SVERIGES GEOLOGISKA UNDERSÖKNING

SER C NR 621 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 61 NR 6

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PETROLOGY OF JOTNIAN ROCKS IN THE GÄVLE AREA

EAST CENTRAL SWEDEN

WITH ONE PLATE

STOCKHOLM 1967

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CONTENTS

ABSTRACT

The Gävle Jotnian is essentially a red subarkosic sandstone with considerable beds of arkose, some conglomerates, and minor argillaceous interbeds. The detritus was derived from three main sources: (1) Archean igneous and metamorphic rocks, (2) quartz and feldspar porphyries, and (3) a formation of well-cemented pressolved sandstone similar to the Jotnian sandstones. A model of compaction, cementation, and pressure solution relationships is developed and employed to investigate the lithification history of the sediments and the sequence of tectonic and hypabyssal magmatic events in the area. Early quartz cementation of the Gävle Jotnian was interrupted by the local deposition of chlorite and carbonate cements associated with the intrusion of Gävle diabase sills into the incompletely cemented sediments. The oliviniferous Mackmyra diabase intruded into a solidly quartz-cemented sediment causing the formation of remelting granophyres which are conspicuously absent at the contacts of the Gävle diabase. The main phases of tectonic deformation succeeded the diabase intrusions and resulted in the division of the sandstone area into several blocks separated by faults and the tilting of the sediments especially in the eastern parts of the region. Whether the latter development essentially involved folding or faulting could not be definitely established. The sedimentation regime of the Gävle Jotnian is discussed.

INTRODUCTION

Precambrian postorogenic sediments of Jotnian age classification are widely spread in Scandinavia and comprise thick diabase-intruded arenites known as the Dala-Trysil, Satakunta, Nordingrå, Mälar, and Gävle sandstone as well as the allegedly Jotnian argillaceous facies in Northern Finland. The Gävle rocks, though first mentioned as early as in the XVIIIth century, were hitherto poorly known and details of their lithology are given here for the first time. The main objective of this investigation was to ascertain the petrological characteristics of the Gävle Jotnian for comparison with previous work on the Precambrian sediments in the Mälaren and Baltic Sea areas. It was further anticipated that specific petrological differences might be established to aid in distinguishing the Jotnian from other late Precambrian sediments currently under investigation in Southern Sweden.

Because of a mantle of till, exposures are few and poor, which means that the stratigraphy, spatial relationships of the beds, and the sedimentation pattern are difficult to elucidate. This applies especially to vectorial features where the development of a coherent transportation pattern based on macrosedimentary structures proved impossible. No attempt to solve this problem by surveying the microscopical orientation of sand grains was included in the present investigation.

Among the numerous papers on the Gävle area those by Igelström (1871), Wiman (1893), and Engström (1956) are limited to enumerating sediment localities and/or to short descriptions of the macroscopical appearance of the rocks. The Geological Survey comments on the map of Gävleborg County (Blomberg 1895) and the review of Swedish Prequaternary sediments by Hadding (1929) both contain chapters on the Gävle Jotnian which are largely based on previously published reference. The first comprehensive description of the Jotnian rocks in the area was given by Törnebohm in 1877. Törnebohm was also first to mention the occurrence of diabase intrusions into the sandstone and to distinguish between two different diabase types. In analogy with conditions in the Dala-Trysil area he interpreted the magmatics as sill intrusions into a sandstone-filled syncline. For a number of reasons later discarded Törnebohm thought that the Gävle sandstone was a littoral facies of the "Lower Silurian" (= Ordovician) limestone formation farther east. Subsequently Törnebohm's interpretation of the diabases as sill intrusions was challenged by Ewetz (1929) who found chalcedony amygdules, "undoubtedly" derived from the Gävle diabase, in a sandstone conglomerate, which led him to conclude that part of the conglomerates in the area were younger than what he, in a somewhat extravagant manner, thought were diabase dikes. In 1925 von Eckermann contributed a special study on the chemical and mineralogical composition of the the Gävle diabase. The hitherto most complete account of the Gävle Jotnian was given by Asklund (1934, 1939) in the Geological Survey descriptions of the Storvik and Gävle map sheets. In agreement with Törnebohm's work Asklund describes the Gävle sandstone area as a syncline disturbed by transversal faults and containing two types of diabase intrusions: a sill of Gävle diabase and a volcanic neck of Mackmyra olivine diabase. He also pays attention to the occurrence of rapakivi-type "Strömsbro granite" to the north of the sandstone area and to porphyries associated with this granite and grouped together with it as "Subjotnian". In the western part of the Jotnian area Asklund divides the sediments into four units: (1) Mottled "Ginborn sandstone", (2) Upper red sandstone, which is partly a coarse arkose with conglomerate inlayers, (3) Light-colored sandstone, and (4) "Bottom layers" consisting of conglomerates, sedimentary breccias, and interbedded (lower-) red arkosic sandstones and white quartzites. The upper part of the "bottom layers" contains the main sill intrusion of the Gävle diabase. Sedimentary structures noted by Asklund include ripple-marks, crossbedding, dreikanters, and mud cracks. According to Asklund the sediments are continental shallow-water deposits. A core drilled through the contact between the Jotnian and Cambrian revealed a layer of Precambrian sandstone between the two, separated by conglomerates from either (Westergård 1939). The age of this particular bed is unknown.

SETTING AND STRATIGRAPHY

The Jotnian sandstone crops out in a belt 1.5 to 7 miles wide and about 30 miles long striking ENE within the Gävle River valley between Gävle and Storvik. With the exception of the eastern end of the belt, terminating against the Baltic, the area is surrounded on all sides by Svecofennian plutonics forming a slightly undulating plateau surface on an average about 60 ft higher than the Jotnian area. The Jotnian rocks are badly covered by glacifluvial and glacial debris and by postglacial clays, which limits the number of available outcrops to about thirty, the small size of the exposures making it virtually impossible to study other directional structures than grain orientation. Crossbedding localities thus number two, ripple-marked outcrops three, while sole markings, cast flutes, etc are found in glacial boulders only. In the absence of core borings this also imposes a limit to the distinction and evaluation of the regional importance of differentiated stratigraphical units. While every gradation appears to exist between subarkose and arkose, the selective predominance of different lithologies at different stratigraphical levels appears to be pronounced and thus allows the sandstone formation to be divided into a number of subarkose and arkose members. On the basis of lithological evidence accumulated by the examination of samples of rock from exposures and comparison with the stratigraphical data and general lithology revealed by a number of churn drillings throughout the area the following tentative stratigraphical succession is suggested for the Gävle Jotnian (cf. map Fig. 1):

(1) "Upper arkose group" including the Ginborn-sandstone of Asklund and comprising well-sorted medium- to fine-grained arkose with sparse siltstone inter-

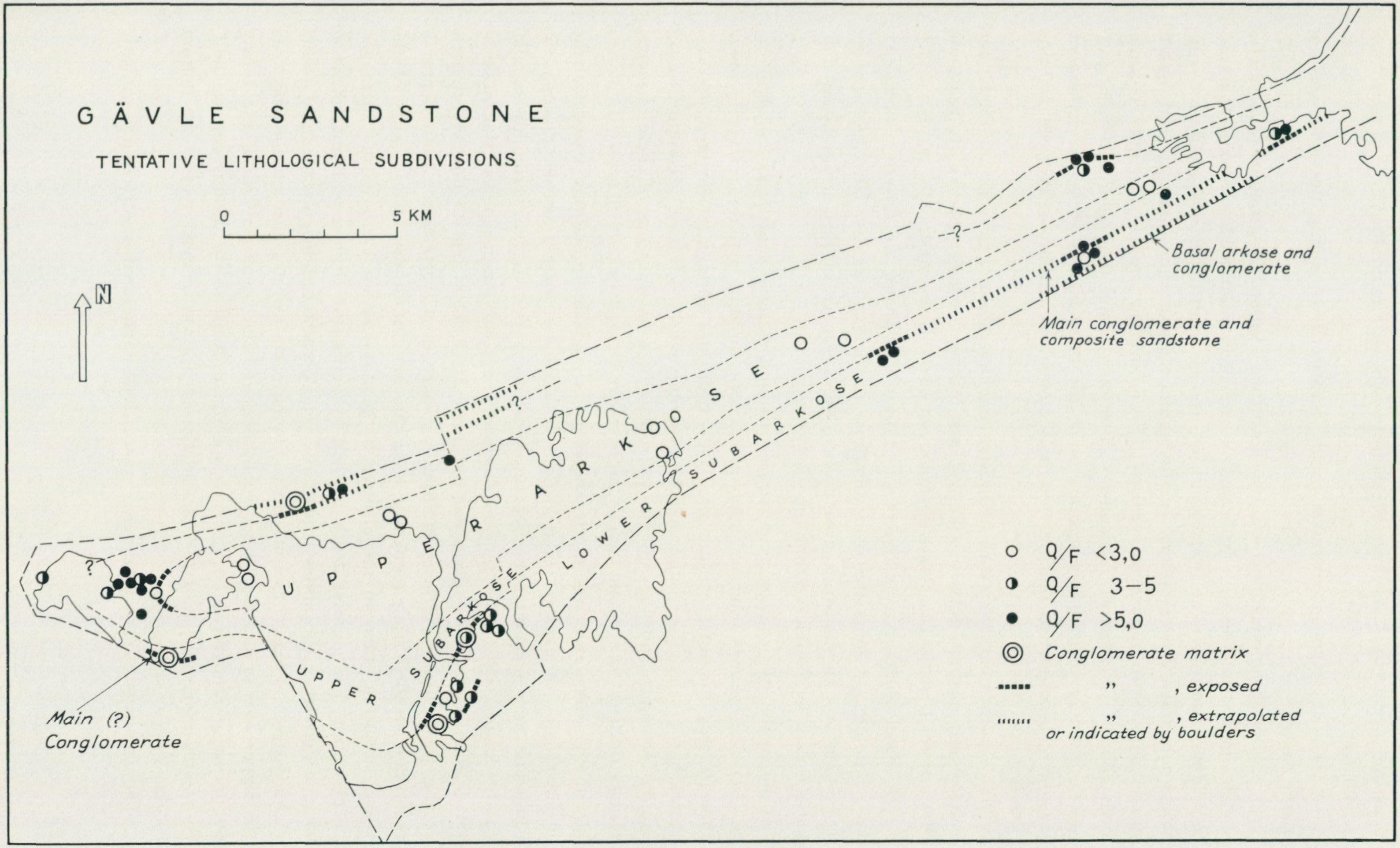

Fig. 1. Tentative lithological subdivisions of the Gävle Jotnian. Q/F is the quartz/feldspar plus rock fragments ratio.

beds and a gravelly layer near the bottom. The minimum thickness of this layer is 500 feet.

(2) "Upper (main-) subarkose" with occasional conglomerates and silty or clayey layers.

(3) "Main conglomerate-composite sandstone" group. A pronounced series of conglomerates interbedded with coarse- to medium-grained subarkose, arkose, and lithic sandstone. The lithic sandstone is characteristic of this group and contains numerous detrital grains of fine-grained sandstone, siltstone, and quartz grains with worn quartz overgrowths. There are occasional silt- and claystone beds and a few layers of sandstone rich in matrix and thus approaching a greywacke lithology. This group appears to be the main habitat of Gävle diabase intrusions. The estimated thickness of the sedimentary sequence is between 200 and 400 feet.

(4) "Lower subarkose" with abundant conglomerate and gravelly interbeds, and subordinate medium-grained arkose. This member, which appears to be about 900 feet thick in the east, tends to taper out towards the west.

(5) "Basal oligomict conglomerate and arkose" with locally derived pebbles. Arkose lithology predominates over subarkose in the sand grades. No exposures are known inside the sandstone area proper, the existence of this group being indicated solely by boulders found in till.

Comparison of outcrops to percussion drilling material and larger coherent exposures and cuttings intermittently produced by building activities in Gävle town, indicate that the total amount of clayey beds and carbonate-cemented rocks is somewhat greater than suggested by the apparently selective predominance of quartz-cemented sandstones in the outcrops. The total thickness of these elements, though difficult to estimate exactly, appears to be well below 10 per cent.

The thickness estimates given above are rough interpretations based on the observed dips of exposed layers and calculated for three traverses through the sandstone area presuming no repetition of strata due to faults roughly parallel to the length-axis of the sandstone area. The total stratigraphical thickness of the Jotnian succession is accordingly around 2 500–3 000 feet in the central parts of the area. Due to complex faulting and steep downwarping the total depth of the sediment-filled trough might exceed this amount in the eastern parts of the Gävle sandstone area. In the absence of geophysical surveys no exact data can be produced. The greatest depth reached by percussion drilling is about 500 ft at three widely spaced localities in the area. The deepest drillings are through steeply inclined strata in Gävle, and in gently dipping rocks of the transition zone between the Upper Arkose and the Upper Subarkose, and the Upper Subarkose and Lower Subarkose at Sandviken and Storvik respectively. None of the drillings in the sandstone area except one near the edge of the Archean at Storvik reached the bottom of the Jotnian succession.

The members of the lithological succession enumerated above follow roughly the pattern given by Asklund in his description of the Storvik quadrangle. Nevertheless, the details of Asklund's subdivision could not be corroborated, and in particular Asklund's "light sandstone" appears to include a variety of rock types lacking common lithological denominators. Generally color appears to be a rather unreliable stratigraphical indicator and is much affected by recrystallization of hematite coatings, oxidation/reduction processes during or following cementation, and secondary chloritization triggered by the intrusion of the Gävle diabase.

The detrital minerals and rock fragments indicate a varied provenance with major contributions from (1) Igneous and highgrade metamorphic Svecofennian rocks, (2) Archean metasediments, (3) Porphyries and granites of rapakivi-type, and (4) Sediments of a lithology similar to that of the Jotnian rocks. (1) and (2) appear to be the main groups of source rocks drawn upon. The overall significance of the petrography will be discussed later in relation to the established variations in lithology and to the indicated tectonic events.

PETROLOGY

CONGLOMERATES

Only one exposure of the member described at the Basal Oligomict Conglomerate was examined during the present investigation. The occurrence is a thin coating of sharpstone conglomerate partly covering a granite outcrop just south of Highway 80 in Övermyra NE of Storvik. This locality is about half a mile off the northern margin of the sandstone area. Local till boulders of a rock built up of an orto- to paraconglomeratic framework of angular to rounded blocks, stones, and pebbles occur at a number of localities south of Gävle and along the southern margin of the sandstone area. From the distribution of boulder localities this rock appears to occupy a stratigraphical level below that of the Main Conglomerate. The conglomerate contains fragments of local granites including the Strömsbro granite, metamorphosed Svecofennian supracrustals, porphyries, and quartz. This character of the conglomerate pebbles suggests that the source area of these sediments was located nearby. Similar till boulders of sharpstone conglomerate have been reported from the vicinity of Sandviken on the northern margin of the sandstone area (Asklund 1934).

The "Main Conglomerate" member forms a heterogenous complex of interbedded conglomerates and sandstones of different lithologies. Though lateral variation is hard to demonstrate due to the smallness of the exposures, the conglomerate appears to form a sequence of lenticular units. The size of the coarse grades ranges from gravel to coarse stones. The composition of the generally well-rounded to rounded pebbles can be referred to several different sources comprising different Svecofennian rocks including rapakivi-type granites, "Subjotnian" porphyries, sandstone, diabase of a lithology rather similar to that of the Gävle Jotnian, and partly deformed pebbles of probably intrabasinal derivation. These pebbles mainly consist of claystone and clayey siltstone. The remainder of the Main Conglomerate member is comprised of medium- to coarse-grained subarkose and arkose with thin clayey layers. Except for a higher content of rock fragments these rocks are similar to and will be discussed together with their counterparts in the adjoining sandstone members.

Pebble counts of material coarser than 2 cm across (> 3 cm at Gavelhyttan) show the following per cent composition of the coarse grades:

Locality:	Sofiedal		Falknäset		Gavelhyttan	
”Svecofennian” source:						
Granite, pegmatite, gneiss, metabasite	14	91	23	88	8	86
Quartzite	45		51		64	
Quartz	32		14		13	
Breccia	–		–		1	
”Subjotnian-Jotnian” source:						
Porphyries	4		8		9	
Sandstone	3		+		4	
Diabase	1		–		+	
Opaline silica	1		–		–	
Intrabasinal source:						
Claystone etc	+		4		1	

Examination of thin-sections has shown the following types of rock fragments in the sand-size grades of the Sofiedal conglomerate locality:

Svecofennian source:
  Granite
  Medium-grained to fine-grained gneiss
  Leptite, skarn, and mica-schist
  Metaquartzite
”Subjotnian-Jotnian” source:
  Quartz-, quartz-feldspar-, and feldspar porphyries
  Porphyry groundmass carrying acicular quartz
  Epidotized feldspar porphyry
  Chloritized diabase showing relict ophitic texture
  Chloritized quartz-bearing diabase(?)
  Strongly pressolved subarkose with quartz and hematite cements
  Same with carbonate cement
  Moderately pressolved sandstone with chlorite and/or fibrous silica cements
  Amygdaloidal, spherulitic or banded chalcedonic and opaline silica (”agate”)
  Pressolved fine-grained cherty sediment
Intrabasinal source:
  Moderately pressolved indented and/or deformed grains of ferruginous sandstone rich in clay matrix
  Ferruginous siltstone
  Claystone or clay aggregates

Fig. 2. The Gavelhyttan conglomerate. Boulder in till 200 m NNW of Gavelhyttan. The handle of the hammer is 45 cm long.

The occurrence of diabase, opaline silica, and sandstone merits closer consideration since it has been taken to suggest (a) the superficial character of the Gävle diabase beds, and (b) the intrabasinal erosion of the Jotnian Gävle sandstone (Ewetz 1929, Asklund 1934, Geijer 1965, a. o.).

As far as the diabase pebbles are concerned, the following observations appear relevant: The conglomerate locality of Sofiedal is traversed by the main sill of the Gävle diabase, which, together with the observed occurrence of pebbles of partly amygdaline diabase at stratigraphical levels situated below the Gävle diabase sills, precludes an origin of diabase pebbles by a "partial denudation (– of the diabase –) during the sandstone's own time of formation" as suggested by previous investigators (Asklund 1939). Provided the Gävle diabase is defined as the rock forming the sills of the Gävle sandstone area, this indicates the occurrence of texturally and possibly petrographically similar rocks of different age.

The analogous problem of the age of the sandstone pebbles included in the Gävle conglomerates was tackled by examining the degree and orientation of pressure solution effects in samples from Sofiedal and Gavelhyttan. Pressure solution is the modification of grain shape by solution under the influence of pressure. Regular relations exist between the degree of compaction, number of contacts per grain, and frequency of different types of grain contacts. Pressure solution effects can be used as an approximative measure of the overburden load effective prior to the complete cementation of arenaceous sediments (Taylor 1950, Kahn 1956, Gorbatschev 1962 and in preparation). The orientation of certain types of pressolved grain contacts can be used as an indicator of the direction of the imposed nonhydrostatical pressure. Based on the results of the investigation thus undertaken the siltstone and sandstone pebbles could be divided into two distinct groups:

(1) A minor group of pebbles with moderately strong pressure solution effects orientated identically with the pressolved texture of the surrounding conglomerate matrix. The pebbles grouped here mostly comprise claystone or clayey silt- or sandstone. The original clay matrix, which is now recrystallized, was apparently the agent responsible for preventing these pebbles from being broken up during redeposition. The moderate degree of pressure solution is probably due to the abundant matrix which prevented many quartz grains from touching each other. ”Lobate corrosion” (Gorbatschev 1962) types of pressure solution were sometimes observed.

(2) Pebbles of sandstone cemented by quartz, carbonate, or fibrous chalcedonic silica cements and exhibiting moderate to strong pressure solution effects, the most pressolved contacts being generally orientated obliquely to their counterparts in the surrounding conglomerate matrix. In some specimens the degree of compaction and pressure solution was found to differ considerably between pebble and conglomerate matrix. These features preclude the possibility of simultaneous pressure solution of the sandstone pebbles and the host rock. The degree of pressure solution in most sandstone pebbles evidences burial under considerable overburden prior to erosion and redeposition and suggests a provenance from a source area other than the depositional basin of the Gävle sandstone proper.

Altogether, the features discussed here clearly suggest the one-time existence of a formation of sandstone and diabase older than the Gävle Jotnian even if rather similar to it in lithology and consequently in the ultimately controlling tectonic regime.

The present investigation revealed no distinct regional disconformities within the Gävle sandstone sequence, and thus no ”cannibalistic” erosion other than on a local scour-and-fill scale is suggested for this area.

The Main Conglomerate member can be traced as a coherent group of repeatedly alternating conglomerates, subarkoses, and arkoses stretching for more than 10 miles from Korsnäs by the Baltic east of Gävle to Sofiedal south of Mackmyra. The Falknäset conglomerate and conglomerate beds at Ursabodarna and Ångersnäs occupy similar stratigraphical positions. The counterpart of the Main Conglomerate in the north are probably the pebbly beds at Bäckebro, whereas the coarse pebbly arkose at Larses to the west of Sandviken appears to occupy a lower stratigraphical position. Due to the lack of outcrops the different lower members of the sandstone sequence could not be traced through the northern limb of the Gävle basin and it is conceivable that changes of lithology and thickness occur here.

The most spectacular occurence of conglomerate is the Gavelhyttan locality which

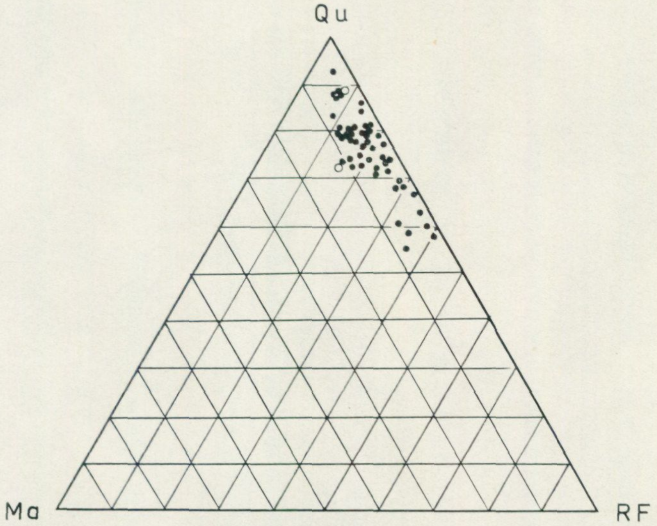

Fig. 3. Lithology of the Gävle sandstone. Dots represent the Gävle Jotnian, circles pebbles of "Prejotnian" sandstone from the Gavelhyttan conglomerate. Qu is stables: quartz, quartzite, chert, oxide ores, and zircon, RF is feldspars and pseudomorphs plus rock fragments and ferromagnesian silicates. Ma is matrix.

includes a small outcrop in the Gavelhytte river bed and extensive occurrences of till boulders, particularly to the northwest of Gavelhyttan. The balls in this conglomerate reach a size of ten inches and more across and are generally well-rounded to rounded and interbedded with stratified or cross-bedded layers of sandstone (Fig. 2). The composition of the conglomerate matrix ranges from lithic arkose to subarkose. The Gavelhyttan conglomerate was previously (Asklund 1934) considered to belong to the "bottom layers". The texture is much different from that of the basal sharpstone at Gävle, Sandviken, and Övermyra while lithological similarities indicate a relation to Falknäset and Sofiero and thus to the Main Conglomerate member. The distribution of glacial boulders around Gavelhyttan indicates a local considerable thickness of the conglomerate which together with the textural features suggests a fluviatile shoestring-type deposit. However, due to the scarcity of exposures in the vicinity of the Gavelhyttan occurrence its stratigraphical position remains doubtful.

SANDSTONES

Gross lithology

The sandstones of the Gävle Jotnian range in composition from arkose to subarkose (Fig. 3) and are generally poor in clayey matrix. Photomicrographs of representative samples are shown in Figs. 4–7. While there is continuous gradation in

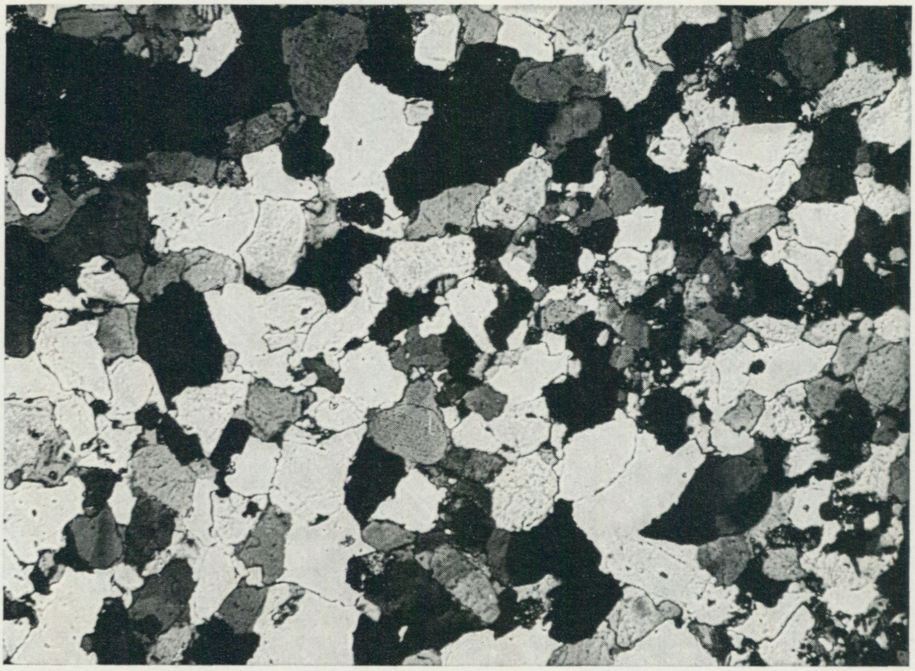

Fig. 4. Subarkose, Upper Subarkose member, Gävle. + nic., 35 x.

mineral composition between the different types of sandstone the selective predominance of either arkose or subarkose lithology is prominent within the medium-grained varieties and has been utilized for subdividing the formation into several arkose and subarkose members. The sandstones are predominantly purple, dusky red, or reddish-yellow when fresh, which suggests an oxidizing environment of formation. White and yellow varieties poor in hematite grain-coatings are subordinate and often produced by the secondary reduction or recrystallization of the ore cement which is evident from the mottled and irregular appearance of many of the lighter varieties. Grain size ranges from very fine-grained to very coarse-grained with a maximum frequency around 1.5–2Φ. Polymodal grain size distribution was found in some conglomeratic or pebbly varieties and in a particular bed of fine-grained dark red sandstone exposed at Lexehällar (Lower Subarkose member) and described by Asklund as the "Schokscha type". Coarse-grained and pebbly beds are important in both the subarkose members, but decrease in number toward the transition into the Upper Arkose. Isolated single pebbles an inch or more across are occasionally found in the well-sorted medium-grained subarkose around Lemstanäs. Bedding structure varies from cross-lamination and crossbedding to thick flat sedimentation units without macroscopical internal structure. Regularly cyclic sedimentation units were found at Korsnäs (Main Conglomerate) and Gävle (Upper Arkose). Ripple marks are fairly common in till boulders derived

Fig. 5. Arkose, Upper Arkose member, Sätra SW of Sandviken. + nic., 37 x.

from different members of the formation. Mud cracks were found in some platy varieties of the Upper Subarkose and Upper Arkose rich in clay layers. Silicified claystone interbeds range from mere partings to layers a foot or more thick. Their distribution appears to be rather irregular and could not be correlated with any of the predominant lithologies. A size/composition relation is apparent in that coarse pebbly sandstones of the lower three members frequently tend to have an arkosic composition or are rich in rock fragments. However, the available results bring out no correlation between size and composition within or between the essentially medium-grained Upper Arkose and Upper Subarkose members.

Bituminous organic matter filling cracks and pseudolithophyses is common in the eastern part of the area. Its deposition is clearly later than both the intrusion of the Gävle diabase and the quartz cementation of the sandstone. No evidence for the derivation of this material from the Jotnian sandstone could be discovered.

Mineral composition, detritus

The mineral composition of the Gävle Jotnian was estimated in 50 thin-sections by point-counting 600–1 000 points per thin-section. The results are reproducible within 3–5 per cent of the major constituents (Table 1). The main constituent is predominantly plutonic quartz exhibiting a wide range of extinction types which,

Table 1. Mineral composition of the Gävle Jotnian sandstones in volume per cent

Tentative stratigraphical subdivision, sample, locality, and classification	Framework constituents										Cement constituents							
	Quartz, chert, quartzite	Potash feldspar	Plagioclase	Altered feldspar	Muscovite	Chlorite, biotite, and pseudomorphs	Rock fragments except chert and quartzite	Oxide ores	Other heavies[1]	Matrix	Quartz	Carbonates	Ores	Chlorite	Feldspar	Zeolites	Total cement and matrix (= non-framework space)	Qu/RF (= maturity index as defined in Fig. 3)
Upper Arkose member:																		
J 11 Gävle	63	16	–	8	0.1	0.2	1½	0.2	z, g, a	0.9	6½	2.5	0.4	–	0.4		10.9	2.5
J 68 Gävle	52½	23½	+	4	+	–	1	0.1	z, e	1.2	15	–	0.2	+	1.7	–	18.3	1.8
J 62 Mackmyra	56½	14½	1½	3	0.5	0.3	4	0.9	z, a, p	1.4	8	–	1.1	0.1	7.6		18.4	2.4
J 59 SW of Forsbacka (local boulder)	64½	12	6½		+	0.5	2½	0.0	z	1.7	11	+	0.5	–	0.7	–	14.0	3.0
J 27 a Sätra	52½	18½	11½		0.1	0.1	4	0.1	e, a	0.8	10½	0.1	0.1	–	2.0	–	11.5	1.5
J 28 Sätra	46½	19	10		0.7	1.1	2½	0.6	g, e, a, s, p, h	5.2	9	3.3	0.4	–	0.9	0.4	18.5	1.5
J 431 Ginbornhalvön (local boulder)	51½	19½	½	8	0.1	0.4	2	0.1	z, g, e, s, p	4.5	11½	–	0.4	–	1.2	0.1	17.6	1.7
J 432 Ginbornhalvön	54½	18½	7		+	+	2½	0.3	z, e, a, s, p	5.1	9	–	1.7	–	1.0	0.1	15.9	1.9
J 31 Lem-Syltbäcken	57½	13½	4		0.1	0.1	9½	0.1	z, e, a, p	0.1	10½	–	0.2	–	3.5	0.3	11.1	2.1
Upper Subarkose member:																		
J 8 Gävle	68	2½	1	6½	0.4	0.2	½	+	z	4.6	16	–	0.5	–	–	–	21.3	6.4
J 9 Gävle	70	6	–	3½	+	0.2	½	+	z, p	0.4	19	–	0.4	–	+	–	19.8	6.9
J 5 Bäckebro	63½	10	5½		0.1	0.1	2	0.1	z, p	3.8	14	–	0.6	–	0.3	0.2	19.0	3.7
J 331 Lem, S.-quarry	69	9½	–	5½	+	+	1	+	z, g, p	7.9	6½	–	0.2	–	0.7	+	15.1	4.4
J 334 Lem, S.-quarry	69	8½	+	4	0.3	+	1½	+	z	3.7	12½	–	0.2	–	0.6	+	16.9	5.0
J 333 Lem, S.-quarry	76	5½	–	1½	+	–	1	+	–	6.6	8½	–	+	–	1.1	0.3	16.3	9.5
J 332 Lem, S.-quarry	70	8	+	2	+	–	1	+	z, g, a, p	2.6	14½	–	+	–	1.5	–	18.8	6.4
J 34 Lem, W.-quarry	68	3	–	6	+	–	4½	+	z, p	1.8	16	–	0.1	–	0.4	–	18.2	5.0
J 421 Lem	68½	4½	½	7½	0.1	+	2½	0.1	z, p	4.4	12	–	0.3	–	–	–	16.6	4.5
J 422 Lem, NE-quarry	65½	3	½	10½	0.1	+	6	0.3	z	4.0	9½	–	0.3	–	+	+	14.0	3.2
J 45 Lemstanäs	69½	4½	–	6	0.1	–	4	0.1	z, p	2.8	13	–	0.1	–	+	–	15.9	4.8
J 150 Lem – Nor (diabase contact)	72½	3	–	1½	+	+	2	+	p	2.8	5	9.9	1.9	0.3	–	–	19.8	10.6
Main Conglomerate member:																		
J 191 Kastet (coarse sandstone)	65	9	–	6	0.5	0.5	4½	+	z, g	1.6	11½	–	0.5	–	0.5	–	14.8	3.4
J 193 Kastet (coarse sandstone)	67	5½	–	3	0.2	0.1	5	0.8	z, g, a, s	1.3	15	–	1.9	–	+	–	18.2	5.0
J 1123 Gävle SW (skjutfält)	68	5½	1	3½	0.2	0.2	1	0.1	z, p	4.9	14½	–	0.3	–	0.1	+	20.0	6.1
J 1122 Gävle SW	56	15					9											2.3
J 101 Gävle SW																		5.4
J 1121 Gävle SW																		6.3
J 125 Sofiedal																		5.4
J 321 Ångersnäs (coarse sandstone)	60½	7½	–	6	0.1	+	7½	+	–	2.1	16½	–	+	–	–	–	18.6	2.9
J 36 Ursabodarna	64½	6½	–	7	–	–	7	+	–	4.5	10	–	0.3	–	0.3	0.2	15.6	3.2
J 37 b Fäbodudden (diabase contact)	48½	7½	1	6½	0.3	0.4	4	0.5	t, p	–	½	12.7	0.9	19.0	–	–	33.3	2.8
J 37 c Fäbodudden	63	4½	6½		0.1	–	5	0.1	p	5.6	12½	–	0.1	–	0.1	–	19.9	3.8
J 41 Falknäset (conglomerate matrix)	64½	12½	1	2	0.2	0.2	5	0.2	z	0.8	8½	–	1.6	–	3.6	–	14.2	3.1
J 64 Larses (coarse sandstone)	48½	18	½	4½	–	+	10½	0.3	z, e, a, s	0.6	13½	–	+	–	2.9		17.1	1.5
J 26 Gavelhyttan (conglomerate matrix)	54½	13½	–	3½	0.1	+	5½	0.4	–	0.6	½	20.1	0.2	–	–	–	22.3	2.5
The stratigraphical position of J 64 and J 26 is doubtful																		
Lower Subarkose member:																		
J 102 Gävle SW																		5.0
J 105 Tolvfors	75	2	–	1	+	+	½	+	z	2.1	19	–	0.2	–	–	–	21.7	22.4
J 113 Tolvfors	77	3½	–	2	0.1	+	1½	+	z	4.2	12	–	0.5	–	–	–	16.3	11.4
J 391 Kalvmuren	64½	8	6		+	+	2½	0.4	z, p	0.9	16	–	1.1	–	0.2	–	18.0	3.8
J 393 Kalvmuren	65½	6½	6		0.1	0.2	3½	0.2	z, p	0.9	15½	–	0.9	–	0.4	+	17.9	4.1
J 392 Kalvmuren	67	8½	4		0.3	0.2	2	0.1	z, p	3.4	13½	–	0.3	–	0.2	0.1	17.5	4.6
J 322 Ångersnäs	67	6	5½		0.1	0.4	2½	0.1	p	2.1	14½	–	0.8	–	0.4	–	17.9	4.7
J 56 Lexehällar (red fine-grained sandst.)	70½	2	+	2	0.7	0.6	1½	0.5	z, e, p	3.3	13½	–	2.6	–	–	–	22.1	10.9
J 58 Lexehällar (red fine-grained sandst.)	67	3	+	3	1.5	0.8	1½	0.7	z, e, p	5.3	16	–	3.3	–	–	–	22.6	7.3
J 54 Lexehällar	62½	6½	+	4½	0.1	+	4½	0.2	p	6.1	15½	–	0.1	–	–	–	21.6	4.0
J 52 Lexehällar	63	5½	–	3	0.1	+	6	+	p	9.2	13	–	0.3	–	–	–	22.4	4.4
J 51 Lexehällar	63½	5½	4		0.2	+	2	0.1	p	4.8	19½	–	0.2	–	–	–	24.7	5.5
J 50 Lexehällar	68	4	–	2½	0.2	+	3	+	p	7.4	14½	–	+	–	–	–	22.0	6.7
J 49 Lexehällar (grey fine-grained sandst.)	65	6½	–	5½	0.1	+	1½	0.1	z, p	5.4	16	–	0.1	–	–	–	21.6	4.9
J 48 Lexehällar	67	4½	–	3	0.1	+	4	0.3	p	5.8	15	–	0.1	–	–	–	20.9	5.8
J 17 Storvik (local till boulder, stratigraphical position doubtful)	62½	9	5		0.1	0.2	1½	0.4	z, g, a	3.0	15		1.2	–	2.0		19.4	4.1
"Subjotnian" sandstone balls in Jotnian conglomerate:																		
J 16 Gavelhyttan	76½	5	2		0.7		+	0.1	z, a, p	1.6	13½	–	0.5	–	–	–	15.7	10.7
J 25 Gavelhyttan	57½	–	–	12	0.7	+	+	0.2	z, p	8.6	19½	–	0.9	–	–	–	29.2	4.7

[1] a = apatite, h = amphibole, e = epidote, zoisite, g = garnet, p = ferromagnesian pseudomorphs, s = sphene, t = tourmaline, z = zircon

Unless otherwise stated the specimens in this table are medium-grained sandstone

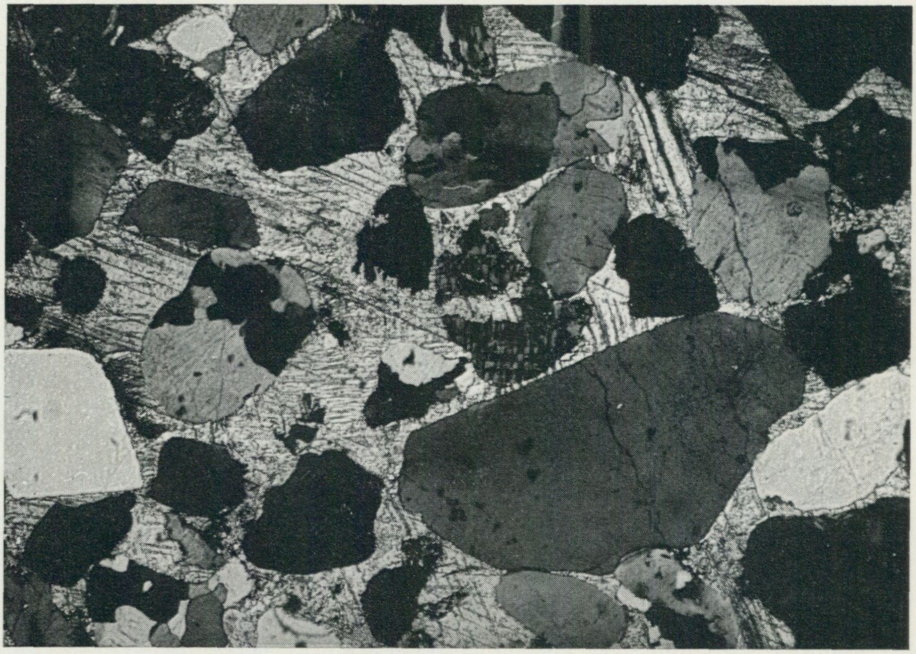

Fig. 6. Carbonate cemented conglomerate matrix. The cement replaces feldspar detritus. Gavelhyttan conglomerate. + nic., 37 x.

considering the variability of rock types in the orogenic Svecofennian are not diagnostic of definite erosion loci. Common composite grains comprise vein quartz, quartz mylonites, stretched and often strongly tectonized metaquartzite of white, buff or red color, and reworked sandstone-quartz grains identified by the presence of truncated quartz cement overgrowths. The relative frequency of the latter is covariant with the occurrence of sandstone fragments and diagnostic of a sedimentary provenance of part of the Jotnian detritus. Accessory amounts (0.1–1 %) of microcrystalline or cryptocrystalline cherty silica material are found throughout the series. Some of these grains show spherulitic texture or banding and intergrowth with minute chlorite flakes which suggests a derivation from amygdules or pneumatolytic/hydrotermal veins related to igneous activity.

The feldspar contents varies between 3 and 30 per cent. The feldspars comprise potash feldspar (almost exclusively microcline or microcline perthites), plagioclase, and feldspar pseudomorphs composed of partly silicified sericite or felty aggregates of sericite and/or kaolinite flakes. Unaltered plagioclase is absent or very low except in some specimens belonging to the Upper Arkose member and in churn drilling debris predominantly derived from that part of the sandstone formation. No coherent relation was found when plotting the Qu/RF maturity index as defined in Fig. 3 versus the potash feldspar / plagioclase + altered feldspar ratio, which indicates that feldspar alteration, though predominantly affecting plagioclase, was not strictly selective. The altered feldspar is of potentially great importance since it may throw decisive light on the tectonic evaluation of the source areas.

Rock fragments range between 0.3 and 10 per cent, the highest contents being found in the Main Conglomerate member and parts of the Upper Subarkose. In analogy with the pebbles of the conglomerates the sand-size rock fragments can be referred to "Svecofennian", "Subjotnian", and intrabasinal sources. In order to distinguish between granitic/plutonic and supracrustal detritus sources the non-granophyric composite feldspar-quartz aggregates have been reckoned with the respective minerals in Table 1. An evaluation of the relative importance of different provenances was attempted by comparing the relative frequencies (number per cent) of different rock fragments in thin-sections from the various members of the Gävle Jotnian. The result suggests a relatively greater importance of the sandstone source in the Main Conglomerate and Upper Subarkose:

	Upper Arkose (average)	J 31 (Base of Upper Arkose)	Upper Subarkose			Main Conglomerate	
			J 331	J 333	J 150	J 100 (Congl. matrix)	J 101
Svecofennian plutonic source:	63	47	25	32	25	38.5	27
leptitic	31	18.5	10	10	7	9	12
granitic	21	26	12	20	17	24.5	8.5
micaceous gneiss	11	2.5	3	2	1	5	6.5
Quartzite, mica-quartzite	24	24	32	32	37	24.5	31
Chert etc	4	3	25	14	7	3	6
Granophyre	+	+	–	–	–	2	1
Porphyry, p.-groundmass	3	22	8	10	3	19	21.5
Diabase	–	–	–	–	–	1	–
Sandstone, siltstone	–	1	4	10	24	7.5	12
Clay, claystone, clayey siltstone	6	3	6	2	4	4.5	1.5

Accessory detrital minerals are predominantly ores and muscovite. Chlorite is a regular minor constituent. A striking feature of the Gävle Jotnian is the scarcity or absence of heavy minerals except ores, zircon, and chlorite throughout the lower members of the formation. A wholesale destruction of these minerals and their partial replacement by chloritic or ferruginous pseudomorphs occurs in the strata which are characterized by the absence of unaltered plagioclase. The Upper Ar-

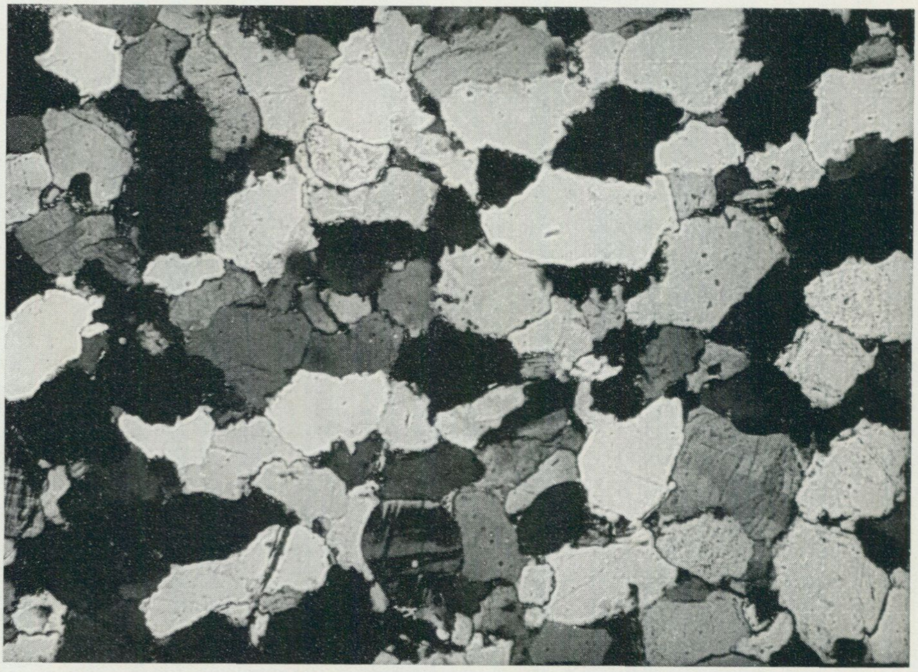

Fig. 7. "Prejotnian" sandstone exhibiting strong pressure solution. Pebble in the Gavelhyttan conglomerate. + nic., 37 x.

kose in contrast has the diversified association of non-opaque heavies which is known from the Mälar Jotnian. Heavy minerals here include ores, zircon, apatite, garnet, epidote, tourmaline, amphibole, and biotite.

The matrix is either unresolvable under the microscope or consists of a microcrystalline aggregate composed chiefly of sericitic mica with small amounts of recognizable kaoline, quartz, and opaques. About 1/3 of the muscovite content given in Table 1 are sizable flakes with frayed borders. These grains are probably formed by matrix recrystallization. The rest are partly bent flakes of apparently detrital origin.

Cement and secondary minerals

Quartz is by far the most abundant cement constituent of the Gävle Jotnian and usually forms overgrowths in optical continuity with the detrital grains. Carbonate cement is next in abundance, but is considerably scarcer and appears to be selectively enriched in the vicinity of Gävle diabase sills. This cannot, however, be taken to suggest that all carbonate cementation was induced by the diabase intrusions. Carbonate cement is a regular minor constituent in conglomerates and in

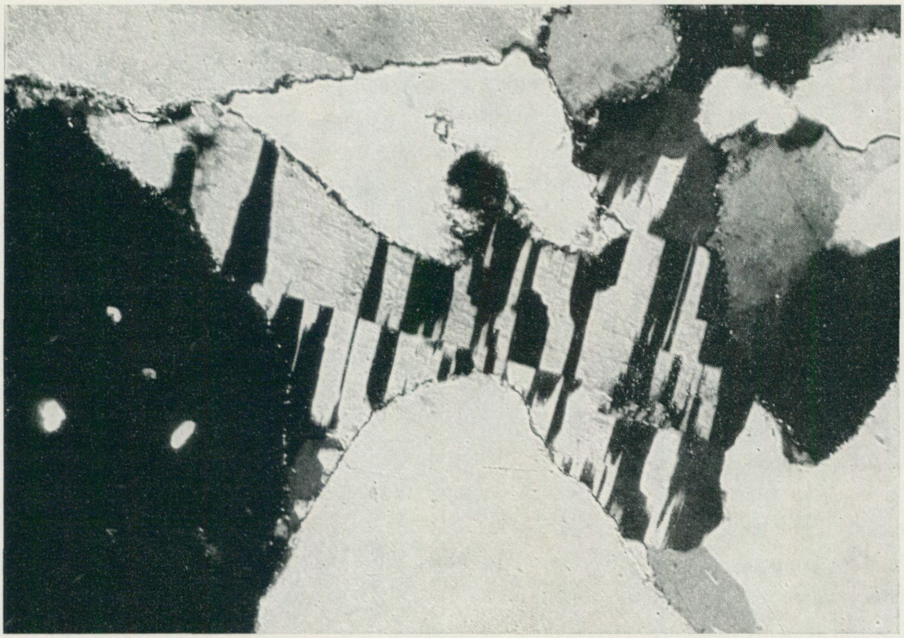

Fig. 8. Authigenic feldspar. Upper Arkose member, Sätra. + nic., 170 x.

Fig. 9. Rim of secondary albite overgrown on detrital microcline. Main Conglomerate member, Falknäset. + nic., 145 x.

large parts of the Upper Arkose member where it forms patches strongly corroding the quartz and feldspar detritus. Original sericitized feldspar pseudomorphs are heavily impregnated or even completely replaced by carbonate. Except in sandstones in the immediate contact zone of the diabase several contiguous voids are usually filled by the same carbonate cement crystal. The majority of calcite cemented sandstones shows thin rims of quartz cement or euhedral quartz crystals interposed between the detritus and the carbonate which indicates that some silica cementation preceded the deposition of the latter. Thin coatings of hematite on detrital grains are ubiquitous throughout the formation and are responsible for the red color of the sediments. The formation of iron-oxide coatings preceded the deposition of other cements and is probably a depositional feature. Fine-grained varieties of sandstone and siltstone are particularly rich in ore cement which is partly due to the greater specific grain-surface area of these sediments. Chlorite and chalcedonic or microcrystalline pseudofibrous silica cements are restricted exclusively to the immediate vicinity of Gävle diabase contacts. Other authigenic or secondary minerals include feldspar, zeolites (mainly laumontite), and some chlorite and near the diabase contacts also some epidote, prehnite, and sphene. The authigenic feldspar usually forms (occasionally chessboard-) twinned overgrowths in crystallographical continuity with the lattice of detrital microcline (Fig. 8). When there is a microcline host, the surface of the detrital feldspar is usually coated with minute crystallites of secondary feldspar or else the secondary feldspar has a rim of minute lenticular twinning lamellae along the contact with the detrital grain. These features are apparently the result of strain caused by differences in lattice spacing of the secondary feldspar and the detrital microcline. All investigated secondary feldspars are albite and the presence of secondary potash feldspar is not established. The composition of an analyzed specimen of secondary feldspar from the Falknäset conglomerate locality is (in mol. %): An 0.35, Ab 99.01, K-fsp. 0.64, which suggests a low temperature of formation (Baskin 1956). Secondary feldspar occurs throughout the formation, but is especially common in conglomerates and in the Upper Arkose member (cf. Table 1) which is similar to the distribution pattern of carbonate cement and possibly due to the late or incomplete silica cementation of these rocks. This is also brought out by the comparatively higher degree of pressure solution and the lower percentage of non-framework space in the Upper Arkose member (Table 1) which suggests a greater amount of compaction prior to cementation and thus probably a comparatively slow elimination of pore space in this member.

Grain size, sorting, and roundness

The grain size distribution and roundness were measured in specimens where the preservation status of the detritus permitted a reliable estimation of these parameters. Grain size is here defined as the long-axis diameter of detrital grains in

Table 2. Size and sorting coefficients of the framework constituents in the Gävle and Mälar Jotnian sediments

Gävle:	$M\Phi$	$\sigma\Phi$	$\frac{\Phi_{84}-\Phi_{16}}{2}$	Mälar:	$M\Phi$	$\sigma\Phi$	$\frac{\Phi_{\cdot 4}-\Phi_{16}}{2}$
Upper Arkose member:				Arkoses:			
J 11 Gävle[1]	2.25	0.77	0.55	E 3	3.26	0.81	0.72
J 28 Sätra[1]	2.06	0.82	0.72	E 15	3.17	0.66	0.61
J 432 Ginborn	1.86	0.77	0.73	E 25	2.88	0.63	0.63
J 59 Heliga landet[1]	1.70	0.65	0.62	E 24 (pebbly lithic arkose)	1.80	1.30	1.29
Upper Subarkose member:							
J 8 Gävle[1]	2.21	0.68	0.46				
J 422 Lem NE-quarry[1]	1.92	0.72	0.56	Subarkoses:			
J 333 Lem, S-quarry[1]	1.63	0.61	0.58				
J 34 Lem, W-quarry	1.58	0.73	0.67	E 19	2.73	0.57	0.44
J 150 Lem–Nor,[1]	1.35	0.79	0.84	E 38	2.48	0.97	0.99
(slightly bimodal)				E 46	2.46	1.03	1.04
J 334 Lem, S-quarry[1]	1.23	0.60	0.47	E 13	2.24	0.90	0.82
				E 12	2.07	0.93	0.81
Conglomerate member:							
J 371 Arkose, Fäbodudden[1]	1.70	0.66	0.54				
J 1122 Arkose, Gävle SW	1.08	0.76	0.73	E 50 (polymodal pebbly subarkose)	1.69	1.18	1.31
J 1123 Subarkose, Gävle SW[1]	2.70	0.85	0.84				
J 1121 Subarkose, Gävle SW[1]	2.25	0.53	0.44				
J 101 Subarkose, Gävle SW	1.45	0.73	0.64				
J 41 Congl. matrix, Falknäset	1.12	0.93	0.78				
J 100 Congl. matrix, Gävle SW	0.96	0.98	0.99				
J 26 Congl. matrix, Gavelhyttan	0.23	0.95	0.94				
Lower Subarkose member:							
J 56 Lexehällar (red polymodal sandstone)[1]	2.66	1.02	1.06				
J 102 Gävle SW[1]	2.61	0.72	0.71				
J 115 Tolvfors[1]	2.37	0.70	0.60				
J 105 Tolvfors[1]	2.28	0.59	0.56				

[1] quartz + chert + quartzite detritus only.

Table 3. Roundness indices of quartz plus feldspar in the Gävle Jotnian sandstones

Classification	R. I.	Classification	R. I.
Upper Arkose:		Main Conglomerate:	
J 11 Arkose	0.46	J 192 Polymodal coarse conglomerate matrix	0.41
J 27 Arkose	0.46	J 26 Conglomerate matrix	0.44
J 28 Arkose	0.49	J 36 Subarkose	0.52
J 43 Arkose	0.48	J 371 Arkose	0.46
Upper Subarkose:		J 41 Conglomerate matrix	0.54
J 8 Subarkose	0.51		
J 9 Subarkose	0.57	Lower Subarkose:	
J 332 Subarkose	0.58	J 17 Subarkose	0.46
J 333 Subarkose	0.57	J 391 Subarkose	0.51
J 334 Subarkose	0.56	J 392 Subarkose	0.56
J 422 Subarkose	0.49		

thin-sections and the measurement results can thus be compared with the data given in Gorbatschev and Kint 1961 and Gorbatschev 1962 b. The grain size statistics are listed in Table 2 which includes the phi mean, phi standard deviation, and the Inman graphic deviation derived from the cumulative curves. The corresponding size parameters of the Mälar Jotnian are given for comparison. Due to the scarcity of outcrops the sampling pattern is not statistically representative of the total Gävle Jotnian; still most phi medians fall between 1.5 and 2 suggesting that the bulk of the Gävle Jotnian belongs to the medium-grained group. This also implies a somewhat coarser grain size than that of the corresponding lithologies of the Mälar Jotnian. It should, however, be remembered that the Lower Subarkose and the Basal Conglomerate members are underrepresented resp. unrepresented in the data of Table 2. All sandstone specimens except the dark red sandstones of Lexehällar are unimodal, which is also true of the grades finer than about 5 mm in most of the ortoconglomerates belonging to the Main Conglomerate. As is seen from the data sorting is good to very good.

Roundness was measured on 200 grains per thin-section by visual comparison with the charts of Powers (1953). The roundness data in Table 3 imply that the mode of transportation had currents of sufficient energy to effectively abrade the sand grains. An overall correlation between roundness and maturity is suggested by Fig. 10, whereas grain size versus roundness or maturity shows no consistent overall relations. This may be due to the existence of more complicated correlations within the different rock types or minerals, which appears to be true in the Upper Subarkose and Arkose members. These relations were, however, not investigated in detail and are not commented here.

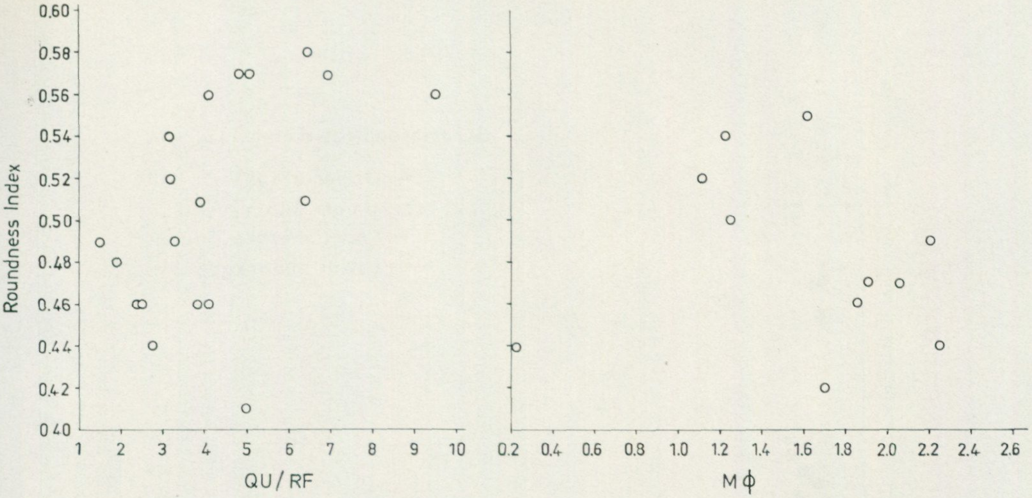

Fig. 10. Roundness versus lithological maturity index (Qu/RF as defined in Fig. 3) and size plot of Gävle Jotnian unimodal medium-grained sandstones and conglomerate matrix (the right part of the fig. is in part based on museum specimens not listed in Tab. 3).

Compaction

Sandstone compaction implies the elimination by pressure solution and cementation of the original pore space, which is about 40 per cent in uncompacted sands. In medium-grained sandstones low in matrix contents there is a regular relationship between the total non-framework space, the number of contacts per grain, the number of "floating" grains in thin-sections, and the frequency of different types of grain contacts. As compaction proceeds, the originally predominant tangential contacts are modified into straight, concavo-convex, and eventually sutured types. The latter can be subdivided into sutured *sensu stricto* and stylolitic, the difference between the two types being one of regularity, orientation, spacing, and height/width ratio of the protrusions or stylolite columns. The stylolite variety which is characterized by the development of regular columns, appears to be largely a result of intense, spatially restricted pressure solution induced for instance by the percolation of hot or strongly alkaline pore fluids in easily permeable zones which may result in the development of regular stylolitic seams. These effects can sometimes be related to periods of magmatic or hydrotermal activity. Thus, stylolitic types of sutured contacts frequently show no consistent relation with the compaction status of a sandstone as indicated by the other compaction parameters listed above.

The measures of compaction can be used for estimating the amount of compaction suffered by a sediment prior to cementation, the sequence of cementation by different secondary minerals, the sequence of igneous events in relation to

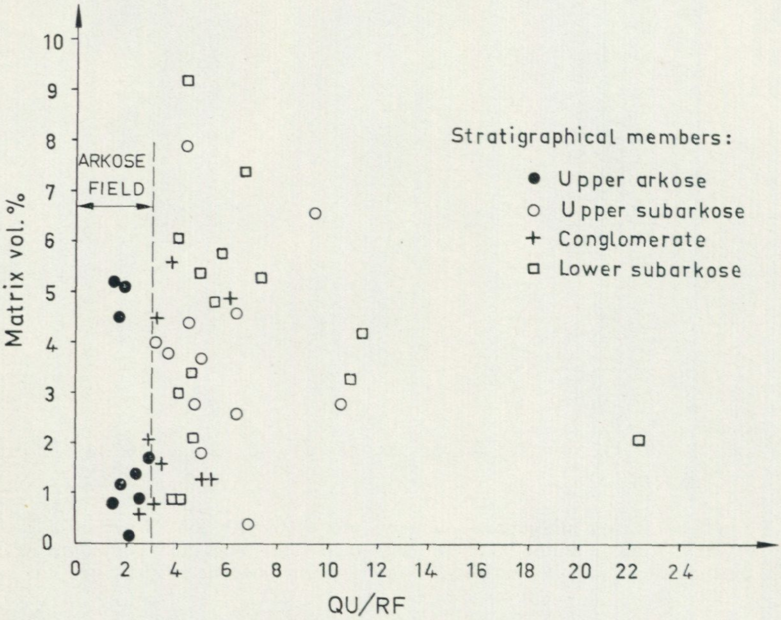

Fig. 11. Lithological maturity index and matrix contents in the different lithological members of the Gävle Jotnian.

overburden deposition, and the depth of pre-cementation burial. The latter estimates frequently cannot be used in more than an approximate manner since the degree of compaction and the time of cementation may depend on influences such as that of the lithology of the sediment and its surroundings, the nature of the pore fluids, etc. Essentially complete cementation will, of course, prevent further pressure solution. Changes of texture similar to those induced by load pressure can presumably be achieved also by tectonic strain, which is lent support by the well advanced status of postdepositional texture modification in many sediments belonging to zones of orogenic deformation. In contrast, secondary effects produced by the tectonic deformation of compacted sediments will result in the obliteration of detrital grain boundaries and can easily be detected from the recrystallization of the quartz grains.

A study of compaction effects in medium-grained sandstones revealed the regular relations sketched in Fig. 12 (Gorbatschev, in preparation). The lower part of this diagram gives the compaction parameters of some Swedish sedimentary formations and can be taken to indicate a measure of minimum pre-cementation overburden. As is expected from the likely thickness of cover suggested by other geological data, the Lower Cambrian sandstones of the Öland–Gotland region show moderate and the Red Sparagmites of Härjedalen (Stålhös 1956) advanced degrees of pre-cementation compaction. The Jotnian sandstones occupy an intermediate position.

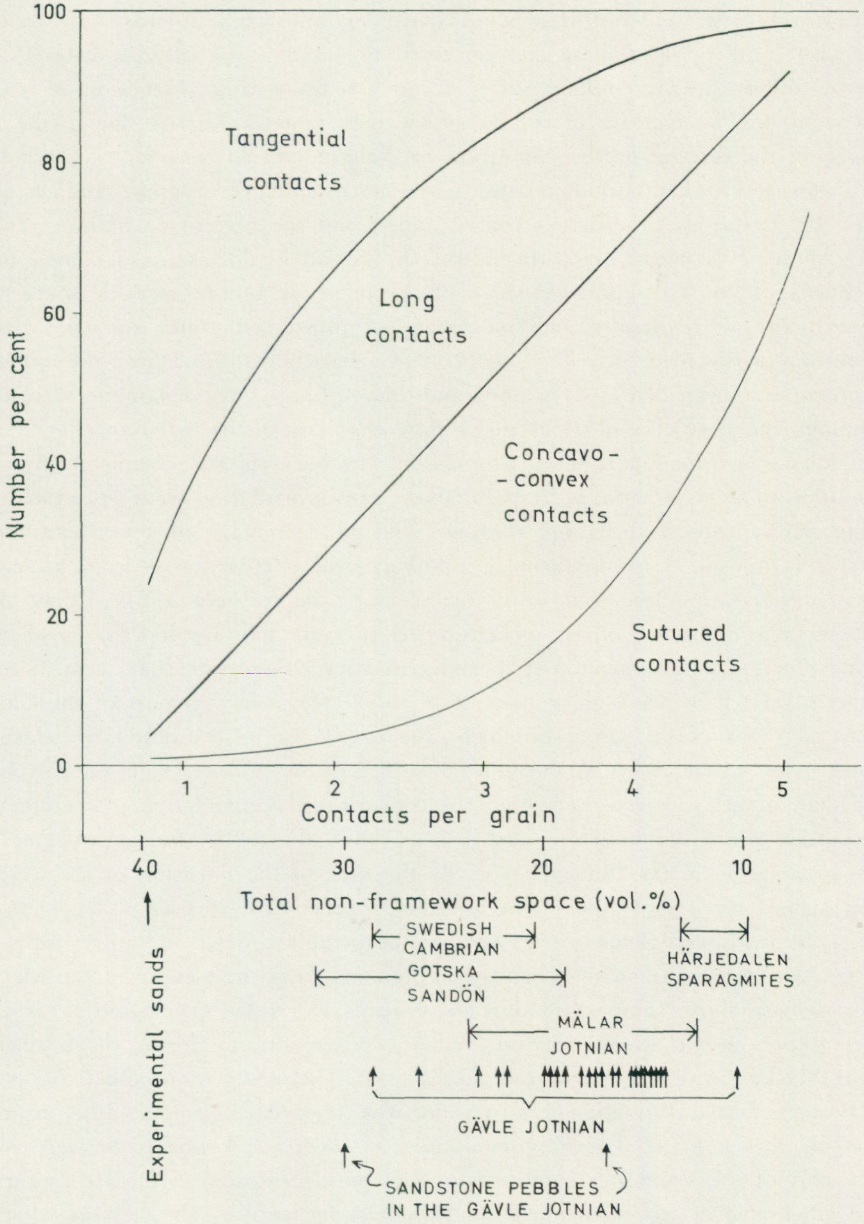

Fig. 12. Compaction measures in medium-grained sandstones (acc. to Gorbatschev, in preparation). The arrows indicate the number of contacts per grain as measured in 0.03 mm thick thin-sections.

A detailed subdivision of the Gävle Jotnian demonstrates a low degree of compaction (> 30 per cent non-framework space) in sandstones situated close to the contacts of the Gävle diabase and cemented by mixtures of chlorite, carbonates, quartz, and/or microcrystalline silica. Secondary framework disruption in these specimens, i. e. an increase in volume of the non-framework space due to the intrusion of the diabase or the deposition of diabase-induced cements, is precluded by the existence of a normal relation between the number of grain contacts per grain, the frequency of different contact types, and the percentage of non-framework space. In contrast, sandstone dikes in the Gävle diabase, and some other specimens of contact sandstone show 35–45 per cent non-framework space together with an abnormally high percentage of pressolved grain contacts, which indicates a disrupted detritus framework (cf. Gorbatschev 1962 a). Still, the amount of pressure solution suffered by the sandstones prior to the magmatic intrusion eliminates the possibility of an extrusive flow character of the diabase.

In sandstone where pore-space elimination was not achieved completely by the deposition of cements induced by the diabase, pressure solution went on ultimately giving the sandstone formation a rather uniform percentage of total nonframework constituents. A comparison of lithology and compaction reveals no consistent differences in the four lower members of the formation. The Upper Arkose, in contrast, shows on an average higher pressure solution and thus probably a longer period of uncemented state under overburden pressure. Late cementation is also suggested by the high amount of fractured grains in that part of the Gävle sandstone. This effect cannot be solely due to the easier disruption of feldspar grains, since arkose layers in the lower members show pressure solution correlate with that of their subarkose neighbors. A considerable accumulation of (? Jotnian) overburden which has been removed later is thus indicated by the high degree of pressure solution in the Upper Arkose. By the time of the intrusion of the Mackmyra diabase the compaction of this member appears to have been well advanced or maybe nearly complete. In spite of the considerable contact alterations induced by the basic melt, specimens of sandstone obtained from the vicinity of the Mackmyra diabase show compaction degrees of the same order of magnitude as the other arkoses in the upper member. Neither were conditions during the intrusion of the Mackmyra diabase conducive to the formation of sandstone dikes.

Throughout the formation cementation was reasonably complete before the onset of the Cambrian. The bituminous matter which was probably derived from some part of the Cambro-Silurian strata, was mostly introduced into temporarily open cracks which are independent of the sandstone texture. The response of the Jotnian sandstones to the Precambrian diastrophism affecting the eastern part of the area was by mylonitization and fracturing implying a high degree of competence, and not by the development of moderate-scale slumping structures which would be expected in an incompletely cemented rock.

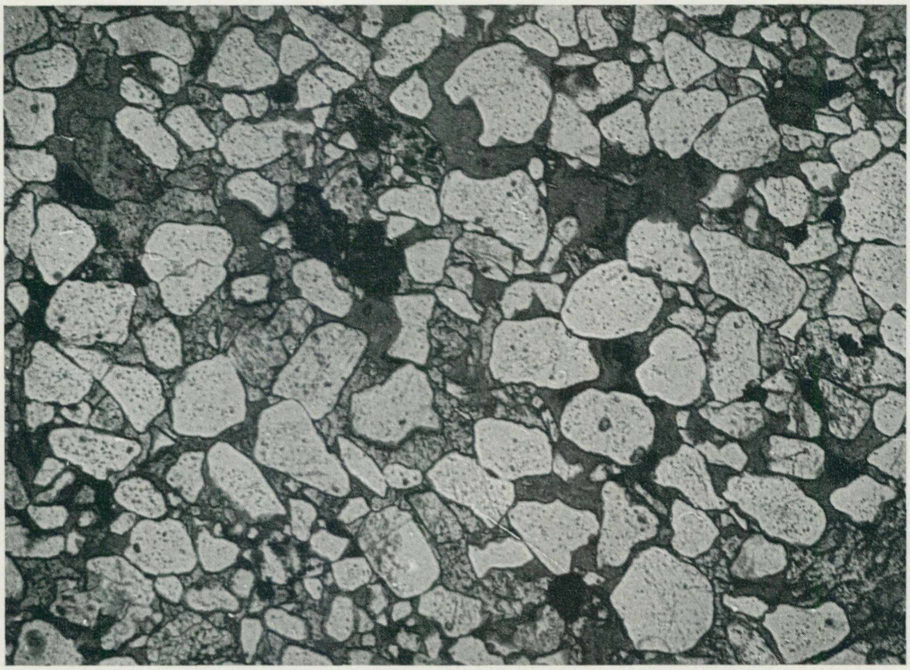

Fig. 13. Chlorite cemented sandstone showing weak pressure solution. Total non-framework space is about 30 per cent. Predominant cements are carbonate and chlorite. Diabase contact in excavation, Fäboudden. One nicol, 37 x.

DIABASES

The Gävle diabase

In the south-eastern part of the sandstone area diabase is exposed in strips of outcrops which can be traced from Gävle to a point SW of Mackmyra, a distance in excess of 10 miles. These exposures belong to the main sill of Gävle diabase which reaches a thickness of about 450 ft and sometimes, as for instance at Sofiedal and SW of Gävle (Gävle skjutfält), splits up into several parallel layers. Whenever the dip of the Gävle diabase sills can be checked either by direct observation of the contacts toward the sandstone or by measuring the bedding in the diabase and in neighboring sandstone outcrops, the diabase is found to conform with the stratification of the Jotnian sediments. Six additional sills could be located in Gävle town where building activities temporarily offered cuttings through the Jotnian strata. Two of the sills are situated south of the main sill and the rest between the main sill and the Gävle river. The width of these beds varies between 4 and 75 feet. Diabase outcrops are few in the western and northern parts of the Jotnian area and the main sill could not be followed in detail. The only outcrops in the northern limb of the sediment area which have sizes comparable to the thickness

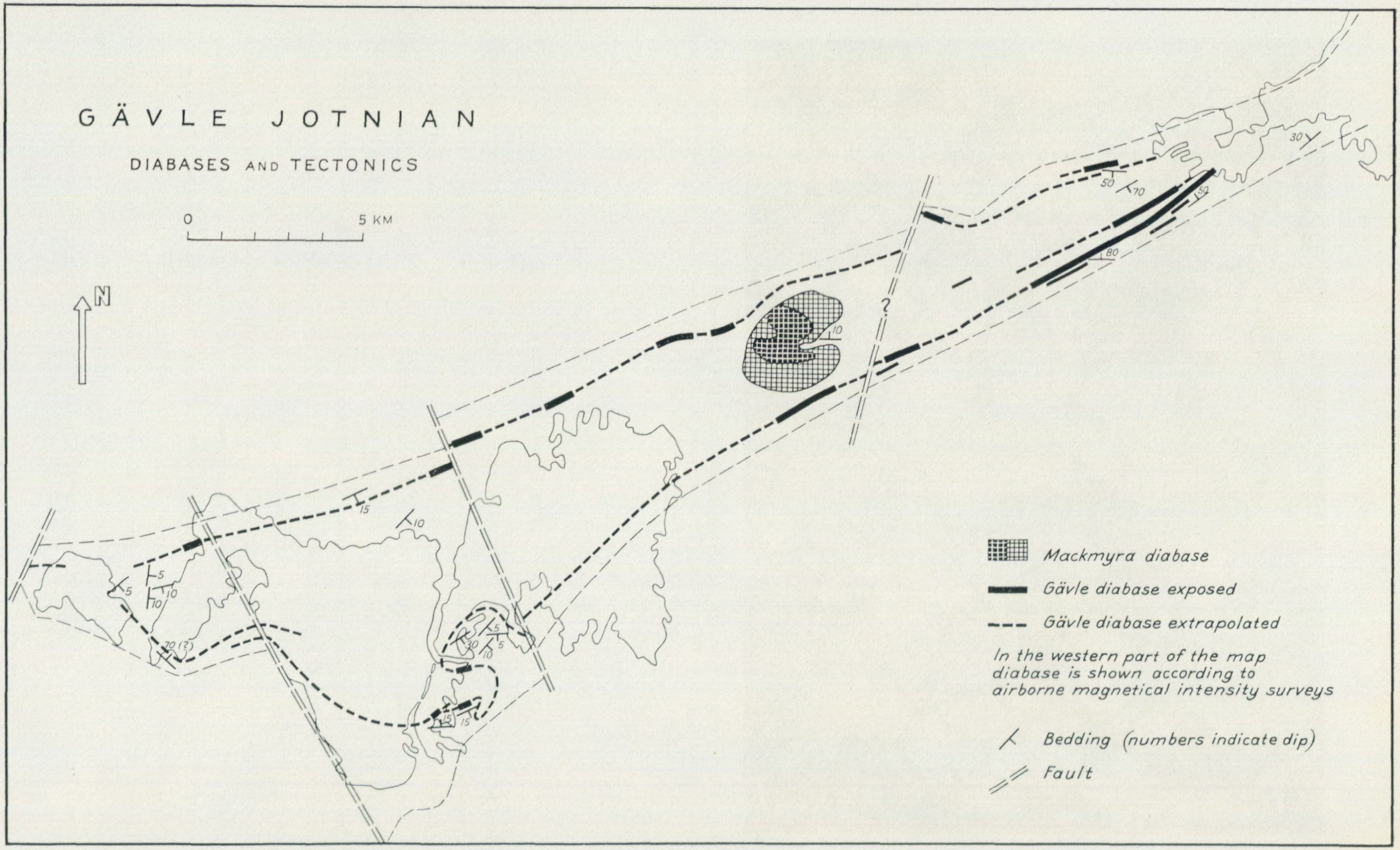
GÄVLE JOTNIAN
DIABASES AND TECTONICS
0
5 KM
N
30
50
70
50
80
?
10
15
10
5
5
10
10
70 (?)
30
5
5
10
15
15
Mackmyra diabase
Gävle diabase exposed
Gävle diabase extrapolated
In the western part of the map diabase is shown according to airborne magnetical intensity surveys
Bedding (numbers indicate dip)
Fault

Fig. 14.

Table 4. Chemical constituents and mineral composition of the Gävle diabase

	J 97 Gävle Kaserngatan	J 66 Gävle varv	J 1 Gävle Brynäsberget, black diabase	J 110 Gävle Brynäsberget, black diabase	J 109 Gävle Brynäsberget, red diabase	J 103 Gävle skjutfält northern sill	J 104 Gävle skjutfält, southern sill	J 104 a Gävle skjutfält southern sill	J 124 b Sofiedal	J 35 Ursabodarna	J 37 Fäbodudden	J 65 Hällhammar	Gävle varv (v. Eckermann 1925)
MgO	5.2	4.8		5.8	4.2	5.0				4.1	4.8	4.0	1.1
Fe_2O_3	6.4	6.6		5.0	11.5	8.5				8.2	3.6	9.0	6.6
FeO	8.6	8.9		10.3	3.6	7.2				5.5	10.6	5.3	9.5
TiO_2	3.0	2.8		3.0	2.8	2.8				2.8	2.7	2.8	3.2
CaO	7.7	8.2		8.2	4.1	5.0				6.3	7.4	5.6	7.1
Plagioclase	4	4	4	4	1	3	4	1	3	4	4	4	
same, saussuritized and sericitized	1	1	1	–	2	2	–	3	2	–	–	–	
same, carbonatized, and calcite	–	–	–	–	3	1	–	2	–	–	–	1	
Alkali feldspar and zeolites	–	–	–	–	–	1	2	2	2	1	–	–	
Olivine	–	–	–	–	–	–	–	–	–	–	1	–	
Olivine pseudomorphs (serpentine, iddingsite)	–	1	1	–	–	–	–	1	1	2	2	1	
Pyroxene	3	–	–	–	–	–	2	1	–	3	3	1	
Biotite	1	–	–	–	–	–	1	–	–	–	2	–	
Green chlorite	2	3	3	3	4	4	3	3	3	2	2	3	
Uralite, amphibole	–	1	1	–	–	2	–	–	–	–	1	–	
Sphene	1	–	–	–	2	2	1	2	2	2	–	1	
Apatite	1	1	1	1	1	1	1	1	1	1	1	1	
Magnetite, ilmenite	2	2	2	2	2	3	3	1	1	2	2	3	
Hematite	1	1	1	–	3	2	1	2	2	2	–	1	
Pyrrhotite, pyrite	–	1	1	1	–	–	–	–	–	–	1	–	
Glass	3	4	3	3	–	1	–	–	–	–	–	–	

Code: 4 = major constituent, 3 = abundant constituent, 2 = minor constituent, 1 = trace constituent.

of the larger sills in the south, are at Hällhammar and approximately one mile NE of Valbo. In addition, diabase has been reached by churn drilling in Storvik, Sandviken, and Forsbacka. The Sandviken drilling fits well with the inferred stratigraphical position of the main sill (the Main Conglomerate member), whereas the others may belong to different diabase bodies. In the western part of the map given in Fig. 14 diabase occurrences have been entered mainly according to the distribution of linear positive magnetic anomalies. On the basis of the contact relations and the cementation status of the sandstone it is concluded that the diabase was intruded as a system of sills into an imperfectly cemented sedimentary formation. This gives basis for a ”Jotnian” age classification of the Gävle diabase.

The Gävle diabase is a fine- to medium-grained black, greenish-grey or grey rock. Purple, brown, and red varieties are due to the replacement of magnetite and silicates by hematite. Typically, hematite occurs as rims or dissipating impregnations around magnetite crystals. Characteristically, red and purple varieties show high Fe^{3+}/Fe^{2+} ratios. Amygdules filled with chlorite, calcite, quartz, and chalcedonic silica are common, especially occurring in what is inferred to be the vicinity of sill contacts. Irregular chlorite-filled voids are less striking, but can easily be detected in thin-sections. The partial chemical analyses listed in Table 4 reveal a reasonable constancy in the contents of ferromagnesian constituents. The Fe^{3+}/Fe^{2+} ratio varies strongly, evidently in response to oxidation induced by pneumatolytic alterations or by the influence of water-logged sedimentary surroundings.

The chemical analyses do not corroborate the low content of MgO mentioned in von Eckermann’s paper of 1925 and used by him as a reason to suggest a new type of diabase. CaO contents are rather variable and characteristically low in varieties of rock rich in large calcite-filled amygdules which were not included in the analyses. There is an inverse relation between the content of calcium and the oxidation ratio of iron which suggests that the breaking down and removal of the anorthite-component in plagioclase was effected simultaneously with and by the same agent as the oxidation of iron. The selective abundance of silica-filled voids in areas rich in other amygdules and calcite suggests a similar relation for the contents of SiO_2 in the diabase.

The main mineral of the diabase is plagioclase which usually constitutes in excess of 50 per cent of the total volume. In pyroxene-bearing or other unaltered diabase the An content is usually between 45 and 60 per cent commonly showing good zoning. In varieties rich in amygdules the plagioclase is frequently somewhat more albitic. Feldspar phenocrysts are rather uncommon. The proportions of the other minerals vary to form a series with the mineral associations plagioclase-chlorite-ores and/or glass, and plagioclase-pyroxene-olivine pseudomorphs-(biotite)-chlorite-ores at the two ends of the gamut. As is seen from the chemical and mineral data in Table 4 this implies no essential change in the total chemical composition. Variations in mineral composition other than those mentioned here are clearly due to the effect of postcrystallization alterations. The pyroxene is an

Fig. 15. Gävle diabase showing plagioclase laths set in pyroxene. Fäboudden. + nic., 35 x.

augite-diopside and either forms large fields carrying ophitically enclosed plagioclase laths (Fig. 15) or occurs as small crystals enclosed in the chlorite-opaques metastasis. The optical properties are: $c\wedge Z$ around 45°, 2 Vz between 44 and 52°. The pyroxene is often somewhat chloritized while uralite is rather uncommon. Biotite occurs in diabase varieties rich in pyroxene and is a late-magmatic crystallization product. Olivine pseudomorphs are easily recognized by their shape and consist of serpentine or yellow and green intergrown or single flaky aggregates of chlorite. The yellow variety was described as iddingsite by von Eckermann (1925). Unaltered remains of olivine are very uncommon. Ores (magnetite and ilmenite) occur in the shape of rods, massive anhedral or subhedral crystals, and crystal skeletons. Hematite has, as stated above, the textural characteristics of a secondary constituent and sometimes forms dendritic growths in chlorite. There is no primary difference in texture between the black and the hematitic red varieties of diabase which is true even at macroscopically sharp contacts between the two types of rock.

Sphene, too, is a secondary mineral resulting from the unmixing of the titanium component in ores or occurring in the shape of irregular replacements in the groundmass or in altered plagioclase.

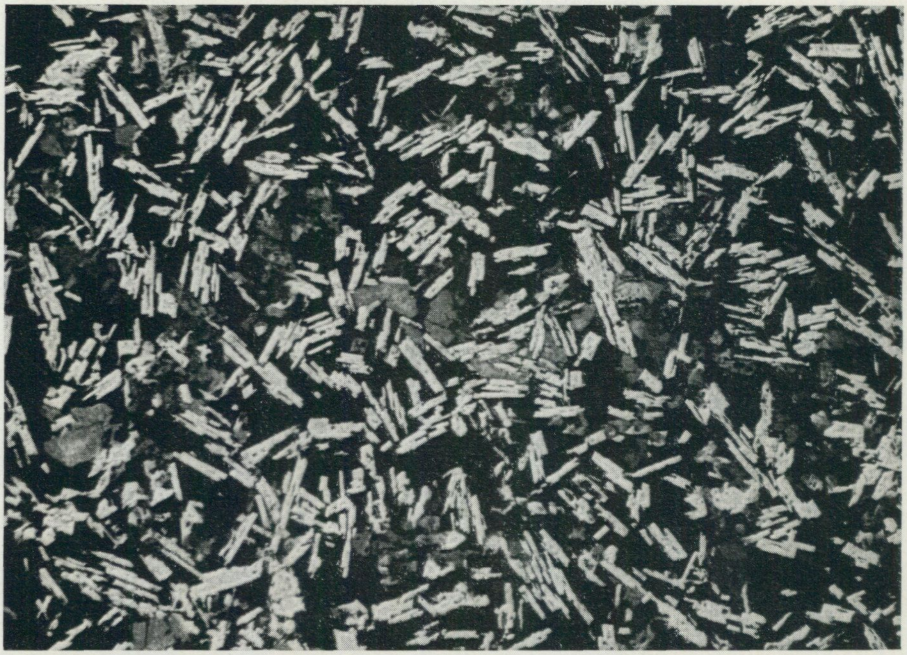

Fig. 16. Gävle diabase, Brynäsberget, Gävle. White is plagioclase, grey chlorite, black opaques (magnetite and magnetite-dusted chlorite). One nicol, 37 x.

Light green chlorite is an important constituent in all investigated specimens and is found either as a mesostasis heavily loaded with opaques or in clear fields, in which case it often exhibits a radially fibrous texture. Most of the chlorite appears to be either a primary crystallization product or the product of devitrification and shows no traces of substituting altered pyroxene. In nearly every case when intergranular or intersertal pyroxenes or pyroxene pseudomorphs are present, their boundaries against the mesostasis chlorite are clean-cut and subhedral.

Glass is common in parts of the main Gävle diabase sill in and SW of Gävle, the semiopaque mesostasis is, however, frequently a close intergrowth of minute ore and ore-infested chlorite grains. No vitreous groundmass was found in the other parts of the Gävle Jotnian area. Carbonates and epidote are late or secondary minerals replacing plagioclase or forming disseminated impregnations in the groundmass. A small amount of alkali feldspars and zeolites is often present, occurring mostly along the margins of the plagioclase laths. No free silica was detected except in amygdules and in traversing veins. Post-solidification cracks are occupied by carbonates, chlorite, prehnite, quartz, ores, and fibrous chalcedonic or cryptocrystalline banded opaline silica. The same minerals minus prehnite occupy amygdules which may reach a size of 10 cm across and preferably inhabit areas rich

Fig. 17. Leucodiabase consisting of albite, calcite, and traces of opaques. Brynäsberget, Gävle. + nic., 35 x.

in secondary hematite, sandstone dikes, chlorite and carbonate-filled veins, etc. Most amygdules are, however, smaller than 5 mm and filled with chlorite.

Small amounts of leucodiabase and albitite (Fig. 17) are commonly forming veins crisscrossing the diabase or occurring as schlieren or pseudonodules previously described as remelted sandstone inclusions. Actually, most of the "remelted sandstone" mentioned in the map-sheet description turned out to be virtually monomineralic albitite. As will be described later no remelting at all has been found at the contacts of the Gävle diabase. The color of the leucoveins ranges from grey or greyish white to red and purplish in varieties of rock rich in disseminated hematite. The mineral constituents are either almost exclusively fan-shaped crystals of albite, or albite-oligoclase plus fair amounts of carbonates and traces of opaques and either pyroxene, or prehnite, or laumontite. Small amounts of sphene and traces of quartz may rarely be present. The average grain-size of the leucocratic rock ranges between 0.2 and 3 mm.

The Mackmyra diabase

The Mackmyra diabase is an ophitic to subophitic oliviniferous medium- to coarse-grained rock. The length of the plagioclase laths mostly ranges between 3 and 15 mm

Table 5. Mineral composition of representative samples of Mackmyra diabase

Minerals	J 120 Coarse diabase, Mackmyra	J 127 Medium-grained diabase, Västbyggeby	J 114 Coarse pegmatitoid diabase, chloritized, Hällholmen
Plagioclase and pseudomorphs	62.7	60.9	51.3
plagioclase	61.5	59.8	48.3
sericite and saussurite	1.2	1.1	3.0
Olivine and pseudomorphs	24.2	18.2	21.5
olivine	20.9	16.5	15.4
talc1)	2.7	1.6	2.71)
serpentine and chlorite	0.6	0.1	3.4
Total chlorite and serpentine	3.9	3.3	8.2
reaction rims	2.3	2.0	3.7
interstitial	1.0	1.2	1.1
Pyroxene	6.8	10.7	14.9
Ores	1.5	3.2	6.0
Biotite	0.7	1.9	0.7
Apatite	0.2	0.5	0.4
Alkali feldspar and zeolites	0.6	1.5	3.3

1) including some phlogopite.

decreasing toward the periphery of the diabase-occupied area where the contact varieties gradually develop an intersertal to intergranular fabric and decrease in olivine with a simultaneous rise in the contents of oxide ores. Pegmatitoid diabase pockets, usually lacking well-defined contacts against the surrounding diabase, are prominent in some of the central parts of the intrusion and develop olivine, plagioclase, and pyroxene crystals reaching a size of several inches. As is shown in Table 5 plagioclase (An usually in excess of 60 per cent), olivine, and pyroxene are the major constituents of the Mackmyra diabase which if anything is simpler in its mineral composition than the Gävle diabase type. The pyroxene is mostly a calcic augite or augite-diopside. Orthopyroxene is rare and, whenever occurring, forms unmixing intergrowths in clinopyroxene hosts. Minor primary constituents are ores, dark-brown biotite, apatite, chlorite, and accessory amounts of alkali feldspar, the two latter minerals together with an unidentified zeolite sometimes forming small interstitial pockets of mesostasis. Quantitatively important replacements of olivine, pyroxene, and plagioclase by secondary minerals (chlorite, sphene, serpentine, ores, and carbonates) are rather uncommon except in pegmatitoidal

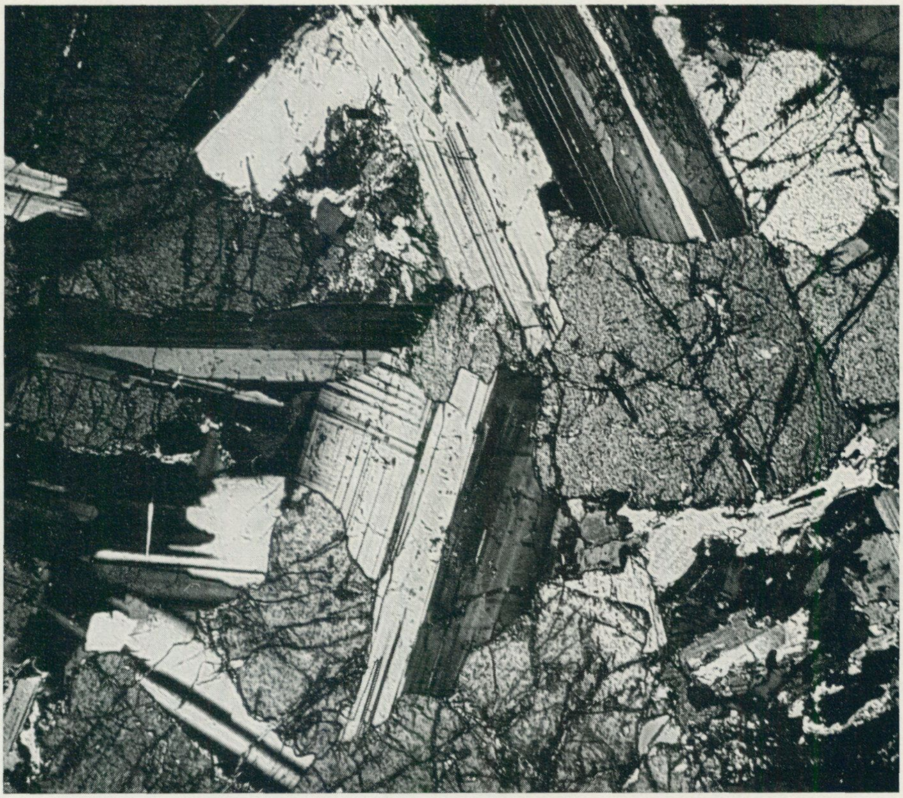

Fig. 18. Mackmyra olivine diabase, Mackmyra. + nic., 43 x.

schlieren and contact varieties. Leucocratic rocks associated with the Mackmyra diabase are restricted to granophyric veins and schlieren occurring at the contact with the sandstone and produced by rheomorphism of the wall sediments.

Diabase-sandstone contact relations

The contact between the sedimentary and hypabyssal rocks of the Gävle Jotnian are accessible for observation at Sofiedal, Gävle SW (Gävle skjutfält), an excavation and boulders at Fäbodudden, and in cuttings along the bed of the Mackmyra dam channel (Mackmyra diabase). In addition, the contacts between Gävle diabase and sandstone have been investigated in a number of cuttings in Gävle town S of the Gävle river. Conclusions on the relations between the diabase and the sandstone have also been drawn from the localities NE of Valbo, at Brynäsberget in Gävle, Gävle Kaserngatan, and Tolvfors NW of Gävle. Here the actual contact is unexposed, but the diabase is rich in sandstone dikes or contains sandstone xenoliths and in some cases has neighboring outcrops of sandstone. The important differences in the geological relations of the two diabase types which arise from these investigations are corroborated by a consideration of the intrusion tectonics of the diabase intrusions.

Gävle diabase contacts: The salient features of the contact relations between the Gävle diabase and the Jotnian sediments are the complete lack of extensive remelting or rheomorphism, the abundance of sandstone dikes in the main sill, and the apparently profound influence exercised by the diabase intrusion on the cementation of the adjacent sediments. Since a closer study of "inclusions" contained in the Gävle diabase revealed that most of these are leucodiabasic differentiates, the number of actual sandstone xenoliths in the diabase is reduced to a very few, primarily encountered at the Brynäsberget locality in Gävle. A survey of the distribution of leucodiabase/albitite and sandstone dikes in this group of outcrops revealed important differences in the occurrence of these rocks: (1) sandstone dikes are restricted to the vicinity of the floor of the diabase sill, (2) leucodiabase and albitite occur in irregular coherent veins near the lower contact of the diabase and, predominantly, as schlieren in the upper parts of the sill below what is inferred to be the immediate vicinity of the roof contact. The general pattern of leucorock distribution is very clearly one of enrichment in the upper central parts (~ upper third) of the main sill. No leucocratic differentiates were observed in any of the other (smaller) sills found in Gävle.

The actual contacts between diabase and sandstone are usually somewhat irregular implying the existence of protrusions and indentations a few inches deep which may sometimes pass into sandstone dikes in the diabase. The contact diabase is usually very rich in chlorite-filled amygdules which may contain isolated detrital quartz grains. Iron oxidation plus carbonatization, sericitization, and chlorite-impregnation of plagioclase are exceedingly common. Generally there is no marked decrease in the size of plagioclase laths in the diabase when approaching the contact. Glass or devitrified glass mesostasis is encountered near the contacts of diabase rich in this material, but is otherwise restricted to a very narrow zone in the immediate vicinity of the sandstone. No glass is found in the sandstone except possibly in rims, fractions of a millimeter wide, bordering directly on the diabase. These rims are generally so heavily loaded with hematite impregnations as to be unresolvable under the microscope. No appreciable corrosion of detrital quartz is seen in any of the thin-sections studied. Quartz grains, however often serve as loci for the deposition of thick hematite rims which may engulf recrystallized clay coatings. Detrital microcline and feldspar pseudomorphs are occasionally silicified, show zeolite rims, or are partly replaced by carbonate and chlorite. Original clay matrix has disappeared or is recrystallized into rim overgrowths consisting of phyllosilicate flakes protruding from the surface of the detrital grains.

The characteristical cements of the sandstones at the diabase contacts are light-green chlorite, carbonate, and fibrous or pseudofibrous silica. The sequence of

Fig. 19. Fine-grained sandstone dike in Gävle diabase, Brynäsberget, Gävle. Cements are chlorite and fibrous silica. One nicol, 35 x.

cement deposition is generally: (pre-diabase quartz) – fibrous silica – chlorite – carbonate – (late massive quartz). The rims of fibrous silica are 0.01–0.05 mm wide and consist of quartz possibly replacing original fibrous chalcedony. Radially fibrous chlorite, and carbonate ranging from fine-grained mosaic masses to large crystals filling several voids cement the remaining interstices. The distribution of carbonate is commonly somewhat patchy alternating with areas cemented by quartz. The areas cemented by carbonate frequently show strongly sutured grain contacts and some detritus corrosion or corrosion of the fibrous silica cement deposited earlier. Secondary minerals in the sandstone which are restricted to diabase contacts include Fe-rich epidote forming euhedral interstitial grains in the immediate vicinity (a few inches) of the diabase contact and, just outside of the epidote zone, occasional grains of prehnite occurring either in the cement or replacing grains of detrital feldspars. In sandstone cemented by chlorite the original ore rims coating the detrital grains have sometimes recrystallized into granules of hematite. Other secondary minerals also found in sandstone remote from the diabase, but increasing toward the diabase contacts are coarse chlorite flakes in what is inferred to be pseudomorphs of ferromagnesian minerals, interstitial zeolites, and a few overgrowths on detrital sphene. Dark emerald-green chlorite is found in brecciating veins at, or close to the diabase contacts and may sometimes also form late spherulites in chlorite-cemented voids. This type of chlorite is always younger than the light-green delessitic variety. Since unaltered detrital garnet and epidote is sometimes found at the diabase contacts, the wholesale destruction of these minerals throughout most of the lower four members of the Gävle Jotnian may be due to the influence of hydrotermal solutions and thus be a secondary effect of the Gävle diabase intrusion. No facts emerged which would establish a definite connection between the formation of secondary albite, the disintegration of detrital plagioclase and the formation of the Gävle diabase.

The partial or complete disruption of sandstone fabric in part of the contact rock is suggested by the existence of relations between non-framework space and grain-contact types which are incompatible with those found in normally compacted sandstones. The texture found in several thin-sections of contact sandstone and in all investigated specimens of sandstone dikes implies a high pre-cementation porosity (35–45 %) sometimes coupled with a relative abundance of concavo-convex and sutured grain contacts, part of which are found in coherent groups of quartz grains which appear to have moved as a unit during the disruption of the sandstone framework. Xenoliths of sandstone in diabase usually show a high pre-diabase porosity eliminated by cementation with chlorite or other cements stemming from the diabase. Several xenoliths have started to break up and dissipate to form sandstone dikes in the diabase. The glossy appearance of some of the sandstone fragments is due to the prominence of pseudofibrous fine-grained silica cements and not to the presence of glass formed by detritus remelting. From the distribution of grain-contact types in contact sandstones and from the relative frequencies and textural relations of the different types of cement it is inferred that the intrusion of the main diabase sill found a sandstone ranging in compaction from beds partly cemented by quartz to layers coherent solely by virtue of some pressure solution. In the sandstones of the Main Conglomerate member non-framework space was on an average about 30 per cent, a considerable part of this being open voids. This moderate degree of compaction nevertheless implies the existence of a considerable load of overburden which rested on the parts of the Jotnian formation invaded by the Gävle diabase sills. Since the solubility of silica in water is covariant with temperature, a substantial accelerating influence of the Gävle diabase on pressure solution in sandstone is implicit in the statement of the existence of high uncemented porosity in the sediments prior to the diabase intrusion.

Variously orientated and developed stylolitic seams, generally running obliquely to both the igneous contact and the bedding of the sandstone, are usually confined to within a few feet from the diabase and equally affect the detrital grains and the cements deposited by contact action. Some of these seams were found to cross over into the diabase. Otherwise, solution zones are rather uncommon in the Gävle Jotnian sandstones and predominantly habitate clayey layers, then usually forming branching subparallel systems of seams orientated to conform roughly with the bedding surfaces. Here, the solution of the scanty quartz detritus usually implies the formation of broad, shallow, curved pits previously described as lobate corrosion (Gorbatschev 1962 b).

Sandstone dikes are found in the eastern part of the Gävle Jotnian in a number of exposures belonging to the main diabase sill, and are particularly common in the lower parts of this body. Most sandstone dikes are irregular and branching and range in size from fractions of an inch to about a foot across. A few fairly straight dikes penetrate far into the diabase sill or may even traverse it. Regular diabase breccias in sandstone have been observed. The sand/silt detritus of the dikes is similar to that of the contact sandstones both in composition and in being virtually unaffected by corrosion except for the partial replacement of a few feldspar or pseudomorphosed feldspar grains by hematite cement. Traces of quartz cement rims older than the diabase intrusion are rather uncommon which suggests that the detritus in the dikes had been derived from uncemented or poorly cemented sandstone. Grain shapes indicate a prehistory of some pressure solution. The cements are as found in the contact sandstones: chlorite, fibrous silica, and carbonate, plus small amounts of hematite and a few secondary grains of epidote. The proportions of the cementing minerals vary between the different dikes, but usually there is the regular sequence of cement rims described from the contact sandstones. The sandstone dikes sometimes contain coherent blebs of chlorite and brecciating veins of chlorite and carbonate. The shapes and contacts of the sandstone dikes mostly indicate forcible intrusion probably assisted by the formation of slumping or contraction cracks in the diabase sill. The inferred mode of emplacement is by the action of supercritical water vapor generated by the heat of the diabase and trapped between the floor of the sill and fairly impermeable (cemented or clayey) beds in the Lower Subarkose member. Other conceivable modes of origin are the disintegration of included sandstone floats and the gravitative settling of sand into contraction cracks formed near the roof of the sill. Whereas the latter mechanism could not be undisputably demonstrated, the dissipation of sandstone inclusions to form dikes was actually observed in two exposures.

Bomb experiments indicate that the solution of silica in supercritical gas phase water is a positive function of temperature if the total pressure is higher than approximately 600 kg/cm^2. Assuming a cover of incompletely cemented, water-saturated sediments having a maximum thickness of 3 000 feet and an average density of 2.0, the total load pressure at the lower contact of the diabase was about 250 kg/cm^2. At this pressure and the temperature expected at the contact (450–600° centigrade) the solubility of silica in vapor is considerably lower than its solubility in the same volume of subcritical steam or liquid water at about 300° (Kennedy 1950). These relations may offer an explanation of the very slight detritus corrosion found in the sandstone dikes and in the immediate vicinity of the diabase contacts. It is considered that the early rims of fibrous silica were formed during a period of maximum heating, possibly contemporaneously with the mixing of vapor derived from the sediments with fully silica-saturated pneumatolytic solutions emanating from the diabase sill and eventually responsible for the deposition of the chlorite cement. A high oxygen pressure is indicated by the universal formation of hematite in those parts of the diabase sill which are rich in sandstone dikes. As the diabase cooled and the temperature of the vapor dropped into the area of maximum silica solubility, corrosion of the quartz grains in the sandstone dikes was prevented by the newly deposited chlorite cement. Along fissures and in other permeable zones increased solubility, however, led to the formation of stylolitic seams. Simultaneously, heavy pressure solution may be expected to have occurred in incompletely cemented sandstones off the zone of chlorite cementation.

Contacts of the Mackmyra diabase: Remelting phenomena and a wide zone of recrystallization are encountered just east of the Mackmyra dam on the Gävle river, which is the only exposure of the contact between the Mackmyra olivine diabase and the Jotnian sediments here represented by the Upper Arkose member. The marginal diabase is medium- to fine-grained and develops an aphanitic contact rim. A partially remelted sandstone xenolith is found in the diabase near the contact. From this inclusion and from the marginal sandstone a number of small sinuous granophyric veins proceed for some distance into the diabase which is here composed of plagioclase laths set in a groundmass of alkali feldspar, small euhedral grains of pyroxene, a few olivine pseudomorphs, chlorite, and minor amounts of amphibole, biotite, opaques, and apatite. The texture is intergranular–interstitial. The marginal diabase is usually virtually free from unaltered olivine, the contents of olivine pseudomorphs being much lower than the amount of olivine in the normal Mackmyra diabase. Several feet off the contact part of the diabase shows strong chloritization and sericitization of the original minerals and considerable amounts of carbonate replacing feldspar and pyroxene or forming disseminated impregnations in the groundmass.

The micrographic veinlets in the diabase and the granophyric margin of the contact sandstone show alkali feldspars, quartz, greenish biotite, and traces of amphibole, chlorite, epidote, sphene, and opaques. The marginal sandstone exhibits a broad zone of contact alteration. Due to considerable uncertainty in tracing the diabase/sandstone contact, the width of this zone could not be established unequivocally, but at least a hundred feet of sandstone appear to show textural modifications attributable to the diabase. Disregarding the occasional development of stylolitic seams, the recrystallization of the original sericitic matrix into large flakes of intergranular muscovite is the first sign of diabase contact influence. Approaching the contact the recrystallized muscovite is replaced by alkali feldspar heavily loaded with hematite dust. Secondary rims develop on detrital sphene, and some distance from the contact there is a zone of prehnite crystallized in the interstices between the framework grains or replacing original plagioclase. Simultaneously the detrital feldspar of the arkose recrystallizes and joins the newly introduced alkali feldspar to form large coherent fields filling several grain interstices. Even in specimens affected by just slight matrix recrystallization the heavily cement-coated quartz starts developing toothed grain outlines, the corrosion pits eventually cutting into the detrital cores of the quartz grains. As the contact is approached, a micrographic

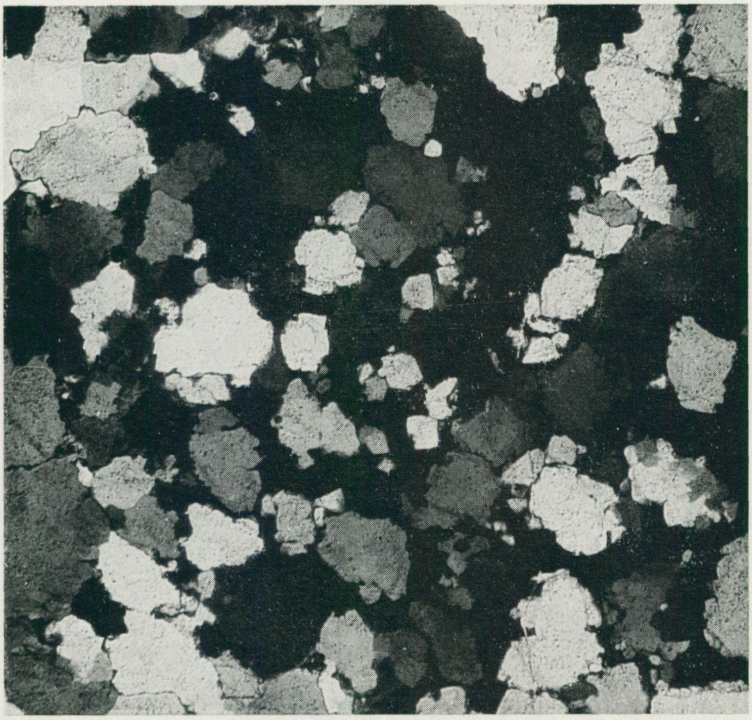

Fig. 20. Incipient corrosion of cement-coated quartz detritus 150 meters from the nearest outcrop of Mackmyra diabase. The black groundmass is essentially alkali feldspar crowded with opaque dust. + nic., 26 x.

groundmass develops between the large corroded quartz individuals and engulfs and incorporates both the newly formed subhedral protrusions growing from the original grains and the remnants of corroded detrital quartz. The lattice orientation of the micrographic feldspars is evidently to some extent controlled by the extinction of the corroded framework quartz. In the immediate vicinity of the contact detrital and secondary minerals merge to form a homogeneous micrographic texture studded with toothed quartz blebs left over from partly dissolved large detrital grains. The total composition of this rock implies a considerable increase in the feldspar content over that found in the unaltered arkose.

From the textural features it is evident that the acid veins at the diabase contact are formed by the partial remelting of sandstone and cannot be explained as granophyric differentiates of the basic melt. It is further clear that the Mackmyra diabase encountered a heavily quartz-cemented Upper Arkose, which of necessity must imply a considerable lapse of time between the intrusion of the Gävle and the Mackmyra diabase.

TECTONICS

Throughout the Gävle sandstone the regional dip of the strata is toward the center of the Jotnian area. Since no directions of detritus transportation could be determined, it remains obscure whether this is entirely due to a postdepositional subsidence of the present Jotnian area or whether the tectonics reflect the existence of an original depression in the depositional basin. In the western part of the Gävle Jotnian the bedding forms a concentrical pattern gently inclined toward the mid of the basin. Local reversions which are probably due to weak folding are found in the Lem area and along the south-eastern shore of lake Storsjön (fig. 14). Thin floats of sandstone occurring just outside of the northern margin of the Jotnian suggest that the NE–SW trending borders of the sedimentary area are normal contacts exposed by subsequent erosion. East of Sandviken where the existence of a major fault, approximately trending NNW, is inferred from topography and the occurrence of breccia boulders in till, the dip of the sedimentary strata is much steeper and reaches subvertical just to the west of Gävle. The sediments in the eastern part of the Gävle Jotnian exhibit small-scale thrust and tear faulting along and obliquely to their strike. Nevertheless, key lithologies can be traced throughout most of this part of the sandstone belt. The question of the relative importance of faulting and folding in this area is impossible to assess in the absence of coherent exposures. Even so a trough subsidence of the Prejotnian substratum is evident from the existing observations. There are no structural data indicating slump folding or tilting contemporaneously with the deposition of the Jotnian sediments. In the absence of these features the very incomplete cementation of large parts of the sedimentary sequence by the time of the intrusion of the Gävle diabase gives basis to assume that no appreciable disturbance of the bedding occurred prior to this magmatic event. Again, the presence of fissures filled with Cambrian sandstone in the surrounding Svecofennian and the observation of Cambrian sandstone resting on top of the tilted Jotnian (Engström 1956) combine – if correct – to lend support to the contention that the trough subsidence of the Gävle area was accomplished mainly before the onset of the Cambrian.

Turning to the diabases the original subhorizontal multiple-sill character of the Gävle diabase is fully brought out by the present investigation. The previously advanced hypotheses of a basaltic flow or a system of dikes (inclined sills) are rejected due, for one thing, to the inferred pressure solution/cementation status of the sandstone during the diabase emplacement. In the absence of contact outcrops and gravity surveys the shape of the Mackmyra diabase intrusion is much more difficult to assess. The newly discovered contact locality in the Mackmyra channel and variation of grain-size in the adjoining diabase outcrops suggest a somewhat irregular sheet of diabase cutting at low angles through the sandstone bedding and dipping toward the inferred center of the diabase intrusion. However, it is not clear whether the sandstone here is continuous with the other sediments and to what extent this contact locality has been tilted by the trough subsidence of the Gävle Jotnian. Combined with observations of diabase texture at other localities the Mackmyra channel contact may be taken to suggest a semicircular inclined intrusion, possibly a vent or dike combined with a cone-sheet truncated by erosion below its upper surface. The absence of Mackmyra diabase in other parts of the Gävle Jotnian militates against a sill-shaped intrusion.

The suggested difference in form between the Gävle and the Mackmyra diabase bodies is accounted for by differences in consolidation of the wallrock sediments. Assuming a basic melt with a density of about 2.7 considerably more work is required to lift the diabase magma to the surface than to intrude it laterally into sediments having an average density of 2.1–2.2. From the cementation status ot the contact sandstones it is concluded that the Gävle diabase melt encountered sediments ranging in (water-saturated) density from a maximum 2.3 at the floor of the sill to approximately 1.9 near the surface of the earth. In this environment the diabase melt may be expected to spread as a sill lifting the sediments on its top. The localization of the main Gävle diabase sill in the Conglomerate member may be due to exceptionally poor cementation and consequently low coherence in the coarse parts of the sediment pile. The Mackmyra intrusion, in contrast, broke through sandstones with a density of approximately 2.5. In addition the Jotnian sediments were now burdened by sills of the Gävle diabase. Thus the difference in density between the wallrock and the melt was insufficient to prevent the hydraulic head of the magma from pushing through the sediments to develop a vent or cone-sheet intrusion. A flattening of the Mackmyra diabase into a sill may have taken place as the melt entered less compacted sediments later removed by erosion.

INTERPRETED GEOLOGICAL RELATIONS

The Jotnian sediments of the area studied are characterized by subarkose-arkose lithology, scarcity of argillaceous deposits, good roundness of the sand- and gravel-size detritus, generally good textural maturity, and red or yellow color caused by the virtually universal presence of hematite grain coatings. In all these respects the Gävle Jotnian is similar to the Mälar sandstone of corresponding age classification and also appears to be well in line with the rather limited data available on the lithology of the other Jotnian sediments of Fennoscandia. The overall lithological features and the information available on sedimentary structures suggests a deposition from running water in intermittently dry sedimentation basins. Aeolian transportation may have been of some importance in redistributing the deposits. The Jotnian sedimentation basin(s) has by some authors been suggested to have been marine (v. Eckermann 1937 b, Lundegårdh 1967). This conclusion is based on the presence of small amounts of chlorine in some chemically analyzed Jotnian sediments (v. Eckermann), the presence of saline or brackish water in a churn

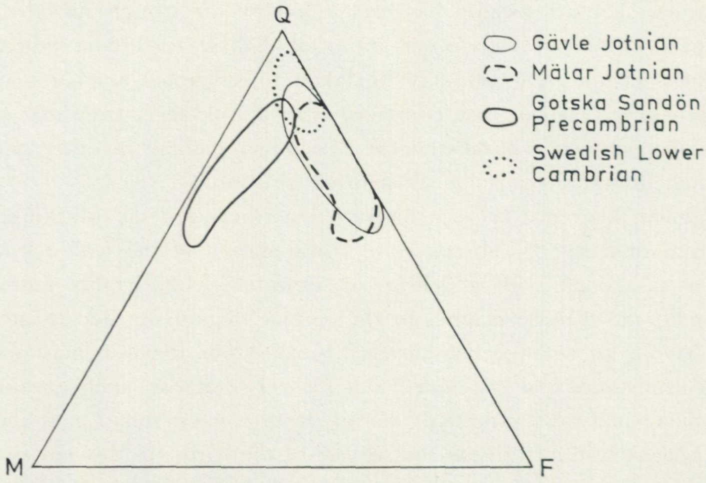

Fig. 21. Lithology of selected Swedish non-orogenic sediments, Q, F, and M correspond to Qu, RF, and Ma in Fig. 3.

drilling into the Gävle diabase at Sandviken (Lundegårdh), and the hypothesis envisaged by von Eckermann for the formation of the Jotnian sediments, which relies on the action of tides racing across a piedmont lowland which permanently adjusted its height to conform with the sea level. To lend these tides sufficient energy to account for the formation of coarse conglomerates von Eckermann suggested that the moon of Jotnian days had been much closer to Earth than at present. The information supplied by this study does not support von Eckermann's concept of the regional blanket character of the Jotnian conglomerates, and considering the great thickness of the sediments as well as the coarse size of the detritus a sedimentation basin or a group of sedimentation basins vicinal to areas of high relief is suggested to be the depositional environment of the Gävle Jotnian. There appear to be no features to show that tidal action was a major agent of sediment transportation or redistribution. As to the problem of basin salinity the available evidence may be accounted for by hydrothermal action and by the introduction of recent marine water into cracks in the Gävle diabase. Even if the depositional basin actually had been saline it is not clear whether this should be attributed to a marine environment or to evaporation in landlocked basins. The grain-size distribution indicates highly variable current strength possibly suggesting occasional periods of sheet flows.

The lithological properties which define each member within the Gävle Jotnian may reflect processes indicative of different climatic conditions, special environments of deposition, or differences in the tectonical regime. Comparing the lithology of the arkose and subarkose members the relative prominence of the "Subjotnian-Jotnian" source in the latter (p. 19) and the uniform distribution of matrix (Fig. 11) show that the differences are not due to the formation of subarkoses by the littoral reprocessing of originally exclusively arkosic material. Reworking by selective abrasion in a shore environment would be expected to result in the simultaneous removal of clay and feldspar and the consequent subdivision of the sediments into feldspathic layers comparatively rich in matrix, and a group of matrix-deficient subarkosic sandstone. This is not true of the Gävle Jotnian where silty layers are not more arkosic than the rest of the rock. The actual lithology is well compatible with river action effecting mechanical separation into mineralogically equally mature or immature sandstones and micaceous siltstones.

In search of an explanation of the almost complete absence of unaltered plagioclase in the Lower Subarkose, Conglomerate, and Upper Subarkose members of the Gävle Jotnian two possible mechanisms merit consideration: (1) intrastratal destruction of the heavy minerals and plagioclase due to hydrothermal action induced by the Gävle diabase, and (2) weathering in the source area or during transportation. A possible clue is offered by the data of Table 1 which show no consistency in the ratio of potash feldspar vs. altered feldspar plus plagioclase, thus suggesting that part of the potash feldspars was involved in the alteration. This militates against the destruction of feldspar by the diabase intrusion. Heterogeneous weathering conditions may thus have been instrumental in the development of the different lithologies. The red coloring of the sediments, which shows variations of intensity between the different bedding units and thus probably developed in the source area or during transportation, is taken to suggest warm, intermittently wet climatic conditions in these areas (Falke 1964). However, if varying climatic conditions had been the sole reason of lithological differentiation the percentage of detritus derived from the resistant "sedimentary Subjotnian-Jotnian" source would be expected to be reasonably constant throughout the sediment pile. On the basis of the selective abundance of sedimentary rock fragments in the Conglomerate and Upper Subarkose members of the Gävle Jotnian (p. 16 and 19) it is concluded that tectonism is the ultimate control of variations in Jotnian rock composition. The model of Jotnian sedimentation in the Gävle area thus emerging includes:

(1) An early period of deposition of locally derived sharpstone conglomerate, conglomerate, and arkose, gradually passing into more fine-grained subarkosic arenites. The minerals of these lower members attest to a shield lithology dominated by large exposures of Archean rocks and including a small, but persistent source of "Subjotnian" volcanics.

(2) The marked conglomerate – composite sandstone horizon of the Conglomerate member is the result of a tectonic pulse which caused a rejuvenation of topography and permitted erosion to penetrate into previously unbreached sediments of the "Subjotnian-Jotnian" source. The Archean source was however still responsible for the bulk of the detritus. Provided the sandstones of Jotnian age classification are actually contemporaneous in the different parts of Scandinavia, the likely source of the strongly pressolved, "Jotnian

type" sandstone boulders found in the Gävle Jotnian is the "Subjotnian" Digerberg formation which probably covered a larger area than the present erosional remnant found to the NW of the Gävle area. Except for the presence of intraformational siltstone and shale fragments showing weak lithification there is no evidence of cannibalistic erosion in the part of the Jotnian studied here.

The Upper Subarkose was deposited during the later stages of this phase of sedimentation.

(3) Continued denudation and a new period of tectonic reactivation responsible for the formation of the gravels at the base of part of the Upper Arkose member brought new fresh areas of Archean bedrock under attack, causing a substantial influx of feldspathic detritus into the depositional area. In the absence of evidence on the relative age of the Upper Arkose and the Gävle diabase it remains obscure whether the diabase intrusion should be attributed to this particular period of tectonic unrest.

In contrast to conditions predominant during the deposition of the Swedish Cambrian sandstones and probably also the Precambrian Gotska Sandön sediments, the Archean source area of the Jotnian was tectonically active providing topographical relief which allowed stream action to erode and transport coarse material and accumulate it into deposits of a thickness unparalleled in the shield sediments of Paleozoic times. The lithology of the Jotnian sediments definitely rules out the possibility of a tectonically undisturbed (unfaulted) Sub-Jotnian peneplain still in universal existence during the deposition of the Gävle and Mälar Jotnian.

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GFF – Geologiska Föreningens i Stockholm Förhandlingar
SGU – Sveriges Geologiska Undersökning

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MAP OF THE GÄVLE SANDSTONE AREA

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