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Regional metamorphism in the Bergslagen Province, South Central Sweden

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Abstract

Regional metamorphism in the Bergslagen Province of South Central Sweden reached but did not significantly extend beyond the granulite facies boundary. It occurred during a less than 20 Ma, and probably less than 5 Ma, period between 1.89 and 1.84 Ga. It resulted from burial metamorphism in an extensional basin under a moderately high geothermal gradient of at least 50° C km^{-1}. Within this relatively warm terrane, submarine areas of recharge are delineated by zones with lower metamorphic facies. The high heat flow produced deep hydrothermal convection through the volcano-sedimentary pile resulting in extensive alteration, particularly alkali metasomatism, and concomitant ore formation.

Migmatite development, related to incipient melting occurred in the pelite-infilled, deeper part of the basin. At this high heat flow, melting occurred at less than 13 km depth. The granitoids resulting from this process represent the *urgranit* of central Sweden and display mixed S- and I-type characteristics. Intrusive activity in a region with intense hydrothermal activity resulted in substantial explosive volcanic activity and the formation of large volumes of volcanoclastics. Sediment and subsequent volcanoclastic loading provided a virtually autocatalytic subsidence driving mechanism for the basin, resulting in extensive melting.

The basin developed through lithospheric stretching and attenuation of an earlier continental crust. Nd isotopic systematics may be reinterpreted to suggest a substantial 2.2–2.0 Ga component in the older granitoids. This is consistent with other isotopic and geochemical data which strongly suggest an ensialic development for the district. The earlier crust is now represented by the older granitoids, which were produced by basement melting at the crust-mantle interface during burial.

The pegmatite-rich younger granitoids are representatives of the 1.8–1.7 Ga intrusives which mantle the Province to the west. These granitoids penetrate the Bergslagen crust sporadically; they may underlie the western edge and have given rise to an extensive veining and pegmatite formation, unrelated to the major metamorphic event.

The development of Bergslagen is similar to Phanerozoic extensional basins, except that a deeper part of the crust is uncovered. In these deeper zones with high heat flow, major deformation was probably ductile rather than by brittle failure. The development of the Bergslagen basin immediately preceded plate collision at the end of the 1.9–1.8 Arizona-Finland Wilson cycle, which is expressed in Bergslagen as intensive folding rather than extensive thrusting.

Introduction

Sederholm (1907) coined the term 'migmatite' for the rocks so beautifully exposed on the coasts of central Fennoscandia, which appear to be mixtures of igneous and sedimentary fragments displaying a bewildering array of compositions and fabrics. He originally defined the characteristics of migmatites as gneisses with 'two elements of different genetic value, one, a schistose sediment or foliated eruptive, the other, either formed by the re-solution of material like the first or by injection from without.' Mehnert (1968) redefined the term as 'a megascopically composite rock consisting of two or more petrographically different parts, one of which is the country rock generally in a more-or-less metamorphic stage, the other is of pegmatitic, aplitic, granitic, or generally plutonic appearance'.

The granitoids of central Fennoscandia comprise both deformed intrusive *urgranites* and less or undeformed anatectic granitoids originally supposed to have been formed through migmatisation at the culmination of orogenesis, but often appearing related to a major regional metamorphic phase postdating the peak of deformation. In this region of central Fennoscandia, foliated rocks with indications of incipient melting are juxtaposed with swarms of granitic and pegmatitic veins and granitoids with ghost foliations and metasedimentary fragments. Although spatially coincident, previous interpretations of the genetic interrelationships between these events have been hindered by a lack of information about the ages of the different aspects of the system.

In this paper I examine what our present knowledge can tell us about the post-depositional PT-t paths followed by the Swedish segment of the central Fennoscandian province in the Early Precambrian.

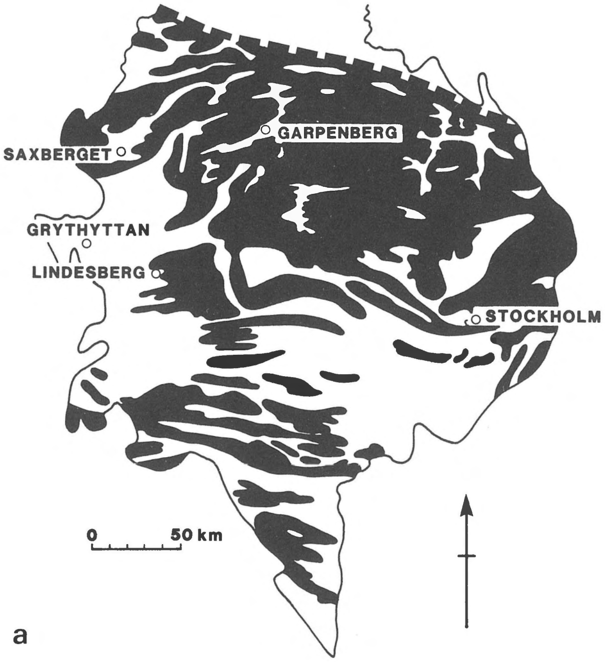
Geological background

The geology of Bergslagen is summarized in Figs 1a and 1b. Bergslagen was originally the name of an area where a certain type of medieval, Germanic, mining legislation operated. It does not constitute a defined national geographic entity and therefore has no strict borders. I use the term in this paper for that area of Sweden bounded to the east by the Baltic Sea, to the north by a mobile zone paralleling a major EW lineament from the Upland coast and to the west by the belt of Småland-Värmland porphyries. This belt of intrusives has been called various things by Gorbatschev and his co-workers over recent years, most recently the Trans-Scandinavian Granite Belt (Gaal & Gorbatschev 1987). Its geotectonic significance was first realized by Nystrom (1982) who called it the Post-Svecokarelian Belt, and suggested that it represents an Andean type margin to the newly formed Baltic crust. The belt intersects the Baltic coast south of Västervik, wedging out the district to the south.

Bergslagen consists of rocks belonging to the 1.9–1.7 Ga Svecokarelian orogen. Metasediments and metavolcanics are concentrated mainly in the septa between extensive granitoid batholiths in the centre and north of the area. In the south, metasediments displaying extensive and pervasive incipient melting characteristics predominate. These partially melted, granitized and veined rocks are described as 'veined gneisses' (*ådergnejs*) in the Swedish literature.

Conventionally, the Fennoscandian granitoids are related to the Svecokarelian orogenic cycle (Sederholm 1932). Thus the granitoids are divided into: (1) synkinematic or primorogenic granitoids – which tend to be gneissose and concordant with the local tectonic grain, (2) late kinematic or serorogenic granitoids – which are seldom foliated and tend to form diapiric intrusions clearly cross-cutting the country rock, and (3) post kinematic or post-orogenic granitoids – which show no signs of deformation.

Radioactive dating has shown that the intrusion of the primorogenic or *urgranit* of Bergslagen took place between 1870–1850 Ma (Welin et al. 1980; Åberg et al. 1983a, b; Åberg & Stromberg 1984). These granitoids appear to be at least in part genetically related to the associated metavolcanics (Åberg et al. 1983b; Vivallo & Rickard 1984) and thus at least in part to intrude their own volcanic piles. They are not easily classifiable into I- and S- types (Chappell & White 1974) and appear to contain



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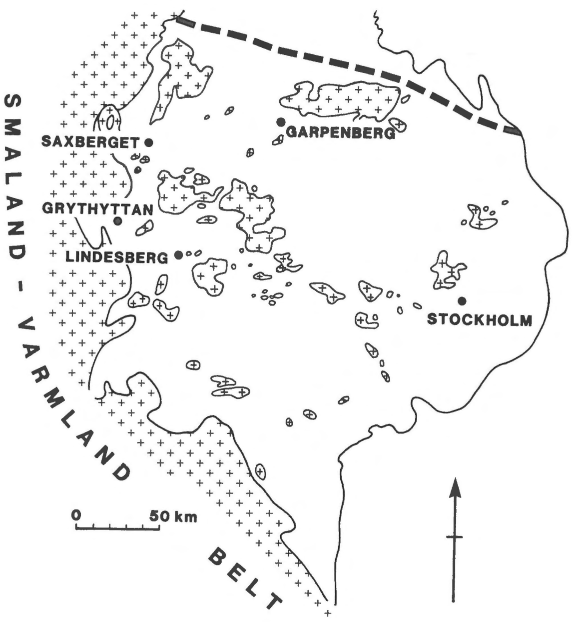

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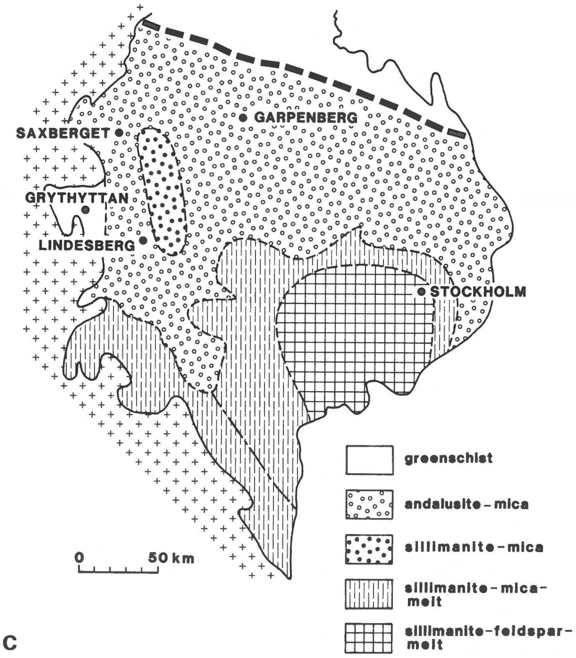

c

Fig. 1a. Distribution of older granites (*urgranit*) in Bergslagen. The sketch is made from data in Magnusson et al (1962) and subsequent mapsheets of the Geological survey of Sweden. There is some doubt as to the age of some of these granitoid masses, but the diagram illustrates the general trend. The heavy dashed line in the north represents the boundary of Bergslagen used in this paper; it is coincident with a zone of veined gneisses possibly paralleling a major structural discontinuity.

Fig. 1b. Distribution of the younger, late and post-orogenic granitoids in south central Sweden.

Fig. 1c. Summary representation of the distribution of metamorphic facies in Bergslagen. The data are taken from the mapsheets and accompanying descriptions of the Geological Survey of Sweden, which has mapped about 40% of the area. This, together with the concentration of granitoids, makes the delineation of boundaries possible only in schematic form. The separation of the sillimanite-mica-melt area into two reflects the possibility discussed in the text that the western area results from the intrusion of the Småland-Värmland granitoids.

examples of both end members (Wilson 1980, Baker 1985, Armands & Xefteris 1987). They are characteristically composed of granodiorites, tonalites and trondhjemites, with associated gabbros and rare central granites. The Bergslagen synorogenic granitoids are considered to be part of the same system that produced the extensive (35000 km^2) central Finnish batholith which shows more definitive I-type characteristics (Front & Nurmi 1987). The Nd isotopic systematics of both suites show a minimal Archean component, although Patchett et al. (1987) remarked that the Berglagen synorogenic granitoids display lower depleted mantle values than subjacent areas of Finland and Greenland.

Two late-orogenic or serorogenic granitoids have been dated by Åberg & Bjurstedt (1986). They both give zircon U-Pb and whole rock Rb-Sr ages of 1750 Ma. Patchett et al. (1987) presented two further zircon U-Pb dates of $1789^{+0.036}_{-0.025}$ Ma for the Stockholm granite and 1782 ± 0.006 Ma for the Fellingsbro granite. The serorogenic granitoids have been classically described as anatectic, being formed through melting of supracrustals (Stålhös 1969). Indeed, Sederholm (1907) originally coined the term migmatite for areas related to these serorogenic granitoids in the contiguous parts of SW Finland, which have a similar age (Patchett & Kouvo 1986). They tend to be composed of true granites with high silica contents and initial $^{87}Sr/^{86}Sr$ ratios of 0.706. (Åberg & Bjurstedt 1986). However, Armands & Xefteris (1987) considered these granitoids more I-type on the basis of an Fe^{3+}/Fe_{tot} vs $Al_2O_3/(Na_2O + K_2O + CaO)$ plot. Patchett et al. (1987) found that the Nd isotope compositions of these granitoids were indistinguishable from the early orogenic intrusives in the same area. It appears that a simplistic application of Chappell & White's (1974) original classification is not appropriate here.

The Bergslagen Province is bordered to the south and west by a distinct belt of highly magnetic, I-type (Wilson 1980) granitoids formed between 1700–1800 Ma (Wilson et al. 1985, Patchett et al. 1987). Nd isotope systematics (Patchett et al. 1987) confirm a slightly more mantle-dominated source than the granitoids within the Bergslagen segment, although there is some overlap. This belt can be traced magnetically beneath the Caledonides to the edge of the Archean craton in the north (Eriksson & Henkel 1983). Nystrom (1982) describes the belt as consisting of a series of linear composite, batholiths of mantle origin. The granitoids display an extensive compositional range, mostly of granitic or granodioritic composition, but also with monzodiorites, monzonites and syenites with minor diorites and gabbros. The belt includes Svecokarelian basement enclaves and the Svecokarelian orogen is thought to have constituted its basement (Nyström 1982).

Migmatites, veined gneisses and pegmatites

There is some uncertainty about the exact meanings of the terms *migmatit* or migmatite, *adergnejs* or veined gneiss and *pegmatitgnejs* or pegmatite-gneiss in the Swedish literature.

The Swedish descriptions are much influenced by transformist philosophy. Thus Lundergårdh & Fromm (1971), writing about the southwestern part of the district state that 'the veined gneisses represent the lowest stage of a continuous transition to late orogenic granites'. Then the interpretation of late, relatively undeformed, pegmatites clearly cross-cutting all earlier rocks as the result of masses of mobilisate collecting at structurally suitable point and 'breaking through' the supracrustals (cf. Geijer & Magnusson 1944) can be appreciated. In this interpretation no genetic distinction is made between the veined gneiss, the pegmatitic gneiss and the clearly later cross-cutting pegmatites.

The constituent parts of a migmatite have been described in terms of the paleosome (the part having the appearance of the parent rock) and the neosome (the newly formed rock). Ashworth (1985) prefers the term mesosome to paleosome, since there is some confusion between paleosome and protolith in some authors. Lundström (1974) suggested from eastern Bergslagen that migmatites with paleosome + leucosome + melanosome were formed *in situ*, whereas rocks with only the paleosome + leucosome, each with contrasting compositions, were formed through injection processes. The difference from the point of view of metamorphic petrogenesis is quite important: the *in situ* migmatites appear to have reached incipient melting conditions, whereas the injection migmatites had these conditions forced upon them.

Lundergårdh (1974) most clearly defined the classical Swedish view of the difference between the veined gneiss and migmatite: 'Older rocks with schlieren and veins of newly crystallized material, mainly medium to coarsely crystalline K-feldspar accompanied by varying amounts of quartz are called veined gneisses, whilst new crystallization of granite and pegmatite with lighter or more disperse mafic material and with sharp or diffuse borders around the remains of older rocks are called migmatites'. Mehnert (1968) defined veined gneisses as migmatite in which the paleosomes are irregularly traversed by vein-like neosomes. In fact, the veins of the common Fennoscandian veined gneisses consist of quartz and feldspar-rich material which quite closely follows the contortions of the gneissose foliation, pinching and swelling irregularly. The veins appear to be leucosomatic material which has been produced *in situ* during plastic deformation of the rock.

The classical Swedish description of veined gneisses includes a transition to a rock with a coarser grained leucosome, which is mapped as *pegmatitgnejs* or pegmatite gneiss (cf. Geijer & Magnusson 1944). The pegmatitic leucosomes in the gneiss appear thicker than the leucosomes or the ordinary veined gneisses. The density of pegmatitic leucosome material varies until very little of the paleosome remains. This variation in leucosome density is important since it increases with increasing temperature (Johannes 1984).

The relationship between the migmatites and granitoids has been the subject of extensive philosophical debates between transformists and plutonists over the years. From the advantage of this point in time it does seem that the connections between the migmatites and any particular granitoid generation in Bergslagen remain unclear. Supracrustal remnants are found within each granitoid generation and gradational boundaries can be found locally within the margins of individual stocks. However, reference to the regional distributions of synorogenic and late orogenic granitoids, and regions of migmatitic affinity (Figs 1a, b, c) illustrate no general spatial relationship. Indeed, the most intensely migmatised areas seem to be concentrated in the supracrustal regions of central southern Bergslagen, in areas where synorogenic granitoids are no abundant. The late orogenic granitoids, classically associated with the peak of metamorphism and considered to have resulted from that process (cf. Magnusson et al. 1962), appear to be randomly scattered throughout the area.

The area of migmatisation on Fig. 1c is compiled from the quadrangle maps of the Geological Survey of Sweden, particularly the modern series Af. This coverage is still incomplete with around 30 of the ca 80 possible map sheets published. Ingmar Lundström (Lundström 1974, 1983) and, especially, Goran Stålhös (Stålhös 1969, 1972, 1982) have paid particular attention to the problems of metamorphic petrology. In Fig. 1c I have collected together all the areas mapped by various workers as migmatites or veined gneiss under two hatchings related to the relative stability of muscovite. The distribution is taken from the available quadrangle maps and is a generalization of these detailed observations complemented by my own general observations from working in the area. The interrupted line divides an apparently more pegmatite gneiss-rich zone which borders the Småland-Värmland intrusions and which was originally noted by Magnusson et al. (1962), although the figure is not exactly coincident with their work. Vein complexes commonly fringe igneous intrusions (cf. Ashworth 1985) but their source may not be obvious if the main intrusion is not exposed.

Lundqvist (1979) notes that the late-orogenic granites are pegmatite-rich compared with the early orogenic phases. This apparent relationship between the late-orogenic granitoids of Bergslagen and pegmatites has an economic significance since, as mentioned above, some of these pegmatites are REE-bearing. This contrasts with classical rare earth pegmatites which are commonly a feature of highly alkaline granitoids and syenites.

Welin & Stålhös (1986) describe three generations of pegmatites: the first was related to the syn-kinematic intrusives, the second to migmatization and the peak of metamorphism and the third to the late-orogenic granites. They dated zircons in a deformed, second generation, pegmatite with the U-Pb method and found an age of 1854 ± 5 Ma coincident with the ages of the synorogenic granitoids. This means that metamorphism was closely related to the intrusion of the early and syn-orogenic granitoids. There is no geochronologic evidence for regional metamorphism after 1840 Ma in Bergslagen.

Stålhös (1969) noted that the third generation pegmatites associated with the late orogenic granitoids are by far the most abundant. At a critical locality in the Swedish Botanical Gardens, just outside the old Geological Survey building in Stockholm, pegmatites clearly cut the veined gneisses but are included in a large fragment within the late orogenic Stockholm granite. Stålhös remarked that the late orogenic pegmatites appear consistently *older* than the late orogenic granites. This is not consistent with the idea of pegmatites being late stage volatile restites from a crystallizing granitic magma. One possible explanation is that the final stage of intrusion of the late orogenic granitoids was through diapiric rise and that they in fact penetrated their pegmatized roofs. Such an explanation is not, however, entirely consistent with the late orogenic granitoids being formed through the culmination of *in situ* melting of metagraywackes (cf stålhös 1969). Welin & Stålhös (1986) appear to consider that the undeformed third generation pegmatites represent one form of intrusion of the late orogenic granitoids. Welin (1980) had previously determined a mineral U-Pb age of 1790 Ma for these pegmatites. This is in agreement with the 1777 Ma whole rock Rb-Sr age derived for the first generation pegmatite, which defines the final stage of orogenesis in this eastern area, and the Rb-Sr ages of 1.81 and 1.84 Ga for muscovite books on the Finnish side (Hopgood et al. 1983). This data coincides with the zircon age of the late orogenic Stockholm granite of 1789 ± 30 Ma (Patchett et al. 1987).

In the southwest of the region, Wikström (1975) distinguished younger granitoids from migmatitic granitoids. The younger granitoid is a microcline granite but includes extensive zones of plagioclase-rich granodiorite. Wikström notes that pegmatites distinctly emanating from these essentially post-orogenic intrusives are relatively scarce. However, in nearby areas pegmatites can make up to 40% of the rock usually with sharp contacts with the older veined gneisses. These pegmatites were related by Wikström (1975) to migmatization and the formation of 'migmatite granites' where the leucosome constitutes 95% of the rock. This would place them in the missing second generation of Welin & Stålhös (1986) in the east of the area.

Regional metamorphism

Magnusson's (1936) original model for the regional metamorphic history of Bergslagen involved two regional metamorphic events. The first was associated with the intrusion of the synorogenic granitoids and the later, and more intense, culminated in anatexis and the formation of the late orogenic intrusions. Stålhös (1969) examined the possibility that there was a single event of increasing intensity over a long time period. Vivallo (1984) identified only one prograde event in the Garpenberg area, a regional high temperature low pressure amphibolite facies imprint. Lundström (1983) identified a similar metamorphic history in the western, Lindesberg, area. Both authors identified an earlier intensive period of hydrothermal metasomatism and a later pervasive, retrograde greenschist facies event. This later event was originally identified by Nyström & Levi (1980) as caused by a post-orogenic period of burial metamorphism. Stålhös (1972, 1982) identified an early prograde phase in the eastern part of the province and suggested that this was related to contact metamorphism by the synorogenic intrusives. However, this spatial relationship is not obvious from the geological maps of the areas concerned.

In the far west of the area, the Grythyttan district displays only greenschist facies metamorphism. Previously, it had been supposed that this area represented a higher stratigraphic level that had missed out on the deeper, transformist processes that had affected the rest of the province. Recently, however, Lundström (1987) has argued that similar stratigraphic levels have suffered upper amphibolite grade metamorphism elsewhere in the province and that the metamorphic changes are gradational. Lundström's conclusion is supported by the absence of any major tectonic zone separating the lower greenschist terrane from the amphibolite terrane. The NE trending Vattern-Gävle fracture zone is situated too far to the east and represents post-orogenic lateral movements of ca 100 km (Henckel & Eriksson, 1987).

A similar though less intensive decrease in metamorphic grade has been observed the far east of the Bergslagen area, in exposures on the island of Uto in the Stockholm archipelago (Stålhös 1982). The change from the veined gneiss terrane to andalusite-bearing mica schists occurs within 5 km. Stålhös (1982) supposed that the veined gneiss terrane represented a deeper section of the crust, but noted that there is no major tectonic zone between the two terranes. Further to the east in SW Finland amphibolite facies metamorphism translates into the granulite facies of the W. Uursma district. On the island of Kemio, in the extreme southwest tip of Finland, Dietvorst (1982) estimated a metamorphic peak of 550–680° C and 3–4 kbar. Similar conditions prevail 40 km east in Orijarvi but rapidly increase to 750–825° C and 3–5 kbar in the granulite terrane (Schreurs & Westra 1985). The age of the metamorphism in southwest Finland has been determined by Hopgood et al. (1983) to 1.89–1.87 Ga, by measurements on a garnetiferous gneiss and the neosome of a migmatite.

The Al_2SiO_5 system in bergslagen

Because different workers mapped different parts of Bergslagen and emphasised different aspects, it is only possible at present to get an overview of the geometry of the regional metamorphism in Bergslagen through a simple system like andalusite-sillimanite-kyanite. Kyanite is virtually absent from this terrane as is usual in early Proterozoic environments. However, andalusite and sillimanite are widespread throughout the province. Sillimanite is almost restricted to the area of veined gneisses in the central eastern area. Reports of widespread sillimanite in the absence of veined gneisses are limited to the western Lindesberg area (Lundström 1983) and the northwestern Saxberget area (Karlsson 1980). However, observations are limited by the abundance of granitoids in the area and these areas may represent a contiguous zone.

Otherwise the district is characterised by the widespread occurrence of andalusite. Staurolite, Winkler's (1976) typical indicator mineral for low pressure, medium grade regional metamorphism is less common. Vivallo (1984) identified it in the Garpenberg area in the central northern part of the province, where it occurs in prograde assemblages in the absence of chlorite.

The triple point for the stability of the Al_2SiO_5 polymorphs of Holdaway (1971) is generally accepted as accurate to within 0.5 kbar and 50° C (cf. Essene 1982) and is plotted on Fig. 2. Small compositional variations can lead to experimental temperature variations towards the limits of the uncertainty, and this probably explains some of the conflicting local observations from Bergslagen.

The mica-K-feldspar system in bergslagen

The importance of muscovite breakdown for releasing water in zones of high temperature–low pressure metamorphism was first recognised in the central eastern part of the Bergslagen district by Stålhös (1969). Reactions involved in this process describe the breakdown of muscovite in the presence of quartz to form K-feldspar:

$$\text{muscovite} + \text{quartz} = Al_2SiO_5 + \text{K-feldspar} + H_2O$$

The water itself becomes an important parameter in determining the possibility of melting.

Kerrick's (1972) experimental data are widely accepted (cf. Essene 1982) and have been used in Fig. 4. The dependence of the mole fraction (X) of water in determining the isograd is apparent from the figure. Basically, the lower the X (H_2O) the greater the area occupied by sillimanite or andalusite + K-feldspar and the smaller the mica + andalusite or silliminate becomes.

The area where muscovite breaks down in the presence of quartz is coincident with the area of veined gneisses in the central eastern area of Bergslagen (Fig. 1c). I have not been able to find any evidence for this reaction in Bergslagen in the absence of the veined gneisses. In contrast, veined gneisses appear in the southwestern part of the province, toward the post-orogenic batholiths of Småland and Värmland in areas where muscovite appears stable in the presence of quartz.

Melting

As mentioned above the veined gneisses appear to represent zones of incipient melting. The melting isograds of materials of granitic composition in terms of the mole fraction H_2O are shown on Fig. 3. As the $X(H_2O)$ decreases the temperature of gran-

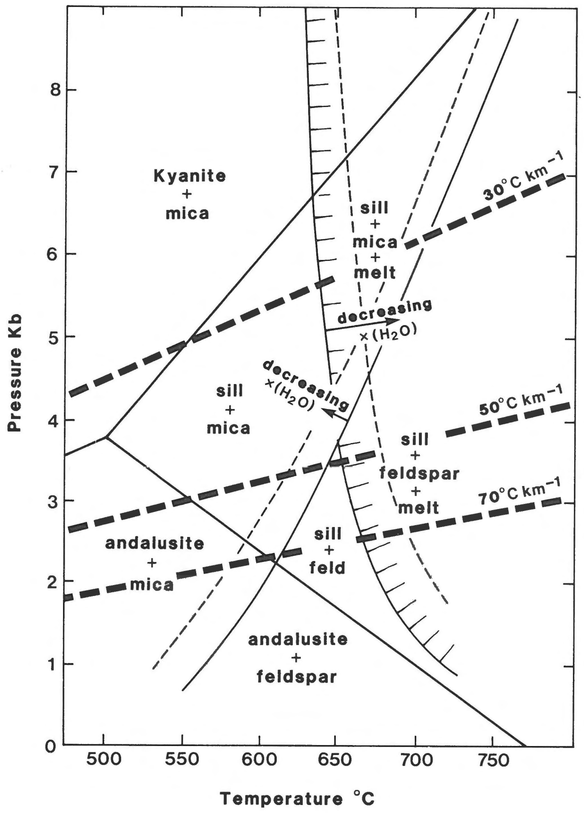

Fig. 2. Typical geothermal gradients for $\varrho = 2.7\,g\,cm^{-3}$ superimposed on a P-T summary diagram for the aluminium silicate, feldspar-mica-quartz and granite melting systems. Data have been taken from Holdaway (1971) and Kerrick (1972) and may be accurate to within ± 50° C and 0.5 kbar.

ite melting increases. Johannes (1984) notes that the amount of water necessary to change a metamorphic rock into a magmatic looking one is small. Perhaps 1 wt% water is all that is required to transform parts of a gneiss into magmatic looking leucosomes. However, progressive metamorphism leads to dehydration and by the time melting conditions are reached the rock will be relatively dry. Stålhös (1969) noted that the veined gneiss zones could occur in isolated areas within unaffected gneisses. He suggested that the muscovite breakdown reaction noted above could provide water at the right place and time to explain these observations. This is consistent with Walther & Orville's (1982) remark that a discrete fluid phase will only be present under these conditions during the devolatization process itself. The evidence from the Kola Deep (Kozlovsky 1986), however, and geophysical measurements within the present day crust may indicate that fluid filled zones are more frequent than was previously supposed (cf. Fyfe 1987).

Discussion

Mg-Fe distribution coefficients for garnet-biotite pairs have been examined in Bergslagen in two studies. Vivallo (1984) found in the north of the province that the K_D vs $X(\mathrm{Mn_{gar}})$ plots were straight lines, indicating that these minerals represent a single metamorphic event at around 550° C. However, these data have been corrected for Mn but not for Fe(III). Three garnet-biotite pairs from the Saxberget district (Vivallo & Rickard in prep) in the northwest of the province give Ferry & Spear (1978) temperatures around 530° C and a garnet-cordierite pair 550° C.

These temperatures are equivalent to the low pressure (up to 2 kb H_2O) estimated for the earliest metamorphic stage in the southeast of the region by Stålhös (1982). However, Stålhös (1969) estimated temperatures up to 700° C in the central veined gneiss areas; i.e. to the limits of granulite facies.

The conditions in Bergslagen can be discussed in terms of Fig. 2. The following assemblages are common: (andalusite + muscovite + quartz), (sillimanite + muscovite + quartz), (sillimanite + feldspar + melt) and (sillimanite + muscovite + melt). The following assemblages are rare or absent: (andalusite + feldspar + melt) and (sillimanite + feldspar with melt absent).

As $X(H_2O)$ decreases on Fig. 2 so the area of stability of sillimanite + feldspar in the absence of melt increases. This assemblage is less common in most of Bergslagen and thus it is probable that high grade metamorphism took place under conditions where $P(H_2O) \rightarrow P(\mathrm{total})$.

As shown on Fig. 1c, sillimanite is limited mainly to areas where incipient melting has occurred. There appears to be no gradient of metamorphism from either of the veined gneiss centres to the andalusite – dominated areas. The two further sillimanite-grade areas with melt absent occur in the west and northwest of the province.

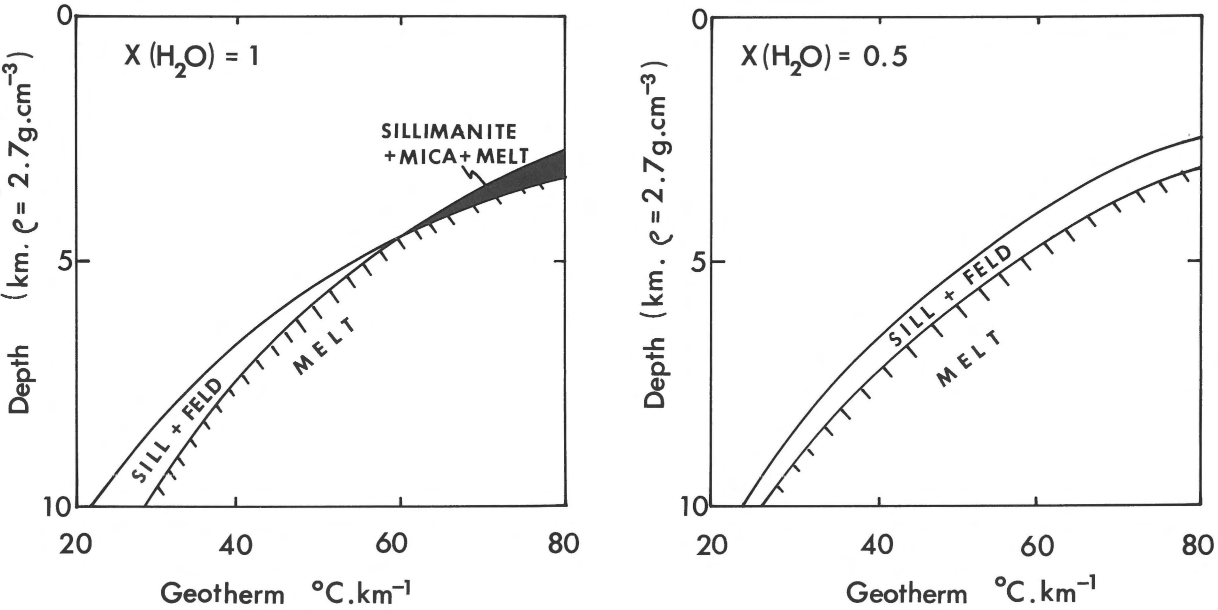

Fig. 3. Diagrams illustrating the effect of varying $X(H_2O)$ values on the sillimanite-mica-feldspar-melt system. As $X(H_2O)$ decreases the sillimanite + feldspar in the absence of melt area expands across the diagram for all geothermal gradients ($\varrho = 2.7\,g\,cm^{-3}$). Since this association is rare in Bergslagen, whereas sillimanite-mica-melt is observed, $X(H_2O)$ during metamorphism was high in Bergslagen.

Geothermal gradients

The temperature data from the Kola Deep (Kozlovsky 1986) suggest that the concept of linear temperature-depth relationships in the modern crust is a very approximate representation of the actual situation. With this in mind, we can construct diagrams for geothermal gradient versus depth for the metamorphic reactions of interest (Fig. 4). The diagrams contain the additional approximation that the density of the crust is consistently 2.7 g cm^{-3} to the depths of interest; i.e. ca 30 km. Any vertical section shows the mineral assemblages expected with depth. The diagrams are interesting because they indicate the possible effects of changing gradients on mineral assemblages, such as might be expected to occur during a regional metamorphic event.

Fig. 4 suggests that at geothermal gradients below 50° C km^{-1} kyanite-bearing assemblages might be expected at depths below ca 10 km during prograde metamorphism. Furthermore, sillimanite + feldspar in the absence of melt should also occur. At gradients above 50° C km^{-1}, the sillimanite + mica + melt assemblage becomes increasingly significant at depths between 8 and 10 km.

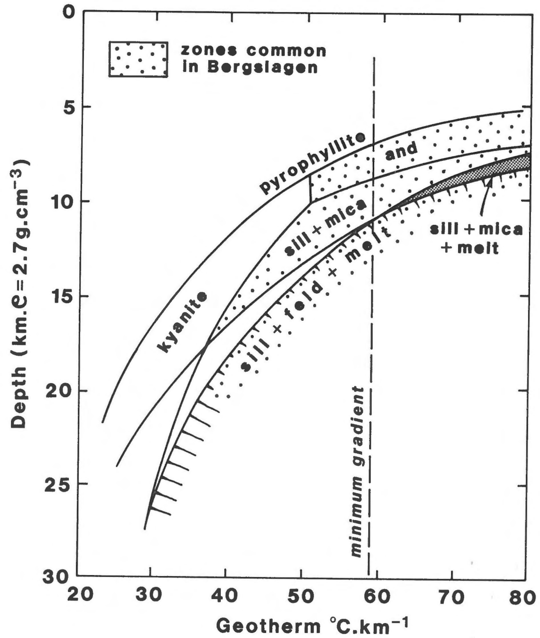

Fig. 4. Depth versus geotherm ($\varrho = 2.7\,g\,cm^{-3}$) for aluminium silicate-feldspar-mica-melt assemblages. The absence of kyanite and sillimanite-feldspar (without melt) in Bergslagen suggests a minimum geotherm of 60° C km^{-1}.

Few thermal gradients have been estimated for Bergslagen. Karlsson (1980) estimated ca 50° C km^{-1} for the Saxberget area. Stålhös (1972) estimated a similar gradient for the Uppsala area in the northeast, although he recalculated the data at that time to take account of the 'thermal front'. For the more intensely metamorphosed central district he actually estimated a lower gradient of around 40° C km^{-1}, which he ascribed to the absence of syn-orogenic granitoids. However, this gradient assumed a pressure equivalent to 5 kb H_2O although in his 1969 paper he estimated a maximum pressure equivalent to 4 kb H_2O. This latter would once again give a gradient of ca 50° C km^{-1}. Baker (1985) estimated a gradient of about 75° C km^{-1} for the Hallefors-Grythyttan zone in the west of the area, based on a rather high Na-K feldspar equilibrium temperature of 150° C.

Contact metamorphism

The relationship between contact metamorphism and regional metamorphism has been explored by Barton et al. (in press) for the Mesozoic of the western United States. They note that compiled dates for that area are consistent with the contemporeneity of magmatism and metamorphism and that regional low pressure metamorphism is closely associated with areas containing >50% intrusions exposed at <14 km depth. The depth of exposure is the dominant control on the character of the contact metamorphism. Barton et al. (op. cit.) calculate the time-temperature distribution for a simple slab model of a granitoid intrusion (Fig. 5a). They calculate that contact metamorphism is limited to areas where the imposed thermal gradient due to the intrusion is considerably higher than the regional gradient. As the regional thermal gradient increases, the contact metamorphic effect due to the intrusion becomes less apparent (Fig. 5b), even if the intrusion is allowed to rise to similar temperature levels in the crust. This diagram implies that the intrusion would have had little effect on the regional metamorphic mineral assemblages produced through simple burial in the early Proterozoic.

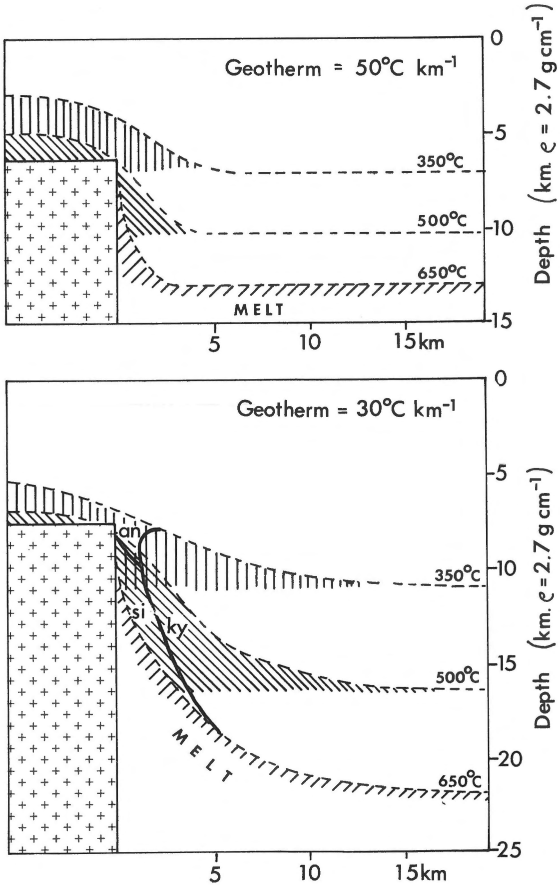

Fig. 5. Diagrams illustrating the relative importance of contact metamorphism in areas with normal geotherms (30° C km^{-1}) and enhanced geotherms (50° C km^{-1}), from Barton et al.'s (in press) model calculations. The shaded areas under the curves illustrate the extent of additional heating (contact metamorphism) for an intrusion rising to approximately the same thermal level in the crust in both cases. The extent of the contact metamorphism on the high geotherm area is limited. This means that even small supracrustal enclaves in closely spaced plutons will not suffer significant contact metamorphism. The aluminium silicate equilibrium is figured on the normal geotherm plot; at higher geotherms this spatial geometry between these phases is lacking. In particular, kyanite PT space is missed by these high thermal trajectories. Note also that the isotherms are time dependent and do not all reach the indicated place at the same time.

Metasomatism

A major consequence of the high geothermal gradients in sub-aqueous or submarine environments is the intensity of the forced aqueous convection systems under steep gradients and concomitant pervasive metasomatism. The province is characterized by marked alkali metasomatism, involving considerable enrichments in Mg, Na and K. Mg metasomatism is closely linked with ore formation and was originally suggested by Berge (1978) and Schemerhorn (1978) to result from sub-sea floor alteration associated with volcanism. More recently, Parr & Rickard (1987) have noted that part of the more exotic and variable alteration chemistries observed in the area may result from non-marine environments. Arvanitidis & Rickard (1981) interpreted Na and K metasomatism as sub-sea floor alteration and noted that in such an environment K enrichment would reflect the cooler upper parts of the hydrothermal system and Na enrichment the warmer lower parts.

With an intensive geothermal gradient of at least ca $50^{\circ}\mathrm{C\ km^{-1}}$, the K-Na feldspar equilibrium boundary at $130^{\circ}\mathrm{C}$ would be situated within 3 km of the sub-sea floor surface, leaving relatively thin zones of K enrichment relative to Na. With a regional gradient of this magnitude, the hydrothermal system would have been relatively vigorous and result in the regionally extensive alteration zones observed in the province. By comparison with present-day geothermal areas, it would also result in intensive hydrothermal eruptions (cf. Elder 1981). This may explain the dominance of fragmental volcanic rocks over lavas in this area.

It is interesting to note that such intensive regional hydrothermal circulation would have a marked effect on the mobility of the ore elements in the area. Furthermore, the marked geothermal gradients would have had significant effects on the precipitation of the ore components both within the volcano-sedimentary pile, on the seafloor and within terrestrial environments. The regional heat flow at a thermal gradient of $50^{\circ}\mathrm{C\ km^{-1}}$ is in the order of $10^{-1}\ \mathrm{Wm^{-2}}$. This compares with ca $35\ \mathrm{Wm^{-2}}$ for the very active ore-depositing Waiotaupu Geothermal System in New Zealand at the present day (Hedenquist & Henley 1985) and $2\ \mathrm{Wm^{-2}}$ the North Island as a whole (Elder 1981). Much of the flow in the North Island is focussed in groups and this is expected to have occurred in the Bergslagen district. Indeed, Oen et al. (1982) and Baker & De Groot (1983) had proposed that Mg metasomatism was concentrated in structurally controlled zones in the west of the area.

Finally, a further important feature of the heat flow in North Island, New Zealand, is the regional heterogenity of its distribution. Elder (1981) notes that in the hydrothermal zone, there occurs an abrupt transitional region, some 40 km wide, in which the conductive heat flow is zero. Even with high regional geothermal gradients, we must therefore expect there to be zones where the heat flow has not been as great, although these will not, of course, be situated near volcanic centres. This may explain the existence of relatively well-preserved areas of sedimentary rocks in Bergslagen, such as in the west around Grythyttan, at the same stratigraphic level as intensely altered rocks in other areas.

High geothermal gradient and basement preservation

The Svecofennian province of the Svecokarelian orogen is defined as that part that has no known basement. However, many of the petrologic characteristics of the Bergslagen province seem to indicate ensialic development (e.g. Johannson & Rickard 1985, Vivallo & Rickard 1985). The only vague evidence for the existence of a pre- 1.9 Ga basement is the 2.2 Ga zircons found in sedimentary quartzites in the south of the area (Åberg 1978) and in the Tampere district of Finland (Huhma 1987). Recent Nd isotopic studies confirm the lack of an Archean component to the crust in this area. However, Vivallo & Rickard (1985) suggested that the pre-existing crust was ca 2.2 Ga old.

Patchett et al.'s (1987) e_{Nd} data for the early volcanics and granitoids splits into two groups, one concentrated around 0 and one around +1.5. Patchett et al. only considered these data in terms of possible Archean sources, and concluded that the mantle in this area was not as depleted as in consanguinous areas of Finland and Greenland, where the mantle was +4 to +5. An alternative explanation would involve a substantial contribution of ca 2.2 Ga crust, which has been suggested for Finland by Huhma (1987). In this model the missing pre-Svecofennian basement is represented by the early granitoids, which consist of more-or-less 2.0–2.2 Ga crust admixed with varying amounts of 1.9 Ga mantle material, and giving rise to granitoids with mixed I- and S-type characteristics.

PT-t pathway for Bergslagen

A P.T-t pathway for a Bergslagen sample is illustrated in Fig. 6. This pathway is, of course, a crude approximation to a possible average experience of a lump of Bergslagen rock. The actual paths followed by Bergslagen samples would occupy a probability envelope around this line (cf. Grant 1985). Samples following pathways below this line would probably be heated sufficiently to suffer batch melting and constitute the stuff of the synorogenic granitoids. The greater part of the Bergslagen supracrustals followed pathways above the line and spent much of the period around 1.85 Ga in the andalusite stability field.

The diagram is constructed for a 50° C km^{-1} geothermal gradient where $P(H_2O)$ approximates P(Load) and where the average rock density is 2.7 g cm^{-3}. The 50° C km^{-1} gradient is considered the minimum average geothermal gradient. Considering modern analogues of high heat flow environments, the geothermal gradients were likely to have varied greatly. At various times zones of virtually zero conductivity occurred together with structurally controlled areas with heat flows several times greater. This is consistent with the varying metamorphic grades observed at the same stratigraphic level (Lundström 1987). Thus some parts of the low grade Grythyttan area might represent recharge areas during some stages of the regional development.

The illustrated pathway (Fig. 6) suggests that the metamorphic relationships can be explained by burial in a zone with a high geothermal gradient. The metamorphic episodes observed in Bergslagen tend to be non-deformative and unrelated to the events that gave rise to deformation (cf. Vivallo 1984). The average crustal thickness of 13 km which is a consequence of the 50° C km^{-1} geothermal gradient is consistent with the average thickness estimated for the Bergslagen supracrustals of 10–15 km.

The pathway is consistent with the conclusions of Vivallo & Rickard (1985), Lundström & Papunen (1986) and Oen (1987) that the Bergslagen development was essentially ensialic, and the supracrustals were deposited on a pre-existing basement. In this model much of the earlier basement would have been buried to depths of greater than 13 km and thus have suffered anatexis.

The high heat flow model has other consequences. In eastern Bergslagen it appears that the lowermost supracrustals are metasediments (Lundström & Papunen 1986). It has always been a problem to explain why sediments underlie volcanics in simplistic geotectonic interpretations, such as might be represented by an island arc model (Hietanen 1975, Patchett et al. 1987). In a high heat flow environment, sedimentation into basins would result in burial of the original basement crust to melting levels. The rise of the intrusives through the sedimentary sequence would result in extensive felsic volcanism. The high heat flow would cause an elevation in the crustal regime where ductile processes dominate over brittle fracture. The granitoids would thus penetrate nearer to the surface. Interestingly, because of the intensive hydrothermal activity set up by high regional heat flows, this would be mainly explosive giving rise to the large relative volumes of felsic pyroclastics observed in Bergslagen.

If burial depth was a major factor in determining the resultant metamorphic grade, the distribution of metamorphic facies reflects basin geometry as well as differential heat flow. Thus the deepest parts of the basin in which the supracrustals were deposited was coincident with the distribution of the veined gneisses in the eastern area. Stålhös (1969) had previously supposed that the metapelites that dominated in that area were more resistant to melting than the metagreywackes of surrounding areas. However, the concentration of metapelites in the areas of highest grade metamorphism is also consistent with this being the deepest parts of the basin in this model. The present geometry of the basin on this model is inverted, and has resulted from post-metamorphic uplift.

The end result of the continual basin filling was a shallow water, terrestrial environment which is

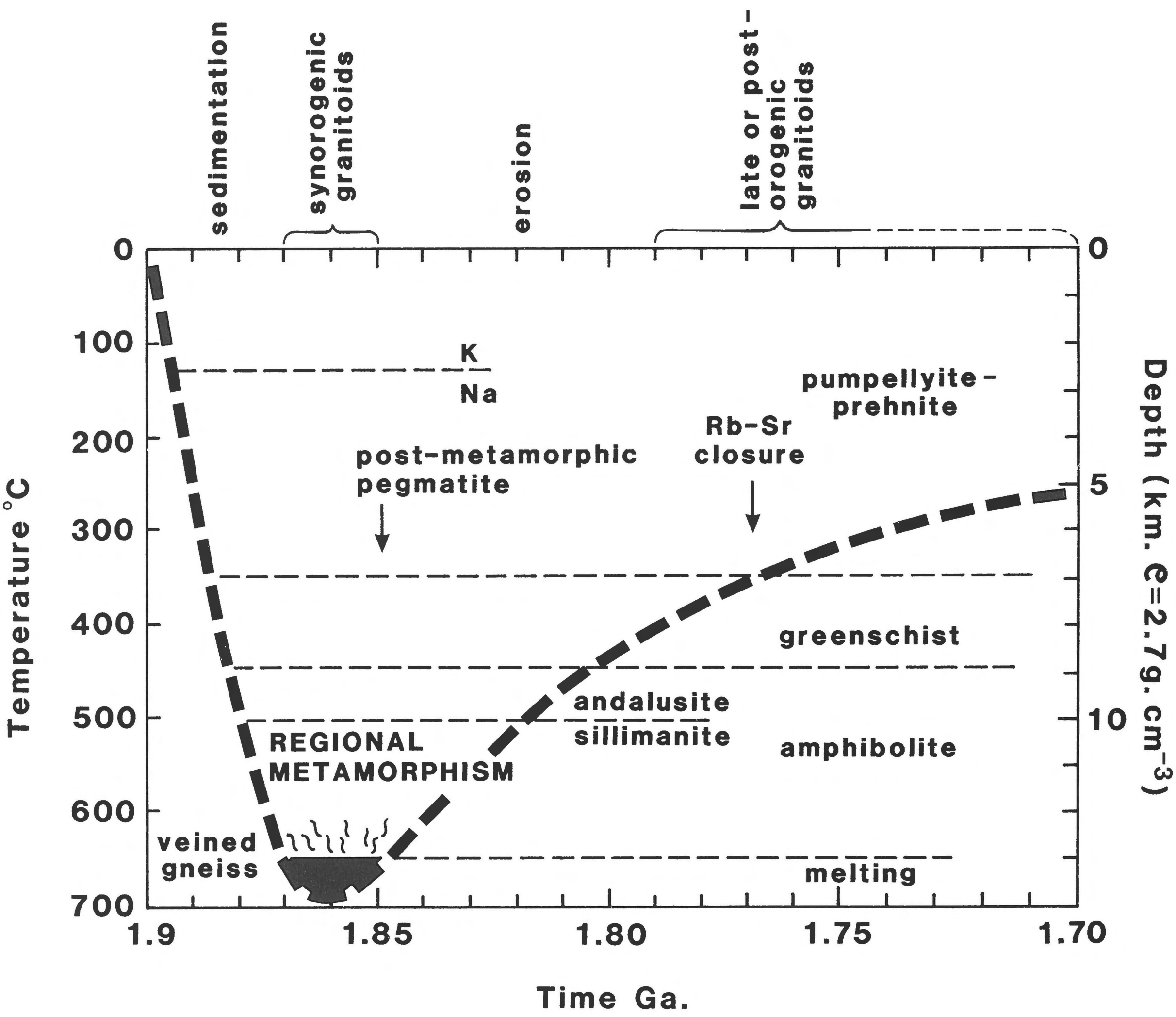

Fig. 6. Average PT-t path for Bergslagen rocks in the early Proterozoic. The actual path occupies a probability envelope around this path. The initial sedimentation and burial system occupied a short time interval, although previous sedimentation episodes occurred, and sedimentation continued through much of the period. The metamorphic peak reached through subsidence of the extensional basin is also probably shorter than indicated, perhaps 5 Ma. Melting initiated during this period produced the early granitoids and large volumes of volcanoclastics which accelerated subsidence. The epeirogenic rebound is figured in such a way that the thermal trajectory reaches Rb-Sr closure around 1.79 Ga, coincident with the intrusion of the post-orogenic granitoids. The shallowness of the trajectory would enable a long equilibration period in greenschist facies conditions. The last stage is long shallow burial producing the pumpellyite-prehnite facies recorded by Nyström and Levi (1980).

well-preserved in the west of the region. Sundius (1923) originally described the Grythyttan paleoenvironment as being characterized by braided streams and ephemeral lakes. This paleoenvironmental model has been found applicable to the easterly adjacent Ljusnarsberg area by Parr & Rickard (1987) and Parr (1988, this volume), where subaerial volcanism has been identified.

Conclusions

I have not produced a chronologic table of metamorphic events in Bergslagen, except as a broad succession of events indicated in Fig. 6 and elsewhere in the text. The reasons are twofold. Firstly, the major events were compressed into a less than ca 20 Ma period and we have insufficient precision dating combined with detailed geological observations to discriminate between them. Secondly, the processes much have been on-going at the same time.

In this model we have a fundamental process of sedimentation and basin fill followed by melting, granitoid intrusion and volcanism. In the shallower, western part of the basin the early sediment-dominated event was not as well developed, and the reduced sediment thickness only allowed greenschist facies to be developed. However, I suppose that sedimentation continued throughout the period, although it was diluted by catastrophic pyroclastic deposition during the middle (dated) part. In both east and west, sedimentation-dominated supracrustals continued to be deposited after the major volcanic episode, with strong evidence for some shallow-water terrestrial deposits at least in the west.

The volcanoclastics and lavas are petrogenetically related to the intrusive synorogenic granitoids (cf. Oen et al. 1982, Vivallo 1984, Baker 1985) and penetrated their own volcano-sedimentary pile. That is, at deeper levels of the crust granitoid magmas were being developed which rose to higher crustal levels at the same time as sedimentation was continuing. The emplacement of the granitoids resulted in increased sedimentation, possibly in caldera-like basins, of volcanically-derived material. The process would have been virtually autocatalytic and resulted in the extreme mixing of an essentially ensialic crust envidenced by the exceptional homogeneity of the common lead isotope data from this area (Johannson & Rickard 1985).

The subsequent 50 Ma appears to have been a relatively quiescent period of uplift and erosion in Bergslagen. This general trend is marked by the apparent closure of Sr-Rb isotope systems around 1.79 Ga (Welin & Stålhös 1986). On Fig. 6 this is denoted as a result of simple epeirogenesis with crustal thicknesses of less than 8 km. Continuation of this trend brought this crustal segment into the pumpellyite-prehnite zone of low grade metamorphism originally identified by Nystrom & Levi (1979) and discussed in the Garpenberg area by Vivallo (1984).

The intrusion into the Bergslagen province of post-Svecokarelian granitoids which constitute the major western marginal Småland-Värmland belt, appears to have been dominantly structurally controlled. Although, essentially magnetite series granitoids, they do show marked alkali trends (Gorbatschev 1971, Nystrom 1982, Parr in prep.). I wonder whether they do in fact represent an Andean style margin or possibly a major failed rift or aulocogen. Whichever geotectonic environment they represent, the identification of these syenite-trending, post-Svecokarelian granitoids with the 'late orogenic' intrusives within the Bergslagen province, is more consistent with conventional igneous associations of the rare earth-bearing pegmatites.

The geotectonic environment of regional metamorphism in Bergslagen

Hietanen (1975), Wilson (1980) and Patchett et al. (1987) have interpreted the Bergslagen province as an island arc. Rickard (1978) noted that these interpretations were not entirely satisfactory from a metallogenetic viewpoint, and suggested the involvement of rifting and marginal basin development. Oen et al. (1982) interpreted the western, Grythyttan area in terms of a rifting model. Vivallo & Rickard (1985) concluded that the province developed in an ensiallic environment in an essentially extensional regime. Their conclusions were based mainly on the bimodality of the volcanism in the area. They invoked a spreading-subsidence process to explain the coincidence of essentially extensional petrologic characteristics with a coincident period of E-W compression (cf. Stålhös 1969). Oen (1987) has collated more evidence from the work of the Amsterdam group for the rifting model and has extended this to the whole of the province.

The major part of the metamorphic history of Bergslagen seems to have been concentrated in a period of less than 20 Ma between 1.87–1.84 Ga. This is consistent with the data from southwestern Finland, which point to a short episode between 1.88–1.86 Ga (Hopwood et al. 1983). At this time sedimentation has reached sufficient thickness so that deep crustal temperatures had exceeded the granite melting. It appears that sedimentation had been intermittent for a long period prior to this. However, the acceleration coincides with a major plate tectonic episode that produced terranes such as the more northerly Skellefteå arc around 1.89–1.87 Ga (Rickard 1986). This event was global in dimension extending from Finland through Arizona and represents an early Wilson cycle (Rickard 1987).

As pointed out by Dewey (1982), the only basin formation process which satisfies the geologic environment of ensialic basins like Bergslagen is the lithospheric attenuation model of Mackenzie (1978). This model is consistent with the pre-1.86 Ga history of the region. Bowes et al. (1984) pointed out that it was only around 1.86 Ga that the Fennoscandian segment of the present Baltic Shield seemed to begin to behave as a structurally coherent segment. This date coincides with the major period of Bergslagen development. After 1.86 Ga, the shield began to behave tectonically as a coherent unit as the final collision of the Wilson cycle occurred. Extensional processes were likely to have been significant prior to this event. The subsidence mechanism was virtually autocatalytic in the Bergslagen province, being driven initially by sediment loading and subsequently, through loading by large volumes of pyroclastics which were the surface expressions of anatexis.

It is obvious that the high heat flow model I have presented in this study displays the characteristics of a typical Phanerozoic extensional environment. These environments are characterised by crustal thinning, extensional basin development, bimodal volcanism, and elevated heat flows.

It is interesting to ask whether the Bergslagen development resulted from extension, or whether the extension resulted from elevated global heat flow during the early Proterozoic. This gradient need not have been imposed on the area by some thermal event, but is consistent with average gradients to be expected in the early Proterozoic due to 1.5–2.0 times higher radioactive heat production at that time. That is a present continental gradient of ca 30° C km^{-1} would be equivalent to 45–60° C km^{-1} in the early Proterozoic. Independent evidence supporting higher 1.9–1.7 Ga heat production has been provided by crustal modelling calculations by Patchett & Arndt (1986).

However, the situation observed in Bergslagen is very similar to that described for the Hercynian development of the Pyrenees (Wickham & Oxburgh 1985). Here the Trois Seigneurs Massif is described as displaying a complete section from shales through andalusite and sillimanite schists to migmatites and a heterogeneous S-type granitoid. The geothermal gradient was sufficient to initiate melting at around 12 km compared with the maximum 13 km estimated independently for Bergslagen. Wickham & Oxburgh (1985) suggest that continental rifting constitutes a major site for high temperature- low pressure metamorphism. The model, involving strike-slip motion and a major continuously subsiding basin with local pull-apart basins, is equally applicable to the Early Proterozoic Bergslagen province.

The answer to the conundrum concerning elevated Proterozoic heat flow together with Phanerozoic-style geotectonic environments probably relates to the intensity of the processes involved. The higher early Proterozoic heat flow probably resulted in deeper and more vigorous crustal hydrothermal systems to remove the heat produced and more rapid mixing of the crust.

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