Adakitic high-Al trondhjemites in the Proterozoic Østfold-Marstrand Belt, W Sweden

BJØRN HAGESKOV & BENTE MØRCH

Hageskov, B & Mørch, B. 2000–02–10. Adakitic high-Al trondhjemites in the Proterozoic Østfold-Marstrand Belt, W Sweden. *Bulletin of the Geological Society of Denmark,* Vol. 46, pp. 165–174. Copenhagen.

This paper investigates the first identified intrusives in SE Norway–W Sweden with the specific signature of adakitic arc magmas, which in recent settings are preferably explained as partial melts extracted from subducted oceanic crust. The studied adakitic high–Al trondhjemites occur as sheets in the Koster archipelago, W Sweden, where they form the oldest recognized granitoids in the metasupracrustals of the Stora Le–Marstrand formation. The trondhjemites were intruded during a short ca. 1.59–1.58 Ga interlude between the early and the main orogenic events of the Gothian orogeny (1.6–1.56 Ga, Åhäll et al. 1998). This interlude is otherwise characterized by ‘ordinary’ calcalkaline magmatism which on Koster is predated by the trondhjemites.

The typical adakitic signature suggests that the trondhjemitic magma was extracted from a MORB (Mid Ocean Ridge Basalt) like source, and that a hornblende eclogite restite was left in the region of melting. The restite composition indicates melt extraction at PT conditions in the range of 18–25 kb/800°C to 13-15 kb/950–1050°C. These requirement can only be met by subduction of warm (young or shear heated) oceanic crust beneath a crust including early Gothian metamorphosed and deformed Stora Le–Marstrand formation or by melting of metabasaltic material at a deep crustal level. The latter is a less likely possibility and demands that the Stora Le–Marstrand formation at the time of melt extraction was part of a ≥ 45 km thick crust.

Key words: Adakites, high–Al trondhjemites, Mesoproterozoic, Gothian Complex, tectonics.

Bjørn Hageskov [*BjornH@Geo.Geol.KU.DK*] *and Bente Mørch, Geologisk Institut, Københavns Universitet, Østervoldgade 10, 1350 Copenhagen K, Denmark. 25 June 1999.*

The growth of the continental crust has been significantly influenced by calcalkaline magmatism which since early Precambrian time is believed to have been located in oceanic and continental arcs developed in plates overriding subducted oceanic lithosphere. In this environment, calcalkaline magmas may potentially be extracted from the subducted basaltic crust (slab-melts), the overlying modified mantle wedge and/or from the lower arc crust. Today the lower arc crust and particularly the mantle wedge are regarded as the main sources and most arc magmas, presumably by fractional crystallization with or without contamination have evolved to the more silicic compositions of the calcalkaline basalt-andesite-dacite-rhyolite (BADR) suite.

Research in the last decade has discovered some calcalkaline andesitic-dacitic-trondhjemitic arc magmas with a specific geochemical signature [high Sr/Y, La/Yb and low Y, HREE (heavy rare earth elements)], which are preferably explained as slab derived melts. These magmas are named adakites after Adak Island in the Aleutian arc (Defant & Drummond 1990). The modelling recalls attention to Green & Ringwood’s (1968) slab-melting model which in the early days of the plate tectonic hypothesis was widely applied to the production of arc andesites.

Recent adakites have been identified in several circum-Pacific arcs (Kay 1978, Rogers et al. 1985, Kepezhinskas 1989, Defant & Drummond 1991a, 1991b, 1993, Yogodzinsky et al. 1995, Kay et al. 1993,

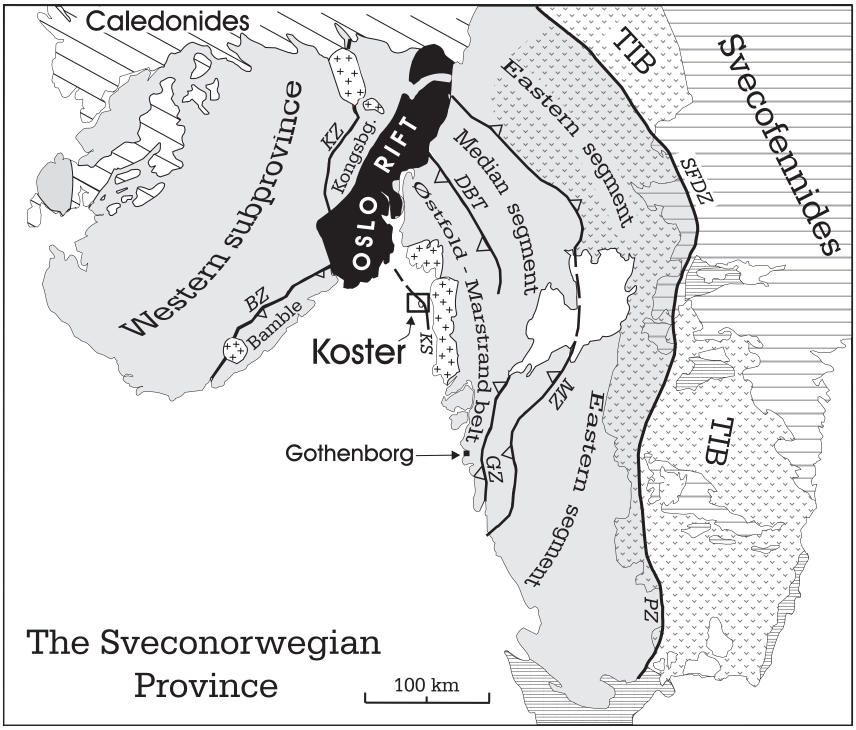

Fig. 1. Major Sveconorwegian lithotectonic units (grey) and their shear zone boundaries.
BZ = Bamble shear zone,
KZ = Kongsberg shear zone,
KS = Koster shear zone,
DBT = Dalsland Boundary Thrust,
GZ = Göta Älva shear zone,
SFDZ (PZ) = Sveconorwegian Frontal Deformation Zone (Protogine Zone) and
TIB = Transscandinavian Igneous Belt. Modifyed from Berthelsen (1980), Hageskov (1980), Wahlgren et al. (1994) and Møller (1998).

Atherton & Petford 1993, Sanoja et al. 1993, 1996, Morris 1995, Stern & Kilian 1996) where they typically occur along the leading edge of the main arc which grows by voluminous 'ordinary' calcalkaline magmatism. Modelling and experimental work indicate that adakitic magmas can be extracted from subducted MORB transformed to garnet amphibolite or eclogite at appropriate P/T conditions of 13–25 kb/ 800–1100° C. Since the temperature criteria can only be met by subduction of a warm (young) oceanic crust, slab melts will generally not be produced (Peacock et al. 1994). Defant & Drummond (1990) suggest an oceanic crustal age ≥ 25 Ma to be sufficient, while the modelling of Peacock et al. (1994) arrives at an age of < 5 Ma if high rates of shear heating are not incorporated.

Although most adakites may have originated as slab melts, magmas with adakitic signature are also, under similar P/T conditions, considered to have been produced by partial melting of basaltic lower crust that had recently been, or was still being, thickened by magma underplating. This modelling is proposed by Atherton & Petford (1993) to explain ca. 5 Ma old adakitic trondhjemites located above the Miocene thickened continental keel of the Central Andes.

Adakitic rocks are of insignificant volumetric importance in post-Archaean complexes, but widespread in the Archaean crust where adakitic compositions are represented by the high–Al tonalite-trondhjemite-dacite suite (TTD). This difference is explained by the higher geothermal gradient in Archaean time which is thought to have caused a more rapid generation and subduction of oceanic crust (see Defant & Drummond 1990, Drummond & Defant 1990, Martin 1999 and references therein).

By applying recent settings and suggested petrogenesis, adakites can significantly contribute to understanding the tectonic evolution of older crustal complexes such as Proterozoic terrains, where the presence of adakites may monitor subduction of young oceanic crust, the presence of a thick basalt-underplated continental crust and changes in plate configuration.

This paper investigates the first identified adakitic arc magma (high–Al trondhjemite) in the Gothian crust of SE Norway–W Sweden, where it occurs as sheets in the Koster archipelago in the westernmost part of the Østfold-Marstrand belt.

Regional geology

During the 1.15–0.95 Ga Sveconorwegian orogeny, the SW part of the Baltic Shield was tectonothermally reworked and cut by shear zone systems into an assemblage of lithotectonic units which include components of a >1.5 Ga basement complex (Fig. 1). Parts of this basement are known from the eastern part of the Sveconorwegian Orogen (SE Norway–W Sweden) where the polyphase orthogneiss-dominated crust, apart from subordinate volumes of 1.5–1.2 Ga mainly granitic and mafic sheets and a few late Sveconorwegian granites (ca. 0.92 Ga), evolved during the period 1.81–1.5 Ga. The evolution includes formation of 1) the 1.81–1.65 Ga alkali-calcic Transcandinavian Igneous Belt (TIB) (Patchett et al. 1987, Andersson 1991, Larsson & Berglund 1992, Wikström 1996) extending from the foreland into the eastern segment of the Sveconorwegian Orogen and 2) the Gothian complex which grew significantly by calcalkaline magmatism in the period 1.66–1.58 Ga and was exposed to the Gothian orogeny dated to 1.6–1.56 Ga (Conelly & Åhäll 1996, Åhäll et al. 1998).

The growth of the TIB belt and the Gothian complex have both been modelled by eastward subduction of oceanic lithosphere beneath SE Norway–W Sweden (Berthelsen 1980, Henkel & Eriksson 1987, Åhäll & Daly 1989, Larsson et al. 1990, Johansson et al. 1993, Åhäll & Gower 1997, Brewer et al. 1998). In the modelling, the TIB magmatism is located in a continental margin developed in the Svecofennian crust while the Gothian complex may represent an amalgamation of arcs (Brewer at al. 1998) which were later involved in the main phase of the Gothian Orogeny (1.58–1.56 Ga., Conelly & Åhäll 1996).

The Østfold-Marstrand belt and the Gothian complex

The Gothian complex, here defined as the body affected by the 1.6–1.5 Ga Gothian Orogeny, includes the > 1.5 Ga basement components within the Sveconorwegian lithotectonic unit of the Kongsberg sector, the Bamble sector and, the Median Segment and the Østfold-Marstrand belt of SE Norway–W Sweden. During the Sveconorwegian orogeny the Østfold Marstrand belt was thrust against the Median segment on the west-dipping Dalsland Boundary Thrust–Göta Älva shear zone system (Berthelsen 1980, Park et al. 1993).

The Østfold-Marstrand Belt differs from the remaining parts of the east Sveconorwegian crust by the occurrence of a monotonous sequence of polymetamorphic greywackes known as the Stora Le–Marstrand Formation (SLM). The formation, which also includes small amounts of mafic rocks (volcanics, cumulitic mafics, ultramafites), was deposited on an unidentified basement. Similar supracrustal gneisses occur also in the Norwegian part of the Median segment (Hageskov 1980, Skjernaa & Pedersen 1982). Recent age determinations on detrital SLM zircons place an interpreted maximum deposition age at 1.598 Ga (Åhäll et al. 1998). The later Gothian evolution includes early Gothian migmatisation and deformation of SLM, intrusion of numerous calcalkaline plutons and the main Gothian orogeny. The oldest precise age obtained from the calcalkaline intrusives (Rönäng tonalite, 1.587 ± 3 Ga, Conelly & Åhäll 1996) and the maximum SLM age indicate rapid SLM sedimentation, since this and the succeeding early Gothian orogenic events must have happened within 15 Ma to satisfy the obtained ages.

In the Median segment part of the Gothian complex, numerous calcalkaline plutons are believed to define a roughly N-S trending, 1.59–1.62 Ga igneous arc developed in a continental margin setting (Brewer et al. 1998). The arc includes the low-grade supracrustals of the Åmål Group which is a dacite dominated 1.614 ± 7 Ga calcalkaline BADR suite interbedded with subordinate metasediments including quartz-rich sandstones (Lundquist and Skiöld 1993, Brewer et al. 1998). The basement of the Åmål supracrustals is not observed, but presumably it includes components of the BADR volcanic-sedimentary sequence of the Horred Formation and their also unknown basement. A metadacitic member from this formation has yielded an age of 1.659 +8/–6 Ga (Connelly & Åhäll 1996). The Horred magmatism represents the earliest recognized calcalkaline magmatism in the Gothian complex and the 1.66 Ga age is so far the oldest zircon age obtained from the complex. The Åmål Group and the Horred Formation are both untouched by early Gothian events (Åhäll et al. 1995).

Geological setting

The studied adakitic high–Al trondhjemites occur in the well exposed Koster archipelago in the westernmost part of the Østfold–Marstrand belt. The archipelago is separated from the main belt by a subvertical major NW-SE trending sinistral Sveconorwegian shear zone which affected the northeastern part of the archipelago. Structural investigations on the shear zone (Hageskov 1985) suggested that the crust southwest of the shear zone (the southern part of the archipelago) has been displaced at least 30 km southwards relative to the crust NE of the zone. Detailed investigations in the excellently exposed archipelago, where the southern part is untouched by Sveconorwegian strain, have resulted in an event stratigraphy which agrees with that obtained from the southern part of the Østfold-Marstrand belt. This is of considerable interest because: 1) it extends the established Gothian event stratigraphy to regions north of the present site of the Koster archipelago and 2) it allows the events on Koster to be correlated with the dated events.

The SLM formation on Koster is as elsewhere in the Østfold-Marstrand belt the fundamental unit. It occurs as intensely poly-migmatised psammitic to semipelitic gneisses which frequently incorporate minor inclusions of early mafic material of suspect origin and emplacement history. Both metavolcanics (pillow lava and agglomerates) and mafic plutonites occasionally showing relic igneous layering have been identified.

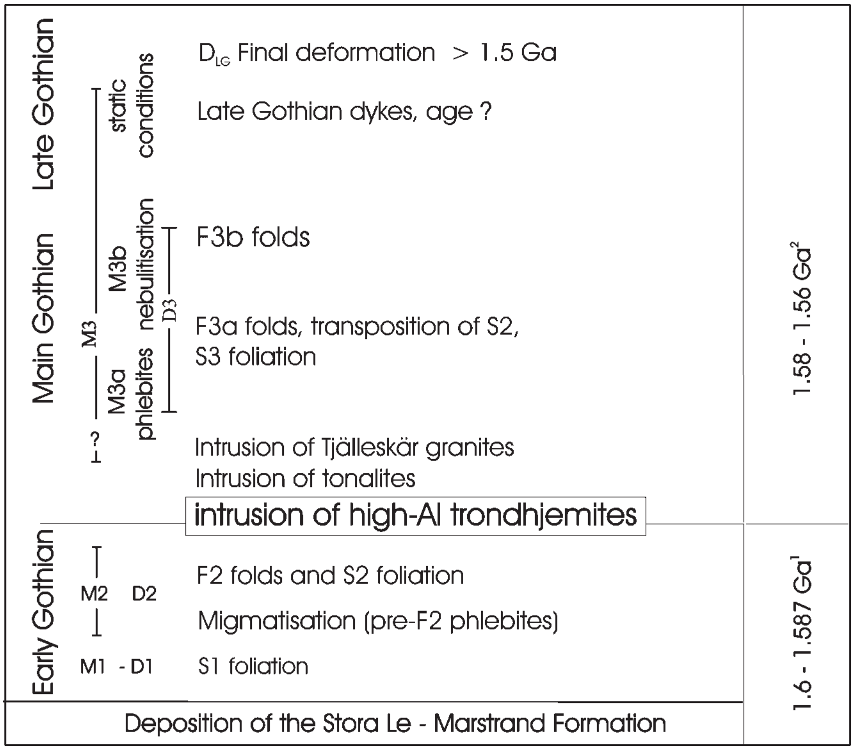

Table 1. The event stratigraphy of the Koster Archipelago. Included ages are from 1) Åhäll et al. (1998) and 2) Conelly & Åhäll (1996).

Roughly 50% of the crust consists of gneissified calcalkaline granitoids represented by a tonalite unit, the Tjälleskär granites, sheets of a porphyritic granite and the subordinate sheets of the adakitic trondhjemite (Table 1). They have all been involved in the main Gothian tectono-thermal events ($D3_{a+b}$ $M3_{a+b}$) and a week ductile event (D4) marking the end of the Gothian strain history (Hageskov 1997).

None of the granitoids have yet been dated but according to the event stratigraphic correlation, the granitoids are thought to have been intruded around 1.59–1.57 Ga. The Koster tonalite suite is presumably related to the widespread 1.59–1.58 Ga calcalkaline plutonism which occurred after the early Gothian events (M1–D1 and M2–D2) which are restricted to the period 1.6–1.59 Ga according to the ages of the SLM formation and the Rönäng tonalite. By correlation, the D3–M3 events arose from the main Gothian orogeny which produced veined migmatites, dykelets of mobilizate and finally nebulites under upper amphibolite facies conditions.

The ‘tonalite unit’ includes compositions varying from quartz diorite to granodiorite. It forms, depending on the structural interpretation, one or two deformed sheets which, based on xenoliths of D2 deformed SLM migmatites and the D3–M3 overprint, were intruded between the early and main Gothain events. Whereas the tonalites represent ordinary calcalkaline arc magmas, geochemical investigations suggest that the granodioritic Tjälleskär granite most likely represents an anatectic magma derived from the SLM metagreywackes from which it has inherited a greywacke REE type of pattern and normal continental arc signature (Hageskov 1997).

The trondhjemites

The investigated four polymetamorphic trondhjemite sheets (Fig. 2) occur in the westernmost part of the shear zone. Sheet 2 may represent a protrusion from the largest body which occurs in the Basteviken region (sheet 1) as the core of an about 400 m wide antiform with steep to subvertical limbs dipping NE and SW respectively. Sheet 2, 3 and 4 are all steeply dipping and have maximal exposed widths of about 30 m, 80 m and 40 m respectively.

The Basteviken sheet is partly surrounded by older amphibolites towards which it has a sharp contact. The southwestern margin is formed against a layered amphibolite believed to represent early volcanics, perhaps a pillow lava. The relations at this margin clearly demonstrate that the layered amphibolite prior to trondhjemite intrusion was exposed to D2 deformation resulting in a layer-parallel foliation including rootless isoclinal folds. The amphibolite also occurs as xenoliths within the trondhjemite. The amphibolites along the remaining part of the boundary do not show pronounced layering and it is unknown whether

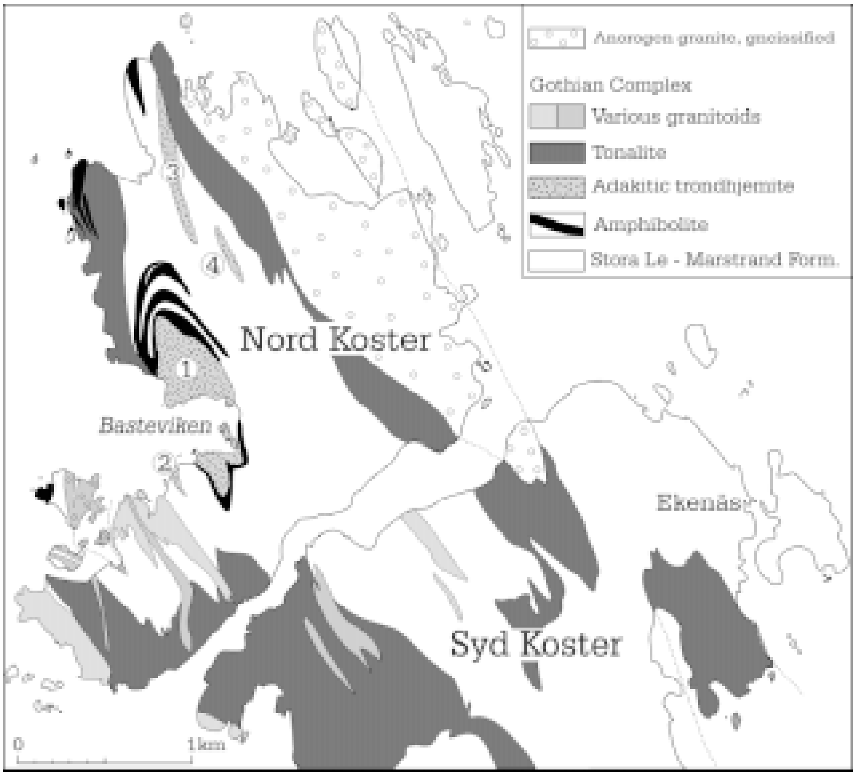

Fig. 2. Sketch map of the northern part of the Koster Archipelago. The investigated adakitic trondhjemite sheets are numbered 1, 2, 3 and 4.

these early mafics represent volcanics or intrusive sheets. Clear evidence of relations to the tonalite is found in the northernmost part of N Koster, where the tonalite sheet includes xenoliths of the trondhjemite in sheet 3. Thus, relations to the host rocks and the tonalite indicate that the trondhjemites were intruded post (or late) kinematically with respect to the early Gothian D2 event and that the trondhjemites are unrelated to the tonalites as also demonstrated by geochemistry.

The trondhjemites themselves are fine- to medium-grained, lineated light grey leucocratic gneisses which contain small amounts of thin (<2 cm wide) quartzofeldspathic veins. The homogeneous and totally recrystallised gneissic part is a slightly retrogressed (chorite and epidote) amphibolite facies gneiss which essentially consists of oligoclase (55–65%), quartz (20–30%), biotite (10%) and ≤ 1% muscovite. A little microcline occurs occasionally while hornblende is rare.

Only the southernmost part of the Basteviken sheet has been exposed to marked migmatisation and is seen as a phlebitic migmatite showing Gothian folds overprinted by minor Sveconorwegian folds and ductile shears. In this body as well as in the other sheets the lineation resulted from constrictional strain within the Koster shear zone.

Sampling and analytical techniques

Homogeneous samples were collected from the four trondhjemite sheets. No samples were taken from the marked migmatised part of sheet 1. The analyses are presented in Table 2. Major elements have been analysed in the chemical laboratories of the Geological Survey of Greenland and Denmark (GEUS) using a Philips PW1600 XRF spectrometer and methods outlined by Sørensen (1975, 1976). Na_2O and MgO were determined by atomic absorption spectrometry. The trace elements were analysed at Geology Institute, Copenhagen University, by J. Bailey on a Philips automatic PW 1400 spectrometer using methods outlined by Norrish & Chappell (1977). REE (rare earth elements), Hf and Th were determined by neutron activation analysis by R. Gwozdz following irradiation at Risø National Laboratory.

Geochemistry

The Koster trondhjemites have a uniform geochemistry and, like most calcalkaline granitoids, they are slightly corundum CIPW normative and mildly peraluminous. The composition is that of a typical high–Al trondhjemites (Table 3) with a moderate SiO_2

Table 2. Chemical analyses of the Koster trondhjernites

sample	6725	67025	50604	50605	50606	67066	6721	51771	591772	67076	67083	67077
sheet	1	1	1	1	1	1	2	3	3	3	3	4
wt.%												
SiO_2	67.10	70.17	70.70	70.79	70.66	68.03	69.21	68.00		66.11	69.86	68.21
TiO_2	0.31	0.27	0.20	0.20	0.20	0.30	0.23	0.30		0.44	0.27	0.37
$A1_2O_3$	16.96	16.03	16.18	16.16	16.18	17.17	16.63	17.53		17.61	16.00	16.67
FeO*	1.88	1.66	1.19	1.12	1.13	1.39	1.50	1.53		2.01	1.54	1.70
MnO	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03		0.03	0.02	0.06
MgO	1.16	0.96	0.92	0.90	0.92	0.99	0.94	1.16		1.39	0.70	0.96
CaO	3.18	2.96	3.27	3.27	3.19	3.45	3.21	3.73		3.94	3.38	3.90
Na_2O	5.54	5.21	5.23	5.25	5.35	5.14	5.30	5.47		4.83	4.77	5.09
K_2O	1.51	1.40	1.21	1.22	1.25	1.34	1.54	1.16		1.99	1.31	0.96
P_2O_5	0.11	0.08	0.08	0.08	0.08	0.09	0.09	0.12		0.13	0.08	0.11
LOI	1.08	1.11	0.37	0.35	0.37	1.42	0.37	0.32		0.59	0.53	0.73
Sum**	99.07	99.90	99.51	99.49	99.47	99.34	99.20	99.50		99.11	98.63	98.75
ppm												
Rb	66	42	38	35	37	60	37	26		47	45	37
Ba	264	404	427	424	426	559	447	386		523	240	256
Sr	649	557	655	628	655	665	693	782		805	620	490
La	14	9	12.4	13.8	13.4	17	12	16.8	16.6	14	26	10
Ce	32	22	26.6	27.9	25.2	32	25	32.7	33.2	30	54	22
Nd	16	10	10.1	11.3	12.3	17	13	14.9	16.2	14	27	13
Sm			1.55	1.5	1.55			2.34	2.36			
Eu			0.43	0.45	0.43			0.69	0.64			
Tb			0.13	0.17	0.16			0.25	0.23			
Yb			0.23	0.21	0.25			0.29	0.26			
Lu			0.03	0.02	0.03			0.04	0.03			
Y	4	2	3	3	2	4	3	3		4	8	3
Hf			1.97	2.01	2.39			2.6				
Th	1	2	1.97	2.11	2.15	3	2	2.36		2	6	
Zr	83	64	65	60	63	81	69	83		86	96	83
Nb	4	4	3.3	3.1	2.9	7	4	3.6		5	6	4
Ni	16	14	14	12	12	13	14	10		10	10	10
V	30	13	13	13	14	19	20	18		21	19	18
Cr	12	14	13	14	15	18	18	11		11	13	9

Sum**. The analytic sum (prior to FeO* calculation)

(69.0%). Compared to the ordinary arc granodiorite (Table 3) of Martin (1999), the Al_2O_3 (16.7%) and Na_2O (5.2%) contents are high, whereas TiO_2 (0.28%), MgO (1.0%), FeO* (1.5%) and K_2O (1.4%) are low. Furthermore the composition is characterised by low K_2O/Na_2O (<0.41), CaO/Na_2O (<0.82) and FeO*/MgO (<1.8) ratios and by high Mg-numbers (Mg# = 45–70).

The samples are generally impoverished in trace elements; but particularly noticeable are the very low contents of HREE (heavy rare earth elements, Yb = 2.48 ppm, Lu = 0.03 ppm) and Y (3.5 ppm), the high contents of Sr (650 ppm), and the very high Sr/Y (78–328) and La/Yb (54–66) ratios. A more detailed insight into the geochemical signature appears from the REE and the primitive mantle normalized diagrams (Figs. 3 and 4).

The REE pattern (Fig. 3) is strongly depleted in HREE relative to LREE without any anomalies. The very high chondrite normalised $(La/Yb)_N$ ratio of 36-44 is mainly ascribed to a HREE content lower than that of the primitive mantle and close to chondritic values.

In the primitive mantle-normalized diagram, the trondhjemites are strongly enriched in LILE (large ion lithophile elements, Rb, Ba, Sr) and depleted in HREE + Y with a positive anomaly at Sr and negative anomalies at Ti, P and in particular at Nb. This pattern is of calcalkaline type, but differs markedly from that of 'ordinary' calcalkaline granitoids, as exemplified by the Koster tonalite (SiO_2 = 67%) in Fig. 4, by the lower element contents and the positive anomaly at Sr. Ordinary calcalkaline granitoids have a negative Sr anomaly resulting from plagioclase fractionation. Besides the mentioned features, it is noticeable that the incompatible HFSE (high field strength elements) such as Nb, Hf and Zr are at about MORB level and that the LILE/LREE (e.g. Ba/La = 30) and LREE/HFSE ratios are high compared to N-MORB.

The geochemical signature of the high-Al Koster trondhjemites fulfills the criteria for being an adakitic magma as seen from Table 3 and from the plot in the

Table 3. Average composition of Koster trondhjemites and the characteristics of high-Al trondhjemites and adakites. Sources: 1) Barker (1979) and 2) Defant & Drummond(1990. A: Adakitic granite (N = 17) from the Tertiary Cordillera Blanca complex, Peru (Atherton & Petford 1993). B: Trondhjemite (N=3) from Trondheim (Barker and Millard 1979). C: Proterozoic trondhjemite (N = 9) from southwest Colorado (Barker et al. 1976). D: Archaean trondhjemite (N = 3-7) from Barberton (Condie & Hunter 1976; Glikson 1976). Average ‘ordinary’ arc granodiorite (N = 250) (Martin (1999).

	Koster-trondhj.	High–Al trondhj.[1]	Adakitic melt[2]	A	B	C	D	Arc grano-diorite
wt. %								
SiO_2	68.98	68–75	>56	71.60	70.07	70.40	69.74	68.10
TiO_2	0.28			0.27	0.23	0.29	0.30	0.54
Al_2O_3	16.65	>15	>15	15.06	16.54	16.90	15.08	15.07
FeO*	1.51			1.54	1.41	2.13	2.30	4.31
mgO	1.00			0.54	0.80	0.66	1.23	1.55
CaO	3.41	<4–4.5		1.96	3.14	2.27	3.04	3.06
Na_2O	5.20	4.4–5.5		4.31	5.50	4.84	5.44	3.68
K_2O	1.35	<2.5		3.51	1.34	2.59	1.41	3.40
P_2O_5	0.09			0.08	0.08	0.09	0.08	0.15
ppm								
Rb	43			120	28	76	43	
Ba				718	328	885	301	
Sr	654		>400	461	613	547	559	316
La	14.6				8.2		16	31
Yb	0.25		<l–1.5	0.36	0.29	0.9	0.45	3.2
y	3.6		<15–18	6.9			3	26
FeO*/MgO	1.51	2–3		2.85	1.76	3.23	1.87	2.78
Sr/Y	187		>40	67			186	12.2
La/Yb	58.9		>20	71	28.3		35.6	9.7

* at SiO_2 = 70%

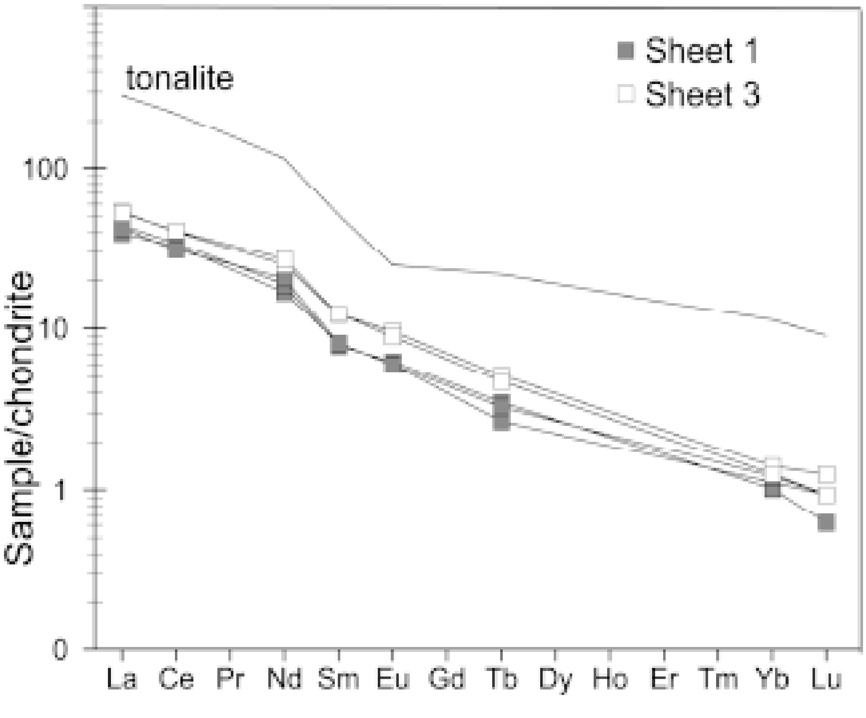

Fig. 3. REE diagram of the samples in Table 2; normalised to Leedey chondrite (Masuda et al. 1973). For comparison is included an ordinary tonalite from Koster.

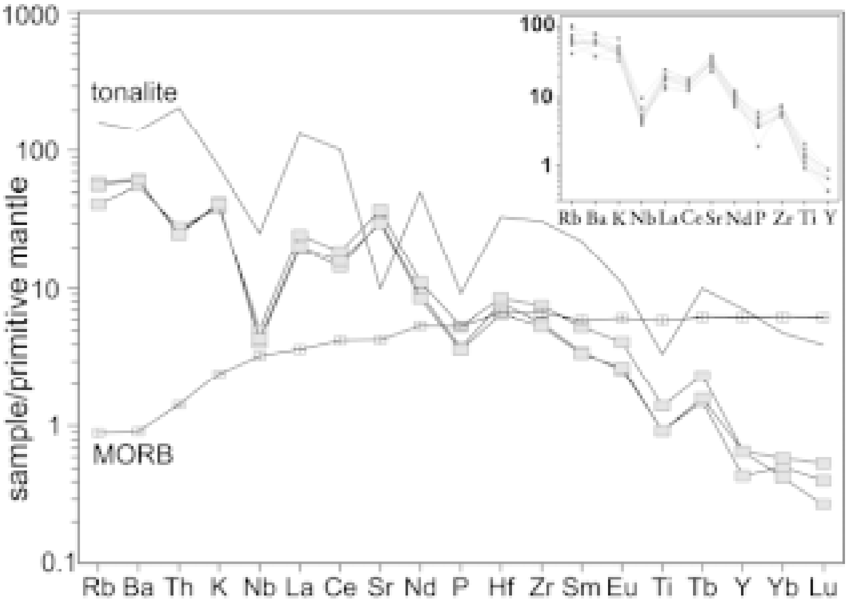

Fig. 4. Trace element patterns of samples 50605, 50606 (from sheet 1) and 51771 (sheet 3) normalised to primitive mantle of Sun & McDonough (1989). For comparison is included an N-MORB (Sun & McDonough 1989) and the tonalite as in Fig. 3. The pattern of all samples is given in insert diagram with reduced numbers of elements.

Y–Y/Sr and Yb_N-$(La/Yb)_N$ diagrams (Figs. 5a-b), which distinguish adakitic rocks from ordinary calc-alkaline andesite-dacite-rhyolite rocks.

Petrogenesis

Numerous geochemical investigations supported by experimental results suggest that andesite-dacite-trondhjemite arc magmas with the distinct adakitic signature (high Sr, Sr/Y, La/Yb and the low Y, HREE contents/ratios) are extracted from an MORB source transformed to amphibolite or eclogite, and that restites essentially composed of garnet + clinopyroxene ± hornblende ± plagioclase are left in the region of melting. The restite phases are of importance in the estimation of the P–T conditions of partial melting.

Fluid-absent melting experiments on amphibolites have given insight into phase equilibria under P and T conditions corresponding to lower crust and upper mantle (Rapp et al., 1991, Rushmer 1993, Wyllie &

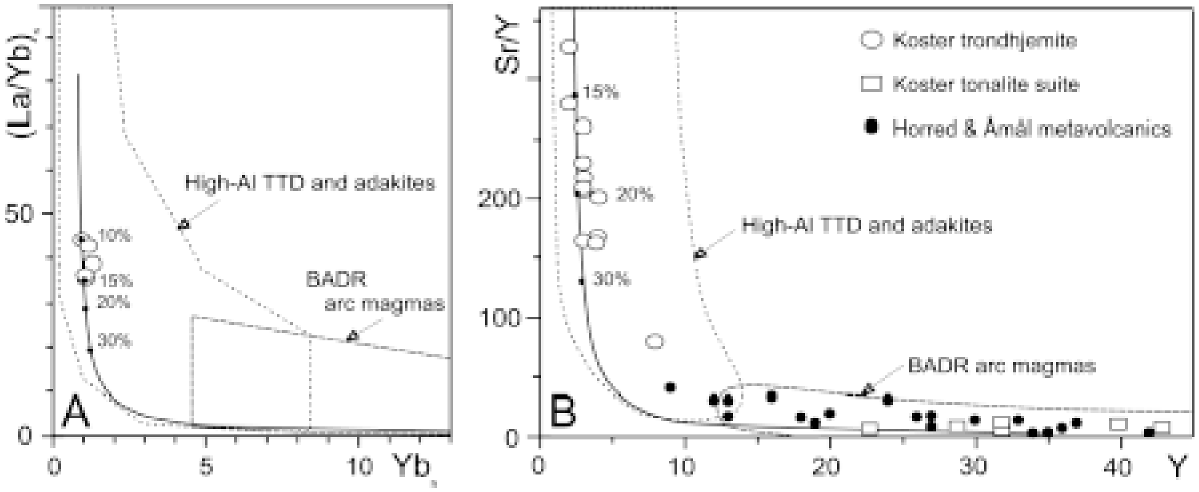

Fig. 5. A) Chondrite normalised plot of Yb_N versus $(La/Yb)_N$. B) Y versus Sr/Y. For comparison is included analyses of the Koster tonalites (authors' data) and the Horred and Åmål metavolcanics (Brewer 1998). Both diagrams include the calculated batch melting curve with the positions of 10–30% melt extraction indicated [source composition: oceanic layer 3 (altered MORB) from Taylor & McLennan (1985); restite composition: garnet (40%), clinopyroxene (45%), hornblende (15%); partition coefficients, see Table 4]. The high-Al TTD and adakite field and the field of the 'ordinary' calcalkaline basalt-andesite-dacite-rhyolite suite are based on Drummond & Defant (1990).

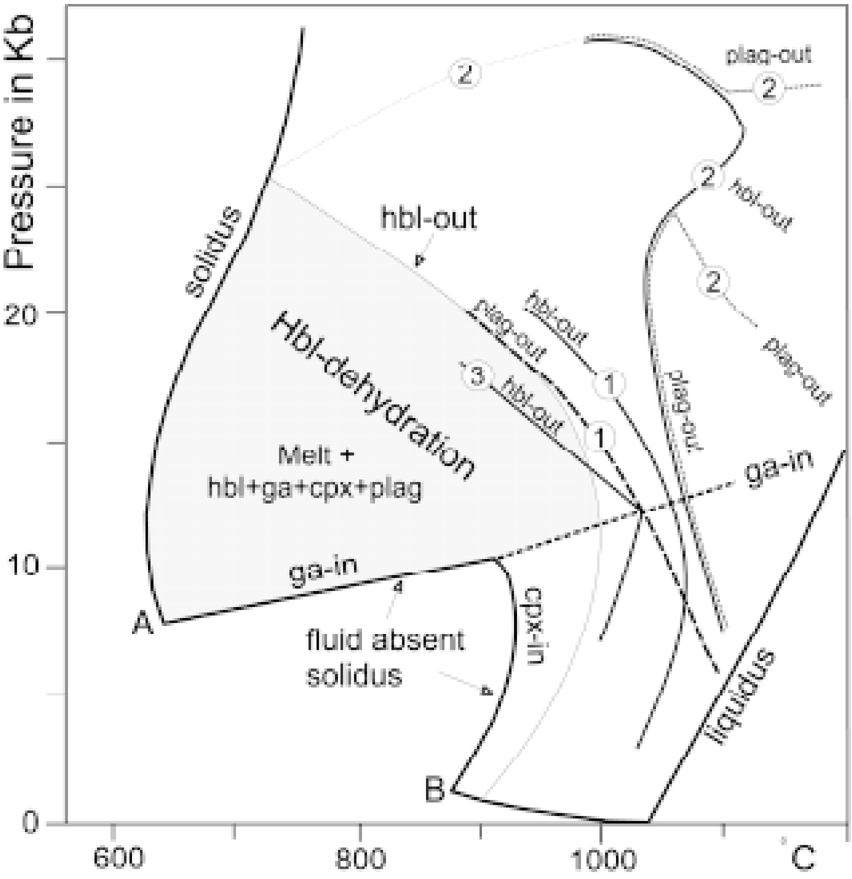

Fig. 6. Fluid absent melting of metabasalts. The phase diagram is based on Wyllie & Wolff (1993, Fig.4), but includes also the hbl-out and plag-out phase boundaries established by Sen & Dunn (1994), Rapp (1994) and Rushmer (1993) from experimental melting of (1) qz-tholeiitic amphibolite, (2) an alkali-rich basalt and (3) alkali basaltic amphibolite, respectively. Notice that these phase boundaries are source dependent. The fluid absent-solidus follows the H_2O saturated solidus at pressures above point A and below point B (Wyllie & Wolf 1993).

Wolf 1993, Rapp 1994, Sen & Dunn, 1994). These experiments simulate natural melting of ‘dry’ amphibolites in which H_2O is only present as structurally bound H_2O in hornblende (and other silicates). The H_2O released by breakdown of hornblende causes melting and is itself directly transferred into the melt.

Phase relations are outlined in Fig. 6. Melting experiments based on amphibolites have shown that adakitic high–Al trondhjemitic (and high–Al tonalitic) melts may coexist with garnet (ga) + clinopyroxene (cpx) ± hornblende (hbl) ± plagioclase (plag) over a wide range of pressures both within the shaded field and above the hbl-out boundary where the melts coexist with ga-cpx-hbl-plag and ga-cpx, respectively. The amount of extracted melt is low near the solidus, but increases with progressive dehydration melting of amphibole and reaches up to about 20% near the hbl-out boundary (Rapp et al. 1991, Sen and Dunn 1994). The increasing melt extraction is accompanied by increasing amounts of garnet and clinopyroxene in the residuum at the expense of plagioclase and hornblende. Beyond the hbl-out boundary, the melt fraction is significant higher 25–40% (Rapp et al. 1991, Rapp 1994). It is to be noticed that the hbl-out boundary delimiting the shaded field is an approximation (Wyllie & Wolf 1993). The phase boundaries, as shown by the included hbl-out and plag-out boundaries established by Rushmer (1993), Sen & Dunn (1994) and Rapp (1994), depend on the composition of the mafic source.

High–Al trondhjemitic and tonalitic melts have by Rapp et al. (1991) and Sen & Dunn (1994) only been produced experimentally at pressures ≥ 16kb and ≥ 15 kb, respectively. The obtained compositions are shown in Fig. 7 together with the Koster trondhjemites. The Koster data agree with the experimental data and are particularly close to the compositions of Rapp et al. though slightly low and high in FeO* and MgO, respectively. The main differences between Rapp et al. and Sen & Dunn’s compositions are seen in the higher FeO*, CaO, Na_2O in the melts of Rapp et al. and the much higher K_2O content in those of Sen & Dunn. The differences between these results are presumably source related (Sen & Dunn): Rapp et al. melted four different ol-normative amphibolites whereas Sen & Dunn used a qz- amphibolite.

Natural adakites are consistent with the experimental results, but are too high in MgO and to some extent in CaO (Sen & Dunn 1994). The MgO enrichment, which is expressed by higher Mg-numbers (Mg#) in adakites (Mg# = 45–75) than in experimental melts [Mg# = 29 ± 6 (Rapp. et al. 1991), Mg# = 33 ± 2 (Sen and Dunn 1994)], is though to result from

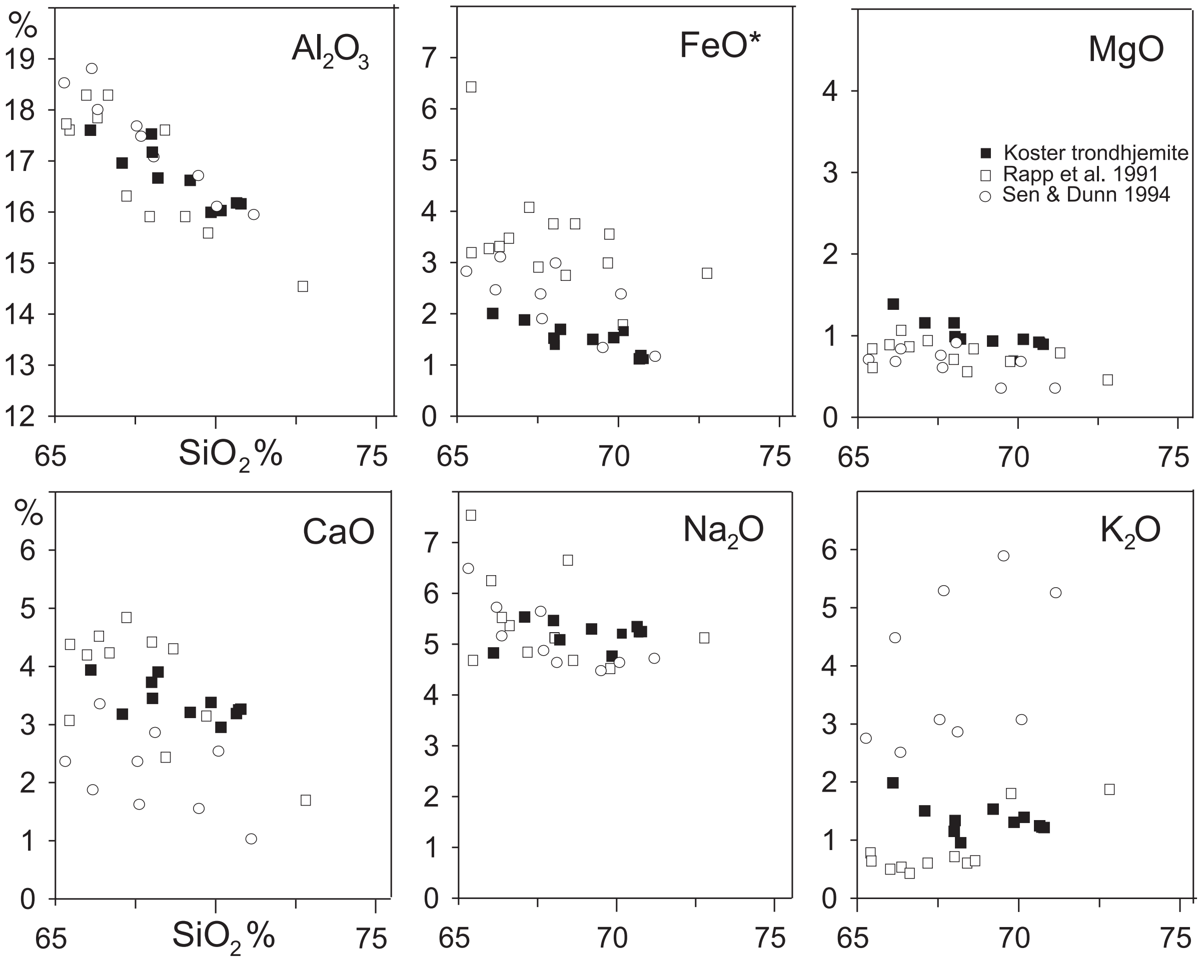

Fig. 7. Major element compositions of the Koster trondhjemites in comparison with compositions obtained by partial melting of amphibolitic sources at 16 and 22 kb (Rapp et al. 1991) and at 15 and 20 kb (Sen & Dunn 1994).

interaction between the ascending adakitic slab melt and the mantle wedge (Kay 1978, Sen & Dunn 1994, Yogodzinsky et al. 1995, Martin 1999). Accordingly, the adakitic Mg# in the Koster trondhjemites may indicate interaction with the mantle wedge.

In establishing the restite composition left by the extraction of the Koster trondhjemite magma, it is noticeable that this, like typical adakitic melts (Defant & Drummond 1990), can not have been significantly changed by fractional crystallization since: 1) plagioclase, due to the high Na_2O, Al_2O_3 and Sr contents cannot have been an important fractionating or restite phase and 2) Mg-bearing mafic phases cannot have been significantly fractionated from the melt as the low FeO*/MgO ratio and high Mg# argue against such modelling. Furthermore, the very low HREE and Y contents suggest that significant amounts of garnet ± hornblende are included in the restite.

An idea of the major phases in the restite composition has been obtained from simple batch melting of MORB-like sources using the mineral/melt partition coefficients given in Table 4. The batch melting modelling in Fig. 8 is based on an altered MORB (oceanic crust, layer 3, Taylor & McLennan 1985) and a primitive N-MORB (Sun & McDonough 1989). With respect to the altered MORB, the REE, Y, and Sr signature of the Koster trondhjemite is explained by 10–20% melting and a restite composed of garnet (45%), clinopyroxene (40%) and hornblende (15%). This residuum satisfies the $(Yb)_N$–$(La/Yb)_N$ and the Sr/Y ratios (Figs. 5a and b). A primitive N-MORB source, like that of Sun & McDonough, demands lower melt extraction (10%) and a garnet (38%), clinopyroxene (54%) and hornblende (8%) restite to reproduce the same part of the signature.

While the batch melting modelling explains important parts of the signature of the Koster trondhjemites by 10–20% melting of MORB-like compositions and a restite composed by garnet, clinopyroxene and some amount of hornblende, but without plagioclase, it is obvious that high Rb, Ba , K and Ti cannot be reproduced from the used source compositions. The much too low Ti content may indicate a source with a lower Ti content, but probably more likely the presence of:

Table 4. Partition coefficients used in the batch melt calculation. The partition coefficients are from dacitic liquids supplemented with data from intermediate liquids tabulated in Rollinson (1993). The garnet/melt Nb partition coefficient (0.03) is from a mafic liquid (Green et al. 1989). The hornblende/melt Ti partition coefficient of 7 is selected to as the highest reported from acid magma (Pearce and Norry 1979).

	garnet	clinopyroxene	hornblende
Rb	0.009	0.02	0.04
Ba	0.017	0.02	0.1
K	0.2	0.02	0.33
Nb	0.03	0.3	1.3
La	0.2	0.015	0.3
Ce	0.35	0.044	0.899
Sr	0.015	0.08	0.2
Nd	0.53	0.166	2.89
Zr	1.2	0.162	1.4
Sm	2.66	0.457	3.99
Ti	1.2	0.4	7
Tb	11.9	0.776	6
Y	35	1.5	2.5
Yb	39.9	0.64	4.89

1) a high-Ti amphibole in the restite, as reported by Rapp (1994) or 2) a minor Ti-bearing restite phase such as ilmenite or rutile as observed in experimental residues at 16 kb and 22 kb/32 kb respectively (Rapp et al. (1991). High-Ti amphibole, ilmenite and rutile cannot bee included in the modelling because of missing partition coefficients. If one of these minerals occurs in the restite, it will besides offering a reduction of Ti in the melt also have reduced the Nb content, which is somewhat high in the calculated melts. [The misfit of Nb and Zr can be eliminated by using a higher known hornblende partition coefficient, but this is not the case with respect to Ti].

The reasons for the enrichment in the mobile elements Rb, Ba and K (and Th) are difficult to judge because it may result from: 1) an amphibolitic source enriched in these elements (by metasomatic alteration ?), 2) incorporation of a minor amount of melted sediments, 3) contamination of the magma by reactions with fluids during the rise through mantle wedge or crust or 4) metasomatic enrichment of the trondhjemites in connection with overprinted metamorphim. The latter possibility appears less likely due to the rather uniform and ordinary high–Al trondhjemitic composition with respect to the mobile elements.

The modelled restite composition with absence of plagioclase, a low hornblende content and high contents of garnet and clinopyroxene indicates together

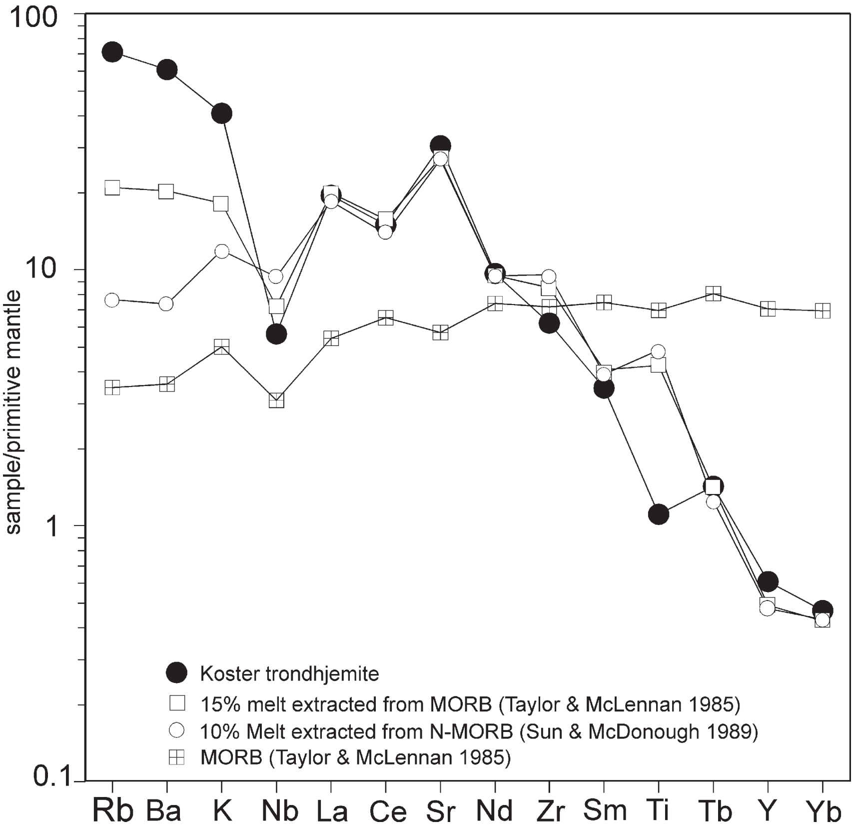

Fig. 8. Primitive mantle normalised patterns of calculated melts extracted from an altered MORB (Taylor & McLennan 1985) and an N-MORB (Sun & McDonough 1989). Also shown is the average Koster trondhjemite and the Taylor & McLennan MORB.

with the amount of melt, that the trondhjemitic melt was extracted from amphibolitic source within a P-T area between a plag-out and a hbl-out boundary, possibly like the area established by Sen & Dunn (1994) (Fig. 6). Nevertheless, the experimental results delimit melting under high (950–1050°C) and low (800° C) temperature conditions to the most appropriate pressures of 13–15 kb and 18–25 kb, respectively. The required minimum pressure corresponding to a depth of ≥ 45 km can only be obtained in subducted oceanic lithosphere or in the roots of exceptionally thick continental or arc crusts; typically these crustal thicknesses are ~30 km and ~20 km respectively.

The preferred interpretation of adakitic arc magmas as slab melts requires subduction of young (warm) oceanic crust. Such conditions are generally not present because the subducted oceanic crust is too cold (old) (Peacock et al. 1994). Defant & Drummond (1990) report an age ≤ 25 Ma , while the numerical modelling of Peacock et al. (1994) indicates that melting only occurs in < 2–5 Ma crust (subduction rate 3cm/yr) if the oceanic lithosphere is incapable of incorporating high rates of shear heating which require shear stresses $\sigma_s \geq 1$ kb at a subduction rate of 3 cm/yr or $\sigma_s > 0.7$ kb at very fast subduction (10 cm/yr) . The required stresses by fast subduction are within the upper limits (0.3–1 kb) calculated by Molnar & England (1990) with respect to Pacific subduction zones where oceanic lithosphere is subducted at rates of 8–11 cm/yr. If the thermal modelling is correct, high shear stresses are needed to explain the adakites from Adak Island where the slab melting occurred in a 40–50 Ma old oceanic crust (Yogodzinsky et al. 1995). Based on the numerical modelling, it appears that very young subduction can induce dehydration melting in an older oceanic crust, but only over a short period of a few million years as discussed by Martin (1999).

Adakitic trondhjemites and the tectonic scenarios

The Gothian complex during the short period (1.59–1.58 Ga) between the early and main Gothian orogenic phases was intruded by large volumes of ordinary calcalkaline magmas. This magmatism in the Koster archipelago is somewhat younger that the post early Gothian trondhjemites which according to the petrogenetic modelling were extracted at a depth of ≥ 45 km from subducted oceanic crust (model A) or, alternatively, from basaltic material in a crust which by tectonic/magmatic thickening had been brought to the appropriate level (model B). The implications of these possibilities are discussed below in relation to the presented, though little known 1.62–1.56 Ga tectonic scenario. This suggests:

(1) Development (in the Median segment) of a 1.614 Ga continental margin arc due to eastwards subduction of oceanic lithosphere beneath the edge of Palaeoproterozoic Baltica which already included an accreted 1.66 Ga island arc (Brewer et al. 1998).

(2) Deposition of the max.1.6 Ga old SLM formation within an outboard island arc system (alternatively as back-arc deposits) located west of the existing Baltic margin (Åhäll & Daly 1990, Åhäll et al 1998, Brewer et al. 1998). Since this arc magmatism must have started well before deposition of SLM, the eastwards subduction beneath the outboard arc may have been ongoing at the same time as that beneath the edge of Proto-Baltica.

(3) Accretion of the SLM-arc system onto the Baltic margin prior to 1.587 Ga by eastwards subduction (Åhäll et al. 1998). The accretion caused the early Gothian orogenic deformation and amphibolite facies migmatisation (Åhäll et al. 1998).

(4) Subduction of oceanic lithosphere beneath the amalgamated Median segment/Østfold-Marstrand belt resulted in formation of the ca. 1.59 Ga N–S belt of calcalkaline intrusions in the Median segment and calcalkaline plutons such as the 1.587 Ga Rönäng tonalite in the Østfold-Marstrand belt (Åhäll et al. 1998).

(5) Onset of the main Gothian orogeny (1.58 Ga) possibly resulting from collision with a continental mass in the west (Hageskov 1997, Åhäll & Gower 1997). Part of this, in a Sveconorwegian sinistrally displaced position, may be present within SW Norway.

Model A: In this preferred model the trondhjemites are explained in accordance with the slab melt origin for adakites. The model supports the subduction related origin of the ordinary 1.59–1.58 Ga calcalkaline magmatism in the Østfold-Marstrand belt (4), but demands the existence of an ocean ridge west of the early Gothian Østfold-Marstand belt and, according to Peacock et al. (1994), demands partial melting of a young (<5 Ma) or somewhat older shear heated subducted oceanic crust. Adakitic melt extraction from newly subducted old oceanic crust appears unrealistic because subduction beneath the Østfold-Marstand belt (2, 3 and 4) had apparantly been ongoing at least 20 Ma before intrusion of the trondhjemites.

The slab model predicts that 1) the adakitic magmatism on Koster can be expected to be contemporaneous with ordinary and more easterly located calcalkaline intrusives, since the site of adakitic magmatism is closer to the trench than the main calcalkaline arc and 2) that the ordinary calcalkaline magmatism in the western part of the belt, such as the Koster archipelago, may be slightly younger than that in the east due to westwards retreat of the trench.

The suggested Gothian collision (5) places the ocean ridge in a position between Baltica and the western continent to avoid subduction of an old and too cold oceanic crust. This position demands, with respect to Gothian docking, ongoing subduction beneath the western continent in which pre-docking (1.58 Ga) calcalkaline magmatism is predicted.

Model B: The proposed accretion onto the western margin of proto-Baltica (1, 2 and 3) may have conceivably produced a sufficient crustal thickness in the Østfold-Marstrand belt and may even have been underplated by basaltic magma at the time of trondhjemite production (4). Thus it cannot be excluded that the trondhjemitic melt was extracted from basaltic material in the lower crust of the Østfold-Marstrand belt. However, if the slightly high MgO content and the typical adakitic Mg# of the trondhjemites resulted from interaction with the mantle wedge, the melt must have been produced from a deeper source (subducted oceanic crust) as argued by Martin 1999.

Since the basaltic material in the thick crust model was capable of melting, more silicic crustal material would also melt and in larger volumes. Consequently, complex magmatic activity must have acted in the region during the 1.59–1.58 Ga period and included both subduction-related calcalkaline magmas (4) and anatectic melt extracted from various crustal sources.

The Østfold-Marstrand belt includes granites which predate the migmatisation and deformation related to the main Gothian Orogeny. When investigated and precisely dated, they may or may not support a 'thick crust model' which is presently unconstrained by any evidence. The outboard arc (2), the depositional setting and the accretion of SLM (3) which potentially may support a thick crust are certainly debatable.

Conclusions

- Adakitic high-Al trondhjemites on Koster were intruded into early Gothian (1.6–1.59 Ga) migmatised and deformed SLM rocks prior to the emplacement of ordinary calcalkaline plutonites and the succeeding tectonothermal event resulting from the main Gothian orogeny.
- The trondhjemites have a typical adakitic (slab melt) signature. Batch melting modelling explains the composition as a 10–20% partial melt extracted from an amphibolitised MORB-like source. During melt extraction, a hornblende-bearing eclogite was left in the region of melting, which according to experimental data took place within a P/T frame of 18–25 kb/800°C to 13–15 kb/950–1050°C. These P-T conditions are attainable in a subducting warm (young or shear heated) oceanic crust or in basaltic material located in a thick crust at a depth of ≥ 45 km.
- Accordingly, the adakitic trondhjemites monitor subduction of warm oceanic crust or less likely (with or without subduction) the presence of a very thick crust in the Østfold-Marstrand belt at the time of melt extraction. The slab melt origin agrees with the east-dipping subduction thought to be responsible for the ordinary 1.59–1.58 Ga calcalkaline magmatism in the Gothian Complex (e.g. Brewer 1998). The existence of sufficiently thick Østfold-Marstrand crust is not constrained by available evidence.

Acknowledgement

The authors wish to thank J. Baily for critical reading and improvements of the English manuscript, and C. Tegner for valuable comments.

Dansk sammendrag

Adakiter er smelter med en specifik geokemisk signatur (adakitic), som anses dannet ved anatexis af subducerende oceanbundskorpe omdannet til amfibolit eller eklogit. Adakiter kendes fra en række recente oceaniske og kontinentale magmatiske buer i Stillehavsområdet, hvor de er repræsenteret ved en andesit-dacit-trondhjemit (rhyolit) suite, som volumenmæssig er langt underordnet i forhold til buernes øvrige kalkalkaline magmabjergarter. En specifik geokemisk signatur [høje Sr/Y, La/Yb og lave Y, HREE (heavy rare earth elements) indhold] adskiller adakiterne fra buernes 'ordinære' subductionsrelaterede kalkalkaline suite, som især repræsenterer smelter ekstraheret fra den underliggende og modificerede kappekile.

Artiklen behandler de første kendte adakitiske intrusiver i det gothiske Østfold-Marstrand bælte, SØ Norge–V Sverige. De optræder som høj-Al trondhjemiter i Koster Skærgården, V Sverige, hvor de repræsenterer de ældste granitoider i Stora Le-Marstrand Formationen; Østfold-Marstrand bæltets ældste kendte enhed. I følge dateringer fra Vestsverige og den etablerede hændelsesstratigrafi intruderede trondhjemiterne under en kort periode (1.59–1.58 Ga), som adskiller en tidlig fase (1.6–1.59 Ga) af den Gotiske orogenese fra hovedfasen (1.58–1.56 Ga). Perioden 1.59–1.58 Ga er ellers præget af en voluminøs, men ordinær kalkalkaline plutonisk magmatisme, som på Koster er yngre end trondhjemiterne.

Den adakitiske signatur formoder, at trondhjemit magmaet er ekstraheret fra en MORB (Mid Ocean Ridge Basalt)-lignende kilde, og at en hornblende-eklogit restite blev efterladt i opsmeltningsregionen, der ud fra restitesammensætningen estimeres til P/T betingelserne 18–25 kb/800°C – 13–15 Kb/950–1050° C. Disse betingelser er kun opnåelige ved subduction af varm (ung eller shear-heated) oceanisk skorpe, eller alternativt ved smeltning af metabasaltisk materiale beliggende i et særdeles dybt skorpe niveau. Sidstnævnte mindre sandsynlige mulighed kræver, at der på opsmeltningstidspunktet var etableret en mindst 45 km tyk skorpe i Østfold-Marstrand bæltet.

References

Åhäll, K.I. & Daly J.S. 1989: Age, tectonic setting and provenance of Östfold-Marstrand belt supracrustals: Westwards crustal growth of the Baltic Shield at 1760 Ma. Precambrian Research 45, 45–61.

Åhäll, K.I., Persson, P-O. & Skjöld, T. 1995: Westwards crustal growth of the Baltic Shield: implications from the 1.6 Ga Åmål-Horred belt, SW Sweden. Precambrian Research 70, 235–251.

Åhäll, K.I. & Gower, C.F. 1997: The Gothian and Labradorian orogens: variations in accretionary tectonism along a late Paleoproterozoic Laurentia-Baltica margin. Geologiska Föreningens i Stockholm Förhandlingar 119, 181–191**.**

Åhäll, K.I., Conelly, J. N., Christoffel, C. & Larson, S. Å. 1997: Evidence for a penetrative regional Gothian gneiss-forming event in the granulite area of the southern Sveconorwegian orogen, SW Sweden. Geologiska Föreningens i Stockholm Förhandlingar 119, 192.

Åhäll, K.I., Cornell, D.H. & Armstrong, R. 1998: Ion probe zircon dating of metasedimentary units across the Skagerrak: new constraints for early Mesoproterozoic growth of the Baltic Shield. Precambrian Research 87, 117–134**.**

Andersson, U. B. 1991: Granitoid episodes and mafic-felsic magma interactions in the Svecofennian of the Fennoscandian shield, with main emphasis on the ca. 1.8 Ga plutonites. Precambrian Research 51, 127–149.

Atherton, M. P. & Petford, N. 1993: Generation of sodium-rich magmas from newly underplated basaltic crust. Nature 362, 144–146**.**

Barker, F. 1979. Trondhjemites: definition, environment, and hypothesis of origin. In Barker (ed.) Trondhjemites, Dacites and Related Rocks. Elsevier, Amsterdam, 1–12.

Barker, F. & Millard, H. T. 1979. Geochemistry of the type trondhjemite and three associated rocks, Norway. In Barker (ed.) Trondhjemites, Dacites and Related rocks. Elsevier, Amsterdam, 517–529.

Barker, F., Arth, J.G., Peterman, Z. E. & Friedman, I. 1976. The 1.7- to 1.8-b.y. old trondhjemites of southwestern Colorado and northern New Mexico. Geological Society of America Bulletin 87, 189–198.

Berthelsen, A. 1980: Towards a palinspastic analysis of the Baltic Shield. International Geological Congress, Colloquium C6, Paris 1980, 5–21.

Brewer, T.S., Daly J.S. & Åhäll, K.I. 1998: Contrasting magmatic arcs in the Palaeoproterozoic of the southwestern Baltic Shield. Precambrian Research 92, 297–315**.**

Condie, K.C. & Hunter, D.R. 1976. Trace element geochemistry of Archean granitic rocks from the Barbaton region, South Africa. Earth and Planetary Science Letters 29, 389–400.

Conelly, J. N. & Åhäll, K. I., 1996: The Mesoproterozoic cratonization of Baltica; New constraints from SW Sweden. In Brewer, T. S. (ed.) Precambrian Crustal Evolution in the North Atlantic Region. Geological Society Special Publication 112, 297–273.

Defant, M.J. & Drummond, M.S. 1990: Derivation of some modern arc magmas by melting of young subducted lithosphere. Nature, 347, 662–665.

Defant, M.J. & Drummond, M.S. 1993: Mount St. Helens: potential example of partial melting of subducted lithosphere in a volcanic arc. Geology 21: 547–550.

Defant, M.J., Clark, L.F., Stewart, R.H., Drummond, M.S., de Boer, J.Z., Maury, R.C., Bellon, H., Jackson, T.E. & Restrepo, J.F. 1991a: Andesite and dacite genesis via contrasting processes: the geology and geochemistry of El Valle Volcano, Panama. Contributions to Mineralogy and Petrology 106: 309–324.

Defant**,** M.J., Richerson, P.M., De Boer, J.Z., Stewart, R.H, Maury, R.C., Bellon, H., Drummond, M.S., Feigenson, M.D. & Jackson, T.E., 1991b: Dacite genesis via both slab melting and differentiation: petrogenesis of La Yeguada Volcanic Complex, Panama. Journal of Petrology 32, 1101–1142.

Drummond, M.S. & Defant, M. J.1990: A model for trondhjemite-tonalite-dacite genesis and crustal growth via slab melting: Archean to modern comparisons. Journal of Geophysical Research 95, 21503–21521**.**

Glickson, A.Y. 1976. Trace element geochemistry and origin of early Precambrian acid igneous series, Barbaton Mountain Land, Transvaal**.** Geochimica et Cosmochimica Acta 40, 1261–1280.

Green, T.H. & Ringwood, A.E., 1968: Genesis of calcalkaline igneous rock suites. Contributions to Mineralogy and Petrology 18, 105–162.

Green, T.H., Sie, S.H., Ryan, C.G. & Cousens, D.R. 1989: Proton microprobe-determined partitioning of Nb, Ta, Zr, Sr and Y between garnet, clinopyroxene and basaltic magma at high pressure and temperature. Chemical Geology 74, 201–216.

Hageskov, B. 1980: The Sveconorwegian structures of the Norwegian part of the Kongsberg-Bamble-Østfold segment. Geologiska Föreningens i Stockholm Förhandlingar 102, 150-155.

Hageskov, B. 1985: Constrictional deformation of the Koster dyke swarm in a ductile sinistral shear zone, Koster Islands, SW Sweden. Bulletin of the Geological Society of Denmark 34, 151–197**.**

Hageskov, B. 1997: Geochemistry and tectonic significance of late Gothian mafic dykes in the Østfold-Marstrand belt of S.E. Norway and W. Sweden. Precambrian Research 82, 287–309**.**

Henkel, H. & Eriksson, L. 1987: Regional aeromagnetic and gravity studies in Scandinavia. Precambrian Research 35, 168–180.

Johansson, Å., Meier, M., Oberli, F. & Wikman, H. 1993: The early evolution of the southwest Swedish gneiss province: geochronological and isotopic evidence from southernmost Sweden. Precambrian Research 64, 361–388**.**

Kay, R.W. 1978: Aleutian magnesian andesites; melt from subducted Pacific oceanic crust. Journal of Volcanology and Geothermal Research 4, 117–132.

Kay, S.M., Ramos, V.A. & Marquez, M., 1993: Evidence in Cerro Pampa volcanic rocks for slab-melting prior to ridge-trench collision in Southern South America. Journal of Geology 1010, 703–714.

Kepezhinskas, P.K. 1989: Origin of hornblende andesites of northern Kamchatka. International Geology Review 31, 246–252

Larsson, S.Å., Berglund, J., Stigh, J. & Tullborg, E.-L. 1990: The Protogine Zone, southwest Sweden: a new model - an old issue. In Gower, C.F., Rivers, T. & Ryan, B. (eds) Mid-Proterozoic Laurentia-Baltica: Geological Association of Canada, Special Paper 38, 317–333.

Larsson, S.Å. & Berglund, J. 1992: A chronological subdivision of the Transscandinavian Igneous Belt -three magmatic episodes. Geologiska Föreningens i Stockholm Förhandlingar 114, 459–461.

Lundqvist, I. & Skjöld, T. 1992: Preliminary age-determination of the Åmål Formation SW Sweden. Geologiska Föreningens i Stockholm Förhandlingar 114, 459–461.

Martin, H. 1999. Adakitic magmas: modern analogues of Archaean granitoids. Lithos 46, 411–429.

Masuda, A., Nakamura, N. and Tanaka, T. 1973: Fine structures of mutually normalised rare-earth patterns of chondrites. Geochimica et Cosmochimica Acta 37, 239–249.

Molnar, P., & England, P. 1990: Temperatures, heat flux, and frictional stress near major thrust faults. Journal of Geophysical Research 95, 4833–4856

Morris, P. 1995: Slab melting as an explanation of Quaternary volcanism and aseismicity in southwest Japan. Geology 23, 395–398.

Møller, C. 1998: Decompressed eclogites in the Sveconorwegian (-Grenvillian) orogen of SW Sweden: petrology and tectonic implications. Journal of metamorphic Geology 16, 641–656.

Møller, C. & Søderlund, U. 1997: Sveconorwegian high grade regional reworking in the eastern segment, SW Sweden: cause, character and consequences. Geologiska Föreningens i Stockholm Förhandlingar 119, 253–254.

Norrish, K. & Chappell, B.W. 1977: X-ray fluorescence spectrometry. In Zussman, J. (ed.) Physical Methods in Determinative Mineralogy, 2nd ed. Academic Press, London, 201–272.

Park, R.G., Åhäll, K.I. and Boland, M.P. 1991: The Sveconorwegian shear-zone network of SW Sweden in relation to Mid-Proterozoic plate movements. Precambrian Research 49, 245–260.

Patchett, P.J., Todt, W. & Gorbatschev, R. 1987: Origin of continental crust 1.9–1.7 Ga age: Nd isotopes in the Svecofennian orogenic terraines of Sweden. Precambrian Research 35, 145–160.

Peacock, S.M., Rushmer, T. & Thompson, A.B. 1994: Partial melting of subducting oceanic crust. Earth and Planetary Science Letters 121, 227–244.

Rapp, R.P. 1994. The amphibole-out phase boundary in melted metabasalt and its control over melt fraction and composition. Eos 75, 16, supplement, p. 359.

Rapp, R.P. Watson, E.B. & Miller. C.F. 1991. Partial melting of amphibolite/eclogite and the origin of Archean trondhjemites and tonalites. Precambrian Research 51, 1–25.

Rogers, G., Saunders, A.D., Terrell, D.J., Verma, S.P. & Marriner, G.F. 1985. Geochemistry of Holocene volcanic rocks associated with ridge subduction in Baja, California, Mexico. Nature 315, 389–392.

Rollinson, H. R. 1993. Using geochemical data: evaluation, presentation, interpretation. Longmans, Harlow.

Rushmer, T. 1993. Experimental high-pressure granulites: some applications to natural mafic xenolith suites and Archean terranes. Geology 21, 411–414.

Sajona, F.G., Maury, R.C., Bellon, H., Cotton, J., Defant, M.J. & Pubellier, M. 1993: Initiation of subduction and the generation of slab melts in western and eastern Mindanao, Philippines. Geology 21, 1007–1010.

Sajona, F. G., Maury, R. C., Bellon, H., Cotton, J. & Defant, M. J. 1996: High Field Strength Element enrichment of Plocene-Pleistocene island arc basalts, Zamboanga Peninsula, western Mindanao (Philippines). Journal of Petrology 37, 693–726.

Sen, C. & Dun, T. 1994: Dehydrating melting of a basaltic composition amphibolite at 1.5 and 1.2 GPa: Implications for the origin of adakites. Contributions to Mineralogy and Petrology 117, 394–409.

Skjernaa, L. & Pedersen, S. 1982: The effects of penetrative Sveconorwegian deformation on Rb-Sr isotope systems in the Römskog-Aurskog-Höland area, SE Norway. Precambrian Research 17, 215–243.

Stern, C.R. & Kilian, R. 1996: Role of the subducted slab, mantle wedge and continental crust in the generation of adakites from Andean Austal Volcanic Zone. Contributions to Mineralogy and Petrology 123, 263–281.

Sun, S.-s. & McDonough, W.F. 1989: Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In Saunders A. D. & Norry, M.J. (eds) Magmatism in the Ocean Basins, Geological Society Special Publication 42, 313–3 45.

Sørensen, I. 1975: X-ray fluorescence spectrometry at GGU. Grønlands Geologiske Undersøgelse, Rapport 75, 16–18.

Sørensen, I. 1976: Progress in calibration of an X-ray spectrometer. Grønlands Geologiske Undersøgelse, Rapport 80, 149–1159.

Taylor, S.R. & McLennan, S.M. 1985: The Continental Crust: its Composition and Evolution. Blackwell, Oxford.

Wahlgren, C-H., Cruden, A.R. & Stephens, M.B. 1994: Kinematics of a major fan-like structure in the eastern part of the Sveconorwegian orogen, Baltic Shield, south-central Sweden. Precambrian Research 70, 67–91.

Wikström, A. 1996: U-Pb zircon dating of a coarse porphyritic quartz monzonite and an even-grained, grey tonalitic gneiss from Tiveden area, south-central Sweden. Sveriges Geologiska Undersökning C 828, 41–47.

Wyllie, P.J. & Wolf, M.B. 1993: Amphibolite dehydration-melting: sorting out the solidus. In Prichard, H.M., Alabaster, T., Harris, N.B.W. & Neary, C.R. (eds) Magmatic Processes and Plate Tectonics, Geological Society Special Publication 76, 405–416.

Yogodzinski, G.M., Kay, R.W., Volynets, O.N. & Kay, S.M. 1995: Magnesian andesites in the western Aleutian Komandorsky region: Implications for slab melting and processes in the mantle wedge. Geological Society of America Bulletin 105, 505–519.