Silurian conglomerate sedimentation and tectonics within the Fennoscandian continental margin, Sunnhordland, western Norway

ROALD B. FÆRSETH & RONALD J. STEEL

Færseth, R. B. & Steel, R. J.: Silurian conglomerate sedimentation and tectonics within the Fennoscandian continental margin, Sunnhordland, western Norway. *Norsk Geologisk Tidsskrift*, Vol. 58, pp. 145–159. Oslo 1978. ISSN 0029-196X.

A thick succession of Silurian conglomerates on Stord, showing clast-supported textures but no internal stratification, has been interpreted as resedimented. A distinct upwards change in composition from mainly sedimentary clasts to mainly igneous clasts, with upwards increasing grain size, suggests a shift in direction of drainage through time, with the latest phase of disposal from an uplifted igneous complex along the basin's northwest margin.

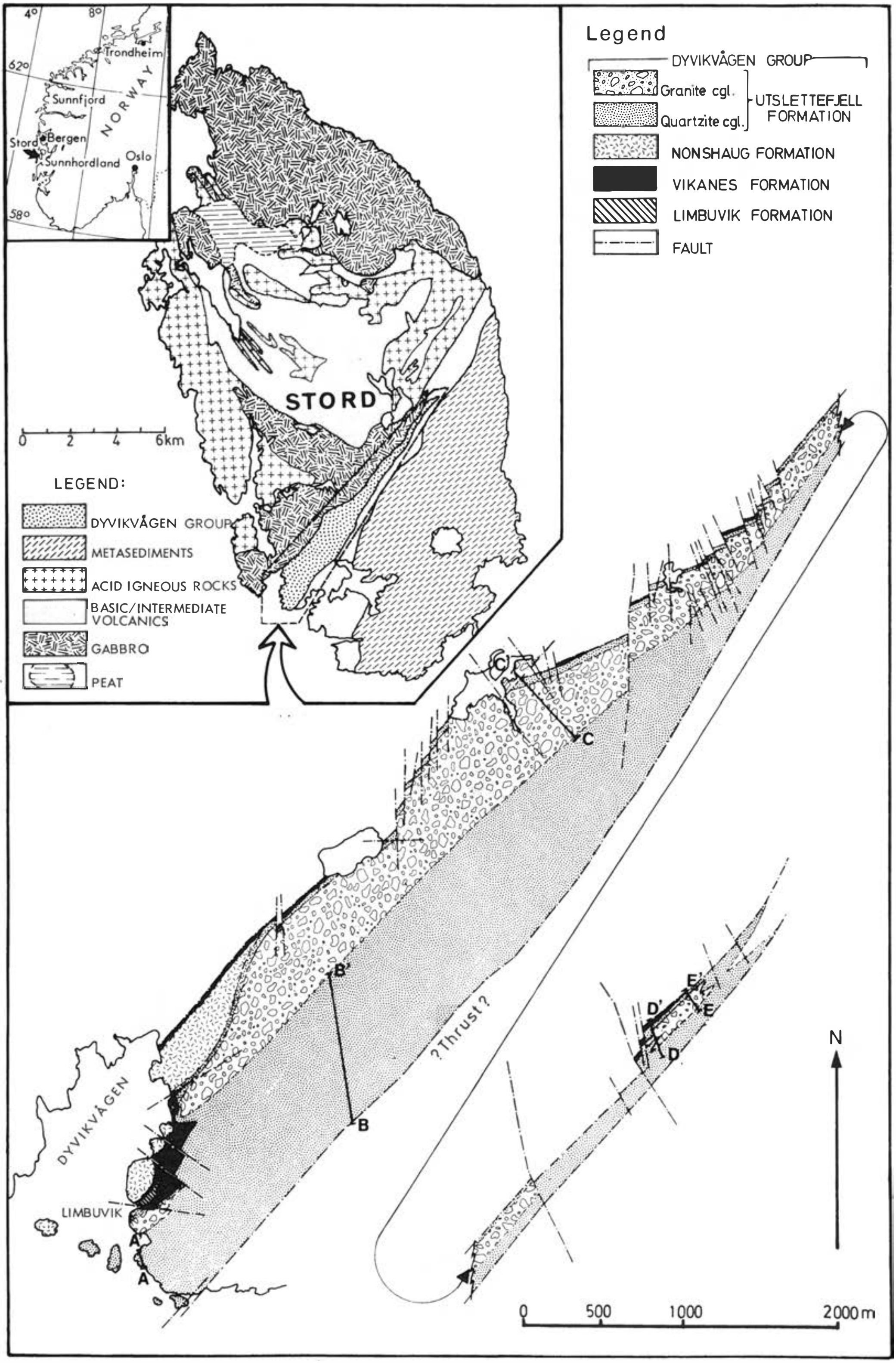
The succession of conglomerates overlying tholeiitic basalts, graptolitic shales, and carbonates is interpreted in terms of an intercontinental rift basin sequence, marginal to a continent-based magmatic arc. The conglomerates record the rifting, early sediment dispersal from the cratonic side of the basin, the later uplift of the magmatic arc, and the gradual unroofing of its plutonic core.

R. B. Færseth, Geologisk institutt, avd. A, Universitetet i Bergen, 5014 Bergen, Norway. Present adress: Norsk Hydro A/S, P. O. Box 490, 1301 Sandvika, Norway. R. J. Steel, Geologisk institutt, avd. A, Universitetet i Bergen, 5014 Bergen, Norway.

The sedimentary history of the early Palaeozoic geosynclinal belt in western Norway is still poorly documented. A recent synthesis of the succession in the Trondheim area, together with new data on the chemistry of the widespread Cambrian to Lower Ordovician basic volcanic rocks in the sequence, led Gale & Roberts (1974) to propose that the early Palaeozoic geography of western Norway was dominated by a western belt (Cambrian/early Silurian) composed of an island arc complex developed on oceanic crust with a back-arc eugeosynclinal pile, and an eastern belt (late Precambrian/Ordovician) of miogeosynclinal character which developed on continental crust.

Based on lithological similarities a common origin has been assumed for the lower Palaeozoic successions in the Trondheim and Sunnhordland regions (e.g, Strand 1960, 1972). However, recent studies of the allochthonous lower Palaeozoic succession in the region south of Bergen, on Stord and Bømlo (Fig. 7), suggest that there the history of events was different from what has been suggested for the Trondheim area.

In the Stord/Bømlo region there are three main groups of rocks: the Sunnhordland Igneous Massif in the west, a more metamorphosed and deformed group of dominantly phyllites and volcanics in the east, and the Dyvikvågen Group, the conglomeratic part of which is discussed here, situated in a narrow zone in the centre (Figs. 1 and 7). The Sunnhordland Igneous Massif consists of acidic (455 ± 5 Ma, Priem & Torske 1973) and basic lavas, pyroclastics, gabbros, granites, and local peridotites. Studies of the volcanics (Furnes & Færseth 1975) have suggested an intracontinental environment. Within the Dyvikvågen Group there are tholeiitic basalts (post-lower Llandovery) with a trace element geochemistry characteristic of ocean floor basalt (Furnes & Færseth 1975) and these are interpreted in terms of crustal thinning and separation within the Dyvikvågen basin, presently lying on the southeast margin of the Sunnhordland Igneous Massif. The conglomerates of the Utslettefjell Formation dominate the Dyvikvågen Group on Stord (Fig. 1). The northwestern and southeastern contacts of the conglomerate belt have previously been considered to be tectonic, possibly thrusts, and it has generally been assumed that the northwesterly contact was of greater importance since it separated sediments from igneous rocks (e.g. Strand 1972). We have remapped these boundaries and suggest that the northwesterly one was a major Silurian normal fault which shows evidence of post-conglomerate reactivation. As a corollary there has been no major horizontal movement along this tectonic


Legend
DYVIKVÅGEN GROUP
Granite cgl.
Quartzite cgl.
UTSLETTEFJELL FORMATION
NONSHAUG FORMATION
VIKANES FORMATION
LIMBUVIK FORMATION
FAULT
Trondheim
NORWAY
Sunnfjord
Stord
Bergen
Sunnhordland
Oslo
4°
8°
62°
58°
STORD
0 2 4 6km
LEGEND:
DYVIKVÅGEN GROUP
METASEDIMENTS
ACID IGNEOUS ROCKS
BASIC/INTERMEDIATE VOLCANICS
GABBRO
PEAT
DYVIKVÅGEN
LIMBUVIK
A'
A
B'
B
C'
C
D'
D
E'
E
?Thrust?
N
0 500 1000 2000 m

line and the Dyvikvågen Group squarely belongs to the igneous belt (Fig. 7).

The Dyvikvågen Group – stratigraphic context

The Dyvikvågen Group consists of four formations:

Utslettefjell Formation – 1000 m polymict conglomerates.

Nonshaug Formation – max. 220 m tholeiitic volcanics, including pillow lavas (Furnes & Færseth 1975).

Vikanes Formation – max. 110 m graptolitic shales, early Llandovery age (Skevington pers. comm. *in* Færseth & Ryan 1975).

Limbuvik Formation – minimum 25 m shelly limestones, Ashgillian (Kiær 1929).

The conglomerates dominate the Group and are well exposed for 20 km both to the northeast of Dyvikvågen and on Bømlo, the island south of Stord (Fig. 7). At Dyvikvågen (Fig. 1) the contact between the graptolitic shales of early Llandovery age and the overlying conglomerate is gradational and in places the lithologies appear to interfinger.

The conglomerates have undergone two phases of Caledonian folding; the first phase was accompanied by a lower greenschist facies metamorphism.

A Rb-Sr age ($\lambda_{Rb} = 1.39 \times 10 - 11_{yr} - 1$) of 409 ± 15 Ma has been reported for a secondary cleavage developed in greenschist facies metamorphosed sediments on Hardangervidda (Andresen et al. 1974). This age was interpreted to represent a late phase of the Caledonian orogeny affecting both the Hardangervidda-Ryfylke Nappe System and the autochthonous sediments. As the rocks of the Dyvikvågen Group apparently have been subjected to this phase of deformation and metamorphism, we assume that the conglomerates were deposited between early Llandoverian and late Silurian time.

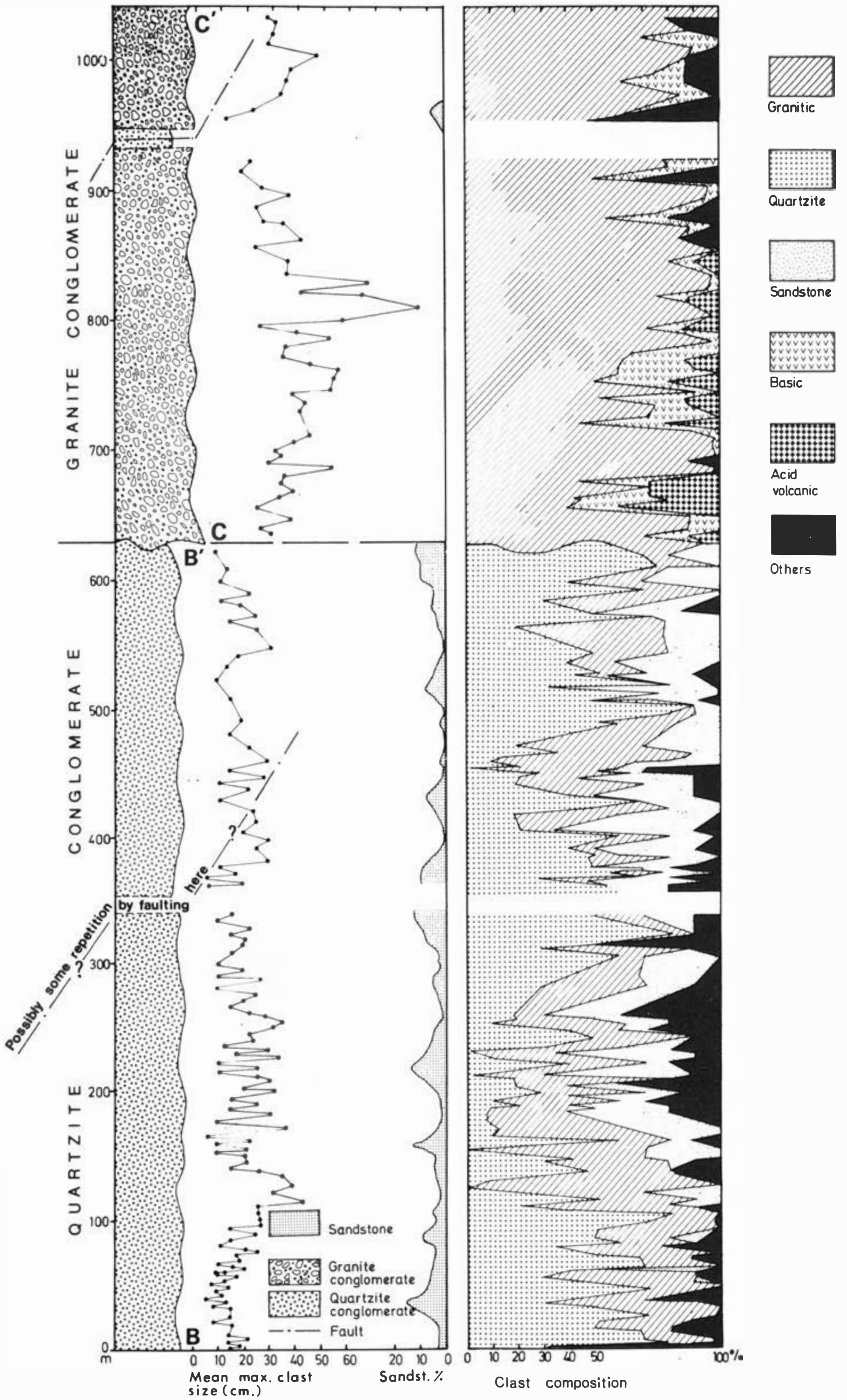
In the rocks of the Dyvikvågen Group major noncylindrical folds and a regional foliation (S1) were developed during the first deformation phase (D1) affecting these rocks. During this phase of deformation, the fragments having an oblate shape were rotated into a position parallel to the axial planes of the folds. Normally the bedding is steep and the foliation is seen to be sub-parallel with general NE-SW trends. Where the bedding is at a lower angle of dip, the long axes of the clasts, which lie within the S1 foliation, are often oriented at a marked angle to the bedding. Late D1 slides parallel to the Sl foliation are common within parts of the conglomerate and usually coincide with local zones of strong pebble deformation. Such movements make accurate measurements of the succession thickness impossible. However, detailed sedimentological measurements across the conglomerate body suggest no major fault repetitions and the total thickness of the sequence probably exceeds 1000 m.

The conglomerates of the Utslettefjell Formation

Two general aspects of thick conglomeratic successions often provide clues to the geographic and tectonic history of the area containing them. In the conglomeratic portion of clastic strata, distinctive compositional features of their source are usually accentuated (Walton 1963) and, although associated sandstones may come from more distant sources, the clasts in conglomeratic sequences therefore provide an unusually clear record of the sites and extent of parent drainage areas (e.g. Bluck 1969). On the other hand, the very coarseness of such clastic sequences is likely to be an indication of contemporary, rapid basin subsidence while the variation of coarseness may provide additional information about the type or intensity of tectonism (e.g. Steel & Wilson 1975). In addition, details of the internal organisation of conglomerates, such as the texture and structure of individual beds, may provide information about the mechanisms and processes involved in their transportation and deposition (e.g. Bluck 1967, Davis & Walker 1974). Considering the relative ease with which most of these properties can be measured (assuming bedding can be identified) it is surprising how few detailed studies have been made in conglomerate sequences.

The present study of the conglomerates of the Utslettefjell Formation has dealt largely with general aspects. Tectonic deformation, especially in the lower part of the succession (quartzite

Fig. 1. Map of the Dyvikvågen Group, showing its position between the igneous complex on NW Stord and the sedimentary/volcanic sequence of SE Stord. Inset, simplified geological map of Stord after Kvale (1937) and Skordal (1948).


C'
C
B'
B
GRANITE CONGLOMERATE
CONGLOMERATE
QUARTZITE
Possibly some repetition here by faulting
?
m
0
100
200
300
400
500
600
700
800
900
1000
Sandstone
Granite conglomerate
Quartzite conglomerate
Fault
0 10 20 30 40 50 60
Mean max. clast size (cm.)
20 10 0
Sandst. %
0 10 20 30 40 50
100%
Clast composition
Granitic
Quartzite
Sandstone
Basic
Acid volcanic
Others

conglomerates), made detailed examination extremely time-consuming. Five profiles, involving detailed logging of pebble composition, sedimentary structures, maximum particle size, and – in places – bed thickness, were made over various parts of the body (Fig. 1). The main aim was to identify any significant vertical variations through the conglomerates and to interpret these in terms of the prevailing tectonic situation. In addition, at several localities, details of the texture of individual conglomerate beds were investigated.

The Utslettefjell Formation consists of two compositionally distinct sequences, now informally named the *quartzite* and *granitic* conglomerates respectively (Fig. 2). The latter usually overlies the former along a well-defined contact (Fig. 1), although the two parts of the succession interfinger at the northeastern end of the area (Figs. 1 and 3), indicating that no stratigraphic break separates the two conglomerates. At the southwestern end of the body the conglomerate succession appears to rest conformably upon Lower Silurian graptolite schists of the Vikanes Formation (Fig. 1). In the same area, however, about 0.5 km north of Limbuvik, an unconformable junction has been interpreted in terms of a large erosional-channel infilling (Færseth & Ryan 1975).

Quartzite conglomerate

The quartzite conglomerate sequence appears to have a maximum thickness of approximately 600 m. Detailed logging at certain localities (Fig. 1) shows that bed thickness rarely exceeds 4 m, at which point mean maximum clast size reaches 30–40 cm. In general there is a decrease in bed thickness with decreasing clast size (Fig. 4). The sandstone percentage (as discrete sandstone beds) in the sequence varies from 5 to 15 % and this also appears to be inversely related to conglomerate coarseness (Fig. 2). As regards the composition of pebbles, it is noticeable that coarser beds typically contain more granitic clasts.

Fig. 2. A composite profile through the Utslettefjell Formation (C–C′/B–B′ are located on Fig. 1) showing mean maximum particle size, sandstone percentage, and clast composition (of the 'maximum particle size' fraction) trends. Note the major clast size and clast composition change at the base of the granite conglomerate.

Sedimentary structures are rare in the conglomerates but cross-stratification or parallel lamination is found in some of the sandstones interbedded with the finer conglomerates. Massive sandstone beds are most common in the coarser parts of the succession. The quartzite conglomerate, apart from its basal 100 m, decreases in coarseness upwards (Figs. 2 and 4).

The conglomerate matrix and the sandstone beds are mainly lithic and feldspathic greywacke. Conglomerate clasts, which are usually well-rounded, include quartzite, sandstone, limestone, granite, granodiorite, quartz diorite, gabbro, basic volcanics, and chert.

A detailed analysis of the conglomerate facies across the entire body has not been attempted, but detailed observation at a number of localities indicates that there is considerable variation in the nature of conglomerate beds or units present.

Bedding is usually marked by variation in the grain size of adjacent units, either by sandstone interbedded with conglomerate or, more often, by interbedding of fine and coarse-grained conglomerates. The latter feature, interbedding of conglomerates with differing mean and maximum particle size, is a very striking aspect of the succession at most localities. This basic alternation together with vertical gradients of grain size either within a bed or within a group of beds, variation in the amount of matrix in the grain population, and the presence or absence of lamination in the associated sandstones, produces a considerable range of sedimentary units in the conglomerate body. Those illustrated in Figs. 5 and 6 have been distinguished in the coastal succession (A–A′, Fig. 1) at the SW end of Stord.

Individual beds with abrupt or erosional upper and lower boundaries consist either of conglomerate or sandstone. The former are usually massive, reverse- or normal-graded (in order of abundance). The latter may occur in single sets (Fig. 6A, 6D) or in cosets (Fig. 5A, 5C) and may be parallel or cross-laminated (Fig. 5D, 6D) or normal-, reverse- or non-graded (Fig. 5C, 5D). Beds commonly occur together in groups, where the beds often have indistinct or non-erosional boundaries and where there is a trend (discontinuous) of grain size. Such groups of beds probably have a close depositional or time-relationship and are here called *units*. As regards the relationship of sandstone beds to such conglomerate units, it is extremely common to find laminated sandstones abruptly capping units (Fig. 5A, 5D, 6D), while massive

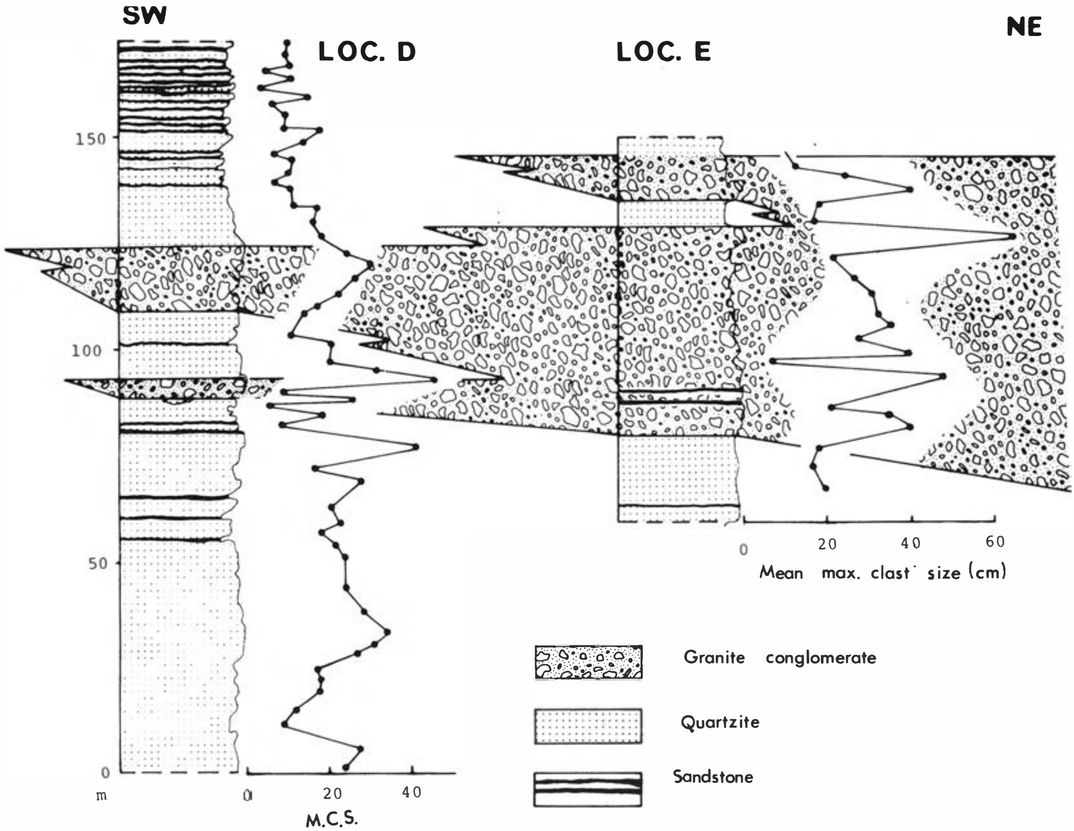


Fig. 3. Profiles through the north-eastern end of the conglomerate body (D–D′, E–E′ in Fig. 1) showing probable interfingering.

sandstones usually occur at the base of reverse-graded units (Fig. 5C, 5D).

Coarsening-upwards conglomerate beds or units are common. Where there are only two beds or grain populations in the unit, the upwards coarsening is often restricted to a thin bottom portion (Fig. 6A, bottom unit). In other cases it occurs on a larger scale, and here the coarsest part of the unit may be either matrix-rich (Fig. 6B, bottom unit) or a tight framework (Fig. 5B). Where there are three beds or populations in the coarsening-upwards unit, each part may show little overlap in mean or range of grain size (Fig. 6A, top unit), or the middle population may appear to be a mixture of the upper and lower (Fig. 6B, top unit).

The fining-upwards conglomerate units are usually more obviously composite than those which coarsen upwards because their two or three component beds are often bounded by more obvious erosion surfaces (Fig. 6D). Small-pebble populations at the top of these units are often better sorted and less well-cemented than similar size fractions in coarsening-upwards units. The cobble or boulder conglomerates of fining-upwards units are often poorly sorted frameworks (Fig. 6E) or are matrix-rich (Fig. 6C, top). Sometimes there is a thin, basal coarsening-upwards portion to a fining-upwards unit (Fig. 6C, middle unit).

The examples of conglomerate beds and units described above (Figs. 5 and 6) may not be representative for the whole conglomerate body. Most of them have been selected from only 100 m of a well-exposed coastal profile (Fig. 4) which is relatively fine-grained. In the inland segments of the conglomerate body, which are both coarser grained and more thickly bedded, we expect that a correspondingly greater thickness of the succession is represented by massive beds. However, the log of mean maximum clast size in the central area emphasises that a dominant

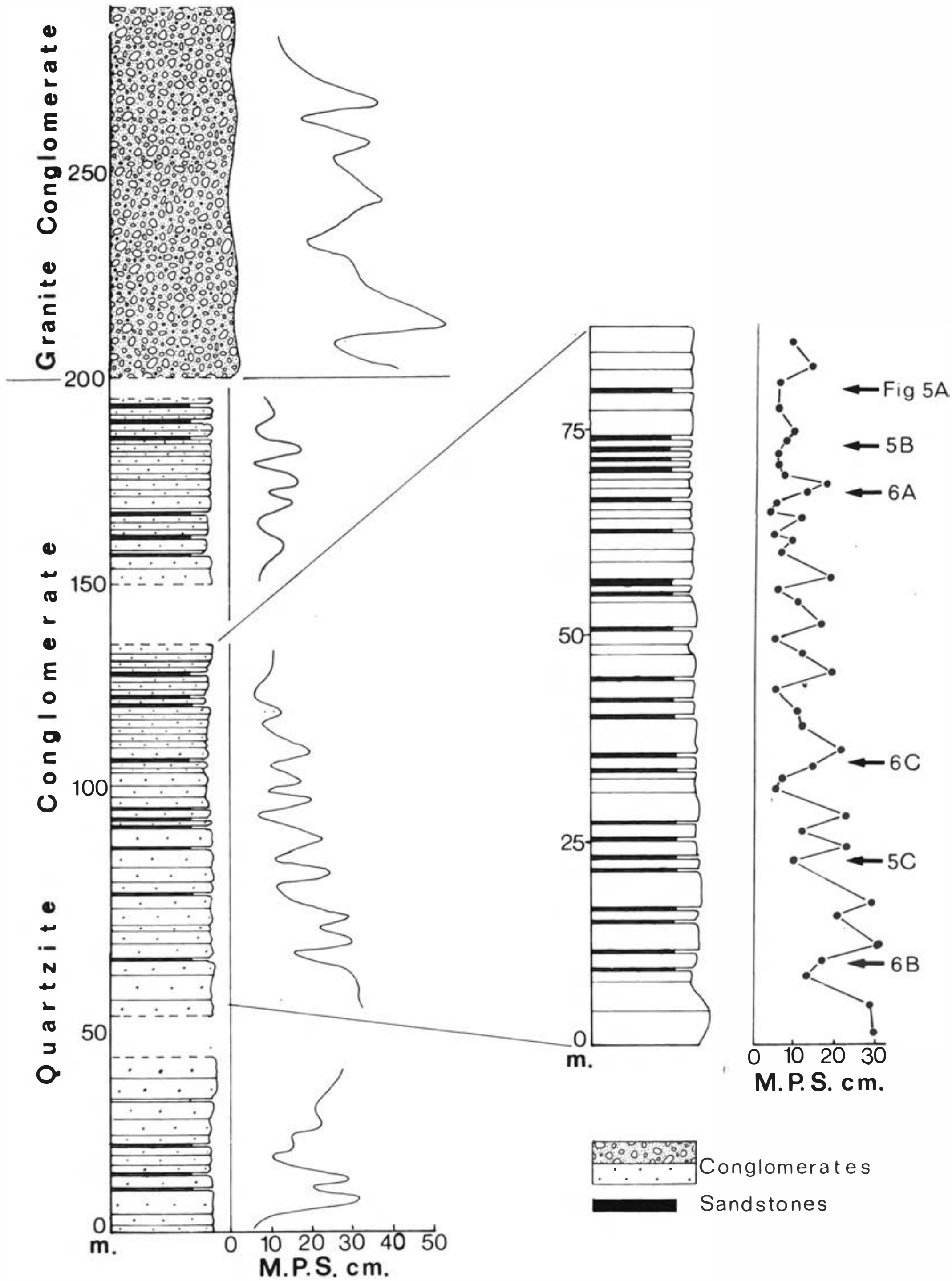


Fig. 4. Sequence through part of the Utslettefjell Formation on the SW coast of Stord (A–A′ in Fig. 1). Examples of textures discussed and figured (Figs. 5, 6) are located in this profile. Note the overall fining-upwards trend in the quartzite conglomerate succession.

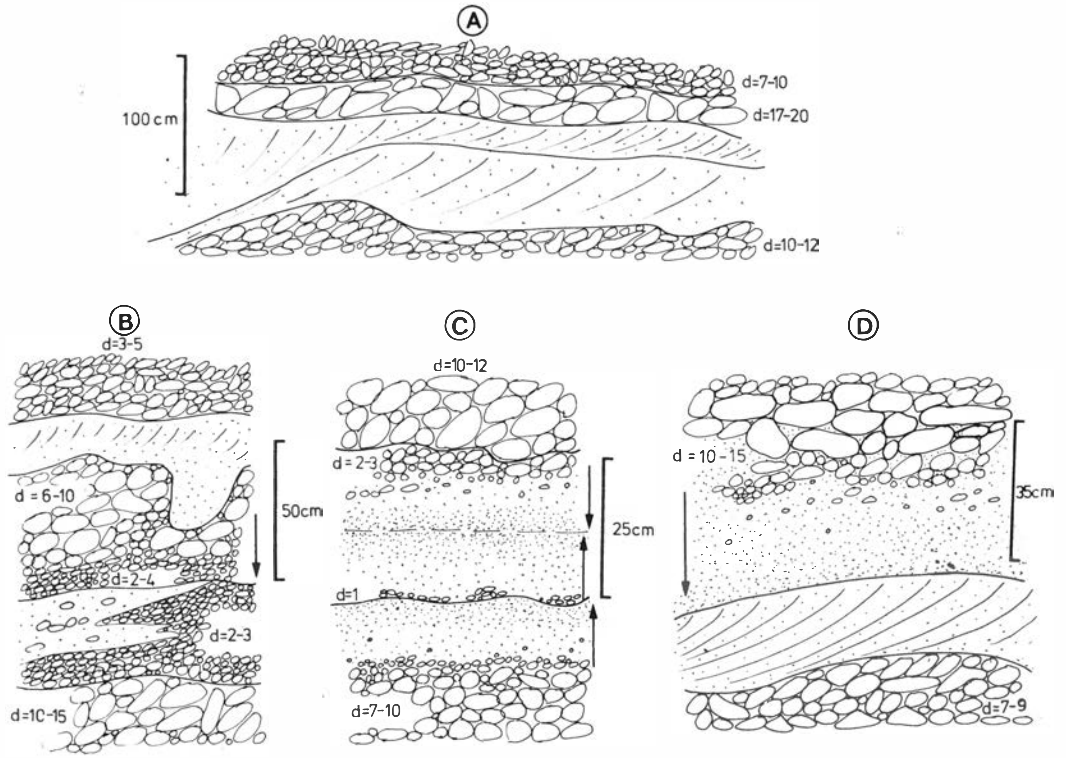


Fig. 5. Examples of some of the different types of sandstone beds in the Utslettefjell Formation. Arrows indicate direction of fining within beds or units. The mode of the 'maximum particle size' fraction in conglomerate beds is shown (D). Erosive or sharp boundaries are shown by solid lines. Conglomerate textures are largely diagrammatic. Some of the examples are located in Fig. 4.

attribute of the sequence here also is the rapid vertical alternation of coarse and fine-grain populations (Fig. 2).

Granitic conglomerate

Conglomerate beds in the granitic conglomerate body resemble those of the quartzite conglomerate in having an abundance of pebble or cobble frameworks and a lack of cross-stratification. Again, the characteristic feature of 'organisation' is a grain-size differentiation (Fig. 6E). In contrast, discrete sandstone beds are extremely rare in this succession (Fig. 2) and the matrix which infills the pebble or cobble frameworks consists, in most instances, of small pebble or granule grade rather than coarse or medium--grained sandstone.

In general, granitic conglomerate beds are thicker than in the quartzite conglomerates and the mean clast size is increased to the 40–70 cm range. Locally, granite boulders of maximum diameter 1–2 m occur. Plutonic clasts, particularly of granite and gabbro, now dominate the succession, while both quartzite and chert clasts are relatively rare (Fig. 2).

The body has a thickness of approximately 400 m, but thins out both southwestwards and northeastwards (Fig. 1). The lower half of the succession appears to coarsen upwards while the top half fines upwards (Fig. 2).

Deformation in the granitic conglomerate sequence is evident from the steeply dipping strata and from several NE–SW trending slides probably of similar age to the late D1 slides in the quartzite conglomerate. Pebble deformation and cleavage are conspicuously absent.

Transporting mechanisms

The conglomerates described above have an apparently anomalous combination of attributes.

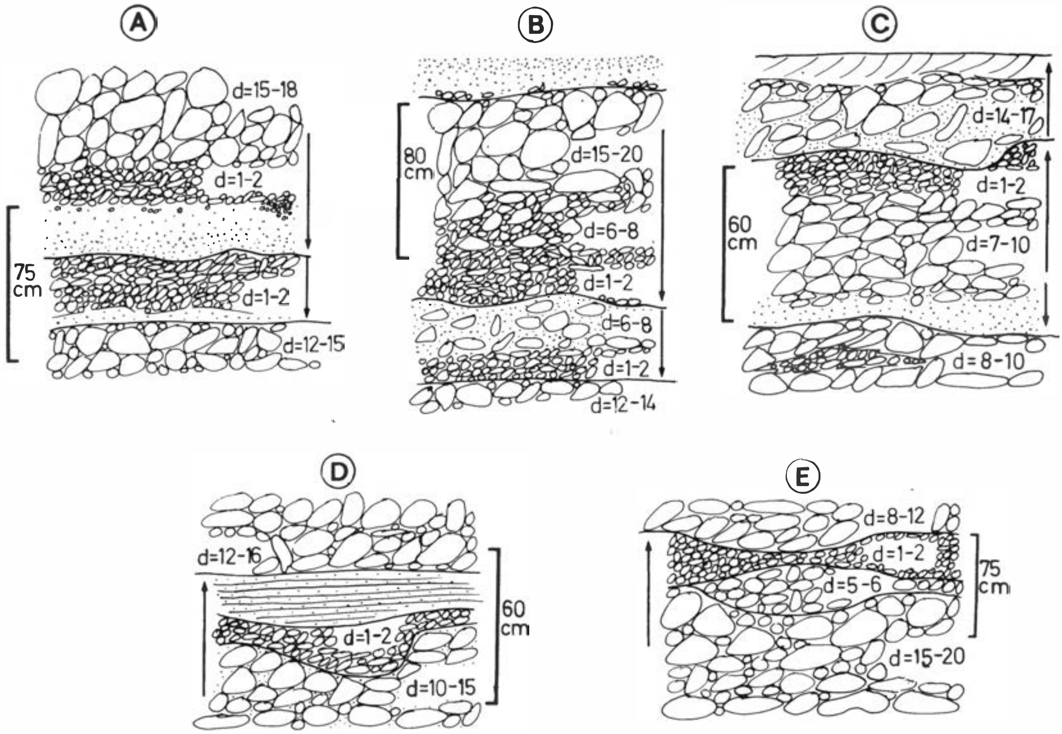


Fig. 6. **Examples of some of the different types of conglomerate beds in the Utslettefjell Formation. Textures are largely diagrammatic. Some of the examples are located in Fig. 4. Symbols as in Fig. 5.**

The conspicuous lack of stratification within conglomerate beds suggests a lack of turbulence and bed-load traction during sedimentation (at least in the sense in which equally coarse-grained fluvial conglomerates become abundantly stratified (e.g. Bluck 1967, Steel 1974), while the abundance of clast-supported beds and the prominent alternation of coarse and fine-grained conglomerates in the sequences suggest the importance of a sorting process during sedimentation: On the one hand a mass flow or other process involving deposition from suspension or dispersion is suggested; on the other hand, a process involving fluid turbulence or some other mechanism capable of sorting sediment.

The same problem has evidently faced other marine conglomerate workers, and they have often judged one or the other of the above sets of attributes to be more prominent in the rocks, or to be more informative about sedimentation mechanisms. Some have emphasised mass flow properties and have invoked debris flow (Hendry 1973) or grain flow (Aalto & Dott 1970); others have considered grain-by-grain movement to be important and have interpreted in terms of fully turbulent currents (Walker 1970, Rocheleau & Lajoie 1974).

Of considerable interest is the recent suggestion that a continuum may exist between certain types of mass flow and turbidity currents (Middleton 1970, Middleton & Hampton 1973). In a recent discussion of some Cambro-Silurian conglomerates (with many characteristics similar to those of the Utslettefjell Formation), Davis & Walker (1974:1211) have proposed a 'turbulent suspension (that is a flow transitional between grain flow and turbidity current)' to account for their origin. According to Davis & Walker (1974), a combination of fluid turbulence and dispersive pressure enabled gravel to be supported above the bed during transportation. Clasts were oriented parallel to flow with long axes dipping upstream and clast sorting took place.

We suggest that similar mechanisms and processes may account for the apparently contradictory features of the conglomerates of the Utslettefjell Formation. Because tectonic deformation has often caused some pebble flattening and rotation we cannot apply one of their arguments, namely that clast a-axis alignment parallel to flow precluded clast rolling on the bed. However, the features of the conglomerates described above, particularly the lack of stratification, suggests that bed-load traction was relatively unimportant during their transportation.

Reverse graded beds, and possibly also some of the reverse-graded units (Figs. 5 and 6), emphasise that the gravel dispersions had a high sediment concentration (Fisher 1971). We suggest that the massive conglomerates may have been deposited under similar conditions. On the other hand it is likely that sandstone beds which cap some of the units and the conglomeratic upper parts of some others, were deposited by normal traction currents because of the parallel or inclined lamination in the sandstones and the fact that the upper parts of conglomerate beds are often lensoid, are finer grained, better sorted and have less matrix content than the underlying main part of the conglomerate units.

In dealing with their resedimented conglomerate sequences, Davis & Walker (1974) have suggested two depositional models, an inverse-to-normally graded one and a graded-stratified one; they have also appealed for data from resedimented conglomerates in other areas for the testing of their descriptive models. From our limited measurements and observations on the Stord resedimented conglomerates we offer the following comments:

Unlike Davis & Walker (1974) we have observed reverse grading in coarse pebble conglomerates and in granule sandstones (contrast Figs. 5 and 6 with fig. 2 of Davis & Walker 1974). These occurrences are both within beds as well as within what we acknowledge to be units. Even in the latter case we suggest that the components of units have been deposited with a close time relationship to each other.

We have observed pebble conglomerates grading up into cobble conglomerates (Fig. 6B. Contrast with Davis & Walker 1974:1204).

Up to 40 % of the sandstone beds in the Stord succession are non-laminated. These usually occur at the base of reverse-graded conglomerate units, and immediately overlie the prominently laminated sandstone which cap units (eg. Fig. 5D). The laminated sandstones are usually less well cemented than the apparently massive sandstones.

In the light of our observations it is possible that resedimented cobble and cobble/boulder conglomerates do not always exist in their own right (cf. Davis & Walker 1974:1206) but may have a close relationship to finer grained assemblages. We have not analysed enough beds to demonstrate this confidently as a general feature of the Stord conglomerates, but we have identified particular examples of it.

Two important characteristics of the conglomerate beds throughout most of both sequences are the presence of pebble or cobble frameworks and the conspicuous lack of sedimentary structures indicative of traction currents. As regards the latter point it should be noted that gravels are apparently not always able to 'take up' many of the structures which appear in sands (B. J. Bluck pers. comm. 1976) although, on the other hand, as discussed below, there are many documented examples of coarse conglomerates with abundant structures. Sedimentary structures are confined to some of the sandstones which accompany conglomerate beds or to the uppermost part of the conglomerate beds themselves.

As suggested above the conglomerates of the Utslettefjell Formation are probably resedimented in a marine depositional environment. A history of reworking is suggested by the good rounding of the clasts, particularly those in the quartzite conglomerates, and by the fact that these rounded clasts now form the framework of a deposit which is poorly sorted. That their final site of deposition was marine is strongly suggested by their association with pillow lavas and particularly their gradual transition and probable interfingering contacts with the underlying marine Llandovery shales. According to the simple scheme suggested by Walker (1975), the clast-supported nature of the Utslettefjell conglomerates suggests that they are not debris flow deposits, while their rare cross-stratification and the fairly common grading suggest resedimentation rather than fluvial or shoreline processes.

Provenance and direction of sediment dispersal

Due to the deformation of the conglomerate body and the present steep dip of the beds, direct palaeocurrent measurements are of little value. Systematic pebble composition measurements were therefore of prime importance in attempting a palaeogeographic reconstruction. In a general sense such measurements indicate the nature of source areas and, indirectly, probable direction of sediment dispersal (bearing in mind that structural deformation may cause a relative displacement of source and depositional areas). When measured systematically, compositional trends may suggest sudden or gradual, vertical/lateral uncovering of the source area. The value of the compositional parameter is increased if evaluated together with grain size, particularly with the size of the coarsest fraction of each bed. In the case where the composition profile shows distinct influxes of different pebble types, consideration of grain size may allow the distinction between a situation in which different rock types were being tapped from the same source area and one where two different source areas, at significantly differing distances from the locus of sedimentation, supplied their own clasts.

The suggested provenance of the main components of the conglomerate body is shown in Fig. 7. Granitic and basic plutonic clasts are easily matched to the igneous complex presently lying along the northwest margin of the conglomerates. Two types of basic volcanic rock that differ particularly in trace element content (Furnes & Færseth 1975) presently occur respectively to the northwest and to the southeast of the conglomerate belt. Chemical analyses of greenstone pebbles have revealed that clasts of both types occur in the conglomerates, suggesting sediment contribution across both margins. Distinctive chert clasts occur preferentially in the lower part of the succession and are comparable to cherts in the area to the southeast. Sedimentary clasts such as quartzite and sandstone are particularly common low in the succession. The latter are probably at least partly intraformational, and the former, although more problematic, are most likely to have been derived from the cratonic or south and southeastern side of the basin.

There is a distinctive compositional change in the conglomerate sequence through time. At the base of the granite conglomerate, plutonic clasts become dominant (Fig. 2) and indicate the sudden new importance of the igneous complex as a drainage area (Fig. 7). Despite this sharp compositional change, occasional influxes of coarse-grained plutonic material are evident at lower stratigraphic levels (Fig. 2) and influxes of quartzitic clasts at higher levels (Fig. 2). This implies that sediment was commonly shed from more than one direction, but that at later times supply across the northwestern boundary was dominant. The quartzite conglomerates, dominant at an earlier period, are likely to have been derived in the opposite direction, across the southeastern boundary of the basin.

Some tectonic implications

Any thick sequence of coarse clastic sediments implies the prior existence of a deep sink within which the sediment accumulated or relative subsidence of the sub-stratum during the sedimentation. In either instance, vertical movements of the earth's crust are implied. In the case of the thick Utslettefjell conglomerate succession, the periodic influxes of coarse plutonic debris from the northwest margin of the basin, in the upper half of the sequence (Fig. 2), indicate contemporaneous subsidence. In this respect the vertical variation of conglomerate coarseness in reflecting varying proximity or relief of the source area is likely to be a useful tectonic index, particularly if that variation is present throughout the length of the body.

Throughout much of the quartzite conglomerate succession there is a trend of fining-upwards (Figs. 2 and 4), despite the likelihood of some of the coarsest modes being due to minor influxes of granite conglomerate from the northwest side of the basin (Figs. 2 and 7). This is suggestive of gradually diminishing relief in the (quartzite) source area or source-wards retreat of the slopes across which the gravel was supplied. It is not certain that either of these changes need have been directly tectonically controlled. They may rather passively reflect the lack of any renewed uplift of the drainage areas to the southeast.

The sudden influx of much coarser sediment at the base of the granite conglomerate succession probably indicates sudden uplift and the creation of a new and major drainage area across the northwest margin of the basin. Debris shed southeastwards off the igneous complex then dominated the basin in the area studied (Fig. 7). There is no obvious time trend of coarseness in this conglomerate sequence common to each of the measured sections. However, these conglomerates, compared to the quartzite conglomerates, are generally very coarse grained (Fig. 2) and are probably proximal representatives of the facies, so that small changes in a local variable such as direction of sediment dis-

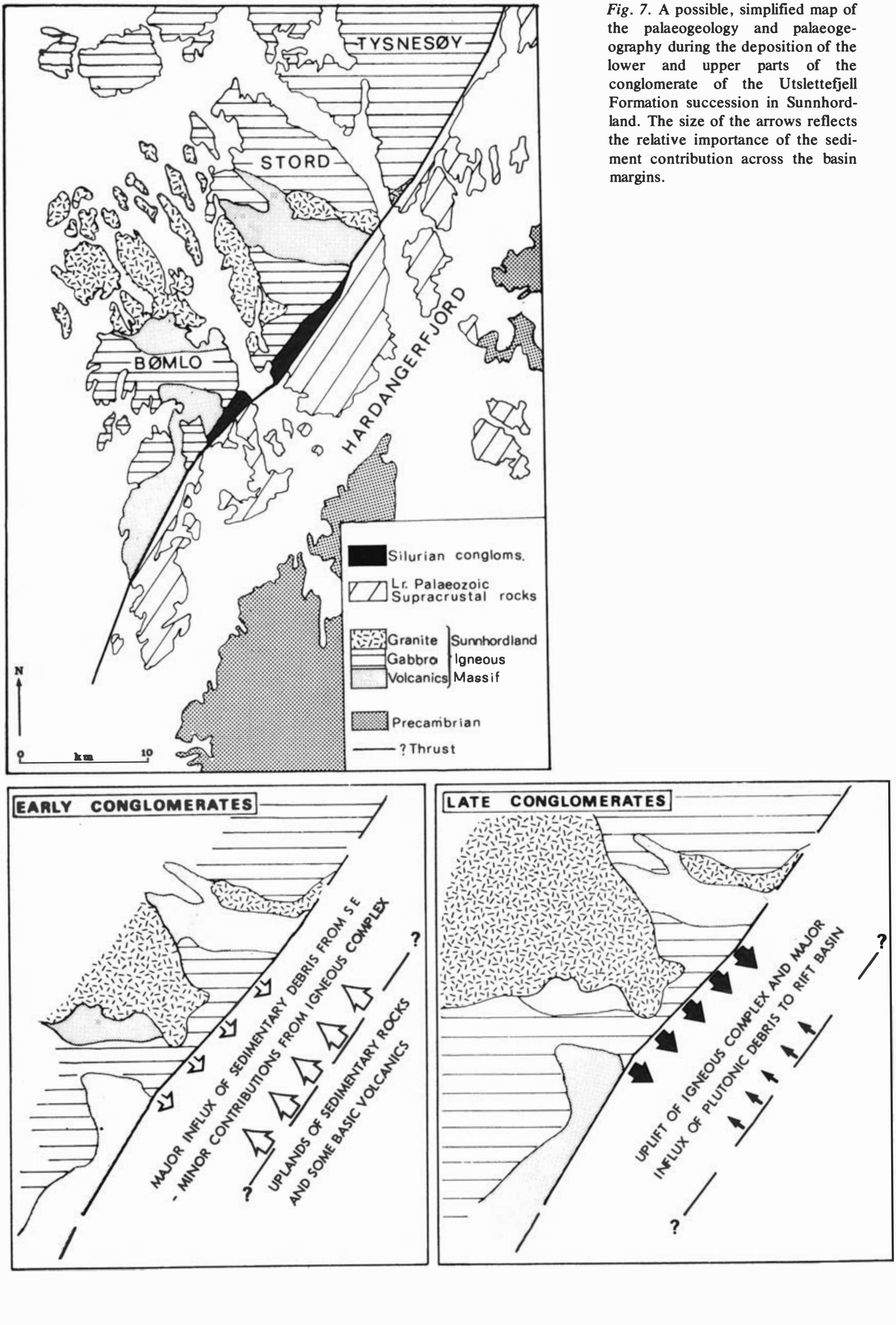


Fig. 7. A possible, simplified map of the palaeogeology and palaeogeography during the deposition of the lower and upper parts of the conglomerate of the Utslettefjell Formation succession in Sunnhordland. The size of the arrows reflects the relative importance of the sediment contribution across the basin margins.

persal may significantly influence sedimentation time trend at these localities.

The regional tectonic context of sedimentation, an uplifting magmatic arc of continental margin type within which there is a developing rift basin, is discussed below. At this stage it is worth commenting on some of the possible causes of pronounced vertical crust movements in such a situation. Vertical motions of crust and lithosphere are commonly related to changes in crustal thickness, in thermal regime and in the conditions for isostatic balance (Dickinson 1974b). In the present case the conglomerates immediately overlie basalts of ocean-floor type (Fig. 1) but are banked against and derived from continental source areas (Fig. 7). In such a situation where thin oceanic crust had been created adjacent to thick continental crust a sediment trap could have been predicted, simply on the basis of crustal elevation differences. The magnitude of the sediment trap was probably further exaggerated by increased uplift of the continental crust on the northwest side of the basin, as suggested by the major influx of the granite conglomerates in the upper part of the succession. This may have been an istostatic response to the thickening of the crust by intrusion of the igneous bodies, an effect apparently more common for continental margin magmatic arcs than for intraoceanic arcs underlain by thin crust (Dickinson 1974a).

The tectonic context

The lower Palaeozoic succession of western Norway (Table 1) displays some characteristics of accumulation in geosynclinal basins of back-arc or Japan Sea-type (Gale & Roberts 1974). Extrusion of submarine basic volcanics, initially of ocean-floor type, was widespread in late Cambrian to earliest Ordovician times. During the remainder of the Ordovician, flyschtype sediments accumulated, although island-arc type basic and acid volcanics are locally important. In most regions during this time parorogenic movements are suggested by the presence of local polymict conglomerate sequences, although in the Bergen area a major phase of deformation is implied prior to the deposition of the Moberg conglomerate by the presence of pebbles having a pre-conglomerate metamorphic fabric and by the angular unconformity at its base (Kvale 1960, Sturt & Thon 1976). By early Silurian time many areas show evidence of the accumulation of shallow marine clastic and carbonate sequences (Table 1). According to the model of Gale & Roberts (1974), based on data mainly from the Trondheim area, this lower Palaeozoic succession accumulated in a back-arc basin behind an island-arc/trench system which existed some way off the present west and central Norwegian coast.

Within the area studied, the present authors suggest additional complexity in Ordovician time when there appears to have been a local thinning of the continental crust with later extrusion of Silurian tholeiitic basalts of ocean floor type and accumulation of conglomerates in a deep, fault-controlled basin. We interpret the present geographical distribution of rock groups in the area (Fig. 7) as follows:

The Ordovician igneous activity represented by the Sunnhordland Igneous Massif shows features of continental rift volcanism producing a thick pile of rhyolites (ignimbrites as well as lava flows) and basalts. On northern Stord the volcanic succession, interpreted as subaerial (Kvale 1937), exceeds 3500 m in thickness. Ignimbrites have also been identified on Bømlo (Songstad 1971). On Stord, recent analysis of the basic volcanics indicates alkaline/calc-alkaline composition (Furnes & Færseth 1975). The initial Sr^{87}/Sr^{86} ratio of 0.7071 obtained by Priem & Torske (1973) is within the range of continental rhyolites and the igneous activity probably corresponds to stages of thinning of the continental crust. On Bømlo there are local pillow lavas and on both Bømlo and Stord there are local but thick accumulations of volcano-clastic sediments, suggestive of local basin development within the igneous complex. These supracrustal rocks were subsequently intruded by gabbros, granitic rocks, basaltic dykes, and local peridotites. The entire massif has been affected by greenschist facies metamorphism, and, on Stord, Kvale (1937) showed that the original features of the igneous rocks are best preserved in the southeast and that the degree of deformation increases towards the northwest.

The Dyvikvågen Group occurs in a narrow belt on the southeast side of the igneous complex (Fig. 7). It is interpreted in terms of relatively late stages in the evolution of a rift basin (Ashgillian–post-Lower Llandovery). Above a sequence of thin carbonates there are graptolitic shales and pillow lavas which are compositionally comparable to ocean-floor tholeiites (Furnes

Table 1. Correlation between generalised Lower Palaeozoic successions in western Norway.

Age	Trondheim area		Sunnfjord area		Bergen area	Sunnhordland area	
Lower Silurian	Horg Group	Graptolite shales Shallow marine clastics	Høyvik group	Shallow marine clastics	Shallow marine clastics Graptolite shales Shallow marine carbonates	Dyvikvågen Group	Resedimented conglomerates Submarine basic volcanics Graptolite shales Shallow marine carbonates
Ordovician	U. Hovin Group	Mostly flysch (basic and acidic volcanics are locally important)	U. Herland Group	Mostly flysch			Basic and acidic igneous rocks (Sunnhordland igneous massif)
	L. Hovin Group	Mostly flysch	U. Herland Group L. Herland Group	Conglomerates (Stubseid) stratigraphic break Mostly flysch	Conglomerates (Moberg) major stratigraphic break pre-conglomerate deformation of the substrate		
	Støren Group	Submarine basic volcanic tectonic contact	Stavenes Group	Submarine basic volcanics	Submarine basic volcanics		
Cambrian		Late Precambrian-Ordovician, Gula Group	Håsteinen Group	Mostly pelites	Mostly pelites		
	Vogt 1945 Roberts et al. 1970 Gale & Roberts 1974		Skjerlie 1969 Skjerlie 1974 Indrevær & Steel 1975		Kolderup & Kolderup 1940 Kvale 1960	Færseth & Ryan 1975 Present account	

& Færseth 1975). This may be interpreted in the context of crustal thinning and incipient continental separation, with the development of a rift basin. From a consideration purely of the isostatic balance of the crust, such a location would be a site of potentially thick sedimentation. The very thick overlying conglomerate sequence records the development of actively elevating highlands, first on the southeast side (the cratonic side) of the basin and later of the magmatic arc itself, with gradual unroofing of gabbroic and granitic plutonic bodies. Because of the present outcrop distribution of this sequence and, in particular, the absence of its southeastern margin, it is impossible to comment either on the width of the trough during this period of uplift and subsidence, or on the likelihood of the trough marking the position of transition from craton to magmatic arc.

The rocks occurring to the southeast of the Dyvikvågen Group (Fig. 1) are a dominantly sedimentary sequence of phyllites, calcareous psammites, cherts, and local thin conglomerate layers, together with spilitic, submarine volcanics, and quartz keratophyres. The succession is of uncertain age, although on Bømlo (Fig. 7) an Ordovician age has been assumed for a sequence of similar rock types (Songstad 1971). These rocks also exhibit a slightly higher grade of metamorphism and a more complex structural history than those belonging to the Dyvikvågen Group, thus indicating that they are older than the late Ordovician/early Silurian rocks.

The association of rock types is not diagnostic of a particular environment, but the occurrence of local conglomerates and abundant calcareous material may suggest periods of shallow marine conditions.

The contact between this southeastern sedimentary and volcanic sequence and the rock groups to the northwest (Fig. 7) is of a tectonic origin. The contact to the southeast of the Utslettefjell conglomerates with greenstones of supposed Arenig age (Kiær 1929, Skordal 1948, Strand 1972) is dipping 60°–70° NW where both rock types are strongly sheared in a zone about 15 m in breadth. This contact could either represent a normal fault or a thrust which has been subjected to later reactivation.

As emphasized above, the present northwestern boundary of the conglomerate body, against the northern igneous complex (Fig. 7), has at no time been a major thrust zone (contrast with Strand 1960, 1972). Any major post-early Silurian thrusting in this area is more likely to have been located along the southeastern boundary of the conglomerate.

Summary

The upper Ordovician/Silurian sedimentary succession on Stord, western Norway, consists of shallow marine carbonates, graptolitic shales, tholeiitic basalts, and a thick sequence of marine conglomerates.

A study of the conglomerates shows that they have an apparently anomalous combination of attributes. The lack of stratification and the common presence of reverse-grading in beds suggests that they originated by a mass flow process, while the abundance of clast frameworks and relatively good sorting suggest turbulent currents.

Examination of the pebble types suggests that they were derived from source areas on either side of the basin. The composition time-trend indicates that initially mainly sedimentary material was derived across the southeast margin but that later, erosion and dispersal from an igneous complex dominated.

The overall time-trend of grain size through the succession, coarsening-upwards of the contribution from the igneous source, and a fining-upwards in that from the sedimentary source suggest that the basin was being filled under the influence of progressive uplift of the igneous area through time.

The sedimentary sequence is interpreted in terms of deposition in a rift basin within the Fennoscandian shield; the igneous complex, with early volcanic episodes (subaerial acidic and basic) and later basic and acid intrusions, is seen as a continental margin arc positioned largely to the west of the basin. The ocean-floor tholeiitic basalts in the basin suggest local thinning and separation of the crust either behind or within the arc area. The overlying conglomerates record rifting and uplift of the magmatic arc and the gradual unroofing of its plutonic core.

The present outcrop of the Dyvikvågen Group, probably only a fragment of the original basin, has, together with the igneous complex, possibly been later thrust eastwards onto a sedimentary/volcanic succession of assumed Ordovician age.

Acknowledgements. – We thank Drs. K. Bjørlykke, B. J. Bluck, G. H. Gale, and D. Roberts for critically reading the manuscript and suggesting improvements.

July 1976

References

Alto, K. B. & Dott, R. H. 1970: Late Mesozoic conglomeratic flysch in southwestern Oregon, and the problem of transport of coarse gravel in deep water. *Geol. Assoc. Canada Spec. Paper no. 7,* 53–65.

Andresen, A., Heier, K. S., Jorde, K., & Naterstad, J. 1974: Preliminary Rb/Sr geochronological study of the Hardangervidda – Ryfylke nappe system in the Røldal area, S. Norway. *Nor. Geol. Tidsskr. 54,* 35–47.

Bluck, B. J. 1967: Deposition of some Upper Old Red Sandstone conglomerates in the Clyde area: a study in the significance of bedding. *Scottish J. Geology 3,* 139–167.

Bluck, B. J. 1969: Old Red Sandstone and other Palaeozoic conglomerates. *Am. Assoc. Petr. Geol. Mem. no. 12,* 711–723.

Davis, I. C., & Walker, R. G. 1974: Transport and deposition of resedimented conglomerates: the Cap Enrage Formation, Cambro-Ordovician, Gaspe, Quebec. *J. Sed. Petrology, 44,* 1200–1216.

Dickinson, W. R. 1974a: Sedimentation within and beside ancient and modern magmatic arcs. *In* Dott, R. H. Jr. & Shaver, R. H. (eds.), Modern and ancient geosynclinal sedimentation. *Soc. Economic Paleont. Mineral. Spec. Publ. 19,* 230–239.

Dickinson, W. R. 1974b: Plate tectonics and sedimentation. *In* Dickinson, W. R. (ed.), Tectonics and sedimentation. *Soc. Economic Paleont. Mineral. Spec. Publ. 22,* 1–27.

Fischer, R. V. 1971: Features of coarse-grained, high-concentration fluids and their deposits. *J. Sed. Petrology 41,* 916–927.

Furnes H. & Færseth, R. B. 1975: Interpretation of preliminary trace element data from lower Palaeozoic greenstone sequences on Stord, west Norway. *Nor. Geol. Tidsskr. 55,* 157–169.

Færseth, R. B & Ryan, P. D. 1975: The geology of the Dyvikvågen Group, Stord, Western Norway and its bearing on the litho-stratigraphic correlation of polymict conglomerates. *Nor. Geol. Unders. 319,* 39–45.

Gale, G. H & Roberts, D. 1974: Trace element geochemistry of Norwegian Lower Palaeozoic basic volcanics and its tectonic implications. *Earth Planet Sci. Letters, 22,* 380–390.

Hendry, H. E. 1973: Sedimentation of deep water conglomerates in Lower Ordovician rocks of Quebec-composite bedding produced by progressive liquefaction of sediment. *J. Sed. Petrology 43,* 125–136.

Indrevær, G. & Steel, R. J. 1975: Some aspects of the sedimentary and structural history of the Ordovician and Devonian rocks of the westernmost Solund islands. *Nor. Geol. Under. 317,* 23–32.

Kiær, J. 1929: Den fossilførende ordovisiske-silurske lagrekke på Stord. *Bergens Mus. Årbok 11,* 8–75.

Kolderup, C. F. & Kolderup, N. H. 1940: Geology of the Bergen Arc System. *Bergens Mus. Skr. 20,* 1–137.

Kvale, A. 1937: Et kaledonsk intrusiv- og effusivfelt på Stord. *Bergens Mus. Årbok, Naturvitensk. rekke no. 1,* 1–138.

Kvale, A. 1960: The nappe area of the Caledonides in western Norway. *Excursion guide. Nor. Geol. Unders. 212e,* 1–43.

Lippard, S. J. 1976: Preliminary investigations of some Ordovician volcanics from Stord, West Norway. *Nor. Geol. Unders. 327,* 41–66.

Middleton, G. V. 1970: Experimental studies related to problems of flysch sedimentation. *Geol. Assoc. Canada Spec. Paper no. 7,* 253–272.

Middleton, G. V & Hampton, M. A. 1973: Sediment gravity flows: mechanics of flow and deposition. *In* Middleton, G. V., & Bouma, A. H. (eds.), Turbidites and deep water sedimentation. *Pacific Coast Section, Soc. Econ. Paleont. Mineral,* Los Angeles. 1–38.

Priem, H. N. A., & Torske, T. 1973: Rb-Sr isochron age of Caledonian acid volcanics from Stord, Western Norway. *Nor. Geol. Unders. 300,* 83–85.

Roberts. D., Springer, J. & Wolff, F. C. 1970: Evolution of the Caledonides in the northern Trondheim region. Central Norway: a review. *Geol. Mag. 107,* 133–145.

Rocheleau, M. & Lajoie, J. 1974: Sedimentary structures in resedimented conglomerate of the Cambrian flysch, L'Islet, Quebec, Appalachians. *J. Sed. Petrology 44,* 826–836.

Skjerlie, F. J. 1969: The pre-Devonian rocks in the Askvoll-Gaular area and adjacent districts, Western Norway. *Nor. Geol. Unders. 258,* 325–359.

Skjerlie, F. J. 1974: The Lower Palaeozoic sequence of the Stafjord district, Sunnfjord. *Nor. Geol. Unders. 302,* 1–32.

Skordal, A. J. 1948: Vulkanitter og sedimenter på sør-østre del av Stord. *Univer. Bergen Årbok, Naturvitens. rekke no. 2,* 1–58.

Songstad, P. 1971: Geologiske undersøkelser av den ordoviciske lagrekken mellom Løkling og Vikafjord, Bømlo, Sunnhordland. Unpublished cand. real. thesis, Universitetet i Bergen.

Steel, R. J. 1974: New Red Sandstone floodplain and piedmont sedimentation in the Hebridean Province, Scotland. *J. Sed. Petrology 44,* 336–357.

Steel, R. J. & Wilson, A. C. 1975: Sedimentation and tectonism (?Permo – Triassic) on the margin of the North Minch Basin, Lewis. *J. geol. Soc. Lond., 131,* 183–202.

Strand, T. 1960: Cambro-Silurian deposits outside the Oslo region. *In* O. Holtedahl (ed.), Geology of Norway, *Nor. Geol. Unders. 208,* 170–284.

Strand, T. 1972: The Norwegian Caledonides: VI, areas with Cambro-Silurian deposits along the west coast of south Norway, 67–71. *In* Strand, T. & Kulling, O. (ed.), Scandinavian Caledonides. Interscience Publishers.

Sturt, B. A. & Thon, A. 1976: A comment on 'The age of orogenic deformation in the Swedish Caledonides'. Discussion. *Am. J. Sci. 276,* 385–390.

Vogt, T. 1945: The geology of the Hølonda-Horg district, a type area in the Trondheim region. *Nor. Geol. Tidsskr. 25,* 449–528.

Walker, R. G. 1970: Review of the geometry and facies organization of turbidites and turbidite-bearing basins. *Geol. Assoc. Canada Spec. Paper no. 7,* 219–251.

Walker, R. G. 1975: Conglomerate: sedimentary structures and facies models. *In* Depositional Environments as Interpreted from Primary Sedimentary Structures and Stratification Sequence, *S.E.M.P. Short Course Notes No. 2.*

Walton, E. K. 1963: Sedimentation and structure in the Southern Uplands. *In: The British Caledonides.* Edinburgh, Oliver and Boyd. 280 pp.