

# Magma mixing, structure, and re-evaluation of the emplacement mechanism of Vrådal pluton, central Telemark, southern Norway

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The Vrådal pluton presents a two-dimensional exposure of part of a granitic diapir having steep, inward-dipping contacts that intruded the middle crust 900–1000 Ma ago. Nearly 25% of the pluton consists of mafic rocks that mingled and mixed synplutonically with granitic rocks. The mafic rocks increased, thereby, the overall density of the pluton, added heat to fuel the upward ascent of the pluton, and helped to heat the wall rocks locally and sufficiently for them to deform viscoelastically above and around the pluton. Gneiss and a thin, concentric and conformable sequence of supracrustal quartzite and amphibolite dip steeply inward around all but the northeast quarter of the pluton, which is faulted. These wall rocks define a concentric rim anticline having a steep limb adjacent to the pluton, and a flat limb farther than 2 km radially from it. Previous interpretations of a rim syncline around the pluton cannot be substantiated. Sparse vertical mineral lineations, vertical necklines of boudins, pluton-up sense of shear in shear folds and associated steep faults, and appressed folds in the supracrustal rocks, all within 100 m of the contact, are relict, mesoscopic evidence of upward and outward expansion of the pluton during its emplacement. The macroscopic downward bending of the wall rocks and consequent formation of the rim anticline may be explained either by ductile return flow of heated wall rocks, or by late-stage magma sinking, or a combination of both processes.

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## Introduction

Even after so many decades of investigations, symposia, memoirs, and e-mail forums about the subject, debates still rage about how large bodies of granite originated, intruded, and emplaced themselves in the Earth's crust. The *origin* of granite is beyond the scope of this paper, but the Vrådal pluton offers field evidence for *emplacement* of granite in the crust.

In the 1960s and 1970s many investigators maintained that field evidence supported intrusion and emplacement of granite in diapirs, that is, inverted tear-drop shaped bodies ranging in size from a few kilometers to a few tens of kilometers in diameter. The Vrådal pluton in southern Norway has been considered to be a prime example of such a granite diapir, because of the presence of a rim syncline around it (Sylvester 1964). More recently, however, an increasingly vocal group of investigators has been equally adamant that granitic diapirism has neither been proven, nor is the phenomenon possible on theoretical grounds (e.g., Clemens & Mawer 1992). This group maintains instead that granitic plutons and batholiths intruded as multiple injections through dikes, coupled with subsequent lateral expansion at high crustal levels (e.g., Nelson & Sylvester 1971; Sylvester et al. 1978; Brun et al. 1990; Fowler 1994; Tobisch & Cruden 1995; Morgan & Law 1998), or by ballooning of a diapiric body (Molyneux 1995, but see Paterson & Vernon 1995).

Other investigators, taking a middle position, maintain that granite intrudes ductile lower crust as diapirs, ponds in flat, disk-shaped bodies, perhaps at the brittle-ductile transition in the crust, and then ascends higher into the brittle crust through dikes (e.g., Stephanson 1975; Vigneresse 1995; McNulty et al. 1996).

'Diapir' is a genetic appellation that is commonly applied to salt domes in the context of their shape and emplacement. The term has also been applied to large magmatic bodies, especially many granitic plutons (e.g., Stephanson 1975). In the context of granite, it has generally implied a magma transport mechanism from a locus of fusion in the upper mantle or lower crust into the upper crust by means of a viscous, buoyant, gravity-driven, tear-drop shaped body (e.g., Marsh 1982).

The Vrådal pluton in southern central Norway was initially interpreted to be the stem of a diapir (Sylvester 1964) based on some piecemeal observations and rather tenuous assumptions rooted in the dogma of the time. Because the pluton was alleged to be one of the few plutons, if not the only pluton, worldwide to possess a rim syncline, a reinvestigation of its field relations to its wall rocks is imperative. This paper presents the results of remapping and a reconsideration of its ascent and emplacement mechanism in the light of new mapping, new concepts, and 30 more years of experience and reflection by the author.

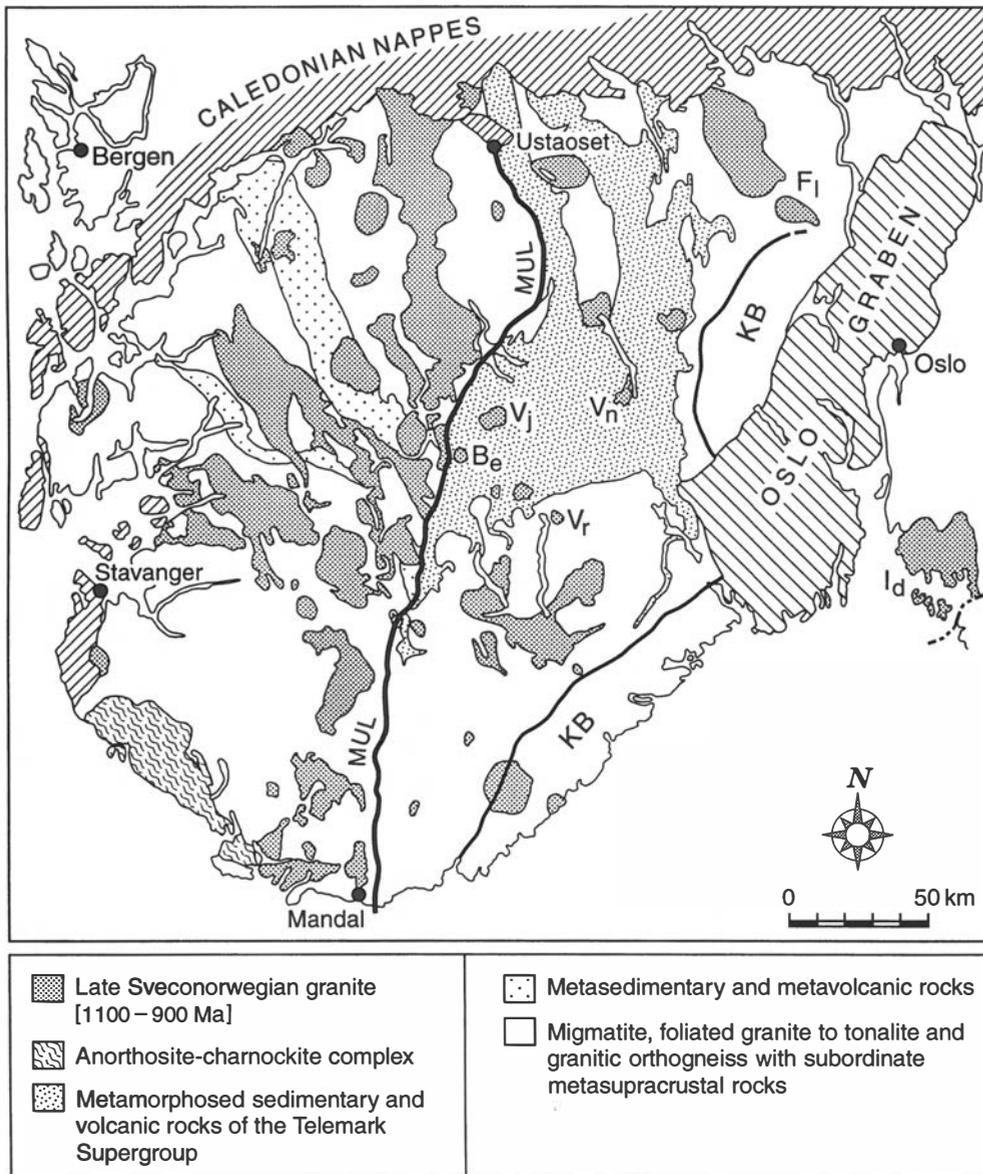


Fig. 1. Location map of Vrådal pluton (Vr) among late Sveconorwegian granitic plutons in southern Norway. Other plutons: Bessefjell (Be); Flå (Fl), Iddesfjord (Id), Venåsfjell (Vn); Vehuskjerringa (Vj). KB = Kongsberg/Bamble area; MUL = Mandal–Ustaoset line (Sigmond 1985). Map from E. Sigmond (1997), with permission and modifications.

## Geologic setting

The Vrådal pluton is one of several granitic plutons in southern Norway (Fig. 1) that intruded late-Proterozoic gneiss and supracrustal rocks near the end of the Sveconorwegian orogeny, 1250–850 Ma ago (Starmer 1993). Most of those late-orogenic or 'post-kinematic' plutons in southern Norway and southwest Sweden have Rb/Sr ages in the time range of 950 to 880 Ma (Table 1). Whole rock samples from Vrådal pluton range from 928 to 888 Ma, with some relatively large uncertainties (Table 1). The two muscovite and microcline ages in Table 1 are from minerals in a pegmatite that cuts the Vrådal pluton. Pegmatite dikes and masses pervade the pluton and surrounding gneiss, and they have comparable ages throughout southern Telemark. It is noteworthy in a regional context that pegmatite is ubiquitous in gneissic basement rocks and plutons south of Vrådal, but is generally sparse or

missing in plutons that intruded supracrustal rocks to the north.

Because of their lithologic and evident temporal similarities, Andersson et al. (1995) postulated that the late Sveconorwegian plutons in southern Norway and Sweden may be part of a batholith that trends northward through central Telemark from the southern tip of Norway to and beneath the Caledonides. Support for that interpretation may be obtained from the aeromagnetic map of Norway (*Norges geologiske undersøkelse* 1992) on which several of the plutons, including Vrådal, stand out prominently and define that trend. Moreover, the Telemark belt of plutons is similar in age and lithology to the Bohus–Iddesfjord batholith (Table 1) in southeast Norway and southwest Sweden, and to its possible extension in southeast Norway, the Flå granite (Fig. 1, Table 1). Together, the two belts of plutonic rocks may demarcate parts of a late Proterozoic magmatic arc.

Table 1. Radioisotopic ages of late Sveconorwegian plutons, southern Norway and southwest Sweden.

County/Pluton	Age (Ma)*	Sr Ratio	Method	Reference
<i>Buskerud</i>				
Flå	893 ± 28	0.7093	Rb-Sr, s.r.	Killeen & Heier (1975)
	920 ± 3		U-Pb	Nordgulen, pers. comm. (1997)
<i>Telemark</i>				
Bandak	1002 ± 0.76	0.76567	Rb/Sr w.r.	Van der Wel (1977)
Bessefjell	903 ± 16	0.7066	do	Killeen & Heier (1975)
	870 ± 50		do	Priem et al. (1973)
	882 ± 23		do	Van der Wel (1977)
Bryteheia	893 ± 50	0.705 (est)	Rb/Sr biotite	do
Fyresvatn	861 ± 50		Rb/Sr w.r.	Venugopal (1970)
	899 ± 50		Rb/Sr w.r.	Venugopal (1970)
Haukelisetter	896 ± 60	0.7070	Rb/Sr w.r.	Berg (1977)
Kviteseid aplite	942 ± 28	0.70426	do	Van der Wel (1977)
Treungen	971 ± 21	0.7086	do	Killeen & Heier (1975)
Vehuskjerringi	822	0.705 (est.)	do	Killeen & Heier (1975)
	932		U/Pb	Dahlgren, pers. comm. (1996)
Vrådal	888 ± 46	0.7064	Rb/Sr, w.r.	Priem et al. (1973)
	895 ± 39	0.70464	do	Kleppe (1980)
	896 ± 27	0.99	Rb/Sr musc	Sylvester (1964)
	928 ± 20	0.71	Rb/Sr micr	do
	962 ± 15	0.70382	Rb/Sr, w.r.	Christiansen, pers. comm. (1996)
	918 ± 36	0.70398	Rb/Sr, w.r.	Christiansen & Madsen (1996)
<i>Setesdal</i>				
Fennefoss	1026 ± 57	0.7044	Rb/Sr, w.r.	Pedersen et al. (1994)
	1032 ± 2		U/Pb	Bingen & van Breeman (1998)
Grendi gr + monz	993 ± 16	0.7035	Rb/Sr	Pedersen et al. (1994)
Grendi granite	1004 ± 200	0.7036	do	do
Grendi granite	973 ± 74	0.7037	do	do
Neset monzonite	972 ± xx	0.7038	do	do
Åraksbø gr + hybrid	961 ± 35	0.7038	do	do
Åraksbø gr + monz	971 ± 16	0.7036	do	do
<i>Aust Agder</i>				
Grimstad	945 ± 66	0.7034	Rb/Sr, w.r.	Killeen & Heier (1975)
Herefoss	909 ± 26	0.7051	do	do
	940 ± 60	0.7056	do	Brueckner (1975)
	926 ± 8	0.7102	U/Pb	Andersen (1997)
	945 ± 53	0.7041	Rb/Sr	Pedersen et al. (1994)
Høvring gr	900 ± 53	0.7041	do	do
<i>Vest Agder</i>				
Holum	980 ± 33	0.7045	Rb/Sr	Wilson et al. (1977)
Kleivan	930 ± u	0.7053	Rb/Sr	Petersen (1977)
Lyngdal	950 ± 5	0.7054	U/Pb	Pasteels et al. (1979)
	932 ± 38		Rb-Sr	Pedersen & Falkum (1975)
<i>Sweden</i>				
Bohus	891 ± 34	0.711	Rb/Sr w.r.	Skiöld (1976)
Iddefjord	918 ± 7	0.7063	do	Pederson & Maaloe (1990)
Bohus	922 ± 5		U/Pb	Eliassen (1992)

\* Rb/Sr ages are as published and are not corrected for differences in constant lamda. gr = granite; monz = monzonite, do = ditto; est = estimate; micr = microcline

## Lithology

The Vrådal pluton intruded gneiss and a thin supracrustal sequence of quartzite and amphibolite that crops out around the north and south sides of the pluton and that dips steeply toward it (Fig. 2). The pluton consists of a core of medium-grained, equigranular white and pink monzogranite and lesser quartz monzonite (Streckeisen 1976, p. 12; hereinafter called granite), about 4 km in diameter, surrounded concentrically by a 500 to 750-m-wide ring of coarse-grained, porphyritic granite. This dimension is comparable to that of stems inferred to be present beneath the Oliverian domes of New York (Lyons et al. 1996). Small irregular-shaped patches of porphyritic granite crop out within the monzonite throughout the pluton, but the inverse was not

observed. Dikes and irregular masses of pegmatite and aplite are ubiquitous throughout the pluton and the surrounding gneissic wall rocks. Thin pegmatite veins are boudinaged locally along with quartzite in the concentric ring of amphibolite schist around the pluton.

About 25% of the pluton comprises irregular masses and dikes of synplutonic mafic rocks that were previously regarded as inclusions and stoped blocks of metabasaltic wall rocks from the pluton's now eroded roof (Sylvester 1964). They are reinterpreted here as synplutonic intrusions of basaltic andesite, diabase, and hybrid combinations of intermediate composition mafic and granitic rocks as described and discussed below. Most of the mafic bodies lie within the granite and at the contact between the granite and the porphyritic granite (Fig. 2). The mafic rocks mingled with granite, porphyritic gran-

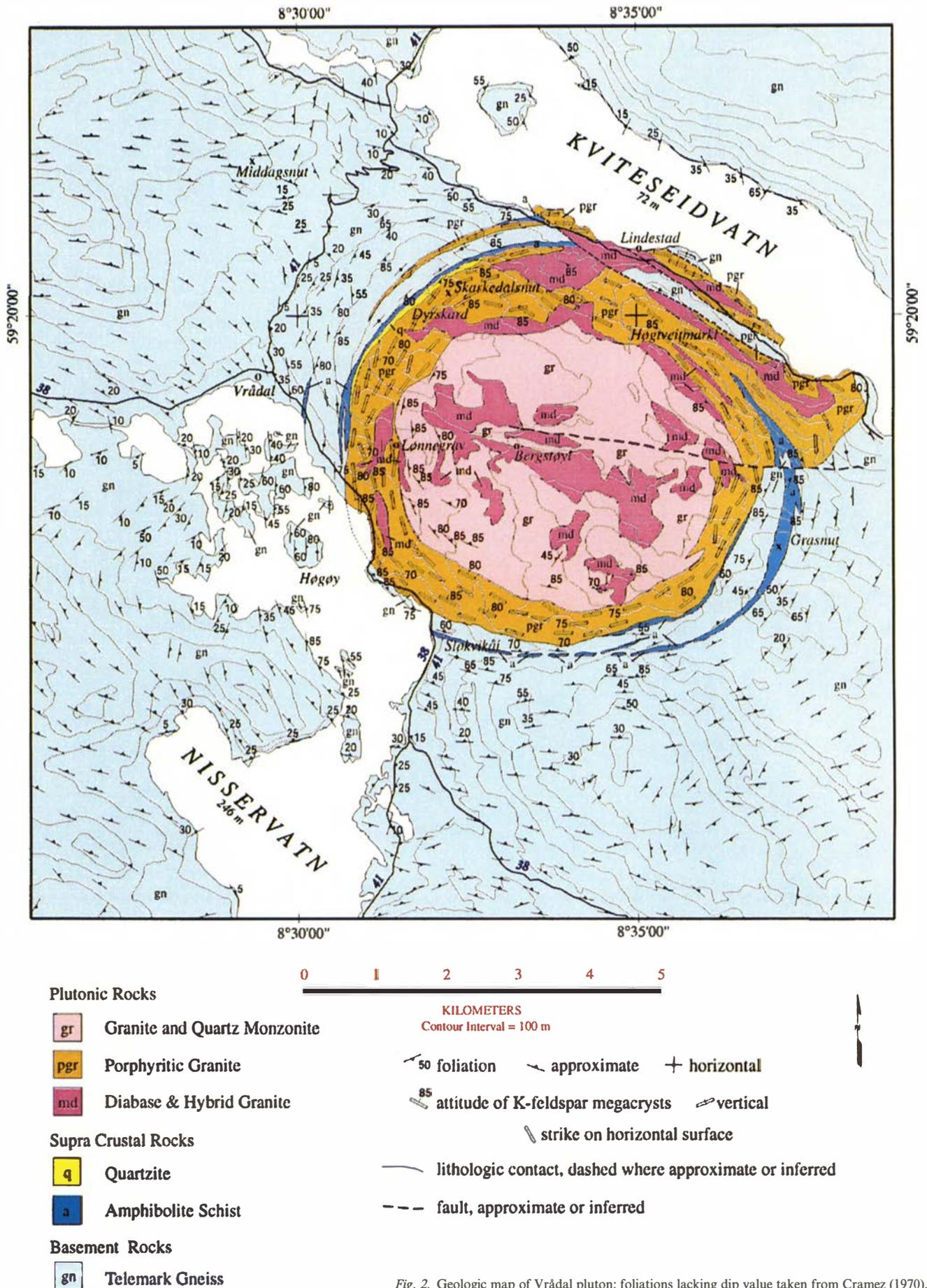


Fig. 2. Geologic map of Vrådal pluton; foliations lacking dip value taken from Cramez (1970).

ite, and aplite, indicating the synchronicity of their intrusion and the duration of intrusion of the mafic rocks.

Mesoscopic to macroscopic outcrops of hybrid rocks, herein regarded as a mafic/felsic mixed magma, also underlie much of the central part of the pluton. Because of their usually small or poor exposures and the intimacy of their field association with granite and feldspathized mafic rocks, the hybrid rocks are not easily separable or mappable everywhere in the pluton. In fact, exposures of both the mafic rocks and mixed rocks are few and poor relative to the more felsic and prevalent granite and porphyritic granite. Fresh roadcuts locally provide spectacular exposures of relations among the several kinds of rocks.

*Granitic rocks.* – Granite in the central part of the pluton is an unfoliated, medium-grained, equigranular rock that comprises plagioclase (40%), perthitic microcline (35%), quartz (20%), and brown biotite (5%) (Sylvester 1964). Characteristic accessory minerals include sphene, apatite, magnetite, zircon, and fluorite. The rock is foliated near its contact with porphyritic granite, the foliation being expressed by the subparallel, planar arrangement of biotite and {010} of microcline and plagioclase. Where it is foliated, the rock also contains microcline megacrysts and large quartz crystals lacking any linear grain shape fabric, so that it resembles the porphyritic granite. Indeed, except where discrete dikes of the one rock cut the other, the contact between the two varieties of granite is gradational in most places and was mapped in the field where the content of megacrysts exceeds about 50%. From their geochemical investigation of the pluton, Christiansen & Konnerup-Madsen (1996) regarded the granite as an uncontaminated, near-eutectic melt that formed in the lower crust.

The porphyritic granite is a very coarse-grained, hypidiomorphic granular rock consisting of white or pink euhedral perthitic microcline megacrysts (35%), plagioclase (30%), smoky quartz (25%), and brown biotite (5%); accessory minerals include sphene, magnetite, and apatite (Sylvester 1964). Magnetite is especially prevalent and may be the reason for the strong magnetic anomaly that is associated with the pluton (*Norges geologiske undersøkelse* 1992), and that gives the rock a relatively high density (2.78 g/cm<sup>3</sup>) compared to most granitic rocks. It is denser than the surrounding gneissic country rocks (2.70 g/cm<sup>3</sup>).

The porphyritic granite is distinguished by the presence of microcline megacrysts, usually 3 cm long, and 1 cm wide that have a strong preferred orientation of {010} (Sylvester 1964, his figure 4). Together with similarly oriented plagioclase and ellipsoid-shaped quartz, all of which lack a linear grain shape fabric, the microcline megacrysts define a steep, concentric, inward-dipping foliation that is nearly everywhere parallel to the pluton contact and to the foliation in the surrounding wall rocks. The megacrysts do not interfere with each other, indicating a flow/stress crystallization control. The concentric symmetry of the foliation, as defined by the preferred orientation of the

microcline megacrysts, indicates that it is a synplutonic, crystallization fabric, developed in the magmatic state, and caused by local, outward, radial stress of a rising, viscous, crystal-bearing, polymeric magma as it pressed against its wall rocks during vertical ascent; the foliation is not a product of superposed tectonic stress or of uniform flow. The increase in the intensity of the magmatic foliation from the core of a pluton outward into a strongly foliated margin is taken as evidence of a decelerating velocity gradient in the flow of magma during emplacement of inner pulses of magma, together with moderate lateral expansion of the magma body itself (Paterson & Vernon 1996).

The K-feldspar megacrysts are pink, even brick red, near faults where, presumably strain energy associated with the faulting promoted ordering of the microcline, leading to diffusion of iron and its consequent concentration within crystal lattice sufficiently to impart color to the crystal (Tom F. W. Barth pers. comm. 1962). Some of the megacrysts have a thin mantle of oligoclase (Sylvester 1962) but only in granite near contacts with mafic rocks, as is described and discussed below. The large size and great number of K-feldspar megacrysts in the peripheral part of the pluton was ascribed to the migration of alkali-bearing fluids from the core to the periphery of the pluton, promoting, thereby, growth of K-feldspar megacrysts during the late stages of intrusion and crystallization (Sylvester 1964). The main control may be nucleation and growth rates (Vernon 1986), however, combined with K<sub>2</sub>O saturation of the magma (Petersen & Lofgren 1986). Alternatively, the porphyritic granite may have been a separate and slightly older magma that evolved in its own way and later was intruded by granite (Christiansen & Konnerup-Madsen 1996).

According to Christiansen & Konnerup-Madsen (1996, p. 2), 'the porphyritic granite owes most of its compositional range to assimilation of up to about 10% of mantle-derived, evolved basic melt into a eutectic-type granitic melt generated by melting of lower crustal material', whereas the granite 'appears to represent an uncontaminated, near-eutectic melt with a lower crustal source similar to that of the porphyritic granite.'

That the porphyritic granite intruded as a magmatic rock is clearly evident by the presence of rare porphyritic granite dikes that intruded all other rocks concordantly and discordantly, including the granite and wall rocks. Granite dikes, on the other hand, were not observed in the wall rocks, but locally in the pluton, they do transect porphyritic granite as if those two rocks were molten at almost the same time.

*Mafic rocks.* – Mafic rocks crop out in discrete dikes and rare sills of fine-grained hornblende-biotite porphyry to macroscopic, irregular-shaped lenses and masses of fine- to medium-grained rock. Macroscopic masses of the mafic rocks crop out only within the pluton and where the northeast edge of the pluton is in contact with gneiss (Fig. 2). The smallest mappable unit is about 100 m long

and 50 m wide; the largest units are up to 2000 m long and 300 m wide and have a cryptic northwest–southeast orientation (Fig. 2), as if they represent mafic feeder dikes.

The bulk of the mafic rocks comprises monzonite and monzodiorite in various stages of hybridization with their granitic host, although a few late, fine-grained dikes of quartz dioritic to granodioritic modal composition may represent the uncontaminated, mantle derived evolved melts (Christensen & Konnerup-Madsen 1996). A representative mode of the hybrid rocks is plagioclase (42%), hornblende (10%), biotite and chlorite (20%), quartz (12%), and microcline (8%); accessory minerals include magnetite (2%), sphene (4%), apatite (1%), and trace amounts of zircon, fluorite, and epidote (Sylvester 1964). In the largest and coarsest-grained masses, the rocks have a relict diabasic texture, whereas the texture is subhornfelsic in fine-grained rocks. Fresh plagioclase crystals (An<sub>28–34</sub>) exhibit oscillatory zoning in sections parallel to {010}; xenocrysts with up to 80% An are locally present (Christensen & Konnerup-Madsen 1996).

The mafic dikes cut all rock types inside and outside the pluton except pegmatite. The dikes are generally vertical, but may dip as gently as 65° (Fig. 3), and range in width from 10 cm to 2 m. The longest mafic dike that could be followed continuously is 40 m long, 30 cm wide, in gneiss on the east shore of Høgøy in Lake Nisser, 500 m west of the pluton. The dikes lack any preferred orientation (Fig. 3), although that conclusion may rest on insufficient data.

The mass of mafic rocks exposed at Steanstuve, 500 m west of Bergstøyl (Fig. 2), is wonderfully instructive, because it clearly displays all aspects of the mafic rocks that are incompletely exposed elsewhere in the pluton.

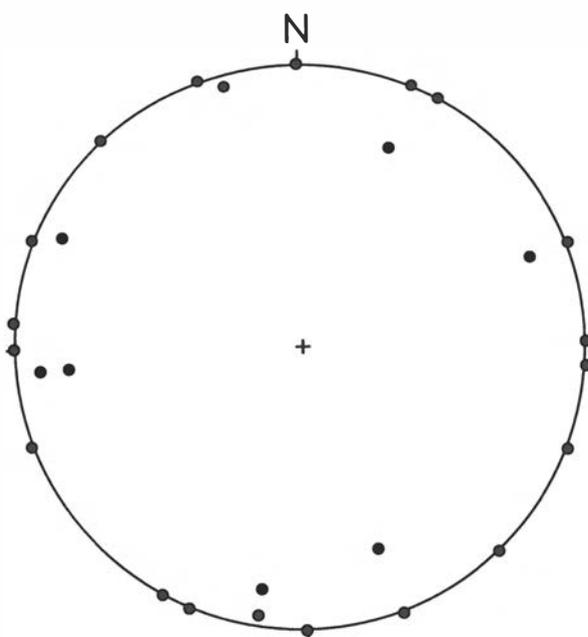


Fig. 3. Poles to 18 mafic dikes for which attitudes could be measured in and around Vrådal pluton. Lower hemisphere stereographic projection.

The main mass is a medium-grained, speckled gray and black mafic rock with a equigranular, subophitic texture comprising nearly equal parts of hornblende, biotite, and plagioclase. One relict grain of clinopyroxene was noted in a single thin section, suggesting that most of the hornblende in the rock developed from uralitization of pyroxene. As one follows the mafic rock mass from its core to its margins, a distance of about 20 m, the grain size decreases to fine-grained and sugary in an aphyric rock that resembles fine-grained basalt that was metamorphosed to hornfels. Dikes that extend from the mafic mass into the surrounding granite, however, are porphyritic with oriented phenocrysts comprising clusters of biotite crystals that have partly replaced acicular, uralitic hornblende needles. The phenocrysts are typically aligned parallel to the dike walls. Oscillatory zoning of plagioclase is present but rare in {010} sections viewed in thin section.

Isolated small enclaves of the mafic rocks are usually clustered near and adjacent to macroscopic mafic bodies in the granite. Locally, trains of amoeboid enclaves are strung out over distances as far as 100 m in the pluton as if they were disrupted dikes. At only one locality on the northeast margin of the pluton 100 m southeast of Lindestad (Sylvester 1964, his Plate IIa) are there enclaves that are spindle-shaped and oriented. Most commonly the enclaves have crenulated, lobate, cusped, convex-outward contacts against the granitic rocks (Fig. 4). Elongate enclaves pinch and swell; locally, veins of granite cut them in the pinched regions and as back veins in more massive mafic bodies.

The rinds of the enclaves are a little darker against the granite than the enclave cores because of a greater concentration of mafic minerals, particularly biotite. The grain sizes in the rind and the core are the same, however, indicating that the mafic rocks were not quenched in the strict sense, although two populations of apatite are evident in thin sections of both coarse- and fine-grained varieties of mafic rocks: equant subhedral crystals up to 0.2 mm long, and acicular needles from 0.1 to 10 mm long, breadth 0.02 mm, in coarse rocks, and up to 0.07 mm long in fine-grained rocks. The presence of acicular apatite is generally regarded as evidence that its host rock was formerly molten and undercooled by quenching upon intrusion or extrusion (Wyllie et al. 1962; Vernon 1984; Castro et al. 1990).

The contact relations of the mafic enclaves to the granite, the mutual back-veining and diking, and the presence of the acicular apatite provide evidence that the mafic rocks were injected and disrupted synplutonically with the granitic rocks (e.g., Vernon 1984; Wiebe 1988, 1993; Larsen & Smith 1990; Barbarin & Didier 1992; Chapman & Rhodes 1992; Pitcher 1993, p. 119). The relatively high concentration of biotite in the rinds of the mafic enclaves and the replacement of hornblende by biotite in the porphyritic mafic dikes are caused by local infusion of alkali-bearing H<sub>2</sub>O from the granite into the Mg and Fe rich mafic system, wherein crystallization of



Fig. 4. Contacts between granite and mafic igneous rocks. (A) Microgranular diorite (dark rock) with rough, irregular, cusped contact against granite (light rock) that intruded as back veins into the mafic rock. Granite is less felsic against much of the mafic rock, and locally, mafic rock has blackened rims where biotite and chlorite are abundant. One-half kilometer west of Bergstøyl. (B) Intrusion of bulbous bodies of porphyritic microdiorite (dark rock) with presumed flow structure defined by elongate, preferred orientation of biotite/hornblende clots into granite (light rock) that, itself, intrudes the microdiorite as back veins. At head of Kilandalsbekken, 200 m southwest of Vråslinut.

hybrid biotite readily proceeds (Hibbard 1991, 1995, p. 250). The granitic rocks are not bleached adjacent to the enclaves, however, an observation that would be further evidence of the migration of alkalis and  $H_2O$  from the granite into the hot mafic enclaves.

*Hybrid rocks.* – The term hybrid and its derivatives are used here to describe various fine- to medium-grained, gray to dark gray rocks that crop out only within the confines of the pluton, and are clearly neither granitic or diabasic: they are a mixture of the two. In weathered outcrops they are difficult to assign to one rock type or the other. Depending on the proportion of coarse crystals and feldspathic veins, they may be described as feldspathized mafic rock or as fine-grained mafic granite. They are heterogeneous with respect to color, texture, grain size, and distribution of xenocrysts. In the field they can be distinguished from diabase and from medium-grained granite by their sugary texture. Commonly they are net-veined.

Microcrystallographic structures and textures indicate

that these hybrid rocks are the products of mixing between mafic and felsic magmas (Hibbard 1995). Especially near contacts with granitic rocks the hybrid rocks contain hornblende-mantled quartz ovoids commonly called quartz ocelli (Fig. 5A; e.g., Angus 1962; Vernon 1990), acicular apatite, hornblende poikilocrysts (e.g., Castro & Stephens 1992), mantled K-feldspar megacrysts (Sylvester 1962, 1964) or porphyrograins (in the terminology of Hibbard, 1995), abrupt step zoning and reverse zoning in subhedral plagioclase xenocrysts, conversion of hornblende to biotite (Fig. 5B), and the prevalence of anhedral crystals.

Sylvester (1964, e.g. his Plate Ia) regarded the quartz ocelli as relict amygdules and concluded, therefore, that the mafic rocks represented stoped blocks of mafic supracrustal rocks. Because I cannot find independent evidence showing that the mafic masses are stoped blocks, and because undoubted vesicles are simply not present in any of the mafic rocks in or around the Vrådal pluton, I prefer to regard the hornblende mantled quartz as quartz xenocrysts which acted as local nucleation sites for hornblende. This is the most common explanation for these microstructures, and they are now regarded as *prima facie* evidence of magma mixing (e.g., Angus 1962; Castro et al. 1990; Vernon 1990; Hibbard 1995, p. 254).

The K-feldspar megacrysts in the hybrid rocks are similar in most respects to those in the porphyritic granite, except that they are invariably mantled with a thin layer of oligoclase and commonly contain dimensionally and crystallographically oriented oligoclase and rare biotite microcrystals (Sylvester 1962, 1964). Mantled K-feldspar megacrysts are more prevalent in the hybrid rocks near contacts with porphyritic granite than in the internal parts of the hybrid rock outcrops. Sylvester (1962, p. 604) vaguely explained the mantles as a reaction product whereby alkalis exsolved from the K-feldspar and reacted with the mafic rocks to maintain thermochemical equilibrium between the K-feldspar and the mafic rocks. Although the exsolution hypothesis of mantle formation may be flawed, I believe the necessity and purpose of the mantle are still the same.

Only plagioclase phenocrysts that are 10 to 50 times larger than groundmass plagioclase retain anything close to a subhedral crystal shape. All other minerals in the hybrid rocks, including and especially biotite, hornblende, sphene, microcline, and quartz, are anhedral, indicating pervasive recrystallization and replacement, presumably during hybridization. Ragged magnetite crystals are pervaded or surrounded by sphene, an exsolution reaction texture whereby ulvospinel exsolved from magnetite at high temperature, reacted with the melt, and formed sphene.

Additional noteworthy evidence of hybridization between felsic and mafic magmas is the presence of exotic, plagioclase xenocrysts having a 'boxy cellular texture' (Hibbard 1995), consisting of plagioclase subgrains surrounding cells filled with quartz, less commonly with microcline (Fig. 5C). Such xenocrysts are heterog-



ously distributed and isolated in feldspathized mafic rocks and hybrid granitic rock. The texture is alleged to result from a relative high rate of growth and a low rate of nucleation in an undercooled environment wherein heat is transferred from the hotter to the cooler magma (Hibbard 1995, p. 256). An alternative explanation for the unique texture is that it represents an arrested stage of xenocryst polygonization, a process of crystal breakdown that occurs before recrystallization.

Anhedral platelets of green hornblende up to 5 mm in diameter exhibit two common forms in thin sections of the hybrid rocks: (1) Mosaics of 0.1 mm in length subhedral grains, and (2) large plates containing amoeboid subdomains of anhedral hornblende in slightly different orientations from the host (Fig. 5D). In the latter case, the texture gives the impression that the subdomains represent parts of the crystal that began to melt due to overheating, but the crystal breakdown ceased part way into the process, and the hornblende in the melting subdomains merely recrystallized. I postulate that the mosaic hornblende grains were subjected to higher temperatures or were heated longer and so recrystallized into mosaics of new, subhedral crystals without undergoing melting, similar to the behavior of quartz in naturally deformed tectonites (Sylvester & Christie 1968). Alternatively, they may have resulted from the reaction of hornblende with the melt (Castro & Stephens 1992).

Christiansen & Konnerup-Madsen (1996) considered the chemical variations they observed among the granitic and mafic rocks in the Vrådal pluton 'to represent various degrees of hybridization and mixing in the source region of the mantle-derived, highly evolved melt and granitic melts, generated by melting of previously LREE- and LIL-enriched lower crustal material.'

## Wall rocks

Outward from the pluton, the wall rocks adjacent to the Vrådal pluton consist of a discontinuous, concentric sheath of quartzite, amphibolite schist, and well-foliated granitic gneiss, designated the Telemark Gneiss (Fig. 2). Whereas the contacts, lithologic layering, and foliation of these rocks wrap concentrically around the pluton and are concordant to it, the quartzite crops out only around its northwest and north sides. Outcrops of both the quartzite and amphibolite schist pinch and swell in plan view around the pluton as if they have been boudinaged in stretching or flattening

(Fig. 6). Primary geopetal structures have not been observed in the succession of supracrustal rocks around Vrådal pluton, however, because such structures, if they ever existed, have evidently been obliterated by extreme recrystallization and ductile flow during deformation associated with the pluton's intrusion.

The quartzite and amphibolite represent part of the supracrustal rocks of the Telemark area as described above, and one may assume that they preserve their original stratigraphic relation to one other and to the Telemark Gneiss. If that assumption is valid, then the facing direction of the amphibolite and quartzite along the northwest and north contact of the pluton and, by extrapolation of the amphibolite around the remainder of the pluton, must be *toward* the pluton, simply because those supracrustal rocks are between the pluton and the gneiss. Crucial to the validity of this assumption and ultimately to the interpretation of the structure and emplacement of the pluton is the fact that amphibolite and quartzite are not *interlayered* with the Telemark Gneiss anywhere in southern Norway.

The quartzite consists primarily of quartz (94%) and white mica (6%); accessory minerals include biotite, chlorite, plagioclase, magnetite, apatite, sphene, zircon, and tourmaline (Sylvester 1964). The quartz grains are large (3–5 mm) and polygonal with serrate borders. The preferred orientation of the quartz c-axes is random (Figs. 7B, C), with the exception of sample K-224 which has a weak crossed-girdle pattern that is fairly symmetric with the foliation and lineation (Fig. 7A). The crossed-girdle pattern of quartz is characteristic of tectonites in thermal aureoles that have been flattened in pure shear normal to the wall of the expanding pluton (Sylvester & Christie 1968; Sylvester et al. 1978; Law et al. 1992). The large size of the grains and the random c-axis fabric in other rock samples indicate to me that the quartzite has undergone considerable strain and annealing recrystallization.

The amphibolite schist is a fine-grained rock with lepidoblastic texture defined by a strong planar orientation of biotite flakes and hornblende needles and plates. It crops out in discontinuous lenses that almost completely surround the pluton, and its schistosity is concordant with the pluton contact. The essential minerals are plagioclase (55%), hornblende (35%), biotite (10%), and minor amounts of apatite and magnetite (Sylvester 1964).

Granitic gneiss surrounds the pluton. It is a medium-grain, equigranular, granoblastic, well-foliated rock consisting of plagioclase (34%), quartz (32%),

Fig. 5. Photomicrographs of minerals in hybrid mafic rocks, Vrådal pluton. (A) Ovoidal quartz crystal mantled by small hornblende crystals. Plane light, bar scale = 2 mm. (B) Conversion of elongate, dark-green hornblende to biotite (tan, pale olive green, greenish brown) and with consequent exsolution of magnetite. Plane light, bar scale = 2 mm. (C) Exotic, subhedral, plagioclase xenocryst with an ovoidal core exhibiting 'boxy cellular texture', consisting of plagioclase subgrains surrounding cells filled with quartz, less commonly with microcline or biotite. Crossed polarizers, bar scale = 2 mm. (D) Large plate of anhedral hornblende containing anhedral subgrains in slightly different crystallographic orientations. Plane light, bar scale = 1 mm.

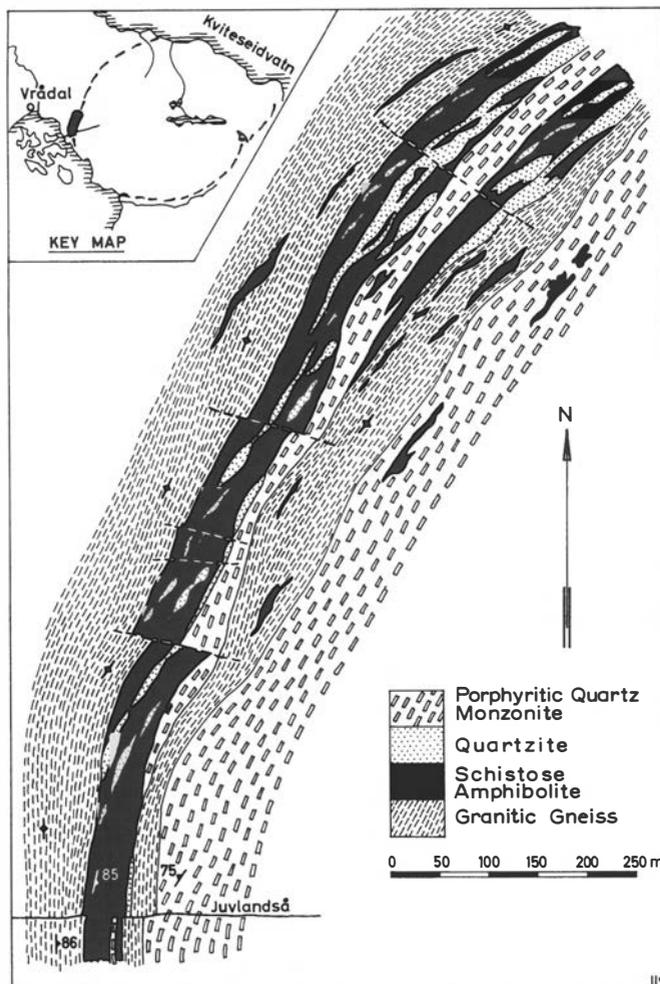


Fig. 6. Geologic map of Juvlandså area depicting pinch and swell of schistose amphibolite and quartzite adjacent to pluton contact. Inset depicts location of map relative to outline of pluton and Vrådalen.

microcline (25%), biotite (4%), hornblende (3%) and small amounts of sphene, magnetite, apatite, and zircon (Sylvester 1964). Biotite and hornblende are concentrated in thin layers and define the foliation thereby. Similar gneiss at Svenseid bridge, 30 km east of Vrådalen, is 1500 Ma (Dahlgren et al. 1990).

Gneiss within 100 to 300 m of the pluton is finer grained, less well foliated, and texturally more homogeneous than most of the gneiss farther from the pluton, as if it were deformed and recrystallized by the pluton together with the quartzite and amphibolite. Mineralogic or textural evidence of contact metamorphism is not evident in that gneiss, however, and its protolith is debatable. Cramez (1970) thought the protolith was felsic metavolcanic rocks correlative with those in the lowermost part of the Bandak group of the Telemark supracrustal rocks. After comparing those two rocks in the field, however, I believe this fine-grained gneissic unit represents the uppermost part of the Telemark Gneiss, now ductily sheared and recrystallized around the pluton by thermo-mechanical effects during its intrusion. Except for its smaller grain

size and weak foliation, it is similar in all other aspects to granitic gneiss 2–15 km west and south of the pluton, as well as to 'pink gneiss' that has been mapped over large areas of Proterozoic crystalline basement in southern Norway (e.g., Falkum 1980). The origin of the gneiss beneath the supracrustal rocks but above undoubted Telemark Gneiss is a subject of a long-standing debate among Telemark geologists, however, and is beyond the scope of this paper.

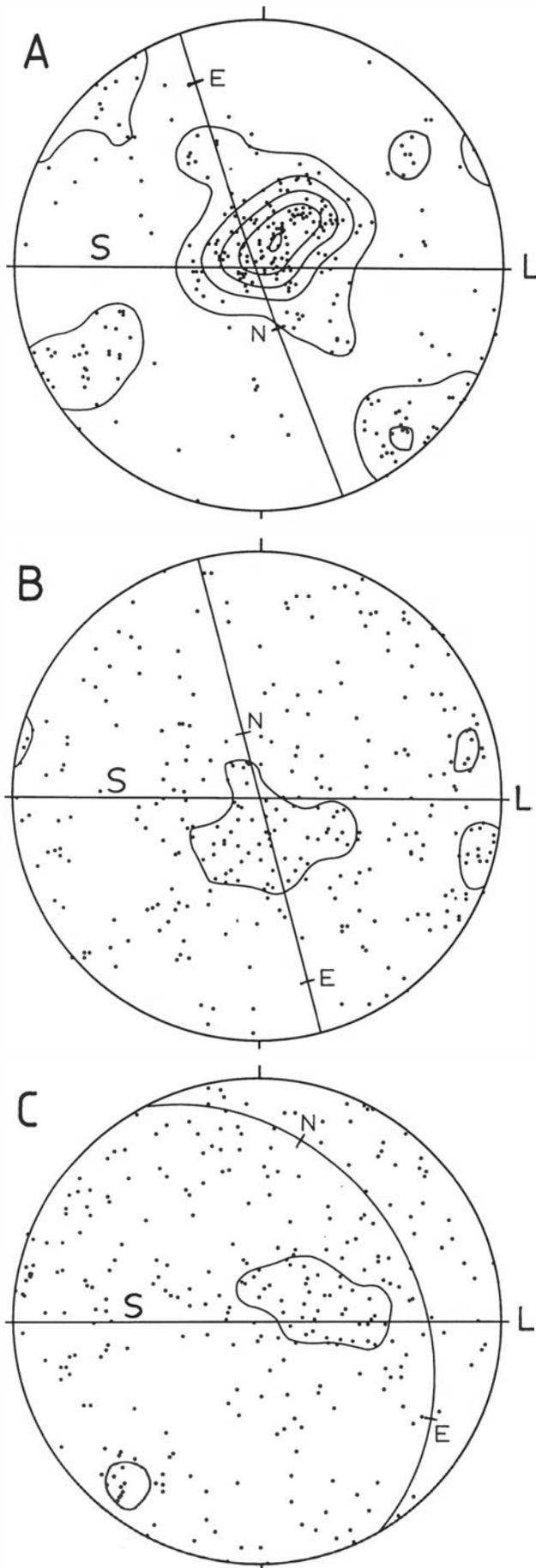
## Structure

### Wall rocks

*Areal structure.* – The pluton is nearly circular in plan view (Fig. 2). Vertical exposures of the contact are rare, but where observed (Fig. 8) the contact is vertical or dips more than 75° toward the pluton. Wall rocks are largely concordant with the contact, so as a first approximation it is reasonable to use the attitude of the foliation in the granite and the adjacent wall rock to determine the dip of the contact where the contact is not exposed. The external contact between the pluton and its wall rocks is very regular, implying that the viscosity of the granitic magma was high during the phase of intrusion now represented by the present outcrops.

Foliation in the wall rocks is defined by lithologic layering, by alternations of mafic and felsic rich layers in granitic gneiss, and by the parallel arrangement of biotite and chlorite in amphibolite schist. The foliation in the pluton is vertical almost everywhere or it dips more than 75° toward the center of the pluton. The foliation in the granitic rocks is defined by the sub-parallel alignment of matchbox-shaped K-feldspar megacrysts (Sylvester 1964, his fig. 4) of smaller plagioclase phenocrysts, of biotite, and of disk-shaped quartz crystals. Its trace is readily visible and easy to map on weathered horizontal surfaces, but it is very difficult to discern in the glacial-carved terrane on vertical surfaces that are commonly covered with lichen and moss.

In general, the gneissic foliation is nearly horizontal or undulates gently over much of the area north, west, and south around the Vrådalen pluton (e.g., Sylvester 1964; Cramez 1970). A gradual change of dip may be discerned 2–3 km from the pluton, steepening progressively toward the pluton, in general, until at the actual contact the wall rock foliation is parallel to the steep margins of the pluton (Fig. 2). A weak, bimodal distribution of attitudes may be discerned in radial transects toward the pluton contact (Fig. 9). Thus, as one approaches the pluton from the west and northwest, the gneissic foliation and lithologic layering steepen progressively from horizontal to about 50° to within 200–500 m of the pluton. Closer to the pluton, the wall rock foliation dip steepens



abruptly toward the pluton from  $70^\circ$  to vertical, concordant with the foliation attitudes in the pluton. The concordance of the foliation in the pluton and wall rocks indicates that both rocks flowed ductily at the same time (Paterson et al. 1996).

An exception to the concentric pattern of the foliation is a triangle-shaped pattern of attitudes in gneiss 2 km northwest of the pluton, 1 km southeast of Middagsnut (Sylvester 1964; Cramez 1970; Fig. 2). There the foliation attitudes change abruptly from steep southwest dips close to the pluton to a northwest-plunging trough that fans outward into gentle northwest dips northwest of Middagsnuten (Fig. 2). These fan-shaped patterns of attitudes near diapiric bodies are termed 'foliation triple points' (Brun & Pons 1981) that are generally regarded as indicators of not only how far pluton-related strain extended into the wall rock (Brun & Pons 1981; Guglielmo 1993), but also that intrusion of the pluton was, at least partly, synchronous with regional strain.

The position of the triple point outside of the pluton indicates that expansion strain was relative high (Brun & Pons 1981). It is noteworthy that the foliation triple point at Vrådal is at the outer edge of the aureole of ductile strain,  $0.3R$ , where  $R$  is the radius of the pluton, at the same place where the foliation begins to dip steeply and consistently toward the pluton.

In the 1–2 km-wide aureole of ductile strain around the pluton where the foliation progressively steepens from nearly flat regional attitudes to steep and concentric attitudes, neither a single large synform, reversals of dip, repetition of the layered rock units, nor small synforms or isoclines were observed that would suggest the presence of a large-scale rim syncline. This null notion supports the structural and stratigraphic evidence that the wall rocks around the pluton are simply downfolded around the pluton as first noted by Barth & Dons (1960, p. 56). They are deformed into a *rim antiform* (Glazner 1994) in contrast to a rim syncline, cryptic or otherwise, as concluded by Sylvester (1964). The downfolding requires explanations that are described in another section below.

*Mesoscopic structures.* – Small structures, including lineations, folds, boudins, and fractures that were related temporally to the intrusion of the pluton ought to yield kinematic information bearing on magma movement during emplacement. Most of the observed strain indicators are in the thin sheath of wall rocks on the northwest

Fig. 7. Preferred orientation of quartz c-axes in quartzite, each from outcrops along north and northwest contact of pluton between Nisservatn and Dyrskard. Lower hemisphere contoured point diagrams, normal to foliation (S) and parallel to lineation (L); N, E, S, W are cardinal compass directions in horizontal plane. (A) Sample K-224: 293 data; contours 1, 3, 5 times uniform distribution. (B) Sample K-225: 298 data; contour 2 times uniform distribution. (C) Sample K-229: 295 data; contour 2 times uniform distribution.

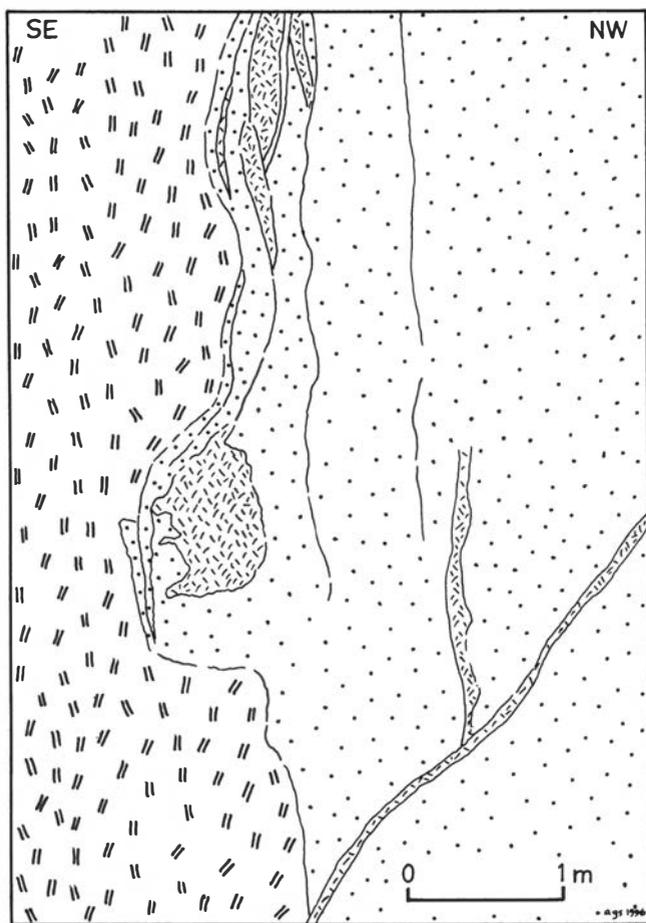


Fig. 8. Field sketch of vertical contact between porphyritic granite (long parallel dashes) and quartzite (dot pattern) in ravine between Dyrskardnut and Skarkedalsnut. Quartz-feldspathic veinlets represented by short dash pattern.

margin of the pluton between Lønnegrav and Skarkedalsmoen, in roadcut exposures near the mouth of Slokvikåi, and southeast of the pluton on Grasnut (Fig. 2). The structures are clearly related spatially to the pluton. A temporal relation cannot be demonstrated with confidence.

Lineations are uncommon around the Vrådal pluton and must be distinguished carefully from equally rare slickenlines on bedding-parallel fracture surfaces. Most of the observed lineations are crenulations and elongate minerals developed at contacts between hornblende schist and quartzite, and they generally plunge steeply toward the pluton (Fig. 10). Their paucity may be explained by models of pluton expansion during non-coaxial tectonic deformation wherein lineations are restricted to domains of maximum constriction (Guglielmo 1993). The sheath of quartzite and amphibolite around the pluton, however, is characterized primarily by boudins and other small structures indicative of stretching rather than of constriction.

Minor, inward-dipping, ductile shear fractures with associated folds indicative of pluton-up kinematics are also uncommon, but transverse profiles of them are well exposed on the wall of a narrow ravine between Dyrskardnut and Skarkedalsmoen (Fig. 11). The mi-

nor shear fractures dip steeply toward the pluton, parallel to the axial surfaces of associated small, similar folds that verge upward and outward from the pluton. Axes of the small folds are nearly horizontal and concentric to the pluton contact. Kinematic interpretation of the shear direction from the asymmetry and vergence of the folds relative to steep fractures is consistent from place to place in quartzite and schist elsewhere around the pluton, clearly indicating upward transport of the pluton relative to the wall rocks or, conversely, downward transport of the wall rocks.

Quartzo-feldspathic veins and the same shear folds are tightly appressed and boudinaged in the sheath of supracrustal metasedimentary rocks around the northwest contact. Fold axes plunge gently in the plane of the foliation; necklines of boudins are steep, parallel to the foliation. These relations, together with the intense development of the concentric foliation, are evidence of a flattening strain superposed on pluton-up (or wall rock-down) simple shear. Thus, these structures imply that the pluton rose upward, expanded outward, and stretched the wall rocks concentrically parallel to the contact as a consequence.

## Discussion

### *Mingling and mixing of mafic and granitic rocks*

Sylvester (1964) regarded the mafic and hybrid rocks within the pluton as stoped blocks of mafic volcanic wall rocks that were pushed upward above the ascending pluton. Nowhere in the pluton, however, are there also blocks or enclaves of the other wall rocks, quartzite and gneiss. Moreover, new roadcuts reveal clear evidence of *mingling* of hot mafic magma and relatively cooler granitic magma (e.g., Wiebe 1993), including the presence of undoubted diabase dikes, back veining of granite into diabase dikes, cusped contacts between the two rock types, pillow-shaped diabase enclaves with 'chilled margins' in outcrop (Fig. 4), and microscopic evidence of undercooling of the mafic rocks, especially acicular apatite (Wyllie et al. 1962).

The black rinds on enclaves indicate that during mingling of felsic and mafic magma, alkalis and water were drawn from the granite to precipitate the growth of biotite in the rinds of the mafic rocks as described above. Introduction of H<sub>2</sub>O into the mafic magma also induced the destabilization of anhydrous mafic minerals (olivine, pyroxene) and transformed them into unalitized *clots* of amphibole or biotite that now comprise the phenocrysts in the fine-grained mafic dikes.

Extensive mixing, hybridization, and homogenization of granitic and mafic magma occurred in the Vrådal pluton, according to field and petrochemical evidence (Christiansen & Konnerup-Madsen 1996; Christiansen

1996), especially in the northeast quadrant of the pluton where the proportion of mafic component is large, and where diffuse schlieren are more evident than discrete enclaves. There, repeated mixing and permeation of mafic rocks with metasomatizing granitic fluids made a dioritic mush carrying phenocrysts of calcic plagioclase and hornblende; this mush became mixed with granitic magma carrying crystals of K-feldspar, andesine/oligoclase, hornblende, biotite, and quartz, to yield a hybrid

rock containing a contrasted and incompatible porphyrocryst assemblage with every variation of crystal size and form. Quartz ocelli, oligoclase mantled K-feldspar porphyrocrysts, and fretted plagioclase porphyrocrysts in feldspathized mafic rocks provide strong petrographic evidence of thermal disequilibrium between granite and the mafic rocks (e.g., Vernon 1984, 1990; Castro et al. 1995).

A continuous input of heat and volatiles is needed to sustain the liquidity of the two components during magma mixing, particularly to reverse crystallization processes that otherwise increase the viscosity, and to provide the constant agitation and convection so necessary for efficient mixing. Thus crystallization of mafic rocks during undercooling rapidly releases latent heat that is absorbed by crystal fusion in the adjacent felsic magma (Frost & Mahood 1987; Hibbard 1995, p. 191). That heat would allow the granitic magma to sustain a relatively high temperature and relatively low viscosity so that it could intrude higher and for a longer period of time. Evidence that heat was sustained is shown in the recrystallization and growth of unusually large grains of quartz in quartzite in the wall rocks together with partial to complete annealing of the crossed-girdle fabric in the quartzite. Moreover, assuming that the microscopic and mesoscopic fabrics in quartzite around the north and northwest parts of the pluton are contemporaneous, the symmetric arrangement of the crossed-girdle pattern of c-axes relative to the foliation and lineation in a single sample of the quartzite suggests that the rocks were flattened in pure shear perpendicular to the foliation (e.g., Sylvester & Christie 1968). This interpretation is fully compatible with the boudinage and stretching of the wall rocks by radial outward expansion of the pluton at the same time that it was rising.

Mafic rocks are not associated with late Sveconorwegian plutons that intruded supracrustal rocks elsewhere in Telemark (e.g., Bessefjell, Vehuskjerringa, Venåsfjell), either because the plutons arrived in higher crustal levels at subsolidus temperatures too low for mixing and homogenization to occur (Pitcher 1993), or the granitic and mafic magmas ascended together, the granite drawing higher and leaving the mafic rocks behind (e.g., Hopson et al. 1991). Mafic rocks are common in those plutons that intrude the Telemark Gneiss, however, including several of those in Setesdal (Pedersen & Konnerup-Madsen 1994).

Even though the supracrustal rocks contain great thicknesses of mafic lava flows and sills, all of the latter are older than the late Sveconorwegian plutons. Thus, the mafic rocks in the plutons must be associated with the episode of granite plutonism.

#### Structure and emplacement

*Pre-intrusion structure.* – The foliation of the gneiss undulates gently everywhere more than 5 km from the

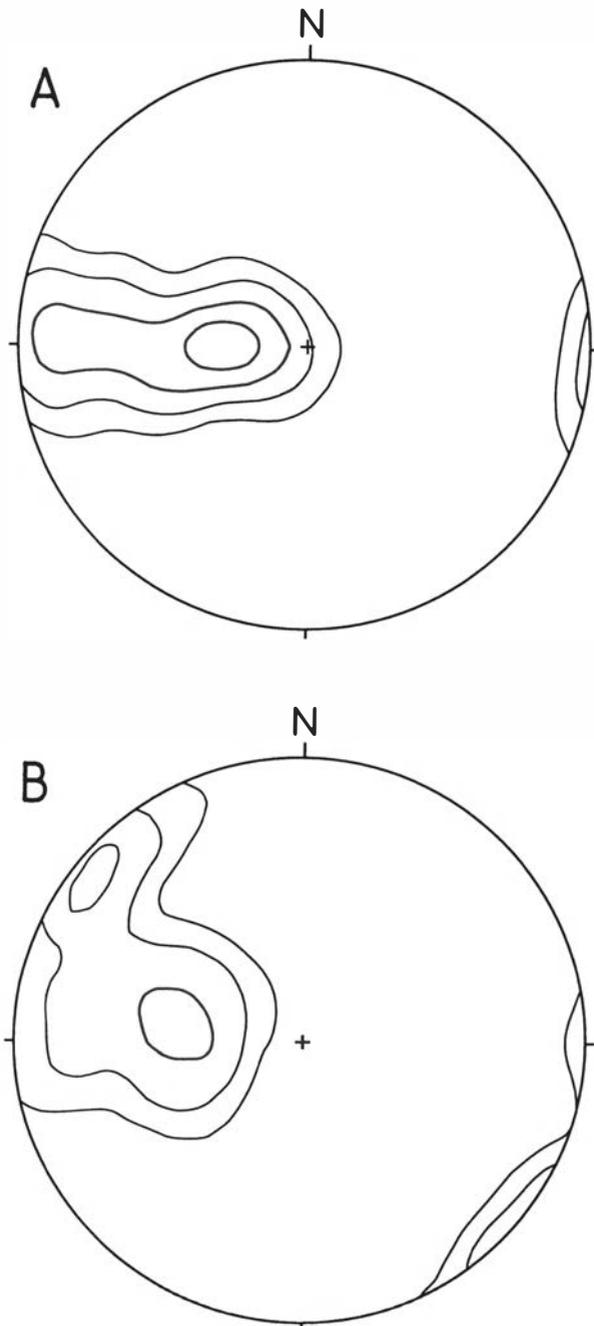


Fig. 9. Bimodal distribution of poles to foliation (S1) in gneiss near Vrådal pluton. (A) 35 poles from islands west of pluton; contours 1, 3, 6, 9 times uniform distribution; (B) 27 poles from area between Nisservatn and Dyrs kard; contours 1, 3, 6 times uniform distribution. Lower hemisphere stereographic projection.

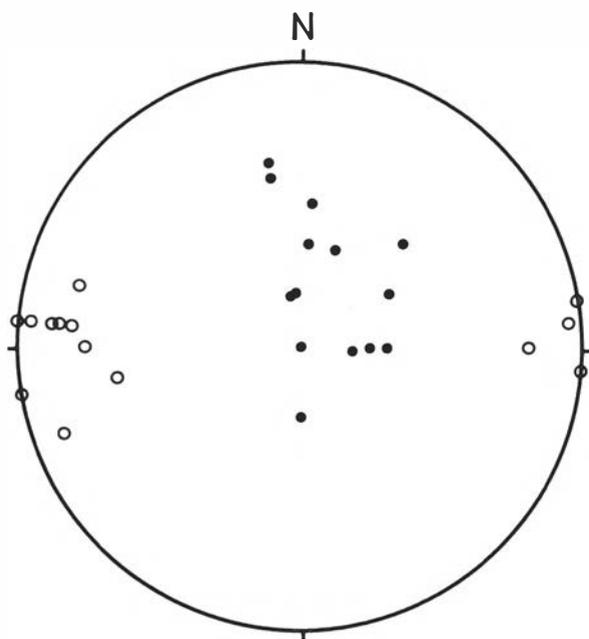


Fig. 10. Lower hemispheric stereographic projection of steep lineation (solid dots) on subvertical foliation (open dots) at Juvlandså; 14 measurements each.

Vrådal pluton, and I infer that this is the way it was when the pluton intruded it. Although his mapping stopped at the northwest quarter of the pluton in his basin evolution diagram, Cramez (1970) concluded that the Vrådal pluton passively intruded a steep-sided synformal structure, based on his measurements of about 80 attitudes of gneissic rocks within a very large area (600 km<sup>2</sup>) south and west of the Vrådal

pluton, but evidently inferred at several hundred other locations (Cramez 1970, his Plate I). Nowhere else in southern Norway, however, is there evidence of funnel- or bowl-shaped basins within the basement with or without plutons in their core. Moreover, to have a single fold abruptly plunge nearly vertically in a region of otherwise gentle folds stretches the imagination greatly, so I reject Cramez' notion that the Vrådal pluton passively intruded an existing, nearly vertical syncline. I believe instead that the steep foliation around the Vrådal pluton was caused by the pluton itself.

*Rim anticline.* – One of the main conclusions obtained from this remapping of Vrådal pluton as described above is that the wall rocks bend progressively downward, everywhere around the pluton, in the form of a *rim anticline* (Fig. 12B). The fact that the supracrustal rocks, quartzite and amphibolite, *overlie* the Telemark Gneiss everywhere in Telemark means that structural interpretations involving *interlayered* gneiss and amphibolite (Fig. 12A) are untenable. The stratigraphic arrangement of quartzite, amphibolite, and gneiss outward from the contact (Fig. 12B) requires the presence of a rim anticline at the present, virtually two-dimensional level of exposure. It must be stressed that evidence of upward drag of the wall rocks, either on the scale of a rim syncline, isoclinal or otherwise, or in the small structures around the contact, was not found in this restudy, except locally where rare, mesoscopic structures inferred to be relict indicate pluton-up, or wall rock-down, shear as described above. As Clemens & Mawer (1992) stressed, however, the present shape of a pluton may not represent its shape and lithologic character whatsoever at various stages of its intrusion.

Plutons surrounded by rim antiforms have been described elsewhere, notably around post-orogenic plutons in southeast Greenland (Bridgwater et al. 1974), southern Norway (Smithson & Barth 1967), the Boulder batholith of Montana (Hamilton & Myers 1967), and the White-Inyo Range of eastern California (Nelson 1966, 1971; Stein & Paterson 1996; Morgan et al. 1998). The rim anticlines around igneous intrusions, however, are quite different in origin from the rim synclines characteristically observed around salt masses (e.g., Halbouty 1979, his figs. 5-1, 7-1, 11-2; Jackson et al. 1990, their fig. 1.74) that have served so commonly as analogs for granitic intrusions (e.g., Wegmann 1930, his fig. 3; Sylvester 1964). The structural differences between the wall rocks of salt and those of granitic intrusions reflect the obvious rheologic differences between rising salt and igneous masses, the most important differences being the thermal-mechanical differences between the density and viscosity of the intrusion and of the wall rocks (Wegmann 1930; Huppert et al. 1982, 1984; Furman & Spera 1985; Glazner 1994).

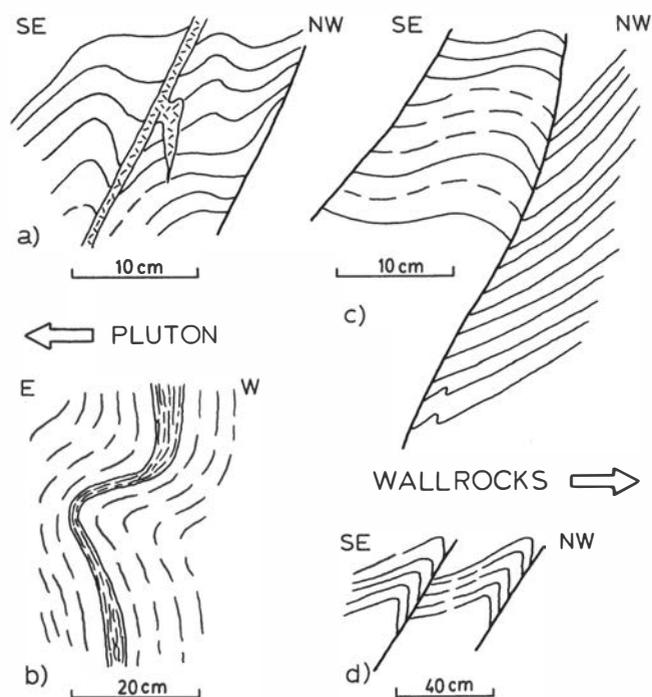


Fig. 11. Field sketches of style of small shear folds in amphibolite at various locations within 50 m of pluton contact. Sense of shear is pluton-up.

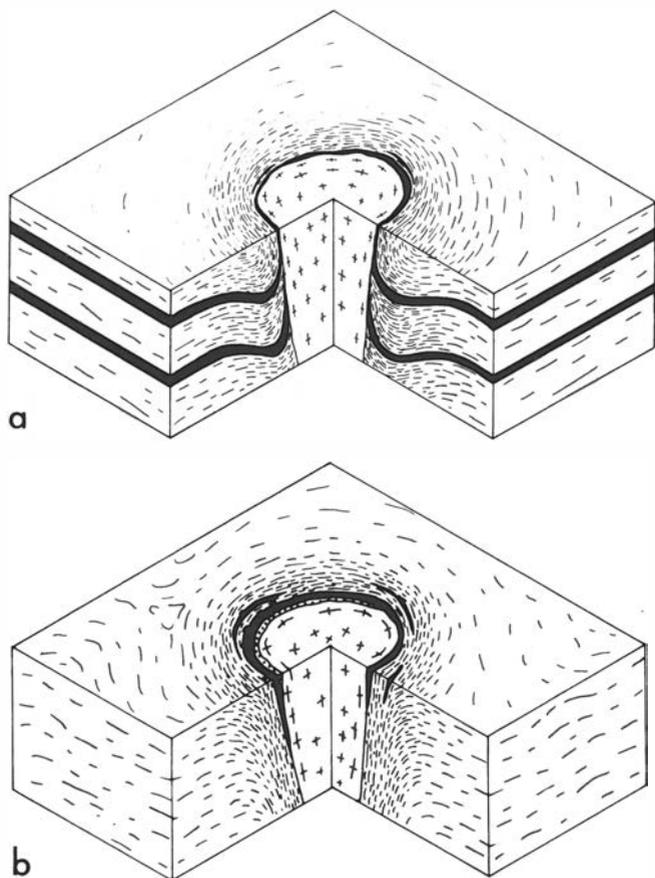


Fig. 12. Schematic representations of Vrådal pluton to its wall rocks, view from south to north, compare with Fig. 2. (A) Rim syncline defined by upturned amphibolite layers (black) and granitic gneiss (Sylvester 1964, his fig. 6); (B) Downfolded quartzite (dotted), amphibolite (black), and gneiss with triple point in plan view.

Downbending of the wall rocks around the stem of granitic diapirs may result from two processes: (1) downward return flow of the wall rocks as a thermal-mechanical consequence of upward transfer of heat with molten rock from the upper mantle or lower crust into ductile middle crust (Paterson & Vernon 1995; Paterson et al. 1996), and (2) late stage foundering of the crystallized pluton within its thermally softened wall rocks (e.g., Glazner 1994; Glazner & Miller 1997).

*Return flow.* – Because the intruding magma is volatile-rich and hot, it is less viscous and more buoyant than the surrounding rocks, as well as the rocks from which it was derived. The heat envelope around a rising granitic mass will warm a pathway in the wall rocks through which a crystalline mass consisting of 70–80% crystals will rise diapirically quite efficiently and effectively (Marsh 1982). This pathway may have been pre-heated initially by intrusion of mafic rocks preceding the granite. The viscosity of the wall rocks will also be reduced where the shear stress is high. Thus the lower the viscosity of the rising mass, the smaller the tangential viscous shear forces in the wall rocks for a given flow rate (Bridgwater et al. 1974), so the wall rocks will yield more readily to downward flow rather than to

upward drag. The magma will therefore, rise faster than lateral flow of equally hot but less viscous rock can fill its evacuated space in the lower and middle crust. The consequence is the return downward flow of thermally softened aureole rocks around the rising pluton to balance the space problem (Paterson & Vernon 1995, Paterson et al. 1996).

*Down sinking.* – Upon cooling, a pluton's density and viscosity may increase, perhaps to a higher density than its quartzofeldspathic wall rocks (Glazner 1994; Glazner & Miller 1997). Then it will stall and may founder, sink, and drag the thermally softened wall rocks downward, thereby, overprinting or obliterating the fabrics produced during ascent. The prevalence of mingled and mixed mafic and hybrid rocks in the Vrådal pluton and its high content of magnetite impart a relatively high density relative to its gneissic wall rocks. That high density and the sparse structural evidence for upward rise of the pluton support the hypothesis of late-stage sinking of the pluton, downbending of the wall rocks, and obliteration of early formed mesoscopic structures.

It is hazardous to estimate the amount of sinking at Vrådal, especially if it has a cylindrical or funnel-shaped form at depth, but given a Stokes settling rate of 0.1–1 cm/yr and an effective viscosity of 1020 Pa, a spherical pluton may sink hundreds or thousands of meters during a few hundred thousand years (Glazner & Miller 1997), certainly enough to cause its wall rocks to bend downward.

#### *Relation to other Telemark plutons*

The same granitic mass has differing degrees of mobility during intrusion, such that the heat balance in a rising diapir will eventually become so strongly negative that the outer shell of the magma body will solidify completely by crystallization, whereas mobile magma may continue to rise within the diapir, pierce the top of the hardened shell, and continue to higher levels (e.g., Hopson et al. 1991) even as the crystallized mass sinks. Further development of the ultimate size and shape of the pluton depends on the relative ease of ballooning by the diapiric shell, extension of the cap roof, local effects of regional deformation before, during, and after emplacement, and eventual upward escape of the magma by means of dike mechanisms so strongly advocated (e.g., Clemens & Mawer 1992) and documented recently by many authors (e.g., McNulty et al. 1996). The more resistant the overlying rocks are, however, the smaller will be resultant dikes and plutons. Because of their generally discordant relations with the wall rocks, the latter plutons are commonly classified as 'post tectonic', whereas their deeper, generally concordant and diapiric parts are classified as 'syntectonic'. The form that the pluton takes according to

its intrusion depth is a reasonable explanation for why, in central Telemark, the Vrådal pluton has the attributes of a concordant, 'syntectonic', granitic diapir at its present exposure level within the Telemark Gneiss, whereas nearly coeval plutons in the overlying Telemark supracrustal rocks, including and especially the Venås pluton (Carter 1962), are regarded as typical, discordant 'post tectonic' plutons (e.g., Starmer 1993). Thus, in terms of an intrusion model of granitic plutons (e.g., Vigneresse 1995), Vrådal represents the stem of a deep (>15 km) level diapir, and Venås that of a relative shallow pluton (<10 km) that may have been fed by a dike or dikes. Examples of granitic dikes that may have fed the high level plutons are exposed in supracrustal rocks 1–2 km east of the Mandal–Ustaoset line (Fig. 1) where it passes along the east edge of Lake Byrte (Nilsen 1981). The analogous, inferred diapiric cap that should have been emplaced at an intermediate position between the present levels of Vrådal and Venås plutons, according to this model, may now be represented by some of the areally large granitic plutons that Sigmond (1975) mapped west of the Mandal–Ustaoset line in west Telemark and Aust Agder.

## Conclusions

Synplutonic intrusions of mafic rocks intimately mingled and mixed with the granite magma to provide thereby a sustained heat supply to overcome the effect of simultaneous crystallization in the granite. The sustained heat also contributed to more penetrative heating of the wall rocks to reduce their viscosity and to decrease the tangential viscous shear forces of the wall host. By such thermo-mechanical processes, Vrådal pluton was able to ascend *en masse* through the presently exposed level of the crust.

A rim syncline, typical around salt intrusions, is not present around Vrådal pluton in contrast to Sylvester's (1964) previous interpretation. Instead, the wall rocks are downfolded into a rim anticline around most of the pluton. The rim anticline, coupled with the increased density of the pluton imparted by synplutonic intrusion of mafic rocks, strongly suggests that the pluton sank downward an indeterminate distance after its initial buoyant, gravity-driven ascent.

Intense flow, recrystallization, concentric stretching and locally intense, radial flattening occurred synplutonic in the wall rocks within a 100 m or so of the contact as expressed by ductile shearing, quartzite boudins, and ptygmatic quartzo-feldspathic veins. Rare kinematic indicators of displacements show that relative pluton-up, or wall rock-down, movements were concentrated in a narrow, concentric zone of shear in the outer margin of the pluton and in the inner zone of the wall rocks. The paucity and restricted localization of these structures suggest that they are relicts of post emplacement annealing and deformation associated with return

flow of the wall rocks or sinking of the pluton made possible by their extended thermal softening by the mafic-rich pluton.

The concentric structural symmetry of Vrådal pluton and its wall rocks, the structural evidence of concentrated ductile flow around its margins, and its bulk dimensions strongly argue for its emplacement as a viscous, polycrystalline, buoyant, gravity-driven, diapiric mass, rather than as an accumulation from one or several dikes. Its steep inward-dipping contacts suggest that the present exposure level represents the stem of the diapir. The structural setting, downfolding of wall rocks, and internal structure of the Vrådal pluton, moreover, are similar in all aspects to stems of granitic diapirs elsewhere (e.g., Vigneresse 1995), notably those that are splendidly exposed in southeast Greenland (Bridgwater et al. 1974). Thus, by analogy, but also on its own merits, it is reasonable to conclude that the Vrådal pluton is the stem of a granitic diapir, although for some markedly different reasons than inferred previously (Sylvester 1964).

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