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The Relationship of Sedimentation to Tectonics in the Solund Devonian District of southwestern Norway

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ABSTRACT

The Solund district of southwestern Norway contains a maximum preserved stratigraphic thickness of 5,200 meters of coarse conglomerate with less amounts of intercalated sandstone. The deposits are thought to be Middle Devonian because of lithostratigraphic similarity to nearby basins containing Devonian plant and fish remains. The sediments are thought to represent post-Caledonian humid alluvial fan deposits analogous to those in the Triassic Newark basins of the Appalachian Mountains. Devonian block faulting and graben formation resulted in the deposition of alluvial sediments in basins adjacent to contemporaneously uplifting highlands. The present structural basin of the Solund district, about 800 square kilometers in area, preserves part of a large, northeast-southwest-striking coalesced fan complex.

The coarse Devonian clastics were deposited on a topographically irregular basement of Cambro-Silurian metasedimentary rocks. Local basal sedimentary breccias composed of angular fragments of immediately underlying basement rocks are found in topographic low areas of the basement. The basement rocks formed part of the Caledonian eugeosynclinal area, with the most common rock types being metamorphosed quartzo-feldspathic wackes and siltstones, feldspathic quartzites, pillowed and layered metabasalts, and intrusive gabbros and granodiorites. Further east and south of the Solund basin, high-grade metamorphic and igneous rocks from deeper levels of the Caledonian geosyncline crop out. Clastic debris from each of the above rock types was incorporated in the Devonian sediments.

The Devonian sequence consists primarily of thick, irregularly bedded polymict cobble and boulder conglomerates having consistently oriented imbrication and alignment of elongate clasts on bedding surfaces. These thick conglomerates contain abundant local, thin, flattened lenses of flat-stratified or gently inclined cross-stratified coarse sandstone. Locally, separated, lens-shaped bodies of interstratified sandstones and finer conglomerates up to several hundred meters in thickness are found. Sedimentary structures within these sandstone-fine conglomerate areas include flat-stratification, various types of trough and planar-bounded (tabular) small and large-scale cross-stratification, straight asymmetrical ripple markings, irregular ripple-drift bedding, primary current lineation, linear cobble-boulder trains, channel cut-and-fill, and irregular conglomerate-sandstone fining-upward cyclic deposits. The conglomerates contain about thirty distinct clast types, with their distribution grossly reflecting the adjacent basement geology. The sandstones are primarily lithic arenites, with finer-grained varieties feldspathic or quartzo-feldspathic.

Sedimentologic data suggests deposition by braided streams, with channel bar, channel lag, and swale-fill deposits preserving bed forms of the upper and lower hydraulic flow regimes. The coarse conglomerates are thought to have been deposited by stream and streamflood processes operating in the upper flow regime. Rapid deposition in braided stream channels in midfan areas is indicated, with paleocurrent data, fabric analyses, and textural and clast distribution patterns suggesting relatively uniform transport from the southeast throughout the preserved area of the depositional basin. The climate was moist, for no mudflow deposits are found, and an abundant supply of rapidly flowing water is indicated by thorough winnowing of the clay-sized material.

Post-depositional faulting and folding have modified the original down-faulted Solund basin. It is now a broad east-plunging anticline; near the syndepositional fault-bounded southeastern margin of the area, the Devonian sediments have been thrust to the southeast over basement rocks. Other post-depositional features include strike-slip faults, bedding-plane faults, and normal faults. Presumably two phases of the Devonian Svalbardian disturbance are recorded: (1) block faulting and graben formation yielding terrestrial deposition in structurally produced basins contemporaneous with active uplift; and (2) post-depositional faulting and folding. The Solund basin, then, as well as the other Devonian basins of western Norway, can be classified as "taphrogeosynclines" of Kay. The major joint patterns in the Solund district, producing "fissure fjords" parallel to the coast line, are suggested to be Cenozoic in age.

INTRODUCTION

Statement of the problem

The following comprehensive study of the Solund area of western Norway was made in an attempt to reconstruct its Devonian history, with an emphasis on the environment and processes of sedimentation in relation to tectonism. The unique thickness and coarseness of the clastic detritus in this particular area of Devonian sediments revealed especially valuable data with respect to the sedimentary tectonics of post-orogenic basin deposition, thus providing a framework for characterizing the Old Red paleogeography of western Norway in relation to that of Great Britain, Spitsbergen, and East Greenland. Use of modern techniques and concepts of sedimentology and structural geology hopefully provide a more definitive picture than that which existed previously.

Location of the area

The Solund district of Devonian sediments is located along the southwestern coast of Norway at the entrance to Sognefjord, the longest of the Norwegian fjords, approximately 100 kilometers north of Bergen (Fig. 1).

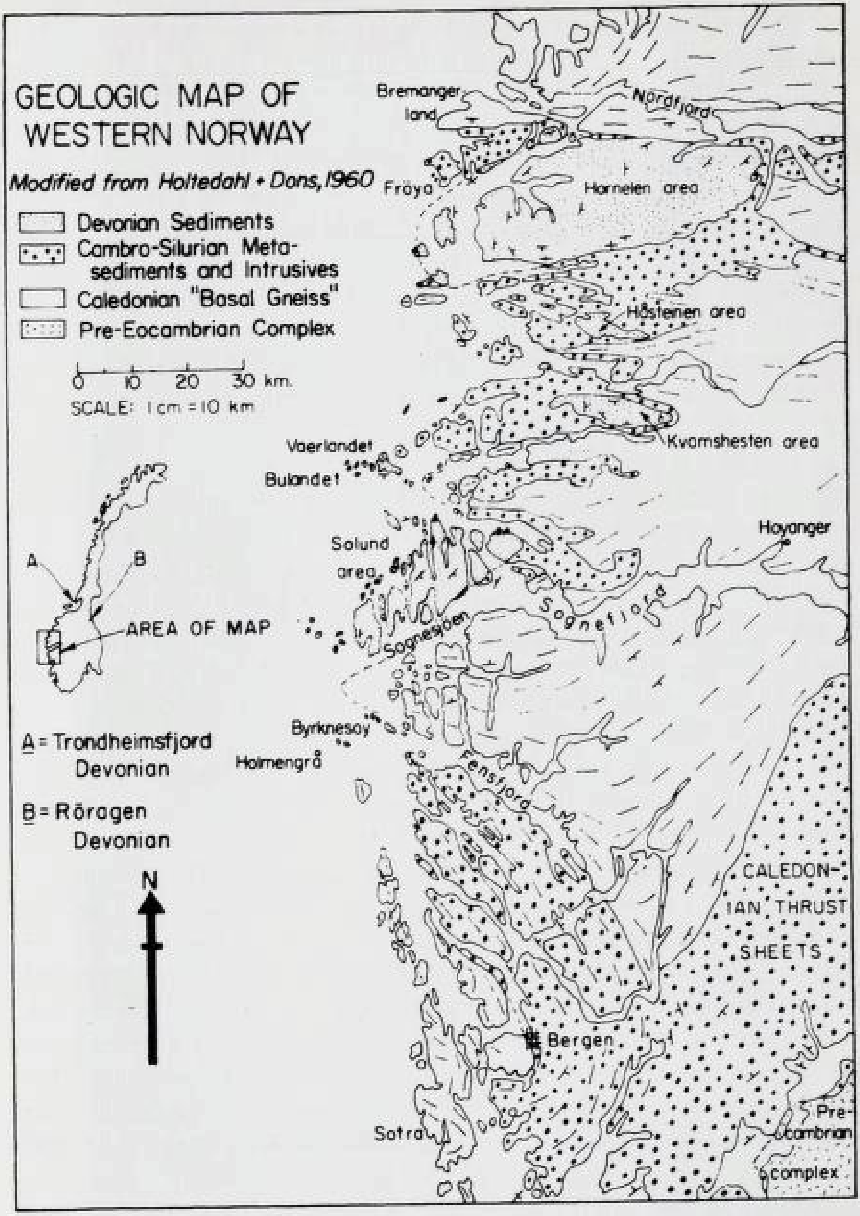
GEOLOGIC MAP OF WESTERN NORWAY
Modified from Holtedahl + Dons, 1960
Devonian Sediments
Cambro-Silurian Meta-sediments and Intrusives
Caledonian "Basal Gneiss"
Pre-Eocambrian Complex
0 10 20 30 km.
SCALE: 1 cm = 10 km
A
B
AREA OF MAP
A = Trondheimsfjord Devonian
B = Röragen Devonian
N
Bremanger land
Nordfjord
Fröya
Hornelen area
Håsteinen area
Kvamshesten area
Voerlandet
Bulandet
Solund area
Hoyanger
Sognefiord
Sognesjoen
Byrknesoy
Holmengrå
Fensfjord
CALEDONIAN THRUST SHEETS
Bergen
Sotra
Pre-cambrian complex

Fig. 1.

The district consists of more than 1000 islands and skerries of the Solund Islands (including the westernmost part of Norway), plus the Lifjell Peninsula to the east. The flat, low-lying islands to the west, in the famous «strandflat» topography of Norway, gradually pass eastward into barren, steep, irregular topography up to 780 meters above sea level.

Solund is one of six separate areas of Devonian rocks along the southwestern coast ((Byrknesøy-Holmengrå, Solund, Bulandet-Værlandet, Kvamshesten, Håsteinen, and Hornelen, from south to north); additional Norwegian Devonian sediments are found at Trondheimsfjord and Røragen (Fig. 1). The Devonian areas are generally relatively inaccessible to detailed study, being found either as widely scattered islets difficult to get to because of rough sea, or as high plateaus above the surrounding older rocks, with few access roads.

Nature and scope of the study

The writer spent the summers of 1964 and 1965 doing field work in the area, and also spent October, 1965 at the Geologic Institute of the University of Bergen examining informal reports, maps, older literature and rock collections. Fortunately, a local population inhabits most of the area (approximately 1500 people), enabling the writer to visit all the major islands during the course of the field work. Transportation in the field was primarily by private boat, with the one major road extending across most of the eastern parts of the area also used extensively. Lodging and food were obtained from various local families, to whom the writer is much indebted.

Previous work

A Norwegian bishop first drew attention to the Devonian areas early in the nineteenth century by a fanciful description of fossils seen in a rock wall in Solund. C. F. Naumann (1824), a German natural scientist, in searching for the fossils, found instead the conglomeratic Solund and Kvamshesten districts. He thought the Solund gravels to result from rapidly flowing water masses running westward down the narrow Sognefjord, suddenly meeting the quieter ocean water, and dropping the sedimentary load at the mouth of the fjord. The pebble types noted in the conglomerate were also found as rock types in innermost Sognefjord. In Kvamshesten, however, he realized that the theory was not as tenable, because the fjord cut through the conglomerate, thus being younger in age than the sediment (Fig. 2).

The Hornelen area was described breifly by Keilhau (1838), and finally the Håsteinen area was surveyed, with the first geologic map of the Devonian areas published by Irgens and Hiortdahl (1864). Irgens and Hiortdahl

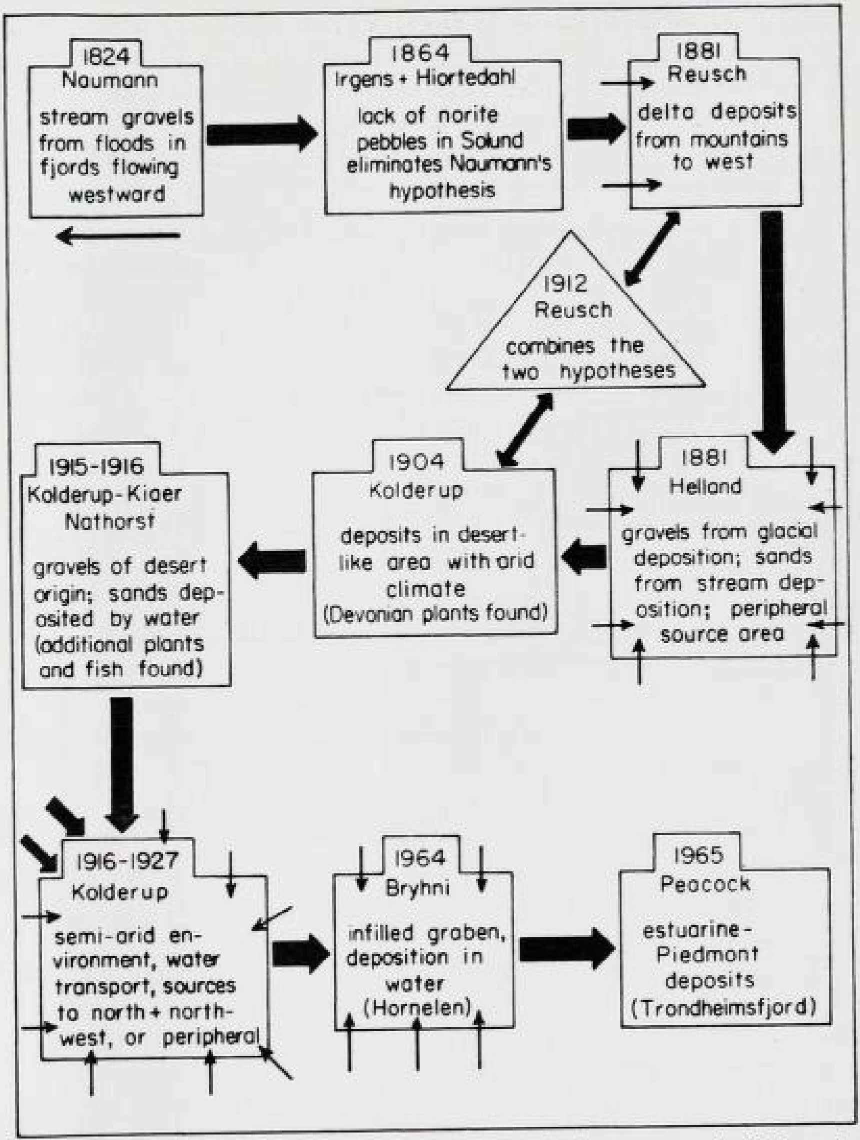

Fig. 2. Schematic diagram illustrating development of ideas on genesis of Devonian sediments in western Norway. (Small arrows indicate inferred transport directions).

distinguished three stages or levels of rocks, an oldest deep-seated gneiss-schist in sharp upper contact with intermediate-level mica schist-greenschist, in turn overlain by uppermost conglomerate-sandstone. They made valuable observations of pebble lithologies in the conglomerates, sedimentary structures, and did much detailed mapping. Naumann's ideas on genesis were rejected because of a lack of norite pebbles in Solund (norite is prominent in inner Sognefjord), but Irgens and Hiortdahl did not suggest an alternate origin, although they thought the conglomerates to be probably Devonian in age.

Reusch (1881) thought the Solund conglomerates to be an old delta formation, with relatively short transport distances, and a source necessarily to the west because of the general easterly foreset dip direction. He concluded that the original deltas were considerably larger than the present outcrop areas, and that the distribution of various pebble lithologies in Solund necessitated deposition from two distinct rivers.

Helland (1881) noted that the conglomerates were deposited into east-west trending trough-shaped basins underlain by synclines of intermediate-stage schists (Fig. 1). Studies of pebble distributions convinced Helland that a single transport direction was insufficient to explain the observed variations, and concluded that sediments were derived from all sides of the basins, with relatively short transport distances. He attributed the conglomerates to glacial deposition, while the sandstones were thought to have been deposited by streams flowing into lakes or other bodies of water.

Based on the discovery of Devonian land fossils in Hornelen, C. F. Kolderup (1904) initiated the theory that the Devonian areas were terrestrial deposits in a desert-like environment. He thought the lack of even a single striated pebble ruled out a glacial origin, and pointed out that many pebbles had faceted shapes resembling windworn pebbles of the desert.

Reusch (1912) restated some of his ideas in the light of the fossil discoveries, suggesting that the source areas to the west were covered with primitive forests. Additional Devonian plant fossils were then found in Kvamshesten, Hornelen, and Bulandet (C. F. Kolderup, 1915a, 1915b, 1916a), as well as in Røragen (Halle, 1916) (Fig. 1). The new paleontologic criteria led to the suggestion that the sandstones were transported by streams and deposited in water-filled basins, with the conglomerates being desert deposits (Nathorst, 1915). The Bulandet rocks were thought to be somewhat younger, of Lower Devonian age, while the remaining areas, on the basis of plant and fish remains, were thought to be Middle Devonian (Kiær, 1918).

C. F. Kolderup published six papers on each of the Devonian areas, concluding in general that the sediments resulted from deposition by powerful, infrequent streams such as occur periodically in arid to semiarid regions, with sources to the north and northwest for Solund, Bulandet-Værlandet, and Hornelen, and from the peripheral surrounding areas in Håsteinen and Kvamshesten (1916b, 1923, 1925a, 1926a, 1927a, and 1927b). Considerable interest was focused on what was interpreted as a post-depositional overthrust sheet of Cambro-Silurian gabbro in the Solund area (C. F. Kolderup 1925b, 1926b).

Later fossil discoveries and reevaluation of previously identified specimens yielded additional information pertaining to correlation of the Devonian areas and to sedimentary environments (Høeg, 1931, 1935, 1936, 1945; Størmer, 1935; Jarvik, 1948). Reusch (1914) and Vogt (1924a, 1929) investigated the conglomerates in the Trondheimsfjord area, and found Devonian plant fossils in one area (Vogt, 1924b). At present each of the Devonian districts is being restudied, but only brief publications have appeared on the Hornelen (Bryhni, 1964a, 1964b, 1964c) and Røragen (Holmsen, 1962) areas to date.

Acknowledgements

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REGIONAL GEOLOGY

The six Devonian areas along the Sognefjord-Nordfjord coastline can be divided into those primarily of conglomerate and breccia (Solund, Byrknesøy-Holmengrå, and Håsteinen), those primarily of sandstone (Hornelen), and those of conglomerate passing upward into sandstone (Kvamshesten and Bulandet-Værlandet). Where basal sedimentary contacts are present, sedimentary breccias typically initiate the Devonian sequence, and pass upward into coarse rounded polymict conglomerate with intercalated sandstone. The upper parts of the sequence may consist of thick sandstones containing plant or fish remains, as in Hornelen, Kvamshesten, and Værlandet. The Solund Devonian is noteworthy for the large thickness, coarseness, and volume of conglomeratic sediment.

The stratigraphy and lithology of the Trondheimsfjord Devonian is similar, while the Old Red rocks of Spitsbergen, East Greenland, and Scotland are generally somewhat finer-grained (Friend, 1961; Butler, 1960; O. Holtedahl, 1960). Fossils found in the Sognefjord-Nordfjord area are of Middle Devonian age, but are generally found only in the upper part of the stratal succession; in the Trondheimsfjord area, *Dictyocaris* found on the island of Hitra suggests a Ludlovian (Upper Silurian) age for the beds, although other rocks in the area are Middle Devonian (Størmer, 1935; David Peacock, personal communication). The Røragen area in eastern Norway contains Lower Devonian fossil plants (Halle, 1916).

Vogt (1929) distinguished six orogenies during the Paleozoic that affected rocks in western Norway: (1) Trysil disturbance, lowermost Ordovician, (2) Trondheim orogeny, Upper Ordovician, (3) Ekne orogeny, uppermost Ordovician-lowermost Silurian (Taconian), (4) Caledonian orogeny, Ludlovian-Downtownian (uppermost Silurian), (5) Svalbardian disturbance, Lower to Upper Devonian (Shickshockian), and (6) Asturian disturbance, Carboniferous (Variscan). In the present paper, the term «Caledonian» will be restricted in use to (a) the name of the early Paleozoic geosyncline in the North Atlantic area, passing through western Norway, and (b) the orogeny affecting the Caledonian geosyncline in the late Silurian. Attempts to extend the use of the term «Caledonian orogeny» to earlier and later orogenic episodes are of interest but not of direct concern to the present paper (Hernes, 1963). Rocks younger than Middle Devonian are not present in western Norway, so that the Svalbardian and Asturian orogenies must be evaluated with respect to orogenic movements in Scotland, Bear Island, and Spitsbergen.

The Caledonian orogeny, in the latest Silurian, apparently migrated from west to east in Norway, for Upper Silurian molasse-type sandstones in the

Oslo are conformable and folded with underlying strata (Strand, 1960, 1961). The Caledonian orogeny resulted in intensive folding of Eocambrian to Silurian rocks, abundant intrusives and extrusives, high grade metamorphism and migmatization, and the incorporation of Precambrian basement rocks in nappe structures that moved southeast-ward toward the Precambrian foreland (Kvale, 1953, 1960). Great difficulty exists in distinguishing between high grade metamorphic rocks of Precambrian and Paleozoic age. In the Sognefjord-Nordfjord area, F. Skjerlie (personal communication) has distinguished three distinct deformation episodes in pre-Devonian rocks: (1) an old relatively tight east-west trending fold system, (2) a younger northeast-southwest trending fold system, presumably formed during the Caledonian orogeny, and (3) a youngest folding along open east-west trends, presumably during the Svalbardian folding episode in the Devonian.

The pre-Devonian stratigraphy of Sognefjord-Nordfjord is described by N.-H. Kolderup (1928, 1931a), with correlations and ages derived primarily from comparisons with the Trondheim and Bergen areas, where fossils are more abundant. The following broad divisions were determined: (1) Precambrian—gneisses, amphibolites, granites and Bergen-Jotun anorthositic rocks; (2) Cambrian—quartzites and sparagmites*, some mica schist; (3) Ordovician-Silurian—mica schists with quartzites and limestones, followed by mica schists with greenschists and quartzites as well as basic intrusives, followed by trondhjemite intrusions; and (4) Devonian—unconformable clastic sediments. Pertinent to the present study was the availability in potential sources of a wide variety of pre-Devonian igneous, metamorphic and low-grade metasedimentary rocks. Recent work has shown that the contacts between the «Precambrian» gneisses and Cambro-Silurian schists in some areas are gradational metamorphic, rather than unconformable or tectonic; thus many of the supposed Precambrian rocks in the Sognefjord-Nordfjord area may have been involved in orogenic movements of the Caledonian orogeny, and may be wholly or in part Paleozoic in age (N.-H. Kolderup, 1950, 1952, 1960; Bryhni and Skjerlie, personal communications).

Older maps of western Norway indicate that the Devonian basins contain sediments that have been folded into synclines. The basins were shown surrounded by large-scale synclinal structures in the underlying Cambro-Silurian schists, leaving basement gneisses exposed between the synclines and to the east

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*) sparagmite—a collective term for the late Precambrian or Eocambrian Scandinavian rocks comprising polygenetic conglomerates, feldspathic grits, arkose, and graywacke (Holmes, 1920).

(Fig. 1). The Devonian rocks commonly have sedimentary contacts to the west, faulted northern and southern contacts, and apparent thrusted contacts to the east. The extent of postdepositional Devonian deformation is unclear, with the evaluation of the relative strength of the Svalbardian orogenic movements being controversial. Vogt (1953, 1954a, 1954b) considered the Svalbardian to extend far into southern and eastern Norway, while O. Holtedahl (1960) thought it restricted to the coastal areas of western Norway. Profound unconformities exist in the Upper Devonian of Spitsbergen and Scotland, suggesting considerable Devonian tectonic activity in Norway as well. Syndepositional tectonism and subsidence is thought to have occurred in the Hornelen and Røragen areas as a result of Svalbardian movements (Bryhni, 1964b; Holmsen, 1962).

GENERAL GEOLOGY OF THE SOLUND AREA

Devonian rocks

The unfossiliferous conglomerates unconformably overlying deformed Cambro-Silurian metamorphic rocks in the Solund district are thought to be approximately Middle Devonian because of overall resemblance to fossiliferous Devonian deposits of the Sognefjord-Nordfjord region. The contacts with basement rocks are of three types: (1) *tectonic*—southeastern boundary, (2) *unconformable*—Leknessund and Hersvik, south of Lågøyfjord, and the westernmost islands, and (3) *tectono-unconformable*—(primarily unconformable, but evidence suggests some movement along the contact)—northern edge of the Lifjell Peninsula (Fig. 3). South and east of the Hersvik area are some irregular bodies of igneous rock within the Devonian.

The top of the Devonian sequence has been eroded, making it difficult to estimate the original stratigraphic thickness. The maximum preserved thickness is found south of Lågøyfjord, with exposed strata thinner to the north and east. From northeastern Indre Solund to Losna, or from Leknessund (north central Indre Solund) to southeastern Indre Solund, the calculated section is 5,200 meters thick, while from north-western Indre Solund to southern Indre Solund it is 4,600 meters thick, and 3,500 meters thick from northern Ytre Solund to southwestern Steinsundøy (Fig. 3).

Thin section study revealed abundant calcite filling fractures and interstices in the conglomerate and underlying basement rocks throughout the area. Open joints parallel to the southern tectonic boundary in southeastern Nesøy contain brecciated conglomerate cemented by quartz and calcite, with chalcopyrite and minor amounts of bornite crystallized in the veins. Quartz cements the breccia on the outer parts of the joint walls, with the central zone filled by coarser calcite crystals and larger amounts of copper sulfides; minor amounts of malachite and azurite are also found. Small chalcopyrite crystals are disseminated in basement rocks of the westernmost islands, and also in rocks adjacent to the southern tectonic boundary; these occurrences are the only proven Devonian or post-Devonian copper mineralization in western Norway, although being of no economic value.

Cambro-Silurian rocks

Basement rocks are exposed in scattered outcrops under the Devonian cover, south of Lågøyfjord and in the westernmost islands as a result of erosion along the crest of anticlinal structures, and in other areas by erosion of the Devonian from elevated parts of the basement topography (Fig. 3). Significantly, these latter occurrences (Hersvik, Leknessund, and the northern edge of the Lifjell Peninsula) are all underlain by quartzite in part, which was probably a very resistant rock during the period of erosion preceding conglomerate deposition. Basement topography had considerable relief and was in places precipitous, explaining the irregular exposure of the basement and uneven trend of the basal unconformity.

A zone of mylonite is found beneath Devonian conglomerate along the southern contact, indicating its tectonic nature. The mylonite post-dates regional metamorphism of basement rocks, because its trend cuts across earlier folds in the basement, and it forms a boundary between the unmetamorphosed Devonian and regionally metamorphosed Cambro-Silurian rocks.

Below the mylonite is a thick, relatively monotonous sequence of gray quartzose phyllite less affected by the dynamic metamorphism along the bounding fault, but showing effects of regional metamorphism. Near the mylonite, the foliation in the phyllite dips parallel to the fault, but abundant folding is present below this zone, with the general dip of the foliation in the southern Lifjell Peninsula toward the north, although bedding is generally indistinct. Reusch (1881) divided the phyllites into several units, but the rock is here considered simply a metasedimentary quartzose shale or siltstone, now composed of angular clastic quartz and smaller amounts of feldspar, with thin bands of chlorite parallel to the foliation. Biotite is less common, with epidote found interstitially. The rock was thus probably metamorphosed in the quartz-albite-epidote-biotite subfacies of the greenschist facies, and locally affected by later dislocation metamorphism (Fyfe, et. al., 1958).

The Sogneskollen Granodiorite is found south of the Lifjell Peninsula and

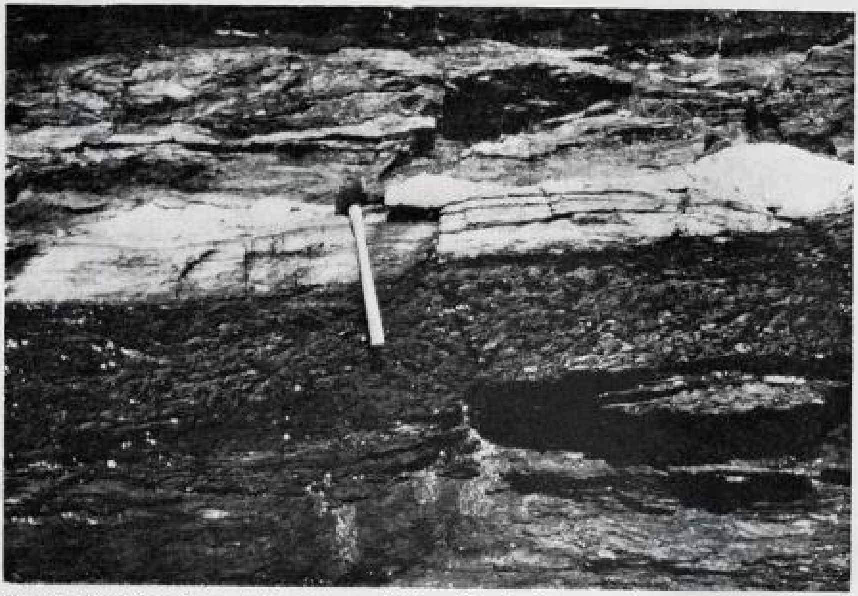

Fig. 4. Boudinaged quartzite interstratified with phyllite, southeastern Indre Solund, near Kråkevåg.

extends to the southeastern edge of Losna, intruding the Cambro-Silurian phyllite, with numerous dikes extending out into the phyllite. This Caledonian intrusive has a cataclastic texture in general (C. F. Kolderup, 1911), but especially so at Losna, where it was affected by dislocation metamorphism and is partly mylonitic.

The gray phyllites on Losna contain local cataclastic quartzite lenses, as well as some obscure conglomerates, possibly intraformational. The foliation or cleavage is strongly folded, although bedding still is obscure. A metasedimentary sequence consisting of microscopically interstratified foliated quartzo-feldspathic arenite, wacke and mudstone (Williams, et. al., 1954), interbedded with thicker boudinaged layers of feldspathic quartzite, crops out along the southeastern edge of Indre Solund beneath a thinner mylonitic zone (Figs. 4 and 5). Clastic quartz and feldspar are poorly rounded, with cataclasis generally present; the fine matrix has not recrystallized, suggesting a somewhat lower metamorphic grade than further east.

The northern edge of the Lifjell Peninsula consists primarily of thickly bedded, partly mylonitic, well-sutured feldspathic quartzite with muscovite flakes scattered parallel to the microlamination. The quartzite is interbedded with lesser amounts of: (1) coarse, tightly folded quartz-muscovite schist, the

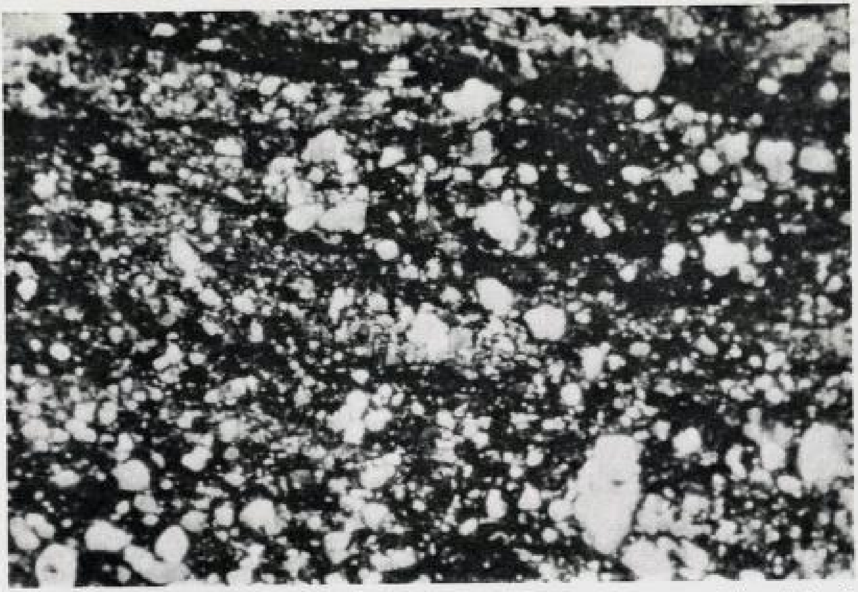

Fig. 5. Microphotograph of metasedimentary phyllite, southeastern Indre Solund, near Kråkevåg (x30). (Crossed nicols; light clastic grains mostly quartz; dark areas partly chloritic matrix).

straining and bending of the mica flakes suggesting that folding postdated mineral growth; (2) an altered fine-grained mafic igneous rock, probably extrusive, with the original crystalline texture and relict flow structures virtually obliterated; and (3) a fine-grained felsic porphyritic igneous rock, present in very small quantities. The last rock type has plagioclase phenocrysts as well as relict spherulitic structures, suggesting an extrusive origin.

Basement rocks at Leknessund, north-central Indre Solund, are lithologically similar to the above, only less metamorphosed. Quartzite is dominant on the island to the north, with phyllite more abundant to the south, underlying the Devonian contact. The phyllite is a chloritic metasedimentary quartzo-feldspathic wacke, with rounded clasts as laminae or dispersed in fine, generally unrecrystallized matrix. Highly altered small irregular bodies of a mafic, porphyritic igneous rock are interbedded with the sediments, and contain plagioclase and amphibole phenocrysts. The sequence is intricately folded, with ill-defined geometry

Basement rocks near Hersvik consist of: (1) flattened quartzite conglomerate and feldspathic quartzite in the higher central parts of the exposure, with (2) gray phyllite in the northern part, interbedded with the quartzitic rocks

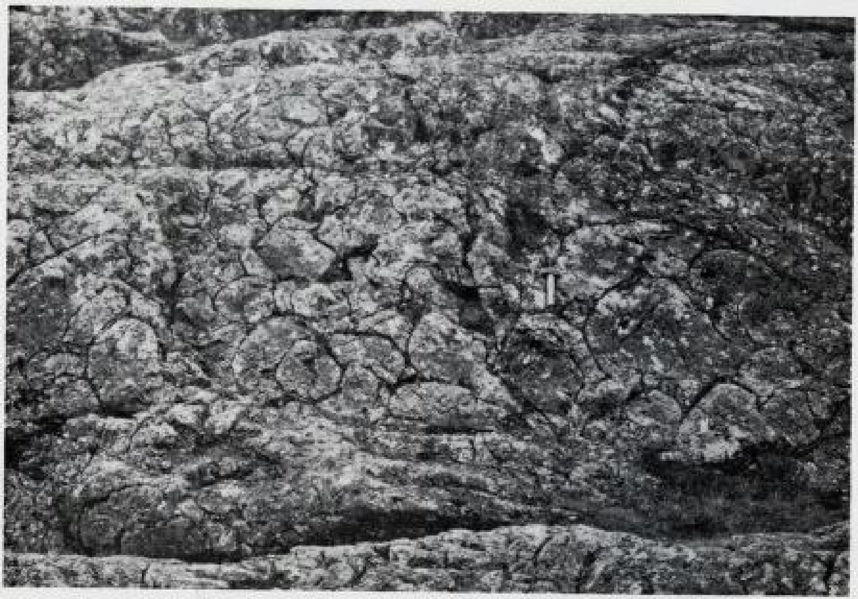

Fig. 6. Pillow lavas in basalt, Ytre Solund. south of Ytrøy.

in the central part, (3) a highly altered aphanitic porphyritic mafic igneous rock of possible extrusive origin to the south, and (4) a few small scattered granodioritic intrusives, similar in composition to the Sogneskollen Granodiorite, and perhaps related to it. The conglomerate contains well-rounded pebbles of coarse, strained interlocking quartz aggregate, without the prominent elongation and suturing characteristic of quartzites to the east; the conglomerate matrix is composed of granular quartz with scattered plagioclase and aligned muscovite. Cross-stratification indicates a general younging direction to the northwest. The phyllite is partly mafic igneous material, with relict shard structures, and partly clastic quartzo-feldspathic wacke. The northwestern tip of Indre Solund contains phyllitic quartzofeldspathic wacke, with chloritic bands parallel to foliation.

A highly altered gabbro, intrusive into the surrounding phyllites and basic extrusives, crops out on Lågøy and surrounding areas south of Lågøyfjord. It is fine to very coarse grained, and contains primarily calcic plagioclase and amphibole (from uralitization of pyroxene). Relict pyroxene structures can be seen, but much of the textural character has been obscured by alteration. To the east of Lågøy, Devonian conglomerate rests on a gabbro breccia on the northern tip of Hågøy. Within the gabbro are foliated zones of basalt,

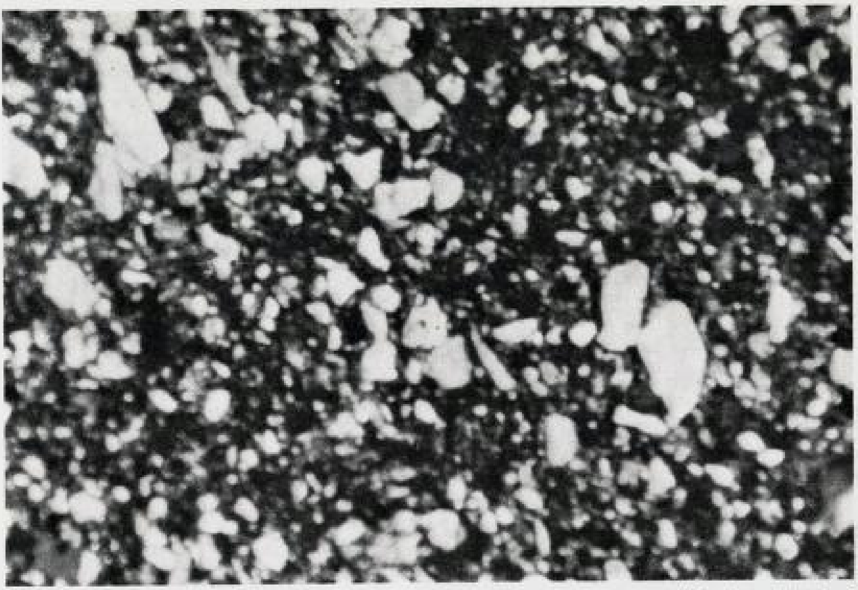

Fig. 7. Microphotograph of quartz wacke, from Husøy, westernmost islands of Solund area (x30). (Crossed nicols; light clastic grains mostly quartz; dark areas unrecrystallized matrix).

trending east-west on Lågøy itself; these may represent xenoliths, country rock, or perhaps finer-grained zones in the gabbroic complex.

Basaltic rock crops out on the islands west of Lågøy, with almost equal mixtures of layered foliated basalt and irregular, sometimes flattened pillow lavas (Fig. 6). Pillow structures are abundant to the west, becoming more flattened and obscure eastward, with the younging direction to the northwest. Folding consists mostly of large open flexures, but tighter folds do occur. The northwestern edge of Steinsundøy is composed of basalt, with fine wacke containing plagioclase and pyroxene clasts to the south; it seems probable that this metasediment resulted from erosion of the mafic extrusives.

Quartz wacke forms the basement of the westernmost islands, with graded bedding indicating younging to the north and west. Clasts of poorly rounded quartz with lesser amounts of plagioclase, muscovite, basic extrusive rocks, quartzite and rare shard-like fragments are dispersed in a fine, dense, essentially unrecrystallized matrix (Fig. 7). The thick sequence contains open folds, little foliation, and repetitive graded stratigraphic units.

A diagrammatic basement paleogeologic map (Fig. 8) suggests the following gross trends in the Cambro-Silurian: (1) increasing grade of regional

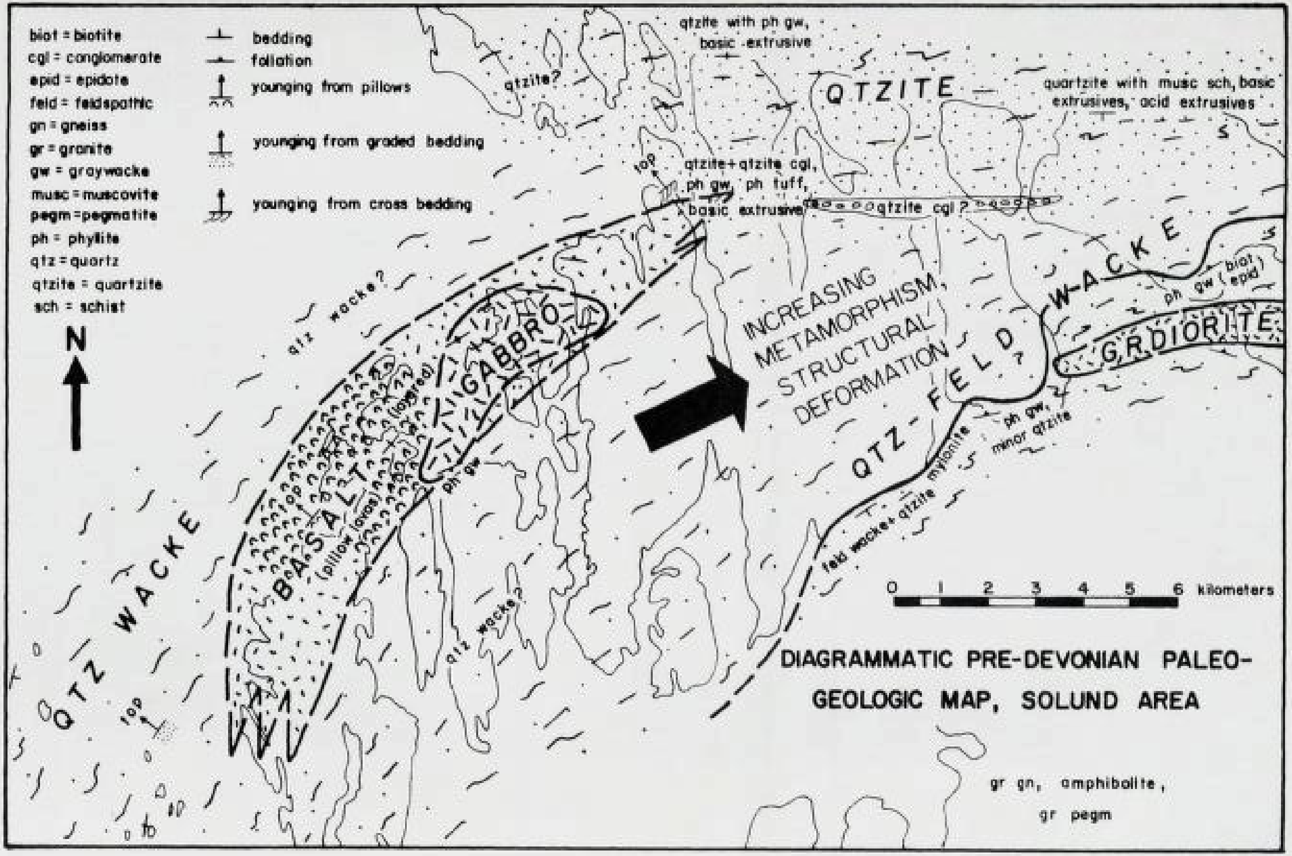
biot = biotite
cgl = conglomerate
epid = epidote
feld = feldspathic
gn = gneiss
gr = granite
gw = graywacke
musc = muscovite
pegm = pegmatite
ph = phyllite
qtz = quartz
qtzite = quartzite
sch = schist
bedding
foliation
younging from pillows
younging from graded bedding
younging from cross bedding
N
qtzite?
qtzite with ph gw, basic extrusive
QTZITE
quartzite with musc sch, basic extrusives, acid extrusives
top
qtzite + qtzite cgl, ph gw, ph tuff, basic extrusive
qtzite cgl ?
qtz wacke?
GABBRO
BASALT
(pillow lavas)
top
(layered)
ph gw
INCREASING METAMORPHISM, STRUCTURAL DEFORMATION
QTZ - FELD - WACKE
?
ph gw (biot epid)
GRDIORITE
ph gw, minor qtzite
feld wacke + qtzite mylonite
QTZ WACKE
top
qtz wacke?
0 1 2 3 4 5 6 kilometers
DIAGRAMMATIC PRE-DEVONIAN PALEO-GEOLOGIC MAP, SOLUND AREA
gr gn, amphibolite, gr pegm

Fig. 8.

metamorphism to the east; (2) increasing structural deformation to the east; (3) felsic intrusives to the east, mafic intrusives to the west; and (4) abundance of quartzite to the northeast, with finer lower-energy sediments to the south and west, although facies changes are uncertain due to lack of outcrop, poor correlation, and structural deformation. Prevalent graded bedding suggests lower energy, probably deeper-water conditions westward; whereas cross-bedding suggests higher energy conditions eastward, although these deposits may not be coeval. Provenance for these sediments was rich in quartz, with feldspar a secondary constituent. From brief investigation, at least two periods of deformation can be recognized, with a brittle style (fracture cleavage, minor faulting, cataclasis) following a more plastic style of folding.

The stratigraphic resemblance to other rocks of the western coast of Norway suggests an Ordovician-Silurian age, with the Solund area probably having been part of the eugeosynclinal region of the Caledonian geosyncline. The mafic intrusives and extrusives would be considered Lower Silurian, and the granodiorite Upper Silurian (N.-H. Kolderup, 1928). Passage into the eastern miogeosyncline may be thought to occur from noted changes in sediment type and decreasing volcanics eastward, but this conclusion is difficult to derive from such a small area of study.

To the south of Sognefjord, high-grade metamorphic rocks, primarily granite gneiss, amphibolite, and augen gneiss, with abundant granites and granite pegmatites, crop out over a large area (unpublished field notes of C. F. Kolderup, N.-H. Kolderup, and H. Askvik, 1917—1965, on file in the Geologic Institute, University of Bergen, Norway). The area, unfortunately, has not been mapped in any detail. To the south and east of the Lifjell Peninsula, various Caledonian schists and gneisses of higher metamorphic grade than the Solund basement rocks crop out, with rock types mentioned in field notes including garnet-mica schists, kyanite-garnet schists, amphibolites, eclogite-amphibolites, talc schists, saussuritic gabbros, quartzites, limestones, various gneisses, and granodiorite (ibid.).

STRUCTURAL GEOLOGY

Folding

Devonian rocks in Solund form a large, open, generally symmetrical anticline with basement rocks cropping out irregulary along the breached crest of the fold in a zone from Husøy to the northwestern tip of Indre Solund (Fig. 3).

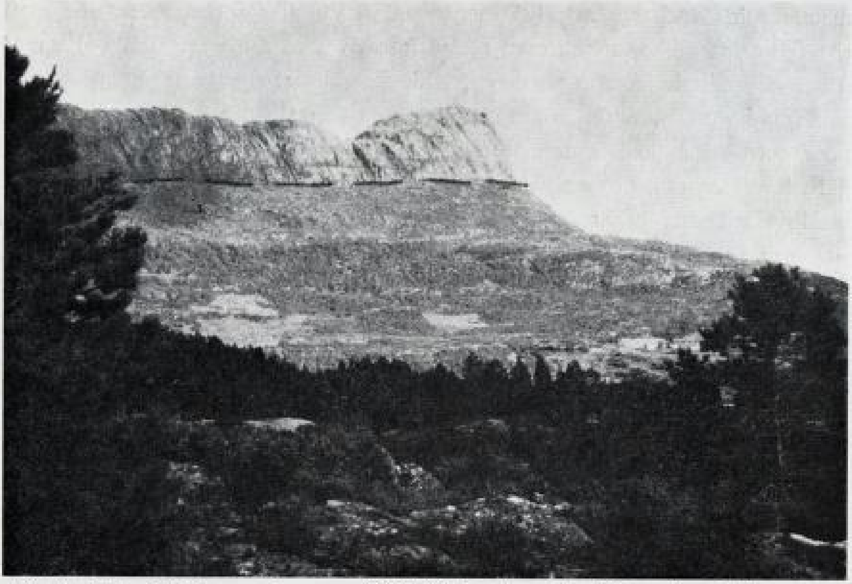

Fig. 9. Solund Fault, southwestern Lifjell Peninsula. (Inked line along fault trace).

The anticline* appears to plunge very gently to the northeast west of Hugøy (west of Hersvik), and gently to southwest northeast of Hugøy, as seen from changing dip directions. Irregularities in basement topography result in an uneven outcrop pattern, but the Devonian dips generally 20—30° away from the axial plane trace, with a maximum dip angle of 50°. It is not certain whether the undulatory trend of the axial plane of this anticline is a primary structure or due to later deformation. Between Begla and Utvær to the west there is a smaller anticline present, but its extent is unknown. In detail, the generally consistent strike and dip of the Devonian bedding has many minor warpings and bends that do not follow a definite pattern, but it is thought that these result from minor variations of the primary sedimentary dip rather than from deformation.

Faulting

South-bounding Solund Fault

The gently north-dipping planar tectonic boundary between the Devonian and Cambro-Silurian to the south is here named the Solund Fault (Fig. 9).

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*) The name «Lågøyfjorden anticline» will be used for this structure.

Fig. 10. Sheared conglomerate above Solund Fault, southwestern Indre Solund, near Kråkevåg.

It is exposed along the southern margins of Indre Solund, Losna, and the Lifjell Peninsula; shearing of conglomerates as far west as Ytre Solund suggests that the fault continues further west under Sognesjøen, forming a major fault in western Norway (Figs. 3 and 10). C. F. Kolderup (1926a) considered the fault a thrust on general appearance, but examination of minor associated structures indicates a more complex movement history.

Shearing of the conglomerates in a zone up to two and one half kilometers wide along the southern boundary of the area decreases northward into normal conglomerate. A thinly laminated mylonitic zone approximately 90 centimeters thick, including associated minor structures, is found along the fault boundary. The minor structures are considered to have been produced by movements along the fault, as they are confined to the zone of mylonite. The mylonite is a well-sutured quartz mosaic with preferential elongation of quartz grains producing a lineation on the surface of the mylonite laminae (Fig. 11). Deformed conglomerate pebbles above the fault are elongated parallel to this lineation, with length to thickness ratios up to 30 : 1. Pebbles with abundant quartz are most deformed, those with feldspar less affected. The southeasterly dipping Devonian stratification has been obliterated above the fault, with deformed pebbles dipping about 15° to the northwest, parallel to the mylonite lamination.

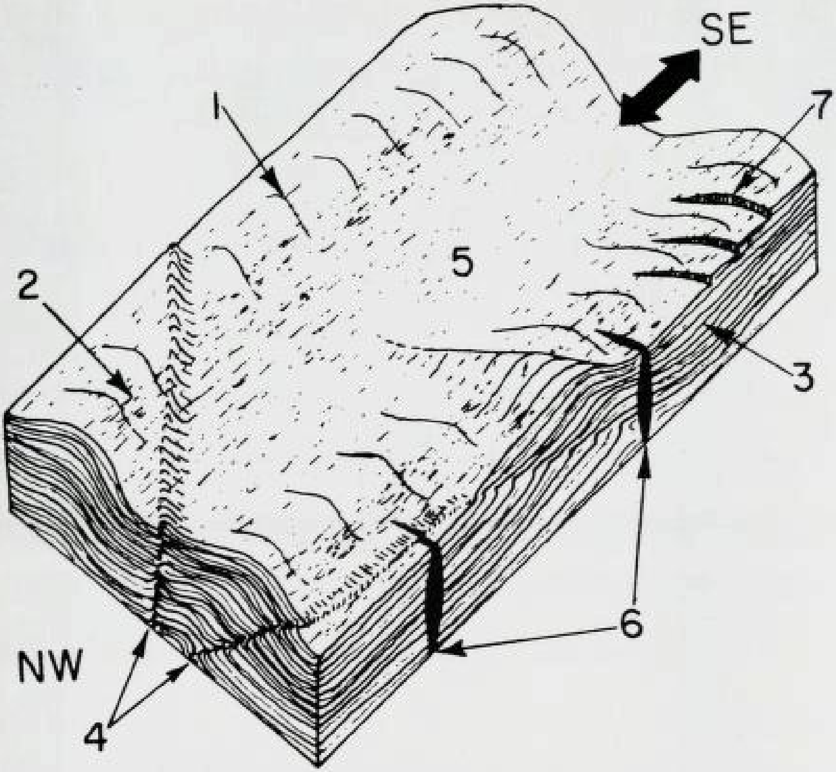


Fig. 11. Diagrammatic sketch of minor structures associated with the Solund Fault. (1 = open folds with axes parallel to lineation; 2 = lineation in mylonite; 3 = thin lamination in mylonite, parallel to fault surface; 4 = conjugate sets of kink bands; 5 = broader asymmetrical folds; 6 = quartz-filled tension joints dipping steeply to the southeast, striking parallel to fault surface; 7 = chatter marks on fault mylonite surfaces; double-ended arrow suggests two directions of movement of fault zone as inferred from minor structures).

A series of relatively broad, open folds trending parallel to the above lineation are present in the mylonite, although a definite movement direction cannot be determined from these structures. If these linear structures are parallel to the initial movement direction, they suggest a slightly oblique movement toward the east rather than simple dip-slip movement (Figs. 11 and 12). A second group of structures consists of conjugate(?) kink bands that grade into broader asymmetrical folds deforming the earlier lamination and lineation. The intersection of the axial planes of these structures yields an intermediate stress axis direction essentially parallel to the lineation. The

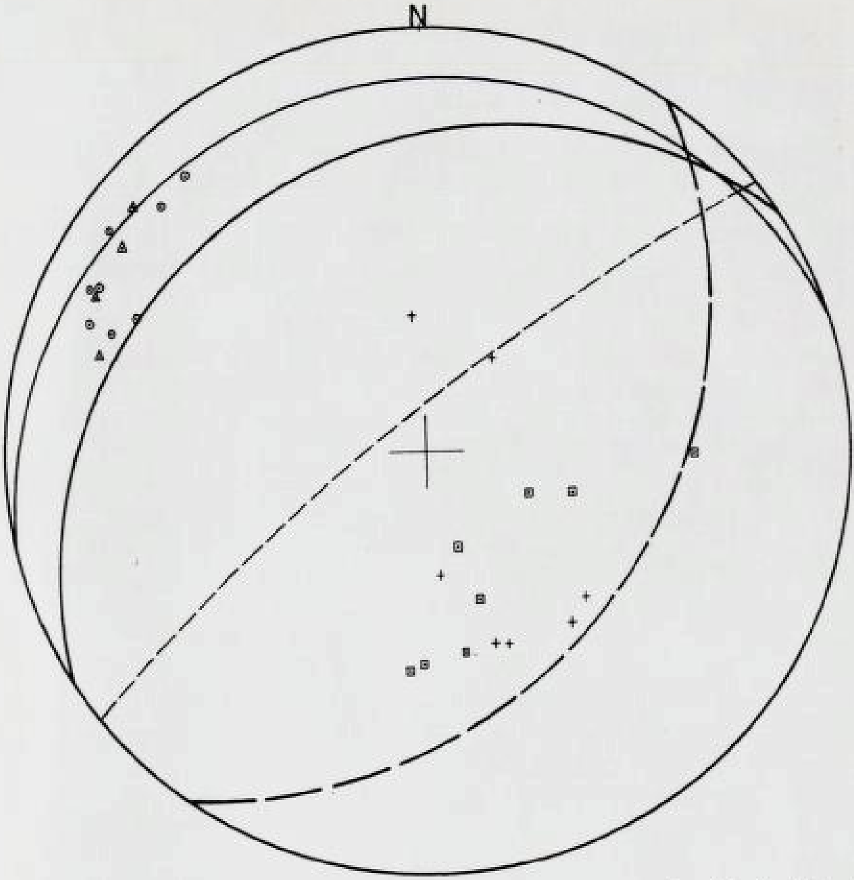


Fig. 12. Stereographic representation of minor structures associated with the Solund Fault.

———— Range of mylonite lamination

— — — — Quartz-filled tension joints

—— —— Vertical surface of chatter marks

Triangles: Plunge of open folds parallel to lineation

Crosses: Poles to axial planes of assymmetrical folds

Squares: Poles to axial planes of kink bands

Circles: Plunge of mylonite lineation

general nature of these structures and of the fault suggests a thrust origin, with younger Devonian conglomerates shoved over the Cambro-Silurian basement rocks.

However, still younger structures, including steeply north-dipping cross-

Fig. 13. North-dipping normal fault, Losna.

cutting quartz-filled tension joints, as well as chatter marks on the mylonite surfaces, indicate movement of the normal type, with the hanging wall downthrown to the north (Fig. 11). After thrusting, perhaps relaxation of stresses resulted in an opposite direction of movement.

North-dipping normal faults

Abundant normal faulting has occurred near the southern edge of the area north of the Solund Fault, with these faults in all cases dipping northward across stratification and exhibiting relatively small displacements up to a few tens of meters (Figs. 3 and 13). The faults are of the normal type, and are thought by the writer to be related to the later normal movement of the Solund Fault, especially because they increase in abundance to the south. Associated structures, including chatter marks, displaced pebbles, and quartz-filled tension joints, suggest movement to the northwest, or the dip-slip direction. The faults dip up to 40° to the northwest, but can be seen to flatten with depth. Locally quartz is found filling the fault surfaces, with copper mineralization on Nesøy, suggesting origin from tensional stresses.

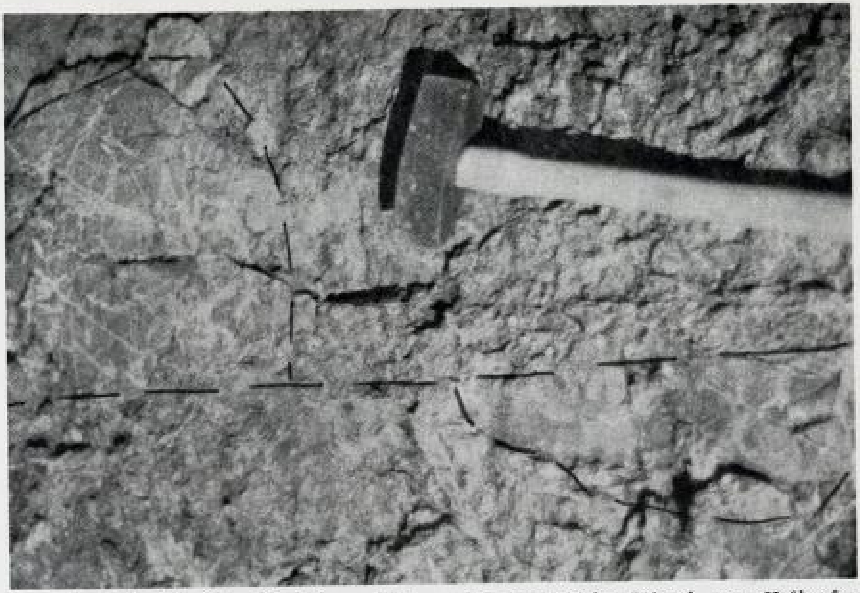


Fig. 14. Strike-slip fault displacing pebble, southeastern Indre Solund. near Kråkevåg. (Inked lines along fault trace and around displaced pebble).

Strike-slip faults

Strike-slip faults with displacements never greater than one to two meters are found sporadically throughout the Devonian sediments (Fig. 14). They generally strike northeast-southwest with vertical dips, and are easily recognized by the displacement of pebbles. No consistent movement pattern was determined, however. These faults are thought to be minor adjustments of the brittle conglomerate to stresses associated with the large-scale folding and faulting, possibly related to oblique movement of the Solund Fault.

Bedding-plane faults

Many bedding surfaces, especially in the southern parts of the area, consist of thin phyllonitized zones with associated slickensides and lineation on micaceous surfaces. The lineation does not occur in discrete planes, but is irregular and wraps around pebbles found in these movement zones, and generally trends northwest-southeast (Fig. 3). The matrix has been strongly affected, with little apparent deformation of pebbles.

The sense of movement along these zones is not clear, but the writer sug-

Fig. 15. Elevated sea cave formed at intersection of vertical joint and bedding-plane fault, eastern Indre Solund, near Krakhelle.

gests that these faults represent slippage along bedding surfaces in response to broad flexural slip folding. This is in agreement with the predominance of these faults in the southern areas, furthest from the fold crest, where bedding-plane slippage would be greatest. In addition, the northwest-southeast slippage perpendicular to the northeast-southwest anticlinal axis would be expected during flexural slip folding. When near sea level, some of these zones underwent considerable wave erosion, and now form uplifted sea caves and arches (Fig. 15).

Jointing

Two distinctive joint types are recognizable: (1) tension joints of mesoscopic size, generally filled with quartz, keratophyre, or calcite, and (2) a macroscopic joint system causing the characteristic geographic outlines of the Solund Islands.

Mesosopic joints

Abundant steeply dipping filled joints are found in the Solund area, extending from a few centimeters to tens of meters in length (Fig. 16). Keratophyre-filled joints tend to be most common in the central part of the area,

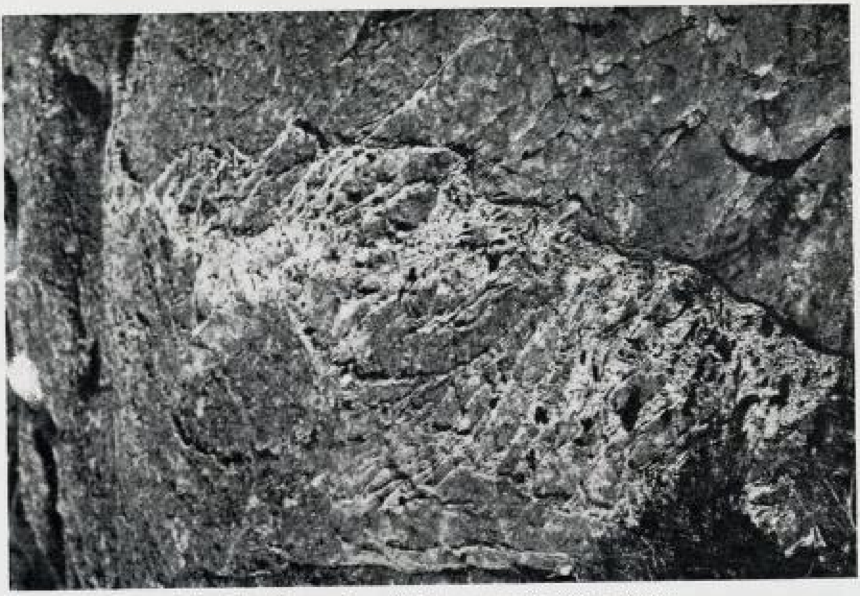


Fig. 17. Keratophyre-filled mesoscopic joints, Losna.

perhaps related to quartz keratophyre igneous bodies near Hersvik (Fig. 17). Quartz-filled joints are most common to the south, while calcite-filled joints are scattered throughout the area. A contoured stereographic representation of poles to the joints indicates a prevalent vertical northeast-southwest trend parallel to the axial plane trace of the Lågøyfjord anticline with other prominent directions of filled mesoscopic jointing appearing in Figure 18.

The mesoscopic joints appear to be related to the large-scale anticlinal folding, and can be interpreted as representing a set of secondary tension joints parallel to the fold axes, two vertical shear joints at approximately 45° to the secondary tension joint, and a fourth vertical («ac») primary tension joint perpendicular to the fold axis, bisecting the two shear joints. The gently dipping joints are apparently related to faulting, for many fill northeast-southwest trending fractures between broken and displaced pebbles.

The mesoscopic joints are thought to have formed early in the post-diagenetic history of the sediment, perhaps contemporaneous with initial folding movements in the area, with fluid material filling the joint spaces by migration of solutions from porous sediment; the abundance of interstitial calcite and analogy to other studied joint patterns supports this contention (Spencer-Jones, 1963). The sandstones locally contain intricate networks of

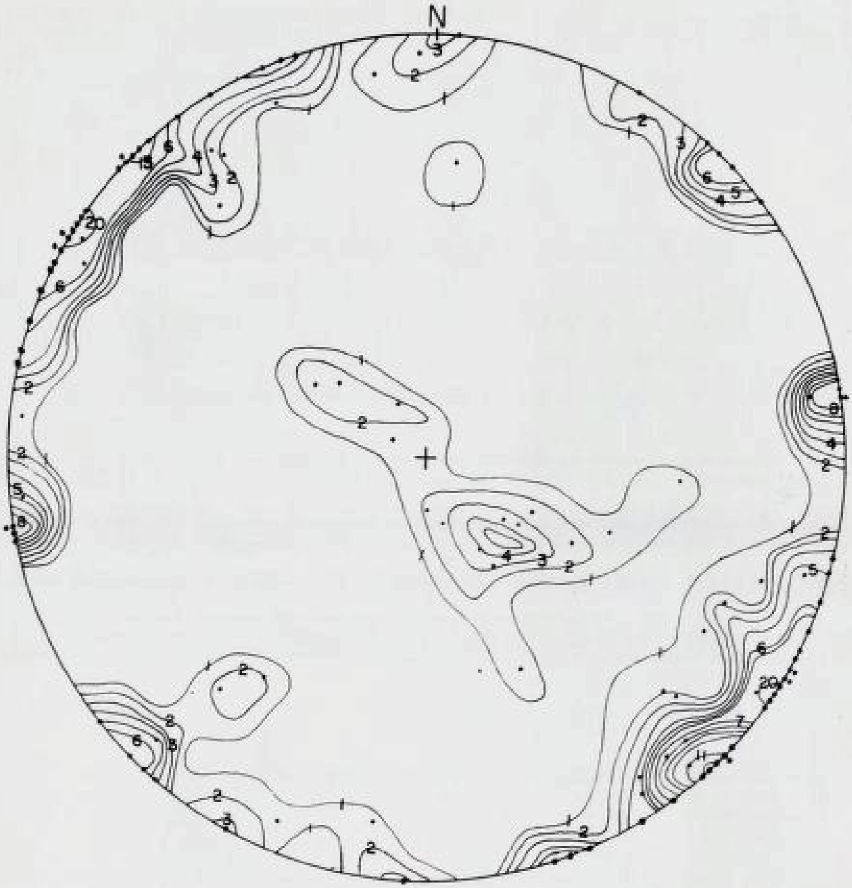


Fig. 18. Stereographic representation of mesoscopic joints. (Poles to joint surfaces plotted and contoured as number of poles in one percent of area of Schmidt net. Lower hemisphere projection, with 77 measurements).

fine joints, along which migrating fluids have apparently re-cemented the fractures, resulting in a complex pattern of narrow low ridges.

Many pebbles, especially larger ones, are fractured by joints confined to the pebbles themselves. These fractures do not generally penetrate the surrounding matrix, but must have resulted from postdepositional stresses, for otherwise the pebbles would have easily been broken during transport. Lack of time and great variation of fractures with pebble lithology prevented detailed study of these fractures, but a quartzite pebble from Skorpa contained five distinct fracture sets, summarized in Figure 16.

Fig. 19. Macroscopic tension joint, Losna.

Macroscopic joints

The most striking feature of the Solund area is the series of intersecting vertical joint sets forming the prominent north-south, northwest-southeast, and northeast-southwest trends of the coasts, sounds, fjords and bays. These joints show separation of the adjacent walls up to ten meters, with many individual joints being traceable for several kilometers (Fig. 19). The most prominent direction, north-south, has been a subject of great interest to Norwegian geologists, as they form distinct fjords along the western coast that are perpendicular to the major east-west trending fjords (N.-H. Kolderup 1931b, 1934). These «fissure fjords» are best developed in the Solund area because of the great resistance of the conglomerate to erosion, and were thought to be closely related to structural trends of rocks in the Caledonian geosyncline, rather than later tectonic events. The larger east-west fjords («strike fjords») seem to follow the general east-west trends of Caledonian metamorphic rocks along the coast, being found commonly in anticlinal valleys of less resistant Cambro-Silurian schists between the Devonian basins.

The writer made a systematic areal study of the macroscopic joint pattern, measuring trends in the basement rocks as well as in the Devonian (Fig. 16). Three dominant joint sets are almost everywhere present, although considerable variation in strike is found. The north-south striking joints show the greatest lateral separation, generally cut the other joint sets, and form the best developed and most extensive joint set. To the southwest the northerly trend shifts to the northwest, and considerable change in strike occurs in the other two primary sets over relatively short distances. The joints almost universally have steep dips, such that only strike directions were plotted in Figure 16. Contrary to earlier ideas of N.-H. Kolderup (1931b), the writer does not recognize any of the major north-south joints as faults, with sedimentologic data supporting this contention.

The nature of the joints and time of genesis are of primary interest. An important factor in this consideration is that even if some of the joint sets appear to follow structural trends of the Caledonian geosyncline, they may still be recent in origin, though controlled in part by older features. The fact that they are so prominent and clearly defined in the Devonian suggests a later origin. The appearance of the joints suggests that considerable crustal stress was required to produce a system of such magnitude. The dominant north-south set cannot be related clearly to any structural trends in pre-Devonian or Devonian rocks, and the writer suggests that these joints may be related instead to Late Cenozoic uplift of the Scandinavian landmass. Marginal channels off the coast of western Norway are thought to be graben structures related to Tertiary uplift (H. Holtedahl, 1958; O. Holtedahl, 1960; O. Holtedahl and H. Holtedahl, 1961).

Joint patterns from the Cambro-Silurian rocks differ from those of the Devonian rocks primarily in having closer, more irregular spacing within sets, more undulatory surfaces, more variable dip angles, and more complex patterns, apparently resulting from a relict pre-Devonian joint pattern and more heterogeneous rock types.

Structural synthesis

The sequence of post-depositional structural deformation can be summed up as consisting of: (1) arching of the sediments into a broad anticline with accompanying bedding-plane slippage faults and a pattern of mesoscopic filled joint sets related to folding, (2) thrusting of the southern margin of the Devonian sediments, apparently to the southeast, over basement rocks, (3) normal movement along the Solund Fault, with associated north-dipping normal faulting near the southern margin of the present basin (cutting the earlier, southeast-dipping bedding plane faults), and (4) formation of a macroscopic joint pattern producing «fissure fjords», possibly in the late Cenozoic (Fig. 20).

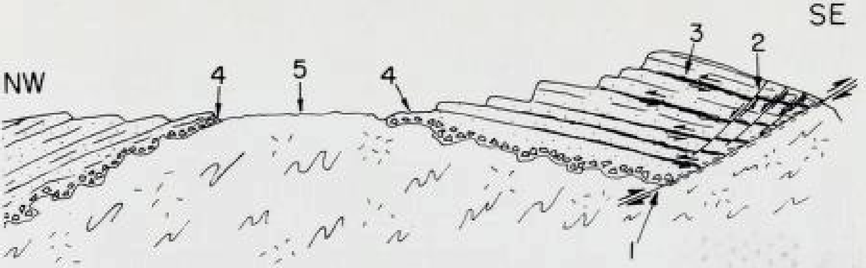


Fig. 20. Diagrammatic cross-section showing relationship between structural features of the Solund area. (1 = south-bounding Solund Fault, primarily reverse fault, with mylonitic lamination parallel to fault surface; 2 = normal faults associated with Solund Fault; 3 = bedding plane movement zones with inferred direction of movement; 4 = basal breccia at unconformable base of Devonian sequence; 5 = approximate crest of broad northeast trending anticline).

The thrusting of the younger Devonian rocks over older basement rocks along the southern margin of the Solund area apparently resulted from compression of the sedimentary basin. Sedimentologic data suggests that the Devonian basin was bounded by an active fault zone along its southern margin that produced an uplifting source area to the south. Later compression caused thrusting of the downfaulted Devonian sediments out to the south over basement rocks.

STRATIGRAPHY

The Solund Devonian rocks do not constitute an orderly sequence or succession of definable stratigraphic units. Rather, they consist of a lithologically relatively uniform thick mass of conglomerate with interspersed, laterally discontinuous pebbly sandstone and sandstone units.

In accordance with the Code of Stratigraphic Nomenclature for Norway (1960), the writer proposes the name *Solund Conglomerate* as a lithostratigraphic formational name for the Devonian sediments found in the area under discussion. The type area proposed is Indre Solund, with best exposures along Hagefjord, north of Eide in south central Indre Solund.

Lacking distinct marker strata, fossils, or stratal sequence, sampling and collection of sedimentologic data was of the simple random type. In addition, the stratigraphic section is exposed primarily in two dimensions, so little can be said about the original extent and areal pattern of deposition (Fig. 3). Lack of stratigraphic control, then, severely limits the types of analysis that are possible.

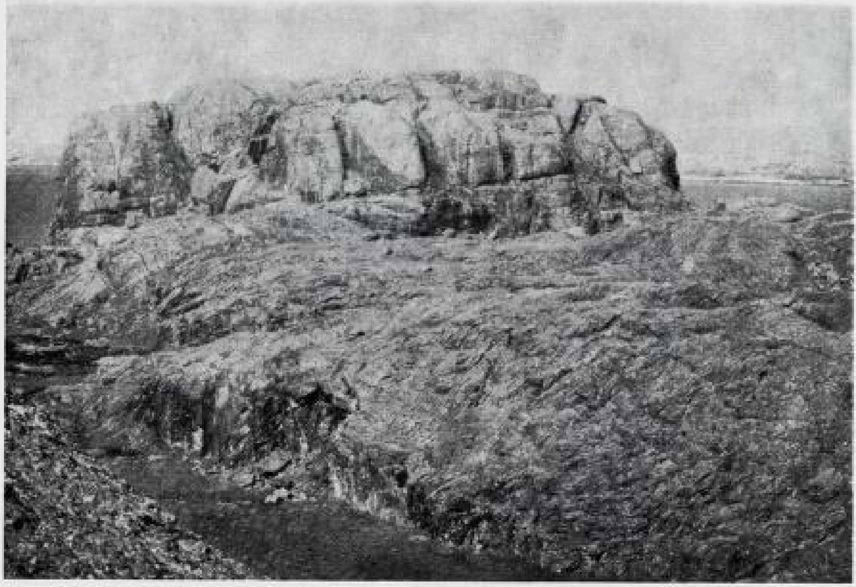


Fig. 21. Erosional outlier of Devonian conglomerate resting on basement, northwestern tip of Indre Solund.

The term «pebble» will be used in this paper as a general term to describe the particles or clasts coarser than sand-sized material in the Solund conglomerates, although most of the coarse clasts are actually coarser than Wentworth's (1922) pebble-size grade limits. Wentworth defines pebbles as ranging from 4 to 64 millimeters, cobbles from 64 to 256 millimeters, and boulders as above 256 millimeters.

A basal breccia consisting of angular fragments of local basement rock is commonly present above the irregular angular unconformity at the base of the Devonian, although locally polymict conglomerate was deposited directly on the basement. The breccia attains maximum thickness in topographic lows of the basement, and is thin or not present over topographic highs. The thickness reaches a maximum of 40 to 50 meters in some basement depressions. Quartzite breccia is rare, as the quartzite formed topographic highs; metagraywacke, phyllite and metabasalt fragments are the most common breccia fragments. This pattern suggests a relatively rapid burial of weathered products found on the older surface by the influx of abundant, abraded debris from a more distal provenance.

The breccias are not clearly stratified, but represent irregular accumulations of debris. No preferred fabric is noticeable, sorting is poor, and packing of

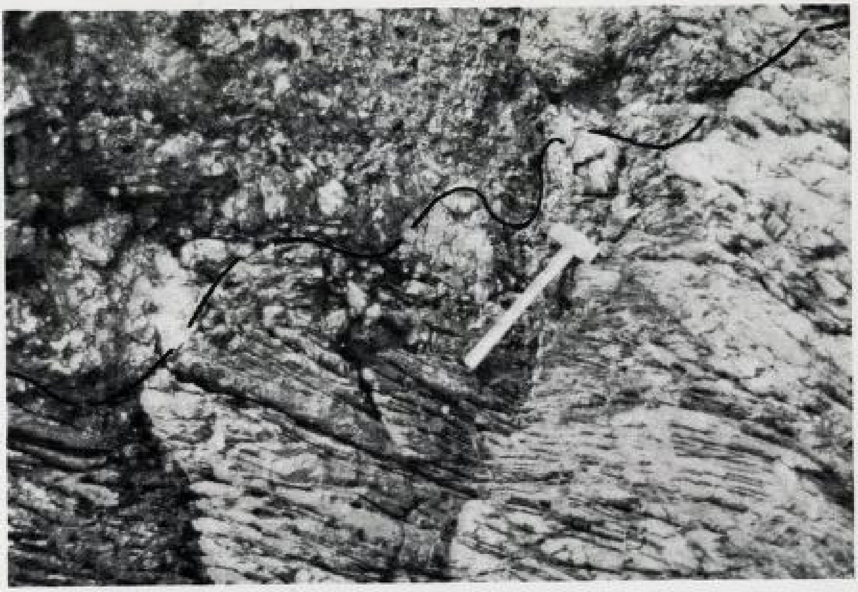


Fig. 22. Basal unconformity, with breccia zone, southeastern Utvær. (Inked line along trace of unconformity surface).

fragments is partly open, partly closed framework, with some corners rounded on a small percentage of fragments. The breccias contain a sandy matrix that is commonly red in color, with a high percentage of interstitial hematite. Before the influx of rounded gravel, apparently little transport of surficial material took place, although no leached zones or preserved organic material were found. The filling of topographic depressions by angular debris may have resulted from physical weathering on higher slopes, with loosened material falling into lower areas, and soil-forming processes.

The best exposures of breccia exist along the northern edge of Ytre Solund, Steinsundøy, and northwestern Indre Solund (Figs. 3 and 21). Breccia was found by writer at southeastern Utvær and western Begla, in the westernmost islands (Fig. 22), and also occurs at Leknessund, Hersvik, and the northern edge of the Lifjell Peninsula.

Coarse, polymict conglomerate lies above the breccia, with a thin zone of finer mixed conglomerate and breccia containing thin red-brown sandstone interbeds forming a transitional zone. These sandstone beds are a common feature, found in Ytre Solund, Steinsundøy, and Utvær, and may represent initial influx of finer material transported the longest distance from the provenance, or reworking of local sand debris into distinct strata by initial

Fig. 23. Thick stratification of conglomerate, with exposed dip-slope bedding surfaces, southwestern Indre Solund. (This is near the type section of the Solund Conglomerate).

currents. The initial conglomerate deposits incorporate abundant breccia debris.

Sandstones within the conglomerate itself are lens-shaped in cross-section and are dispersed throughout the entire stratigraphic section, but are larger and more laterally persistent in higher parts of the section (Fig. 3). The sandstones can be traced discontinously along the southern boundary of the area from Ytre Solund to the Lifjell Peninsula, with other mappable sandstones irregulary distributed, as are innumerable unmappable thinner pebbly sandstone and sandstone horizons. The sandstones are variable, but most characteristically are coarse grained, with some pebble debris, and have either flat-stratification or very gently inclined cross-stratification.

The largest sandstone body is found on the southeast dip slope of Polletind, a large mountain in western Indre Solund, which apparently was laterally continous with another topographically isolated body to the west. This lens-shaped sandstone body is more than four kilometers wide, with a thickness of approximately 700 meters, although much fine conglomerate is intercalated. Other sandstones have similar cross-sectional configurations, ranging in size down to less than one meter in width.

The conglomerates are irregulary stratified, with thickness of stratification correlating roughly with coarseness of the clasts. Measurement of stratal thicknesses was unfeasible because of the steepness of outcrop walls, large thicknesses of strata, and inability to correlate over even short distances. The widely spaced bedding surfaces are abundantly exposed on the dip slopes of elevated areas, especially in the south, where erosion along bedding-plane faults has occurred. In the north, where the conglomerates are generally coarser and sandstones sparser, bedding surfaces are difficult to distinguish except from at distance (Fig. 23). To the east, on the Lifjell Peninsula, the conglomerate and sandstone are exceptionally well-indurated, perhaps as a result of movements along the Solund Fault, and exposed bedding surfaces are rare. In almost all cases, however, inspection of outcrops permits distinction of bedding through the orientation of flattened or elongate pebbles, common sandstone lenses, and subtle vertical variations in sorting and coarseness. The bedding surfaces in the conglomerates are rarely parallel or flat, but undulate and contain irregularities, with the strike of the same or adjacent bedding surfaces varying continously. Bedding thicknesses up to 100 meters of more or less homogeneous conglomerate are not uncommon. The bedding surfaces must record a significant alteration or pause in the depositional process.

PETROGRAPHY

Conglomerate

The Solund Conglomerate is a very polymict sediment, with at least thirty distinct pebble lithologies present. The writer undertook pebble counts throughout the area to determine variations of conglomerate composition as an aid to defining provenance, transport directions, and relative influxes of different lithologies in time and space. The sampling procedure consisted of counting 100 randomly selected clasts larger than four centimeters in diameter at 110 scattered localities (Fig. 24). Dispersal or distribution pattern maps for each pebble type, as well as petrogenically related types, were then constructed by contouring the percentage distributions, thus indicating visually the relative abundance of a pebble type at all localities. Dispersal maps are presented for the dominant pebble types, which show the principal distribution patterns, although approximately 40 separate dispersal maps were prepared. Some of the lithologic types are found in the Cambro-Silurian basement in the Solund area, as outlined in the chapter on «General geology of the Solund area».

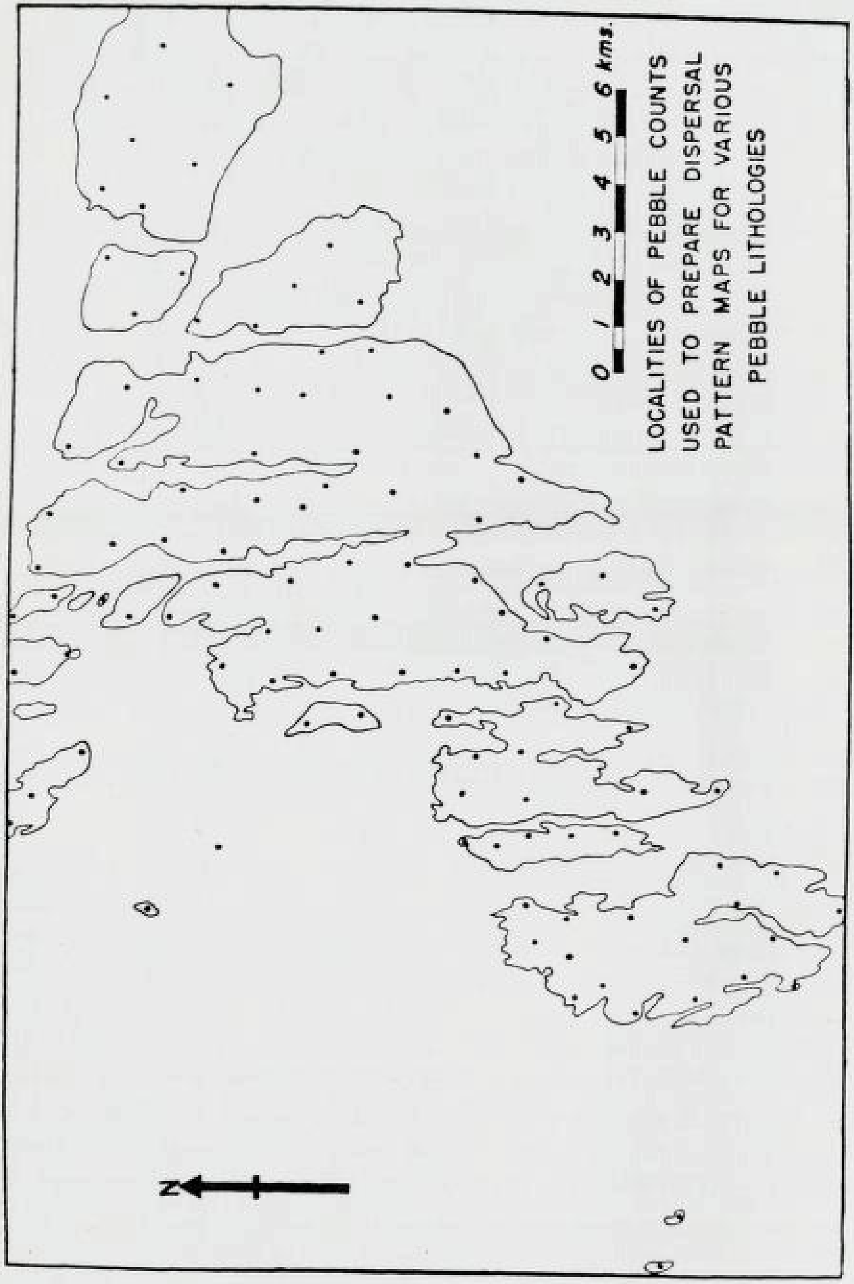

0 1 2 3 4 5 6 kms.
LOCALITIES OF PEBBLE COUNTS
USED TO PREPARE DISPERSAL
PATTERN MAPS FOR VARIOUS
PEBBLE LITHOLOGIES
N

Fig. 24.

It was hoped that the sequence of rock types eroded from the source area would be revealed, allowing valuable paleogeographic and paleotectonic conclusions to be drawn. Comparison of pebble distribution patterns with paleoccurent determinations, assuming relatively short transport distances for the coarse debris, would enable provenance geology to be determined. Unfortunately, the interpretive value of pebble dispersal data is somewhat limited in the Solund area because of the nature of the exposures, lack of well-defined stratigraphy, poor correlation over even short distances, and lack of lateral exposure of proven similar-aged strata in a north-south direction. Nevertheless, many of the apparent dispersal patterns are distinctive and helpful in paleogeographic analysis. The patterns reveal an extremely complex provenance, composed of abundant felsic and mafic plutonic and volcanic igneous rocks, large tracts of granite gneisses and amphibolites, abundant quartzites and graywackes, plus many other subordinate rock types. No clearly-defined sequence of stripping off of topmost low grade metasediments, progressing to higher grade metamorphic and then igneous rocks, is revealed in the vertical stratigraphic section of the Solund Conglomerate, although this type of progressive stripping of source areas is common in areas of relatively simple provenance geology (e.g., Sharp, 1948). The complexity of the Solund dispersal patterns may result from complicated provenance geology, indirect or complex transport to the site of deposition, reworking and movement of sediment in the depositional basin, complicated tectonic uplift of the provenance, or combinations of these factors.

Sedimentary pebbles

Sedimentary clasts consist of *graywackes* and *siltstones*, many of which display low grade metamorphism. Graywacke pebbles are primarily quartz wacke, with smaller amounts of sand-size detrital feldspar and lithic fragments scattered in a fine-grained, unrecrystallized matrix, identical to the quartz wacke found on the islands west of Ytre Solund (Fig. 7). Graywacke clasts comprise about 5—10 percent of the conglomerate, but increase locally in the southern half of Ytre Solund to more than 50 percent. They are generally completely absent along the northern edge of the area, from Ospa to the Lifjell Peninsula.

Interstratified with the graywacke is finer-grained siltstone of essentially similar composition and texture, with open framework packing, and abundant fine, unrecrystallized matrix. The «siltstone» wacke crops out in the basement of the islands west of Ytre Solund, and in southeastern Indre Solund near Kråkevåg, where it is phyllitic (Fig. 5). The siltstone also comprises about

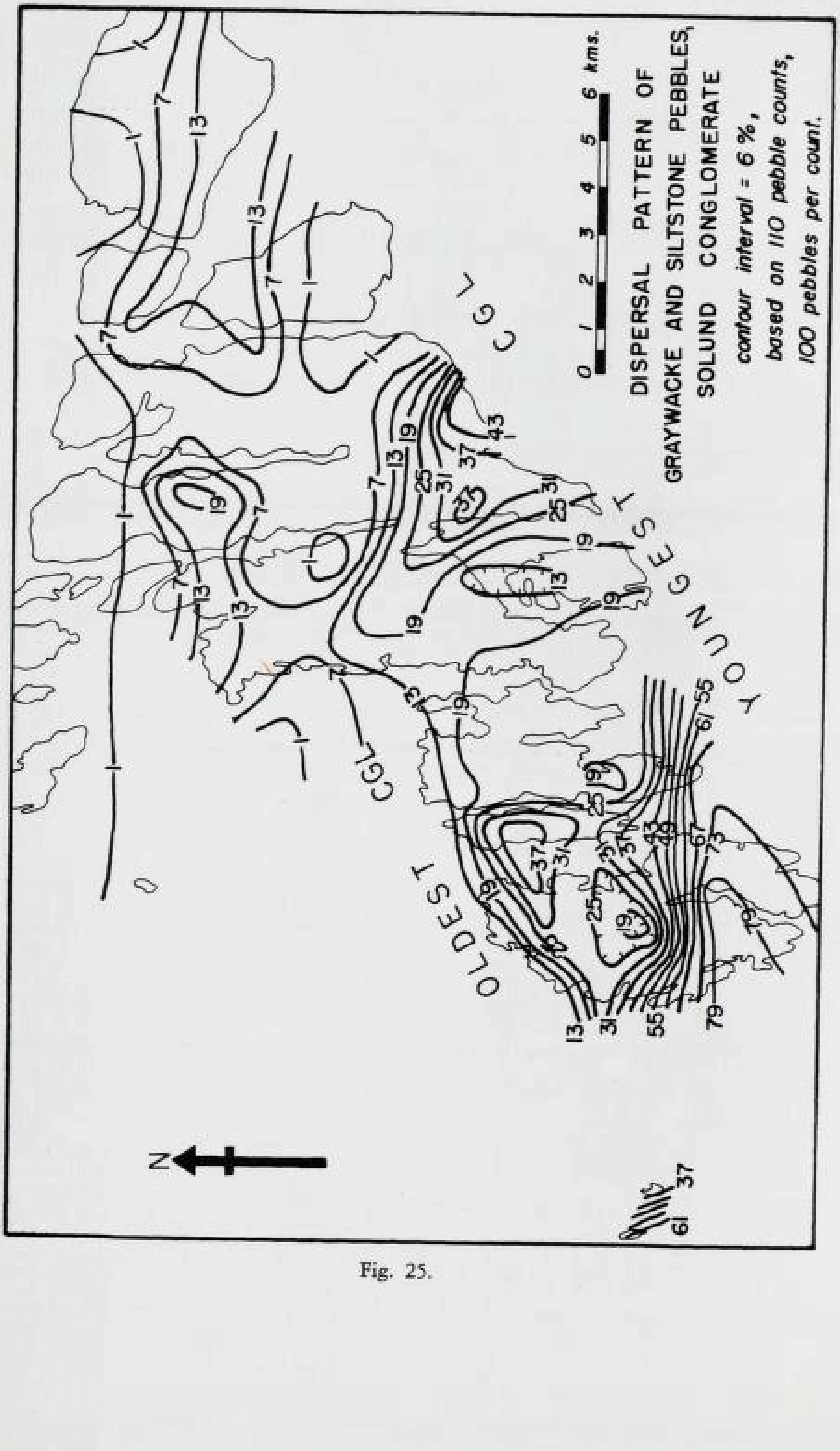

DISPERSAL PATTERN OF
GRAYWACKE AND SILTSTONE PEBBLES,
SOLUND CONGLOMERATE
contour interval = 6%,
based on 110 pebble counts,
100 pebbles per count.
0 1 2 3 4 5 6 kms.
OLDEST CGL
YOUNGEST CGL
N
61
37
1
7
13
19
25
31
37
43
49
55
61
67
73
79

Fig. 25.

5—10 percent of the conglomerate, but locally reaches 25 percent west of Kråkevåg, and increases in southern Ytre Solund to about 45 percent; it is generally lacking in the north and northwest.

A single pebble dispersal map for the combined percentages of the graywacke and siltstone pebbles (as they appear to be intimately associated in the field) is presented in Figure 25. The dispersal pattern indicates that the conglomerate in the southwestern part of the area is dominated by these pebble types, and that they are lacking in the northernmost areas, or the oldest conglomerate. The relative percentage of these clasts tends to increase abruptly in younger strata, however, reaching 85 percent near Kolgrov on Ytre Solund.

Igneous pebbles

Granitic pebbles range in composition from true granite to granodiorite, with syenitic types less common. Many of these clasts resemble the Sogneskollen Granodiorite, but others are quite similar compositionally to granite gneisses found to the south of the Sognesjøen, in the «basal gneiss.» Many of the granitic lithologies have a slight foliation in thin section, resulting from the crude alignment of elongate crystals. Minor minerals are primarily muscovite, with less biotite and opaque grains, and a tight, interlocking, well-sutured crystalline texture is typical. The various granitic types have been grouped together in one dispersal pattern map (Fig. 26), which indicates prevailing amounts of 5—15 percent, but with less amounts locally and complete absence in the extreme southwest.

Granite pegmatite pebbles have simple compositions, containing quartz and feldspar with minor amounts of muscovite-sericite. Graphic-type intergrowths are found, but are less common than simple crystalline textures. The major feldspar is orthoclase, with microcline, perthite, and acidic plagioclase also present. Sericitic alterations, as well as calcite stringers and veins, are common. The dispersal pattern is very irregular, with the amounts varying from 0—12 percent; however, the pattern contains large, linear north-south trending zones where pegmatite is lacking. In the extreme southwest and west, it is not found in the conglomerate.

Pebbles of *fine-grained porphyritic felsic igneous rocks* are scattered in small amounts throughout most of the Solund Conglomerate (0—8 percent). Textures noted in thin section include microlaminated flow structures, shard structures, spherulites, and corroded phenocrysts. The fine matrices are holocrystalline, composed of irregular crystals of feldspar and quartz, with accessory sericite; in some cases, however, the matrix may have resulted from

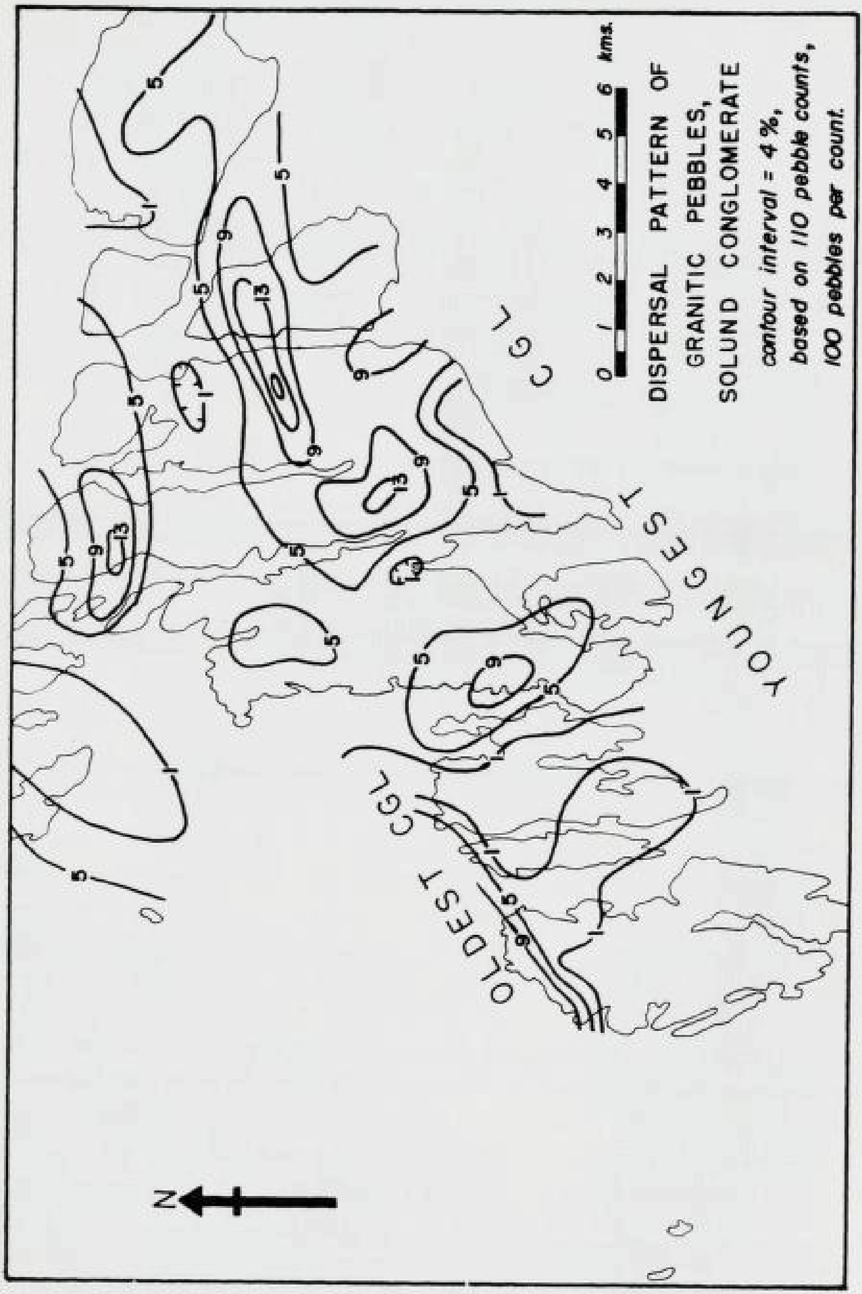

DISPERSAL PATTERN OF
GRANITIC PEBBLES,
SOLUND CONGLOMERATE
contour interval = 4 %,
based on 110 pebble counts,
100 pebbles per count.
0 1 2 3 4 5 6 kms.
YOUNGEST CGL
OLDEST CGL
N

Fig. 26.

devitrification of glass. Phenocrysts are composed of feldspar, generally orthoclase, and are scattered irregularly or arranged in laminae. These rocks range from rhyolite to rhyodacite, of both pyroclastic and flow origin. The pebbles are generally absent along the northern edge of the area, the extreme southwest and west, and in the central southern parts; maxima occur in Northern Losna and the south-western part of the Lifjell Peninsula (6 percent), east of Hersvik (8 percent), and north of Polletind (5 percent). The clasts are similar to fine-grained acidic igneous rocks found in small quantities in the basement along the northern edge of the Lifjell Peninsula.

Plutonic igneous rocks of intermediate composition include quartz diorites, diorites, and monzonites, with porphyritic varieties common. Ferromagnesian mineral content averages 15—25 percent, and is primarily hornblende, with abundant chlorite as an alteration product. The feldspar is generally oligoclase-andesine, with orthoclase occurring in some varieties as large, altered, poikilitic grains in which other minerals are embedded. Quartz is found as interstitial grains in some varieties. The hornblende is generally finer-grained, forming irregular plates or prisms which may be fibrous. Porphyritic types generally contain severely altered plagioclase or orthoclase as phenocrysts. Field identification was based primarily on percentage of dark minerals, with a large range of grain sizes noted. The diorite pebbles are abundant on the Lifjell Peninsula, Skorpa, and Losna, comprising up to 20 percent of the conglomerate clasts, but are completely lacking west of Dombefjord and south of Krakhelle.

Varieties of *gabbroic* pebbles are complex in texture and composition, with abundant saussuritization of plagioclase and uralitization of pyroxene. The sizes of crystals range from fine-grained (grading into basalts) to porphyritic, to extremely coarse-grained varieties containing individual grains up to 5 centimeters in length. Plagioclase occurs generally as euhedral laths, with diabasic texture common. Pyroxene is the most common ferromagnesian mineral, with hornblende found often as an alteration product or sometimes as an interstitial constituent. Severely altered olivine was noted in one thin section; opaque minerals are generally uncommon. The dispersal pattern of the gabbroic pebbles indicates a fairly uniform and widespread distribution, with amounts ranging from 5—15 percent, but with local areas where it is lacking, and local «highs» up to 35 percent along the southern edge of the outcrop area (Fig. 27).

Some of the gabbros resemble closely the gabbroic basement rocks found on Lågøy. A special variety of *very coarse-grained gabbro* was counted separately

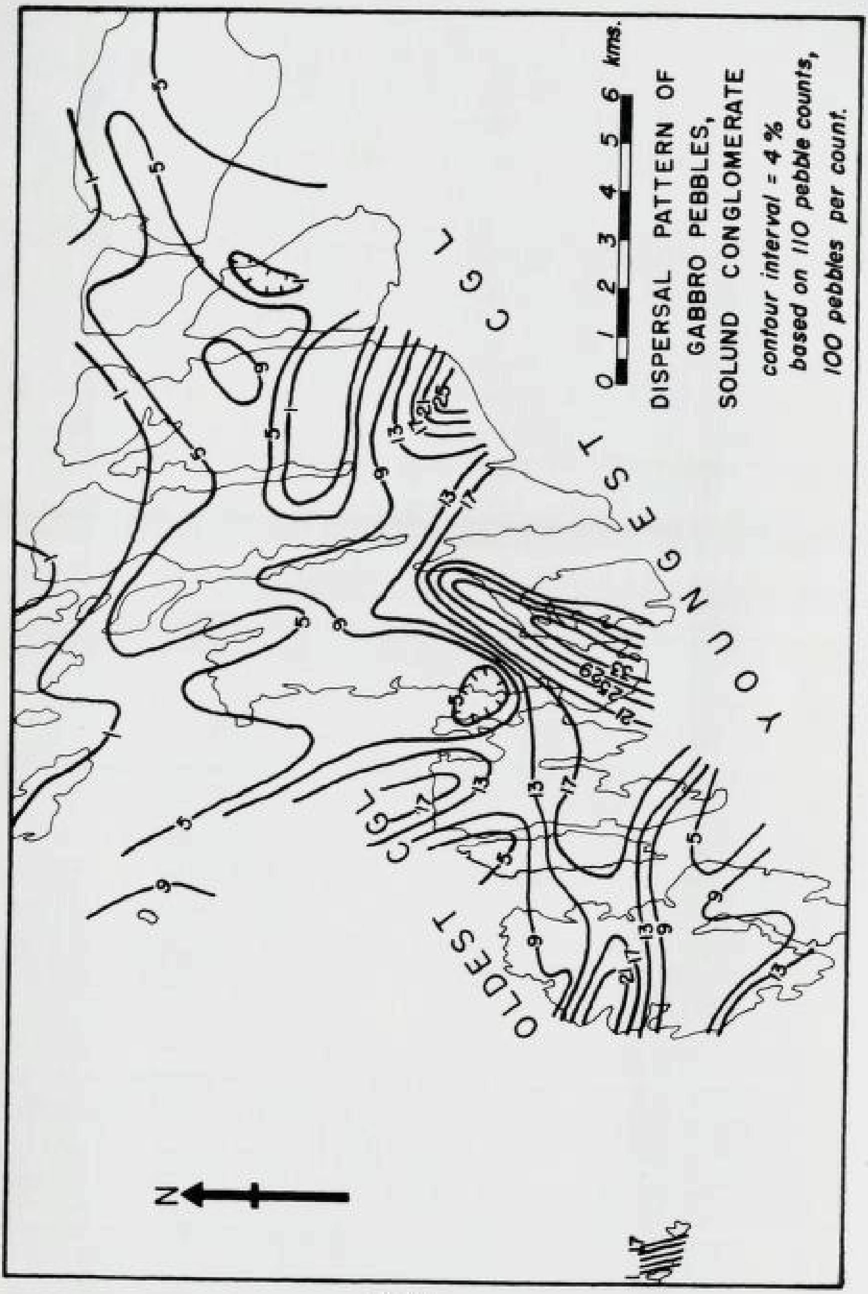

0 1 2 3 4 5 6 kms.
DISPERSAL PATTERN OF
GABBRO PEBBLES,
SOLUND CONGLOMERATE
contour interval = 4 %
based on 110 pebble counts,
100 pebbles per count.
YOUNGEST CGL
OLDEST CGL
N
1
5
9
13
17
21
25
29
33

Fig. 27.

and shows an interesting dispersal pattern (Fig. 28). The separate linear areas with amounts up to 15 percent, between areas where this pebble type is completely lacking, seems to be indicative of transport processes, as discussed later.. This rock type is found in the basement south of Strand, in northwestern Indre Solund.

Basaltic pebbles are typically quite altered, thus obscuring their textures and compositions. They are composed of calcic plagioclase laths and pyroxene, and texturally grade into diabases and gabbros. Foliated basalts, or greenschists, are common, and are included with nonmetamorphosed basalts. The Solund Conglomerate basalt clasts are generally not porphyritic, and resemble basaltic rocks found in the basement south of Lågøyfjord. Textures are primarily doleritic, with pyroxene interstitial between plagioclase laths. The dispersal pattern map (Fig. 29) indicates widespread basalt distribution, with a 5—15 percent abundance in the east, increasing westward to 31 percent near Gjønnevåg in central western Ytre Solund, and 37 percent at Utvær. Rare pebbles of jasper-like rock and quartz-pyroxene rock comprise less than one percent of the conglomerate. Both are associated with basalts in the basement south of Lågøyfjord, with the latter type apparently derived from the interstices of adjacent pillows.

A common constituent of the conglomerate is coarse, undulatory, well-sutured, interlocking *quartz aggregate* pebbles of probable vein origin. The clasts are distinguished in the field by white, vitreous, coarsely granular quartzose surfaces. The quartz has abundant bubble inclusions, minor cataclasis along grain boundaries, and stringers of sericite in fractures. The widespread vein quartz pebbles are found in abruptly changing amounts of 0—10 percent, with the maximum abundance being 14 percent in Ytre Solund.

Metamorphic pebbles

Various types of metamorphic clasts are found in the Solund Conglomerate, with *feldspathic quartzites* being most abundant. These quartzites have prominent foliation from the alignment of muscovite flakes parallel to preferential elongation of quartz grains. Quartz is the dominant mineral (50—95 percent), and is characteristically very strained and elongated, with sutured grain boundaries. Feldspar occurs as unrecrystallized, sericitized porphyroblasts, not elongated parallel to foliation; some specimens have large amounts of feldspar (more than 50 percent) and may represent metamorphosed felsic intrusives. The muscovite is of variable size, either scattered through the quartzo-feldspathic rock or aligned into laminae or irregular stringers. Commonly it is bent and distorted, indicating post-crystallization deformation.

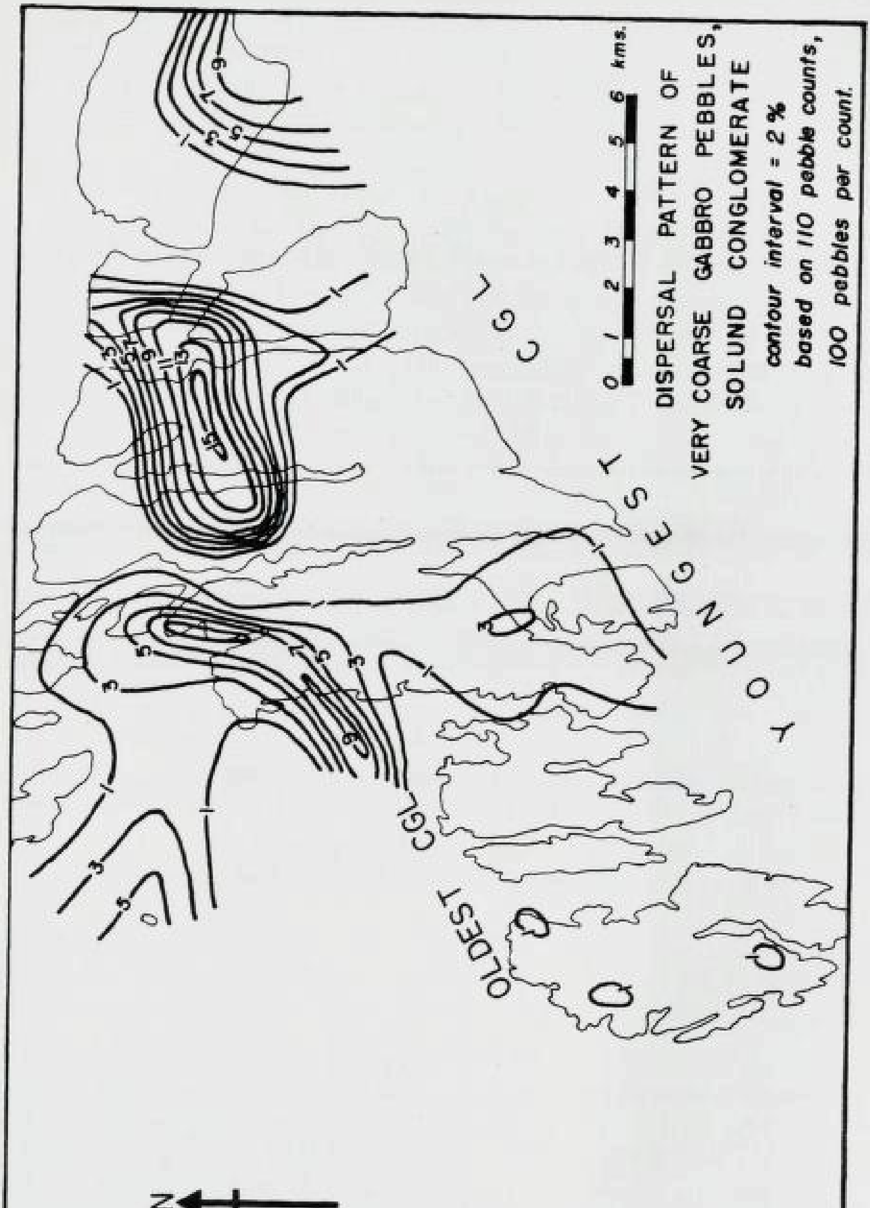

DISPERSAL PATTERN OF
VERY COARSE GABBRO PEBBLES,
SOLUND CONGLOMERATE
contour interval = 2 %
based on 110 pebble counts,
100 pebbles per count.
0 1 2 3 4 5 6 kms.
OLDEST CGL
YOUNGEST CGL
N
1
3
5
7
9
11
13
15

Fig. 28.

Minor constituents include garnet, chlorite, and opaque minerals, with uncommon lithic quartzite clasts.

Depending upon the amount and arrangement of muscovite flakes, the feldspathic quartzites have either massive (unfoliated), slightly foliated (elongation of quartz, but little muscovite), schistose (abundant scattered parallel muscovite flakes), or gneissose (muscovite flakes arranged in parallel laminae alternating with quartzo-feldspathic bands) textures. These different quartzite pebbles are distinguished easily in the field, although representing a gradational series. Individual dispersal patterns have been prepared for each type, but whether they represent separate or complexly interstratified and laterally gradational provenance quartzites is difficult to determine. The varieties of quartzites appear to be intermixed where observed in basement rocks, such as at Leknessund and Hersvik, but do show relatively distinct areal variations as pebbles in the Devonian conglomerate.

The massive quartzite is least abundant in the conglomerate, being found only on Skorpa, where it comprises 1—10 percent of the clasts, and on the Lifjell Peninsula, where it comprises up to 19 percent at the easternmost Devonian exposures. The mildly foliated variety comprises about 15—20 percent of the pebbles throughout the area, although decreasing regularly to the south in younger strata; it increases northward to 30—35 percent, to over 60 percent in the basal conglomerate-breccia at Leknessund and along the northern edge of the Lifjell Peninsula. The schistose variety is widely distributed, generally composing 10—25 percent of the conglomerate, forms very distinct north-south trending highs, and is less abundant (0—10 percent) in the eastern and western extremities of the outcrop area. The gneissose variety has sporadic distribution, forming high percentages in the central southern part of the area (35 percent), although generally forming only 5—20 percent. It is absent from large areas, especially along the northern, western and southwestern edges of the area.

Figure 30 presents a combined dispersal pattern map for all of the *feldspathic quartzite* varieties, and indicates an average quartzite pebble abundance of 25—60 percent throughout the entire area except for the southern part of Ytre Solund, where it is lacking. The percentage decreases to the south, with highest values along the northern edge of the area (almost 90 percent at Leknessund).

Non-feldspathic quartzites, composed of highly sutured, fine-grained, non-micaceous quartz mosaics, have very limited distribution as pebbles in the Solund Conglomerate. This pebble type appears to be recrystallized mylonite, is microlaminated with quartz grains elongated parallel to the lamination,

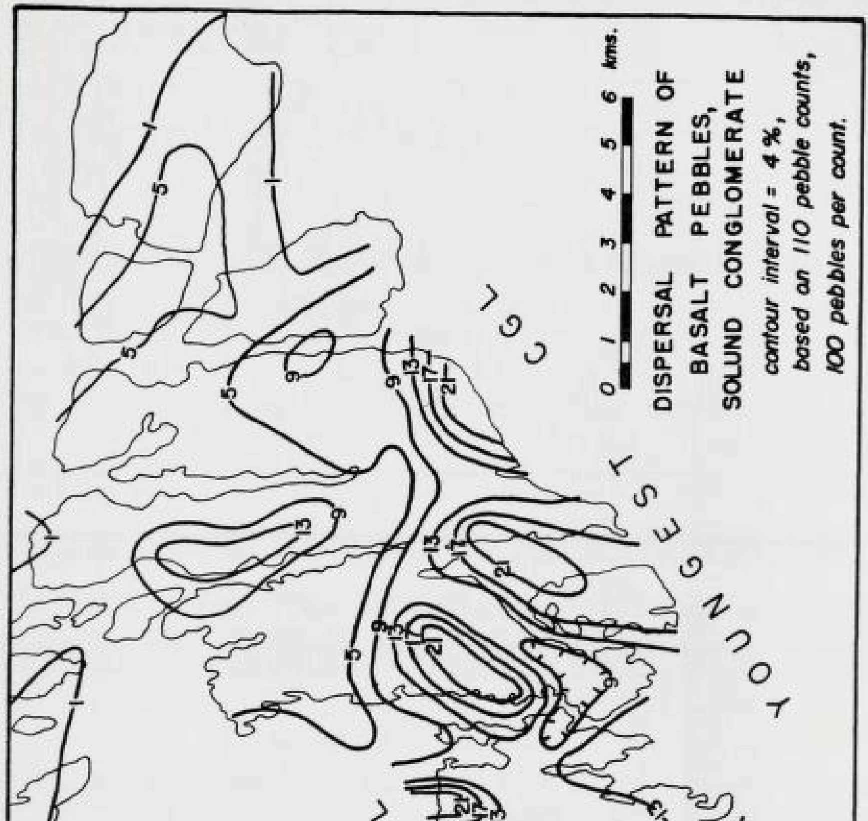

DISPERSAL PATTERN OF
BASALT PEBBLES,
SOLUND CONGLOMERATE
contour interval = 4 %,
based on 110 pebble counts,
100 pebbles per count.
0 1 2 3 4 5 6 kms.
YOUNGEST CGL
OLDEST CGL
N
1
5
9
13
17
21
25
29
33

Fig. 29.

and contains minor amounts of opaque grains. A similar rock crops out in the basement as interstratified quartzite lenses in phyllites on Losna. As pebbles, these quartzites occur locally, averaging 1—3 percent of the clast composition, but reaching as much as 5 percent at Tungodden in southwestern Steinsundøy.

Clasts of *quartzite metaconglomerate* similar to the basement metaconglomerate cropping out near Hersvik are widespread in the Devonian conglomerate. These pebbles occur sporadically, generally amounting to 0—8 percent of the clasts, but locally are as much as 12 percent in northern Ytre Solund. They are generally lacking east of Krakhellesund and along the southern edge of the area. However, in one stratigraphic zone along the southern edge of Skorpa, they comprise 100 percent of the conglomerate clasts. The composition of the rounded, elongate fragments in the metaconglomerate is largely quartzose, with clasts composed primarily of fine quartzite, vein quartz, and irregular quartzose aggregates in a quartzo-feldspathic matrix. Other subordinate clasts found include porphyritic rhyolite, feldspar, quartz-mica schist, and occasional irregular quartz-chlorite fragments. Variable amounts of sericite and muscovite occur in the matrix, with scattered opaque minerals. With decreasing grain size, the metaconglomerate grades into the feldspathic quartzites.

Less than 3 percent of *chlorite schist* and coarse-grained *mica schist* clasts occur in a few widely scattered localities. The chlorite schist distribution is restricted, found only on Losna and the northern edge of the Lifjell Peninsula. Coarse mica schist, composed of coarse muscovite flakes and minor amounts of quartz, occurs in minor amounts in the conglomerate of western Skorpa, Færøy—Buskøy—Leknessund, Ospa—Gåsvær, and along the basal sedimentary contact from Tveranger to the northern edge of Steinsundøy. It occurs in the Cambro-Silurian basement at the northwest edge of the Lifjell Peninsula. These two pebble types are undoubtedly limited in occurrence because of their low resistance to abrasion during transport. Abundant coarse mica flakes and chloritic fragments found in the sandstones support this contention.

High grade metamorphic clasts include felsic gneisses, with compositions varying from granite to granodiorite to syenite, and amphibolites, with less common amphibolite gneisses. The amphibolites and felsic gneisses are interstratified in many coarse pebbles, with granite pegmatite veins also associated, suggesting a close relationship of these rock types in the source area. Textures of the granitic gneiss pebbles result from irregular parallel laminae of biotite or muscovite, with minor amounts of chlorite. These gneisses are widely distributed in the conglomerate, but sporadic in occurrence. The maximum relative percentage of clasts that they comprise is 23 percent; they decrease in abun-

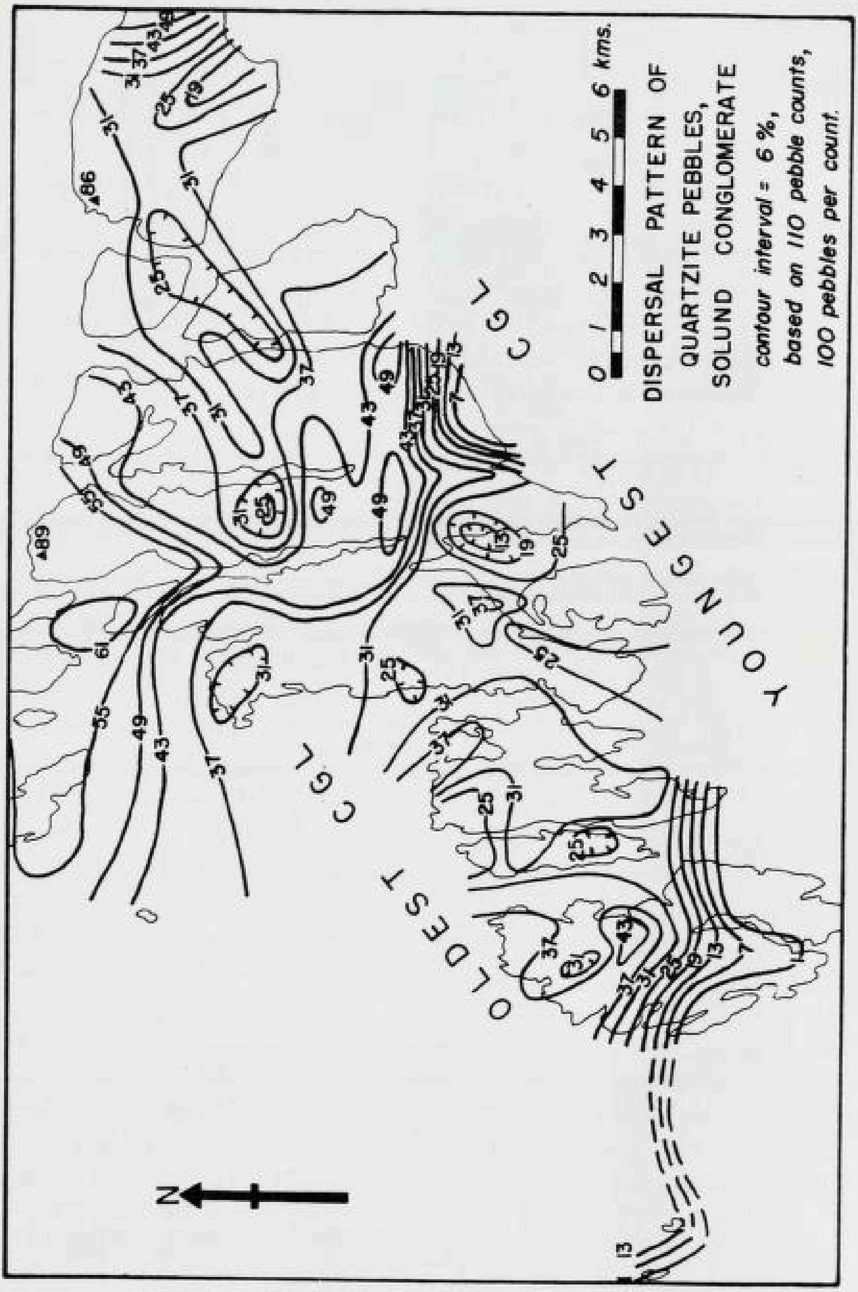

DISPERSAL PATTERN OF
QUARTZITE PEBBLES,
SOLUND CONGLOMERATE
contour interval = 6 %,
based on 110 pebble counts,
100 pebbles per count.
0 1 2 3 4 5 6 kms.
N
YOUNGEST CGL
OLDEST CGL
86
89
61
55
49
43
37
31
25
19
13

Fig. 30.

dance to the south, and are lacking completely in southern Ytre Solund, Utvær, Begla, southern Ravnøy, and southern Steinsundøy. Some samples are similar to gneissic parts of the Sogneskollen Granodiorite, but most are similar to the large tracts of "basal gneiss" found to the south of Sognesjøen.

Amphibolite clasts are characterized by well-developed foliation formed by the parallel orientation of elongate amphibolite grains. Their composition is typically intermediate plagioclase and amphibole (mostly hornblende), with variable minor amounts of chlorite, garnet, apatite and scattered opaque minerals. The feldspars are sericitized, and the chlorites commonly have "Berlin blue" interference colors. Amphibolite gneiss pebbles are found only along the northern edge of the area, where they amount to 5—6 percent of the clasts in Ospa—Færøy—Buskøy and northeastern Indre Solund. The non-banded amphibolites occur throughout the area in amounts ranging from 5—19 percent. They diminish in abundance toward the southern edge of the area, and are almost completely lacking west of Indre Solund.

A combined dispersal pattern map for granitic gneisses and amphibolites is presented in Figure 31. Consistent decrease in abundance of high grade metamorphic pebbles toward the south and southwest is noted, with highest values along the northern edge.

Rare pebbles of *talc schist* were found in the eastern parts of the area, comprising less than one percent of the conglomerate. The schists were composed of fine-grained foliated masses of talc flakes and scattered opaque minerals. Talc schist has been reported in basement rocks east of the Lifjell Peninsula.

Summary

The Solund Conglomerate has been shown to be a mixture of various sedimentary, igneous and metamorphic clasts. Three gross conglomerate lithologies can be discerned on the basis of the pebble dispersal patterns: (1) conglomerate composed almost wholly of graywacke and siltstone pebbles, found in the extreme southwestern part of the present Devonian area; (2) conglomerate dominated by high percentages of feldspathic quartzite pebbles, found along the northern edge of the area; and (3) polymict conglomerate, with no single pebble lithology exceeding 30 percent of the total pebble composition. In a general manner, the pebble distribution is a reflection of the adjacent basement geology (see Fig. 8), with graywacke and siltstone clasts abundant to the southwest, quartzites to the north, basalts and gabbros more abundant to the southwest, and granite and rhyolite pebbles more abundant to the east. The reader must be reminded that the percentage abundance of each pebble type depends upon that of other pebble types, and that the percentages thus indicate only relative abundance.

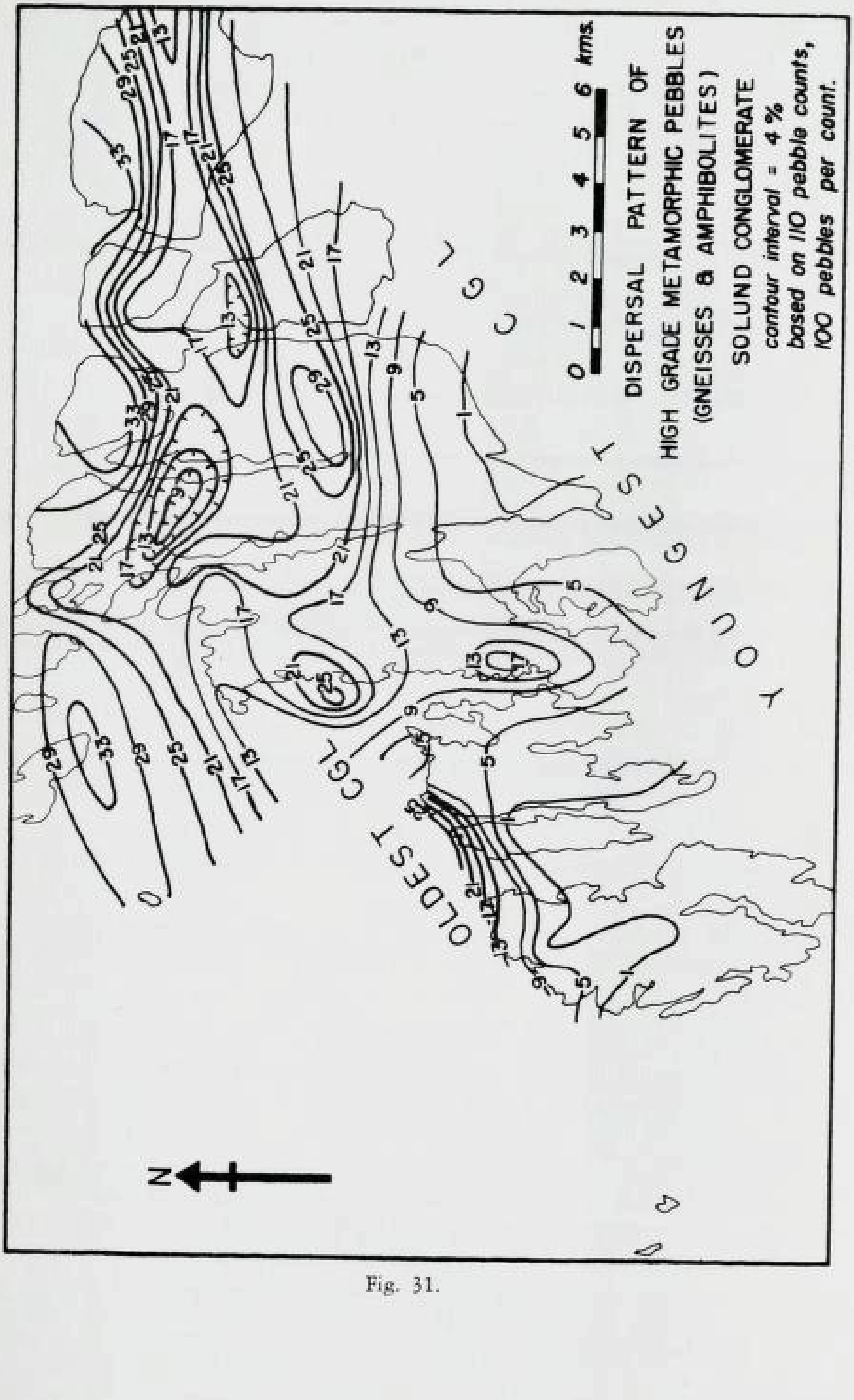

0 1 2 3 4 5 6 kms.
DISPERSAL PATTERN OF
HIGH GRADE METAMORPHIC PEBBLES
(GNEISSES & AMPHIBOLITES)
SOLUND CONGLOMERATE
contour interval = 4 %
based on 110 pebble counts,
100 pebbles per count.
YOUNGEST CGL
OLDEST CGL
N

Fig. 31.

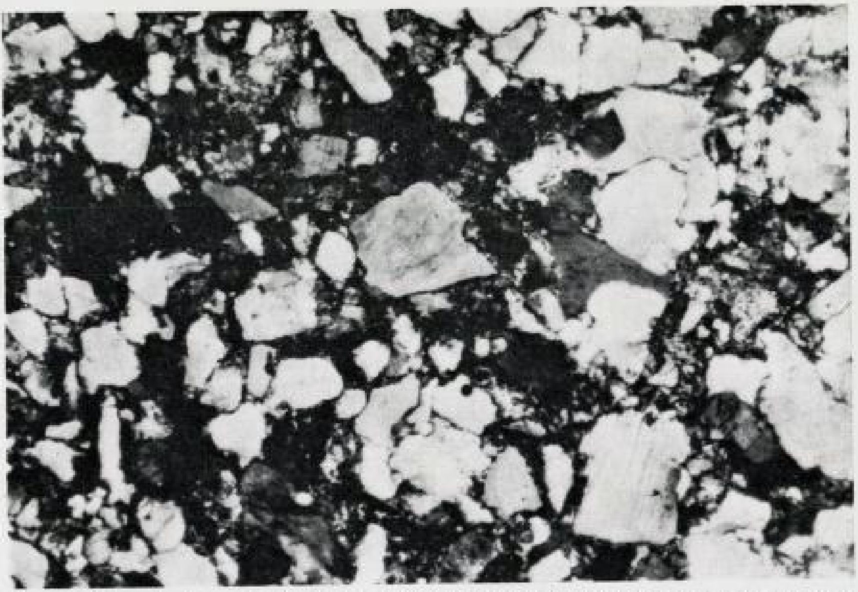


Fig. 32. Microphotograph of typical sandstone lithology, eastern Lifjell Peninsula (x30). Note poor sorting and rounding of clasts. (Crossed nicols; most of lighter grains quartz, orthoclase and plagioclase feldspar).

Sandstone

Because the wide compositional range of the Solund sandstones is dependent on grain size, which has been demonstrated in other areas of Old Red Sandstone (Allen, 1962b), and resultant difficulty in arranging field sampling procedures, no systematic areal study of sandstone composition by modal analysis was attempted. Instead, only the general lithologic and textural characteristics have been determined, with gross variations emphasized. The coarser sandstones contain higher percentages of lithic fragments, which are distributed in the sandstones approximately similarly to their distribution in the conglomerates. The fine-grained sandstones have higher relative percentages of mineral grains, predominantly quartz, feldspars, and muscovite.

According to the sandstone classification of Williams et. al. (1954), most of the coarser sandstones in the Solund Devonian are lithic arenites; the finer varieties are quartzo-feldspathic arenites, with a compositional range including feldspathic, arkosic, and lithic arenites. The sandstones are compositionally immature, with abundant feldspar and labile rock fragments. Texturally they are submature to mature (Folk, 1954), based on their low rounding and low matrix percentage (Fig. 32). The matrix is typically less than 15 percent, and is composed of silt-sized quartzo-feldspathic debris with considerable sericite. The sandstones normally weather to a light red-brown color, but on fresh surfaces are either pinkish or bluish gray in color. The sandstones, like the conglomerate, are extremely well indurated, such that sampling commonly is difficult.

In thin section, the rock is closely packed and tightly bound, having a high «condensation» value, or large number of contacts per grain (Pettijohn, 1957b). Some cataclasis of grain boundaries and fracturing of clasts, with microfaulting, is present, probably as a result of compaction and compression. Interstices and microfractures are filled with crystalline calcite cement, which is prominently twinned and typically distorted, indicating post-crystallization stress. Fine-grained sericite or microcrystalline calcite mosaic fills some pore spaces, with chlorite less common, apparently from authigenic growth or load metamorphism. Fine hematitic and clayey dust is abundant along grain contacts and on grain surfaces, and is probably responsible for the red-brown and pink colors of the rock in outcrop.

Analysis of a sandstone from Polletind in western Indre Solund (C. F. Kolderup, 1926a) indicates a bulk chemical composition most closely resembling that of some graywackes, when compared with published average compositions of various types (Table 1). In comparison with subgraywackes, the Polletind sandstone contains more MnO, MgO, FeO, Fe_2O_3, CaO, Na_2O, and K_2O, with less SiO_2. In comparison with average arkoses, it contains 8 percent less silica, less Na_2O and K_2O, but more Al_2O_3, FeO, Fe_2O_3, CaO, and MgO, probably reflecting the admixture of considerable amounts of ferromagnesian minerals and calcic plagioclase in the Solund sandstones. Thus, the compositional immaturity of the sandstones, including abundant labile rocks fragments, is substantiated by having a bulk chemistry similar to that published for graywackes.

The major clastic mineral grains are quartz, feldspars, and muscovite, with lesser amounts of chlorite, amphiboles, pyroxenes, uralitic fibrous pyroxene, magnetite, other opaque minerals, garnet, epidote, apatite, and less common olivine, sphene and zircon. Quartz is dominant, ranging generally from 30 to 75 percent of the clasts, and commonly is bubbly. The most common feldspars are orthoclase and sodic plagioclase, with lesser amounts of perthites and calcic plagioclase; microcline is generally lacking. Potassium feldspars are commonly sericitized, with other feldspars generally fresh and not severely altered or weathered. Muscovite is ubiquitous, and locally so abundant that it gives the sandstone a very micaceous appearance. The muscovite flakes are oriented parallel to stratification and are irregularly scattered, rather than arranged in distinct laminae. They are invariably bent, flexed or broken, indicating considerable post-depositional compaction of the sediment. Chlorite occurs as irregular fragments, locally in radial clusters filling interstices. Some has resulted from alteration of pyroxenes and amphiboles, which are commonly present in small percentages (0—10). Epidote and garnet are common in the eastern part of the area, but never comprise more than a few percent of the clasts.

	A Graywacke	B Arkose	C Polletind
SiO_2	64.7	76.37	67.92
TiO_2	0.5	0.41	0.82
Al_2O_3	14.8	10.63	12.89
Fe_2O_3	1.5	2.12	3.73
FeO	3.9	1.22	2.42
MnO	0.1	0.25	0.10
MgO	2.2	0.23	2.69
CaO	3.1	1.30	3.84
Na_2O	3.1	1.84	1.82
K_2O	1.9	4.99	1.59
P_2O_5	0.2	0.21	0.06
SO_3	0.4		
$CO_2{}^+$	1.3	0.54	1.28
H_2O	2.4	0.83	0.89
H_2O—	0.7		0.17
S	0.2		0.05

Table 1. Comparison of chemical composition of sandstone from Solund area with average compositions of graywacke and arkose.

A. Average composition of 23 graywackes (Pettijohn, 1957b, p. 307).

B. Average composition of 5 arkoses (Pettijohn, 1957b, p. 324).

C. Composition of sandstone from Polletind, western Indre Solund, Norway (C. F. Kolderup, 1926a, p. 33).

Lithic fragments are similar to those found in the conglomerate, but with more chlorite and mica schist fragments, and less plutonic igneous and coarse-grained metamorphic rock fragments. This is apparently a result of rapid abrasion of labile rocks to finer grains, and the abrasion or weathering of coarse grained rocks to mineral fragments. Both felsic and mafic extrusive lithic fragments are abundant, as are fine granular quartzo-feldspathic(?) clasts probably derived from devitrification of glassy or partly glassy igneous rocks. In coarser sandstones, granitic, granitic gneiss, and dioritic lithic clasts are common. Mosaic quartzites and vein quartz occur in addition to the more common feldspathic quartzite fragments. A variety of metasedimentary fragments of low grade metamorphism are found, including graywacke, siltstone, and chloritic phyllites and slates.

The general distribution of clasts suggests at least three distinct sandstone lithologies: (1) to the northwest, abundance of feldspathic quartzite, vein quartz, quartz, and sodic plagioclase clasts, (2) to the extreme east, abundance of orthoclase, perthite, and granitic gneiss clasts, and (3) to the extreme southwest (southern Ytre Solund and Utvær), abundance of quartz and sedimentary rock clasts, with higher matrix percentage at Utvær. Sandstones in the rest of the outcrop area have well-mixed compositions that are not lithologically distinctive.

Igneous rocks

C. F. Kolderup described in detail the petrography and occurrence of igneous rock bodies in the Hersvik area of northwestern Indre Solund (1925b, 1926a, 1926b). A large, flat, lens-shaped body of gabbroic rock crops out as several erosionally isolated parts of what may have been a continuous mass, with three parts found on the island of Hugøy and just south of it on the west side of Hagefjord, and five separated masses east and south of Hersvik (Fig. 3). Kolderup calculated the maximum thickness to be about 80 meters east of Hersvik, the gabbro thinning to the south and east to about 30 meters or less. The gabbro overlies Devonian conglomerate, and is in turn overlain by stratigraphically younger conglomerate; parts of the upper and lower contacts are movement zones, which suggested emplacement of the gabbro by thrusting from the west or northwest into the younger conglomerate.

The gabbroic bodies are complex, being composed primarily of gabbro somewhat similar to that on Lågøy, but having also large brecciated masses, some vertical fractures filled with red sandstone, brecciated phyllite inclusions, abundant epidote veins, and some irregular granitic masses and veins (C. F. Kolderup). In addition, the present writer found abundant irregular inclusions of fine-grained felsic igneous rocks with preserved flow structures, "floating" in gabbroic matrix. South and east of Hersvik, both upper and lower contacts of the gabbro and conglomerate appear to be movement horizons, but do not suggest a great deal of displacement — there is little mylonitization or disturbance of conglomerate.

In the area of gabbro occurrence, smaller, thinner, irregular lens-shaped bodies of felsic igneous rocks occur, which on the basis of comparative petrology and chemical composition, were classified as quartz keratophyres (Fig. 3; C. F. Kolderup, 1926a). About one kilometer south of Hersvik, five distinct layers up to 12 meters thick are crudely interstratified with conglomerate; the writer found another body about one kilometer north of Hersvik, and other smaller, irregular masses. Some of the bodies have distinct flow structures, others are spherulitic, while still others are irregular breccia accumulations, suggesting tuffaceous origin. In the north-central part of the area, mesoscopic joints are filled with similar, fine-grained porphyritic igneous rocks, suggesting that part of the keratophyre was intrusive in the area. Phenocrysts in the keratophyre consist of microcline, microperthite, albite, and some quartz, with the groundmass composed of alkali feldspars, quartz and magnetite, with lesser amounts of ilmenite, muscovite, biotite, chlorite and epidote (C. F. Kolderup). Considerable chemical variation exists between the various keratophyre bodies, especially with respect to SiO_2, Al_2O_3, and alkali components.

The writer suggests the possibility of an intrusive rather than thrust origin for the gabbro, although this is based on limited field and petrologic study. The following observations support this hypothesis: (1) the gabbro contacts indicate little or no movement along these horizons; minor dislocation can be explained by slippage along the lithologic contacts during arching of the Lågøyfjord anticline, an origin similar to the bedding-plane faults within the conglomerate. Thrust origin should have resulted in greater deformation along all parts of the contacts. (2) The gabbro body is concordant within the conglomerate stratification, and thins at its extremities. Thrust origin requires shoving of the gabbro into the conglomerate by a wedging action, with a minimum of 10,000 feet of overlying conglomerate. (3) Some lateral contacts of the gabbro with conglomerate are dike-like, with vertical contacts and small apophyses or tongues of gabbro extending outward into the conglomerate. (4) The keratophyre and gabbro occur together near the crest of the major anticline, suggesting perhaps a close relationship between them and the fold. Keratophyre inclusions in the gabbro, as well as veins and irregular masses of granite in the gabbro, suggest origin of the keratophyre as a differentiation product of a more mafic magma. The gabbro contains potassium feldspar locally, and is similar to an earlier Cambro-Silurian gabbro on Lågøy, indicating the presence of gabbroic magma in this area previously. (5) The gabbros on the east and west sides of Hagefjord occur at different stratigraphic levels; this can be explained by two intrusives at different levels, rather than by hypothesizing a vertical fault running under the Hagefjord (C. F. Kolderup, 1926a). In fact, the writer found a smaller concordant gabbroic mass about two kilometers south of Hersvik, at a higher stratigraphic level, thus indicating the multiple occurrence of gabbro.

It seems plausible that during folding of the Solund area, fissures developed in basement rocks permitted gabbroic magma to rise and intrude the conglomerate along bedding surfaces as sills in the crestal part of the anticline. The keratophyre may have come to the surface earlier as small flows or pyroclastic accumulations, with fragments of it and basement phyllites carried upward by the gabbro as xenoliths during later intrusion.

SEDIMENTOLOGY

Sedimentary structures

Background

The coarse conglomerates, comprising the greatest thickness of the Solund Devonian sediments, are generally lacking in internal as well as bed surface sedimentary structures. The sandstone lenses within the conglomerates are marked by either flat-stratification or very low inclination trough cross-stratification. In areas of thicker sandstone accumulation, however, a rich suite of sedimentary structures is present, dominated by cross-stratification.

The flow regime concept will be used here as defined by Simons and Richardson (1961), in which the flow generating various bed forms has been classified into upper- and lower-flow regimes. With lower-flow regime, ripples and dunes form, flow resistance is high, the transportation rate of bed material is low, water surface undulations are out of phase with bed undulations, and segregation of material occurs. With upper-flow regime, plane beds and antidunes form, flow resistance is low, the transportation rate of bed material is high, water surface and bed undulations are in phase, and segregation of material is negligible. Important interrelated variables that affect bed forms include velocity, slope, fluid viscosity, size distribution of bed materials, and the concentration of very fine sediment. Many other factors are involved, as summarized by Simons et.al. (1965).

Flat-stratification

The sandstone areas consist primarily of alternating cross-stratified and flat-stratified (horizontally stratified) sets or cosets of sediment. Sandstone lenses in both fine and coarse conglomerates are commonly flat-stratified rather than cross-stratified or ripple marked.

Experimental and modern sediment studies indicate that flat- or planar-stratification is formed in the upper-flow regime, and is common in many fluvial upper-flow environments (Harms and Fahnestock, 1965). Upward

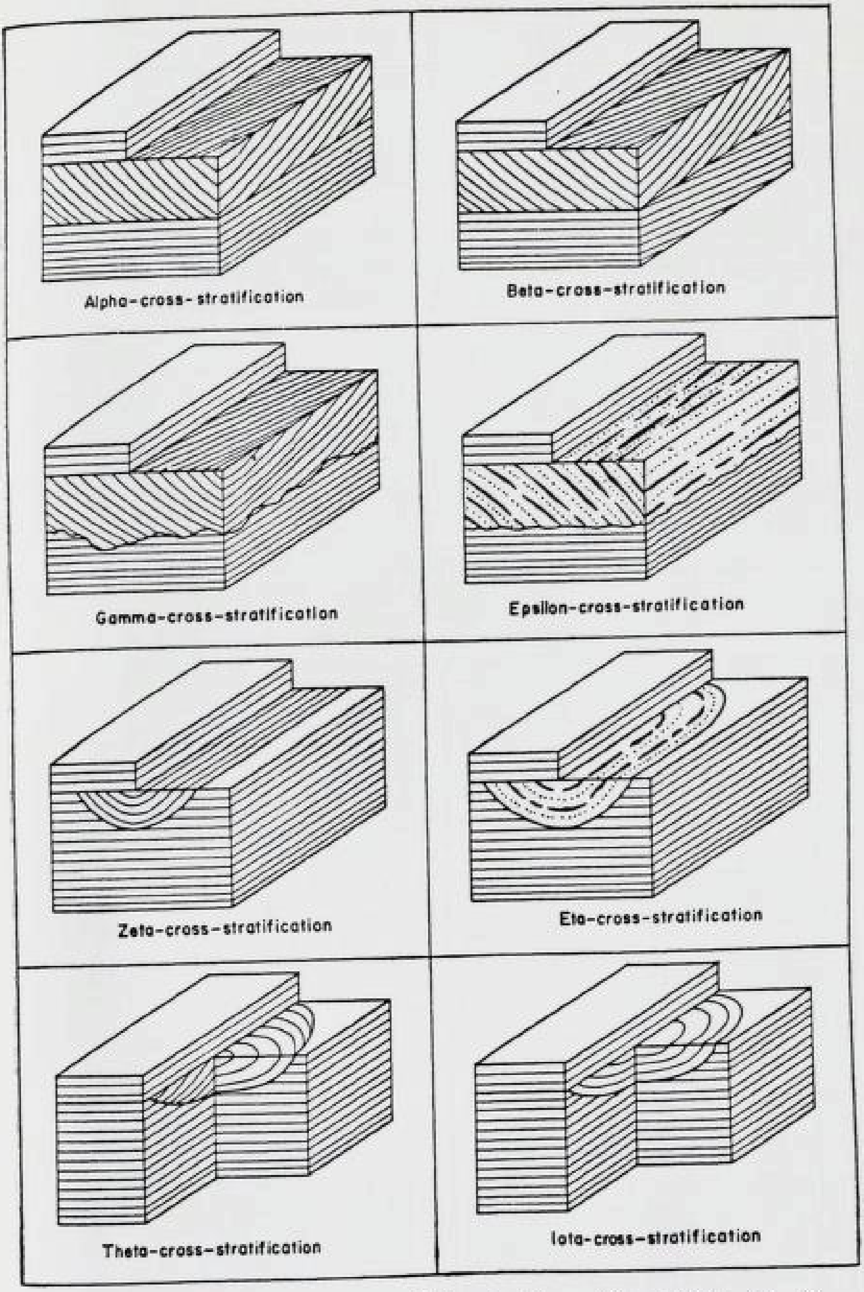


Fig. 33. Classification of cross-stratified units (from Allen, 1963b, Fig. 3).

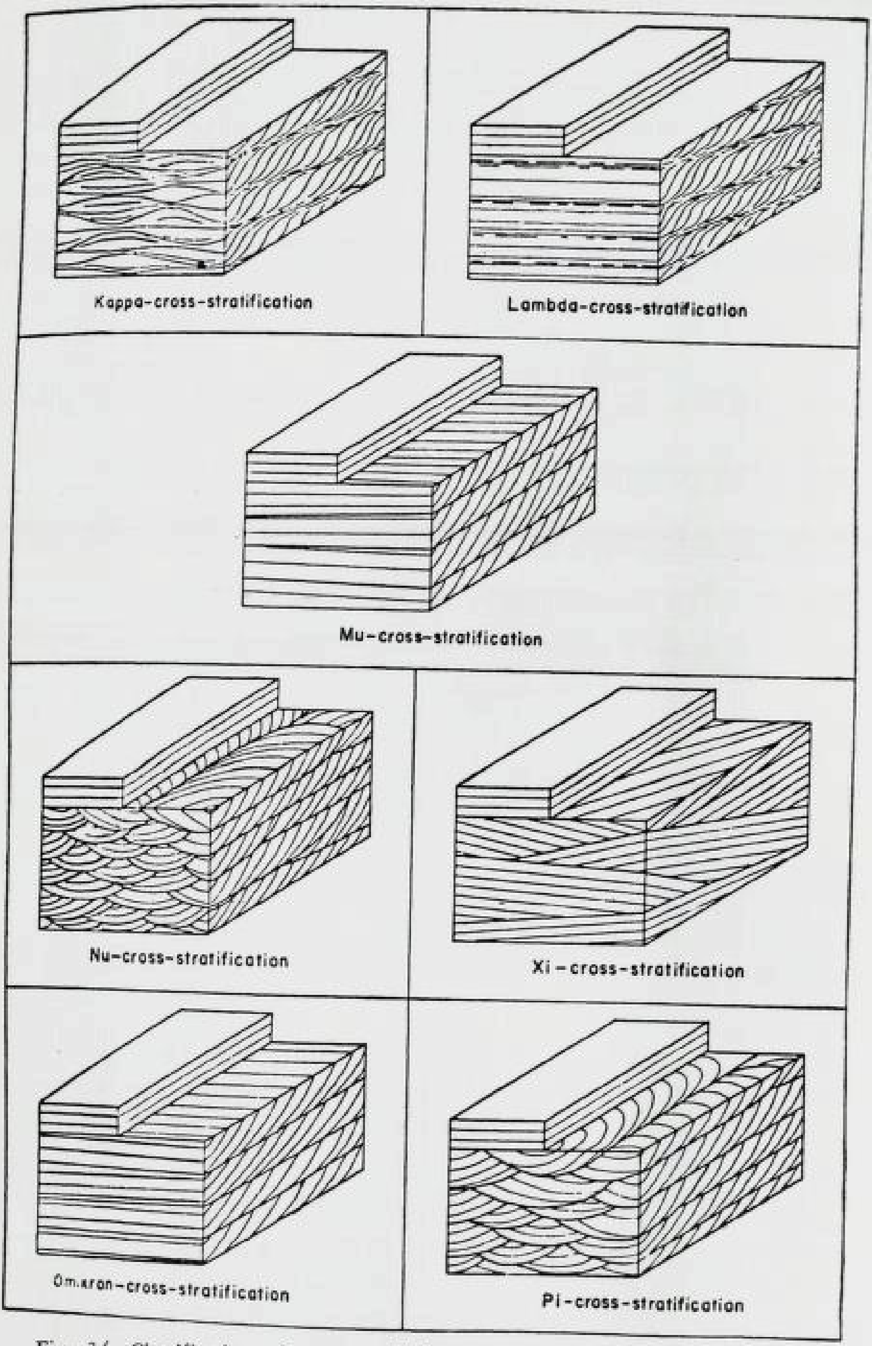


Fig. 34. Classification of cross-stratified units (from Allen, 1963b, Fig. 4).

gradation into cross-stratified sandstone indicates change to the lower-flow regime; this occurs repetitively in the Solund area, with the flat-stratification often preserved by deposition of thin conglomerate layers over it, instead of being reworked to lower-flow regime bed forms. Preserved continuous thicknesses of flat-stratification are small, amounting to 6 or 7 centimeters at most, and extending laterally in pockets up to 15 or 20 meters.

Cross-stratification

Many types of cross-stratification are present in the Solund sediments, reflecting a variety of depositional conditions and sediment textures. The most common variety consists of gently plunging troughs, although lesser amounts of simple and planar cross-strata are found, in the terminology of McKee and Weir (1953). Criteria for classification of cross-strata, however, will be based largely on the system of Allen (1963c), which provides for more inclusive subdivision and allows for easier relation of geometry to formational processes (Figs. 33 and 34).

Both solitary and grouped cross-strata are present, with solitary sets of plunging "trough-type" cross-strata common as sandstone lenses in pebbly sandstone and finer conglomerate; various types of grouped cross-strata are found in thicker sandstone accumulations. Most cross-strata are large-scale, having thicknesses, or amplitudes, greater than five centimeters. The bottom surfaces of the solitary trough types are commonly erosional. For the various grouped cross-strata cosets, non-erosional bottom surfaces are most common, although erosional and gradational surfaces can also be found. The bottom surfaces of solitary cross-strata are scoop or trough-shaped usually, while grouped cross-strata have either scoop, trough, planar, or irregular bottom surfaces. The angular relationship of cross-strata to bottom surfaces is most commonly discordant. Cross-strata in the coarse Solund deposits commonly have lithologic heterogeneity, with medium and coarse sandstones alternating with pebbly horizons.

The large-scale solitary "trough-type" cross-strata are most commonly of the Eta type, with heterogeneous lithology, scoop-shaped bottom surfaces (plunge in only one direction), and cross-strata discordant to the erosional bottom surfaces. Iota and Theta types, with solitary trough-shaped bottom surfaces (doubly-plunging) and homogeneous lithology, are less common. The scoop-shaped Eta cross-stratification in Solund is noteworthy for the low plunge angles of the scoops, and long length in comparison with amplitude. The true size of the scoops is difficult to measure due to limited exposure, but many are more than 10—20 meters in length and much less than a meter in thick-

Fig. 35. Trough-type cross-stratification in sandstone, Utvær.

ness. Because of the relatively flat geometry, it is often difficult to determine the plunge directions of the scoops; Appendix I summarizes the plunge angles measured for trough or scoop axes used in paleocurrent analysis. These axes, being easily measurable, had the steepest plunge angles. However, even these scoops have abundant plunge angles less than 10° (these axes include measurements from grouped "trough-type" cross-strata as well).

Eta cross-stratification is found commonly in sandstone or pebbly sandstone lenses within coarser conglomerate (Figs. 35 and 36). This cross-stratification type in longitudinal section resembles flat-stratification over short distances, because of the low inclination angles, but when traced over longer distances can be seen to be discordant with bottom surfaces and bounded by trough-like curved erosive bottom surfaces in transverse cross-section. The solitary trough and scoop-shaped cross-strata are thought to result from cutting and filling of isolated channels, pits or hollows, with cutting and filling not necessarily simultaneous (Allen, 1963c); filling by later sedimentation is definitely indicated in some channels (Fig. 36). Locally, primary current lineation can be found on the long scoop cross-strata.

Grouped cosets of "trough-type" cross-strata are common in areas of sandstone accumulation, producing what is commonly termed "festoon" cross-strata,

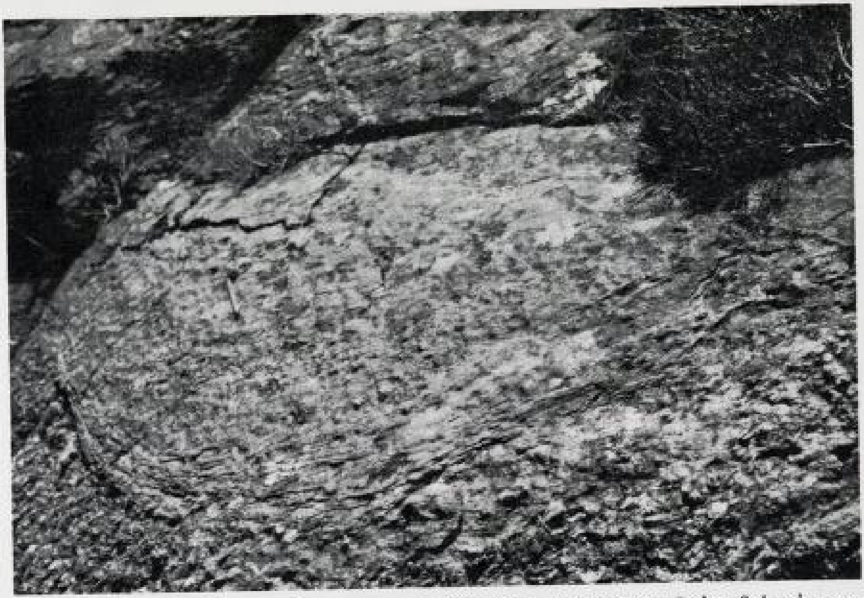


Fig. 36. Channel with trough-type cross-stratification, southeastern Indre Solund, near Kråkevåg.

which probably results from the migration of complex asymmetrical ripple markings. In the Solund area, Nu and Pi cross-strata are common, with plunging scoops, both accordant and discordant bottom surfaces, and cross-cutting relationships. Cosets of cross-cutting plunging scoops attain thicknesses of several meters locally, before being interrupted by planar erosive surfaces, flat-stratified sandstones, irregularly bedded conglomerates, or changing to other types of cross-strata. Lambda and Kappa cross-strata, modified by erosion, are found locally, and discussed under "ripple-drift bedding".

The dimensions of "trough-type" cross-strata measured for paleocurrent analysis (Appendix I), combining both solitary and grouped varieties, yields an average amplitude of about 11 centimeters and an average width of 80 centimeters, based an 67 measurements. The measured sizes, however, are less than true values due to the limited exposure. The plunge angle averages about 10.5°, low in comparison with average dip angles of cross-strata, thus confirming general field observations of low plunge angles, especially for the solitary sets (Table 2).

Table 2. Relation of mean dip of beds to mean inclination of cross-bedding (modified from Pettijohn, 1957a).

Formation and Locality	No. of Measurements	Mean dip	Mean inclination	Reference
Pennsylvanian (Illinois and vicinity)	531	0°	16.5°	Potter and Olson (1954)
Lorrain Quartzite (Bruce Mines)	119	19°	20.2°	Pettijohn (1957a)
Baraboo Quartzite (Wisconsin)	283	46°	23°	Brett (1955)
Lorrain Quartzite (Lacloche)	32	77°	25.8°	Pettijohn (1957a)
Keyes Lake Quartzite (Florence, Wisconsin)	144	84°	25.2°	Nilsen (1964)
Sturgeon Quartzite (Michigan)	80	ca 90°	28.1°	Trow (1948)
Solund Conglomerate (western Norway)				
tabular type	264	ca 25°	14.8°	this paper
trough type	67	ca 25°	10.5°	this paper

Various types of planar-bounded cross-strata are found (as opposed to the "trough-type" of McKee and Weir, with curved bottom surfaces), but are classified with difficulty into Allen's system 1963c). Alpha, Beta, Gamma and Epsilon types were recognized, but also seemed to grade into the "trough-types", with the planar bottom surfaces becoming gently curved, perhaps noticeable only in exposed surfaces perpendicular to the plunge directions of scoops or troughs. The planar-bounded cross-strata are less common than "trough-types", but have been used more for paleocurrent analysis because of ease of measurement and general lack of three-dimensional exposures of troughs that enable measurement of plunge directions. A great many of the tabulated "inclined", or planar bounded cross-strata recorded in Appendix I were undoubtedly measured from the side walls of «trough-type» cross-strata; accordingly, they show greater scatter of paleocurrent directions than do trough axes alone. However, the low plunge angle and large width compared to amplitude of the Solund "trough-type" cross-stratification probably yields values for planar-bounded cross-strata that are similar in paleocurrent orientation to the trough axes, especially with a large sample.

The amplitudes of the 264 planar bounded cross-strata measured for paleocurrent analysis average about 12 centimeters, with inclination angles averaging almost 15°. Both angles are higher than for the "trough-types". Compared to published data on inclination angles (Table 2), the values are low, still probably a reflection of low plunge angles of scoops and troughs. The large-scale cross-strata that are bounded by planar or irregular surfaces are thought to result from the migration of solitary banks under water, with curving or linear fronts (Allen, 1963c).

No systematic areal or stratigraphic variation of cross-stratification geometry or size was noted in the Solund area. General morphology and types compare favorably with cross-stratification types found in fluvial environments (e.g., Harms and Fahnestock, 1965).

Ripple markings

In three localities, straight current ripple markings restricted to part of an exposed bedding surface were found. In each case, cross-stratification in cross-section dipped in the direction of the steepest, downcurrent slope of the asymmetrical crests. Ripple amplitudes ranged from 2.5 to 4 centimeters, with wavelengths from 5 to 35 centimeters, yielding ripple indices ranging from 2 to 9. The ripples were not steeply asymmetrical, but had rounded, smoothed-off crests, suggesting considerable scour. A larger asymmetrical sand wave of uncertain origin, consisting of one crest only and with strata in cross-section parallel to the surface form, was noted in sandstones near Kråkevåg. The variability of ripple size suggests considerable range in depositional conditions and current activity; ripples are not characteristic of the sequence, however, as they are in other areas of finer-grained Old Red sediments (e.g., Friend, 1965).

Ripple-drift bedding

Local zones of ripple-drift bedding up to a meter or so in thickness were found within areas of thick sandstone. The structures preserved have the stoss sides of consecutive ripples eroded, suggesting deposition by tractive currents (type 1 of Walker, 1963). Erosion has occurred between deposition of successive sets of rippled bedding, however, yielding irregularly repetitive layers with common discordances between layers. This is not usual in ripple-drift bedding, which is generally recognized by the regular succession of similarly rippled strata above one another. Allen (1963a) suggests that vigorous erosion in ripple troughs is primarily responsible for these discordances. The writer considers this ripple-drift bedding a result of movement of considerable amounts of sediment, but with frequent interruptions in the depositional process, perhaps largely from current velocity fluctuations.

Ripple-drift bedding is most characteristic of fluvial deposits in environments of rapid periodic sand accumulation, such as on flood plains during flooding, when sediment-laden waters quickly lose velocity (McKee, 1965). In the Solund sediments, the structure is uncommon, and was not noted to occur in any particular stratigraphic position or lateral relationship to other sedimentary structures or cyclic deposits.

Fig. 37. Pebble "train" on bedding surface, southeastern Indre Solund, near Kråkevåg.

Pebble "trains"

In the coarse conglomerates and finer pebbly sandstones, linear zones of coarser pebbles within relatively uniform-sized sediment were noted (Fig. 37). In the fine sediments, these features merge into coarse-grained, widely-spaced primary current lineation (Fig. 38). Elongate pebbles within these "trains" are characteristically aligned parallel to the linearity of the train, and in longitudinal cross-section pebbles are uniformly imbricated. The origin of these structures is not clear, however. Some appear to fill linear erosional channels in underlying sediment, apparently representing a basal coarse bed load deposit; others do not fill channels, but appear to represent coarser material deposited by stronger linear eddies or currents in an area of generally finer clastic detritus. Boulders up to three meters in diameter were found in some "trains", representing strong current activity.

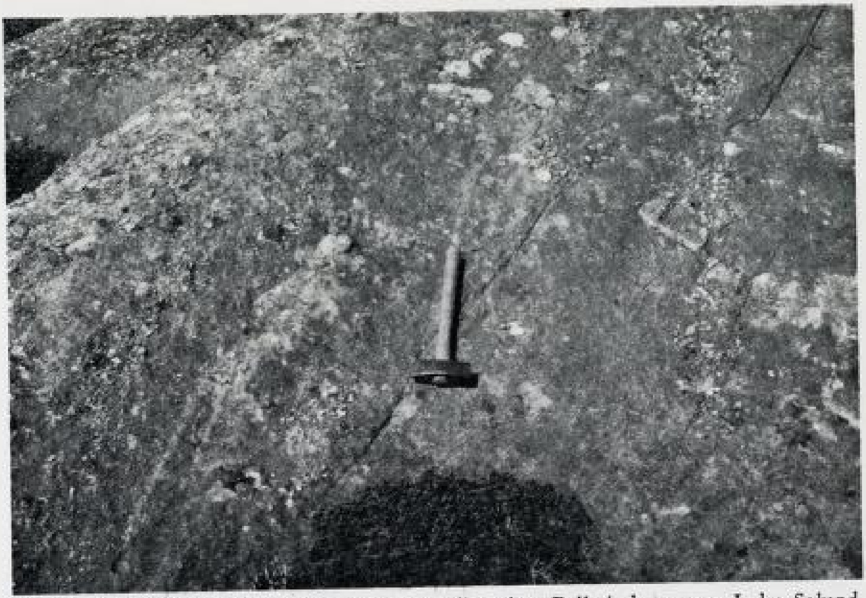


Fig. 38. Pebble "trains" with primary current lineation, Polletind, western Indre Solund.

Primary current lineation

Scattered exposures of primary current lineation (Stokes, 1947) are found in the Solund Devonian rocks. The structure consists of more or less regular parallel ridges of low relief (less than one-half centimeter), sometimes up to several centimeters in width, although commonly being much narrower. The lineations are found on flat-bedded or long, gently inclined cross-bedded surfaces of sandstone accumulation. They are best visible at low angles of reflected sunlight. Published studies show orientation of elongate sand grains parallel to the lineations, and that primary current lineation forms parallel to current flow (Allen, 1963b); therefore, this structure is a useful paleocurrent indicator.

Experimental studies suggest that this structure is formed on flat-stratified surfaces in the upper-flow regime, and that it is commonly found on submerged fluvial sand bars passed over by persistently unidirectional flow, or in beach areas of swash and backwash (Allen, 1963b). In the Solund area, abundant coarser debris on bedding surfaces has resulted in many short, irregular discontinuous linear ridges and depressions. These are probably related to primary current lineation.

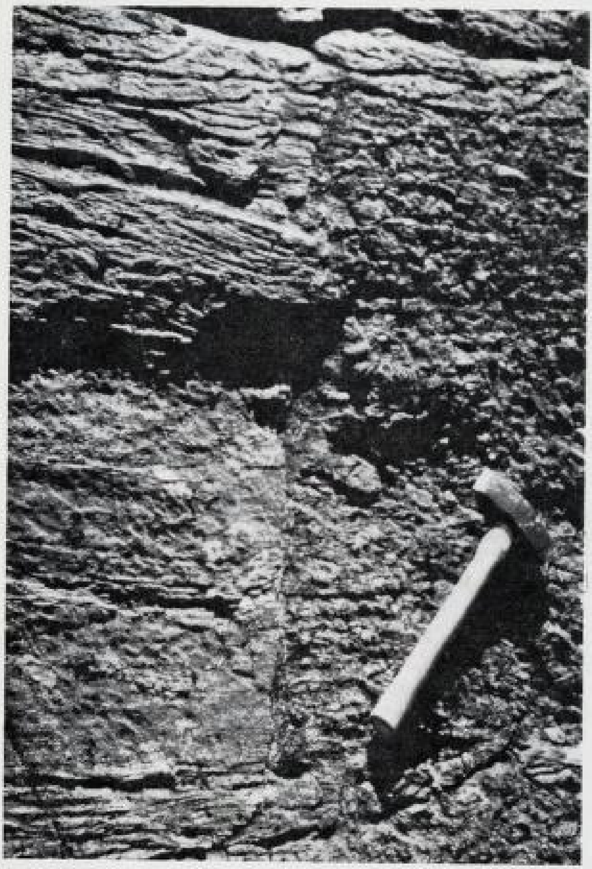


Fig. 39. Vertical depositional contact between conglomerate and sandstone, southeastern Indre Solund, near Kråkevåg.

Channel scours

Within the sandstone and pebbly sandstone sequences, evidence of erosion has been preserved in the form of abundant channels cut into underlying sediment. No bottom scour features such as sole markings have been found, probably due to the lack of cohesive finer silt-mud depositional interfaces. Erosive channels grade into the previously discussed trough-type cross-stratification, with most containing cross-stratified material filling the eroded channel. However, many channels are filled with irregularly sorted, poorly stratified gravel, apparently deposited in the previously eroded channels. The channels are generally restricted in width, rarely exceeding 5 meters, and vary in depth up to one or two meters. No channels were clarly visible in the coarser conglomeratic sequences. Those in the pebbly sandstones often have steep side walls (up to 60°), indicating considerable cohesiveness of the unconsolidated sediment. The geographic surface pattern or course of the channels was not determinable, except for some of the pebble "trains" resulting from channel fill material.

Vertical contacts between different sediment types have been noted at several localities, with no evidence that post-depositional faulting was responsible. Figure 39 shows a vertical contact between well-stratified sandstone and irregularly stratified conglomerate, suggesting a faulted contact. However, the undisturbed continuous sandstones extending above and below the zone of conglomerate suggests that the sandstone had been a relatively steeply walled erosive channel bank at the time of deposition, with gravel then introduced into the channel, eventually filling it. The vertical wall may have resulted from fluvial undercutting on the convex side of a stream meander, with slumped or eroded material carried away by the stream. Entrenching of a stream channel due to changes in base level, hydrodynamics, or topographic elevation may also be responsible.

Fig. 40. Appearance of metaconglomerate-clast zone, southeastern Skorpa.

The above features indicate that despite predominance of depositional sedimentary structures in the Solund Devonian, erosion at various stratigraphic levels, preserved mainly in the sandstones, was a prominent feature of the paleo-environment. Erosion undoubtedly also occurred during transport of gravel debris, but evidence from sedimentary structures is lacking. Erosion probably resulted from climatically induced changes in discharge, changes in base level, or migration of laterally eroding streams.

Rockslide(?) deposits

Along the south shore of Skorpa, a zone of very coarse, angular metaconglomerate fragments within normal polymict conglomerate crops out (Fig. 40).

This exposure was previously described as a local, structurally disturbed part of the Devonian conglomerate (C. F. Kolderup, 1926a). The exposure contains, however, a stratigraphic thickness of about ten meters of metaconglomerate fragments that are partly folded, structurally flattened, and composed of quartzite pebbles in a quartzitic matrix. Rocks identical to this is found in the Cambro-Silurian basement of Hersvik. No evidence indicates structural deformation of the Devonian strata; flattening and folding are restricted to the fragments, with the matrix between the fragments undisturbed. Normal, polymict conglomerate that contains rounded fragments is found stratigraphically above and below this zone.

The following evidence suggests a catastrophic origin for this zone: (1) monomict composition of clasts, (2) angularity of clasts, (3) coarseness of clasts, and (4) intercalation within normal conglomerate. Because the metaconglomerate when found in the basement rocks occupies topographic highs on a basement of considerable relief, the writer suggests that this deposit represents sudden local deposition of a continuous layer of coarse, angular, unsorted debris. This may have resulted from sliding of loosened material from a resistant topographic high area within the basin of deposition. The basement geology at Skorpa, by lateral extension from basement outcrops, should consist of steeply dipping interstratified quartzites (with local metaconglomerates) and phyllitic graywackes, certainly conducive to formation of topography with high relief (Fig. 8). Normally the metaconglomerate composes only 0—8 percent of the conglomerate clasts.

A talus origin is rejected because the deposit is wholly interstratified with conglomerates, implying movement of the material to its site of deposition. Based on criteria of Kent (1966), the above features indicate origin by catastrophic rockfall or rockslide, rather than creep or mudflow. Burchfiel (1966) describes a similar recent deposit from California.

Cyclic deposits

Characteristic of the depositional sequence is irregularly cyclic stratification in the sandstones and pebbly sandstones; no cyclicity of strata was noted in the thicker conglomerates. The term «cyclothem» has been applied to regularly repetitive depositional sequences described from many Old Red Sandstone areas (Allen, 1962a, 1964, 1965; Friend, 1965; Bryhni, 1964c). The Solund cyclic deposits are noteworthy for their irregularity, coarseness of sediment, and modified structures associated with the cyclic pattern.

Previously described Old Red "cyclothems" consist of (1) a basal scoured surface with sole markings, (2) a cross-stratified coarse member with common

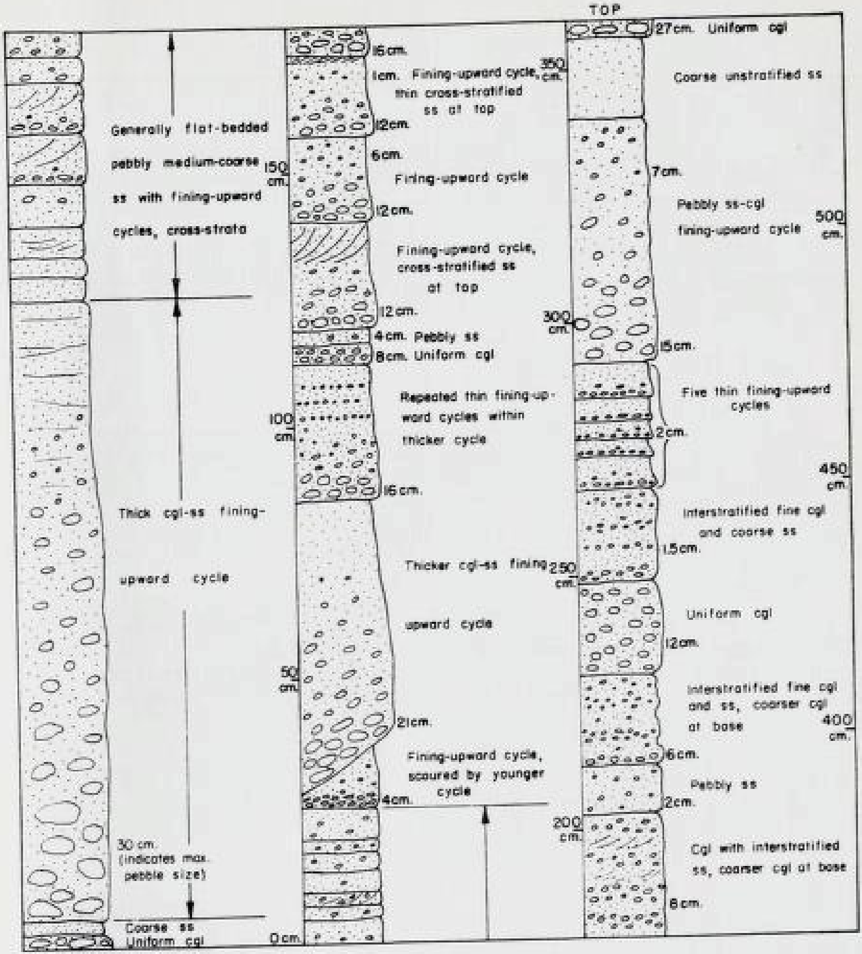


Fig. 41. Measured stratigraphic section showing fining-upward cyclic deposition, eastern Lifjell Peninsula.

intraformational conglomerates, and (3) a fine member with variable sedimentary structures. The sequences are characterized by fining-upward in alternating sandstone-siltstone layers. Structures found in these "cyclothems" include flat-stratification, large and small-scale cross-stratification, primary current lineation, ripple markings, and various sole markings. The "cyclothems" are thought to form by alternating deposition and erosion in a fluvial environment.

Cyclic deposition in the Solund Devonian contains coarser clastic material,

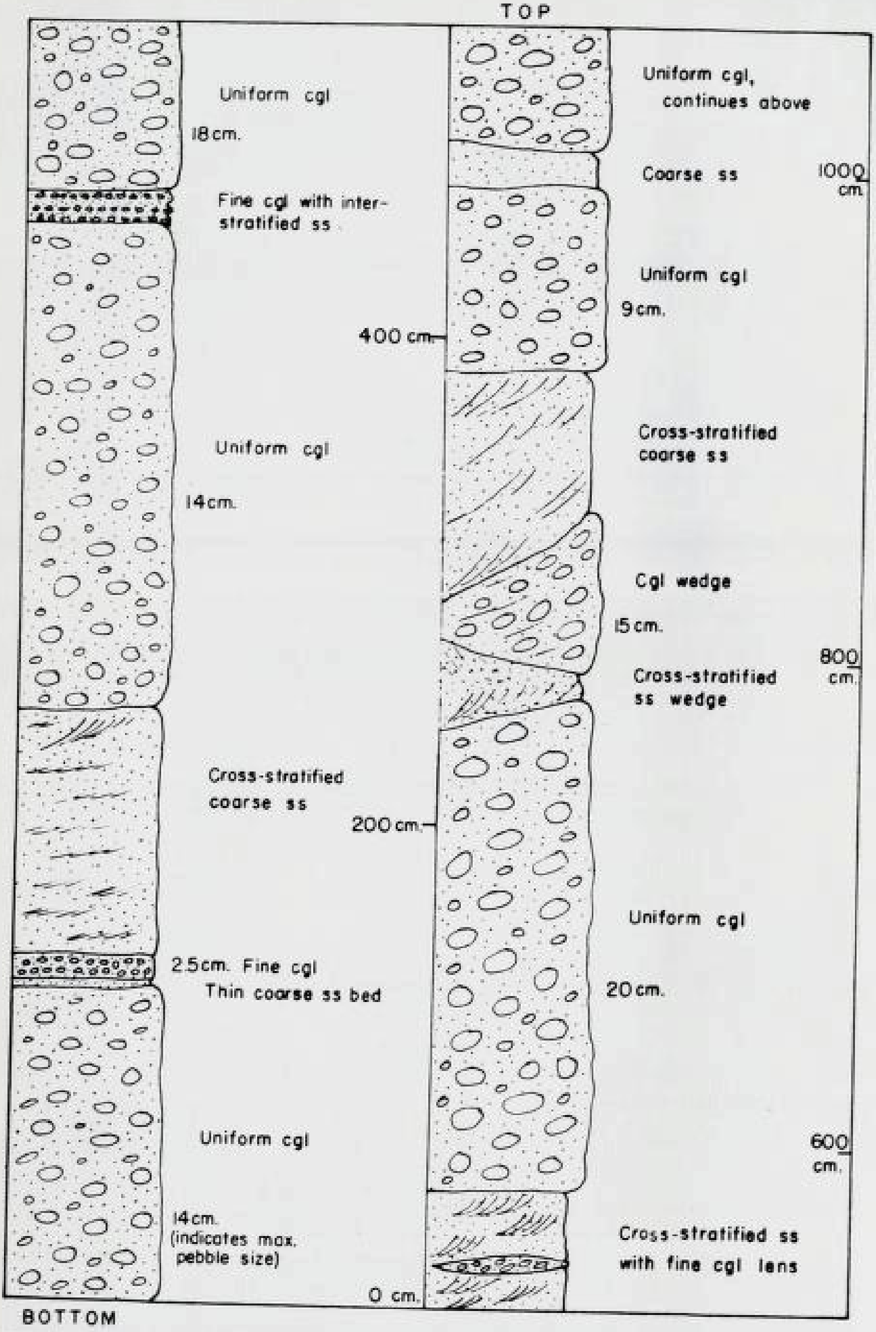


Fig. 42. Measured stratigraphic section showing repetitive sandstone-conglomerate deposition, southeastern Indre Solund, near Kråkevåg.

Fig. 43. Thin, fining-upward cyclic deposition in pebbly sandstone, eastern Lifjell Peninsula.

with pebble zones forming the base of the cycles. The entire fining-upward cycle is commonly restricted to a relatively thick deposit of conglomerate or pebbly sandstone. Siltstone layers are not found, leaving repetitive alternations of conglomerate and sandstone; sole markings at the base of the cycles are not present, probably due to the lack of a cohesive mud or silt substratum. Two measured stratigraphic sections reveal the complexity, irregularity, and wide variation in thickness and coarseness of the Solund cyclic deposits (Figs. 41 and 42). The most diagnostic feature is fining-upward of each successive sedimentary unit, regardless of absolute coarseness, thickness, or sedimentary structures present (Fig. 43). Certain of the repetitive alternations of conglomerate and sandstone are not fining-upward in nature, however, and may result from other processes than the fining-upward cycles (Fig. 42). The basal surface of each cycle is irregular, but not always clearly erosional; perhaps rapid influx of coarser material resulted in a primarily depositional interface. The bottom of the cycles consists typically of irregularly stratified conglomerate, with the tops of cycles cross-stratified, either with trough or planar-bounded varieties. Other sedimentary structures, such as irregular ripple-drift bedding and ripple markings, have been noted in the upper parts of cycles.

Elsewhere, Old Red "cyclothems" are thought to form characteristically by lateral migration of streams across depositional flood plains (Allen, 1965a); but the nature of the Solund cyclic deposits suggests formation in a somewhat different environment.

Sedimentary fabric

Background

Fabric studies enable deductions of fluid flow in the absence of useful sedimentary structures. Voluminous literature exists pertaining to methods of analysis and interpretation of sand and pebble fabrics, with laboratory studies providing especially useful data. The orientational response of particles to fluid flow is complex, being dependent upon factors such as the size, shape, distribution, roundness and density of the clasts in relation to the nature, strength, viscosity, type of flow, and orientation of the moving fluid. The majority of studies have shown that the maximum projection plane of particles dip into the oncoming current, with long dimensions parallel to the flow. In unidirectional flow, then, both planar and linear clastic particles tend to develop monoclinic symmetry, with the variability of bed shape producing additional turbulence, but not basically changing the symmetry. Experimental studies of sands have substantiated the theoretical considerations based on fluid mechanics (Schwarzacher, 1951; Rusnak, 1957).

Natural fluvial gravels have been shown to have the most complex fabric responses to fluid flow, with planar-shaped gravel clasts in modern streams overwhelmingly imbricated up-current at angles between 10° and 30°, although down-current imbrication has also been noted. Long axes in fluvial gravels can be either parallel or perpendicular to stream flow. No generally consistent theory is at present applicable to ancient deposits; differences are thought to depend on factors such as shape, size, packing density, sorting and stream gradients (see summary, Potter and Pettijohn, 1963, p. 35-36). Johannson (1963) has experimentally defined some of the controlling factors in long-axis orientation of topset and foreset beds, with Sengupta (1966) confirming the flume results in cross-stratified fluvial gravels. Of particular relevance to the present study are Krumbein's determinations of long axes of coarse flood gravels in California parallel to the flow directions (1940, 1942).

Analysis of the orientation of blunt and tapered ends of the well-aligned elongate pebbles was made, because theoretically the blunt ends should be oriented facing the upcurrent direction. This procedure is reported in the literature, primarily in quartzose sandstone fabric studies, with poor results (Dapples and Rominger, 1945). Little data is available for fluvial gravels, although preferred orientation has been noted in glacial tills. Studies of tapered elongate fossil fragments, such as orthoceracone cephalopods and high-spired gastropods, have indicated orientation consistent with paleocurrent directions (e.g., Chenoweth, 1952).

Orientation of pebble long axes

A strong preferred orientation of the long axes of elongate pebbles on bedding surfaces is found throughout the Solund Conglomerate, with the orientation reflecting paleocurrent directions, and perhaps paleoslopes (Fig. 44). The writer measured the elongation direction of 50 randomly selected pebbles at 78 essentially random, well-dispersed localities throughout the area. The orientations have been plotted as rose diagrams, with two-dimensional vector means determined according to Curray (1956); standard deviations have been calculated mathematically and plotted about the vector means to statistically indicate dispersion (Fig. 45). Measurement of 50 pebbles per locality was considered sufficient, in accordance with general fabric analysis procedures (Johannson, 1963). Rigid mathematical determinations of elongation ratios was impractical due to lack of time, so the writer utilized for measurement pebbles with visually estimated ratios greater than about 1.5:1.

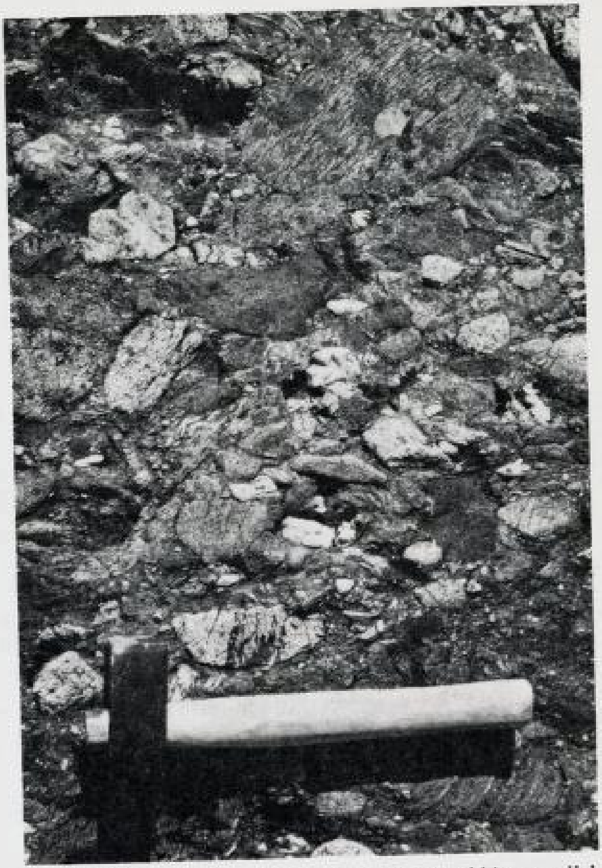


Fig. 44. Preferential alignment of elongate pebbles parallel to hammer on bedding surface, northwestern Indre Solund, near Tveranger.

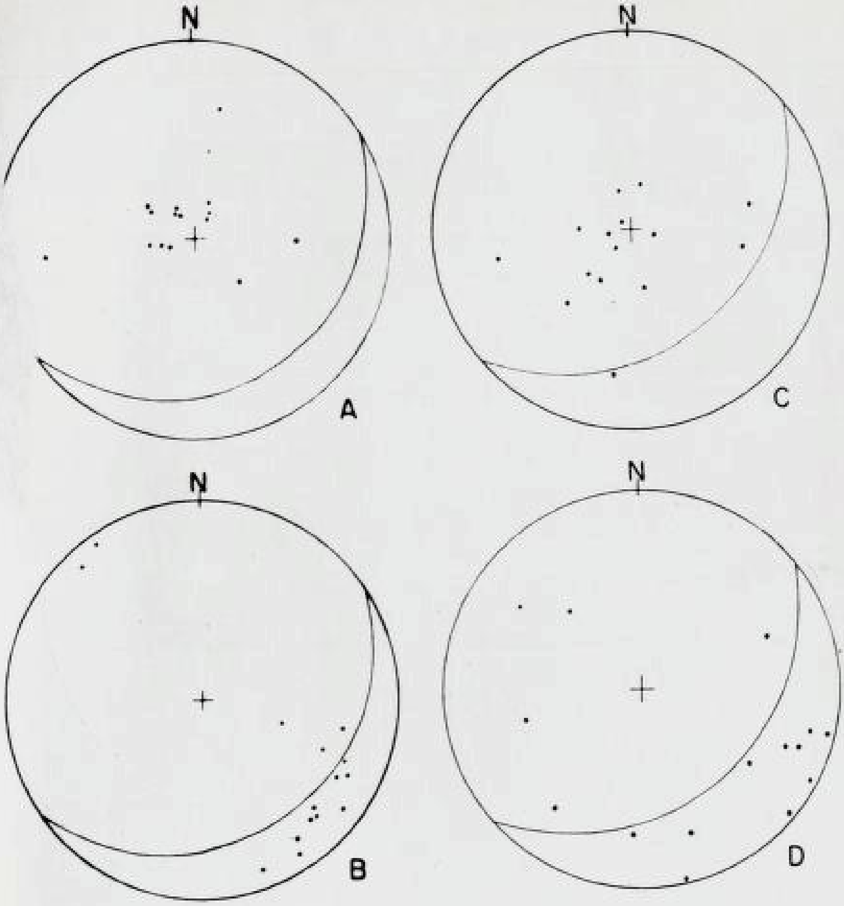
Fig. 46. Pebble imbrication, northern Ravnøy, near Tangenes. (Tape parallel to stratification, pebbles preferentially dip to right).

Consistent orientation of blunt and tapered ends of elongate pebbles throughout the preserved area of the Solund Conglomerate reflects abundance of elongate tapered pebbles and probably strong current activity during deposition. Twenty-five pebbles were examined for tapered orientation at 71 localities, with the percentage of respective orientations plotted on Figure 45 at the ends of the two-dimensional vector means of long axis orientations.

Pebble imbrication

The inclination of elongate and flat pebbles to the surface of sediment accumulation (whether flat-bedding or cross-bedding) was measured in vertical sections approximately parallel to the preferred long axis orientation of elongate pebbles on bedding surfaces. The inclination angles of 50 randomly selected pebbles that presented elongate cross-sections were measured at 51 scattered localities, with great caution taken to ascertain bedding surface orientation (Figs. 46 and 47). Abundance of sandstone lenses enabled determination of bedding orientation and widespread northwest-southwest-striking joints facilitated measurements parallel to the long axis orientation.

The bases of cyclic deposits commonly contain well-imbricated pebbles, succeeded upward by irregular, scattered, statistically preferential imbrication.



Figs. 48 (A,B) — 49 (C.D):

Krakhelle, Indre Solund:

A. Poles to maximum projection area of flattened pebbles.

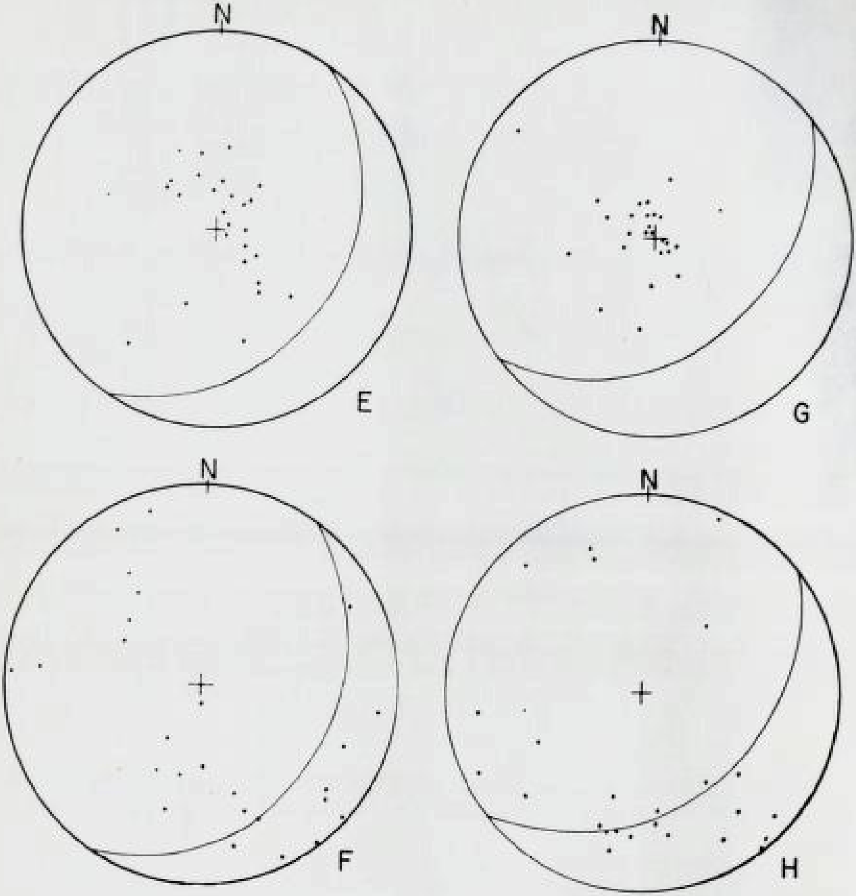
B. Plunge directions of elongate pebbles.

North of Gylta, Indre Solund:

C. Poles to maximum projection area of flattened pebbles.

D. Plunge directions og elongate pebbles.

Very few examples were noted of consecutive inclined pebbles stacked upon one another; the consistent pattern in Figure 47 represents a statistically preferred inclination not always so clear in the field. The orientation of blunt and tapered ends of 25 elongate pebbles in vertical cross-section was deter-



Figs. 50 (E,F) — 51 (G,H):

North of Tveranger, Indre Solund:
E. Poles to maximum projection area of flattened pebbles.
F. Plunge directions of elongate pebbles.

Tangenes, Ravnøy:
G. Poles to maximum projection area of flattened pebbles.
H. Plunge directions of elongate pebbles.

mined at 8 localities, yielding directions and percentages similar to those from bedding surfaces. The consistent, preferential imbrication in such coarse conglomerate (Fig. 47) indicates strong current activity, steady in orientation, throughout the recorded depositional history of the area.

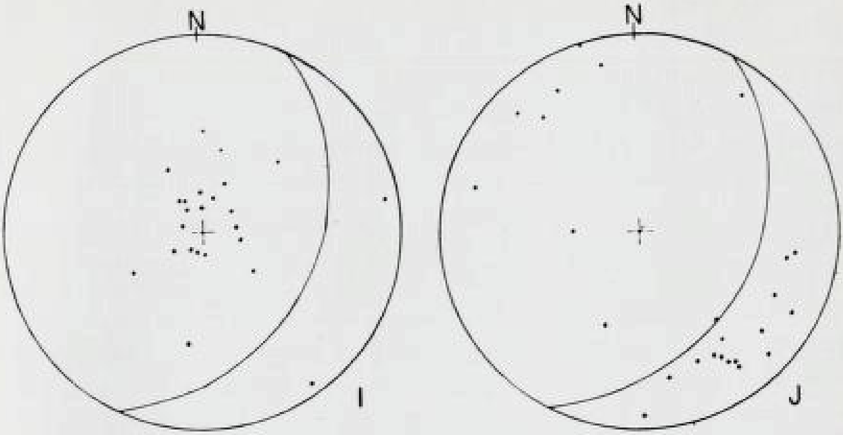


Fig. 52. South of Ytrøy, Ytre Solund.
I. Poles to maximum projection area of flattened pebbles.
J. Plunge directions of elongate pebbles.

Three-dimensional pebble orientation

At five localities, indicated on Figure 47, the matrix material of the conglomerate was sufficiently weathered out that the three-dimensional orientation of flat and elongate pebbles could be determined. Fortunately, stratification was present in each case, such that poles to the strike and dip of the maximum projection area of flat pebbles and the plunge direction of elongate pebbles could be plotted on the lower hemisphere of a stereonet, with respect to the surface of sediment accumulation (Figs. 48—52). In each case, the data (based on 15—25 measurements) substantiates the pebble fabric determined by separate two-dimensional analyses: with respect to bedding restored to the horizontal plane, elongate pebbles preferentially plunge southeastward, and flat pebbles preferentially dip southeastward.

Texture

Size distribution

Abrupt vertical and lateral changes in coarseness of sediments occur in the Solund area, especially where cyclic deposition is present. Because of the large range in size of clasts, no practical field sampling plan enabled measurement of size distribution; sorting of the conglomerates is universally poor due to the presence of matrix materials. Consideration of depositional dynamics suggested that measurements of the maximum pebble sizes throughout the depositional area would provide the best representation of the competence of the transporting medium. Variations in competence, or the coarseness of clastic material available for transport, would perhaps permit stratigraphic subdivision of the deposits. Accordingly, the writer measured the ten largest visible clast diameters at 237 localities, with the means of these measurements plotted and contoured in Figure 53. No measurements of sandstone coarseness were made, but large sandstone areas are plotted on the map to indicate their effect on the maximum pebble size distribution.

The maximum pebble size map suggest the following broad stratigraphic trends: (1) the oldest conglomerate, including basal breccia, is generally uniformly coarse; (2) intermediate-age deposits are generally finer, with abundant sandstones such as at Polletind, Losna, etc.; and (3) the youngest deposits become coarser again. The east-west trending contours suggest that transport was not from the east or west; otherwise, one might expect general fining in either of these directions of the lower, middle, or upper units.

Values from the basal breccia are included on the map except where anomalously coarse; in general, the breccia is coarser than the overlying polymict conglomerate, but not uniformly so, as it is very thin or absent locally. The metaconglomerate deposit on Skorpa is included, but not contoured, as it is considerably coarser than the surrounding conglomerate. Four readings from pebble "trains", with their exceptionally coarse nature apparent, are included in the data.

Pebble roundness

General measurements of pebble roundness without respect to pebble lithology or coarseness of pebble size were made throughout the area, using the comparative visual charts of Krumbein and Sloss (1958, p. 81). It was hoped that gross trends of roundness variation would be a useful and diagnostic criterion for transport directions in such coarse sediments. Accordingly, 25 randomly chosen pebbles, longer than 10 centimeters ,were measured at 81 scattered localities. The mean roundness value at each locality was determined, and a contour map (excluding the basal breccias) was made with .01 roundness units for a contour interval (Fig. 54). The roundness was determined from the pebble shape on bedding surfaces, with additional measurements from various cross-sectional orientations showing no consistent differences from the plan view. The roundness pattern contains northeast-southwest trends, with many irregularities to the north above the basal sedimentary breccia, but a consistent decrease in roundness toward the southeastern margin of the area.

Brief comparison was made of the overall roundness of the conglomerate to the roundness of particular pebble types, especially between foliated and non-foliated lithologies. A tabular summary in Appendix II indicates no significant differences in roundness between the lithologies selected for limited sampling, and that roundness thus appears not to be strongly affected by pebble lithology in the Solund Conglomerate. This indicates, then, that the major control of roundness variation in the Solund Devonian was transport history, and that the clast roundness map is a useful tool in determination of provenance direction.

Mean roundness values from the basal breccia have been plotted, with lower values apparent, although the variance at each locality is not significantly lower than for the conglomerate. Of importance is the fact that the breccia is never completely angular, but contains many partly rounded fragments. The general lack of thick breccia at Hersvik, Leknessund, and the northern edge of the Lifjell Peninsula, and consequent abrupt admixture of polymict rounded pebbles, is reflected in higher roundness means and greater variances than in normal (topographically lower) breccia exposed further west. The zone with metaconglomerate clasts at Skorpa has anomalously low roundness values.

Pebble sphericity

Procedures used to measure sphericity and to prepare a pebble sphericity map were identical to those used for roundness, with measurements taken concurrently. The map (Fig. 55) indicates no consistent trends, nor any correlation with either size or roundness. Values for the basal breccia and zone of metaconglomerate clasts are not greatly different from the normal conglomerate, suggesting that sphericity is of little value in the Solund area for delineating sedimentary trends. Sphericity measurements of pebbles in vertical cross-section have considerably lower mean values than those of pebbles on bedding surfaces, indicating a relatively high percentage of flattened, or disc-shaped pebbles.

Of particular interest is the variation of sphericity with pebble lithology, especially between foliated and non-foliated types (Appendix II). Although based on minimal data, it can readily be seen that gabbro and basalt pebbles have significantly higher sphericity values than the average for the conglomerate, while schistose quartzite pebbles have approximately similar values. These data suggest, as would be expected, that foliation or bedding has a strong influence on the sphericity of pebbles in the Solund Conglomerate, more so than the abrasion history. The resulting inconsistent sphericity pattern is largely, then, a result of mixing of pebble lithologies, with the original shape of fragments having the strongest influence on sphericity. In summary, transport analysis could be based on roundness, but not on sphericity, which only very imperfectly may reflect the results of abrasion.

TRANSPORT DIRECTION

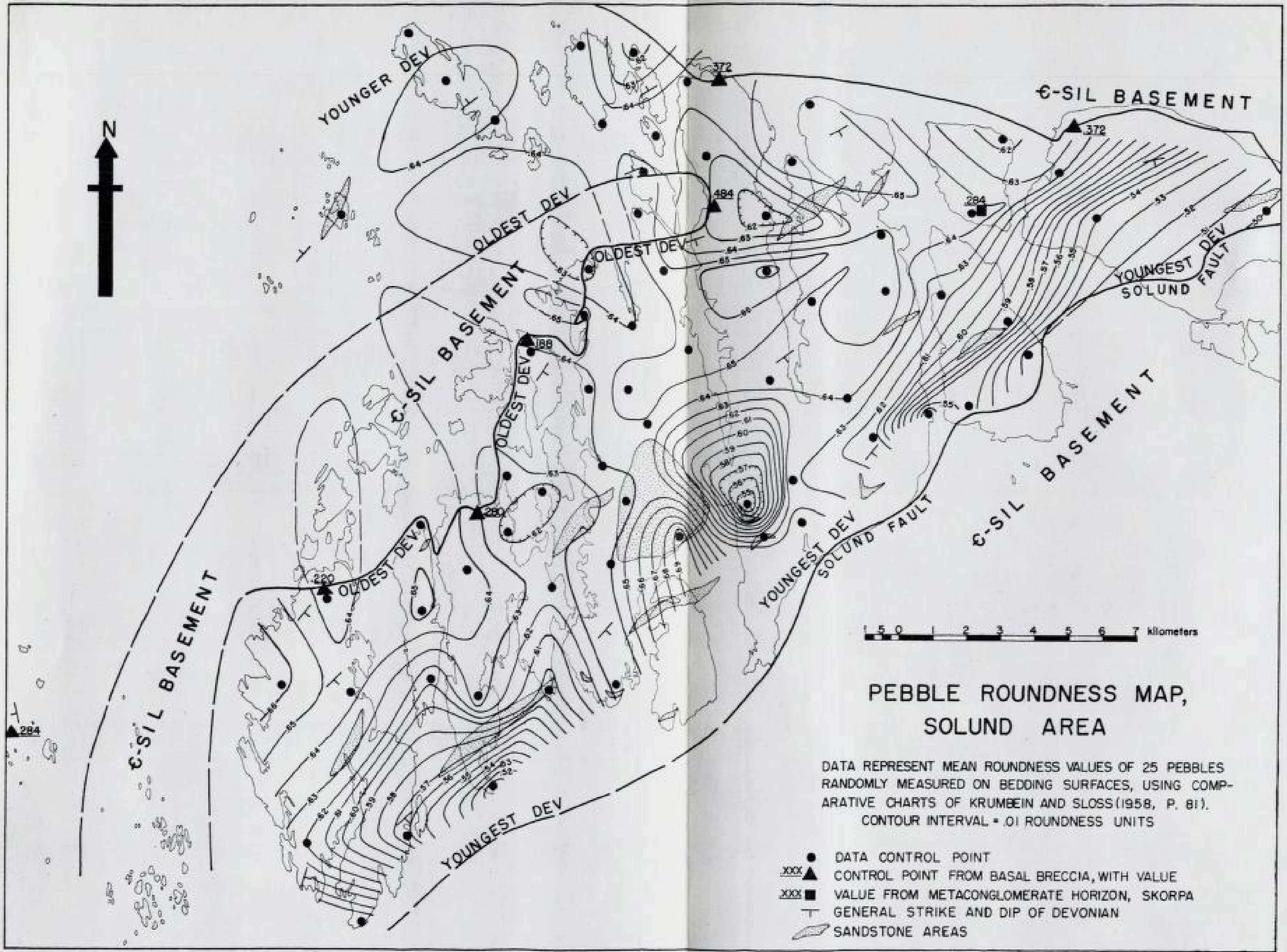
Background

The direction of transport of clastic material is best determined by combining several different types of sedimentologic analyses, which will hopefully corroborate each other within the framework of reconstructed paleogeography. The Solund area is of relatively small size, making conclusions of transport directions of only local importance. However, the amount of detailed sedimentologic and petrographic data available allows a rather complete basin analysis to be made, with application to other areas of similar geology. The coarseness of the deposits, and hence relative nearness to provenance, allows more confident statements of paleoenvironment and paleotectonics. The presence in the Solund area of both conglomerates and sandstones necessitates independent transport data for each, for it is possible that they represent material from different sources. In addition, the above studies of stratigraphy and sedimentology suggest fluvial origin of the deposits; if this be so, then previous studies have shown that the transport directions will closely reflect the paleoslopes of the depositional basin.

Sedimentary structures

Structures applicable to paleocurrent analysis in the Solund area include cross-stratification, ripple markings, primary current lineation, and pebble "trains". These structures are generally restricted to areas of sandstone and fine conglomerate; fortunately, the widespread distribution of such exposures provides an adequate sample for construction of a useful paleocurrent pattern (Fig. 56). The writer's sampling procedure consisted simply of measuring all available current-formed structures, which included a total of 331 cross-strata (approximately 100 are from the thick sandstones of the Polletind area in western Indre Solund).

Measurements were restored to the horizontal plane using a stereonet. Single restored values of cross-stratification, current ripple markings, primary current lineation, and pebble "trains" are plotted directly on the paleocurrent map, while more sophisticated statistical treatment was given to localities where larger numbers of cross-strata data were obtained. Measurements from inclined and trough cross-strata were kept separate, because of the possibility of the structures being hydrodynamic reflections of two or more different current regimes. Vector means and consistency (L) values were calculated according to Curray (1956), with standard deviations mathematically calculated and plotted symmetrically around the vector means; rose diagrams with 30°



PEBBLE ROUNDNESS MAP, SOLUND AREA

DATA REPRESENT MEAN ROUNDNESS VALUES OF 25 PEBBLES RANDOMLY MEASURED ON BEDDING SURFACES, USING COMPARATIVE CHARTS OF KRUMBEIN AND SLOSS (1958, P. 81).
CONTOUR INTERVAL = .01 ROUNDNESS UNITS

● DATA CONTROL POINT
XXX ▲ CONTROL POINT FROM BASAL BRECCIA, WITH VALUE
XXX ■ VALUE FROM METACONGLOMERATE HORIZON, SKORPA
┬ GENERAL STRIKE AND DIP OF DEVONIAN
▨ SANDSTONE AREAS

Fig. 55.

imbrication in pebble "trains" indicates transport to the northwest. In a study of fluvial Devonian sediments in Spetsbergen, Friend (1965), for instance, found that primary current lineation and ripple markings were far more consistent and profitable in paleocurrent analysis than cross-stratification. The Solund deposits differ in containing coarser clastic material, perhaps indicative of higher stream gradients. As a result lateral migration and meandering presumably were inhibited yielding more consistent orientations of cross-strata. General paucity of other current features necessitates primary dependence on cross-stratification in the Solund area.

Sedimentary fabric

Pebble long-axis orientation in the Solund area is strongly preferred in a northwest-southeast direction throughout the area, with slightly more east-west trends to the north and west (Fig. 45). Variation in mean directions is surprisingly small, with all but one of the measurements of imbrication indicating preferential dips to the southeast (Fig. 47). These data suggest transport of coarser conglomeratic material from the southeast; little change in direction occurred from the beginning to the end of the recorded depositional history (see p. 74-79). The consistent 10°-30° imbrication dip angle correlates with the dip angles from other fluvial gravels. Scattered three-dimensional fabric analyses of elongate and flattened pebbles substantiates the above data (Figs. 48-52). The statistical orientations of blunt and tapered ends of elongate pebbles in the Solund Conglomerate (Fig. 45) confirm the consistent pattern of transport of debris from the southeast (see p. 74).

Textural and petrographic distributions

Other sedimentologic parameters such as rounding, sphericity, size, sorting, and geographic compositional distributions commonly provide useful criteria for deciphering the transport history of sediments, although each is dependent upon more indirect analysis than geometric measurements of current-formed sedimentary structures and fabric. Use of textural or petrographic data normally requires abundant horizontal control in the direction of transport plus vertical stratigraphic control. Use of these data for transport information is severely limited in the Solund area, because neither requisite is satisfied. Lateral control is present only in an east-west direction, perpendicular to the suspected transport direction, and no clear stratigraphic subdivision can be traced over the area. Nonetheless, some crude generalizations can be made, especially as the paleocurrent pattern has been determined by independent means.

intervals are included to give the reader a realistic impression of the dispersion of values. The number of readings for both inclined (planar-bounded) and trough types per locality is presented, with a data summary included in Appendix I.

The sample measurements suggest rather consistent paleocurrent flow in he Solund Devonian sediments from the southeast, with flow from the east ore prevalent in the western parts of the area. The overall vector mean for ross-strata is 323°, with a vector consistency (L) value of 51 percent and a standard deviation of ± 69°. Some localities indicate flow to the northeast; in fluvial sandstones, variations such as this would be expected as a result of meandering and local changes in stream courses. It must be remembered that paleocurrent data was collected from depositional structures, which may be expected to show more variation in orientation than erosive features of streams (Friend, 1965). The trough directions yield a more consistent pattern than inclined cross-strata, as expected if one assumes that many of the planar-bounded cross-strata were measured from the flanks of troughs (Appendix I).

Previous studies on the variability of cross-strata in fluvial sandstones support the supposition that the Solund deposits are stream deposits. Hamblin (1958) found a standard deviation of 23-83° in modern fluvial-deltaic stream deposits, with the value dependent largely upon stream gradients. Jungst (1938) found that stream cross-strata generally plot within a rose sector of 90-120°; in Solund, 65 percent of the total values plot within a 120° rose sector. Many other basin studies have shown good agreement between cross-strata directions and stream patterns, as well as paleoslopes (Potter and Pettijohn 1963). The Solund data suggests deposition by northwest-flowing streams draining highlands to the southeast.

Data from ripple markings suggest general transport from the east. Previous studies have indicated that fluvial current ripples are generally oriented perpendicular to the cross-strata dip directions and parallel to the depositional strike and paleoslope (Fahrig, 1961). As preserved ripples in the Solund sequence are rare (only three measured), and the particular local environment causing their formation and preservation is not known, the mean ripple orientation cannot be considered statistically significant.

The most consistently oriented paleocurrent structures are primary current lineation and pebble "trains", although limited sampling may have obscured a greater dispersion. The parallelism in orientation of pebble "trains" with other current-formed structures supports the hypothesis that these depositional features result from linear water flow, perhaps within a linearly restricted channel. The current sense of the current lineation is northwest-southeast, and

Size and roundness, in particular, demonstrate marked changes with transport in fluvial gravels. Size distribution in the Solund area cannot be related clearly to transport directions, however, suggesting that various tectonic or climatic pulses in time and space have produced an irregular distribution of maximum clast sizes (Fig. 53). Pebble roundness values have irregular distributions in distal areas, but indicate a relatively consistent decrease toward the southeastern edge of the area. This change apparently must be interpreted as largely time dependent, i.e., decreasing roundness in younger strata (Fig. 54). The steady decrease in roundness toward the southeast may also to some degree reflect proximity to provenance. The source area was probably relatively close to the present outcrop edge, considering the coarseness of the deposits. Certainly roundness should be quite sensitive to distance of transport in coarse fluvial deposits. No quantitative data are available on sorting variability, and composite sphericity measurements for all pebble lithologies show no relation to transport direction (Fig. 55).

The distribution of various pebble lithologies in the Solund Conglomerate suggests a general transport sense direction of northwest-southeast. The consistent linear trends in this direction, although extending through strata of different ages, more plausibly result from fluvial transport in this directional sense, rather than in east-west directions (Figs. 25-31). The consistent linear trends of areas of abundance as well as areas of scarcity of many pebble types in northwest-southeast directions can be traced laterally across correlative strata in an east-west direction; certainly very unusual depositional conditions would be required to explain such periodic gaps and "high" areas as due to eastward or westward transport of debris. Unusual dispersal patterns such as that of the very coarse gabbro pebbles (Fig. 28) strongly support this contention.

Synthesis

Abundant evidence demonstrates that sand and gravel debris was transported into and deposited in a basin occupying the Solund area by currents flowing toward the northwest. Data from both sediment types indicate transport from a more easterly direction in the western parts of the area. Greater consistency of conglomerate fabric orientation as compared with cross-strata data may reflect differences in depositional processes, rates of sedimentation, amounts of turbulence, or sizes of clastic material.

DEPOSITIONAL HISTORY AND TECTONIC RELATIONSHIPS

Background

The Solund Devonian rocks are unique among the areas of preserved terrestrial Old Red deposits of the North Atlantic region by virtue of the combined coarseness and thickness of the conglomerates. Somewhat unusual tectono-environmental factors must have caused the deposition of this material in the Solund area; paleogeographic reconstruction within the framework of a suitable stratigraphic-sedimentologic model hopefully will yield some understanding of the variables and responses controlling deposition. General geologic relationships described above suggest that the Solund deposits represent a portion of a small-scale clastic-wedge stratigraphic model (Sloss, 1952), with only the thickest, coarsest, near-source part of the wedge presently exposed. The depositional basin in the Solund area was apparently restricted in size and was of local occurrence, perhaps similar to the block-faulted basins of the basin and range province of the western United States or the Triassic basins of the North American Appalachian Mountains.

The Triassic Newark areas are generally accepted as models for terrestrial basins formed in geosynclinal areas after major orogenies. Kay (1947) used the term "taphrogeosyncline" for these intrageosynclinal structurally-produced basins of sediment accumulation. Krynine (1950), Reinemund (1955), and Klein (1962) have described some of the Newark basins in detail, permitting profitable comparison with the Solund area.

The Newark basins are typically half-graben structures with steep or step-faulted boundaries. The basins did not become involved in Alpine-type orogenies, but considerable post-depositional folding and faulting of the basins attests to continued crustal instability in these areas. Sedimentation was active during movements along the bordering fault, with thick continental deposits derived from the fault-bounded edges of the basins. Diabase dikes, sills and lava flows are common. Ponding of drainage at various stages in the basin histories produced lakes and swamps in which marls and coals were deposited.

Both the Newark basins and the Solund basin are characterized by thick, red-brown, coarse clastic sediments deposited subsequent to major orogenies in their respective geosynclinal belts. The scattered, separated distribution of the Norwegian Devonian basins along the longitudinal axis of the Caledonian geosyncline is similar to that of the Newark basins, which extend intermittently from Canada's Maritime Provinces to North Carolina. The Triassic basins individually are larger in areal extent, with fanglomerates preserved along the margins of the sedimentary influx from the uplifted source areas. These fanglomerates record recurrent uplift and rejuvenation of the bounding fault scarps and downwarping of the basins of sediment accumulation.

If the Newark and Solund basins are indeed as similar as they appear to be, the detailed sedimentologic data presented in the present paper should permit further clarification of the stratigraphic-sedimentologic model in the area of accumulation of the coarsest sediment, closest to the provenance.

Processes of deposition

General stratigraphy, sedimentary structures, paleocurrents, textures, and pebble fabric suggest deposition of the Solund Conglomerate by fluvial processes. The variety of sedimentary structures and sizes of clastic materials indicate a range of depositional processes and sub-environments within the fluvial macro-environment. Fortunately, much recent work on modern sediments and experimental studies provides considerable background for interpretation of depositional processes from preserved bed forms and stratigraphic associations (e.g., Harms and Fahnestock, 1965; Allen, 1965b, 1966; McKee, 1957; Sundborg, 1956).

Proximity of the Solund Devonian to other Devonian areas in western Norway that contain remains of fresh-water fish and land plant fragments further substantiates a terrestrial sediment origin hypothesis. Evidence for glacial or eolian transport or deposition is not found; windfaceted or striated fragments do not occur. In addition, stratigraphic, sedimentologic and paleontologic evidences for marine, deltaic, beach, lagoonal, swamp, or lacustrine conditions are lacking.

Sedimentary structures indicating current processes, probably fluvial, are channels, abundant flat-stratification and trough-scoop cross-stratification, primary current lineation, ripple-drift bedding, and fining-upward cyclical deposition. Consistent orientation of elongate pebbles and pebble imbrication, as well as paleocurrents, over the entire area suggests uniformly oriented depositing currents to be found in fluvial environments with relatively high gradients.

Pebbles and cobbles larger than about 2.5 centimeters are known to be transported only in the upper-flow regime (Harms and Fahnestock, 1965). The areas of thick, irregularly stratified Solund Conglomerate, then, with abraded boulders up to three meters in diameter, represent transportation of debris in the upper-flow regime. Matrix material probably resulted from infiltration of finer gravel and sand-sized material into interstices during periods of decreased discharge. The pebbles, cobbles and boulders represent tractive, or bed loads, while the sand may have been largely suspended load, as observed in gravels of the Black Hills (Plumley, 1948). This difference in transportation process may thus partly explain differences in abrasion history and resulting textural parameters of the different sizes of clastic material.

Qualitative interpretation of bed form structures in the sandstones and finer conglomerates indicates variability, in some cases repetitively, between upper- and lower-flow regimes (see p. 58). The sandstones were deposited under a wider range of current conditions than the coarse conglomerates, with flat-stratification and primary current lineation indicative of the upper-flow regime, and ripple markings, ripple-drift bedding, and cross-stratification indicative of the lower-flow regime.

The thin, widely-occurring sandstone lenses within the thicker conglomerate sequences, characterized by flat-stratification or very gently-plunging troughs, with sporadic primary current lineation, probably resulted from deposition in a lower part of the upper-flow regime during local or temporary decreases in current velocity. Unidirectional flow, common in fluvial environments, produces flat-stratification and primary current lineation. The general low inclination angles associated with cross-stratification in the Solund area (Appendix I) suggests relatively higher velocities and depth ratios than would more normal, steeper inclinations (Jopling, 1965). Some of the low-inclination cross-strata and gently-plunging troughs have up-current dips, indicating current flow directly opposite to that of the majority of orientations (see rose diagrams, Fig. 56). Rather than being errors in measurement, the writer believes that these structures represent normal upper-flow regime anti-dune bed forms, preserved in sandstones by rapid burial and deposition of overlying conglomerates transported in the upper-flow regime. Up-current-dipping strata observed by Harms and Fahnestock (1965) were uniformly of low inclination (less than 10° in sand-sized material), and considered to result from anti-dune bed forms. This structure is normally associated with the highest transport rate for sediments, with current velocities generally higher in the upper-flow regime as well.

In areas of thick sandstone accumulation, dominated by abundant small and large-scale cross-stratification, lower-flow regime conditions prevailed. Ripple markings, formed during still slower rates of sediment transport in the lower-flow regime, are common. Fining-upward cycles indicate repetitive changes from upper-flow regime conditions at the base or initiation of deposition, changing upward to the lower-flow regime at the top of each individual cycle.

In general, predominantly lower-flow regime stream flow characterizes low gradient perennial streams with prominent meanders, erosion-resistant banks, low sediment loads and deposition of sand in cross-stratified sets. Streams characterized by upper regime flow, on the other hand, are characteristically either high gradient, perennial streams, or high gradient ephemeral streams with abundant sedimentary load and less-resistant banks (Harms and Fahnestock, 1965).

The streams draining into the Solund area had high competence and high capacity, with the finer silt and clay-sized fractions not deposited anywhere within the present limits of the structural basin. The fines were probably winnowed out and transported further north or west. Paleocurrents indicate a more westerly transport in the northern and western parts of the area, suggesting a continuation of the basin beneath the present North Sea, where sandstones, siltstones, and shales presumably were deposited. Gravel debris became rounded as a result of very rapid abrasion rather than long transport distances; roundness normally increases rapidly at first, especially so in steep gradient streams, which tend to increase the amount of abrasion (Barrell, 1925). The sands are poorly rounded, but either very long transport distances or long abrasion histories are required to round sand-size clasts; neither stipulation was true of the Solund area, where sediment burial must have been rapid.

Examination of sedimentary structures and detailed stratigraphy reveals no evidence of significant meanders in channels, which are invariably straight where visible. No deposits or typical cross-sections interpretable as point bars were noted, suggesting that streams were relatively straight, or of low sinuosity (Wright, 1959). No clearly defined overbank, or topstratum deposits, such as natural levees, crevasse-splays, flood basins or backswamps were observed (Wolman and Leopold, 1957). The streams draining the Solund basin did not form typical floodplain deposits characteristic of mature streams. They did not accrete laterally and vertically in the normal sense, but were quite different in character, as the abundance of coarse conglomerate and preserved upper-flow regime structures indicates.

Channel formation, and subsequent filling, indicates periodic entrenchment or incisement of stream channels rather than just lateral migration. Deepening is normally associated with increased discharge, often forming "channel within channel" structures. Filling of channels with coarser gravels is common in the Solund sediments, suggesting origin as channel bar deposits (Doeglas, 1962). Channel bars are found in braided streams, with gravel forming bars that are built downstream by lateral accretion. Commonly the deposits will fine upward, with gravel at the base and large- and small-scale cross-stratification within the bars. Some of the finer-grained pebble "trains" in the sandstone areas appear to be channel bar deposits (Fig. 37).

Thin lenses and accumulations of conglomerate and pebbly sandstone within thicker sandstone sequences suggest significant residual accumulation of coarse material in the deeper parts of the stream beds as channel lag deposits. The clasts may be concentrated into sheets by winnowing, with sand transported over the lag deposit, resulting commonly in a fining-upward sequence (Lattman, 1960).

The occurrence of thin sandstone strata within pebbly sandstones, containing gently inclined cross-strata or less commonly asymmetrical ripple markings, is thought to result from swale-fill deposits of alluvial channel bars (Doeglas, 1962). These thin sandstone bodies originate from finer material deposited in backwaters of channel bars whose upstream ends may be closed off during low water stages; return to high water stage results in the thin elongate sandy lenses becoming covered once again with sandy gravels from the migrating bars.

The irregular nature of the conglomerate and pebbly sandstone layers within areas of thick sandstone accumulation, the preserved sedimentary structures, coarseness of the deposits, and well-defined fabric all suggest that the depositing streams had braided channel patterns characterized by successive division and rejoining with islands. These channels are generally steeper, shallower and wider than meandering or straight channel patterns. The three types of channel patterns are known to form a continuum, with the specific channel form a function of discharge, amount of load, type of load (grain size), width, depth, velocity, slope and roughness. All three types occur throughout the entire range of discharges, but one type will form as a result of certain combinations of flow factors. None of the forms are unstable hydro-dynamically, for all three separately are in quasi-equilibrium (Leopold and Wolman, 1957).

In summary, braided streams characterized by upper-flow regime conditions, and with consistent orientations over the entire preserved basins of deposition were responsible for transportation and deposition of the coarse clastic Devonian rocks of the Solund area. No open framework packing or chaotic fabrics were observed, indicating that mudflow or earthflow deposition did not take place.

Environment of deposition

Reconstruction of the depositional environment of the Solund sediments requires consideration of sedimentologic, stratigraphic, paleotectonic, paleogeographic, paleoclimatic, and paleontologic data coupled with available information from modern environments. Many of the above types of data are scarce or lacking, but considerable inference is possible nevertheless. The writer feels that the Solund Conglomerate resulted from alluvial fan deposits built out to the northwest by streams draining a highland to the southeast. Adjacent fans coalesced into a broad piedmont plain sloping to the northwest.

Blissenbach (1954) defined alluvial fans as sediment bodies built up by streams at the base of mountain fronts, with the apex of a fan being the point at which the stream emerges from a mountain canyon (or the highest elevation of the fan). The fanhead area is that part of the fan closest to the apex, and the fanbase is the outermost, or lowest part of the fan. He listed ten criteria for recognition of ancient alluvial fan deposits, most of which are found in the Solund area: (1) coarse detrital sediment facies, (2) abrupt changes in maximum pebble size and roundness, (3) common sheetflood deposits, (4) sorting generally in the range 0.5-3.0, (5) variable cross-stratification, (6) common channel cut and fill structures, (7) pebbles with pronounced up-source imbrication, generally less than 30°, (8) stratal thicknesses ranging from one inch to twenty feet, (9) common lenticularity of deposits, and (10) interfingering of fan deposits toward the source area with talus deposits, which are distinguishable by lack of sedimentary structures, poor rounding of fragments, and coarser fragment sizes.

Fans are thought to be most common in arid to semiarid regions of bold relief, where large amounts of erosion and deposition follow flash denudations. However, they are also known from subarctic areas (Leggett, et. al., 1966) and mountainous areas in various climatic zones, such as the Himalayas, Alps and Andes. Climatic data suggests that the greater the amount of precipitation in an area, the less common are mudflow deposits in fan sequences, and that precipitation greater than 25 inches per year will generally prevent mudflow formation (Blissenbach, 1954). Fossils are typically lacking in fan deposits, although plants or plant fragments may be locally abundant.

Deposition on arid alluvial fans is by sheetfloods resulting in blanket deposits from water emerging out of streams channels during times of high rainfall, streamfloods resulting in linear deposits during times of high rainfall confined to channels, or by normal stream processes supplying a steady amount of discharge and debris confined to channels (Blissenbach, 1954). Bull (1964b) classified deposits of arid alluvial fans in California into mudflow, water-laid, and intermediate or transitional deposits. Mudflow deposits result from viscous muddy sediment flows that yield blanket-shaped sediment bodies characterized by a chaotic orientation of gravel-size fragments, very poor sorting, high clay matrix content (average 31 percent), and abrupt well-defined flow margins. These correspond to the streamflood deposits of Blissenbach. Water-laid deposits are well-sorted sandstones and siltstones, averaging 6 percent clay matrix, and deposited as irregular sheets by braided streams or in channels of entrenched streams. Intermediate deposits are characterized by properties transitional between the above sediment types.

The Solund Devonian deposits all were water-laid, with the clay-sized fractions winnowed out and a well-developed pebble fabric formed in the upper-flow regime. They cannot, then, be considered fan sediments characteristic of an arid environment. Moreover, paleontologic evidence from nearby Devonian basins, including plant debris and fresh water fish remains, do not suggest an arid climate during Devonian time in western Norway.

Krynine (1950) discusses at length the nature and origin of arkosic sediments, including arkosic fanglomerates, formed under humid and even tropical climates. The mature weathering of humid regions produces widespread red soils, which yield the red color of arkoses resulting from erosion of uplifted areas containing these soils. However, fresh unweathered detritus will be supplied in still greater amounts from vertical erosion of steep, incised canyons dissecting rugged uplifted source areas. Arkoses with fresh feldspars and other unstable minerals can thus dominate the petrography of thick alluvial fan accumulations of humid regions. The necessary factors responsible for alluvial fan formation are rugged relief in the source area, a sharp break in slope at the base of this area (commonly caused by active faulting of basin margins), and intermittent or seasonal rainfall distribution. Thus, fanglomerates will form in arid, subarctic, temperate or humid regions wherever suitable topography and significant catastrophic or seasonal fluctuations in rainfall occur. The alternation of wet and dry seasons in many tropical areas can thus contribute to humid-fan formation.

The fanglomerates of the Triassic basins, thought to have been deposited under humid climatic conditions, have not been described in detail with respect to their sedimentology. In addition, little data is available from modern fans in humid regions. The writer, of necessity, then, will compare the Solund fanglomerates with modern arid alluvial fan deposits about which much is known. This procedure should reveal interesting similarities and differences, which hopefully will be corroborated by future sedimentologic studies of humid fans.

Streams flowing on arid fans form either braided, straight, or meandering channels, with straight channels most common for ephemeral streams, meanders for entrenched streams in the fanhead areas, and braided patterns for the midfan areas of distributary streams, but not in the fanhead area or in entrenched streams. Fanhead entrenchment has been shown to correlate with periods of high rainfall in Fresno County, California (Bull, 1964a). In the Solund area, the fanhead deposits located to the southeast have not been preserved, having been eroded away. Thus, only the sands and gravels of midfan braided streams are found; abundant channeling in these deposits may be suggestive, however, of considerable entrenching in the original fanhead area. Lateral up-source gradation into talus deposits or sedimentary breccias, common in modern alluvial fans (Drewes, 1963), is not preserved here.

Sedimentary structures and stratigraphy of the Solund deposits correspond roughly to published descriptions from modern arid alluvial fans. McKee (1957) observed that the stratigraphy and structures of arid fans were dependent on the relative contributions of sheetflood, streamflood, and stream deposits, with only stream and streamflood deposits producing the sorting, stratification, and gravel fabric noted in the Solund area. Stratified fan deposits of the Santa Rita Mountains are irregular and lensing in nature, with low dip angles. Thin layers or tongues of gravel alternate with sandstones and siltstones, and lens-shaped bodies of parallel strata with low initial dip angles similar to those in the Solund deposits are commonly found as channel-fill deposits (McKee, 1957). Blissenbach (1954) noted prominent cross-strata of lenticular geometric shapes in stream deposits as channel fills, with gravel commonly at the base of the fills. Boulder trains, or linear zones of coarse debris, are common on fans. Extremely large boulders can be transported long distances from the fan apexes by confinement of floods to deep, narrow channels of the fanhead area, thus yielding temporary increases in transporting competence (Beaty, 1963). The very coarse boulder trains of the Solund deposits can be explained in this manner.

The consistently oriented areal paleocurrent pattern of the Solund Conglomerate is typical of alluvial fan deposits, where current flow and stream pattern directions depend primarily on the direction of fan slope. Lack of significant meanders and braided nature of stream channels on the regional slope of coalescing piedmont deposits yields well oriented bed form structures. The Solund paleocurrent pattern suggests in part a radial pattern of current movement from the southeast, perhaps a result of radiating distributaries on convex fans (Fig. 56). The well-defined conglomerate fabric suggests deposition by water-rich streamfloods, rather than viscous, mud-rich streamfloods. A large percentage of these gravel deposits are braided stream deposits as well. Paleocurrent patterns from the Triassic Newark basins are also consistently oriented perpendicular to the bounding fault margins.

The slopes of arid fans vary greatly, but are generally less than 10°, with those greater than 5° classified as steep (Blissenbach, 1954). The initial dip of the Solund fanglomerates probably varied through time, with different slopes prevailing during periods of gravel or sand deposition, and the slope angle decreasing away from the fanhead area. The coarseness, fabric orientation, and apparent rapid burial of sediment suggests a relatively high slope angle to the Solund fans.

The coarse-grained, irregularly developed cyclic stratification of the Solund deposits can best be understood as resulting from alternating channel bar and swale-fill deposition and periodic flooding of braided channel patterns in the midfan areas. No evidence indicates origin from lateral migration of streams, as suggested for finer-grained fluvial cyclothems (Allen, 1964). Ultimately, the build-up of thick, repetitive fining-upward cycles with coarse debris is probably related to tectonic activity in the source area, with individual cycles of conglomerate deposition controlled by climatic factors or channel bar migration.

The distribution of maximum clast sizes in the Solund deposits is consistent with observations from modern arid fans. As a general rule, size decreases from fanhead to fanbase, with the coarsest percentile decreasing downslope, and clay content increasing downslope (Blissenbach, 1954; Beaty, 1963; Bull, 1964b; Drewes, 1963; Sharp, 1948; Ruhe, 1964). Bluck (1964) found an exponential decrease in maximum pebble size away from fan apexes, both for stream and mudflow deposits, as a result of selective sorting during transport. The maximum pebble size map for the Solund Conglomerate indicates a rough increase in size along many parts of the fan deposits toward the southeastern margin, or fanhead area (Fig. 53). The many irregularities in the size distribution, however, are explained by fanhead trenching, which allows deposition to be irregularly spread out further down the fans (Buwalda, 1951).

Blissenbach (1954) found a linear relationship between roundness of clasts from the same size grade and distance of transport on arid fans, with no changes in sphericity. Decrease in pebble roundness toward the southeastern margin of the Solund area, or the fanhead area, is thus probably a reflection of approach to source; the irregular sphericity pattern is also consistent with data from modern fans (Figs. 54 and 55). Arid fans containing only angular clastic material result from mudflow deposition, which produces minimal abrasion during transport of debris (Ruhe, 1964).

The lithologic composition of modern fans, as well as the Triassic Newark fan deposits, correlates closely with provenance geology. This is a result of short transport distances, limited chemical weathering, and minor lateral mixing or transport between adjacent fans, although mixing increases away from the fanhead areas by radial coalescence of adjoining fans. From east to west, three distinct fan complexes can be recognized in the Solund Conglomerate on the basis of lithologic variations in pebble content (see p. 51). Close correlation of clast distributions to nearby basement geology suggests relatively short transport distances.

The linear northwest-southeast trending areas of higher relative percentages of particular pebble lithologies is indicative perhaps of entry of a particular lithology consistently through time from the same mountain canyon stream as a linear tongue, with restricted lateral mixing (Figs. 24-31). In several cases, completely separate linear tongues occur, indicating introduction of the pebble type from distinct sources to the southeast (Fig. 28).

Modern fans of the western United States have stratigraphic thicknesses up to about 700 meters, considerably less than the preserved 5,200 meters of the Solund Conglomerate. However, ancient fan deposits formed near active fault zones attain much greater thicknesses, such as the almost 10,000 meters of coarse Tertiary alluvial debris accumulated at the base of the San Gabriel Fault scarp in the Ridge Basin of southern California (Crowell, 1954). The Triassic Newark basin sediments attain thicknesses of about 5,000 meters in Connecticut (Krynine, 1950) and 3,000 meters in North Carolina (Reinemund, 1955). The maximum original thickness of the Solund deposits is difficult to estimate, but certainly 10,000 meters is not unreasonable.

The preserved part of the Solund fanglomerates cover an area of about 800 square kilometers, with probable fan radii of 20-25 kilometers. Modern fans range in size from one square kilometer up to about 900 square kilometers (Bull, 1964a), with some individual fans in the southwestern United States having radii up to 10 kilometers (McKee, 1957). In general, the fan size is related to the size and lithology of the drainage basin (source area), with large, deep, canyons producing broad fans of low gradient, and short ravines producing small fans of steep gradient.

The Solund fanglomerates represent a very large, broad coalesced fan complex built out to the northwest from a rising source area to the southeast of the present Devonian outcrop area. Fan radii and area, as well as coarseness and thickness of sediment, suggest alluvial fans of considerably larger scale than those found presently in the arid regions of the western United States. The drainage basin covered a very large area of bold, rugged relief, with diverse rock types; it was cut by large, deep canyons supplying continuous amounts of fresh detrital material from vertical erosion. Large amounts of debris were transported to the north and deposited on the fan piedmont by streams characterized by high discharge, high sediment capacity and competence, braided channel patterns, relatively steep gradients, and abundant amounts of rainfall in a humid climate. The climate also must have been steady during the period of deposition, for no finer lacustrine or swamp deposits are recorded, as is common in the Newark basins. Also, no development of weathered depositional interfaces or red soil formation was noted in the sedimentary sequence, suggesting rapid burial of the coarse debris. Sedimentary structures in the deposits indicate periodic flooding and channel cutting, perhaps related to seasonal fluctuations in rainfall.

Tectonic factors in Devonian sedimentation

Restoration of the tectonic framework of sedimentation in the Solund area must be made by consideration of regional Devonian tectonics in western Norway, the North Atlantic region in general, and by analogy with modern sedimentary deposits showing similar lithostratigraphic features. The fact that the size of clasts does not gradually become finer upward in the stratigraphic section of the Solund Conglomerate indicates that erosion was vigorous and that uplift occurred throughout the period of recorded deposition. Because the fanhead areas are not presently exposed, and correlation within the fan deposits is virtually impossible, only a rough relationship between sedimentation and tectonics can be determined.

Tectonic-sedimentologic relationships can be especially complex in alluvial fan deposits, with youngest deposits found either in the fanhead areas closest to the apex, or farthest out in the lower parts of the fan (fanbase). The site of new fan deposition depends upon stream gradients as well as rate and location of vertical uplift. Segmented fans, or depositional fan surfaces characterized in longitudinal cross-section by a series of straight-line segments at different slope angles, result from periodic tectonic uplifts of the source area (Bull, 1964a). Processes of this type, as well as the nature of particular fan morphologies, cannot be discerned in the Solund Conglomerate; uplift of the drainage basin, whether periodic or continuous, can only be inferred from the abundant influx of coarse debris from the southeast.

Alluvial fans are built up at the base of mountain fronts usually bounded by faults or sharp flexures, commonly in areas of block faulting or horst-graben structures (Allen, 1965b). The original bounding fault margin, thought to form the southeastern edge of the depositional basin of the Solund area, probably lies to the southeast of the present structural basin. The northeast-southwest trending Sognesjøen undoubtedly follows the approximate trend of that fault, or fault zone, and may have resulted from differential erosion along its strike. A wide zone of step faults, with displacements occurring within a linear area rather than along a single faulted surface, probably formed the southeastern boundary of the Solund basin. Half-graben origin of the Solund fanglomerate deposits seems most plausible on the basis of data presented herein. The present south-bounding Solund Fault, in fact, may represent one of the older fault surfaces or a zone of weakness along which later thrusting occurred.

Considerable post-depositional faulting disrupted the fan deposits, including the Solund Fault and abundant minor faults (see p. 22-28). Formation of the Lågøyfjorden anticline was also post-depositional, as paleocurrent data suggests uniform transport of all sediment from the southeast.

Evidence presented for syndepositional as well as post-depositional igneous activity in the area suggests crustal instability during sedimentation related to penecontemporaneous uplift of the drainage area to the southeast. The extrusive flows and breccias of keratophyre occur only near the crest of the anticline, indicating igneous activity and crustal instability in this area during sedimentation. Later arching of the Lågøyfjorden anticline led to intrusive igneous activity near Hersvik. Igneous activity is common in many recent arid fans of the western United States (Drewes, 1963).

At least two periods of tectonic activity, then, are preserved in the Solund area following the Caledonian orogeny at the end of the Silurian period. The first yielded uplift of a rugged area to the southeast, resulting in the spreading of alluvial fan deposits to the northwest during the Devonian. The second resulted in post-depositional folding and faulting of the Devonian fanglomerates. Both deformations were of the brittle type, occurring in the upper parts of the crust.

Paleogeography

All evidence suggests generally analogous paleogeography of the Solund fanglomerates and the Newark Triassic humid fan deposits. The larger volume of coarser, well-abraded debris in the Solund area requires some modification of the Newark model, however. The intense abrasion of Solund debris records transport on steep slopes over relatively longer vertical distances. The moderate relief needed to explain the Newark deposits must probably be modified with respect to the Solund fanglomerates, which were derived from an area of mountainous relief.

The red sandstone matrix of the basal sedimentary breccias underlying the Solund Conglomerate may further suggest a humid climate, which produced a red soil by chemical weathering. Fine hematitic films on many clastic grain surfaces perhaps reflect soil formation on the inter-canyon areas of the uplifted drainage basin. Calcite such as that filling interstices and fractures in the Solund Conglomerate is common in humid areas with seasonal rainfall, and is not indicative of arid climates in any way (Krynine, 1950). The assumed primary dip and lack of fines in the fanglomerates allowed easy circulation of ground water and resulting thorough cementation and induration.

DEVONIAN HISTORY OF WESTERN NORWAY

The various preserved areas of Devonian rocks in western Norway were apparently local, separate depositional basins, whose sediments were derived from surrounding nearby source areas. The lithologies of clastic debris in each basin suggest local derivation, with the coarse Solund deposits thought to be alluvial fan deposits. Bryhni (1964a, 1964b) described the Hornelen area as an infilled graben, with sediment derived laterally from the upfaulted bounding scarps and deposited in the resulting basin in a migrating pattern down the tilted longitudinal axis of the graben. With what is now known of the Solund deposits, and the presence of thick coarse terrestrial sediments in the other basins (Kvamshesten, Håsteinen, Byrknesøy—Holmengrå), it is apparent that the Nordfjord—Sognefjord area must have undergone vertical tectonic movements during the Devonian period, producing block-faulted and horst-graben structures. This tectonic activity initiated sedimentation in the structurally formed, separated basins, resulting in coarse terrestrial deposits of considerable thickness.

The Devonian deposits of western Norway reflect post-Caledonian tectonic activity, probably from general tensional stresses resulting from crustal uplift in the final stages of the Caledonian orogeny. Syndepositional post-Caledonian tectonism also occurred in the Trondheimsfjord and Röragen areas. The respective basin deposits of the western coast were not exactly synchronous, but apparently formed at different times in the Devonian. This is suggested by differences in floral assemblages.

The western Norwegian Devonian deposits were previously thought to have been deposited in uniformly westward-plunging synclinal basins developed in the underlying Cambro-Silurian schists, which surround each of the Devonian areas (Fig. 1). Deeper-level gneisses and igneous rocks found in the inter-basinal areas resulted from erosion of the crests of intervening anticlines (C. F. Kolderup, 1916a). This hypothesis, however, does not adequately explain the formation of coarse fanglomerates and other terrestrial deposits, the thick sequence preserved, or evidence of half-graben formation and one-sided derivation of sediments.

Recent work indicates that the supposed Cambro-Silurian synclines containing the Devonian sediments are not simple synclines, but parts of complex structures produced by the Caledonian orogeny. Bordering mylonites and Cambro-Silurian phyllites have a foliation parallel to the trends of faults bounding the Devonian areas, giving the false impression of synclinal structures. The foliation of these mylonitic rocks must be late Devonian or post-

Devonian in age, and a result of the fault movements. Investigations along the eastern margins of the supposed westward-plunging synclines have revealed vague boundaries between the schists and gneisses, with a gradation into higher metamorphic facies in some areas (F. J. Skjerlie and I. Bryhni, personal communications). Detailed examination of the structural attitudes of the Cambro-Silurian rocks of the Solund area by the writer fails to reveal the presence of a broad syncline, but instead indicates a more complex structure.

The writer suggests that block faulting and graben formation with subsequent erosion of highlands and deposition in basins, is responsible for the surrounding outcrop patterns of Cambro-Silurian schists with respect to the Devonian basins. The uplifted interbasinal highland areas were rapidly eroded, supplying sediment to the adjacent basins, thus eventually exposing higher-grade metamorphic and igneous rocks that originated at much greater depth. This process explains the presence of the so-called "Caledonian basal gneiss" between the Devonian areas in the Nordfjord—Sognefjord region (Fig. 1). The immediately surrounding "synclinal" schists have been exposed by extensive post-Devonian uplift and denudation of the Norwegian coastal area, such that the "basal gneiss" areas are now at lower topographic elevations than the Devonian basins. The dissection and erosion of the Devonian areas, especially along the original basin margins (i.e., the fanhead parts of the Solund fanglomerates), has exposed the immediately underlying schists in these areas, rather than the deeper-seated gneisses. Post-depositional folding and faulting of the Devonian areas have facilitated this process, and also caused the schists to be exposed in other parts of the basin areas (i.e., the Lågöyfjorden anticline of the Solund area).

The Devonian deposits, then, are thought to occupy structurally formed east-west trending fault basins rather than simply eroded lowlands. Graben formation probably proceeded intermittently during the Devonian period, yielding deposition contemporaneous with tectonism at various times. It is reasonable to expect that there were additional basins of deposition in the Devonian that were eroded during subsequent uplift of the Scandinavian landmass, but probably there never were extensive sheets of terrestrial sandstones as characterize the Devonian of southern Great Britain. The isolated occurrences of Devonian rocks in the Trondheimsfjord and Röragen areas, as well as abundant Devonian terrestrial deposits in Scotland, the Orkney and Shetland Islands, Bear Island, Spitsbergen, and eastern Greenland, suggest somewhat similar tectonic and sedimentologic conditions throughout this area: local basins of coarse sediment accumulation formed by post-Caledonian tectonics.

Because only the lower stratigraphic levels of the Devonian basins are preserved, it is difficult to predict the original extent of the Devonian in Norway. Presumably the basins extended further westward, where finer clay-siltstone deposits would be expected either as flood plain or fanbase sediments. Available paleocurrent data suggests local derivation of detritus, with no large-scale blanket-type sedimentary covers. The Devonian deposits of Norway are completely terrestrial, with no evidence of deltaic environments or gradation into marine rocks, as occurs southward in Great Britain or eastward toward the Russian platform. Local climatic conditions may have been variable through time, as expected in an area of rugged relief and intermittent uplift.

Post-depositional folding and faulting represents the effects of the Svalbardian disturbance of Vogt (1929b). That this deformation in western Norway is of Devonian age and not later is suggested by analogous tectonism throughout the North Atlantic region, where younger post-Devonian rocks and definable stratigraphy have enabled dating of the Svalbardian movements as Lower to Upper Devonian in age. Many structural features in the older rocks to the south and east may have been caused by Svalbardian movements, but are not recognized as such because of insufficient knowledge about tectonism in the Devonian basins themselves. Some of the faults bounding the Devonian basins can be traced into older rocks, and presumably formed during the Svalbardian disturbance. The effects of the deformation extending southeastward into the Precambrian foreland are ill-defined, but they are probably of some significance, especially when the extent of Devonian tectonism from Spitsbergen to Great Britain is considered.

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Abbreviations:
NGU = Norges Geologiske Undersøkelse
NGT = Norsk Geologisk Tidsskrift.

APPENDIX I

Summary of cross-stratification paleocurrent data

Localities listed below consecutively from east to west across Solund area, with map representation in Figure 56. Abbreviations used:

(1) n = number of measurements at locality,
(2) amp = mean amplitude of cross-strata in centimeters,
(3) inclin = mean inclination angle of cross-strata in degrees,
(4) W = width of cross-strata troughs in centimeters,
(5) curr = mean current direction determined by vector method (Curray, 1956),
(6) L% = percentage value of L, or vector consistency, and
(7) S.D. = standard deviation, computed mathematically.

	Inclined cross-strata						*Trough cross-strata*						
Locality	n	amp	inclin	curr	L%	S.D.	n	amp	W	inclin	curr	L%	S.D.
Lifjell Peninsula	3	9.3	12.0	350	96	20							
Losna	4	13.3	17.9	329	97	17							
Hamnefjell	11	16.3	11.0	23	71	42	6	15.8	84.2	14.8	330	89	30
SE Indre Solund	14	11.4	14.2	318	66	54	3	5.7	61.0	8.7	322	99	6
NE Indre Solund	14	10.6	14.5	359	82	35							
Kråkevåg	28	10.6	14.2	23	60	60	16	10.2	66.0	7.5	335	61	77
Eide	9	9.0	12.1	353	39	80	3	6.7	73.0	6.7	304	33	126
E. Polletind	39	13.2	12.5	284	16	96	4	6.0	78.0	6.5	317	98	9
W.Polletind	47	12.6	16.0	299	81	37							
Nesøy	16	8.3	13.6	327	90	26							
SW Indre Solund	25	14.0	18.3	328	34	85	8	12.3	80.1	13.1	341	58	66
NE Steinsundøy	4	18.8	12.0	16	81	42							
NW Steinsundøy	15	11.0	16.8	290	46	86							
SW Steinsundøy	3	7.7	9.7	279	98	11							
N Ravnøy	5	11.0	16.8	7	37	97	3	12.7	135.0	22.7	261	51	75
Gåsvær	8	7.5	14.8	279	60	63							
Begla	14	11.5	14.2	270	95	18	5	10.6	77.6	5.8	304	24	101
Utvær	3	8.0	20.3	8	57	70	14	7.0	52.6	7.4	325	67	65
Total	264	11.9	14.8	321	51		67	11.1	80.3	10.5	325	58	

(includes additional scattered individual measurements)

Combined total measurements

n	curr	L%	S.D.
331	323	51	69

APPENDIX II

Summary of pebble roundness and sphericity data

Tables below present comparative statistics from roundness-sphericity measurements of particular pebble types to overall measurements of the Solund Conglomerate at several localities, with numerical values from visual comparative charts (Krumbein and Sloss, 1958, p. 81). Abbreviations used:

(1) n = number of measurements at locality,
(2) Rmean = mean of roundness measurements,
(3) Smean = mean of sphericity measurements,
(4) Var = variance,
(5) S.D. = standard deviation,
(6) cgl = conglomerate
(7) sch = schistose,
(8) qtzite = quartzite.

Locality	Pebble type	Roundness for pebble types				Roundness for conglomerate			
		n	Rmean	Var	S.D.	n	Rmean	Var	S.D.
Eide	gabbro	10	5.00	2.22	1.49	25	5.40	1.92	1.38
Tveranger	gabbro	10	7.00	0.44	0.67	25	6.56	1.67	1.29
Nåra	gabbro	10	6.30	0.46	0.68	25	6.44	1.17	1.08
Nåra	basalt	10	6.80	0.84	0.92	25	6.44	1.17	1.08
Nesøy	sch qtzite	10	6.60	1.60	1.27	25	5.88	1.44	1.20
Tveranger	sch qtzite	10	6.70	0.46	0.68	25	6.56	1.67	1.29
Nåra	sch qtzite	10	6.50	0.72	0.85	25	6.44	1.17	1.08
Nåra	vein quartz	10	6.50	0.94	0.97	25	6.44	1.17	1.08
Nåra	graywacke	10	6.50	2.28	1.51	25	6.44	1.17	1.08

Locality	Pebble type	Sphericity for pebble types				Sphericity for conglomerate			
		n	Smean	Var	S.D.	n	Smean	Var	S.D.
Eide	gabbro	10	7.60	1.60	1.27	25	5.64	4.58	2.14
Tveranger	gabbro	10	6.20	2.40	1.55	25	5.84	3.61	1.90
Nåra	gabbro	10	7.10	2.10	1.45	25	5.96	3.31	1.82
Nåra	basalt	10	7.30	2.68	1.64	25	5.96	3.31	1.82
Nesøy	vein quartz	10	5.50	3.61	1.90	25	5.96	3.31	1.82
Tveranger	sch qtzite	10	5.60	3.38	1.84	25	5.68	4.41	2.10
Nåra	sch qtzite	10	5.60	2.71	1.65	25	5.84	3.61	1.90

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