¹⁴⁴Nd value (#5d). Initial ϵ_{Nd} values were calculated at 1.80 Ga, which is a rough average age for the TIB-1 rocks in the present area (cf. Mansfeld, 2004). However, ± 100 million years will have only a limited effect, as the shift in ϵ_{Nd} will be very small. With only two exceptions (at +0.7 and 0), the $\epsilon_{Nd}(1.80)$ values lie between +1 and +2. Thus, except for one sample with a chondritic initial composition, all rocks show a mildly depleted Nd isotopic character (Fig. 12).

A regression through all the analytical data, calculated using the Isoplot 3.00 program (Ludwig, 2003), yields an errorchron age of 1769 ± 150 Ma with MSWD = 38. Although overlapping the assumed 1.80 Ga age within error, this age is statistically untenable. Moreover, the likelihood that mafic magmas in all these widely separated intrusions would stem from a magma chamber with a common initial composition is small and the data may, even if the statistical correlation is valid, represent a rotated mixing line (cf. Romer, 1994), similarly as was concluded by Andersson (1997a) from TIB rocks further north. Hence, the Sm-Nd-

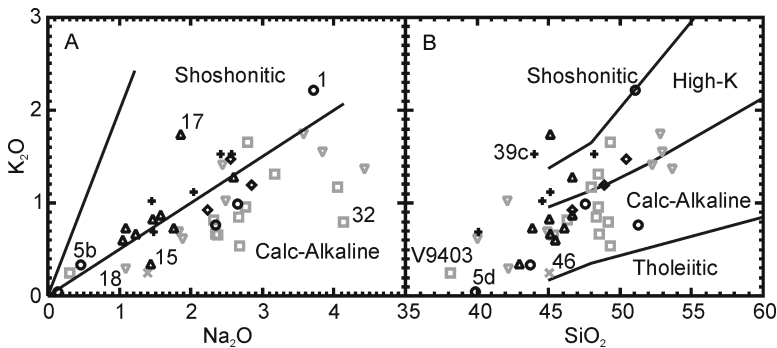


FIG. 7. A. Mafic plutonic TIB-1 rocks in southeast Sweden are mostly calc-alkaline, but some are shoshonitic in their character in a K₂O vs. Na₂O diagram (Turner et al., 1996). B. In a K₂O vs. SiO₂ variation diagram (after Rickwood, 1989), the rocks trend from calc-alkaline to high-K calc-alkaline. Symbols are the same as those used in Figure 4. The sample numbers correspond to Figure 1 and the tables.

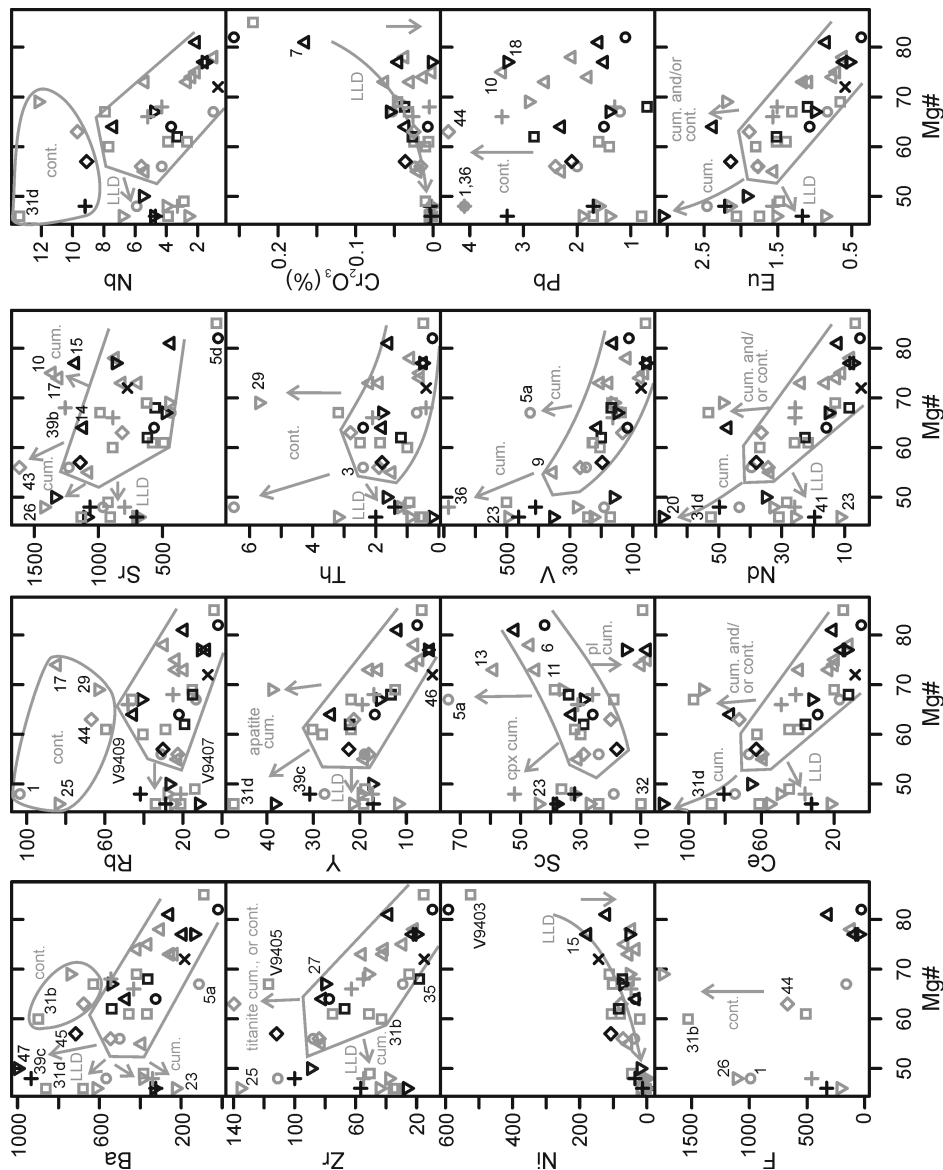


FIG. 8. Selected Mg# variation diagrams of trace elements. The concentrations of the trace elements are in ppm, except in wt% for Cr_2O_3 . Abbreviations: LLD = liquid line of descent; cont. = contamination; cum. = cumulation; cpx = clinopyroxene. The arrows mark evolution directions. Symbols are the same as in Figure 3. Sample numbers correspond to Figure 1 and the tables.

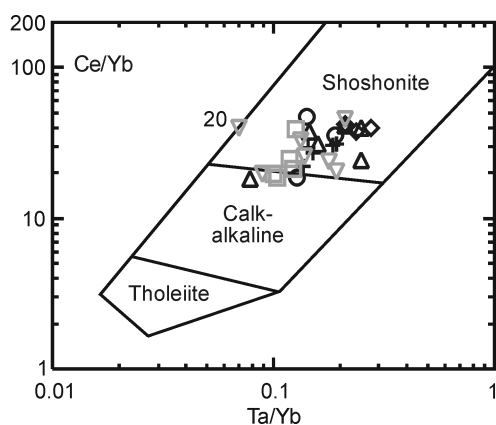


Fig. 9. Trace elements in the Ce/Yb vs. Ta/Yb diagram (after Pearce, 1982) show a more shoshonitic character than the major-element diagrams (Figs. 6 and 7). Symbols are the same as those used in Figure 4. Sample numbers correspond to Figure 1 and the tables.

whole-rock “age” calculation has little geological significance.

Sr Isotopes

The Sr isotopic data of 15 selected samples are reported in Table 3. Due to the variation in major-element geochemistry of the samples, the contents of Rb and Sr in these mafic plutonic rocks vary considerably, from 2.0 to 45.4 ppm Rb and from 68 to 1324 ppm Sr. The ultrabasic sample (#5d) has the lowest values for both elements, whereas a number of the other samples have Sr contents above 1000 ppm.

The $^{87}\text{Rb}/^{86}\text{Sr}$ values are low, as generally expected for basic rocks, and vary from 0.0199 to 0.2507, while the main parts of the samples are distributed in three main groups, 0.0199–0.0364, 0.0765–0.0898, and 0.1124–0.1300. Cumulative processes have lowered these values in several samples, as compared to primary mantle melts.

Measured $^{87}\text{Sr}/^{86}\text{Sr}$ values range between 0.7032 and 0.7087, which when recalculated at 1.80 Ga results in initial $^{87}\text{Sr}/^{86}\text{Sr}$ values in the range 0.7022–0.7029, with one outlier at 0.7033 (sample #41). Most samples have values higher than that estimated for the bulk earth, i.e., uniform reservoir (UR), at 1.80 Ga (0.7024; McCulloch and Chappell, 1982; Faure, 2001; e.g., see Fig. 20), resulting in positive $\epsilon_{\text{Sr}}(1.80)$ values (Table 3), while all are

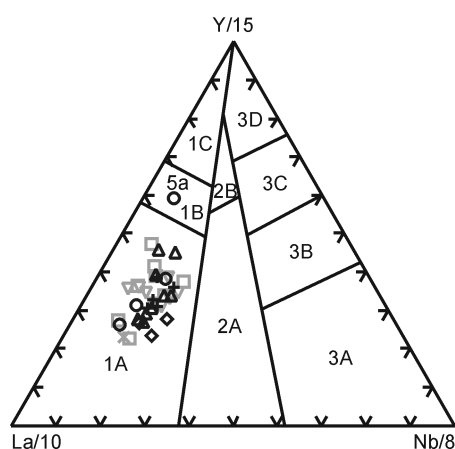


Fig. 10. La/10–Nb/8–Y/15 diagram. Almost all the rocks plot inside the field of calc-alkali volcanic-arc basalts; only sample #5a is more tholeiitic. Field 1: volcanic-arc basalts: 1A = calc-alkali basalts; 1B = volcanic-arc tholeiites; 1C = overlap between 1A and 1B. Field 2: continental basalts: 2A = continental basalts; 2B = back-arc basin basalts. Field 3: oceanic basalts: 3A = alkali basalts from intercontinental rifts; 3B = enriched E-MORB; 3C = weakly enriched E-MORB; 3D = normal N-MORB (after Cabanis and Lecolle, 1989). Symbols are the same as in Figure 4.

above that of the depleted mantle (0.7014, $\epsilon_{\text{Sr}}(1.80) = -14$; Taylor and McLennan, 1985; as seen later in Fig. 20). This suggests that the rocks have not experienced significant post-crystallization modifications of the Rb/Sr ratios or lost radiogenic Sr, but retain their primary magmatic isotopic signatures.

An Rb–Sr isochron calculation for all samples yielded an errorchron age of 1789 ± 210 Ma, with a MSWD of 608. Although similar to the Nd age above, this result is statistically meaningless.

Discussion

Geochemical evolution

Systematics of the broad trends in the variation diagrams vs. Mg# (Figs. 3 and 8) permit some generalizations about magmatic evolution and processes that may have affected individual samples, even though the investigated intrusions are scattered over a wide geographic area. The three most primitive samples #5d, #7, and #V9403, with Mg# > 80, are ultramafic, of which the two first are less altered olivine + clinopyroxene-cumulate-enriched rocks (cf. Fig. 5). A number of samples indicate broad

generalized liquid lines of descent (LLDs) from Mg# 80 to 57, as sketched in most elemental diagrams, with numerous aberrations. For example, sample #5a from the same complex as #5d indicates cumulation of clinopyroxene and Fe oxides (e.g., high Mg, Ca, Fe, Sc, and V, but low Al, Na, and Si) at a much more evolved stage compared to #5d (Mg# 67 and 82, respectively).

A group of samples of intermediate evolutionary level tend to show elevated contents of elements that typically are high in the continental crust (e.g., Si, K, Na, Rb, Ba, Nb, Th, and REE), most clearly in samples #29, #17 and #V9405 (Figs. 3 and 8). Variations in the degree of elevation for individual elements may be due to selective contamination by certain rocks (or minerals), e.g., mica schists or arenite.

A number of relatively less evolved rocks (Mg# 70–80) north of middle OJB (samples #6 and #13) tend to show elevated Al and Ca values, with little evidence of plagioclase accumulation (limited elevation of Sr, and no Eu anomalies; cf. Fig. 11A), indicating the existence of high-Al basaltic compositions. Claeson (2001) and Claeson and Meurer (2004) invoked hydrous, high-Al olivine tholeiites as parental magmas for basic intrusions in the TIB.

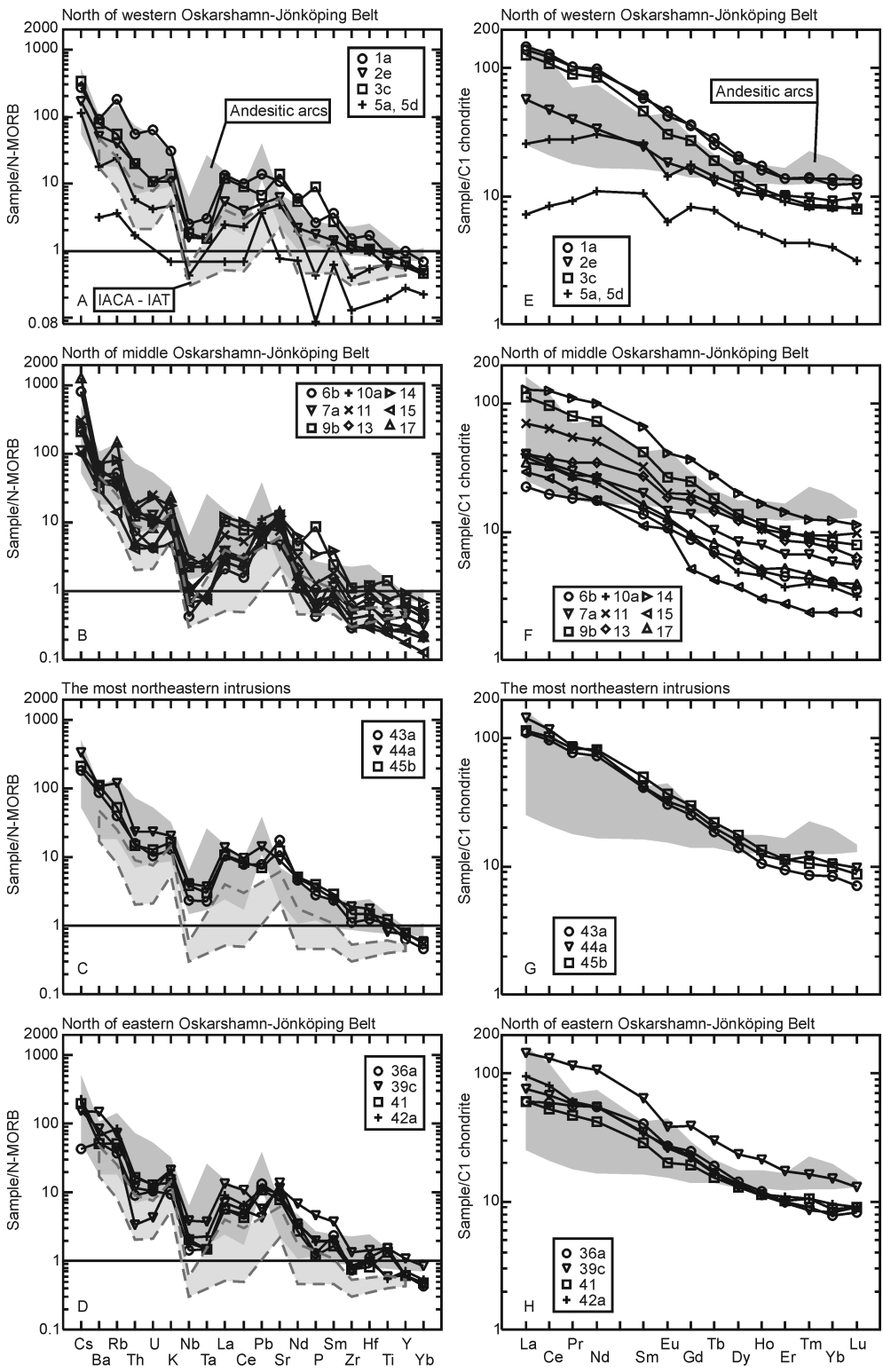
Among the most evolved rocks, Mg# <57 (Figs. 3 and 8), a distinct division into two principally different trends are clearly visible. One group of samples trends toward higher Fe, Ti, V, Ca, Sc, and partly P, and comprises samples enriched in cumulated Fe-Ti oxides, apatite (particularly sample #20; normative apatite = 4.2%, Table 2), and possibly some titanite, mainly from north of the eastern OJB and southernmost SVB. The other group show elevated contents of mainly Si, Na, and Ba, representing evolved liquid-dominated compositions; with several samples from south of the OJB, and samples #25 and #47 from southernmost SVB. Among the evolved samples, Y and REE are mainly enriched in samples with cumulative apatite. Only few of the evolved samples show clear geochemical evidence for crustal contamination, of them particularly samples #1 and #25 (high in Si, K, Rb, and Th, and low in Fe and Ca).

Though crude, and with variably large cumulus components (cf. Claeson and Meurer, 2004), the general evolution from primitive compositions to Mg# 57, with decreasing Mg, Ca, Ni, Cr, Sc, and increase in most other elements, mainly suggest olivine and pyroxene $\pm$ minor plagioclase fractionation (Figs. 3 and 8). The generally low contents of Ni and

Cr in the most primitive rocks (Fig. 8) suggest that they do not represent primary mantle magmas, but have experienced pre-emplacement fractionation of olivine, spinel, and pyroxene (cf. Claeson, 2001). At Mg# 57 (SiO_2 approximately 48–49 wt%) the magmas become saturated in oxides and apatite, possibly also titanite. Many of the primitive rocks plot close to the border between olivine tholeiite and alkali basalt in Figure 5, and most of the intermediately evolved within the olivine tholeiite field. The oxide-enriched samples, and some plagioclase-cumulitic rocks, tend to become undersaturated and plot in the alkaline field, whereas the most evolved magmas and crustally contaminated samples cross the boundary into the quartz tholeiite field. A fractionation trend dominated by olivine, clinopyroxene, and plagioclase, with minor spinel ($\pm$ amphibole), would drive the residual melts toward the quartz-saturated field, as would crustal contamination. This variation is also reflected in Figure 4. In Figure 6, the evolution from Mg-rich rocks toward the calc-alkaline field is split into a tholeiitic cumulative and a calc-alkaline liquid/contamination trend.

In a few cases of relatively primitive rocks, the REE patterns show positive Eu anomalies. These cannot in most cases be correlated with any other indices of plagioclase accumulation, e.g., Sr, Al, Ca, etc. (Figs. 3 and 8). In contrast, most patterns display no such anomaly, but a tendency for increasingly negative anomalies with higher REE abundances can be detected in several areas (Figs. 11E–11H and 11L–11N). However, no apparent correlation exists between increasingly negative Eu anomalies with decreasing Mg# (Fig. 13A). Many primitive rocks also display negative anomalies, suggesting that plagioclase were removed at varying stages in the history of mafic magma evolution in the southeastern TIB (cf. Lindh et al., 2001b). In fact, the primary magmas may, at least partly, carry positive Eu anomalies inherited from their metasomatized mantle source regions (Claeson, 2001), such as has been observed for island arc tholeiites, where it has been ascribed to reduced, Eu^{2+} -rich fluids from the subducted slab (Woodhead et al., 1998). The correlation between Eu/Eu^* and Ba/Ce (Fig. 13B) can be taken as an indication that the H_2O -dominated fluids that metasomatized the mantle wedge carried both Ba^{2+} and Eu^{2+} (compare with Fig. 14, discussed later).

The calc-alkaline to shoshonitic character of the 1.8 Ga mafic plutonic TIB-1 rocks is pronounced in the diagrams of Figs. 7, 9, 10, and 16 (discussed



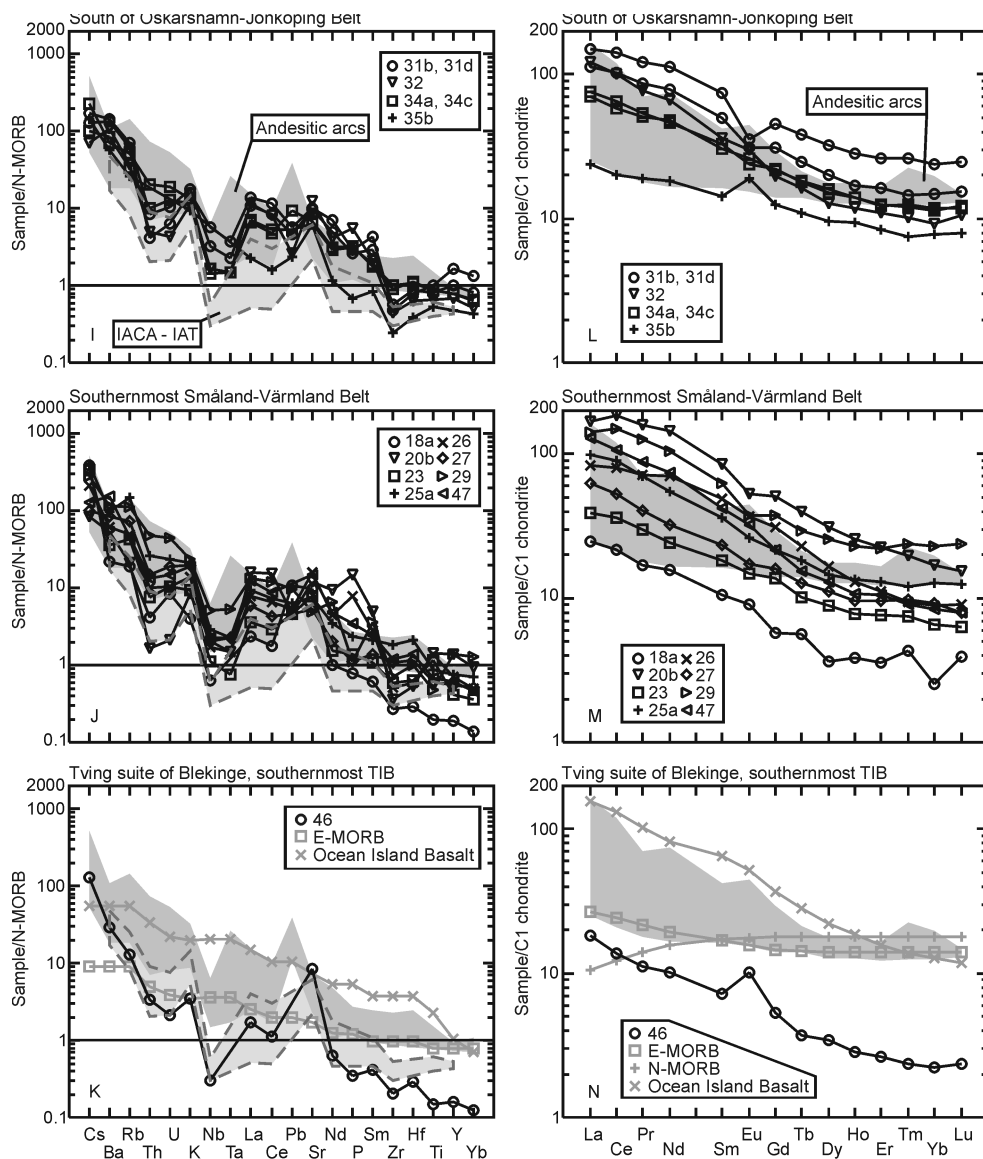


FIG. 11 (includes facing page). A–D and I–K. Spider diagrams normalized to N-MORB (Sun and McDonough, 1989). E-MORB and ocean island basalts also from Sun and McDonough (1989). IACA-IAT = the field between average composition of oceanic island-arc calc-alkaline basalts and island-arc tholeiites (after Sun, 1980); andesitic arcs = the field between average composition of most depleted and most enriched andesitic arc rocks, calculated from the data in the file “Av-Andesite2.xls” in http://www.geokem.com/earths_average_composition.html, by Dr. Bernard M. Gunn, 2004. E–H and L–N. REE diagrams normalized to C1-chondrite after Sun and McDonough (1989), from where also the values for E-MORB, N-MORB, and ocean island basalts in N are taken.

below), with a tendency for the northern rocks to be slightly more shoshonitic. The typical patterns in the spider diagrams, with elevated LILE, LREE, and depleted Nb, Ta, and HFSE in comparison with

N-MORB (Fig. 11), are common for all of the studied rocks irrespective of geographical position or evolutionary level, although variable in detail. The individual enrichment level for each rock is mainly

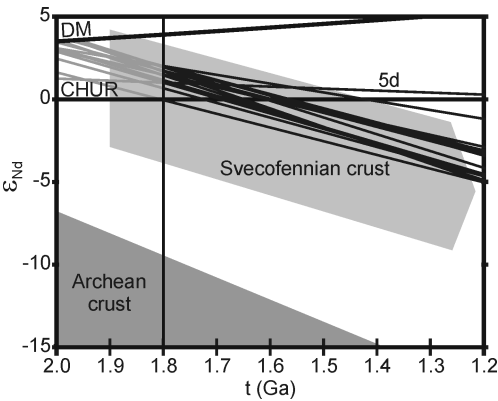


FIG. 12. ϵ_{Nd} vs. time diagram. Abbreviations: DM = depleted mantle (+3.9 at 1.8 Ga; DePaolo, 1981); CHUR = chondritic uniform reservoir. Evolution lines for Archean and Svecofennian crust according to Andersson (1997a) and Andersson et al. (2002). The vertical line at 1.80 Ga represents the approximate intrusion age of the mafic plutonic rocks of the present study. Sample numbers correspond to Figure 1 and the tables.

dependent on degree of fractionation, more evolved rocks having higher contents of most trace elements (cf. Fig. 8). In addition, cumulate-enriched rocks are lower in all incompatible elements but tend to be elevated in certain compatible elements (e.g., P and Ti in samples #3, #9b, #20b, #26, #36a and #39c; Fig. 3).

Source character

Geochemical evidence. In general mafic plutonic TIB-1 rocks show typical arc-like patterns in spider diagrams, with strong enrichment in LILE and

LREE, and depletion in HREE and HFSE relative to N-MORB (Fig. 11; cf. Claeson, 2001). In most cases this enrichment markedly exceeds that of typical oceanic arc rocks, but overlaps with the compositions of mafic continental-arc rocks (Wilson, 1989; Pearce, 1996; the file “Av-Andesite2.xls” in http://www.geokem.com/earths_average_composition.html, by Dr. Bernard M. Gunn, 2004; Fig. 11). The patterns are clearly distinct from those of oceanic island basalts (OIB), N- or E-MORB. Cs, Rb, Ba, K, Pb, and Sr are all highly non-conservative elements, enriched in fluids derived from subducting slabs that percolate into the overlying mantle wedge, while U, Th, and LREE are moderately conservative (Pearce, 1996; Kerrich and Wyman, 1996). Thus conservative elements are retained in the downgoing slab. In several of the geographic areas of the present study, however, some samples have lower contents of LILE and LREE, as well as stronger depletion in HFSE, overlapping those of oceanic arcs, particularly north and northwest of the OJB, and in the south (Fig. 11). In all cases, arc-like element patterns are retained. In some cases very strong depletion in HFSE is noted. One intrusion north of western OJB (Stenskar; samples #5a and #5d) is distinct in showing REE patterns reminiscent of N-MORB with relative LREE-depletions (Fig. 11), however, with accompanying strong HFSE depletions and LILE enrichments. This intrusion appears to stem from a mantle source that has preserved MORB-like LREE, but was enriched in LILE and strongly depleted in HREE and HFSE. In fact, many samples show stronger depletions in HFSE than N-MORB. Though this partly reflects a cumulative nature, it also suggests that the source regions for the mafic TIB-1 magmatism in southeast Sweden

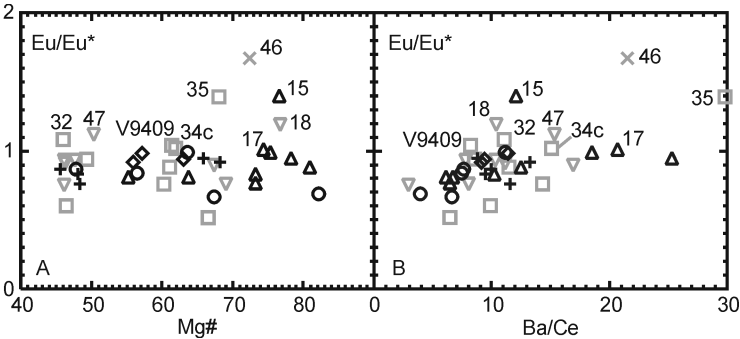


FIG. 13. A. Eu/Eu^* vs. $Mg\#$. B. Eu/Eu^* vs. Ba/Ce . Samples with $Eu/Eu^* > 1$ are numbered, and sample numbers correspond to Figure 1 and the tables. Symbols are the same as in Figure 4.

were, at least in part, strongly depleted prior to enrichment in LILE and LREE.

Strong enrichment of LILE alone, or in comparison with the LREE, is normally considered related to H_2O -dominance in the fluids that metasomatized the mantle sources (Hawkesworth et al., 1994; Thirlwall et al., 1996; You et al., 1996; Becker et al., 2000), and typical for mafic rocks in oceanic arc settings (e.g., Ewart and Hawkesworth, 1987; McCulloch and Gamble, 1991; Macdonald et al., 2000; Fig. 11). In continental arc settings, slabs commonly are situated deeper and melts from the oceanic crust and subducted sediments may have percolated into the overlying mantle wedge to a greater extent (Pearce, 1982; Hoogewerff et al., 1997), bringing higher relative amounts of Th, Ba, and the LREE (Turner et al., 1996; Thirlwall et al., 1996; Becker et al., 2000), while retaining the HFSE in refractory minerals in the slab (Brenan et al., 1994; Münker, 1998) keeping the general arc shape of the pattern. In the mafic rocks of southeastern TIB, a trend of increasing Ce/Yb with decreasing Ba/La can be observed, while La/Nb remains high (Fig. 14). In spite of numerous exceptions, there is a tendency for higher Ce/Yb and lower Ba/La values north of OJB, suggesting generally somewhat higher contributions of melts from the slab and/or sediments (cf. Macdonald et al., 2000; Sun and Stern, 2001) in the mantle sources going northward.

The olivine gabbro from the Tving suite of Blekinge (TSB; sample #46) shows a tholeiitic island-arc character in the spider diagram (Fig. 11). Otherwise it tends to show overlapping geochemical signatures with mafic plutonic rocks within the SVB (cf. Rimša, 2002). More tholeiitic and oceanic affinities are also shown by a number of samples from north of the middle and western OJB, as well as south of the OJB (Figs. 6 and 11). Two samples (#20b and #31d) show exceptionally low Th and U and high Nb and Ta values, relative to the REE and the rest of the HFSE. Both are highly evolved rocks with Mg# of 46. Sample #20b is strongly enriched in apatite (Figs. 3 and 11), which can partly explain its low Th/REE values. Additionally, fractionation of zircon or baddeleyite, lowering the Zr, Hf, U, and Th abundances, seems to have affected both samples and causes them to plot aberrantly in several of the discrimination diagrams discussed below.

In the Th-Ta-Hf/3 diagram (Fig. 15) essentially all samples plot within the field of volcanic-arc basalts (except the aberrant samples #20b and

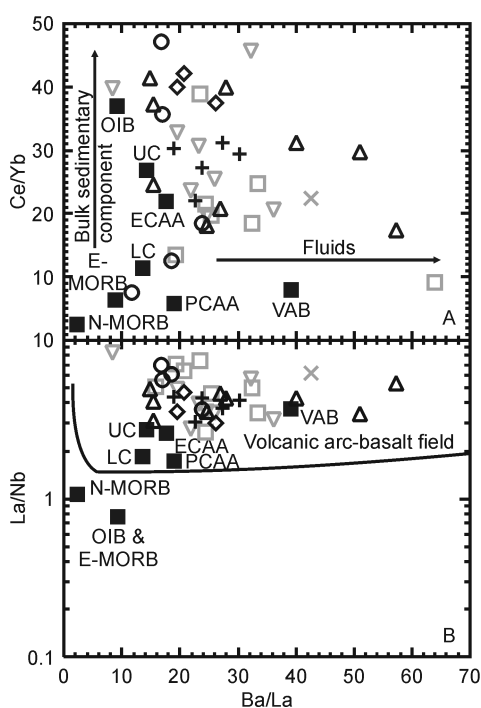


FIG. 14. Trace element diagrams selected to indicate mantle source types and processes for the mafic TIB-1 rocks in southeast Sweden. A. Elevated Ce/Yb are normally interpreted as a bulk sedimentary imprint on the source region, while elevated Ba/La ratios are considered typical for a H_2O -mediated fluid imprint, typical for oceanic arc rocks (e.g., Sun and Stern, 2001). B. High La/Nb distinguishes arc basalts from those of other source types (Hawkesworth et al., 1995). Abbreviations: VAB = volcanic arc basalts (oceanic); LC = lower crust; UC = upper crust; PCAA = primitive continental andesitic arcs; ECAA = evolved continental andesitic arcs. The reference data are from Taylor and McLennan (1985), Sun and McDonough (1989), Hawkesworth et al. (1991, 1995), Condie (1993), and the file "Av-Andesite2.xls" in http://www.geokem.com/earths_average_composition.html, by Dr. Bernard M. Gunn (2004). Symbols are the same as in Figure 4.

#31d), in the corner for most enriched compositions (Wood, 1980), and conform better with an influence by subduction zone enrichment rather than crust-magma interaction. In addition, the diagram of Th/Yb against Ta/Yb (Fig. 16; after Pearce, 1983) shows in general a calc-alkaline active continental margin character with a weak, but discernible, trend toward a more oceanic affinity for the rocks in the south. Although some samples are displaced to high Nb/Zr ratios (presumably due to zircon/baddeleyite

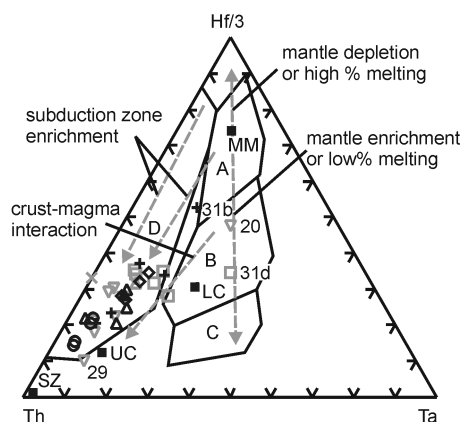


FIG. 15. Th-Ta-Hf/3 diagram. A = N-MORB; B = E-MORB and within-plate tholeiites; C = alkaline within-plate basalts; D = volcanic-arc basalts; MM = N-MORB mantle source; SZ = subduction zone component (after Wood, 1980 and Pearce, 1996). The majority of samples plot in the field of volcanic-arc rocks. The arrows mark the directions of trends for mantle source regions. The mafic plutonic TIB-1 rocks in southeast Sweden are dominantly influenced by subduction zone enrichment. Symbols are the same as in Figure 4. Sample numbers correspond to Figure 1 and the tables.

fractionation) in a Nb/Zr vs. Nb/Ba diagram (after Hooper and Hawkesworth, 1993), the majority of samples plot close to the field for subcontinental lithospheric mantle compositions (Fig. 17), with no similarity to MORB or OIB.

Condie (1997) introduced the Th/Ta vs. La/Yb diagram as a means to discriminate between different source and contamination components of mafic rocks (Fig. 18A). In this diagram the mafic TIB-1 rocks of southeast Sweden show elevated values for both ratios, plotting in the arc-field or at even higher La/Yb values, overlapping the upper crust. Among mafic arc rocks, those of continental-margin arcs have the highest values. A number of samples plot closer to enriched plume-type mantle and lower crust compositions, which in part may be due to late-stage zircon fractionation. Plume sources include recycled sediments and residual oceanic crust that apparently do not appear until the Neoproterozoic, which may reflect the time it took for the first Archean slabs to sink to the bottom of the mantle, and to be rejuvenated into rising plume sources (HIMU and EM; Condie, 1997). According to Condie, assimilation or fractional crystallization can cause a rise in both ratios in Figure 18A. How-

ever, no apparent correlation exists between degree of fractionation (expressed in Mg#; Fig. 19A) and these ratios. Nor is any correlation with indices of crustal contamination (Rb; Fig. 19B) observed. A tendency for rocks from southernmost SVB to fall within the arc field is observed, whereas rocks from north of the OJB mostly plot at higher La/Yb ratios. This may also be related to progressively deeper levels of magma generation northward beneath the continental margin, partly within a garnet-bearing mantle.

The mafic plutonic rocks of the present study have La/Nb ratios between 2.6 and 7.5 (Fig. 14B), whereas MORB normally is below 1.4. Arc-related basalts have values from 1.4 and upward (Condie, 1999). Because the La/Nb ratio for average upper crust is 2.8 (Condie, 1993) and our samples in most cases are higher, with an average of 4.4, a subduction-related geochemical component in the mantle source region is again indicated.

Kerrick et al. (1999) devised a diagram to separate sources and contaminants based on Ce/Nb vs. Th/Nb (Fig. 18B). In this diagram essentially all samples plot between depleted mantle–N-MORB compositions and those of arcs, where the imprint of a subduction component increases to the right in the diagram. The influence of crustal contamination is not apparent in this case, although some of the spread toward lower Ce/Nb may result from that. The affinity for plume-type OIB or E-MORB sources appears insignificant.

In summary, the geochemistry of the ~1.80 Ga mafic plutonic rocks of the TIB in southeast Sweden is calc-alkaline to shoshonitic, with increasing alkalinity northward. The bulk-rock compositions show magmatic arc signatures, mostly of continental-margin type but with increasing oceanic affinity southward. The magma sources resided in the lithospheric mantle (imprint of asthenospheric sources are not evident); the mantle apparently was strongly depleted prior to enrichment of LILE and LREE by subduction-zone fluids, primarily H₂O-dominated, but with an increasing contribution of melted subducted sediments northward.

Implications from Nd and Sr isotopes. The initial ϵ_{Nd} values (calculated at 1.80 Ga) of all mafic plutonic rocks investigated in the present study fall within the range +0.7 to +2.0, except for one at ± 0 (Figs. 12, 20 and 21, Table 3), indicating a moderately depleted mantle source. Such mildly depleted initial ϵ_{Nd} values are typical for mafic TIB rocks of all ages, with only few data reported in the range

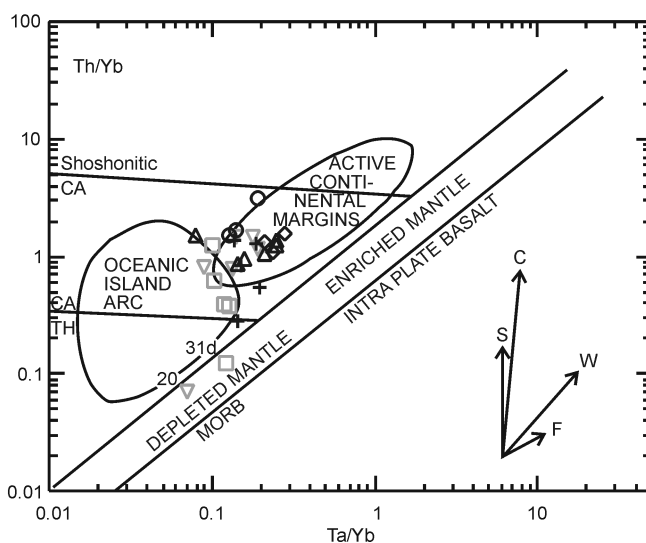


FIG. 16. Th/Yb vs. Ta/Yb shows in general a calc-alkaline active continental margin (continental arc) or island setting for the mafic plutonic TIB-1 rocks in southeast Sweden. Two samples have particularly low Th/Yb, Zr, and Hf. The labeled arrows indicate effects of various processes on the geochemistry of the resultant magmas. Abbreviations: CA = calc-alkaline; TH = tholeiitic; S = influence of subduction component; C = crustal contamination; W = within-plate enrichment; F = fractional crystallization (diagram after Pearce, 1983, and Wilson, 1989). Symbols are the same as in Figure 4. Sample numbers correspond to Figure 1 and the tables.

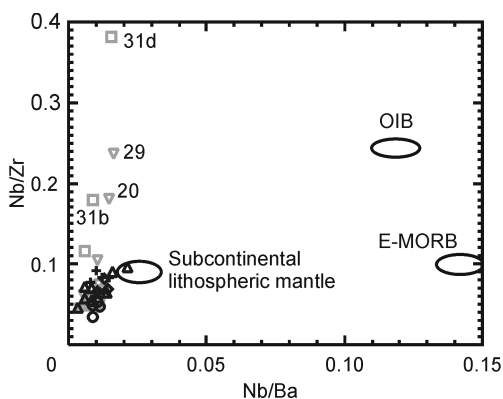


FIG. 17. Nb/Zr vs. Nb/Ba (after Hooper and Hawkesworth, 1993) demonstrates a subcontinental lithospheric mantle origin for the mafic plutonic TIB-1 rocks of southeast Sweden. Samples with high Nb/Zr are evolved and seem to have experienced zircon fractionation. Symbols are the same as in Figure 4. Sample numbers correspond to Figure 1 and the tables.

+2.0 to +3.5 (Andersson, 1997a; Claeson and Andersson, 2000; Claeson, 2001; Nyström, 1999; Andersson et al., 2004a; Rutanen et al., 2006). Initial ϵ_{Nd} values significantly below zero, similar to

certain younger mafic rock in the Fennoscandian shield (Lindh et al., 2001a; Andersson et al., 2002; Rämö et al., 2004; Nyström, 2004; Söderlund et al., 2005), were not measured for the presently studied mafic TIB rocks (Figs. 12 and 20), and have not been reported earlier for mafic TIB rocks, except in one case from the Dala province (Rutanen et al., 2006). Moreover, reported initial ϵ_{Nd} values for the TIB granitoids are all higher than -1.3 (Wilson et al., 1986; Patchett et al., 1987; Andersson, 1997a; Nyström, 1999; Andersson et al., 2002; Andersson and Wikström, 2004, and references therein). The present results show that basic magmas in the southeastern TIB cannot have been derived directly from a "normal" depleted mantle (ϵ_{Nd} ca. +3.9 at 1.80 Ga; DePaolo, 1981). Either their mantle sources were originally only mildly depleted, or an originally more depleted source must have become enriched at some later stage by the addition of crustal material in some form. It is noteworthy that there is no particular correlation between evolutionary level of the magma (e.g., Mg#) and initial ϵ_{Nd} value (Fig. 21A). Irrespective of composition, essentially all samples fall within the "mildly depleted" initial ϵ_{Nd} range +1 to +2. This fact, in combination with the strong

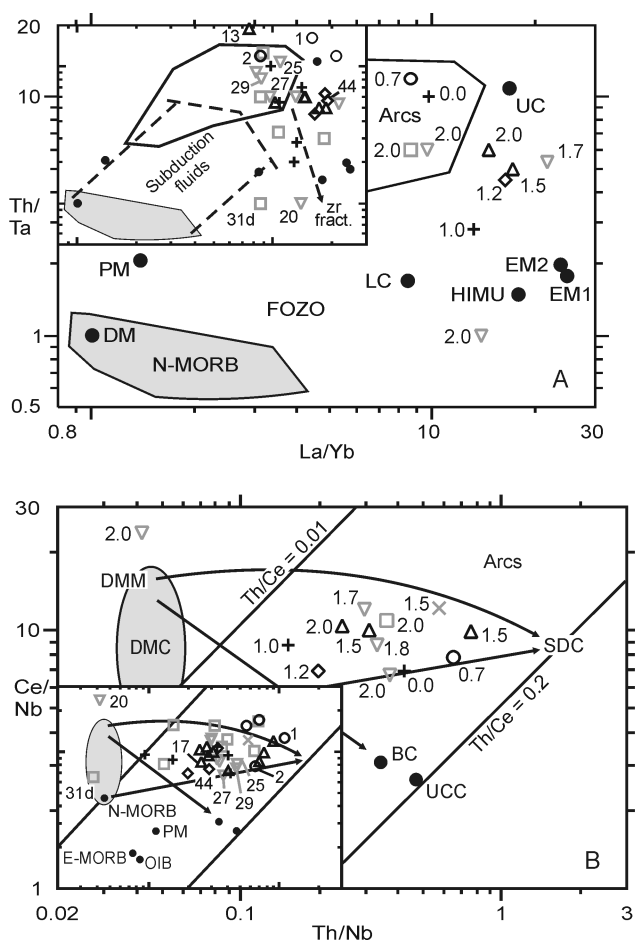


FIG. 18. A. Th/Ta vs. La/Yb diagram modified after Condie (1997). Abbreviations: DM = depleted mantle; PM = primitive mantle; N-MORB = normal MORB; FOZO = lower mantle plume component (focal zone); LC = lower crust; UC = upper crust; HIMU = high U/Pb mantle source; EM1 and EM2 = enriched mantle. B. Ce/Nb vs. Th/Nb diagram. Modified after Kerrich et al. (1999). Abbreviations: DMM = depleted MORB mantle; DMC = depleted melt compositions; BC = bulk crust; UCC = upper continental crust; SDC = subduction-derived component; E-MORB = enriched MORB; OIB = ocean island basalts. "Evolution lines" between DMM and SDC and between N-MORB and SDC are drawn, as well as a "contamination" line between DMM and BC. $\epsilon_{\text{Nd}}(1.80)$ values for the samples analyzed for isotopes are marked. In the inset figures all geochemically analyzed samples are included. Dashed arrows in A indicate effects of processes affecting the samples of the present study. Symbols are the same as in Figure 4. Sample numbers in the insets correspond to Figure 1 and the tables.

geochemical evidence for LILE and LREE enrichment of a strongly depleted source, favor an enrichment of the mantle source in less radiogenic Nd through subduction zone fluids, rather than contamination from crustal material.

Patchett et al. (1987) reported Nd-isotope results for two mafic rocks from just south of the OJB that on field criteria can be included in the TIB-1 group.

Recalculating the initial ϵ_{Nd} values to 1.80 Ga result in similarly "mildly depleted" values (+2.2 and +0.8). Johansson and Larsen (1989) presented Nd isotopic data for mafic rocks from the TSB and one diorite from the southernmost SVB. Recalculated to 1.80 Ga, the initial ϵ_{Nd} values of these rocks also fall between +1 and +2, with one exception at -0.4. These data thus completely overlap our data (e.g.,

sample #46 in Table 3), and emphasise that the “mildly depleted” mantle character can be extended also to the TSB. Furthermore, Rimša (2002) has pointed out the subduction zone character of mafic rocks on both sides of the Småland-Blekinge deformation zone, within both the SVB and TSB.

There is a clear trend of higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ values (calculated at 1.80 Ga) for rocks from north of the OJB (0.7025–0.7033), than those from south of the OJB (0.7022–0.7026), a trend that correlates with the northward-decreasing $\epsilon_{\text{Nd}}(1.80)$ (Fig. 20). Only the southernmost sample from the TSB (#46) shows a slightly higher $^{87}\text{Sr}/^{86}\text{Sr}(1.80)$ value, overlapping those north of the OJB. A majority of the samples south of the OJB plot lower than the “uniform reservoir” (UR), whereas all samples north of the OJB plot above the UR value. Sample #41 is clearly the most enriched, with $^{87}\text{Sr}/^{86}\text{Sr}(1.80)$ of 0.7033 and $\epsilon_{\text{Nd}}(1.80)$ of ± 0 .

The Rb-Sr system is known to be more sensitive to later disturbances than the Sm-Nd system, because of the higher fluid mobility of Rb and Sr, both being low-field-strength elements (e.g., Kerrich and Wyman, 1996). Such effects have been observed previously for mafic TIB rocks from elsewhere (cf. Andersson, 1997a). However, because all rocks in the present study show $^{87}\text{Sr}/^{86}\text{Sr}(1.80)$ values above depleted mantle (DM), close to UR and above, they appear to record undisturbed initial values. Moreover, the quite good correlation with the $\epsilon_{\text{Nd}}(1.80)$ values further supports this contention (Fig. 20).

The data clearly indicate that mantle sources for the basic intrusions on the southern side of the OJB are isotopically more depleted, and counterparts on the northern side are significantly more influenced by older crustal material (Fig. 20). North of the OJB, rocks in the middle appear to be least enriched, with increasing crustal influence both to the west and east.

In contrast, no correlation exists between the degree of magma evolution and the isotopic parameters (Fig. 21), except for sample #41, which belongs to the most evolved samples of the present study. Furthermore, in Figures 18A and 18B, the isotopic ratios (initial ϵ_{Nd}) show no discernible trends with respect to the geochemical ratios. Those samples containing olivine (samples #5d and #46; Table 1) are not isotopically the most depleted, but are intermediately enriched, despite being geochemically least enriched (e.g., Figs. 3, 8 and 11). This circumstance supports the concept that the isotopic signa-

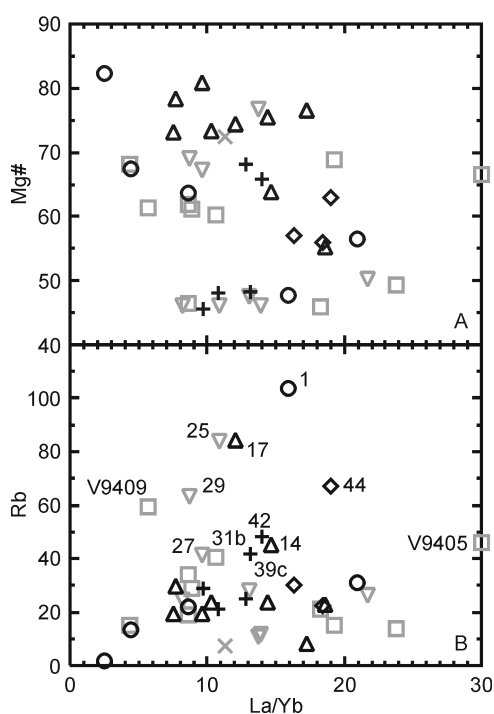


FIG. 19. A. Mg# vs. La/Yb.

B. Rb vs. La/Yb. No correlation between these parameters is apparent. Samples with Rb > 40 ppm may have experienced crustal contamination. Symbols are the same as in Figure 4. Sample numbers correspond to Figure 1 and the

tures of the samples are largely primary and inherited from the mantle source, rather than being an effect of contamination of the magmas in the crust. Sample #41 is a Fe-Ti-enriched clinopyroxene-hornblende norite of evolved composition (Mg# 46), but no element supports any clear contamination with crustal material (Figs. 3 and 8).

In Figure 20, a comparison is made with Nd and Sr isotopic data from other mafic TIB rocks as well as rocks of 1.8 Ga age elsewhere in the Fennoscandian shield. Data from the ca. 1.69 Ga Rymmen gabbro intrusion (TIB-3) overlap the isotopically most depleted rocks of the present study (Claeson, 2001). It is noteworthy that the Rymmen gabbro is situated south of the OJB and also overlaps the depleted TIB-1 rocks south of the OJB investigated here. The 1.85–1.80 Ga (TIB-0 and 1) mafic rocks farther north in the SVB, close to the Svecofennian margin (Andersson, 1997a), plot at slightly elevated initial $^{87}\text{Sr}/^{86}\text{Sr}$ and partly lower initial ϵ_{Nd} values compared to most of the presently investigated samples,

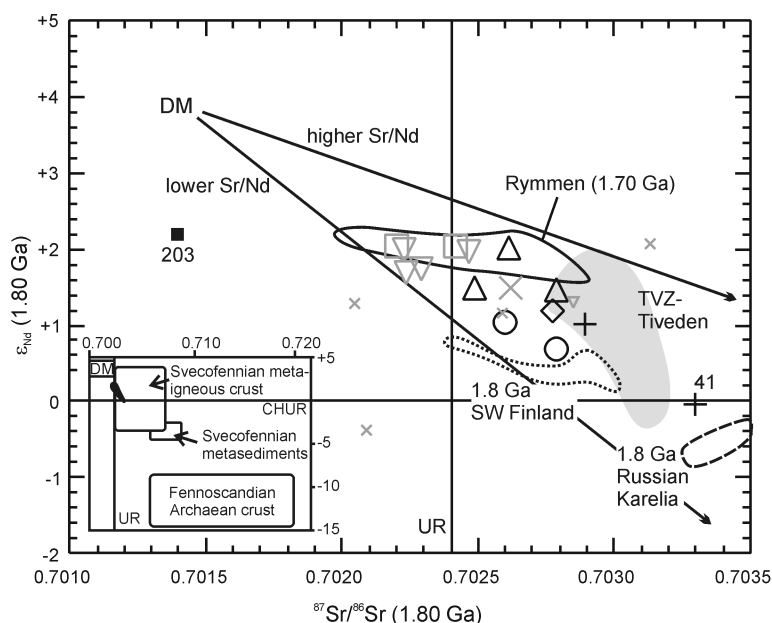


FIG. 20. $\epsilon_{\text{Nd}}(t)$ – $^{87}\text{Sr}/^{86}\text{Sr}(t)$ diagram for ~1.8 Ga mafic plutonic TIB-1 rocks in southeast Sweden. Abbreviations: DM = depleted mantle ($\epsilon_{\text{Nd}}(1.80) = +3.9$; DePaolo, 1981 and $^{87}\text{Sr}/^{86}\text{Sr}(1.80) = 0.7014$; Taylor and McLennan, 1985); CHUR = chondritic uniform reservoir; UR = uniform reservoir (0.7024 at 1.80 Ga; McCulloch and Chappell, 1982; Faure, 2001). The light-grey shaded area marks mafic plutonic TIB rocks in the 1.85–1.81 Ga Tjällmo-Vättern zone (TVZ) and Tiveden farther north in the SVB; area encircled by unbroken line is the 1.70 Ga Rymmen gabbro west of the present study area (Claeson, 2001); stippled line encircles 1.8 Ga post-collisional intrusion in southwest Finland (Andersson et al., 2006a); hatched line encircles 1.8 Ga post-collisional intrusion in Russian Karelia (Andersson et al., 2006a); black quadrangle = a TVZ-lherzolite (sample #203 in Andersson, 1997a). Symbols are the same as in Figure 4, with the exception of the smaller symbols (from Johansson and Larsen, 1989) that mark a diorite (in SVB; triangle apex down) and amphibolites (in TSB; crosses). The arrows represent two proposed metasomatic “end-member” trends. The sample numbers correspond to Figure 1 and the tables. The inset summarizes the isotope compositions of three Fennoscandian crustal components (modified after Andersson et al., 2006a), with the black area corresponding to the samples of the present study.

except #41. The ultramafic TVZ-lherzolite, sample #203 in Figure 20, most probably has a disturbed Rb–Sr system. The amphibolitic rocks of the TSB (Johansson and Larsen, 1989), plot in part overlapping and intermediate among our samples (one sample is close to #46), but in part at considerably lower initial $^{87}\text{Sr}/^{86}\text{Sr}$ values. For the latter, the Rb–Sr system appears disturbed after crystallization. Coeval ca. 1.8 Ga mafic rocks further inside the Svecofennian domain (Andersson et al., 2006a), in southwest Finland and at the Archean margin in Russian Karelia, plot at relatively lower initial ϵ_{Nd} values, the latter also at higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

Xu et al. (2003) argued that their trend of increasing $^{87}\text{Sr}/^{86}\text{Sr}(t)$ and decreasing $\epsilon_{\text{Nd}}(t)$ indicated an increasing degree of carbonate-rich fluid/

melt metasomatism in the mantle source regions of the magmas (cf. Fig. 20). Strong increase in $^{87}\text{Sr}/^{86}\text{Sr}(t)$ with only moderate decrease in $\epsilon_{\text{Nd}}(t)$ have been interpreted to indicate that H_2O from subducted oceanic crust dominated in the metasomatic fluids causing a stronger enrichment in LILE compared to LREE (e.g., Hawkesworth et al., 1991; Thirlwall et al., 1996). The relative amount of less radiogenic Nd would increase if the metasomatizing agents were enriched in melts or carbonates from subducted sediments (e.g., Hoogewerff et al., 1997; Sun and Stern, 2001), as has been proposed for coeval mafic ~1.8 Ga rocks further northeast in the Fennoscandian Shield (Andersson et al., 2006a). In Figure 20 we have sketched two metasomatic end-member trends; a lower trend with a higher relative

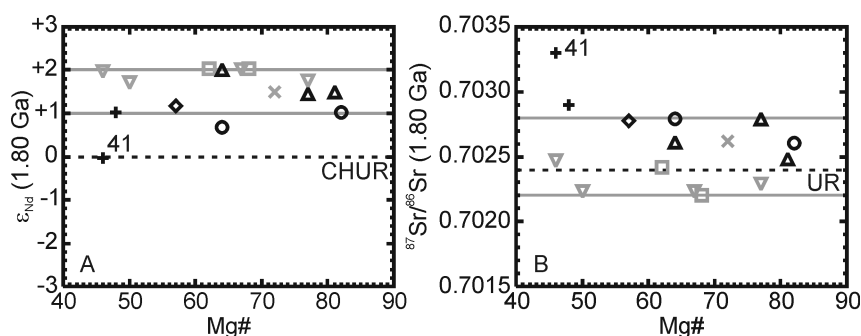


FIG. 21. $\epsilon_{\text{Nd}}(1.80)$ vs. Mg# (A) and $^{87}\text{Sr}/^{86}\text{Sr}(1.80)$ vs. Mg# (B), showing the relationship between chemical evolution and isotopic parameters for the mafic TIB-1 plutonites in southeast Sweden. Abbreviations: CHUR = chondritic uniform reservoir; UR = uniform reservoir (Faure, 2001). The grey lines encompass suggested approximate ranges of isotopic compositions of a “mildly depleted mantle” at 1.8 Ga, typical for TIB-related mafic rocks. Symbols are the same as in Figure 4. Sample number corresponds to Figure 1 and the tables.

component of Nd added to the mantle source and an upper with a higher metasomatic Sr/Nd ratio. Mafic rocks of the southeastern TIB spread out in between these two extremes, but in general trend to higher $^{87}\text{Sr}/^{86}\text{Sr}(1.80)$ at comparable $\epsilon_{\text{Nd}}(1.80)$ compared with rocks from more strongly carbonated mantle sources further inside the 1.80 Ga Fennoscandian continent in the northeast (cf. Andersson et al., 2006a). Contamination or assimilation with upper rather than lower crust would generate similar trends (cf. insets for Fennoscandian crustal sources in Fig. 20) but is not supported by the geochemistry.

Our results for 1.80 Ga mafic TIB intrusions support the model of Claeson (2001) who suggested a depleted mantle source, overprinted by a fluid-dominant subduction component, with very minor crustal contamination for the 1692 ± 7 Ma Rymmen gabbro, slightly westwards from the present study area, based on geochemistry and isotopes with initial ϵ_{Nd} values around +2 and initial $^{87}\text{Sr}/^{86}\text{Sr}$ between 0.7020 and 0.7029 (Fig. 20). Previous studies on ~1.85–1.77 Ga mafic plutonic rocks in the SVB and TSB (Johansson and Larsen, 1989; Andersson, 1997a; Nyström, 1999; Claeson and Andersson, 2000; Andersson et al., 2004a) have, in general, yielded mildly depleted isotopic signatures. This is consistent with the inference from geochemistry that the basic TIB magmas were derived from previously melt-depleted mantle sources, overprinted by variable degrees of metasomatic enrichment (Fig. 20; Andersson, 1997a; Nyström, 1999; Claeson, 2001).

The subduction-related mantle enrichment should have occurred shortly before, or in conjunc-

tion with, the basic TIB-1 magmatism itself, in the time frame 2.2–1.8 Ga, as shown by the T_{DM} -ages (Table 3; cf. Andersson, 1997a; Andersson et al., 2006a). In contrast, it is important to note that more strongly depleted mantle sources, partly of MORB character, were present in the area during OJB magmatism (1.83–1.82 Ga; just prior to TIB-1), inasmuch as mafic OJB rocks have initial ϵ_{Nd} values of +2.0 to +5.1 (Mansfeld et al., 2005).

Paleotectonic implications

The general trend of more alkali-rich, continental arc character, including more evolved isotopic compositions, of the TIB-1 mafic rocks north of the OJB, versus the more calc-alkaline to tholeiitic character, straddling oceanic affinities, and less evolved isotopic compositions of the corresponding rocks south of the OJB and in the TSB is mimicked by a similar trend among the coeval granitoid rocks. This indicates that the TIB-1 granitoids are more alkali-rich north of OJB and become progressively more calc-alkaline southward, and particularly so in the TSB (Gorbatshev, 2001; Lindh et al., 2001b). These general trends are indicative of an oceanward continental margin transect moving southward across Småland and Blekinge (at ~1.8 Ga), similar to what is observed in western North America (Bate-man, 1983; Gastil, 1983; Miller and Barton, 1990). North- or northeastward-directed convergence and transpressional tectonics ensued after 1.85 Ga, following the assembly of the juvenile crust in the southern Svecofennian province of Bergslagen (Lindroos et al., 1996; Sjöström and Bergman, 1998; Beunk and Page, 2001; Andersson et al., 2004d).

The 1.83–1.82 Ga OJB represents a sliver of juvenile, post-Svecofennian, calc-alkaline crust (Mansfeld, 1996) that separates the SVB into northern and southern segments. It formed during subduction either as a mature oceanic arc or along the Svecofennian continental margin (Beunk and Page, 2001; Mansfeld et al., 2005), and includes MORB-like, strongly depleted components (Sundblad et al., 1997) that formed during a relatively late (ca. 1.81 Ga) rifting event within the OJB or within a forearc to the OJB just prior to 1.81 Ga (Mansfeld et al., 2005). Isotopic data support a major component of Svecofennian crustal material, but nothing older, within the felsic OJB rocks (Mansfeld et al., 2005). It is likely that the mafic OJB magmatism tapped somewhat shallower, less enriched oceanic mantle sources outboard of the continental margin.

Oceanward retreat of subduction created the voluminous TIB-1 magmatism of the southern SVB and TSB by massive mafic underplating and reworking of the juvenile Svecofennian and OJB crust. Mantle magma input is demonstrated by the TIB-1 mafic plutonic rocks. A younging of TIB-1 crust from 1.81–1.79 Ga north of the OJB to 1.79–1.75 Ga south of it has been invoked from available geochronological data (Mansfeld, 1991, 2004; Kornfält et al., 1997; Gorbatschev, 2004). Although not entirely conclusive, it would support continued southward migration of the subduction-related magmatic activity.

Traces and indications of fossil subduction zones have been revealed through seismic imaging. Abramovitz et al. (1997) noted the remnants of NE-dipping reflectors extending into the upper mantle in the north along the margin between the SVB and the Bergslagen area (i.e., South Svecofennian Province), interpreted as a subduction suture active until ~1.86 Ga, and a stepwise thinning of the crust southward to Blekinge. Both Lund et al. (2001) and Korja and Heikkinen (2005) extended the model, based on seismic data, to include a successive stepwise accretional and collisional crustal growth from Bergslagen in the north to Blekinge in the south over the period 1.84–1.77 Ga. In the crustal block south of Blekinge, numerous NE-dipping reflectors are present in the lower crust, some of which extend into the mantle (BABEL group, 1993; Balling, 2000). These have been interpreted in terms of stacking after plate convergence and accretion by northeastward subduction during TIB-1 time, 1.84–1.76 Ga, with remnants of a fossil subduction zone continuing into the upper mantle (Balling, 2000). In fact, recent

teleseismic tomography data (Eken et al., 2007) appear to record an enormous slab of relatively higher P-wave velocity character that continues from the lower crust south of Blekinge dipping northward, reaching depths of >300 km in the mantle below central Sweden. This structure may represent the remains of a subducted slab from the time of building of the TIB in southern Sweden, inactivated at ~1.75 Ga, and preserved as an eclogitic high-velocity layer (e.g., Warner et al., 1996; Eaton, 2006) within the sub-Fennoscandian mantle. Ca. 1.8 Ga tectonic activity within the southern parts of the Svecofennian domain is mostly in accordance with N-S convergence, and may represent further continentward responses to the active margin in the south (Sjöström and Bergman, 1998; Högdahl and Sjöström, 2001; Andersson et al., 2004d), as does the ~1.8 Ga magmatism further inside the continent where the mafic magmas tap increasingly metasomatized, deep lithospheric mantle sources (Eklund et al., 1998; Andersson et al., 2006a).

In fact, all available data, including the geochemical and isotopic data presented here, seem to corroborate the idea of an active continental margin along the southern edge of the newly formed Fennoscandian continent, beginning at ~1.85 Ga. North or northeastward convergence above a retreating subduction zone resulted in massive mafic underplating and accompanying complete reorganization of the Svecofennian crust from Bergslagen south(west)ward. Concurrently, the juvenile OJB arc was formed in, or accreted to, the continental margin and shortly after also subjected to magmatic reworking. South of the OJB, the oceanward retreat of subduction resulted in reworking of the juvenile OJB crust in the form of continued TIB-1 magmatism, followed in the southernmost part (Blekinge) by the production of yet younger, juvenile calc-alkaline crust at 1.77–1.75 Ga (Johansson et al., 2006), before inactivation of this particular plate movement.

Conclusions

1. Despite a considerable range in chemical composition, i.e., variations in evolutionary level and cumulus components, the investigated mafic plutonic Transscandinavian Igneous Belt (TIB-1; 1.81–1.76 Ga) rocks from the southern Småland-Värmland Belt (SVB) and the Tving suite of Blekinge (TSB) in southeast Sweden consistently show arc-type geochemical character, with enrich-

ment in LILE and LREE, and depletion in HFSE and HREE. The levels of enrichment are generally higher north of the Oskarshamn-Jönköping Belt (OJB), with rocks having a shoshonitic to high-K calc-alkaline character, changing to calc-alkaline and partly tholeiitic character towards Blekinge in the south. This is coupled with a progression from distinctly continental-arc type rocks in the north to less strong enrichments, approaching oceanic affinities further south.

2. The strong depletion in HFSE, generally more depleted than MORB, suggests strongly depleted mantle sources for the mafic magmas; sources subsequently experienced a superimposed strong metasomatic enrichment in LILE and LREE due to percolating fluids/melts from a subducted slab. This is corroborated by the isotopic data, where no samples show strongly depleted mantle characteristics. Initial ϵ_{Nd} values are typically "mildly depleted," in the range +0.7 to +2.0, with one exception at ± 0 . Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are in the range 0.7022–0.7029, with one exception at 0.7033. The lack of covariation between major-element composition, e.g., SiO_2 or $\text{Mg}\#$, and the isotopic ratios do not support a major role for crustal contamination of the mafic magmas, although some samples not analyzed isotopically show signs of contamination. There is a geographical variation in the isotopic data, with the highest initial ϵ_{Nd} and lowest initial $^{87}\text{Sr}/^{86}\text{Sr}$ for the rocks in the south and lower initial ϵ_{Nd} and higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ north of OJB, i.e., a covariation with increasing continental geochemical affinities and less depleted isotopic values northward. In general, the southern TIB mafic rocks show a tendency for higher Sr/Nd ratios in their metasomatized mantle sources compared to age correlatives further continentward in the Svecofennian domain, indicating H_2O -dominant fluids in southeast Sweden and more CO_2 farther inland. The depleted mantle sources were enriched not long before the magmatic event, i.e., during the preceding 2.1–1.86 Ga Svecofennian orogeny, 1.84–1.82 Ga OJB subduction, or during the TIB-1 magmatism itself at ~ 1.80 Ga, as shown by the relatively small enrichment of the isotopic ratios.

3. The paleotectonic scenario extracted from these data, and geophysical observations indicating north- or NE-dipping remains of subduction zones, is consistent with a convergent continental margin setting with oceanward retreat of subduction from the southern Svecofennian margin southward, or southwestward after 1.85 Ga. Massive subduction-

generated mafic underplating of the continental margin resulted in complete reorganization of the pre-existing crust and formation of the TIB-0 and TIB-1 magmatic rocks north of the OJB during the period 1.85–1.79 Ga. The calc-alkaline, juvenile 1.83–1.82 Ga OJB formed further oceanward after the continental reworking had started in the north. Reworking of the juvenile OJB crust followed, with TIB-1 magmatism continuing southward at 1.79–1.76 Ga, ending with calc-alkaline crust-formation in Blekinge during 1.77–1.75 Ga. This subduction then ceased, and did not resume until ~ 1.71 Ga in the west.

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