

Evidence for gravity subsidence and granite diapirism in the 1.8–1.9 Ga Proterozoic succession of W. Bergslagen, Sweden

P.A. de Groot¹, J.H. Baker² & I.S. Oen¹

¹ *Geologisch Instituut, Universiteit van Amsterdam, Nwe Prinsengracht 130, 1018 VZ Amsterdam, The Netherlands;* ² *Geologisch Museum, Universiteit van Amsterdam, Nwe Prinsengracht 130, 1018 VZ Amsterdam, The Netherlands*

Received 2 October 1987; accepted in revised form 16 December 1987

Key words: Proterozoic, ensialic rifting, tectonic development, granite diapirism, gravity subsidence, Bergslagen, Sweden

Abstract

Western Bergslagen, Central Sweden contains a number of large scale features including long, narrow, synformal, sediment-filled basins, separated by wide intervening areas of felsic metavolcanics in which anticlinal structures are absent. Synvolcanic granites intrude the felsic metavolcanics. Bedding, foliation and mineral lineations are sub-parallel both where bedding is sub-vertical or more rarely sub-horizontal. These features, taken in their geological context, are consistent with a dynamic system in which granite diapirism and gravity tectonic processes operated. Previous models (Oen et al., 1982; Oen, 1987) emphasize the continental rift setting of Bergslagen. We propose the following four stage tectono-magmatic model to account for the structure of the area:

Phase 1: A primary crust forming event at about 2.1 Ga.

Phase 2: Subsequent attenuation produced rifting accompanied by melting of the lower crust to give large scale felsic volcanism, contained predominantly in sinking grabens of a wider rift structure. Granite diapirism was initiated.

Phase 3: Tectonic inversion followed, with an uplift of the graben floors, and a higher emplacement of the granite diapirs. At the same time a second generation of rift basins evolved on the flanks of the updomed areas, to be filled with debris derived from the felsic volcanics. A gravity instability developed as the heavier sediments filled the grabens, contributing to the overall tectonic process.

Phase 4: A younger event of granitic magmatism.

The development of the sediment filled rift basins is the surficial expression of the deeper gravity tectonic system.

Introduction

The available geological information on the ore province of Bergslagen, Central Sweden has been used to support various interpretations of a geotectonic setting, including an orogenic model with synformal depressions caused by folding (Sundius,

1923; Magnusson, 1925, 1970), back-arc and subduction related models (e.g. Hietanen, 1975), a continental rift/aulacogene model (Oen et al., 1982; Oen, 1987), and an active, Andean type, continental margin model (Vivallo & Rickard, 1984). No detailed structural analysis has been published on W. Bergslagen and structural consider-

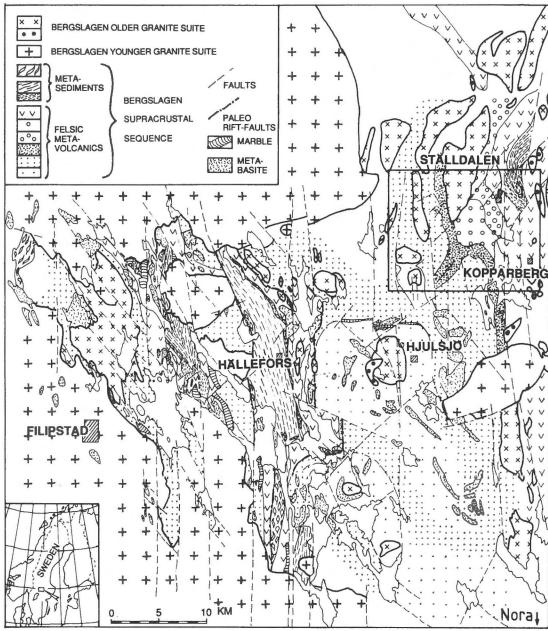


Fig. 1. Geological sketch map of western Bergslagen, compiled from Oen et al. (1982) and Baker (1985), with additional material from Lundström (1983) and Helmers (1984). Inset shows location of Fig. 3.

ations are often ignored in making geological interpretations. Previous structural investigations in Central Sweden include those of Stephansson (1975) and Stålhös (1984). Lundström & Papunen (1986) note that while two phases of deformation are generally invoked, a one-stage model is now favoured, due to constraints placed on the time available for deformation by radiometric dating. This paper summarizes the structural features of W. Bergslagen (Fig. 1), in the light of the continental rift model of Oen et al. (1982) and Oen (1987), and extends the rift model by introducing the concept of granite diapirism and gravity tectonic processes which gradually replace the epeirogenic tectonism of the rift stage.

Geological synopsis

The 1.8–1.9 Ga Bergslagen Supracrustal Sequence, comprises a >10 km thick pile of felsic metavolcanics in which metasediments appear in the higher levels, predominating at the top of the sequence

(Fig. 1). In W. Bergslagen the Bergslagen Supracrustal Sequence (BSS) is divided into three lithostratigraphic groups.

The Lower Leptite Group comprises large ignimbritic flows, possibly laterally transitional into sub-volcanic domes and intrusions (Van Meerten 1987, personal communication) in which limestone and/or ore horizons are either absent or thin and discontinuous.

The Middle Leptite Group, unconformably overlying the Lower Leptite Group in the area N of Hjulsjö (Fig. 1), is also composed predominantly of felsic pyroclastics, but contains large limestone and iron ore horizons.

The Upper Leptite – Hällefrinta and Slate Group contains a lower unit of felsic pyroclastics which pass upwards into tuffite, overlain by a sulphide-bearing black shale unit. This unit is overlain in turn by quartzitic grey shales, immature sediments derived by the reworking of the underlying pyroclastics. Lenses of coarse conglomerate are present in this upper group but are not part of a single stratigraphic unit, rather mark local unconformities. Mafic intrusives and spilites are developed towards the close of the felsic magmatism.

Submarine deposition of the felsic volcanics is supported by marine carbon isotope values ($\delta C^{13} = 0 \pm 1\%$) for marble intercalations in the BSS (De Groot & Sheppard, in press).

Felsic metavolcanics in the Yxsjöberg area have been dated at 1.9 Ga (U-Pb; Åberg & Fredriksson, 1984), while the metasediments yield an age of 1.86 Ga (Sm-Nd; Miller et al., 1986). Granite intrusions can be divided broadly into two groups, the Bergslagen Older Granite Suite (Oen, 1987) with ages of 1.9–1.88 Ga (U-Pb; Welin et al., 1980; Åberg et al., 1983a, b; Welin, 1987; Rb-Sr: Oen et al., 1984), and the Bergslagen Younger Granite Suite with ages of 1.78–1.6 Ga (Welin et al., 1977; Oen, 1982, 1983; Åberg & Bjursted, 1986). The Bergslagen Older Granite Suite comprises largely syn-volcanic intrusions (Baker, 1985; Oen, 1987) coeval with the main period of felsic volcanism. A minor phase of Hyttsjö mafic magmatism occurred at around 1.84 Ga (Oen & Wiklander, 1982) coinciding with the peak of metamorphism and compressive deformation (Moorman et al., 1982).

A continental setting for W. Bergslagen

Oen et al. (1982), Oen & Verschure (1982), and Oen (1987) developed a model of continental rifting to account for the geological phenomena seen in W. Bergslagen. Arguments supporting this model are summarized by Baker (1985). Oen et al. (1982) equate the Lower Leptite Group with an early volcanic stage, prior to an initial rift stage and rift stage marked by the Middle Leptite- and Upper Leptite-Hällefrinta and Slate Groups, respectively. Nd-Sm data from this area (Beunk et al., 1985; Miller et al., 1986) are in agreement with the findings of Wilson et al. (1985) in suggesting that the crustal precursor to the 1.8–1.9 Ga BSS had an age of about 2.1 Ga. This led Baker (1985) to suggest that rifting was affecting a 2.1 Ga basement and encompassed the whole BSS development, including the Lower Leptite Group assigned by Oen et al. (1982) to the initial volcanic stage. Chemical evidence (Vivallo & Rickard, 1984; Baker, 1985; Johansson & Rickard, 1985) indicate that this crust must have had an intermediate to felsic composition. In common with Archean and Proterozoic mobile zones, no older basement has, as yet, been found in the Bergslagen region. One striking feature of W. Bergslagen is the strong bimodality between the felsic metavolcanics and mafic rocks (Van der Velden et al., 1982; Vivallo & Rickard, 1984; Lagerblad & Gorbatshev, 1985) shown by Martin & Piwinski (1972) to be a characteristic of magmatism in extensional regimes. In the model of Oen et al. (1982) compressive tectonism caused deformation (flattening, shear folding) and low pressure metamorphism of greenschist to amphibolite grade in a post rift stage. Several phases of metamorphism related to granite intrusions have been suggested by Helmers (1984). High-grade metamorphism is confined to the aureole of the Horrsjö granite (e.g. Linthout, 1983). Sub-seafloor metamorphism and related hydrothermal alteration resulting from the syn- and post-volcanic plutonism, resulted in an annealing recrystallization in the felsic volcanics. This was preserved and enhanced during subsequent tectonic processes.

Structural aspects of West Bergslagen

W. Bergslagen comprises a number of long, narrow synformal structures, made up of meta-sediment units, flanked by large thicknesses of felsic supracrustal rocks. These felsic supracrustals are cut off or enclosed by massifs of the Bergslagen Older Granite Suite (e.g. east of Nora, Lundström, 1983), or cut off by younger (1.7 Ga) granites. The absence of large scale isoclinal folds, the presence of homoclinal successions within the synformal structures, and the occurrence of discordancies at the base of several formations, suggest these structures are basins. In addition a number of paleofaults have been recognised in the field (see Fig. 1), located between the volcanic units and upper meta-sedimentary units, marked by mafic intrusive breccias. Two sets of faults, one N-S, the other NE-SW and NW-SE, cross the BSS and granites. W. Bergslagen is characterized by a predominance of sub-vertical to vertical structures in the supracrustal sequence (Fig. 2). Sub-vertical bedding which strikes N140E in the north of the area bends to an E-W strike south of Järnboås (see Fig. 2). A predominant NE-SW strike is present east of a N-S trending fault zone running from Nora to Kopparberg (see Fig. 1) (Lundström, 1983). The foliation (S_1) is generally sub-vertical to vertical and makes a very low angle (usually less than 10°) with the bedding. A later, open low angle kinking (S_2) has affected the S_1 foliation in the rocks NE of Hjulsjö. Extension lineations are formed in the S_1 plane by amphiboles, nests of biotite, elongated quartz grains or lenses, and stretched quartz pebbles, lithic fragments and lapilli. In the rare cases where the bedding is sub-horizontal, the S_1 foliation and lineations are also sub-horizontal. This can be seen in the Gåsborn area (Fig. 1), where numerous F-rich pegmatites, thought to originate from an underlying granite pluton, cut the felsic supracrustals (Damman, 1987 personal communication). Structures of this type have been described in the diapirism models of Ramberg (1967, 1981), Talbot (1974), and gravity tectonic models of Dixon & Summers (1983). Evidence for a combined gravity and diapirism tectonism comes from the septum-like structure at Ställdalen (see Fig. 1). The geolog-

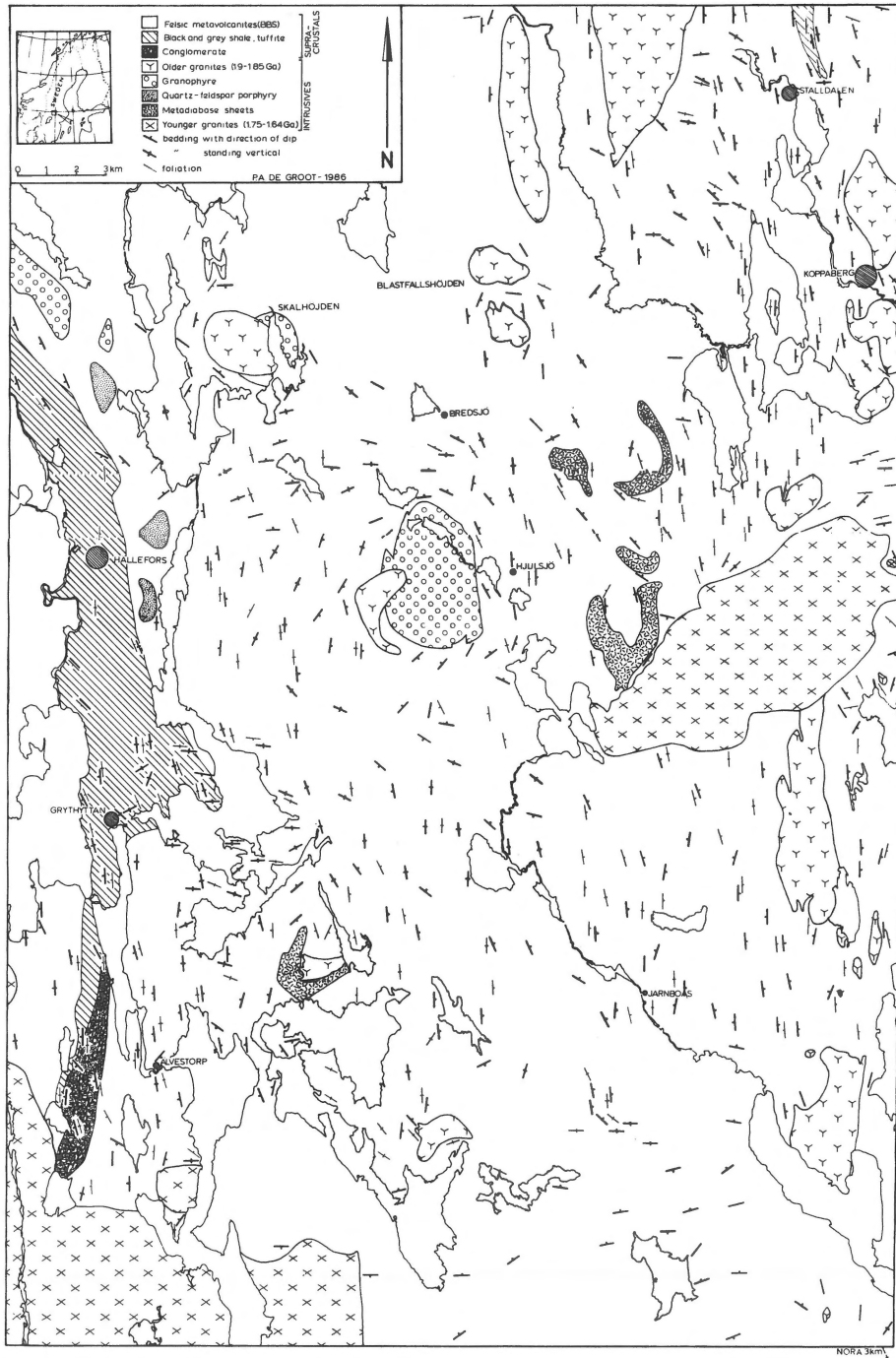


Fig. 2. Structural map of the Hällefors-Kopparberg-Nora area, showing bedding and foliation, and position of shales, metabasites, meta-conglomerates and granites from the Bergslagen Older and Younger Granite Suites.

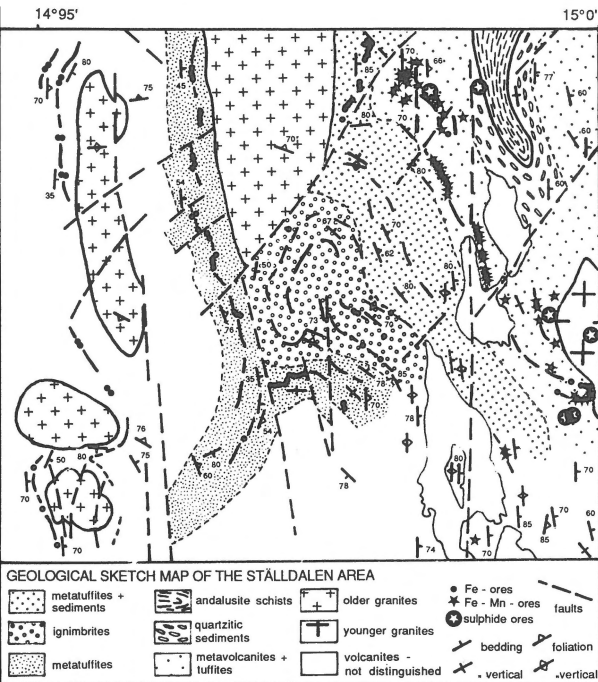


Fig. 3a. Geological sketch map of the Stålldalen area, showing the septum-like structure, enhanced by the stratigraphic iron ore marker horizons.

ical relationships of the area W of Stålldalen are given in Figure 3a, which shows a stratigraphic sequence younging from SW-NE, and a number of granite intrusions from the Bergslagen Older Granite Suite. A detailed description of the stratigraphy of this area is given by Parr (in press). The lowest stratigraphic unit comprises well banded metatuffites, and includes calcareous metasediments and a sedimentary exhalative iron ore horizon, marked by a series of iron ore mines. This is overlain by a unit of coarse ignimbrites and includes pyroclastic flows, with occasional lapilli or crystal tuffs, and an iron ore horizon in the north (Fig. 3a). A unit of metatuffites with metasediments follows, and is in turn overlain by a unit of metavolcanites and tuffites which contain carbonate beds and lenses and two Fe-Mn volcano-exhalative ore horizons. These units of banded metatuffites and metasediments can be correlated with the Upper Leptite-Hälleflinta and Slate Group of Oen et al. (1982), or the Usken Formation of Lund-

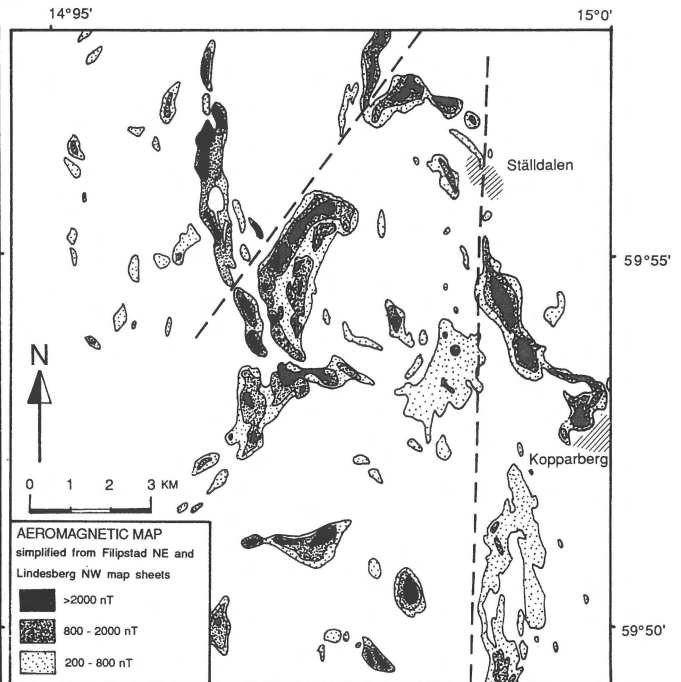


Fig. 3b. Sketch map of the main magnetic features interpreted from the aeromagnetic maps Filipstad 11E NE and Lindesberg 11F NW (Lundström, 1983).

ström (1983). A unit of quartzitic metasediments is overlain by andalusite-bearing metasediments which form the synformal, trough-like structure in the E of the map area (Fig. 3a). The area is cut by a N-S set of faults, and a NE-SW set of faults (Fig. 3a) reflecting the pattern developed across the whole region (see Fig. 1), but they do not obscure the geological relationships. The volcano-exhalative ore horizons form clear stratigraphic markers in the area, confirming the bedding measurements in the supracrustals. The structure of the area is seen particularly well on the aeromagnetic maps (Fig. 3b). The iron ore horizon in the lowest metasedimentary unit runs south between two older granites before bending sharply SW towards the Bastfallshöjden granite. The horizon then folds back along itself (see magnetic map, Fig. 3b) to run E-W before bending again to run south. The stratigraphically highest ore horizon, located in the metavolcanite and tuffite unit (Fig. 3a), shows a hinge-like structure located along the NE-SW axis

of the structure shown by the lower ore horizon. Figure 3a also shows that the bedding in the supracrustals, where close to the older granites, runs parallel to the contacts with the granite massifs, even following the contacts in between the two small Bastfallshöjden plutons (Fig. 3a; Melkert, 1987, personal communication). The fold structure defined by the lower iron ore horizon, comprises three bedding directions (N-S, NE-SW and NW-SE), which meet under angles of about 120°, with bedding dips varying between 35° and vertical, mostly more than 65°. This, and the apparently sub-vertical fold axis and axial plane is an unlikely product of orogenic folding as required by the classic structural interpretation of Bergslagen (e.g. Magnusson, 1970). The structure is, however, compatible with the subsidence structures produced in diapirism and gravity tectonic experiments (e.g. Talbot, 1974; Ramberg, 1971, 1981; Dixon & Summers, 1983, 1985). It is our contention that the septum-like structure at Ställdalen, taken together with the subparallel bedding/older granite contact relationships, are consistent with gravity controlled tectonic processes in this region. This coalescence of three bedding directions (N-S, NE-SW, E-W) is not unique to the Ställdalen area. A similar structure is also present just NE of Hällefors (Fig. 1). While this structure was previously interpreted in terms of local disconformities (e.g. Oen et al., 1982), the structure is not inconsistent with a gravity tectonic interpretation.

The tectonic development of W. Bergslagen

W. Bergslagen is an elongate zone in the crust characterized by predominantly felsic igneous activity, low to high temperature and low pressure metamorphism, and minor migmatization (e.g. NE of Filipstad). The tectono-magmatic development of this area, including a consideration of the roles of tensional and gravity determined tectonism, can be divided into the following four stages (Table 1, Fig. 4).

Phase 1: primary crust forming event

An initial phase comprises the formation of pri-

mary crust from the mantle at about 2.1 Ga; an inference based on an interpretation of Sm-Nd data (Beunk et al., 1985; Miller et al., 1986).

Phase 2: attenuation, rifting, volcanism and diapirism

In the second phase low density asthenospheric mantle diapirism causes tensional stresses in the crust resulting in attenuation and rifting (e.g. Ramberg, 1978; and Fig. 4a). Subsidence of the lower crust (Fig. 4b) developed a series of grabens, while melting of the lower crust, presumably caused by underplating with mafic magma, produced magma of a relative homogeneous composition. An immense volume of felsic magmatism resulted, developing a volcanic pile of several km's thickness. The massive, uninterrupted outpourings of felsic magma indicate a rapid sinking of the crust, and melting of material to be vented as fissure eruptions or through individual volcanoes (Fig. 4b). The sinking of the graben basements within the developing rift zone ensured the containment of the felsic eruptives in the multiple rift grabens, though topographic highs were also covered (e.g. Fig. 4c). Granite diapirism was initiated at this stage, with the deeper seated intrusions being emplaced into the lower levels of the developing volcanic pile in the grabens. The freezing granite magma chambers, which had fed the rhyolitic volcanoes became, in a later stage, the granite diapirs. Isotopic age data on the older granites suggest Phase 2 started at about 1.9 Ga, and continued until after 1.88 Ga (Welin et al., 1980; Welin, 1987).

Phase 3: uplift, sedimentation and gravity subsidence

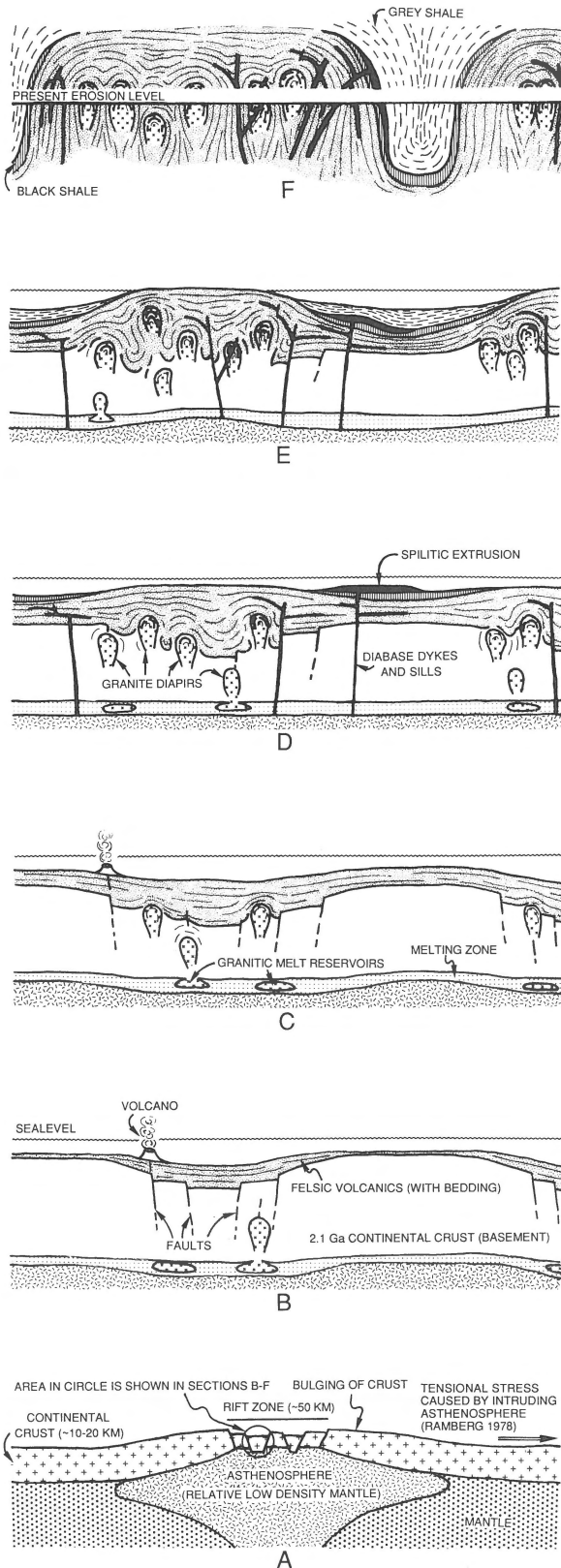
Phase 3 starts with a clear change in tectonic and magmatic evolution, and is heralded by the incoming of more tuffitic rocks towards the top of the stratigraphic sequence, and a period of volcanic quiescence marked by the black, graphitic and pyritiferous shales. Mafic magmatism is mostly developed during this period, where crosscutting dykes and sills have their extrusive, spilitized equivalents located in, or just under the black shales. This period of crustal relaxation, between sinking of the graben floors and uplift, in which the mafic mag-

matism occurs, marks the change to an inversion stage (Fig. 4d). While the graben floors now apparently rose, new grabens were initiated on the flanks of these rising blocks. The original grabens inverted to horsts. Although there was still sporadic felsic

volcanism, the tendency was to erosion of the felsic supracrustals on the rising horsts, to allow the deposition of sediments (black and grey shales) in the newly formed, downfaulted basins (Fig. 4d). This period is, in part, the initiation of a gravity flow

Table 1. Four stage model, and geochronological relationships for the evolution of the W. Bergslagen ensialic belt, modified from Oen et al. (1982).

Ga.			Period associated with later orogenic events
1.64–	Younger granite suite: – Dala-Järna granite – Fellingsbro granite – Värmland-Småland granite (Oen and Verschure, 1985b)	<i>Phase 4:</i> Younger granite intrusions ± contact metamorphism ± deformation	
1.74–	?	<i>Phase 3:</i> Gravity flow tectonics + metamorphism + 2nd phase granite intrusion (W-Mo association) + continued sub-seafloor alteration processes	Gravity flow tectonics
? –	-W-Mo granites – 2nd phase granites	Grey shale deposition (minor felsic volcanism) Isostatic processes Black shale deposition Mafic magmatism (sheets and dykes – spilites)	
1.84–	– metamorphism period of gravity flow tectonics		
1.86–	– initiation of gravity flow tectonics – uplift of volcanics by isostatic re-adjustment processes, erosion, deposition of grey shales – minor felsic volcanism – period of quiescence; formation of black shales – diabase sheet and dyke intrusion – extrusion and spilitization of basalt (pillow lava's)		
1.88–	– solidification of 1st phase granites (e.g. Horrsjö, Gillershöjden granite, Hjulsjö granophyre)	<i>Phase 2:</i> Sub-seafloor alteration processes (e.g. Hjulsjö hydrothermal system + associated sedimentary exhalative Fe (Mn) ore deposits on the seafloor) Felsic magmatism (volcanics + 1st phase granites)	Rifting
1.90–	– start of felsic volcanism and diapirism – anatexis of 2.1 Ga. crust		Primary crust formation
2.1 –	----- formation of crust from mantle	<i>Phase 1:</i> Formation of oldest crust	



← Fig. 4. Proposed evolutionary model for the main structures of W. Bergslagen; A. sketch showing initiation of tensional regime in the lower crust through asthenospheric mantle diapirism (after Ramberg, 1978). Section runs W-E; B. initial volcanic phase, with large eruptions of felsic material; C. sinking of graben floor allows containment of felsic extrusiva predominantly within the grabens. Granitic diapirism is initiated; D. start of inversion phase, with an elevation of the original graben floor and emplacement of granite batholiths, while sedimentary basins start to develop in the intervening areas. Mafic magmatism accompanies this period of crustal relaxation; E. granite diapirism accompanied by the initiation of gravity subsidence in the sedimentary basins leads to the development of subvertical bedding and foliation, and sub-parallel contact relationships with the granites; F. completion of the diapirism – gravity subsidence process develops the structural features currently seen in W. Bergslagen, for which vertical rather than lateral (orogenic) forces were responsible.

system, and is equivalent to the main rifting stage of Oen et al. (1982). As the sediments fill the trough-like depressions between the rising horsts, the troughs themselves, with their heavier sediments add to the crustal instability, and their sinking lends a clear character to the deformational style (e.g. Kuipers, 1987). The diapirism initiated during phase 2 with the emplacement of granite bodies was enhanced in phase 3, during which the sub-vertical stand of the bedding, with sub-parallelism of foliation and lineation was achieved through gravity tectonics (Fig. 4e). Lateral constraints apparently prevented further growth in the rift (e.g. Illies, 1981), which thus developed the characteristic vertical structures seen in W. Bergslagen. A sub-vertical parallel layering, with sub-parallel foliation and lineation is typical of the sediment filled basins, and is predicted by the experiments of Dixon & Summers (1983) for trough-like basins at depth. Granite intrusions often have sub-parallel contacts with the felsic metavolcanics, which are developed as septum-like structures (e.g. Stålldalen, see Fig. 3) between the granites, similar to the models of Ramberg (1967, 1981). In this model there is no necessity of assuming a regional compressive phase in the crust to develop the structural elements observed in W. Bergslagen, although compression cannot be totally ruled out. Deformation of the type seen here or in Archean gneisses is not in itself evidence of crustal short-

ening (Carey, 1954). Gravity flow (Rayleigh-Taylor type processes) and diapirism (temperature gradient dependent) remove the need for the previously assumed Svecokarelian orogeny in western Bergslagen.

Phase 4: younger granitic magmatism.

Phase 4 comprises a 1.74–1.64 Ga period of renewed granitic igneous activity after a period of relative quiescence. This phase will not be discussed here, since it post dates the period of gravity tectonics under consideration. It led to the development of the Bergslagen Younger Granite Suite (Oen, 1987), part of the Trans-Scandinavian granite belt. The later S₂ foliation is probably developed at this stage.

Discussion

Large scale structures in Bergslagen include long, narrow, synformal, sediment-filled basins separated by large areas of felsic supracrustals in which antiformal structures are absent, but in which volcano-plutonic complexes with sub-circular structures are developed. The layering and foliation in these felsic supracrustals folds around the granites, while the foliation in the marginal zones of the granite runs parallel to the contact with the felsic supracrustals forming structures comparable to mantled gneiss domes (Eskola, 1948). Variations in specific gravity (SG) have been measured (Table 2). The difference in SG measured in rock samples is similar to that to be expected between the sediments and felsic pyroclastics. The sediments are clearly heavier than the felsic volcanics or the gran-

ites, which have approximately similar SGs. The relatively heavier sediments deposited onto felsic volcanics with a lower SG provide a gravity instability in the crust. In addition the volcanogenic sediments, even if originally less dense than some of the sialic crystalline basement, become more dense by burial compaction, diagenesis, and metamorphic effects, the slightly metamorphosed equivalents of most sediments being denser than most acid gneisses (Clark, 1966; Talbot, 1974). This instability is thought to complement the granite diapirism and contribute significantly to the sinking of the heavy sediments into the underlying felsic supracrustals and eventually the continental basement in a way as described by Ramberg (1971, 1981) and Dixon & Summers (1983, 1985), controlled by density contrasts (Rayleigh-Taylor instabilities). This process contrasts with simple granite diapirism, where temperature differences drive a convective process (Weyermars, 1987, personal communication).

Conclusions

The rifting model of Oen et al. (1982) is expanded to include and suggest an explanation for the structural features encountered in W. Bergslagen. A four-phase crustal – tectonic evolution is envisaged. The first phase is an initial crust forming event at about 2.1 Ga. Phase 2 is the melting of the lower part of this initial crust, probably caused by underplating by mafic magma during a phase of crustal attenuation. A >10 km thickness of felsic volcanics developed, contained in grabens in the opening rift structure. The intrusion of granite plu-

Table 2. Numbers (N), averages, standard deviations (SD), and ranges of specific gravities (SG), in granites, felsic pyroclastics and metasediments from W. Bergslagen. (granite values from Baker, 1985).

Rock	N	SG average	SD	SG range
Granite	6	2.622	–	2.603–2.632
Felsic pyroclastics	73	2.646	0.036	2.550–2.740
Basin sediments	12	2.749	0.035	2.679–2.794

tons and initiation of diapirism is coeval with the rifting and volcanism. Granite diapirism occurred chiefly in phase 3, in a convective system controlled by temperature differences, contrasting with the Rayleigh-Taylor instability type process. Phase 4 comprises a younger phase of granitic magmatism.

We consider the whole volcanic phase to be rift related, not just the higher parts of the stratigraphic sequence, while the sedimentary stage culminating the sequence is considered to be the surficial expression of the gravity tectonic system, which engulfs the whole pile.

While this model does not explain all the structural complexities of W. Bergslagen it attempts to provide a chronological reconstruction of the main tectonic events, which should serve as a basis for future investigations.

Acknowledgements

An earlier draft of this paper was greatly improved by the comments of C.J. Talbot, R. Weyermars, and an anonymous reviewer. Geological mapping in the Stålldalen area was made by JHB in 1985 for Sveriges Geologiska AB, and is published with permission of Dr S. Ljung, Nämnden för Statens Gruvegendom, Stockholm. Some figures were drawn by F. Kievits, and photographed by J. Gorau.

References

- Åberg, G. & Fredriksson, G. 1984 Radiometric dating of the post orogenic Järna granite, South Central Sweden – *Geol. För. Förh.* 106: 171–174.
- Åberg, G. & Bjurstedt, S. 1986 Radiometric dating of the serorogenic Enkullen and Fjällberg granites, south central Sweden – *Geol. För. Förh.* 108: 73–77.
- Åberg, G., Bollmark, B., Björk, L. & Wiklander, U. 1983a Radiometric dating of Horrsjö granite, South Central Sweden – *Geol. För. Förh.* 105: 78–81.
- Åberg, G., Levi, B. & Fredriksson, G. 1983b Zircon ages of metavolcanic and synorogenic granitic rocks from the Svärdsjö and Yxsjöberg areas. South Central Sweden – *Geol. För. Förh.* 105: 199–203.
- Baker, J.H. 1985 The petrology and geochemistry of 1.8–1.9 Ga granitic magmatism and related sub-seafloor hydrothermal alteration and ore-forming processes, W. Bergslagen, Sweden – PhD thesis, GUA Papers of Geology, Ser. 1, 21, University of Amsterdam: 204 pp.
- Beunk, F.F., Baker, J.H. & Van Raaphorst, J.G. 1985 A Sm-Nd isotope study of the 1.85 Ga Hjulsjö volcano-plutonic complex, W. Bergslagen, south central Sweden – (*Abstr.*) *Terra Cognita* 5: 278.
- Carey, S.W. 1954 The rheid concept in geotectonics – *Geol. Soc. Aust.* 1: 67–117.
- Clark, S.P. 1966 Handbook of physical constants – *Geol. Soc. Am. Mem.* 79: 587 pp.
- De Groot, P.A. & Sheppard, S.M.F. (in press) Carbonate rocks from W. Bergslagen, Central Sweden. Isotopic (C, O, H) evidence for marine deposition and alteration by hydrothermal processes. In: Baker J.H. & Hellingwerf R.H. (eds): *The Bergslagen Province, Central Sweden. Stratigraphy, Structure and Oreforming processes* – *Geol. Mijnbouw* 67.
- Dixon, J.M. & Summers, J.M. 1983 Patterns of total and incremental strain in subsiding troughs: experimental centrifuged models of interdiapir synclines – *Can. J. Earth Sci.* 20: 1843–1861.
- Dixon, J.M. & Summers, J.M. 1985 Recent developments in centrifuge modelling of tectonic processes: equipment, model construction techniques and rheology of model materials – *J. Struct. Geol.* 7: 83–102.
- Eskola, P. 1948 The problem of mantled gneiss domes – *Geol. Soc. Lond. Q. J.* 104: 461–476.
- Helmers, H. 1984 Stages of granite intrusion and regional metamorphism in the Proterozoic rocks of Western Bergslagen, C. Sweden, as exemplified in the Grängens area – *Neues. Jahrb. Miner. Monatsch.* 150: 307–324.
- Hietanen, A. 1975 Generation of potassium poor magmas in the Northern Sierra Nevada and the Svecofennian of Finland – *J. Res. U. S. Geol. Surv.* 3: 631–645.
- Illies, J.H. 1981 Mechanism of graben formation – *Tectonophysics* 73: 249–266.
- Johansson, A. & Rickard, D. 1985 Some new lead isotope determinations from the Proterozoic sulphide ores of central Sweden – *Mineral. Dep.* 20: 1–7.
- Kuipers, G. 1987 Volcaniclastic facies associations in the mid-Proterozoic Grythyttan rift-basin and their lithostratigraphic relationship, West-Bergslagen, central Sweden – GUA papers of Geology, Ser. 1, 28, University of Amsterdam, 162 pp.
- Lagerblad, B. & Gorbatshev, R. 1985 Hydrothermal alteration as a control of regional geochemistry and ore formation in the Central Baltic shield – *Geol. Rundsch.* 74: 33–49.
- Linthout, K. 1983 Medium-grade intermediate-pressure metamorphism in the western outskirts of the Svecokareliides related to 1.7–1.81 Ga rifting subsidence W and SE of Filipstad, central Sweden – (*Abstr.*) *Terra Cognita* 3: 257.
- Lundström, I. 1983 Beskrivning till berggrundskartan Lindesberg SV. Sver. – *Geol. Unders.*, Ser Af 126: 140 pp.
- Lundström, I. & Papunen, H. 1986 Proterozoic geology of southwestern Finland and the Bergslagen Province, Sweden. In: Lundström, I. & Papunen, H. (eds): *Mineral deposits of Southwestern Finland and the Bergslagen Province, Sweden*

- Sver. Geol. Unders., Ser Ca 61: 6–10.
- Magnusson, N.H. 1925 Persbergs malmtrakt och berggrunden i de centrala delarna av Filipstads bergslag i Värmlands län – Kungl. Kommerskollegium, Beskrivning över mineralfyndigheter 2, Stockholm: 2–231.
- Magnusson, N.H. 1970 The origin of the iron ores in Central Sweden and the history of their alterations – Sver. Geol. Unders., Ser C 643: 364 pp.
- Martin, R.F. & Piwinski, A.J. 1972 Magmatism and tectonic settings – J. Geophys. Res. 77: 4966–4975.
- Miller, R.G., O’Nions, R.K., Hamilton, P.J. & Welin, E. 1986 Crustal residence ages of clastic sediments, orogeny and continental evolution – Chem. Geol. 57: 87–99.
- Moorman, A.C., Andriessen, P.A.M., Boelrijk, M.A.I.M., Hebeda, E.H., Oen, I.S., Priem, H.N.A., Verdurmen, E.A.T., Verschure, R.H. & Wiklander, U. 1982 K-Ar and Rb-Sr mineral ages of skarns and associated metabasites and leptites in the Hjulsjö area of the Bergslagen ore province, Central Sweden – Geol. För. Förh. 104: 1–9.
- Oen, I.S. 1982 Isotopic age determinations in Bergslagen, Sweden: II The Filipstad-type granite of Rockesholm, Grythyttan area – Geol. Mijnbouw 61: 305–307.
- Oen, I.S. 1983 Isotopic age determinations in Bergslagen, Sweden: IV Granites of the Grängen area, East of Hjulsjö – Geol. Mijnbouw 62: 301–303.
- Oen, I.S. 1987 Rift-related igneous activity and metallogenesis in SW Bergslagen, Sweden – Precamb. Res. 35: 367–382.
- Oen, I.S., Helmers, H., Verschure, R.H. & Wiklander, U. 1982 Ore deposition in a Proterozoic incipient rift zone environment: A tentative model for the Filipstad-Grythyttan-Hjulsjö region, Bergslagen, Sweden – Geol. Rundsch. 71: 182–194.
- Oen, I.S. & Verschure, R.H. 1982 Isotopic age determinations in Bergslagen, Sweden: I. Introduction – Geol. Mijnbouw 61: 301–304.
- Oen, I.S., Verschure, R.H. & Wiklander, U. 1984 Isotopic age determinations in Bergslagen, Sweden: V The Hörrsjö granite, Filipstad area – Geol. Mijnbouw 63: 85–88.
- Oen, I.S. & Wiklander, U. 1982 Isotopic age determinations in Bergslagen, Sweden: III The Hyttsjö suite of gabbrodiorites and tonalite-granites, Filipstad area – Geol. Mijnbouw 61: 309–312.
- Parr, J. (in press) Stratabound base metal mineralizations and associated metasediments. Ljusnarsbergs district, Central Sweden. In: Baker, J.H. & Hellingwerf, R.H. (eds): The Bergslagen Province, Central Sweden. Stratigraphy, Structure and Ore-forming processes – Geol. Mijnbouw 67.
- Ramberg, H. 1967 Gravity, deformation and the Earth’s crust – Academic Press, London, England: 214 pp.
- Ramberg, H. 1971 Dynamic models simulating rift valleys and continental drift – Lithos 4: 259–276.
- Ramberg, H. 1978 Experimental model studies of rift valley systems – (Abstr.). In: Ramberg, I.B. & Neumann, E.R. (eds): Tectonics and geophysics of continental rifts – Reidel Publ. Co. Dordrecht: 39–40.
- Ramberg, H. 1981 Gravity, deformation and the Earth’s crust – 2nd ed. – Academic Press, London, England: 452 pp.
- Stålhös, G. 1984 Svecofennian folding and interfering macrostructures in eastern Central Sweden. In: Kroner, A. & Greiling, R.E. (eds.): Precambrian Tectonics Illustrated – Schweizerbart, Stuttgart, Germany: 369–379.
- Stephansson, O. 1975 Polydiapirism of granitic rocks in the Svecofennian of central Sweden – Precamb. Res. 2: 189–214.
- Sundius, N.L. 1923 Grythyttfältets geologi – Sver. Geol. Unders., Ser C32: 354 pp.
- Talbot, C.J. 1974 Fold nappes as asymmetric mantled gneiss domes and ensialic orogeny – Tectonophysics 24: 259–276.
- Van der Velden, J.W., Baker, J.H., De Maesschalck, A.A. & Van Meerten T. 1982 Bimodal early Proterozoic volcanism in the Grythytte field and associated volcano-plutonic complexes, Bergslagen, Central Sweden – Geol. Rundsch. 71: 171–181.
- Vivallo, W. & Rickard, D. 1984 Early Proterozoic ensialic spreading-subsidence. Evidence from the Garpenberg enclave, Central Sweden – Precamb. Res. 26: 203–221.
- Welin, E. 1987 The depositional evolution of the Svecofennian supracrustal sequence in Finland and Sweden – Precamb. Res. 35: 95–113.
- Welin, E., Gorbatshev, R. & Lundegårdh, P.H. 1977 Rb-Sr dating of rocks in the Värmland granite group in Sweden – Geol. För. Förh. 99: 363–367.
- Welin, E., Wiklander, U. & Kähr, A.M. 1980 Radiometric dating of a quartz-porphyritic potassium rhyolite at Hällefors, South Central Sweden – Geol. För. Förh. 102: 269–272.
- Wilson, M.R., Hamilton, P.J., Fallick, A.E., Aftalion, M. & Michard, A. 1985 Granites and early Proterozoic crustal evolution in Sweden: Evidence from Sm-Nd, U-Pb and O isotope systematics – Earth Planet. Sci. Lett. 72: 376–388.