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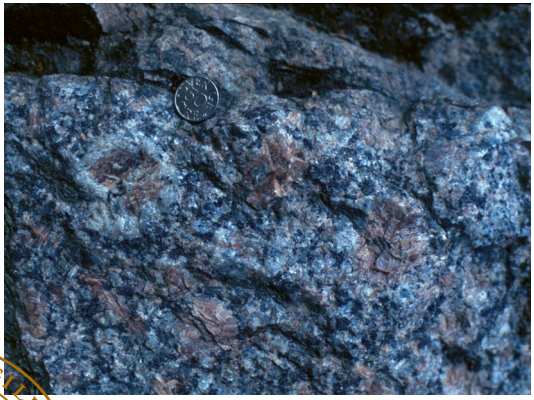

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Title and subtitle Tectonic implications of ca. 1.45 Ga granitoid magmatism at the southwestern margin of the East European Craton

Abstract

Between ca 1.53 and 1.40 Ga, the southwestern margin of the East European Craton was subjected to extensive magmatism and deformation. While various suites of anorthositic, mangeritic and charnockitic-granitic rocks were emplaced between ca. 1.53 and 1.50 Ga, a major event of A-type granitic magmatism took place around 1.45 Ga. During that event, numerous voluminous plutons were intruded in a wide region around the southern Baltic Sea ("the SBS region").

Petrologically, the various SBS granitoids are rather similar to each other. Like many A-type granites worldwide, they are enriched in silica, high field strength elements (HFSE) and rare earth elements (REE), and have high Fe/Mg and K/Na ratios. The most common ferromagnesian silicate minerals are biotite and amphibole, clinopyroxene occurring occasionally.

Another feature characteristic of the SBS plutons is their formation by the emplacement of multiple pulses of melt. Such pulses were occasionally responsible for separate suites of rocks and appear to have originated from slightly different sources. In general, however, the melt sources of the SBS granitoids were relatively juvenile and rich in aluminum and potassium as well as in HFSE:s and REE:s. The isotopic characteristics of the rocks may also suggest some interaction between crustal and mantle materials.

During the ca.1.45-Ga event, the Blekinge-Bornholm region experienced notable regional compression and ENE-WSW shortening. That compression caused syn- and post-magmatic deformation of the involved granitoids as well as deformation and metamorphism of the host rocks. Due to its activity, also EW-striking shear zones were either developed or reactivated and apparently controlled the emplacement of the SBS granitoids. As different from the traditional concept of a liaison between A-type granitic magmatism and anorogenic extension of the crust, the present study thus strongly evidences that the SBS granitoids were intruded during compressional tectonic processes. Causally, they are interpreted to have been related to the Mesoproterozoic Danopolonian orogeny which may have led to the collision of the East European Craton with another proto-continent, possibly Proto-Amazonia (Bogdanova, 2001).

Key words: Mesoproterozoic, granite, syntectonic, geochemistry, petrology, structural geology, anisotropy of magnetic susceptibility, Danopolonian orogeny, southern Sweden

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The picture on the front cover is a typical Karlshamn granite with large microcline phenocrysts mantled by plagioclase (rapakivi texture). Note that some grains contain core of plagioclase. The photograph was taken a few kilometres northeast from Kallinge, Blekinge. The coin is 22 mm in diameter.

Contents

“There is no kingdom where granites are not present, or where they may be not suspected”

Jean-Etienne Guettard (1715-1786), French geologist, initiator in Europe of geological mapping*

* Cited from Bouchez, J.L., Hutton, D.H.W. and Stephens, W.E. (Editors), 1997. Granite: from segregation of melt to emplacement fabrics. Kluwer Academic Publishers, Dordrecht, 358 pp.

Abstract

Between ca 1.53 and 1.40 Ga, the southwestern margin of the East European Craton was subjected to extensive magmatism and deformation. While various suites of anorthositic, mangeritic and charnockitic-granitic rocks were emplaced between ca. 1.53 and 1.50 Ga, a major event of A-type granitic magmatism took place around 1.45 Ga. During that event, numerous voluminous plutons were intruded in a wide region around the southern Baltic Sea (”the SBS region”).

Petrologically, the various SBS granitoids are rather similar to each other. Like many A-type granites worldwide, they are enriched in silica, high field strength elements (HFSE) and rare earth elements (REE), and have high Fe/Mg and K/Na ratios. The most common ferromagnesian silicate minerals are biotite and amphibole, clinopyroxene occurring occasionally.

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During the ca.1.45-Ga event, the Blekinge-Bornholm region experienced notable regional compression and ENE-WSW shortening. That compression caused syn- and post-magmatic deformation of the involved granitoids as well as deformation and metamorphism of the host rocks. Due to its activity, also EW-striking shear zones were either developed or reactivated and apparently controlled the emplacement of the SBS granitoids. As different from the traditional concept of a liaison between A-type granitic magmatism and anorogenic extension of the crust, the present study thus strongly evidences that the SBS granitoids were intruded during compressional tectonic processes. Causally, they are interpreted to have been related to the Mesoproterozoic Danopolonian orogeny which may have led to the collision of the East European Craton with another proto-continent, possibly Proto-Amazonia (Bogdanova, 2001).

Populärvetenskaplig sammanfattning

Planeten Jordens yttersta lager består av fast berg och kallas jordskorpan. Det finns två olika typer.av jordskorpa. Den ena är ocean, den andra kontinental. Den oceana jordskorpan är relativt tunn och uppbyggs av tunga, basaltiska bergarter. Den nybildas ständigt vid de s.k. mittoceana ryggarna ur smältor som där uppstiger ur Jordens mantel. Efter detta förstörs den dock åter i s.k. subduktionszoner där den dras ned i manteln. Den oceana jordskorpan blir därför aldrig särskilt gammal.

Den kontinentala jordskorpan däremot består i huvudsak av tämligen lätta granitiska bergarter. Den kan bli blir bortåt 80 km tjock. Till skillnad från den oceana jordskorpan, dras den lätta kontinentala jordskorpa endast med svårighet ned i jordmanteln inom subduktionszonerna. Den kvarligger därför gärna vid jordytan och kan nå åldrar av flera miljarder år.

När jordskorpan rör sig från de mittoceana ryggarna ut mot subduktionszonerna är den uppdelad i fasta s.k. plattor . Därav benämningen plattektonik. Plattorn består oftast av ocean såväl som kontinental jordskorpa. Under sina rörelser kan plattorna rotera, skava mot varandra, brytas sönder eller tryckas ihop. Själva subduktionen i subduktionszonerna är en process där den ena plattan dyker ned under den andra. Antalet plattor har varierat under tidernas lopp, men oftast verkar det ha funnits bortåt tio större plattor och dessutom ett antal småplattor och plattskärvor.

Till skillnad från den oceana jordskorpan, nybildas den kontinentala inte vid mittoceana ryggar. Nytillskott uppkommer däremot i subduktionszoner där en del av berggrunden i den nedåtgående plattan ger upphov till smältor (”magmor”) som stiger uppåt mot jordytan. På så sätt bildas vulkaniska öbågar och andra bälten av magmatiska bergarter. Med tiden sammanfogas dessa till större kontinentala landmassor och t.o.m bergskedjor. Sådana processer kallas ”orogena”.

En annan typ av orogenes uppkommer när två block av kontinental jordskorpa ”krockar” med varandra efter det att all mellan dem befintlig ocean jordskorpa dragits ned i en subduktionszon. Orogenes av denna typ kallas kollisionsorogenes.

Granitiska smältor kan dock även bildas utan samband med orogena processer, dvs på ett ”anorogent” sätt. Dels kan jordskorpan smälta när den utsätts för tension, förtunning samt åtföljande trycksänkning och dels kan ur jordmanteln uppträngande magmor smälta den omgivande berggrunden.

Föreliggande avhandling rör granitiska bergarter, dvs. de bergarter som uppbygger det mesta av den kontinentala jordskorpan. Graniter kan bildas antingen genom kompessionalla, vanligen orogena, eller tensionella, i huvudsak anorogena processer. De har mycket att berätta såväl om jordskorpans utveckling som om dess beskaffenhet och sammansättning på djupet.

Två grupper av problem behandlades under arbetets gång. Den ena problemgruppen rörde geokemiska, den andra strukturella och tektoniska spörsmål. Dessutom utreddes frågan om den i området kring södra Östersjön vida utbredda gruppen av ca. 1,45 miljarder år gamla graniter av så kallad A-typ har ett orogent eller anorogent ursprung. Denna fråga står i samband med den mer generella frågan om A-gruppens betydelse som indikator av granitsmältornas tektoniska bildningsmiljöer.

Konkret omfattade arbetet tektoniska och geokemiska detaljundersökningar av de ungefär 1450 miljoner år gamla A-typs graniterna i Karlshamns- och Stenshuvudsplutonerna i Sverige och dessutom en kemisk-petrologisk undersökning av ett större granitmassiv av samma ålder och karaktär under det fanerozoiska sedimenttäcket i Litauen. Flera tiotal bergartsprov analyserades med avseende på sina kemiska och isotopgeokemiska egenskaper. För Karlshamnmassivets del möjliggjordes därmed en bestämning av hela denna intrusions kemiska uppbyggnad. Liknande information kunde tas fram även för de övriga granitmassiven. Resultaten visar att samtliga dessa granitkroppar har en flerfasig bildningshistoria med en föjld av smärre, delvis kemiskt olika delintrusioner. De tidigare beräknade intrusionsåldrarna kunde preciseras.

De strukturella undersökningarna, däribland en detaljerad utredning av den magnetiska susceptibilitetens anisotropi, resulterade i en tektonisk helhetsbild som beskriver Karlshamnmassivets och dess sidobergs utveckling från magmatiska flyt- til först duktila och därefter spröda deformationsstrukturer. Dessa gör det även klart att Karlshamnsplutonen och de andra undersökta A-graniterna måste ha bildats under en tidsperiod som kännetecknades av närmast öst-västlig kompression och förkortning av jordskorpan. Denna tektoniska process kan knappast ha varit annat än orogen. Den hörde sannolikt samman med den danopoloniska kollisionsorogenesen (Bogdanova 2001).

Av dessa resultat kan man dra den allmänna slutsatsen att graniter av kemisk A-typ inte nödvändigtvis behöver vara anorogena.

1. Introduction

Granitic rocks occur in all types of tectonic environments and are by far the most important component of continental crust. The largest volumes of granites are produced in orogenic subductional and collisional settings, only a small proportion having origins not related to orogeny at all. To the latter, the term "anorogenic" is applied. Anorogenic granites mostly occur in major zones of extension, commonly related to rifting of the crust with or without participation of mantle plumes.

The rocks of major granitic bodies carry abundant information in regard both to their modes of emplacement and the sources of their melts. Important controls of their composition are the tectonic settings of magma generation and the processes of melt evolution during its ascent as well as within magma chambers. Interaction with wallrocks is common and syn-plutonic dyking may exercise an additional influence. There is also the possibility that several successive magma pulses mix with each other. Therefore, almost any sample of granite is a great source of information in regard to the processes of magma evolution occurring at depth.

Apart from their compositional features, granitic plutons also contain information on the fields of stress that prevailed during and after their emplacement. Such information is recorded by a range of structural elements varying in scale from millimetres to tens of kilometres. The study of these elements also allows conclusions in regard to the geodynamics of crustal plates during the times when the granitic plutons were emplaced.

For all these reasons, the study of granitic intrusions at various scales and regarding various aspects and properties is a task very important to the understanding of the development of continental crust and the related plate-tectonics processes.

The target of the present study is the granitoid plutons in the area around the southern Baltic Sea (Figs. 1 and 2) that were intruded into Palaeoproterozoic continental crust ca. 1.45 Ga ago. Previously, these granites were regarded as being A-type anorogenic rocks (Åberg, 1988), this conclusion having been based essentially on a combination of geochemistry with the assumption common at that time that A-type granites could not be other than anorogenic in origin (cf. below, text section 1.1).

The great extent of the South-Baltic granitic magmatism and its apparent association with large shear zones in the western part of the East European Craton (EEC) made the current work particularly interesting in the context of the EUROBRIDGE - EUROPROBE traverse and related projects (Bogdanova et al., 1996; Bogdanova et al., 2001). The aim of this Ph.D. task was therefore defined as "constructing a consistent geodynamic model of the anorogenic magmatism in the studied region and establishing its relationship with active shear zones" (NFR project G 650-1998-1513, 2000).

Three key intrusions, viz. the Karlshamn in Blekinge, the Stenshuvud in eastern Scania, and the Zemaiciu Naumiestis in western Lithuania were studied in particular detail to create a reference model for the 1.45-Ga granitoid igneous event (Fig. 2). Within that general context, research was conducted mainly in two fields of thematic study. One of these was essentially petrological, while the other concerned the tectonical evolution of the granitic plutons.

In the petrological field of study, the three key granite intrusions were surveyed petrographically, mineralogically and chemically. Their main- and trace- element compositions were assessed, the isotope and mineral chemistries were investigated, and the necessary geochronological data were obtained. Here, the most important objective was to ascertain the "chemical structure" and build-up of the plutons, and use that information to infer the histories of melt evolution and the nature of the melt sources. Comparisons with other A-type granitoid bodies in the South-Baltic region were also carried out. The results are reported in Papers I through III. In this field of study, the present author was responsible for most of the chemical and petrological work, while the geochronology and related aspects were handled by the involved specialist co-authors.

In the tectonic field of study, detailed structural analyses and the anisotropy of the magnetic susceptibility were employed to assess the microtextures, foliations, lineations, shear zones, and cross-cutting dykes within the two key intrusions in Sweden and their country rocks. The aim was to reconstruct the histories of melt emplacement and of the syn- to post-emplacement structural evolutions. The tectonic aspects of the overall study are considered in Paper IV and partly also in Paper II.

1.1. Some remarks on terminology

Although the concept of A-type granites had been proposed by Loiselle and Wones in a GSA Abstract already in 1979, its first rigorous definition did not appear until three years later in a paper by Collins et al. (1982). That definition is strictly geochemical and not based on tectonic settings at all. Nevertheless, Collins et al. commented that most A-type granites were formed in ”tensional regimes”, however without insisting upon ”anorogenic” in that context.

By the definition of Collins et al. (1982), A-type granites contain interstitial mafic phases, which are most obvious and a diagnostic characteristic. The principal geochemical criteria are high contents of HFSE and Ga/Al-ratios higher than those in other types of granite. These authors also found that A-type granites are not always ”alkaline”, some of them even being peraluminous. Also, the anhydrous character of the A-type granites was said to be ”relative” rather than total. Subsequently, the definition by Collins et al. (1982) was expanded somewhat by Whalen (1987) and others.

In conclusion, it would appear that A-type granites must not necessarily be ”anorogenic, alkaline and anhydrous”, as it has been accepted traditionally (e.g. Anderson and Bender, 1989; Windley, 1993; Best and Christiansen, 2001). In the present thesis, therefore, the term ”A-type” is used only in a strictly chemical sense, while the designation ”anorogenic” is solely applied to rocks and geological events lacking any perceptible connection with orogenic processes.

2. Summary of the component papers

Paper I

Audrius Cecys, Åke Johansson, Svetlana Bogdanova, Andrius Rimsa, and Viktor Kovach. The Mesoproterozoic multiphase, A-type Karlshamn pluton, southern Sweden: geochemistry and NORDSIM zircon ages. *Lithos* (submitted).

Summary:

Paper I deals with the petrological characteristics and ion-probe (”NORDSIM”) isotopic ages of the ca. 1.45-Ga granitoids in the Karlshamn pluton. That pluton is one of the largest and best exposed bodies of A-type granitoids in south-easternmost Sweden and around the southern Baltic Sea. Its rocks are metaluminous and ferroan, with alkali-calcic, shoshonitic compositions.

The Karlshamn pluton was formed by multiple emplacements of melts that belonged to two different suites, here named the ”eastern” and the ”western” ones. The eastern suite comprises quartz monzodiorites, quartz monzonites and granites, while the western consists of adamellites to granites, the latter comprising even-grained, finely porphyritic, leucocratic and red aplitic leucocratic varieties. These two suites could only be distinguished from their chemistries, since petrographically the rocks

of both suites are quite similar. Many rocks contain large microcline phenocrysts, commonly with rapakivi and anti-rapakivi textures, and carry interstitial, mostly accessory ferromagnesian minerals. Amphibole and biotite often form intergrowths, commonly aggregated with accessory zircon, apatite and magnetite. The compositions of the minerals in the rocks with similar SiO_2 contents in the two suites are almost the same. The biotites contain nearly equal amounts of the annite and phlogopite end-members, while the amphiboles are dominantly ferro-edenites. However, the magnesium proportions in these two ferromagnesian minerals are higher in the eastern than in the western suite. Similarly, the plagioclases in the granitoids of the eastern suite usually have higher anorthite contents.

Geochemically, the rocks of the two suites differ in regard to both the major and trace elements, and define separate trends on Harker variation diagrams. While the variation trends for the elements specific of the ferromagnesian minerals (Ti, Mg, Fe, and Mn) are parallel in the two rock suites, those for Ca, K and Na, i.e. the feldspar elements, are intersecting. This suggests that the evolutions of the melts were somewhat different in the two cases and that these differences were mainly due to the dissimilar differentiation of the feldspars. The REE patterns indicate that in the cases of both suites, virtually no feldspar remained in the source rocks of the melts. These patterns also militate against significant feldspar fractionation during the evolution of the melts of the eastern suite, while such fractionation had been of some importance in the case of the melts of the western rocks.

In both suites, ε_{Nd} values of ca. $-2_{(t=1.45\ Ga)}$ and T_{DM} model ages of 1950 Ma indicate the involvement of older crustal materials. The chemical differences between the eastern and western suites imply that the two must have originated from somewhat different sources. The source of the western suite appears to have been more mafic than that of the eastern suite, and had substantially lower contents of Al.

According to the "total-Al-in-hornblende" geobarometer and the calculated zircon saturation temperatures, both suites of Karlshamn granitoids were crystallized at relatively high temperatures of ca. 860°C and moderate depths of ca. 12 km (0.4 GPa).

Ion-microprobe ("NORDSIM") zircon dating techniques were employed in this study to obtain the crystallisation ages of each suite of rocks. A monzonite from the eastern suite with concordant to nearly concordant U-Pb isotopic composition yielded a weighted-mean $^{207}Pb/^{206}Pb$ age of 1445±11 Ma with MSWD=1.2 and the error estimate at the 2σ level..

An adamellite from the western suite with rather complex zircons yielded somewhat more scattered age data, all of them lower, however, than those obtained from the monzonite of the eastern suite. Despite the complexity of the zircons, no signs of older, inherited, materials were found in this rock and no significant age differences could be detected between the core-like domains and the seeming overgrowths. The former yielded a weighted-average $^{207}Pb/^{206}Pb$ age of 1431±20 Ma with MSWD=1.5, while the rims gave 1424±19 Ma and MSWD=4.2.

The overall age value obtained from all the dated zircons of the western suite is 1426±11 Ma, with the error estimate at the 2σ level and a MSWD of 2.6. At the face value of these data, the Karlshamn pluton therefore took ca. 20 Ma to form.

Paper II

Cecys, A., Bogdanova, S., Janson, Ch., Bibikova, E. & Kornfält, K.-A., 2002. The Stenshuvud and Tåghusa granitoids: new representatives of Mesoproterozoic magmatism in southern Sweden. *GFF*, Vol. 124 (Pt. 3, September), pp. 149–162.

Summary:

In this study, the Stenshuvud pluton from the Stenshuvud National Park in eastern Scania, southern

Sweden, were investigated. The work included petrological and structural investigations as well as isotope dilution - thermal ionisation mass spectrometry (ID-TIMS) zircon age determinations. In the studied area, granitic melts were intruded into country-rock gneisses and migmatites of unknown age at c. 1450 Ma.

The Stenshuvud pluton consists of two rock suites. The first one, Stenshuvud was formed by the emplacement of quartz monzonites, tonalites, monzogranites, and late aplites at 1458±6 Ma. Typically, these rocks have glomeroporphyritic textures defined by monomineralic aggregations of feldspar or quartz and polymineralic clots of amphibole, biotite, and magnetite.

At 1442±9 Ma, granites of the Tåghusa suite were intruded along the contact between the Stenshuvud granitoids and the country-rock gneisses. These granites have streaky appearances due to the presence of short, sub-parallel aggregations of mafic minerals.

Geochemically, all these granitoids are part of a metaluminous to marginally peraluminous, ferroan, high-K calc-alkaline to shoshonitic rock sequence. Trace elements indicate similar source materials for both the principal intrusions, however the evolutions of the melts were probably different. An ε_{Nd}-value of –0.6 and a T_{DM} model age of 1.85 Ga indicate the involvement of older crustal materials in the generation of the melt(s). The studied granitoids feature both I- and A-type characteristics but are not typical of either type.

The structural elements of the Stenshuvud granitoids suggest that these rocks were intruded during NE–SW compression and crustal shortening, which caused shearing and folding. In contrast, the Tåghusa granites show no signs of solid-state deformation and must therefore be later than the compression.

Paper III

Gediminas Motuza, Audrius Cecys, Aleksander B. Kotov and Ekaterina B. Salnikova. The Zemaiciu Naumiestis granitoids: new evidence of Mesoproterozoic magmatism in western Lithuania. *GFF (*submitted).

Summary:

Paper III presents a new occurrence of ca. 1.45 Ga old granitic rocks in western Lithuania. Numerous A-type granitoids of that age have previously been described from southern and central Sweden and from the Danish island of Bornholm, but none have been known for certain from the eastern side of the Baltic Sea..

During the reported investigation, the large granitoid pluton of Zemaiciu Naumiestis was discovered under the Phanerozoic sedimentary cover in western Lithuania. Attendant petrological studies demonstrated that the intrusion consists of quartz monzodiorites as well as monzo- and syenogranites. All these rocks contain biotite and more rarely clinopyroxene. Their textures vary from fine- to coarse-grained and are often porphyritic. Chemically, the studied granitoids are dominantly alkali-calcic and shoshonitic, metaluminous to peraluminous, and ferroan to magnesian. According to their mineralogies and geochemistries, they belong to the A-type. In all probability there exist two rock suites that originated from slightly different sources. One of these comprises monzodiorites and monzogranites, the other mostly syenogranites.

The rocks within the Zemaiciu Naumiestis pluton have been foliated to various degrees, however some are rather massive. Locally they are cataclased.

Two samples of monzogranite yielded ID-TIMS U-Pb zircon ages of 1462±8 (MSWD=1.09) and 1459±3 Ma (MSWD=0.28).

Paper IV

Audrius Cecys and Keith Benn. Emplacement and deformation of the ca. 1.45 Ga A-type Karlshamn granitoid pluton, southern Sweden, during ENE-WSW shortening. Precambrian Research (submitted).

Summary:

The ca. 1.45 Ga A-type granitoid plutons in south-easternmost Sweden have hitherto mostly been regarded as anorogenic (Åberg, 1988). This was largely a consequence of previous views ascribing anorogenic origins to all A-type rocks and thus taking the chemical compositions as more or less infallible indicators also of the tectonic settings.

The objectives of the study reported in Paper IV were to study the histories of the emplacement and structural evolution of the Karlshamn pluton (southern Sweden) using detailed structural data and also employing the anisotropy of the magnetic susceptibility. In a second step of study, the validity of the structural conclusions was checked against information derived from other sources.

As described in Paper I, the Karlshamn pluton is one of the largest metaluminous A-type granitoid intrusions of ca.1.45 Ga age in southern Sweden. It is made up of two rock suites that differ in composition but have similar ages of crystallization.

During the work for Paper IV, magmatic foliations, ductile shear zones and pegmatite-filled fractures within the pluton as well as metamorphic foliations and extension lineations in the metamorphic country rocks were mapped and analysed. Since most magmatic foliations and lineations inside the pluton could not be mapped in the field, they were assessed from the anisotropy of the magnetic susceptibility.

The obtained overall structural pattern indicates that the magmatic fabrics within the pluton are continuous with the metamorphic fabrics in the country rocks. Both these fabrics were folded during an event of ENE-WSW compression, which took place while the pluton was still in the state of a magma mush.

The orientations of the stress field during the subsequent cooling of the pluton were determined from the magmatic, ductile and brittle structures that had been formed successively during that process.

Since the main compressional event that deformed the Karlshamn pluton is considered to have been part of the ca. 1.5-1.4 Ga Danopolonian orogeny (Bogdanova, 2001), the Karlshamn granitoids and the other rocks of similar composition and age in the area around the southern Baltic Sea, should most probably be regarded as syn-compressional and therefore synorogenic rather than ”anorogenic” as assumed previously.

3. Overview of the ca. 1.45 Ga event in the area around the southern Baltic Sea

3.1 Extent

The Proterozoic crust in the southwestern marginal parts of the East European Craton (EEC) had been stabilised by ca. 1.55 Ga (Gorbatschev and Bogdanova, 1993). Subsequently, however, it was modified substantially by several tectonothermal events between ca. 1.53 and 1.40 Ga (Åhäll and Connely, 1998; Andersen et al., 2004). To our best present knowledge, these comprised two principal phases of igneous activity that differed in regard to the type of magmatism. An older phase between ca. 1.53 and 1.50 Ga was characterised by anorthosite – mangerite – charnockite - (rapakivi) granite (AMCG) rocks, while the rocks of the younger are dominantly granitic with occasional, locally clinopyroxene-bearing quartz monzodiorites. These were intruded between ca. 1.47 and 1.42 Ga, the entire second igneous phase being referred to as the 1.45 Ga event in the following text. Whether there was a distinct time break between the two indicated phases of magmatism in the southern Baltic Sea region is still unclear

While the 1.53 to 1.50 Ga old AMCG rocks are known from central Sweden (Persson, 1999 and references therein), southern Lithuania and northern Poland (Sundblad et al., 1994; Claesson et al., 1995; Doerr et al., 2002; Skridlaite et al., 2003), the 1.45 Ga granitoid province appears to have a somewhat larger extent, its intrusions also being more numerous.

According to the currently available geochronological and petrological data, the granitoids of ca. 1.45 Ga age occur in southeasternmost Sweden (Åberg et al., 1985; Kornfält, 1993; Kornfält, 1996; Claesson and Kresten, 1997; Kornfält and Vaasjoki, 1999; Cecys et al., 2002), on Bornholm (Callisen, 1932; Micheelsen, 1971; Johansson et al., 2004), within the offshore foreland of that island (Obst et al., 2004), and beneath the Phanerozoic cover of Gotland (Sundblad and Claesson, 2003) as well as western (Paper III) and central Lithuania (G. Skridlaite, pers. comm., 2004; Table 1; Fig. 1). In the Sveconorwegian domain of southwestern Sweden, the ca. 1.45 Ga event is marked by dated granitic dykes and migmatization (Christoffel et al., 1999; Söderlund et al., 2002), whereas throughout southern Sweden there exist numerous, in part even large undated granite intrusions of potentially the same age (e.g. Johansson et al., 1993). Similar rocks possibly also extend far to the northeast, e.g. into the Lake Ladoga region of Karelia, where the Valaam pluton is a conceivable candidate (T. Rämö, pers. comm.). In addition, the growing geochronological and geochemical databases reveal new occurrences of ca. 1.45 Ga and/or A-type granitoids not only in the area around the Baltic Sea but also farther to the east, in Belarus and probably also the Ukraine.

Many of the ca. 1.45 Ga Mesoproterozoic plutons are rather voluminous. In Blekinge and northeastern Scania, these rocks occupy more than 50% of the crystalline basement. On Bornholm, they even make up almost the entire Precambrian area. In western Lithuania, under the Phanerozoic cover, there exist plutons of ca. 1200 km^2 size (Paper III). In central Sweden, however, the ca.1.45 Ga granitoids appear to form smaller plutons. Thus, apparently, the distribution of these plutons is well localised and they are concentrated to a number of specific areas.

3.2 Compositional characteristics

The ca. 1.45 Ga granitoids in Sweden have previously been referred to as anorogenic A-type rocks (Åberg, 1988). As stated above, however, there is a clear difference between these two terms and, as the present thesis ventures to show, the studied rocks are chemically of the A-type but still not anorogenic.

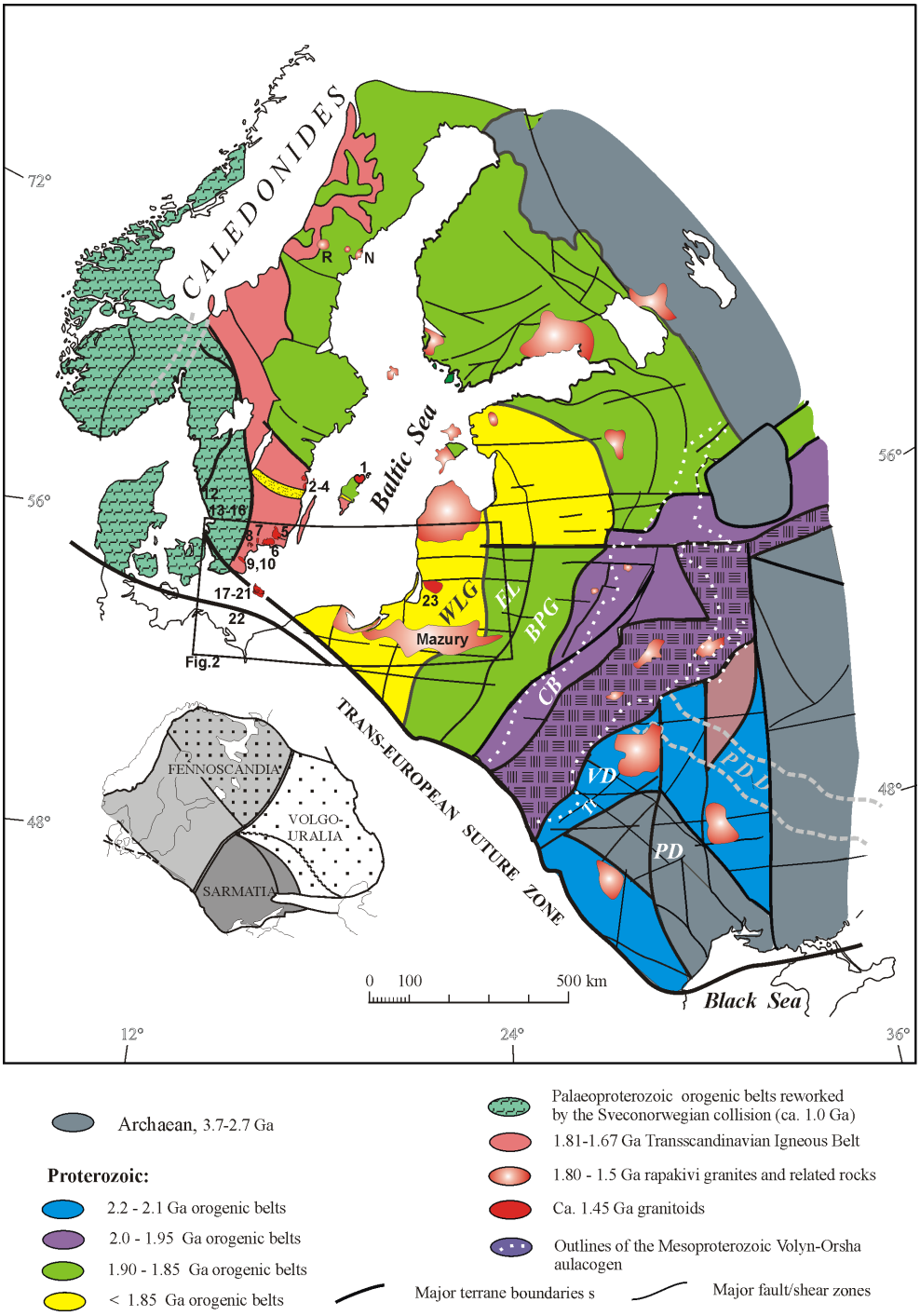
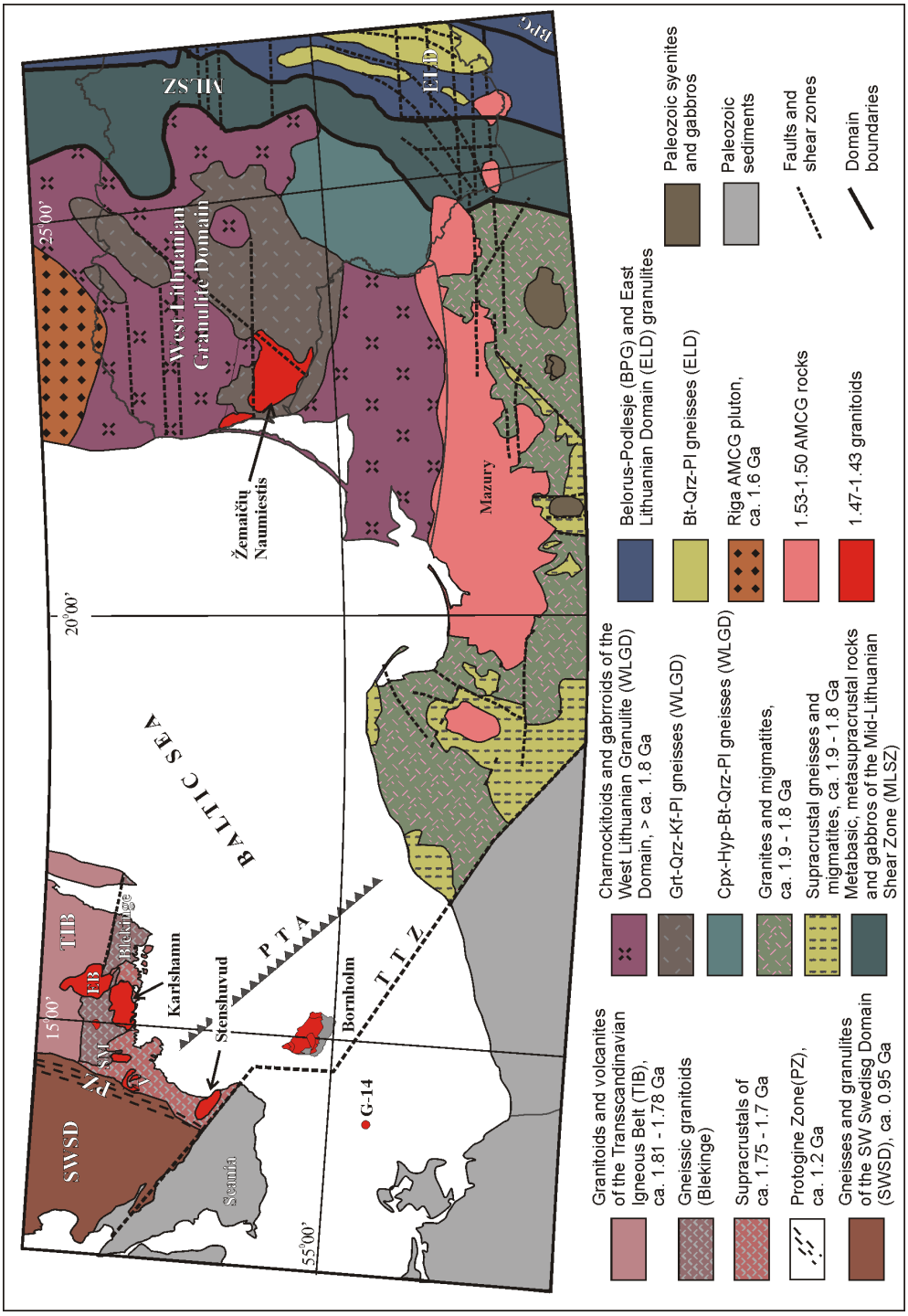


Fig. 1. Sketch map of the crustal structure in the western part of the East European Craton (modified after Bogdanova at al., 2001). The numbers refer to Table 1. The letters are: CB – Central Belarussian Belt; EL – East Lithuanian-Latvian Belt; N – Nordingrå; PDD – Pripyat-Dniepr – Donets Palaezoic Aulacogen; R – Ragunda; VD - Vitebsk domain; and WLG – West Lithuanian Granulite domain.

Table 1. Compilation of age data of Mesoproterozoic granitic rocks in western EEC that are related to the ca. 1.45 Ga event. Ages are in millions of years. Cf. Fig. 1 for sampling localities. WR - whole rock, Min – mineral.

Nr.	Rock	U-Pb zircon	Rb-Sr WR	Rb-Sr WR-Min	K-Ar model	Reference
	Gotland					
1	Grötlingbo granite	1490				Sundblad and Claesson (2003)
	SE Småland					
2	Uthammar granite	1441 +5-3				Åhäll (2001)
3	Jungfrun granite	1480 +40/-31	1386 ±21	1380 ±10	1412 ±20	Åberg et al. (1983)
		1441 ±2				Åhäll (2001)
4	Götemar granite (west)	1468 +53/-47	1377 ±27	1352 ±21	1383 ±20	Åberg et al. (1984)
	Götemar granite (east)	1382 +75/-61	1377 ±27	1380 ±21	1418 ±20	Åberg et al. (1984)
		1452 +11-9				
5	Eringsboda granite		1358 ±114			Åberg and Kornfält (1986)
		1447 +4-3				Åhäll (2001)
					1420	Magnusson (1960)
	Blekinge					
6	Karlshamn granite	1395				Welin and Blomqvist (1966)
			1422 ±31			
		1403 +121±86				Åberg et al. (1985)
		1445±10				Kornfält (1996)
		1452±8				Kornfält and Vaasjoki (1999)
		1465±11				Kornfält and Vaasjoki (1999)
	Karlshamn granite (east)	1445 ± 11 Ma *				Paper I
	Karlshamn granite (west)	1426 ± 11 Ma*				Paper I
	Karlshamn leucogranite		1358 ± 24			Springer (1980)
7	Spinkamåla granite			1358±23		Patchett (1978)
8	Vånga granite	1584 +54/-45	1452±24	1240±7	1221±18	
		1448±25 (U-Pb-Th zircon)				Geisler and Schleicher (2000)
	SE Scania					
9	Stenshuvud granite	1458 ±8				Cecys et al. (2002)-Paper II
10	Tåghusa granite	1442 ±9				Cecys et al. (2002)-Paper II
11	Beden granodiorite	1449 +23/-11				Johansson et al. (1993)
	SW Sweden					
12	Gällared S granite dyke	1444 ±8				Söderlund et al. (2002)
	Gällared S metamorphism	1464 ±8				Söderlund et al. (2002)
13	Granite dykes	1426 +9/-4				Christoffel et al. (1999)
14	Pegmatite swarm	1399 +7/-6				Christoffel et al. (1999)
15	Charnockite	1399 +12/-10				Christoffel et al. (1999)
16	Metamorphism of mafic gneiss.	1438+12/-8				Christoffel et al. (1999)
	Bornholm					
17	Bornholm gneiss	1472 +66/-36				Tschernoster (2000)
18	Rønne granodiorite	1441 +24/-18		1385±26		Tschernoster (2000)
		1469±26				Johansson et al. (2004)
				1400±60		Larsen (1980)
19	Vang granite			1400±60		Larsen (1980)
20	Svaneke granite	1453±19				Johansson et al. (2004)
21	Hammer granite	1424±25 (U-Pb-Th zircon)				Geisler-Wierwille (1999), Obst et al. (2004)
22	G-14 granite (offshore)	1460±3 (Pb-Pb zr)				Obst et al. (2004)
		1455+12/-10				Tschernoster (2000)
	Western Lithuania					
23	Zemaiciu Naumiestis granite	1462±4				Paper III
		1459±3				Paper III

*NORDSIM data


MLSZ
ELD
BPG
25°00'
West Lithuanian Granulite Domain
Žemaičių Naumiestis
20°00'
Mazury
BALTIC SEA
PTA
TTZ
Bornholm
G-14
55°00'
15°00'
TIB
EB
Blekinge
Karlshamn
Stenshuvud
SM
P/
SWSD
Skania
Belorus-Podlesje (BPG) and East Lithuanian Domain (ELD) granulites
Bt-Qrz-Pl gneisses (ELD)
Riga AMCG pluton, ca. 1.6 Ga
1.53-1.50 AMCG rocks
1.47-1.43 granitoids
Paleozoic syenites and gabbros
Paleozoic sediments
Faults and shear zones
Domain boundaries
Charnockitoids and gabbroids of the West Lithuanian Granulite (WLGD) Domain, > ca. 1.8 Ga
Grt-Qrz-Kf-Pl gneisses (WLGD)
Cpx-Hyp-Bt-Qrz-Pl gneisses (WLGD)
Granites and migmatites, ca. 1.9 - 1.8 Ga
Supracrustal gneisses and migmatites, ca. 1.9 - 1.8 Ga
Metabasic, metasupracrustal rocks and gabbros of the Mid-Lithuanian Shear Zone (MLSZ)
Granitoids and volcanites of the Transscandinavian Igneous Belt (TIB), ca. 1.81 - 1.78 Ga
Gneissic granitoids (Blekinge)
Supracrustals of ca. 1.75 - 1.7 Ga
Protogine Zone(PZ), ca. 1.2 Ga
Gneisses and granulites of the SW Swedisg Domain (SWSD), ca. 0.95 Ga

Within this project, three granitoids plutons were studied in detail. Other intrusions in the south Baltic Sea (SBS) region have been described by various authors (see Table 1 and the previous text section for references) and their data, where available, were compared with those from the Karlshamn, Stenshuvud (both southeastern Sweden) and Zemaiciu Naumiestis (western Lithuania) plutons (Fig.2; Papers I, II, and III, respectively).

Despite the wide spatial distribution, all the ca. 1.45 Ga old granitoids in the area around the SBS share many petrographical, mineralogical and geochemical features, which are comparable with those of other A-type granites worldwide (e.g. Anderson and Bender, 1989; Best and Christiansen, 2001).

While the SBS granitoids show substantial textural variation, they are rather uniform in regard to composition and are dominantly granites in the strict sense of the word. Only some minor bodies are made up of quartz monzodiorites. A principal attribute of these granites is theirK-feldspar megacrystic, porphyritic nature. In some varieties, e.g. in the Karlshamn massif, the phenocrysts reach sizes of ca. 10 cm. In such rocks, rapakivi and antirapakivi textures are rather common. As is commonly the case in A-type granitoids, the ferromagnesian minerals are relatively abundant and form interstitial clots. This type of texture indicates relatively dry magma systems, in which the concentration of water increases during the crystallization of anhydrous minerals.

Characteristically, in all the 1.45 Ga SBS granitoids the clots of ferromagnesian minerals often contain numerous zircon, apatite and magnetite grains. Allanite and sulphides also occur in these clots, however they are rare. Sphene is an abundant mineral in the granitoids in southern Sweden but rather rare in those of western Lithuania. In all cases, it is usually associated with magnetite and form separate crystals or thin films around that mineral.

Except for the quartz monzodiorites in the Zemaiciu Naumiestis pluton, where ilmenite is present, magnetite is the only iron oxide mineral in all the studied granitoids. Previously, Ishihara (1977) noted that A-type granites commonly constitute an "ilmenite series" where magnetite is low or absent. In contrast to that, in the SBS granitoids magnetite is a common mineral, which indicates elevated oxygen fugacities in their magmas. Therefore, the SBS granitoids are an exception to Ishihara's generalisation and belong to an "A-type magnetite series" like some Mesoproterozoic granitoid series in the North American Craton (Anderson and Bender, 1989).

Table 2. Average compositions of amphiboles in the Karlshamn and Stenshuvud granitoids.

	KHE-QMD	KHE-QM	KHE-G	KHW-AG	SH-TH	SH-Grd	SH-GP
N	4	15	3	21	11	6	12
Na_2O	1.19	1.3	1.3	1.33	1.56	1.28	1.32
MgO	9.2	8.58	7.97	7.86	7.01	10.02	15
SiO_2	43.52	42.57	39.51	42.17	41.63	43.68	48.24
K2O	1.41	1.52	1.46	1.52	1.35	1.04	1.02
MnO	1.11	1.17	1.3	1.38	0.67	0.96	1.69
FeO	20.12	20.92	19.28	21.99	22.8	18.25	12.07
Al_2O_3	8.97	9.2	8.95	9.19	9.28	9.68	6.75
CaO	11.95	11.75	11.41	11.67	11.5	11.92	11.93
TiO_2	1.44	0.81	0.71	0.91	1.45	0.76	0.25
Total	98.91	97.82	91.9	98.02	97.26	97.59	98.27
OxNum	23	23	23	23	23	23	23
Si	6.61	6.58	6.52	6.55	6.53	6.64	7.04
Al	1.6	1.68	1.74	1.68	1.72	1.73	1.17
Al^{IV}	1.39	1.42	1.48	1.45	1.47	1.36	0.96
Al^{VI}	0.22	0.26	0.26	0.24	0.25	0.37	0.21
$Fe^{2+(tot)}$	2.56	2.71	2.66	2.86	2.99	2.32	1.48
Mg	2.08	1.98	1.96	1.82	1.64	2.27	3.26
Ca	1.95	1.95	2.02	1.94	1.93	1.94	1.87
Na	0.35	0.39	0.41	0.4	0.47	0.38	0.38
K	0.27	0.3	0.31	0.3	0.27	0.2	0.19
Ti	0.16	0.09	0.09	0.11	0.17	0.09	0.03
Mn	0.14	0.15	0.18	0.18	0.09	0.12	0.21
Mg/ (Mg+Fe)	0.45	0.42	0.42	0.39	0.35	0.49	0.69

Fig. 2 (opposite). Simplified geological map of the South Baltic Sea (SBS) region, after Micheelsen (1971) and Stephens et al. (1994). The letters are: EB – Eringsboda; PTA - Proterozoic Teranne accretion, from Meissner and Krawczyk, 1999; SM – Spinkamåla; TTZ - Tornquist-Teisseyre Zone; and V- Vånga. Other letters are explained in the legend.

In regard to the presence of their ferromagnesian silicate minerals, the SBS granitoids belong to different types. In Blekinge, eastern Scania and on Bornholm, these granitoids contain both hornblende and biotite. Amongst these two minerals, biotite dominates distinctly. In the granitoids of western Lithuania and the G-14 borehole, in contrast, hornblende is absent and only biotite is present. Pyroxenes occur in quartz monzodiorites that form small bodies both in western Lithuania and on Bornholm.

The amphiboles from the granitoids of the Karlshamn and Stenshuvud plutons (Fig. 3; Papers I and II) are similar in composition and plot tightly together. Most of them fall into the ferro-edenite field (Fig. 3a and Table 2), but several analyses from Stenshuvud are just across the boundary toward edenite compositions. The amphiboles richest in silica and iron have been interpreted to derive from subsolidus or metamorphic reactions (Paper II).

In the granitoids of the Karlshamn, Stenshuvud and Zemaiciu Naumiestis plutons, most biotites show no significant variations in aluminum (Table 3 and Fig. 3b). An exception is the syenogranites of the latter pluton, where the biotites have higher contents of Al. This probably reflects the peraluminous character of that rock.

In regard to their Mg/(Mg+Fe) proportions, the biotites of the investigated SBS rocks vary from about 0.32 to 0.81. The most extreme compositions are represented by the biotites from the Stenshuvud area, where those from the Stenshuvud granites are richest in magnesia and those from the Tåghusa richest in iron. The biotites from the other studied rocks contain roughly similar amounts of the annite and phlogopite end-members.

Like the amphiboles and biotites, also the plagioclases of the Karlshamn and Stenshuvud granitoids are similar in composition, varying from ca An_{20} to An_{48}. As different from that, the plagioclases in the granitoid rocks of the Zemaiciu Naumiestis pluton are more calcic on average, simultaneously, however, representing a narrower range of compositions between An_{40} and An_{47}. The Zemaiciu Naumiestis quartz monzodiorites contain labradorites of about An_{50}.

In summary, the ca. 1.45 Ga plutons in southeastern Sweden and western Lithuania are similar in regard to the compositions of their ferromagnesian minerals but vary somewhat in regard to plagioclase. The higher An contents of the plagioclases in the Zemaiciu Naumiestis granitoids can possibly be

Table 3. Average compositions of biotites in the Karlshamn, Stenshuvud and Zemaiciu Naumiestis granitoids.

	KHE-QMD	KHE-QM	KHE-G	KHW-AG	SH-GdP	SH-GdP	SH-GP	SH-GP	SH-TH	SH-Ton	ZN-SG	ZN-MG
N	8	17	5	61	13	16	77	78	27	6	11	24
MgO	10.61	12.01	11.03	10.41	12.24	10.44	16.18	16.01	8.37	13.68	7.59	11.06
FeO	18.93	19.35	17.59	20.97	18.02	15.73	12.40	12.32	23.59	14.53	21.15	18.97
TiO_2	2.99	2.2	1.43	2.14	1.35	1.14	1.19	1.18	1.86	1.29	2.78	2.62
MnO	0.66	0.87	1.02	0.96	0.76	0.67	1.01	1	0.69	1.25	0.37	0.44
SiO_2	36.73	37.23	35.36	37.02	36.63	38.68	38.81	38.91	35.69	38.14	35.6	37.3
K2O	10.4	10.14	9.72	10.23	9.59	9.79	10.14	10.15	9.79	10.1	10.44	10.6
Al_2O_3	14.12	13.29	13.06	13.55	15.60	17.87	13.92	14.09	14.43	14.95	17.36	14.16
Total	94.54	95.15	89.27	95.35	94.41	94.48	94.09	94.1	94.57	94.47	95.36	95.19
Based on 22 atoms of oxygen.												
Mg	2.45	2.77	2.69	2.41	2.80	2.38	3.61	3.57	1.97	3.07	1.75	2.53
$Fe^{2+(tot)}$	2.45	2.5	2.41	2.72	2.32	2.01	1.56	1.55	3.13	1.85	2.74	2.44
Al^{IV}	2.30	2.26	2.21	2.25	2.37	2.2	2.18	2.17	2.35	2.24	2.49	2.26
Al^{VI}	0.28	0.16	0.32	0.23	0.45	0.93	0.28	0.31	0.34	0.42	0.68	0.3
Ti	0.35	0.25	0.18	0.25	0.16	0.13	0.14	0.13	0.22	0.15	0.32	0.3
Mn	0.09	0.11	0.14	0.13	0.10	0.08	0.13	0.13	0.09	0.16	0.05	0.06
Si	5.7	5.74	5.8	5.75	5.63	5.8	5.82	5.83	5.65	5.76	5.51	5.74
K	2.06	2	2.03	2.03	1.88	1.88	1.94	1.94	1.98	1.94	2.06	2.08
Mg/ (Mg+Fe)	0.50	0.53	0.53	0.47	0.55	0.53	0.70	0.69	0.39	0.62	0.39	0.51

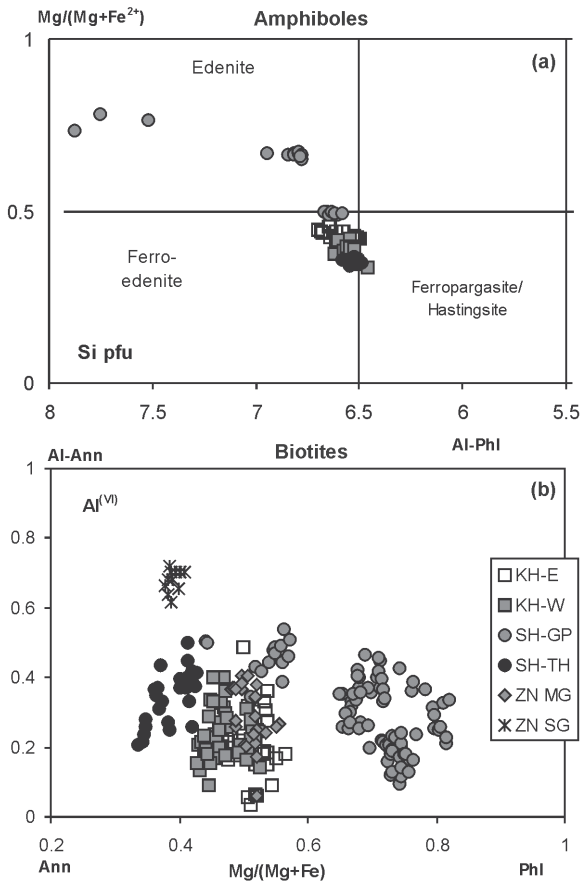


Fig. 3. Chemical compositions of minerals in the studied granitoids. (a) Classification of amphiboles, after Leake et al. (1997); (b) Classification of biotites after Speer (1984). Ann – annite, Phl – phlogopite, Al-Ann and Al-Phl – Al annite and Al phlogopite, respectively. Abbreviations: KH-E and KH-W - granitoids of the eastern and western suites, respectively, in the Karlshamn pluton; SH-G and SH-TH – the Stenshuvud and Tåghusa granitoids, respectively, in the Stenshuvud pluton; ZN-MG and ZN-SG – monzogranites and syenogranites, respectively, in the Zemaiciu Naumiestis pluton.

explained by the absence of other Ca-rich phases, e.g. sphene.

Along with their mineralogical features, the 1.45 Ga granitoids in the SBS region have chemical compositions similar to those of many A-type granites elsewhere in the world (e.g. Loiselle and Wones, 1979; Collins et al., 1982). Typically for A-type granites, they are rich in silica and therefore mostly true granites (Fig. 4a). Their modified alkali-lime indices (MALI) increase with the contents of SiO_2 and define alkali-calcic trends. At silica contents above 73 vol.%, however, the compositions plot within the calc-alkaline field (Fig. 4b). This is probably due to something earlier crystallization of K-feldspar and consequent depletion in potassium in the most evolved compositions.

Most of the studied granitoids are subalkaline and metaluminous, however their agpaicity increases with the degree of aluminum saturation until it reaches the boundaries between the subalkaline-alkaline and the metaluminous-peraluminous fields (Fig. 4c). Thereafter, agpaicity decreases as the aluminum saturation index continues to increase, and the rocks gain a peraluminous character. Those with the highest peraluminosity contain high-alumina biotite and occasionally sillimanite (Paper III). Characteristically of A-type granites, the ca. 1.45 Ga rocks in the SBS area feature high contents of potassium and are therefore classified as shoshonitic (Fig. 4d). Also these granitoids have K_2O-contents initially increasing with increasing SiO_2, but at the highest silica contents (above ca. 73%) correlation becomes negative.

Like in other A-type granites, the FeO/(FeO+MgO) ratios are high and the rocks therefore plot in the ferroan field (Fig. 4e). These ratios are fairly uniform in most of the ca. 1.45 Ga old rocks and begin to increase only at about 73% of SiO_2.

The named features indicate that the studied granitoids are in general alkali-calcic, subalkaline, metaluminous, ferroan, and shoshonitic. They follow similar variation trends from metaluminous to peraluminous compositions, show MALI, K_2O and FeO/(FeO+MgO) values increasing with SiO_2, and all have characteristic trend changes at about 73 vol. % SiO_2. However, at least some individual

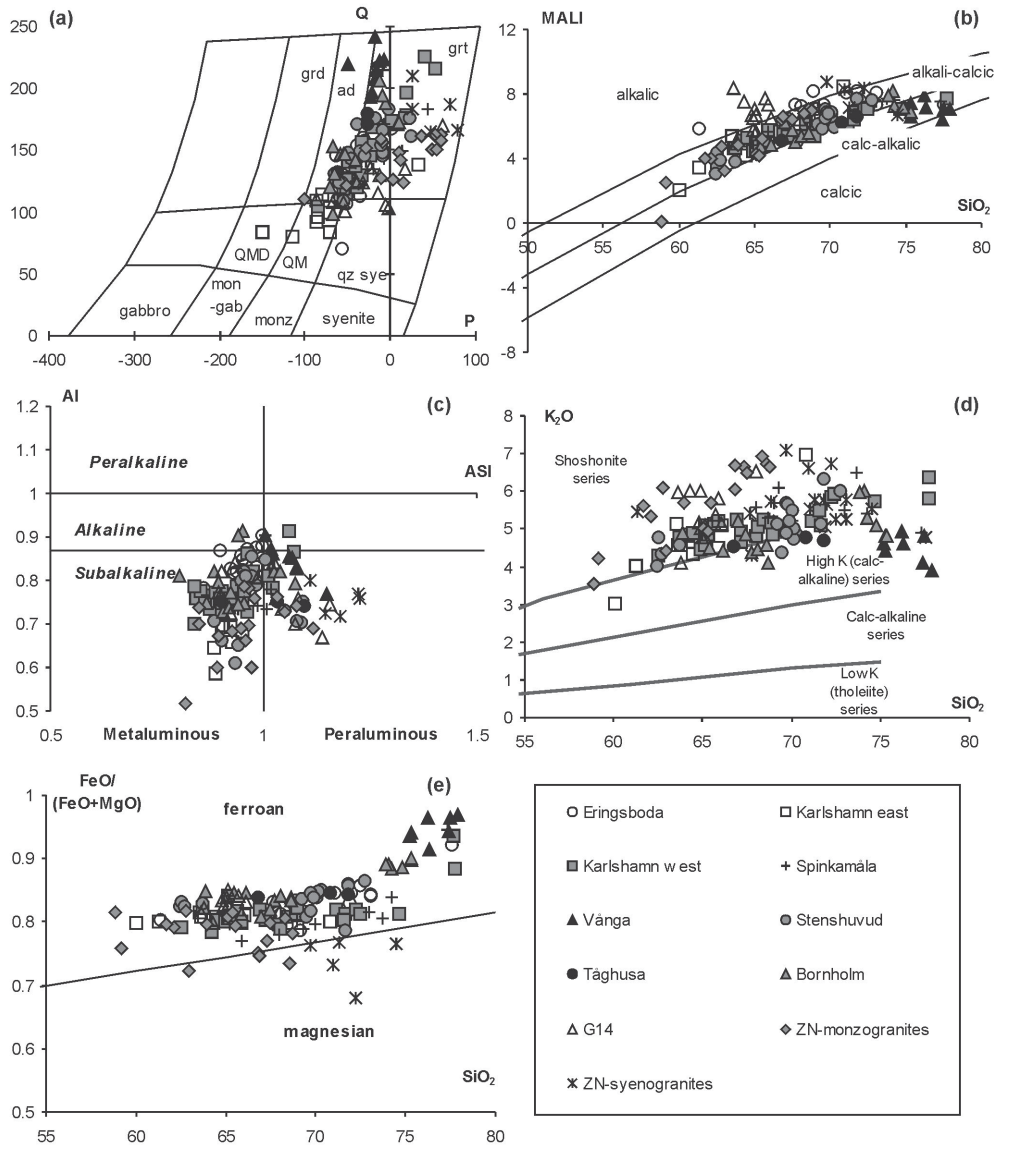


Fig. 4. Major element classification diagrams for the SBS granitoids. a) QP, after Debon and Le Fort (1983), Q=Si/3-(K+Na+2Ca/3), P=K-(Na+Ca), both parameters are expressed as gram-atoms x10^3 of each element in 100 gr of the rock. A – adamellites, G – granite, QMD – quartz monzodiorites, QM – quartz monzonite, and QzS – quartz syenite; b) plot of modified alkali-lime index (MALI) against SiO_2. MALI is defined as Na_2O+K_2O-CaO. Definition and boundaries are after Frost et al. (2001); c) agpaitic (AI) versus aluminum saturation index (ASI; Shand, 1943; Frost et al., 2001). AI and ASI are defined as the molecular ratios of (K+Na)/Al and Al/(Ca+Na+K), respectively. The limit at AI=0.87 is after Liégeois and Black (1987); d) the subdivision of subalkalic rocks using the K_2O vs. silica diagram (Rickwood, 1989); e) Fe# (FeO*/(FeO*+MgO)) versus SiO_2 diagram, the boundary between ferroan and magnesian plutons is after Frost et al. (2001). Abbreviations: ZN - Zemaiciu Naumiestis.

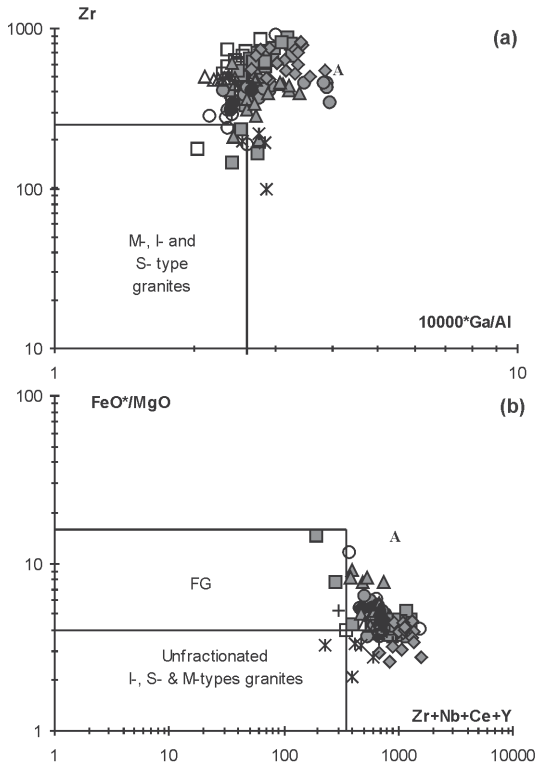


Fig. 5 Discrimination diagrams for A-type granites. a) Zr vs. Ga/Al and b) FeO*/MgO vs. Zr+Nb+Ce+Y plots. The star-symbol marked by "A" is average of A-type granites (Whalen, 1987). Symbols are as in Figure 4.

intrusions are made up of different rock suites that have somewhat dissimilar chemical compositions (Papers I to III). In the few studied cases, the presence of such suites was interpreted as being due to derivation from different melt sources (Paper I).

An important diagnostic compositional characteristic of A-type granitoids is their enrichment in high-field-strength elements (Ti, Ga, Zr, Nb, Y) and REEs (Loiselle and Wones, 1979; Collins et al., 1982; Whalen, 1987; Eby, 1992). As a rule, also the ca. 1.45 Ga granitoids in the SBS region contain high abundances of those elements (Fig. 5).

3.3 PT-conditions

The calculated zircon saturation temperatures indicate that all the ca. 1.45 Ga old granitoids in the SBS area have crystallised at similar temperatures between ca. 800 and 900°C, only the most evolved varieties showing lower temperatures (Fig. 6a; Watson and Harrison, 1983). These temperatures are most probably not very precise because of the effects of inherited zircons. Nevertheless, they indicate that the studied rocks crystallised at the rather high temperatures characteristic of A-type granites.

According to the total-Al-in-hornblende geobarometer of Johnson and Rutherford (1989), most of the 1.45 Ga granitoids in Blekinge and Scania were emplaced at depths corresponding to 0.35-0.40 GPa (ca. 12 km; Fig. 6b). The fine-grained porphyritic Stenshuvud granites (Paper II), however, were emplaced at a somewhat shallower level (ca. 0.25 GPa, ca. 8 km).

3.4 Sources and emplacement

As indicated by the petrochemical studies of the present project (Papers I to III), the ca. 1.45 Ga granitoids in the SBS area have several features in common in regard to the emplacement of their melts and the melt sources. Characteristically, the plutons were formed by multiple melt emplacements. From both the textural and the chemical evidence, the products of the various pulses can be recognized to belong to at least two different rock suites. The important feature in this context is that the rock suites within the same pluton may differ in regard to their contents of major and trace elements but have similar isotopic characteristics. For instance, the western and eastern rock suites in the Karlshamn pluton have identical set-ups of oxygen and Nd isotopes, but the former suite is richer in ferromagnesian components and most trace elements, while the latter has higher contents of the felsic and LILE elements. This suggests that the two rock suites were generated from parental melts undergoing

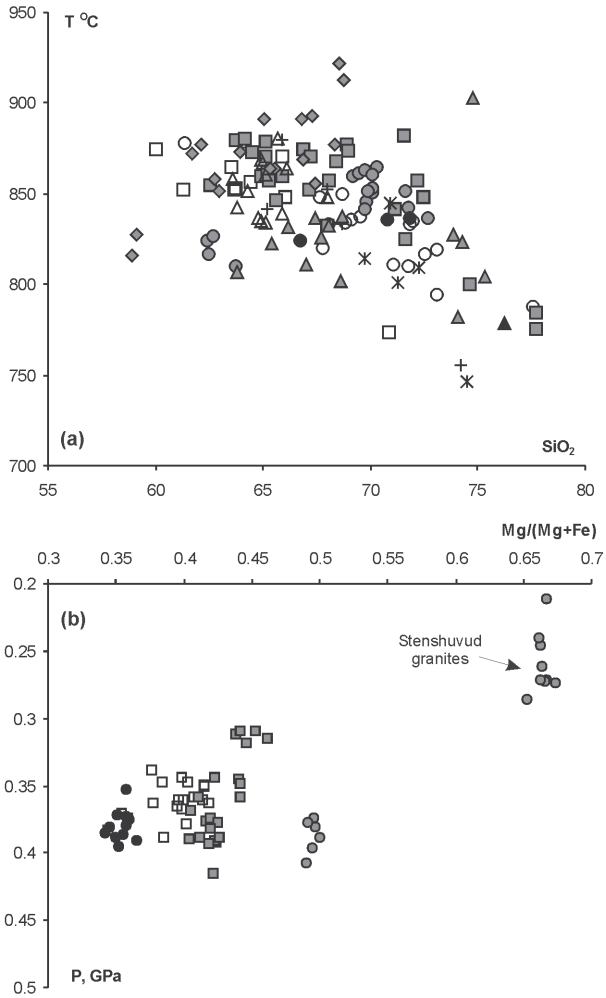


Fig. 6. a) Calculated temperatures (Watson and Harrison, 1983) plotted against SiO_2 in the studied granitoids; b) calculated pressures (total-Al-in-amphibole; Johnson and Rutherford, 1989) vs. magnesium number in amphiboles. Symbols are as in Figure 4.

somewhat different differentiation processes and derived from chemically different but isotopically identical sources. Contamination by materials from the surrounding rocks would probably have resulted in different isotopic signatures. The nature of the source rocks for the various A-type granitoids is problematic and many different models have been proposed in the literature (cf. text section 9.2 in Paper I). The geochemical, including isotope data for the ca. 1.45 Ga granites in the SBS region suggest that these rocks most probably originated from high-alumina potassic lithologies, such as syenites, with rather juvenile characteristics. As indicated in Paper II, the TIB granitoids in southeastern Sweden may be a good candidate, but additional isotopic studies are required.

3.5 Tectonic settings

From the structural and AMS data presented in Paper IV and partly Paper II, it can be concluded that the emplacement of the 1.45 Ga granitoids in southeasternmost Sweden occurred simultaneously with ENE–WSW crustal shortening (in terms of present-day coordinates).

In extensional settings, magmatic foliations usually develop due to magma flow and ballooning. The granitoids of southeastern Sweden, however, were emplaced in compressional settings, and therefore the magmatic foliations in these rocks must have been reorientated by the prevailing tectonic stresses.

During the magmatic stages of the development of these plutons, when their rocks were still not fully crystallised and highly ductile, they could accommodate much greater amounts of deformation than the country-rocks. As a result, the latter must have been strongly deformed and folded, while the rocks within the plutons only developed magmatic foliations. Therefore, the early-formed magmatic foliations within the plutons became continuous with the metamorphic foliation in the country rocks. During the following stages of deformation, first ductile and later brittle-ductile foliations and shear zones were formed as the plutons passed the solidus and continued to cool. Finally, during the latest stage of development, the pluton had cooled well below the solidus and responded in a brittle fashion to the regional ENE-WSW compression. At that time, extensional fractures filled with

pegmatite, granite and quartz veins were formed.

The Tåghusa granites (Paper II) of the Stenshuvud pluton in eastern Scania were emplaced in a compressional regime, however the compression ceased before the final solidification of the granites. Although the U-Pb zircon ages are similar (within errors) in the Mesoproterozoic granitoids in Scania and Blekinge, the Tåghusa granites are probably one of the latest intrusions that formed during the ca. 1.45 Ga event.

As a result of this project, the Mesoproterozoic granitoids in southeasternmost Sweden, and other granites of similar ages in Lithuania and on Bornholm can no longer be considered anorogenic. Instead, they represent ca. 1.45 Ga syntectonic plutonism in the area around the southern Baltic Sea.

4. Tectonic settings of A-type granitoids

The results of the present project support the concept that A-type granites occur in orogenic settings. This work along with other studies indicates that A-type granites can occur in both anorogenic and orogenic settings. The most important tool in discriminating between these two settings is structural geology. In large-scale extensional settings, the intruding granitoids will have only magmatic flow fabrics discontinuous with those in the host rocks. In contrast, in compressional (orogenic) settings, granitoids will contain both syn- and post-magmatic structures and these will be continuous with the ones in the country rocks. Problems may arise when the plutons are emplaced late in the orogenic process during relaxation time. Such plutons will be structurally similar to those intruded in anorogenic, strictly extensional settings. However, in orogenic settings, the plutons that were intruded during extension should associate with coeval intrusions that show compression during their emplacement.

An illustration of what is stated above is the discussions that currently take place around the ca. 1.4 Ga granitoids in northern America. There, A-type granites are considered as anorogenic by some researchers (Anderson and Bender, 1989; Anderson and Morrison, 1992; Windley, 1993; Frost et al., 2001) and as orogenic by others (Nyman et al., 1994; Kirby et al., 1995). Interestingly to note, those who argue for anorogenic character of these granites quote only geochemical work, while those who argue for orogenic setting base their arguments on structural studies.

5. The Danopolonian Orogeny

The new geochronological data presented in this thesis as well as published data (Table 1) indicate widely spread magmatic activity in the western part of the EEC during the middle Mesoproterozoic. (Hubbard, 1975) interpreted ca. 1.4 Ga high-grade metamorphism and magmatism in southwestern Sweden to reflect an orogenic cycle that he named ”the Hallandian event”. The concept of Hallandian orogeny was introduced at a time when age data for metamorphism were essentially lacking and late-Sveconorwegian granulite facies metamorphism and tectonics were poorly understood, and thus not properly considered.

Based on the presence of extensive magmatism and deformation in the area around the southern Baltic Sea, where the Sveconorwegian reworking of the crust is absent, Bogdanova (2001) proposed to re-name the ca. 1.45 Ga event the ”Danopolonian orogeny” in order to avoid confusion with the Hallandian event as defined by Hubbard (1975). Based on palaeomagnetic data and tectonic correlations, she tentatively suggested that collision of the EEC with another continent (e.g. Amazonia) could be the most plausible explanation for the compressional tectonics and reactivation of the continental crust.

The Danopolonian orogeny followed the ca. 1.70-1.55 Ga ”Gothian” orogenic events, due to which the crust in SW Sweden was formed and reworked. The 1.53-1.50 Ga AMCG magmatism in

northern Poland and southern Lithuania as well as that in central Sweden may therefore represent the final stage of the Gothian or, alternatively, the first phase of the Danopolonian orogeny.

The main event of the latter orogeny is marked by extensive ca. 1.47-1.43 Ga magmatism and shearing. As mentioned earlier, that magmatism is mainly characterised by voluminous multiphase plutons of A-type granitoids in the wide region around the southern Baltic Sea.

In Papers II and IV, the implications of the Danopolonian orogeny for the tectonic settings of the Blekinge-Bornholm region (BBR) are considered. These studies show that the BBR experienced ENE-WSW compression and crustal shortening during the emplacements of ca. 1.45 Ga granitoids. That shortening was interpreted as a result of Danopolonian subduction and collision. In response to the compression, also E-W shear zones were developed. Apparently, these zones controlled the emplacement of the ca. 1.45 Ga granitoids.

The overall structural pattern in the BBR is compatible with the NE-dipping collision structure discovered by the BABEL and DEKORP seismic reflection data obtained in the offshore area between Sweden and Bornholm (Fig. 2). Abramovitz et al. (1997) and Meissner and Krawczyk (1999) suggested that this structure could be related either to a Gothian thrust or to the Sveconorwegian Front. Based on the structural data obtained during this Ph.D. project, it may, however, be suggested that this is a collisional structure formed during the Danopolonian orogeny.

Conclusions

(1) At ca 1.45 Ga, the southwestern margin of the East European Craton experienced extensive, mainly granitoid igneous activity and deformation. That event was preceded by a period of AMCG magmatism between ca. 1.53 and 1.50 Ga.

(2) Chemically, the granitoid rocks formed during the ca. 1.45 Ga event belong to the A type. They are rich in silica, high-field-strength elements and REEs, and have high Fe/Mg and K/Na ratios. The most common ferromagnesian silicate mineral is biotite. Amphibole is also common but occurs in much lesser amounts and not in all rocks. Clinopyroxene is occasionally present.

(3) In several cases, the ca. 1.45 Ga plutons were formed by the emplacement of multiple pulses of melt. These pulses may belong to separate geochemical suites, which appear to have originated from slightly different sources of melt.

(4) The source rocks of the 1.45 Ga granitoids were rich in aluminum and potassium as well as in HFSEs and REEs. Their isotopic characteristics suggest relatively juvenile crustal materials.

(5) During the 1.45 Ga event, the Blekinge-Bornholm Region (BBR) experienced regional ENE-WSW compression and crustal shortening. This caused syn- and post-magmatic deformation of the granitoid plutons as well as deformation and metamorphism of their host rocks.

(6) Due to the compression, EW-striking shear zones were either formed or reactivated and did apparently control the emplacement of the 1.45 Ga granitoids.

(7) The compressional tectonics was most probably related to an orogenic event, presumably belonging to the Mesoproterozoic Danopolonian orogeny, first defined by Bogdanova (2001).

(8) Because the ca.1.45 Ga A-type granitoid rocks in the southwestern marginal part of the EEC were formed during compression and shortening of the crust, they are orogenic rather than anorogenic.

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