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Relationships between the Western Gneiss Region and the Trondheim Region: *Stockwerk*-tectonics reconsidered

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ABSTRACT

Low-grade volcanosedimentary successions of the Trondheim Region overlie the so-called Basal Gneisses of the Western Gneiss Region of southwestern Norway. Structural and metamorphic studies show that low-grade rocks of the Trondheim Region were already thrust-emplaced before completion of strong Caledonian metamorphism and deformation of the underlying Western Gneiss Region. Although a detailed Caledonian tectonostratigraphy including some Precambrian crystalline rocks is now recognized, many of the concepts of *Stockwerk* tectonics, applied here by Wegmann in 1935, are still considered valid. Rocks of the Trondheim Region form a superstructure and the Western Gneiss Region an infrastructure, although the '*Abscherungszone*' is a major thrust surface and no migmatitic front is found.

Within the Oppdal district, metamorphism of the superstructure increases downward (westward), from chlorite to biotite to local garnet grade. In the infrastructure the metamorphic grade also increases westward from about 580°C ($K_D{}^{\mathrm{gar+bio}}_{\mathrm{FeO/MgO}} = 5.4$) to about 660°C ($K_D = 4.0$) about 30 km to the west where Caledonian granitic intrusions first appear. Westward, at still deeper levels, Caledonian eclogites and granitic intrusions are common, but PreCambrian and Caledonian rocks and metamorphic events are not fully differentiated.

Large recumbent folds formed within the infrastructure adjacent to the superstructure. They are refolded by younger upright folds that are tight at depth (westward) and open up dramatically near and within the superstructure. The Surnadal synform is such a late fold, which is open in the superstructure but tightens downward, becoming isoclinal and recumbent toward the west. The Surnadal folding juxtaposes greenschists of the superstructure with eclogites of the infrastructure, and both are partially recrystallized under amphibolite-facies conditions.

Introduction

The gneisses of the Western Gneiss Region of Norway are overlain to the east by the fossil-bearing Palaeozoic rocks of the Trondheim Region. The gneisses were traditionally interpreted to represent Precambrian basement rocks and Caledonian sediments that were intensely deformed, metamorphosed, and granitized during the Caledonian orogeny (Holtedahl 1953; Strand 1961). These processes were thought to have occurred in place, beneath the thick cover of the Trondheim Region. The Western Gneiss Region has often been called the Basal Gneiss Region, a term which originally referred to the concept that basal parts of the Caledonian stratigraphic succession were transformed to gneisses (Holtedahl 1944).

Wegmann (1935) mentioned the Western Gneiss Region as the *Unterbau* and the Trondheim Region as the *Oberbau* in his classic interpretation of migmatites and regional granitization. Haller (1956, 1971) developed these interpretations in the East Greenland Caledonides. He illustrated the *Stockwerk*-tectonic model, with the mobile *infrastructure* undergoing deformation, metamorphism,

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and granitization beneath the shallow, more brittle *superstructure*. The *Abscherungszone*, a zone of detachment and steep metamorphic gradient, separates the two main levels, or *Stocken*, of the structure. Although this terminology was rarely used in Norway, the model was considered to describe accurately relationships between the Western Gneiss Region and the Trondheim Region (Wegmann 1959). The geological map of Norway (Holtedahl and Dons 1960) clearly shows the common interpretation. The Western Gneiss Region—the infrastructure—includes K-rich augen gneisses, which are shown as developing by metasomatism or granitization in various Caledonian sediments. The low-grade rocks of the Trondheim Region—the superstructure—are shown stratigraphically above the gneisses and their sparagmitic cover. A major 'tectonic discordance' below the low-grade rocks (Holmsen 1955) was not shown on the map. It was apparently considered to be an *Abscherungszone* without great displacement. The higher grade schists folded with the gneisses were considered to be rocks from the Trondheim Region that became involved in the infrastructural processes. Some parts of these schists are shown as fading into the basal gneisses toward the west.

Recently, this *Stockwerk*-tectonic interpretation has been discredited. Geochronological studies have demonstrated that many of the presumably Palaeozoic gneisses are in fact Precambrian rocks (Brueckner *et al*. 1968; Pidgeon and Råheim 1972; Råheim 1977), and that even the well known augen gneisses are Precambrian (Solheim 1980). These results led to many interpretations that the schists were also Precambrian and that the Western Gneiss Region was a Precambrian metamorphic complex (*cf*. Krill and Griffin 1981). Furthermore, the general recognition that the fossil-bearing Palaeozoic rocks of the Trondheim Region are allochthonous allows the interpretation that there is no metamorphic or structural relationship between the Trondheim Region and the Western Gneiss Region. However, tectonostratigraphic, structural, and geochronologic data from the eastern margin of the Western Gneiss Region reaffirm that much of the infrastructural style orogenesis was in fact Caledonian (Krill 1980b). Some relationships between the Western Gneiss Region and the Trondheim Region are outlined here, with the suggestion that the *Stockwerk*-tectonic interpretation be modified but not abandoned.

Tectonostratigraphy of the Oppdal District

The Oppdal district includes parts of both the Trondheim Region and the Western Gneiss Region between Surnadal and Dombås (Fig. 1). A seven-unit tectonostratigraphy may now be recognized; some units were described earlier (Krill 1980b), but all are briefly presented here, from the base upwards.

The *Lønset* gneiss complex includes granitic, granodioritic, and heterogeneous gneisses. The degree of Caledonian deformation and recrystallization is quite variable. Some eastern parts are nearly undeformed, while many western parts are migmatitic, and much of the migmatization was presumably Caledonian. Small gabbros and amphibolites are common and some contain eclogitic parts or relicts of eclogite. Rb–Sr geochronologic studies of the gneisses and gabbros have yielded only Precambrian whole-rock dates (Råheim 1977; Solheim 1980; Tørudbakken 1981). The Lønset gneiss is presently considered a single tectonostratigraphic unit, and some mapped subdivisions are not shown on Fig. 1.

The *Åmotsdal* unit is dominated by 'sparagmite-type' psammites. In a few well preserved areas, basal conglomerates demonstrate that both foliated gneiss and massive granodiorite of the Lønset complex formed the basement to the Åmotsdal sediments. Generally, the basal unconformity is strongly deformed, or tectonically repeated; only the major thrust or fold repetitions are shown on Fig. 1. Attempts to date the metamorphism of the psammites (Solheim 1980) are not considered reliable (Krill 1983). Gee (1980) recognized possible glacial features in the sandstones, which suggest a Vendian age. He also correlated graphitic schist, marble, and quartzite with the fossiliferous Cambro-Ordovician stratigraphic succession of the Caledonian front. The Åmotsdal sediments are thus considered to be Late Precambrian to Lower Palaeozoic in age.

The *Risberget Nappe* is characterized by coarse augen gneiss, but also includes rapakivi granite, gabbro, anorthosite, felsic granite, and heterogeneous gneiss with some calc-silicates. Abundant Rb–Sr geochronological studies have yielded only Precambrian (c. 1100–1700 Ma) whole-rock dates (Solheim 1980; Krill 1980b). The augen gneisses can be interpreted as deformed megacrystic granites, and the Precambrian dates as intrusive ages. The least deformed rapakivi granite and anorthosite gabbro preserve relict granulite-facies mineralogy or high-temperature igneous mineralogy.

The *Sætra Nappe* consists of feldspathic psammite and amphibolite. The rocks are commonly strongly deformed but where best preserved the amphibolites clearly originated as tholeiitic dolerite dykes that cut sedimentary layering in undeformed fluvial sandstone. The tholeiitic dolerite yielded a Rb–Sr whole-rock date of 745 ± 37 Ma, interpreted as the pretectonic igneous age (Krill 1983).

The *Blåhø Nappe* includes garnet–hornblende

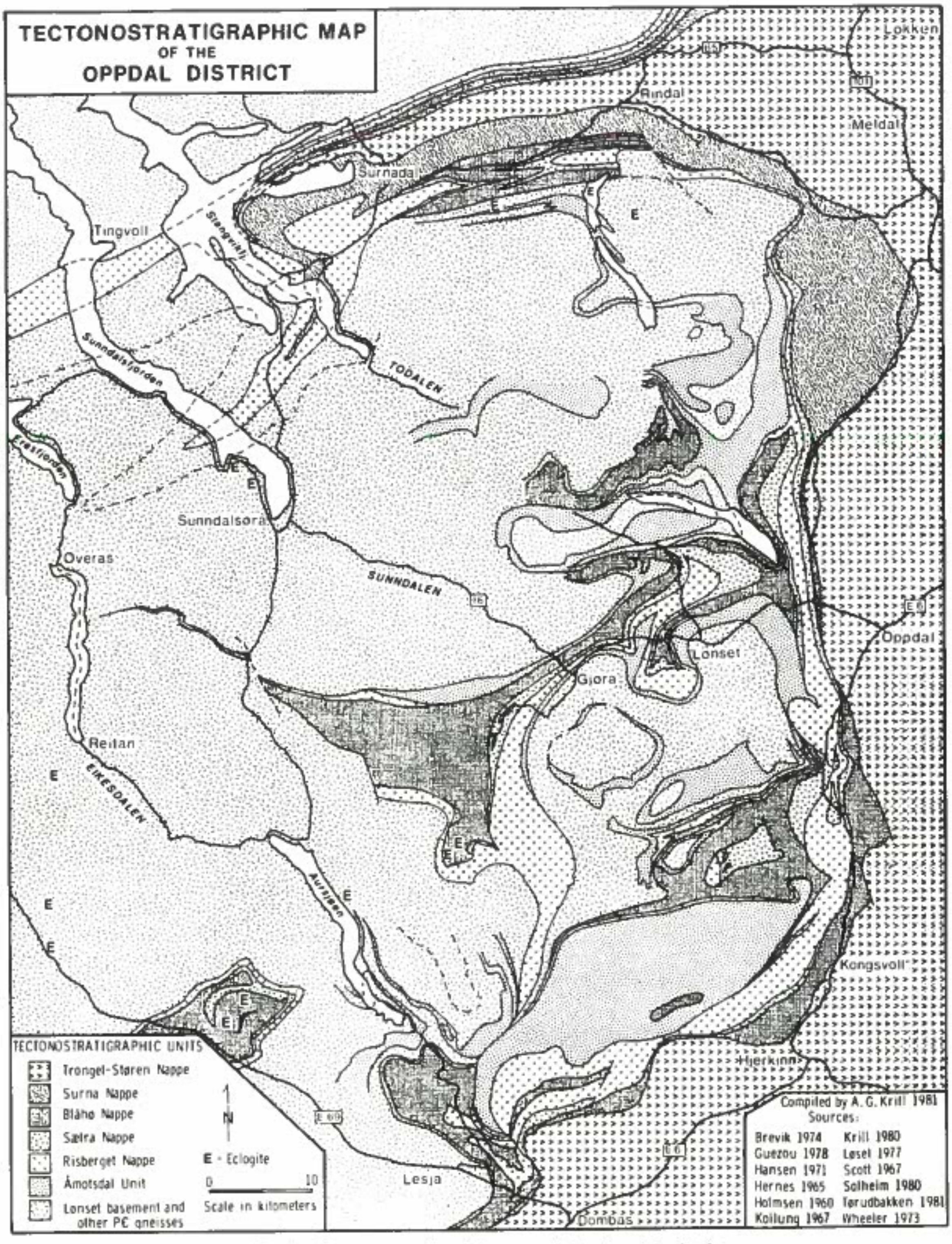

Fig. 1 Tectonostratigraphic map of the Oppdal district

schist and amphibolite, with some serpentine bodies, marble, psammite, and gneiss. The rocks are characteristically low in K_2O and Rb, and have proven difficult to date by the Rb–Sr whole-rock method. An intermediate gneiss yielded a nine-point errorchron date of 583 ± 69 Ma (Krill and Röshoff 1981). Other dating attempts have yielded no whole-rock dates, but the data (Solheim 1980; Krill 1980b) strongly suggest maximum model ages for the sediments of about 800 Ma.

As newly defined here, the *Surna Nappe* overlies the Blåhø Nappe in the northern part of the district.

The Surna rocks are similar to Blåhø rocks and may have originally been closely related, but the Surna Nappe is readily distinguished by its abundant dykes and bodies of trondhjemite. The nappe is continuous at least to Orkanger, 50 km to the northeast, where the presence of trondhjemites still distinguishes it (Gangåsvann group, Johnsen 1979) from the nearby Blåhø Nappe (Sjuråsen group). Near Rindal, fine-grained trondhjemite dykes clearly cut an early schistosity in amphibolite and schist of the Surna Nappe. The Surna rocks apparently contained the metamorphic foliation and trondhjemites before their emplacement as a nappe above the Blåhø Nappe. Towards the west, pegmatitic trondjemite is typically strongly deformed with the schist. The contact between the Blåhø and Surna Nappes is quite sharp but not yet well mapped. Where uncertain, the rocks are shown as the Surna Nappe on Fig. 1. An attempt to date the Surna ('Røros') schist (Råheim 1977) yielded no isochrons, but errorchrons at about 460 Ma might indicate an Ordovician metamorphic age.

The *Tronget–Støren Nappe* includes rock types similar to the Blåhø and Surna Nappes, but only in greenschist-facies metamorphic grade. Mafic volcanic rocks and various volcanoclastic sediments are dominant, whereas pelitic rocks are rare. Near Oppdal, the 'Tronget unit' (Krill 1980) includes a large Oppdalite massif and smaller trondhjemitic intrusions (Holmsen 1955). To the north, trondhjemites are notably absent in the Løkken volcanics and in their westward extensions, and help to distinguish them from the underlying Surna Nappe. The Tronget rocks were recently remapped as part of the Gula Nappe Complex, and the Løkken rocks as part of the Støren Nappe (Guezou 1981). They are here considered to be a single unit, as shown by earlier mapping (e.g. Nilsen 1978), and it is here termed the Tronget–Støren Nappe. Fossils in the Løkken area suggest an Arenig age for some of the volcanic rocks (Ryan *et al*. 1979), and a Lower Palaeozoic age is presumed for all the rocks of the Tronget–Støren Nappe.

Each of the five nappes described here is apparently allochthonous on the scale of the present map (Fig. 1), as indicated by the following evidence. Mylonites and a metamorphic discontinuity mark the base of the Tronget–Støren Nappe. Trondhjemites are abundant in the Surna Nappe but markedly absent in the underlying Blåhø Nappe. Ultramafic bodies are common in the Blåhø Nappe but never below. Dolerite dykes are not recognized beneath the Sætra Nappe. Finally, the gabbros, anorthosites, and granitic orthogneisses of the Risberget Nappe overlie the monotonous Åmotsdal psammite, where any intrusives would be easily recognized, if present. Parts of the Lønset and Åmotsdal units are also allochthonous, or at least parautochthonous, but these nappes have not been adequately mapped or differentiated. Correlation of the Risberget Nappe and Sætra Nappe with the Tännäs Augen Gneiss Nappe and the Särv Nappe, respectively, indicates Caledonian thrusting and stretching of several hundred kilometres. A suggested correlation of the Blåhø and Seve Nappes (Krill 1980a) is not supported, as the Seve is a heterogeneous complex including Precambrian gneisses (Claesson 1981). The Surna Nappe presumably correlates with the trondhjemite-intruded Gula Nappe, which tectonostratigraphically underlies the (Tronget–) Støren Nappe on its eastern side (Wolff 1976; Nilsen 1978, Guezou 1981). The Tronget–Støren Nappe appears to form the structurally highest level within the Trondheim Region.

The recognition of the complex tectonostratigraphy in the Western Gneiss Region significantly modifies the original *Stockwerk*-tectonic interpretation, because gneisses interlayered with the sediments can no longer be considered metasomatic. Lønset and Risberget units contain Precambrian igneous rocks, and their occurrence above Caledonian metasediments, and even local interlayering and gradational contacts, are best interpreted as the result of thrusting and folding, not granitization.

Fold Structures

Following the main thrusting, the nappes were multiply folded together with the basement. Giant recumbent folds, with the Risberget Nappe in the anticlinal cores and the Blåhø Nappe in the synclinal cores, repeated the tectonostratigraphy over much of the Oppdal district. The recumbent folds appear to verge away from several large gneiss domes in the centre of the district. The Holberget recumbent fold pair (Krill 1980a) verges southeastward along northeast-oriented axes (sections C–C′, D–D′, E–E′, Fig. 2). Other early recumbent folds south of the Surnadal synform appear to verge northward along east-plunging axes (B–B′, Fig. 2). However, they are tightly refolded and somewhat obscured by the Surnadal synform and other late, tight folds. The Surnadal synform also verges northward along an east-plunging axis (B–B′) and northwestward (A–A′) where it becomes recumbent as well (Rickard, this volume).

The recumbent folds are commonly refolded in upright folds with east-plunging axes (Fig. 2). Many of these folds (Krill 1980a), including also the Surnadal synform and the synform that refolds it at Tingvoll, are tight or isoclinal toward the west, and

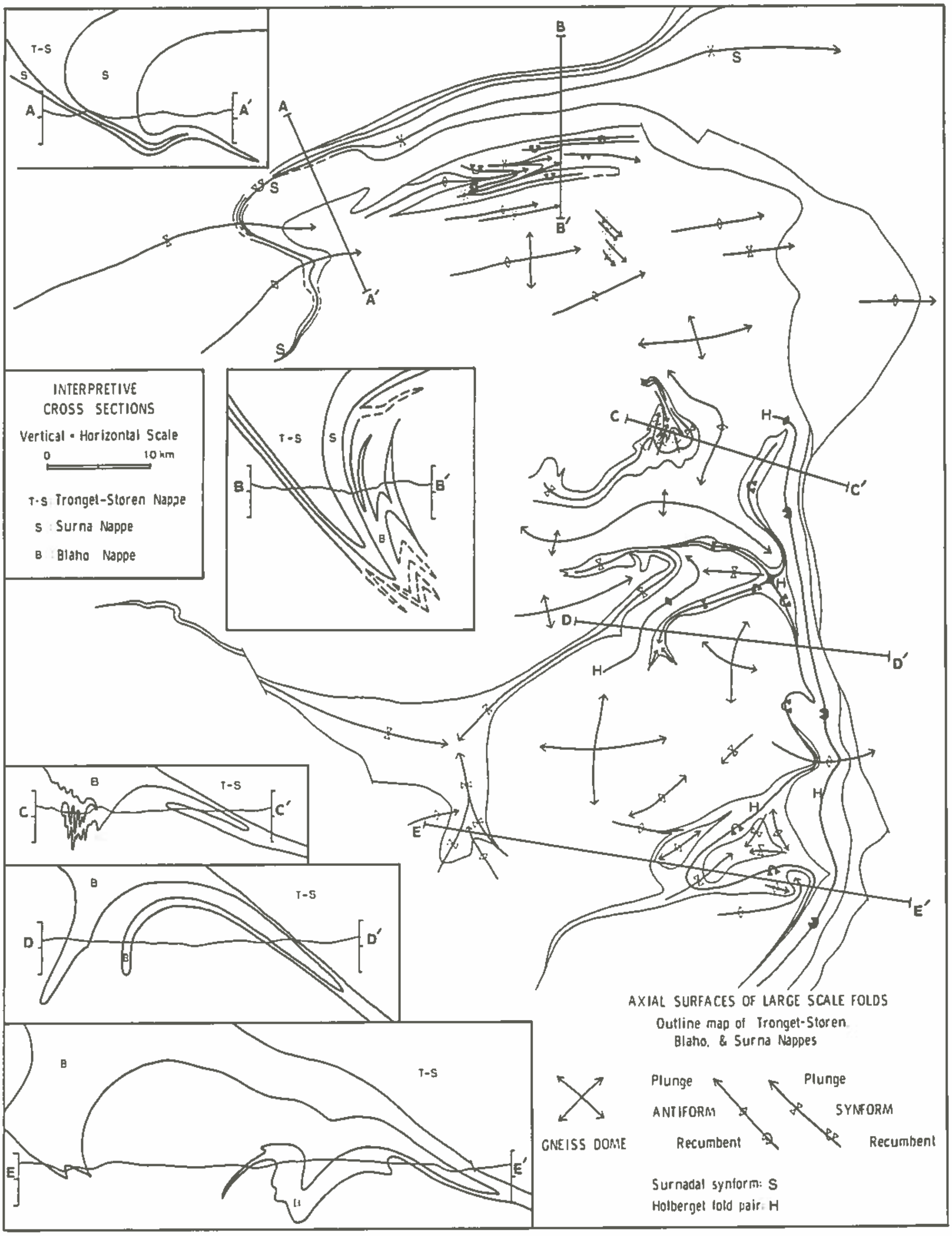

Fig. 2 Cross-sections and folds of the Oppdal district

become more open eastward. Although most folds ‘die out’ disharmonically before reaching the Tronget–Støren Nappe, none are actually truncated by the nappe, and some continue weakly into it.

The early recumbent folds do not appear to involve the Surna Nappe or the Tronget–Støren Nappe, but the later folds, including the recumbent Surnadal synform, involve all the nappes. The Surna and Tronget–Støren Nappes were apparently thrust emplaced during or after the early recumbent folding, but folds of similar style and orientation continued to develop after their emplacement.

The structural pattern corresponds well to the classic *Stockwerk*-tectonic model, with tight ductile folding being restricted to the infrastructure. The Tronget–Støren and Surna Nappes may have acted as a stiff upper barrier to the development of the ductile recumbent folds and dome structures.

Metamorphism

A metamorphic discontinuity (Holmsen 1955; Hansen 1971; Råheim 1979), caused by late thrusting and high-angle faulting, generally separates the greenschist-facies rocks of the Tronget–Støren Nappe from the amphibolite-facies rocks below, and the metamorphism must be considered separately on each side of the discontinuity.

Metamorphism of the Trondheim Region was mapped by Goldschmidt (1915; and see Fig. 1.2 Miyashiro 1973). He showed the metamorphic grade as increasing rapidly westward, but did not recognize any metamorphic discontinuities.

Within the Oppdal district, the rocks are in the chlorite zone at Løkken and Meldal and the metamorphic grade increases westward, or structurally downward. Biotite porphyroblasts occur locally in volcaniclastic conglomerate and greenschists near the base of the Tronget–Støren Nappe, and the first small fresh garnets appear west of Rindal (locations in Krill and Röshoff 1981). Goldschmidt (1915) mapped these rocks in the biotite zone; indeed, the garnets are very rare and relatively spessartite-rich almandine (FeO:MgO:MnO) = (65:4:31). Similar garnets also occur in primary biotite–chlorite schists at the western edge of the Tronget–Støren Nappe near Kongsvoll and garnet–biotite temperature estimates ($K_{D[\frac{Gt+Bio}{FeO\,MgO}]}$, Thompson 1976) show prograde zoning to c. 500°. Garnets are still extremely rare in the Tronget–Støren rocks farther west in the Surnadal synform, but where found they are strongly prograde-zoned and show higher K_D-temperatures, up to 550° (Fig. 3). It is clear that the metamorphic grade increases westward (structurally downward) within the Tronget–Støren Nappe.

The rocks of the Surna Nappe are in garnet grade, as shown by Goldschmidt (1915), but the presence of cross-cutting trondhjemite dykes shows that an early garnet-grade metamorphism preceded the thrusting. If the trondhjemites are coeval with Gula trondhjemites, the early metamorphism may have been Ordovician (Klingspor and Gee 1981). This early metamorphism yielded K_D temperature estimates of c. 650° (Fig. 3). The Surna rocks were mainly remetamorphosed, together with the other rocks. The strongly foliated Surna rocks near the contact with the Tronget–Støren Nappe are partially retrogressed to chlorite-grade near Rindal, but garnet and biotite are stable within the folded thrust contact west of Surnadal in the deeper parts of the Surnadal synform (*cf.* Rickard, this volume). Detailed petrographic study of the Blåhø–Surna contact has not yet been made.

Metamorphic grade within the Western Gneiss Region also appears to generally increase westward, as in the western part of the Trondheim Region. The gradient is suggested by the abundance of eclogites, granulites, and migmatites toward the west, and by calculated temperatures and pressures of *in situ*-metamorphosed eclogites (Krogh 1977; Griffin *et al.*, this volume).

Within the Oppdal district, the metamorphic gradient is also suggested by the westward abundance of eclogites, migmatites, and granitic pegmatites, and by calculated temperatures of garnet–biotite pairs within the Blåho Nappe. Garnet–biotite pairs from Blåhø samples near Hjerkinn, Oppdal, and Lønset show prograde zoning, with highest K_D–temperature estimates up to only 550° (Eggen 1977; Krill unpublished data). The deep synform west of Gjøra provides continuous exposure of Blåhø rocks far to the west, and garnet–biotite pairs crudely show a metamorphic gradient (Fig. 4). Garnets show prograde zoning in some specimens (W28, W33, X5, X10) and retrograde zoning in others (W74, W23); only maximum temperatures within each mineral pair analysed are shown in Fig. 4. Along this traverse, temperatures increase from about 580° to 660°, a gradient of about 2°/km. The gradient is similar to that shown by eclogites, and garnet–biotite temperatures from specimen W23 agree well with the calculated garnet–omphacite temperatures of 610° from the nearby eclogitic amphibolite (spec. 51, Griffin *et al.*, this volume). West of specimen W33, cross-cutting granitic pegmatites are common, whereas none are found in eastern parts of the Blåhø Nappe. The Blåhø schists also become partly migmatitic, and garnets become scarce, as they are progressively replaced by biotite.

Eclogites are much more abundant in the western parts of the Oppdal district, but the mapping there is less detailed and only the distinctive roadside eclogites have been found. Eclogites south of the Surnadal synform (Fig. 1) are the closest eclogites to the Trondheim Region. One eclogite there provides temperature estimates of c. 630° (Tørudbakken 1981), far greater than estimates for greenschists of the nearby Tronget–Støren Nappe (Fig. 3). However, both the greenschists and the eclogites show strong disequilibrium. Prograde zoning in Tronget–Støren garnets may reflect a rapid temperature increase. The eclogites are thoroughly retrogressed to garnet–amphibolite and biotite–epi-

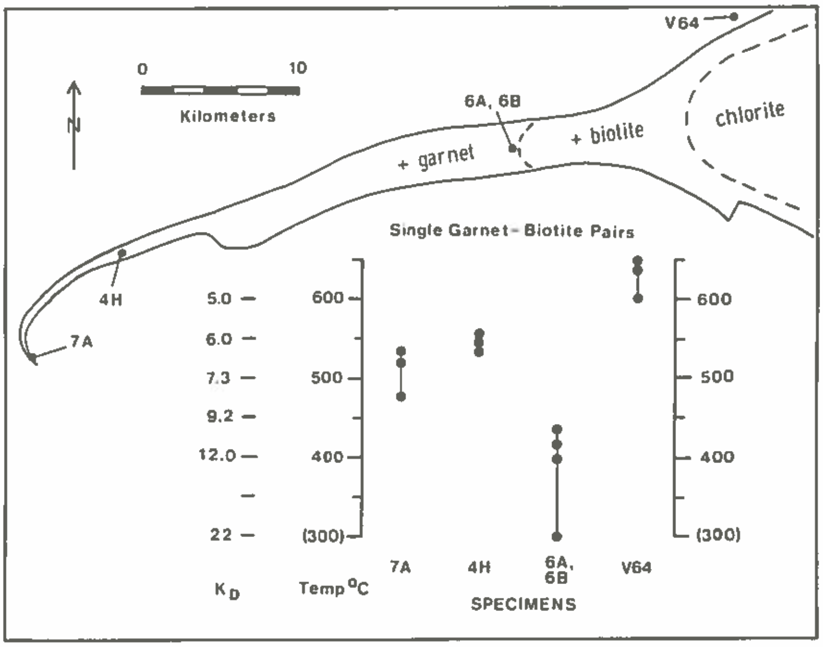

Fig. 3 Map of sample locations and estimated K_{D}[illegible]-temperatures from schists. Temperature calibrations after Thompson 1976, and Perchuk 1969

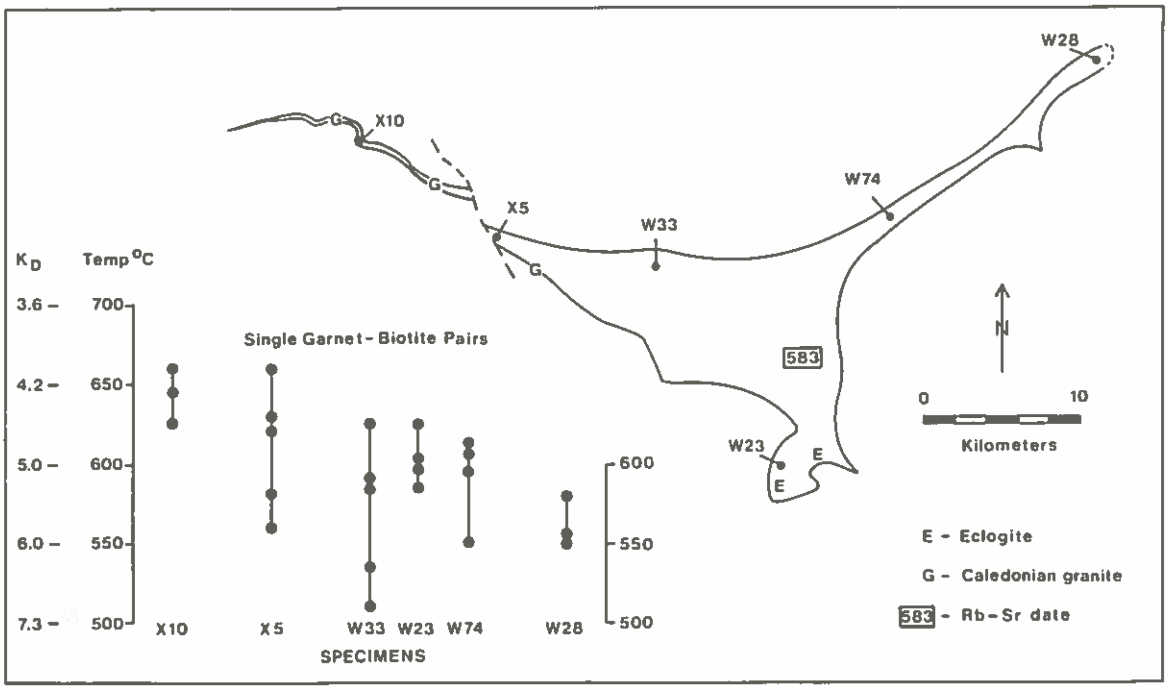

Fig. 4 Map of sample locations and estimated K_{D}[illegible]-temperatures from schists. Temperature calibrations after Thompson 1976, and Perchuk 1969

dote-amphibolite toward their margins, and only the retrogressed parts show the horizontal E–W mineral lineations, consistent with the Surnadal structures (Krill and Röshoff 1981). The eclogites apparently formed before or during the early recumbent folding, and before the final thrust emplacement of the Tronget–Støren and Surna Nappes. The juxtaposition of the rocks by thrusting and deep folding apparently led to a temperature convergence, and both the greenschists and eclogites began to recrystallize under amphibolite-facies conditions.

Age of Orogenesis

The ages of thrusting, folding, and metamorphism are very poorly bracketed. Early thrusting was certainly younger than 745 ± 37 Ma (intrusion of Sætra dolerites), and presumably younger than 583 ± 69 Ma (volcanic age? of Blåhø intermediate gneiss). The major metamorphism was apparently coeval with the early recumbent folding. It presumably peaked about 425 Ma (Sm–Nd dates of eclogites, Griffin and Brueckner 1980), and was essentially over in the Oppdal district by 375–395 Ma (Rb–Sr mineral isochrons, Solheim 1980; Krill unpublished data). The Surna Nappe and the Tronget–Støren Nappe were presumably thrust-emplaced during late stages of this metamorphism and folding.

Revised *Stockwerk*-tectonic interpretation

The *Stockwerk*-tectonic model was developed when the granitization theory was popular and long-distance thrusting was not. Without accepting thrusting, this static interpretation was the best explanation for the sharp lithologic, metamorphic, and structural discontinuities within and above the Western Gneiss Region. Recognition of the thrusting requires modification of the *Stockwerk*-tectonic interpretation, but several features of the original model, including the upper limit of gneiss domes and recumbent folds, the upward opening of folds, and the upward decrease in metamorphic grade, all apply to the Oppdal district. They suggest that the Western Gneiss Region acted as a Caledonian infrastructure, and was bordered rather sharply above by a relatively cold, stiff superstructure. The Tronget–Støren and Surna Nappes of the Trondheim Region clearly formed this superstructure only during the late orogenic stages. The superstructure was apparently in continual motion as a thrust unit, with the thrust fault beneath it serving as an *Abscherungszone*. The rocks that formed the superstructure during the eclogite formation and the early recumbent folding may now form parts of the Seve, Gula, or other eastern nappes. There was no mobile 'migmatite front', and granitization was not an essential feature of the infrastructure, although migmatization of both cover and basement units did occur in western parts.

Since the original *Stockwerk*-tectonic model must be revised to apply accurately to this Norwegian example, it could be argued that the terminology be abandoned. It is retained here to emphasize that not all the structural and metamorphic features of the Scandinavian Caledonides are the result of thrusting. Both thrust-tectonics and *Stockwerk*-tectonics played a role in the Caledonian development of the Western Gneiss Region.

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