GEOLOGINEN TUTKIMUSLAITOS

BULLETIN

DE LA

COMMISSION GÉOLOGIQUE

DE FINLANDE

N:o 214

PETROGRAPHY AND SEDIMENTATION of the PRECAMBRIAN JATULIAN QUARTZITES OF FINLAND

RICHARD W. OJAKANGAS

OTANIEMI 1964

GEOLOGINEN TUTKIMUSLAITOS
BULLETIN DE LA COMMISSION GÉOLOGIQUE DE FINLANDE N:o 214

PETROGRAPHY AND SEDIMENTATION of the PRECAMBRIAN JATULIAN QUARTZITES OF FINLAND

RICHARD W. OJAKANGAS

OTANIEMI 1964

Helsinki 1965. Valtioneuvoston kirjapaino

ACKNOWLEDGEMENTS

This investigation was made possible by the award of a Fulbright Fellowship for study at the University of Helsinki from August 1960 to August 1961. I am deeply grateful to the government of the United States of America for this award, and also to personnel of the United States Educational Foundation in Finland for their interest and assistance.

This research topic was suggested by Dr. Ahti Simonen of the Geological Survey of Finland. During the course of this study, he provided valuable suggestions and arranged for use of all facilities of the Survey, where most of the laboratory work was conducted. Innumerable other persons at the Survey, especially Dr. Vladi Marmo, Dr. Maunu Härme, Dr. Mauno Lehijärvi, and Dr. Atso Vorma, provided valuable assistance. Mr. E. Halme took some of the photographs and Mrs. Elsa Järvimäki drew the plates. Mr. P. Ilola prepared the thin sections.

Professor Martti Saksela of the University of Helsinki offered valuable advice on several occasions. Professor Pentti Eskola's continued interest was sincerely appreciated. In the field, E. Viluksela, P. Isokangas, P. Rouhunkoski, H. Wennervirta, M. Lehijärvi, and J. Saastamoinen, to mention some, were very helpful. Dr. Paavo Haapala arranged for cooperation of Outokumpu personnel. Toivo Mikkola provided the locations of some cross-bedded quarzite outcrops.

To my wife, Beatrice, and children Cathy and Greg, I extend my thanks for their patience and for their company during part of the fieldwork. Numerous relatives and friends, especially Lilja Risku and Kerttu Risku of Kauhajoki, provided lodging.

Final petrographic studies and manuscript preparation were done at Stanford University, California. Drs. A. Simonen, W. R. Dickinson, Arthur O. Beall and John C. Green read the manuscript and offered suggestions. To all of the above persons, and to many others not mentioned, I extend my sincerest thanks.

Stanford, February 1964

Richard W. Ojakangas

University of Minnesota
Duluth, Minnesota

ABSTRACT

The Jatulian quartzites, metamorphosed 1 800 m.y. ago, were studied in eastern, central, and northern Finland in order to decipher the sedimentary history of the original sandstones. Erosional remnants of the formation, several hundred meters thick, indicate an initial distribution over an area of about 400 000 km^2. The quartzites at some localities are completely recrystallized; at other localities they are sheared but retain sedimentary characteristics. Most of the quartzites were formed under conditions of the amphibolite facies, with the degree of metamorphism increasing from east to west.

The sandstones were mainly clayey orthoquartzites, clayey subarkoses, and clayey arkoses. The clayey matrix has been recrystallized into mica. Zircon is the only abundant nonopaque detrital heavy mineral; most other heavy minerals were formed during metamorphism.

The source rocks were mainly granitic with indeterminate proportions of granites and gneisses. Zircon varieties indicate derivation from both para- and orthogneisses. Large portions of the formation are mineralogically and texturally mature; evidently detritus on the weathered, vegetation-free landmass, as well as similar sediment supplied by streams from the east, was reworked by wind and then by the shallow sea. Clay was probably carried into the sea with quartz sand, separated there by weve and current action, and the again mixed with sand prior to burial. Carbonates and shales were deposited upon the sandstones.

Analysis of cross-bedding indicates that the major paleocurrent movement in the Jatulian Sea was toward the WNW, with a secondary but prominent current movement toward th SSW. One of these currents probably moved parallel to the shoreline and the other normal to it. The sea probably transgressed eastward upon a stable, low-lying landmass.

CONTENTS

	Page
INTRODUCTION	7
METHODS	12
FIELD DESCRIPTIONS OF SAMPLED LOCALITIES	13
KIIHTELYSVAARA	13
PAUKKAJANVAARA	14
VUOKATTI	15
KIVALO	16
KALLINKANGAS	16
OUNASVAARA	17
EAST KARELIA	18
KUOPIO AREA	19
NORTHERN LAPLAND	19
LESKELENVAARA	19
SEDIMENTARY STRUCTURES	20
PALEOCURRENT PATTERNS	22
PETROGRAPHY	25
MINERALOGY	25
ROCK TYPES	36
HEAVY MINERALS	38
APATITE	39
TOURMALINE	40
ZIRCON	42
SEDIMENTATION	46
PALEOCURRENT INTERPRETATION	46
NATURE OF THE SOURCE ROCKS	47
CLIMATE OF THE SOURCE AREA	50
MATURITY OF THE JATULIAN SANDS	51
ENVIRONMENT OF DEPOSITION	53
RELATIVE AGES OF THE QUARTZITES	55
METAMORPHISM AND METASOMATISM	58
DEFORMATION	61
CONCLUSIONS	69
REFERENCES	71

INTRODUCTION

This investigation was undertaken to decipher the sedimentary history of the sandstones which were transformed by metamorphism 1750—1850 m.y. ago (Kouvo,1958) into the Jatulian quartzites.

The Precambrian metamorphic rocks of Finland can be divided into three main units (Simonen, 1960 a): the granite gneiss and granulite complex of eastern and northern Finland; the Svecofennian belt of western and southern Finland, characterized by mica gneisses; and the Karelian schist belt of eastern and northern Finland, characterized by an abundance of quartzites. The Karelian belt was long thought to be younger than the more highly metamorphosed Svecofennian belt, but it has recently been suggested that both belong to the same orogenic cycle (the Fennian orogeny of T. Mikkola, 1961), with the quartzites representing the pre-geosynclinal stage of sedimentation upon a peneplaned continental platform, deposited prior to deposition of the thick Svecofennian graywacke sequence of the geosynclinal trough (T. Mikkola, 1953 and 1961; Metzger, 1959; Simonen, 1960 a and 1960 b).

The standard section of the Karelian belt in eastern Finland, according to Väyrynen (1933), is as follows:

Kalevian phyllites and mica schists

Jatulian	Marine Jatulian phyllites and dolomites Kainuan quartzites Sariolian arkoses and conglomerates	penetrated by uralite diabase sills

Great unconformity

Granite gneiss basement

A similar section is present in northern Finland, with greenstones an important addition. Still further north, in Finnish Lapland, the correlative Lapponian sequence consists of quartzites, mica schists, and basic volcanics (E. Mikkola, 1941). In East Karelia (U.S.S.R.) and on the Karelian Massif, the Jatulian Series consists of a lower Segozerian section of quartzites, quartz conglomerates, and diabases and an upper Onegian section of conglomerates,

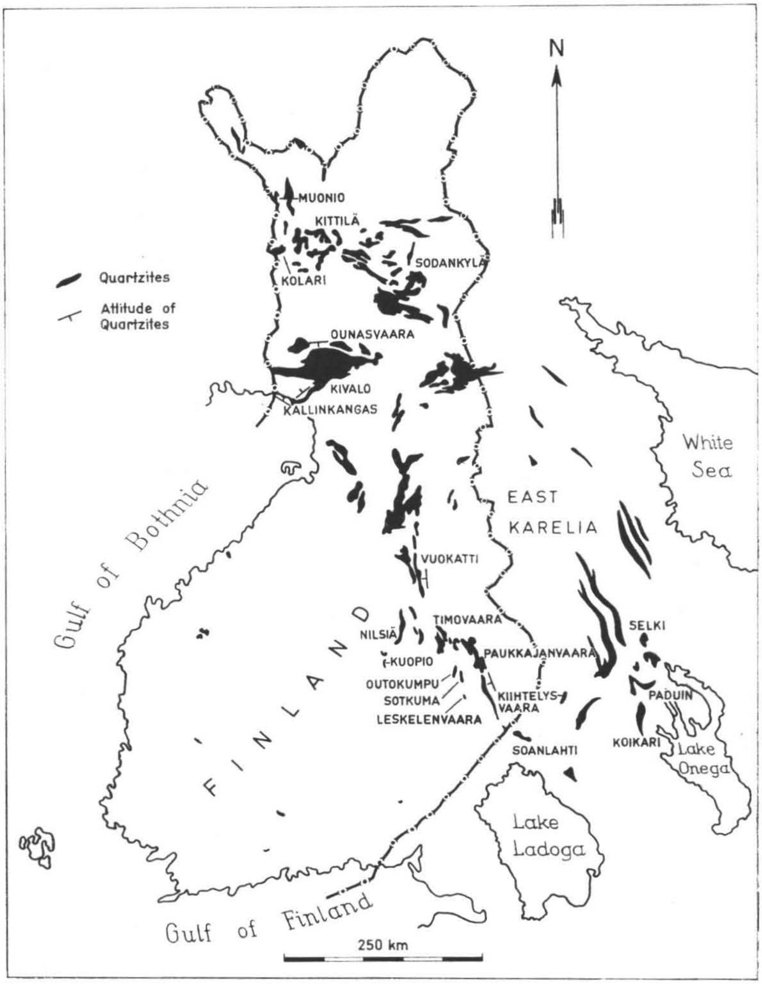


Fig. 1. Map of sample localities.

dolomites, slates, and volcanics (Kharitonov, 1960). Eskola (1963, p. 165—189) presented an excellent summary of the Karelian rocks in Finland.

The quartzites form a long, discontinuous belt which extends for 1000 km from southeast Finland to Lapland and nearly to the Arctic Ocean. Numerous small quartzite locales occur to the west of the main belt and several small parallel zones of quartzite are present to the east in East Karelia; the distribution in an east-west direction is over 400 km (Fig. 1.) Therefore, the formation once covered an area of more than 400.000 square km; how much further it may have extended to the east in Russia and to the west in Finland

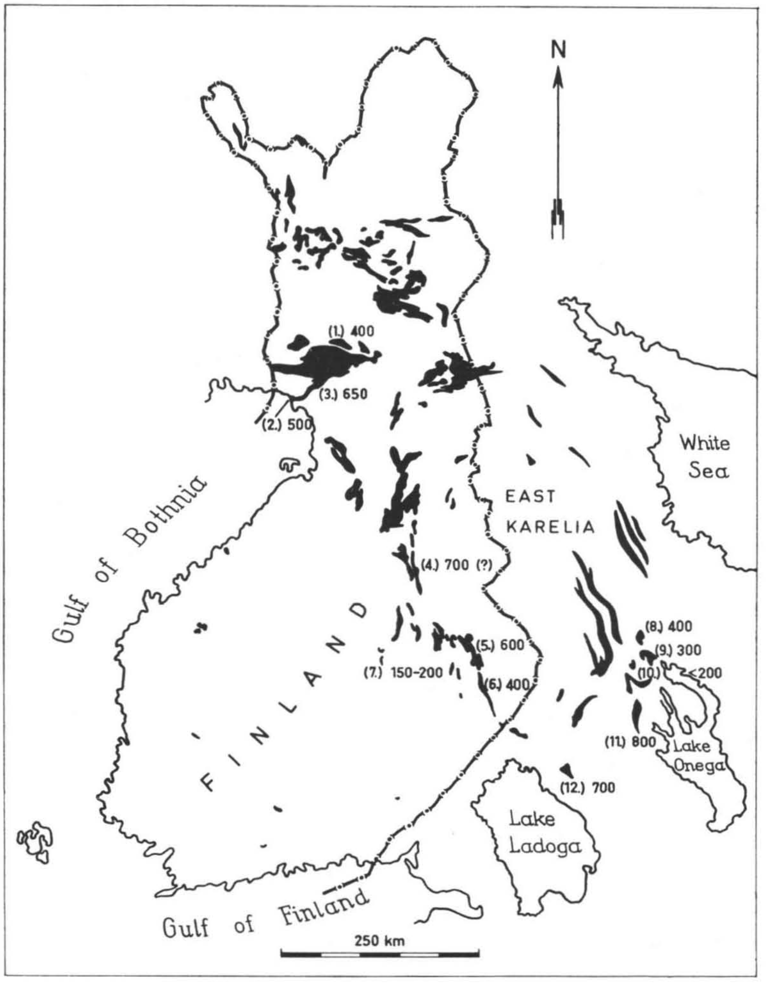


Fig. 2. Map of quarzite thicknesses — generalized, in meters. 1, Ounasvaara; 2, Kallinkangas; 3, Kivalo; 4, Vuokatti; 5, Koli (Atomienergia Oy, 1960); 6, Kiihtelysvaara; 7, Kuopio (Preston, 1954); 8, Seesjärvi (Kharitonov, 1937); 9, Tsobina-Paduin (Kharitonov, 1937); 10, Koikari (Tuominen, 1944); 11, Suojärvi (Metzger, 1924); 12, Soanlahti (Hausen, 1930).

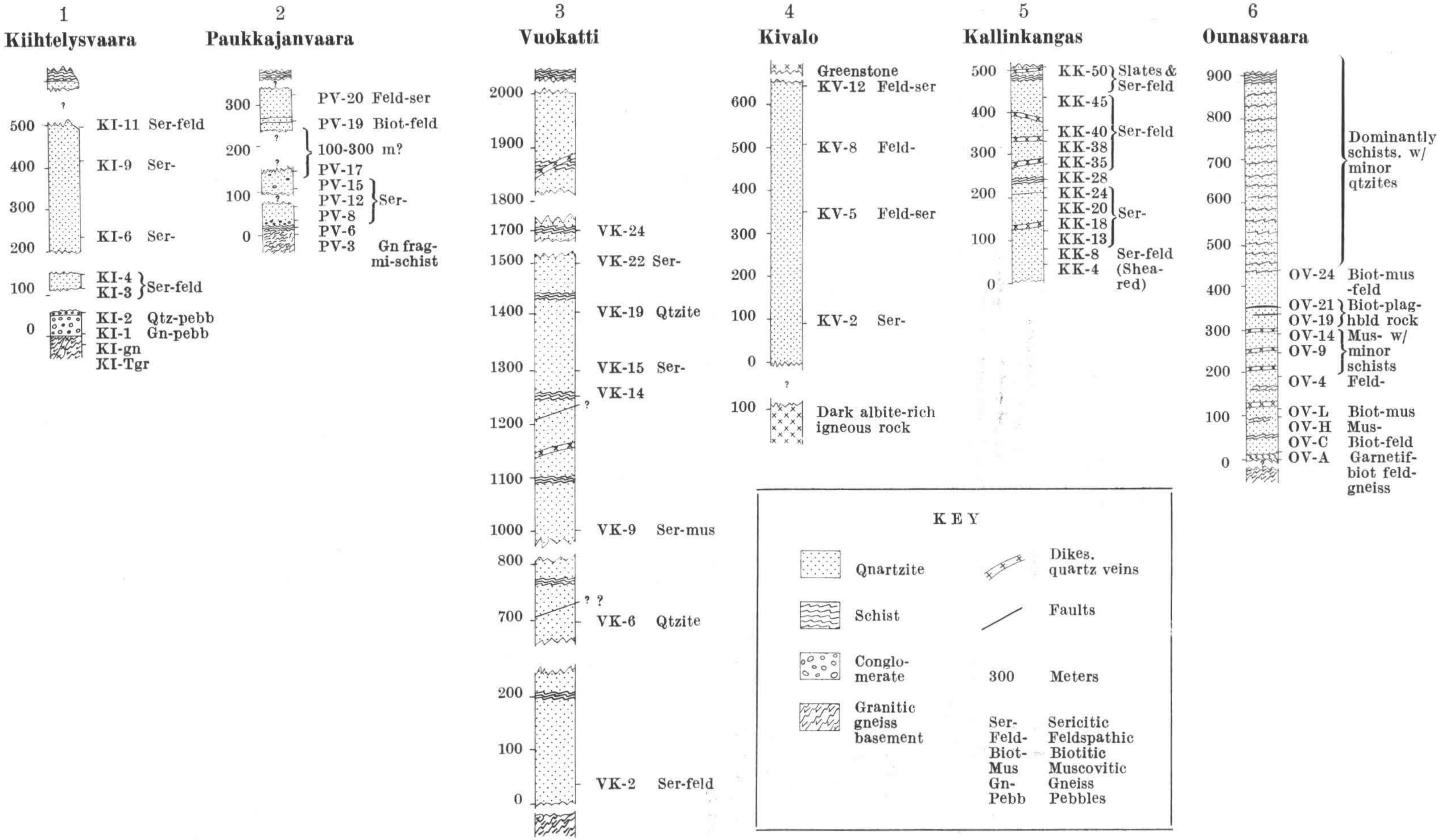
is not known, as most of the quartzite has been removed by erosion. Due to severe metamorphism and intrusion in central and western Finland, it has not been possible to correlate the small quartzite patches of western Finland, 250 km west of Kuopio, with the main quartzite belt (see Preston, 1954, p. 97).

The major exposures in Finland are preserved in several synclinal basins. Gneissic basement rocks dated at 2500 m.y. (Kouvo, 1958), upon which the

Karelian units rest, are exposed on the eroded axial culminations between the synclines and over large areas in eastern Finland and East Karelia.

The formation ranges in thickness from 200—400 m in eastern East Karelia to 600—800 m near Lake Ladoga (Fig. 2.) The westernmost quartzite exposures in eastern Finland, at Kuopio, are 150—200 m thick (Preston, 1954, p. 44). Obscured faults may have influenced many of these thicknesses; T. Mikkola (1961, p. 57) stated that the quartzite »does not exceed some hundred meters» in thickness.

Fig. 3. Measured stratigraphic sections.



METHODS

Thin section petrography, a heavy mineral study, cross-bedding analyses, and field work were utilized in this study. Because of limited time, field work was restricted to cross-bedding measurements at 14 widely-separated localities, measurement and sampling of six thick, widely separated quartzite sections, and sampling at some additional points (Fig. 1). Detailed field and petrographic information for several areas can be found in the literature and is not repeated in this study.

Approximately 175 quartzite samples were collected in stratigraphic sequence from the measured sections (Fig. 3). Fifty-seven of these and a few samples of the pre-Jatulian basement rocks were selected for detailed laboratory analysis. Thin sections and heavy mineral residues were point-counted to arrive at quantitative estimates of the mineralogy.

FIELD DESCRIPTIONS OF SAMPLED LOCALITIES

KIIHTELYSVAARA

This quartzite locality on the Selki Ridge, 9 km southeast of Kiihtelysvaara and just north of Särkilampi Lake, is the southernmost locale studied in the quartzite belt of eastern Finland (North Karelia). The vicinity has been mapped by geologists of Outokumpu Company and Suomen Malmi, and their maps were made available for this study.

The dips of the conglomerates and quartzites vary from 60° to vertical, with the average value about 80° to the west. The strike is approximately N 20° W.

Fig. 4. Contact of Sariolian basal conglomerate and granitic gneiss basement at Kiihtelysvaara. Gneiss is at upper right, a one meter thick weathered basal zone appears dark and eroded, and overlying conglomerate (nearly vertical) is at the bottom left.

A 50 m thickness of basal Sariolian conglomerate consists predominantly of pebbles of basement granitic gneiss, tourmaline granite, and vein quartz. The lower one meter seems to be primarily a weathering product of the basement gneiss, although tourmaline granite pebbles are also present (Fig. 4). The pebbles in this lower 1 m- thick zone reach 30 cm in diameter, in the middle portion of the 50 m thick unit they are about half as large, and they are only 5 cm in diameter near the top of the unit. Irregular silt-clay bands to 10 cm thick occur in the upper portions of the unit. The generally well-rounded pebbles vary in shape from spherical to elongate. Pebble elongation, probably due to tectonism, is very prominent in one bed high in the unit.

An overlying quartz-pebble conglomerate contains pebbles about 1—2 cm in diameter. Scattered pebbles of fuchsite are present in what is probably the same conglomerate in a roadcut 3 km south of this section, just north of the Viesimonjoki River bridge.

The thick, white to gray quartzites are megascopically very uniform; they are predominantly glassy although clastic texture is generally visible in hand specimens and is prominent in thin sections.

Black mica schists overlie the quartzites.

PAUKKAJANVAARA

The quartzites of the Koli region were sampled at the Paukkajanvaara uranium mine, 22 km southeast of Koli, where the basal part of the quartzite section and its contact with the basal gneiss are exposed (Fig. 3). The beds strike N-S and dip approximately 30° to the west. The section in the mine shaft is approximately 50 m thick and an additional 10 m are exposed at the surface of the shaft. The change from basal gneiss to »gneiss-fragment mica schist» (metamorphosed weathered basement) is apparently gradational. A 15 m thick dominantly quartz-pebble conglomerate with pebbles generally less than 5 cm in diameter underlies the white, buff, and occasionally reddish quartzite; the lowest 25 m of this quartzite are coarser than the higher quartzites and contain conglomeratic lenses.

Another 50 m thickness of stratigraphically higher, white to reddish, glassy quartzite (samples PV-15 and PV-17) is exposed on adjacent Sikovaara Hill; quartzite and quartz pebbles up to 10 cm in diameter (Fig. 5) are sparsely scattered in the quartzites.

Samples PV-19 and PV-20 are from a roadcut 3 km north of the mine; this portion of the section lies stratigraphically above the other sampled units (Tyni, 1962). PV-19 is from a few-meter thick biotite-rich, very well-laminated unit, and sample PV-20 is from a thick, coarse, feldspathic unit in which feldspar grains reach diameters of 2 cm. The same unit is over 300 m thick

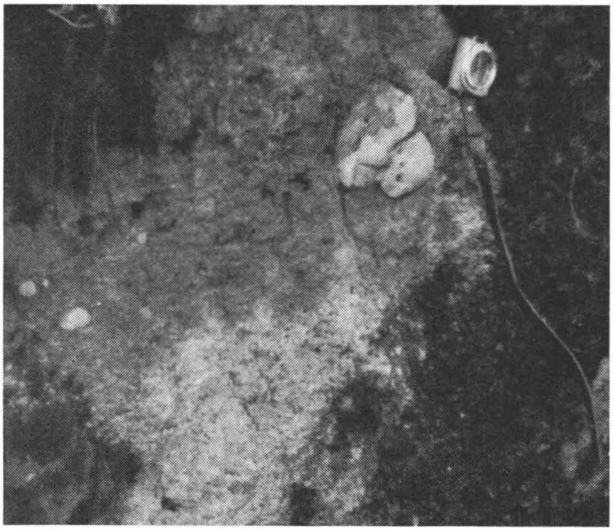


Fig. 5. Pebbly quartzite unit in upper part of Paukkajanvaara quartzite section (unit PV-17). Pebbles are quartzite and vein quartz.

near Koli, and the vertical change to feldspathic quartzite from a 300 m thickness of quartzite occurs within 2—3 m (verbal communication, Atomienergia Company geologists).

VUOKATTI

The quartzites of Vuokatti Hill, 7 km west of the town of Sotkamo, are part of the »quartzite schists» mapped and described by Wilkman (1921, Nurmes Map Sheet). Vuokatti Hill is the highest point (330 m) in the range of hills comprising the eastern flank of the Oulujärvi depression.

The quartzites strike approximately N-S and dip to the west at angles of 80° (in the lower part of the section) to 60°. The estimated thickness of the visible quartzites is 2000 m; the calculated thickness from the basal contact with the gneiss to the upper contact with the black schists, according to Wilkman's map, is about 2500 m. Repetition by faulting is extremely likely, and the true thickness may be closer to 700 m. The measured section extends from near the junction of the highway and the railroad westward to the fire tower on top of the hill and down the road on the western slope. The granite gneiss basement and the basal schist of Wilkman (1921, p. 58) were not visible.

The rock in the lower 1100 m of the section (Fig. 3) is a rather uniform white to gray, glassy quartzite, whereas the quartzite of the upper 900 m is pink to gray, glassy, and exhibits some cross-bedding. Original bedding in the quartzites seems to have been thin, as gray and white parallel bands (some micaceous) only a few cm thick are commonly visible. Six beds or lenses of mica schist ranging from 15 cm to 5 m in thickness are exposed within the section.

KIVALO

The quartzites of the Kivalo Ridge have been mapped and described by Härme (1949). They were sampled at a point east of Juoka, 20 km northeast of Kemi, on the bend where the ridge assumes a more northerly trend. Numerous outcrops occur in a terrane literally covered with large quartzite boulders. The strike of the beds is N 40° E and the average dip is 50° to the northwest. The estimated thickness of the quartzite is 650 m, and the top of the section was not observed. Undetected repetition due to faulting is a possibility.

The quartzites are megascopically very uniform in composition and texture; they are white to gray, medium- to coarse-grained, and display well-preserved clastic textures and well-rounded grains. Beds range in thickness from a few cm to several m. Well-preserved cross-bedding is abundant and pseudo-ripple marks (T. Mikkola, 1960) of tectonic origin are common in the highly sheared quartzites of the lower part of the section.

KALLINKANGAS

This section, a faulted extension of the Kivalo Ridge (Härme, 1949; T. Mikkola, 1960), is only 10 km west of the Kivalo section but was sampled because it is exellently exposed, contains abundant original sedimentary structures, and possesses more varied rocks types than Kivalo.

The beds strike N 30° W and the average dip is 70° to the northeast. Individual beds and units were measured in the field. The total exposed thickness is about 500 m; the top and bottom contacts are not exposed, and thus the total thickness is still greater. However, some faults of undetermined importance are present and may have caused some repetition.

The section can be divided into three zones on the basis of rock type (Fig. 3): the lower 200 m thickness is composed of alternating buff quartzites and greenish mica schists, highly sheared; the next 250 m are predominantly buff quartzites; and the upper 50 m consist of alternating buff quartzites and black phyllites and slates. The upper zone thus seems to be grading upward into the phyllite and schist zone which overlies the quarzites at most localities in Finland.

Fig. 6. View from top of Ounasvaara Hill, with Rovaniemi in the background. Note the well defined bedding in ice-polished, white recrystallized quartzite and darker schistose quartzite units. In the middle distance in the trees, the rock type changes from predominantly quartzite to predominantly mica schist.

Layers of green sericite schist fragments (up to 15 cm long) are present in the upper part of the section; they may be portions of what were once lenses or beds of clay which have been dislocated, either before complete lithification or during shearing, and metamorphosed. Similar fragments were observed on a microscopic scale. A few quartzite beds to 20 cm thick are extremely porous, possibly a result of the solution of original carbonate cement; minor carbonate is present in a few samples.

Cross-bedding is very abundant and mud cracks are also present. Original clastic texture is evident in both hand specimens and thin sections.

OUNASVAARA

The quarzites of the Rovaniemi area were mapped by Hackman (1910, Rovaniemi Mapsheet) who classified the rocks comprising 200 m high Ounasvaara hill as Kalevian. They are now considered Jatulian, similar to those in Kainuu and North Karelia, but they have undergone complete recrystallization.

The E-W striking rocks on Ounasvaara dip steeply to the south (Fig. 6), with a dip of 65° in the bottom half of the section and 80° in the upper half.

The section can be divided into four zones (Fig. 3) on the basis of the dominant rock type: the lower 100 m thickness is composed of schistose quartzites, the next 75 m of alternating quartzites and schists, the next 225 m thickness is dominantly quartzite with schistose quartzites and minor schists, and the upper 500 m (poorly exposed) consist predominantly of quartz-mica schists with only minor quartzite interbeds. Thus, only the lower 400 m of the 900 m total constitute the quartzite portion of the section. Faults, if present, were not observed.

The lowermost exposures are located in an excavation below a ski run at the base of the north side of the hill, about 100 m south of the road on the south bank of the Kemijoki River. The rock is a garnetiferous biotite-plagioclase gneiss with almandine porphyroblasts over 1 cm in diameter. The foliation of this gneiss seems to be perfectly conformable with the overlying quartzites. The gneiss may have once been part of the Jatulian sediments, or may be granulite basement rock. If the latter is true, then this is further evidence that the Karelian units were involved in the deformation which affected the granulite series of Lapland (Eskola, 1963, p. 163).

Two beds of black, biotite-plagioclase-hornblende rock, probably originating from calcareous beds, occur near the top of the hill between the observation stand and the ski chalet; the lowermost (sample OV-19) is a lens about 50 m long and 2 m thick, and thirteen meters higher is a similar 2 m thick bed (OV-21) which can be traced for about a hundred meters. Zones of quartzite with disseminated light green amphiboles (tremolite-actinolite) are present throughout the section. Thin interbeds of quartzites and mica schists at one horizon (OV-24) are suggestive of sand and clay alternations in the original sediment.

EAST KARELIA

A few samples and thin sections of quartzites from East Karelia were selected for study from the archives of the University of Helsinki and the Geological Survey.

The quartzites of East Karelia form belts which are subparallel to the quartzite belt of eastern Finland (Fig. 1) and are gently folded in the same manner. Dips vary from nearly horizontal to vertical, and numerous anticlinal and synclinal structures have been mapped. Gafarov (1961) described this portion of the Baltic Shield as consisting of a system of synclinoria which are filled with thick volcanic-sedimentary Karelian formations and separated by areas of older rocks. Thus, the geological setting is very similar to that of eastern Finland.

Several Finnish geologists have worked in areas now east of the Finnish border, and some references in which special attention has been given to the quartzites are listed below: Metzger (1924), Eskola (1925 and 1948), Väyrynen (1938), Hausen (1930), A. Mikkola (1943), Härme (1944), and Tuominen (1944). Russian workers include Timofejev (1935) and Kharitonov (1937 and 1960).

KUOPIO AREA

Quartzite samples were collected at Nilsiä, Timovaara, and Outokumpu and samples from Kuopio and Sotkuma were selected from the archives at the Geologicial Survey; all are from isolated outcrops not physically connected to the North Karelian quartzite belt. In addition, numerous thin sections from rocks of this area were also observed.

NORTHERN LAPLAND

Several samples and thin sections of quartzites of northern Lapland were selected for study and observation from the archives of the Geological Survey.

LESKELENVAARA

Leskelenvaara Hill in North Karelia near Karhunsaari on the northeast shore of Orivesi Lake was studied even though typical quartzites are not present. Deep, pre-metamorphism residual weathering of basement granitic gneiss (Saksela, 1933) is well-illustrated here. Six samples of the weathered rock and of normal unweathered gneiss (from south of Lake Niinikkolampi near Liperinsalo on the west side of Orivesi Lake) were collected. The thickness of the section is roughly estimated at 100 m. Black schists overlie the weathered gneiss.

SEDIMENTARY STRUCTURES

Well-preserved large-scale cross-bedding is common in the quartzites at several localities (Figs. 7—11). Allen's (1963) alpha-, pi-, xi-, and omicron-cross-stratification types are present (identifications based on photographs). Allen attributes these types to migration of solitary banks or large-scale asymmetrical ripple marks. The above types encompass McKee and Weir's (1953) planar, simple, and trough cross-bedding, with the former the most abundant.

The quartzites at Kallinkangas contain ripple marks, and argillaceous interbeds display mudcracks (Berghell and Hackman, 1923; T. Mikkola, 1955 and 1960). Ripple marks are also present in a roadcut on Rukatunturi Hill near Kuusamo (Fig. 12). The literature contains several references to sedimentary structures in the quartzites of Finland and East Karelia.

Fig. 7. Well-preserved cross-bedding in completely recrystallized quartzites in a roadcut on Vuokatti Hill, near sample VK-11.

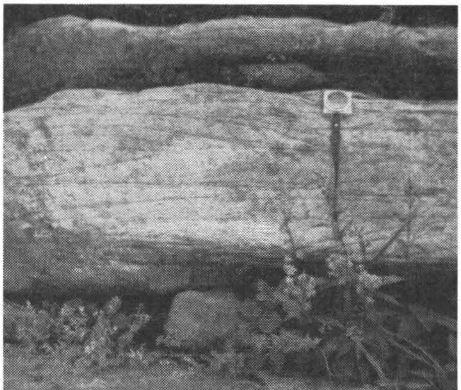


Fig. 8. Cross-bedded quartzites at Orakoski Rapids on the Kitinen River, 8 km south of Sodankylä. These quartzites (E. Mikkola, 1941) are part of the Oraniemi-Kumpu Series and are slightly younger than the Lapponian (Jatulian) quartzites.

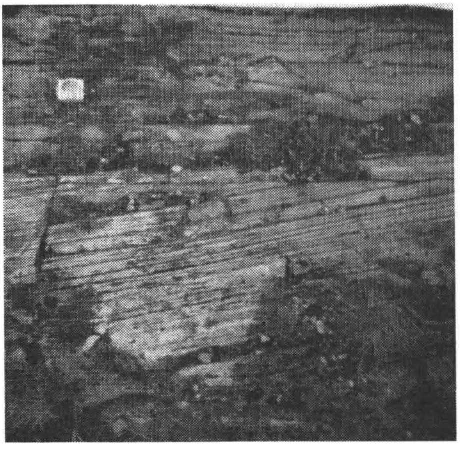


Fig. 9. Cross-bedding in quartzites at the north end of Selki Ridge on the south bank of the Pielinen River, 7 km SW Eno.

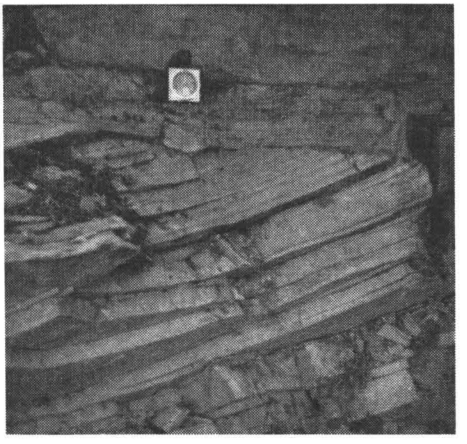


Fig. 10. Cross-bedding in quartzites at the northern end of the Kivalo Ridge, about 6 km SW of Sompujärvi Lake.

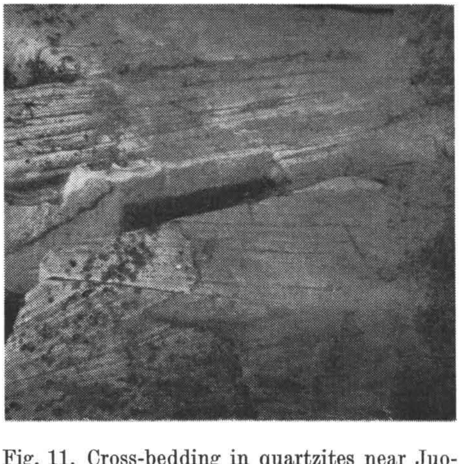


Fig. 11. Cross-bedding in quartzites near Juokua on the Kivalo Ridge. Field of view is about one meter wide.

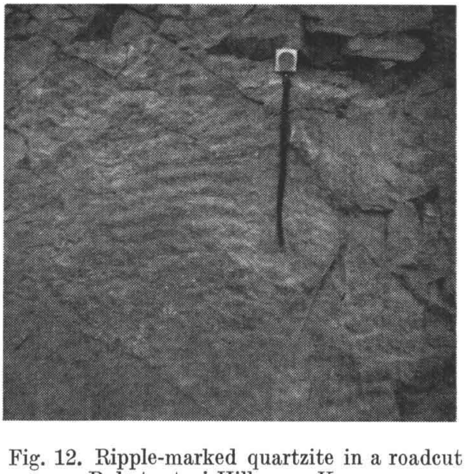


Fig. 12. Ripple-marked quartzite in a roadcut on Rukatunturi Hill, near Kuusamo.

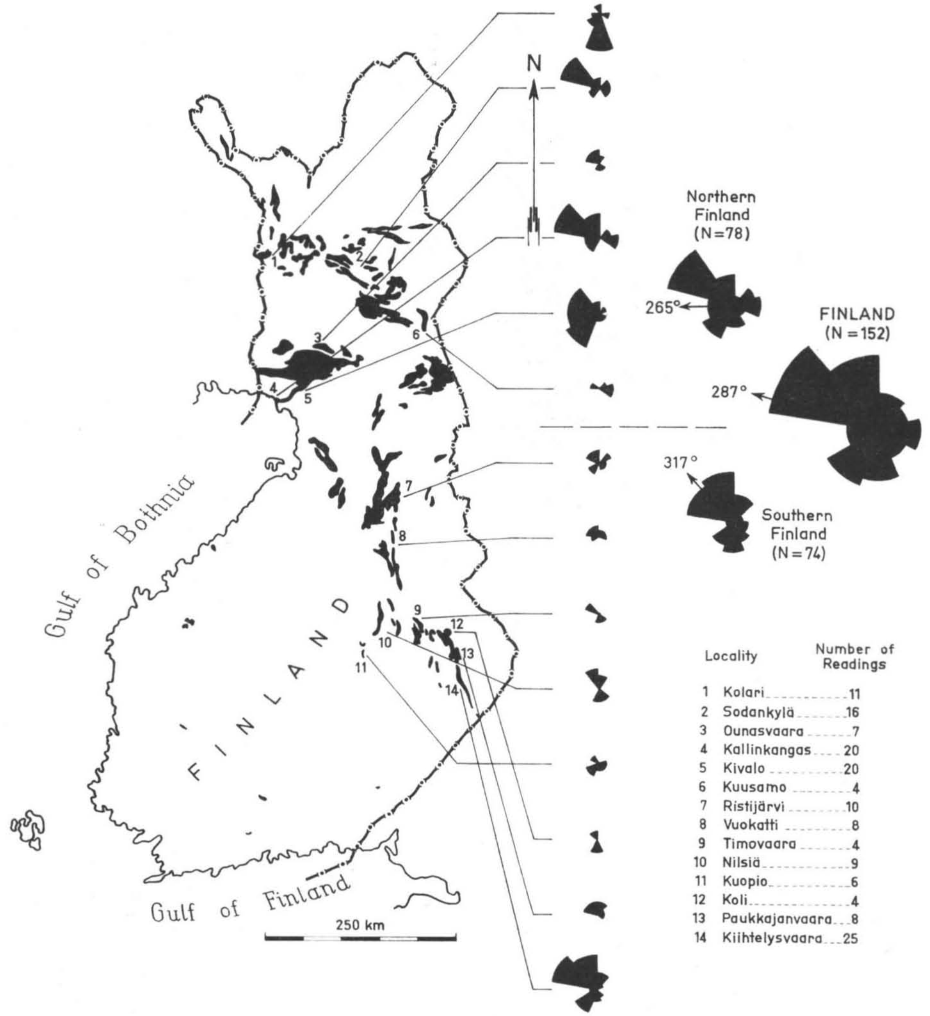


Fig. 13. Cross-bedding map.

PALEOCURRENT PATTERNS

A total of 152 cross-bedding measurements was recorded from 14 widely-separated quartzite localities (Fig. 13). Only one reading was taken from any given set of cross-beds, but several readings were taken at each locality. The readings were rotated around the strike to horizontal by means of a Schmidt stereographic net. No corrections were made for plunge of folding (T. Mikkola,

Table 1. Cross-bedding analyses.

Locality	No. of readings	Average angle inclination (degrees)	Vectorial mean (degrees)	Percentile of statistical significance
1. Selki Ridge, near Kiihtelysvaara	25	15	293	99
2. Selki Ridge, Paukkajanvaara, & Koli (including no. 1 above) .	37	16	317	99.5
3. Southern Finland, including no. 1 & 2 above	74	17	317	95
4. Kallinkangas, Kivalo, and Ounasvaara	47	18	278	99.5
5. Tapojärvi, near Kolari	11	16.5	190	99.5
6. Lapland, including no. 4 and 5 above	78	18	265	99.5
7. Finland, all-- including no. 1—6 above	152	17.5	287	99.5
8. Timovaara, Nilsiä, and Kuopio	19	18	197	Non.-sig.
9. Sodankylä	16	18.5	295	Non.-sig.
10. Sodankylä, Kolari, and Kuusamo	31	18	212	Non.-sig.

1960); plunge measurements were not generally available, and at most localities the plunge angle is probably small.

Tukey (1954) designed a simple statistical test for treating oriented data (Rusnak, 1957, p. 53; Potter and others, 1958, p. 1022). The Tukey Chi-square orientation test yields the vectorial mean dip direction of the cross-beds and tests its statistical significance. It is based on departures from a uniform distribution, is sensitive to both the orientation and the number of observations with that orientation, and can be used even when large numbers of readings are not available.

T. Mikkola (1955, 1960) has done the only previous work on cross-bedding in the quartzites. On the basis of 90 measurements on the Selki Ridge (the Kiihtelysvaara area of this study), he ascertained a paleocurrent trend to the northeast. In the present study, a total of 25 readings from the same ridge yielded a bimodal distribution and a statistically significant vectorial mean of 293° (Table 1), consistent with the trend for the quartzites as a whole but differing considerably from Mikkola's results. His other study, based on over 500 readings in the Kallinkangas and Kivalo quartzites, indicated strong trends to the southwest and northwest. The statistically significant mean of 278° for the 47 readings from Kallinkangas, Kivalo, and Ounasvaara in the present study is in good agreement with his results, and the bimodal distribution that he noted here is also evident (Fig. 13; Table 1).

The non-significant test result for the readings from Timovaara, Nilsiä, and Kuopio, in contrast to the highly significant tests for the Koli-Kiihtelysvaara quartzite belt which lies just to the east, may be partially due to the poor quality of these measurements. The non-significance of the tests at

Sodankylä, Kolari, and Kuusamo may be related to the fact that many beds are overturned at these localities.

In conclusion, all the readings together, as well as the readings for several localities and portions of Finland, form a statistically significant pattern showing a dominant current movement towards the west-northwest and a secondary but prominent movement towards the south-southwest.

PETROGRAPHY

Fifty-seven thin sections of the quartzites and interbedded rocks (cut perpendicular to bedding), and nine thin sections of the underlying basement rocks were studied and their mineral compositions determined by point-counting (Table 2). More than 100 additional thin sections from the archives of the Geological Survey and the University of Helsinki were also observed.

In hand specimens, the generally medium-grained quartzites have either glassy, schistose, or clastic textures (Sederholm, 1932), but in thin sections each type commonly shows distinct characteristics of one or both of the other types as well. Detailed petrographic descriptions of the quartzites can be found in numerous map explanations and other publications on eastern and northern Finland.

MINERALOGY

Quartz. Four types of quartz were distinguished; each includes both undulose and nonundulose grains:

(1) Unit quartz — grains composed of a single, generally fairly large, optically continous unit — sources may be granites, gneisses or quartz veins.

(2) Polycrystalline quartz — grains composed of units separated by either planar or irregular boundaries — primary sources may be granites, schists, or gneisses but could also form during deformation of the quartzite.

(3) Crushed quartz — mosaics of generally small units with planar boundaries — common in the extensively sheared, nonrecrystallized quartzites.

(4) Recrystallized quartz — mosaics of fairly large grains with planar interlocking boundaries — a result of complete recrystallization.

Mica. Micas include sericite, muscovite, and biotite, with the former by far the most abundant. Muscovite dominates in samples from Ounasvaara where complete recrystallization has occurred. In the Kiihtelysvaara section, commonly-leached tan detrital biotite, apparently derived from the underlying biotitic gneiss, occurs as individual grains and in gneiss fragments. Green biotite is present in samples PV-19 and basement sample KI-gn, the biotite of samples OV-19 and OV-21 is deep red-brown, and that in samples

Table 2. Thin section

Section and sample number	Estimated meters above base	Metamorphic rock type	Quartz					Feldspar					
			Unit	Polycrystalline	Crushed	Recrystallized	Total Quartz	Microcline, fresh	Microcline, altered	Plagioclase, fresh	Plagioclase, altered	Perthite, fresh	Perthite, altered
Ounasvaara													
OV-24	440	Biot-mus-feld-Qtzite	—	—	—	66	66	—	—	—	5	—	—
-21	355	Biot-plag-hblde-Rock	—	—	—	7	7	—	—	36	—	—	—
-19	340	Biot-plag-hblde-Rock	—	—	—	×	×	—	—	—	28	—	—
-14	285	Muscov-Qtzite	—	—	—	82	82	—	—	—	—	—	—
- 9	250	Muscov-Qtzite	—	—	—	76	76	—	—	—	—	—	—
- 4	180	Feld-Qtzite	—	—	—	72	72	—	—	—	8	—	—
-L	120	Biot-muscov-Qtzite	—	—	—	71	71	—	—	—	—	—	—
-H	100	Muscov-Qtzite	—	—	—	92	92	—	—	—	1	—	—
-C	10	Biot-feld-Qtzite	—	—	—	48	48	—	—	1	12	—	—
-A	1	Biot-feld-Gneiss	—	—	—	39	39	—	—	—	34	—	—
Kivalo													
KV-12	800	Feld-ser-Qtzite	43	2	30	—	75	4	1	—	—	—	—
- 8	600	Feld-Qtzite	56	3	30	—	89	4	2	—	—	—	1
- 5	300	Feld-ser-Qtzite	45	3	26	—	74	2	3	—	×	—	×
- 2	100	Ser-Qtzite	48	—	47	—	95	—	—	—	—	—	—
Kallinkangas													
KK-50	520	Ser-qtz-Schist	29	5	27	—	61	×	×	—	—	—	—
-45	445	Ser-feld-Qtzite	22	1	39	—	62	12	2	1	×	1	×
-40	370	Ser-feld-Qtzite	29	6	28	—	63	5	3	—	—	×	1
-38	325	Ser-feld-Qtzite	31	3	39	—	73	7	1	—	—	—	1
-35	280	Ser-feld-Qtzite	28	×	52	—	80	2	2	—	—	—	1
-28	240	Ser-qtz-Schist	28	3	19	—	50	—	—	—	—	—	—
-24	220	Ser-Qtzite	32	2	40	—	74	—	—	—	—	—	—
-20	200	Ser-Qtzite	31	4	47	—	82	1	—	—	—	—	×
-18	175	Ser-Qtzite	32	4	44	—	80	×	2	—	—	—	—
-13	115	Ser-Qtzite	33	4	40	—	77	—	—	—	—	—	—
- 8	80	Ser-feld-Qtzite	31	1	48	—	80	9	4	—	—	×	1
- 4	50	Ser-feld-Qtzite	36	5	38	—	79	5	9	1	×	—	—
Vuokatti													
VK-24	1 700	Ser-qtz-Schist	—	—	—	58	58	—	—	—	—	—	—
-22	1 500	Ser-Qtzite	—	—	—	81	81	—	—	—	—	—	—
-19	1 400	Qtzite	—	—	—	98	98	—	—	—	—	—	—
-15	1 300	Ser-Qtzite	—	—	—	86	86	—	—	—	—	—	—
-14	1 250	Biot-mus-qtz-Schist	—	—	—	36	36	—	—	—	—	—	—
- 9	1 000	Ser-Qtzite	—	—	—	91	91	—	—	—	—	—	—
- 6	700	Qtzite	—	—	—	96	96	—	—	—	—	—	—
- 2	50	Ser-feld-Qtzite	—	—	—	81	81	—	—	—	—	—	—
Paukkajan-vaara													
PV-20	300?	Feld-ser-qtz-Schist	13	9	28	—	50	6	2	—	—	—	—
-19	250?	Biot-feld-Qtzite	47	—	33	—	80	5	3	—	—	—	—
-15	75	Ser-Qtzite	33	1	52	—	86	—	—	—	—	—	—
-12	60	Ser-Qtzite	32	—	49	—	81	—	—	—	—	—	—
- 8	40	Ser-Qtzite	30	—	52	—	82	—	—	—	—	—	—
- 6	10	Ser-qtz-Schist	37	—	37	—	74	—	—	—	—	—	—
- 3	2	Gneiss frag-mica-Schist	8	7	6	—	21	—	—	—	—	—	—

compositional data.

Orthoclase, fresh	Orthoclase, altered	Total detrital feldspar	Rock frag.: Microcline-Qtz	Rock frag.: Biotite gneiss	Rock frag.: Tourmal. granite	Microcline (metasomatic)	Mica: Sericite	Mica: Muscovite	Mica: Biotite	Chlorite	Carbonate	Amphiboles	Epid-clinoz-zoisite	Tourmaline	Miscellaneous minerals	Ratio, Quartz/Detrital Feldspar + Rock Fragments: Quartz	Ratio: Feldspar + Rock Fragments
—	—	5	—	—	—	—	2	8	12	—	—	—	1	×	Cordier-3; cordier alt-3	93	7
—	—	36*	—	—	—	—	—	—	8	×	—	43	—	×	Sulphide-5		
—	—	28*	—	—	—	—	5	—	25	—	—	38	—	×	Sphen-2; Rutil-1;Apat-×		
—	2	2	—	—	—	—	—	14	2	—	—	—	—	×	Zircon-×	98	2
1	—	1	—	—	—	×	—	19	4	—	—	—	—	—	Apat-×	99	1
—	—	8	—	—	—	8	—	2	1	1	—	4	3	×		90	10
—	1	1	—	—	—	1	—	18	8	—	—	—	×	×		99	1
—	—	1	—	—	—	—	—	6	—	1	—	—	—	—		99	1
—	28	41	—	—	—	—	—	—	9	2	—	—	—	—		54	46
—	—	34	—	—	—	—	—	—	22	1	1	—	—	—	Garnet-2; Apatite-×	53	47
—	×	5	—	—	—	—	20	—	—	—	—	—	—	—		94	6
—	—	7	1	—	—	—	3	—	—	—	—	—	—	×		92	8
—	—	6	—	—	—	—	19	—	—	—	—	—	×	—	Zircon-×	92	8
—	—	—	—	—	—	—	5	—	—	—	—	—	—	—		100	0
—	—	1	—	—	—	—	33	—	—	—	5	—	—	×		98	2
—	1	18	3	—	—	—	16	—	—	—	2	—	—	—		75	25
—	1	10	1	—	—	—	26	—	—	—	—	—	—	×		85	15
×	1	10	1	—	—	—	16	—	—	—	—	—	—	—		87	13
—	—	5	—	—	—	—	9	—	—	—	5	—	—	×	Apatite-1	94	6
—	—	—	—	6	—	—	43	—	1	—	—	—	—	—		89	11
—	—	—	—	—	—	—	26	—	×	—	—	—	—	—		100	0
—	—	1	×	—	—	1	16	—	—	—	—	—	—	—		98	2
—	—	2	—	—	—	—	18	—	—	—	—	—	—	—		98	2
—	—	—	—	—	—	—	23	—	—	—	—	—	—	—		100	0
—	×	15	—	—	—	—	5	—	—	—	—	—	—	—		84	16
—	—	15	—	—	—	—	6	—	—	—	—	—	—	—		84	16
—	—	—	—	—	—	5	32	—	—	—	—	—	5	×		100	0
—	—	—	—	—	—	6	11	—	—	—	—	—	2	×		100	0
—	—	—	—	—	—	—	2	—	—	—	—	—	—	—		100	0
—	—	—	—	—	—	—	14	—	—	—	—	—	—	—		100	0
—	—	—	—	—	—	—	—	57	6	—	—	—	×	×	Magnetite-×	100	0
—	—	—	—	—	—	1	8	—	—	—	—	—	—	—		100	0
—	—	—	—	—	—	—	4	—	—	—	—	—	—	—		100	0
—	—	—	—	—	--	10	9	—	—	1	—	—	×	×		100	0
2	—	10	6	3	—	—	30	—	×	—	—	—	—	×		72	28
1	—	9	—	—	—	—	4	—	5	—	1	—	—	—		90	10
—	—	—	—	—	—	—	14	—	—	—	—	—	—	—		100	0
—	—	—	—	—	—	—	19	—	—	—	—	—	—	—		100	0
—	—	—	—	—	—	—	18	—	—	—	—	—	—	—		100	0
—	—	—	—	—	—	—	26	—	—	—	—	—	—	—		100	0
—	—	—	—	32	**	—	45	—	—	2	×	—	—	—		40	60

Table 2.

Section and sample number	Estimated meters above base	Metamorphic rock type	Quartz					Feldspar					
			Unit	Polycrystalline	Crushed	Recrystallized	Total Quartz	Microcline, fresh	Microcline, altered	Plagkoclase, fresh	Plagioclase, altered	Perthite, fresh	Perthite, altered
Kiihtelysvaara													
KI-11	375	Ser-feld-Qtzite	39	13	28	—	80	4	1	—	×	1	—
- 9	325	Ser-Qtzite	41	12	32	—	85	—	—	—	—	—	—
- 6	225	Ser-Qtzite	19	5	65	—	89	×	×	—	—	—	—
- 4	150	Feld-ser-Qtzite	16	26	19	—	61	9	—	—	—	—	—
- 3	110	Feld-ser-Qtzite	16	24	27	—	67	7	×	—	—	—	—
- 2	50	Quartz pebble-Conglom	6	2	11	—	19	—	—	×	1	×	—
- 1	1	Gneiss pebble-Conglom	1	4	16	—	21	—	—	—	×	—	×
-gneiss ...	—	Basement biotite Gneiss	—	—	—	49	49	—	—	—	5	—	—
-T.granite .	—	Basement tourm. Granite	—	—	—	—	39	1	—	—	26	4	1
Leskelenvaara													
LV-6	100?	Weath.biot.gneiss Basement	—	—	—	67	67	—	—	3	—	—	—
-5	75?	Weath.biot.gneiss Basement	—	—	—	44	44	—	—	—	1	—	—
-4	50?	Weath.biot.gneiss Basement	—	—	—	52	52	—	—	—	1	—	—
-3	25?	Weath.biot.gneiss Basement	—	—	—	48	48	—	—	—	×	—	—
-2	6?	Weath.biot.gneiss Basement	—	—	—	53	53	—	—	—	1	—	—
-1	5?	Weath.biot.gneiss Basement	—	—	—	36	36	—	—	—	3	—	—
-A	—	Fresh biot.gneiss Basement	—	—	—	39	39	—	—	—	7	—	—
East Karelia													
Paduin	?	Ser-Qtzite	35	6	48	—	89	—	—	—	—	—	—
Koikari cong.	?	Granite & qtz pebb Cong	25	34	2	—	61	7	1	—	×	—	—
Koikari520/43	?	Ser-Qtzite	24	24	22	—	70	—	—	—	—	—	—
Selki	?	Ser-feld-Qtzite	44	—	6	—	50	—	—	4	20	—	—
Selki diabase-qtzite contact	—	Epid-biot-Qtzite	7	—	41	—	48	—	—	—	3	—	—
Kuopio Area													
Kuopio	?	Sillimanite Qtzite	—	—	—	86	86	—	—	—	—	—	—
Nilsiä	?	Qtzite	—	—	—	99	99	—	—	—	—	—	—
Timovaara ..	?	Feld-Qtzite	—	—	—	77	77	—	—	—	—	—	—
North Lapland													
Petäjänvaara, Rovaniemi	?	Ser-Qtzite	—	—	—	90	90	—	4	—	—	—	—

× = denotes trace amount
* denotes feldspar formed during metamorphism ** denotes chlorite-quartz (gneiss) fragments

OV-A and OV-C is light brown. Alteration to chlorite was noted at Kiihtelysvaara, Paukkajanvaara, and in the lower part of the Ounasvaara section.

Petrographic observations indicate that the mica content can be used as an approximation of the original clayey matrix; sericite occurs as a matrix

Cont.

			Rock frag.				Mica									Ratio, Quartz/ Detrital Feldspar + Rock Fragmetts	
Orthoclase, fresh	Orthoclase, altered	Total detrital feldspar	Microcline-Qtz	Biotite gneiss	Tourmal. granite	Microcline (metasomatic)	Sericite	Muscovite	Biotite	Chlorite	Carbonate	Amphiboles	Epid-clinoz-zoisite	Tourmaline	Miscellaneous minerals	Quartz	Feldspar + Rock Fragments
—	—	6	7	—	—	—	6	—	—	—	—	—	—	—		86	14
—	—	—	—	—	—	—	15	—	—	—	—	—	—	—		100	—
—	—	×	—	—	—	—	11	—	—	—	—	—	—	—		100	—
—	—	9	9	—	—	—	22	—	—	—	—	—	—	—		77	23
—	—	7	4	—	—	—	15	—	2	—	5	—	—	—		86	14
—	1	3	—	39	1	—	9	—	12	1	18	—	—	—		31	69
—	—	×	—	43	7	—	1	—	18	—	9	—	—	—		30	70
—	27	32	—	—	—	—	—	—	12	4	2	—	×	—		—	—
—	22	54	—	—	—	—	1	—	—	—	—	—	—	6		—	—
—	25	29	—	—	—	1	—	2	×	2	—	—	—	—		—	—
—	23	35	—	—	—	11	—	5	5	3	7	—	×	—	Rutile-1	—	—
—	34	35	—	—	—	—	—	3	1	7	1	—	—	—	Zircon-1	—	—
—	25	34	—	—	—	9	—	1	7	5	5	—	—	—		—	—
—	36	37	—	—	—	—	—	3	2	4	×	—	—	—	Rutile-×	—	—
—	52	55	—	—	—	—	—	3	4	2	—	—	—	—		—	—
44	—	51	—	—	—	—	—	1	7	2	—	—	—	—		—	—
—	—	—	—	—	—	—	11	—	—	—	—	—	—	—		100	0
—	2	10	18	—	—	—	10	—	—	—	—	—	—	—		69	31
—	4	4	—	—	—	—	17	4	—	—	—	—	×	5		95	5
—	—	24	—	—	—	—	17	—	7	—	—	—	2	—		68	32
—	—	3	—	—	—	—	2	—	24	2	8	—	12	1		94	6
—	—	—	—	—	—	—	2	—	—	—	—	—	—	—	Sillimanite-12	100	0
—	—	—	—	—	—	—	×	—	—	—	—	—	—	—	Kaolinite-1	100	0
—	7	7	—	—	—	5	2	—	1	2	—	1	5	—		92	8
—	×	4	—	—	—	—	5	—	—	—	—	—	—	—		96	4

between sand grains in the unrecrystallized samples (Fig. 14), sericite laminae parallel to bedding are present, and complete alteration of feldspar to sericite (noted in samples OV-19 and KI-4) is rare. Production of matrix by shearing and recrystallization of unstable rock fragments (Cummins, 1962) is not compatible with the petrographic observations; there is no evidence that

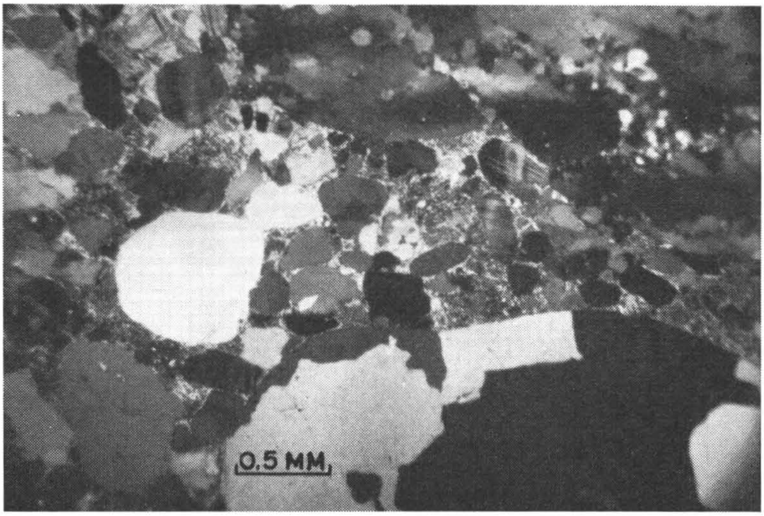


Fig. 14. Photomicrograph of conglomeratic sample from Koikari, East Karelia. Two types of large quartzite pebbles are present; both have obviously inherited their texture from the source rocks rather than receiving it during deformation after deposition. Note rounded boundaries of pebbles and sand-sized quartz and feldspar grains. Matrix is sericite. Crossed nicols.

rock fragments other than granite and gneiss were ever present. Väyrynen (1928) attributed the origin of the sericite to potassium metasomatism and recrystallization of kaolinite; that such metasomatism has occurred is confirmed by K-feldspar stringers and patches in the quartzites. However, if the original clay was kaolinite, a total structural and chemical reconstitution, with the addition of K and Si, would have been necessary; if the original clay was dioctahedral montmorillonite the addition of K would have been required; and if the clay had been illite, only a simple recrystallization could have produced the sericite. Kaolinite has been reported in the Jatulian rocks (Hausen, 1930; Väyrynen, 1938, 1939; E. Mikkola, 1941, Matisto, 1958), but confirmation by X-ray is not available; however, it seems unlikely that kaolinite would have survived the regional metamorphism.

F e l d s p a r. The feldspar is mainly microcline, occurring as both fresh and weathered grains. Minor amounts of plagioclase, perthite, and orthoclase, each in both fresh and weathered states, are also present. Plagioclase and orthoclase are most abundant at Ounasvaara; however, most of this plagioclase may be of metamorphic origin, formed from marly beds. Detrital feldspar is absent at Vuokatti and from several horizons at other localities (Table 2).

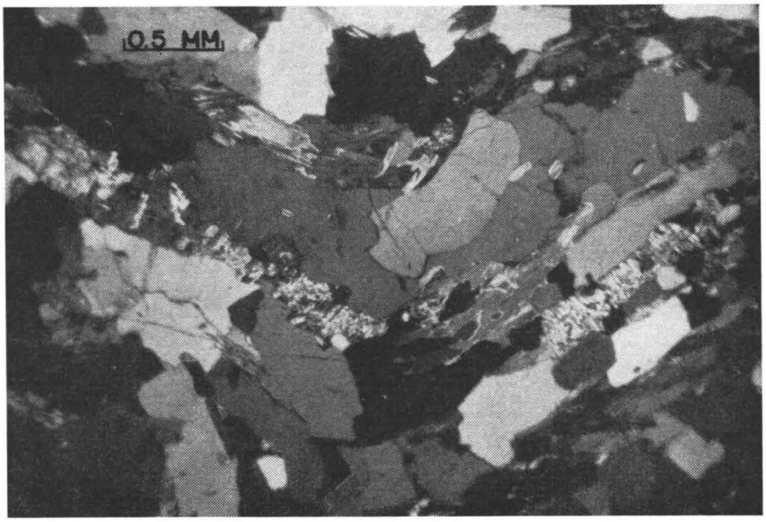


Fig. 15. Photomicrograph of sample OV-24 from Ounasvaara. Note small-scale folding, recrystallized quartz, and mica orientations parallel to bedding (horizontal in photo) and at about 45° to the bedding. Plagioclase stringer crossing center of field is highly sericitized. Thin lamina near top contains cordierite and its alteration products. Crossed nicols.

R o c k f r a g m e n t s. Rock fragments, present in a few samples, consist of four types: microcline-quartz (granite), tourmaline granite, biotite gneiss, and biotite- or chlorite-quartz (probably a variation of biotite gneiss). Microcline-quartz fragments are the most widespread. The greatest variety of fragments occurs in the Kiihtelysvaara and Paukkajanvaara sections.

C a r b o n a t e. Carbonate is present in three of the higher samples from Kallinkangas, and could have been formed during diagenesis of the sediment. Carbonate in the conglomerates and lower quartzites at Kiihtelysvaara is probably metamorphic in origin, as indicated by the fact that the basement gneiss samples also contain carbonate. Carbonate in the Selki sample may be related to associated diabase.

C o r d i e r i t e. Cordierite and an alteration product are present in sample OV-24 at Ounasvaara (Table 2), occurring in thin laminae parallel to micaceous laminae (Fig. 15). Perhaps magnesium-bearing clayey laminae were altered during metamorphism to yield this single noted occurrence of cordierite in the Jatulian quartzites. Eskola (1938) observed cordierite in the Svecofennian Tiirismaa quartzite of southern Finland and attributed it to the metamorphism of sand which contained highly aluminous clay. Cordierite is common in associated schists of the quartzite belt.

Table 3. Heavy

Section and sample number	Estimated meters above base	Metamorphic rock type	Detrital								
							Tourmaline				
			Zircon	Sphene	Rutile, yellow	Rutile, red	Blue-purple	Black-green	Blue-pink	Dark blue-blue	Brown-yellow
Ounasvaara											
OV-24	440	Biot-mus-feld-Qtzite	57	—	—	—	×	—	—	—	—
-21	355	Biot-plag-hblde-Rock	—	—	—	—	—	—	—	—	—
-19	340	Biot-plag-hblde-Rock	1	—	—	—	—	—	—	—	—
-14	285	Muscov-Qtzite	39	—	—	—	—	—	—	—	—
- 9	250	Muscov-Qtzite	47	—	—	—	—	—	—	—	—
- 5	180	Feld-Qtzite	1	×	—	—	—	—	—	—	—
-L	120	Biot-muscov-Qtzite	43	—	—	—	—	—	—	—	—
-H	100	Muscov-Qtzite	47	—	—	—	—	—	—	—	—
-C	10	Biot-feld-Qtzite	76	—	—	—	—	—	—	—	—
-A	1	Biot-feld-Gneiss	—	—	—	—	—	—	—	—	—
Averages	—		31	—	—	—	—	—	—	—	—
Kivalo											
KV-12	800	Feld-ser-Qtzite	52	×	—	1	1	—	—	×	—
- 8	600	Feld-Qtzite	33	—	×	—	—	—	—	—	—
- 5	300	Feld-ser-Qtzite	33	—	—	—	—	—	—	×	—
- 2	100	Ser-Qtzite	10	—	—	—	—	—	—	—	—
Averages	—	—	32	—	—	—	—	—	—	—	—
Kallinkangas											
KK-45	445	Ser-feld-Qtzite	28	—	—	—	1	—	—	—	—
-40	370	Ser-feld-Qtzite	4	—	—	—	—	—	—	—	—
-38	325	Ser-feld-Qtzite	24	×	—	—	—	—	—	—	—
-35	280	Ser-feld-Qtzite	41	—	—	—	—	—	—	—	—
-28	240	Ser-qtz-Schist	63	—	—	×	—	—	—	—	—
-24	220	Ser-Qtzite	24	—	—	1	—	×	×	×	—
-20	200	Ser-Qtzite	38	×	—	—	—	—	—	—	—
-18	175	Ser-Qtzite	16	—	—	—	—	×	×	×	—
-13	115	Ser-Qtzite	12	—	—	—	—	—	—	—	—
- 8	80	Ser-feld-Qtzite	26	—	—	—	—	×	—	—	—
- 4	50	Ser-feld-Qtzite	45	—	—	—	—	—	—	—	—
Averages	—	—	29	—	—	—	—	—	—	—	—
Vuokatti											
VK-24	1 700	Ser-qtz-Schist	1	—	—	—	—	—	—	—	—
-19	1 400	Qtzite	33	—	—	1	—	×	—	—	—
-15	1 300	Ser-Qtzite	2	×	—	—	—	—	—	—	—
-14	1 250	Biot-mus-qtz-Schist	1	—	—	—	—	—	—	—	—
- 9	1 000	Ser-Qtzite	27	×	—	×	—	—	—	—	—
- 6	700	Qtzite	7	—	—	—	—	—	—	—	—
- 2	50	Ser-feld-Qtzite	15	—	—	—	—	—	—	—	—
Averages	—	—	12	—	—	—	—	—	—	—	—
Paukkajanvaara											
PV-20	300?	Feld-ser-qtz-Schist	35	×	—	1	—	—	—	×	—
-19	250?	Biot-feld-Qtzite	40	—	—	—	—	—	—	—	—
-15	75	Ser-Qtzite	82	×	—	3	—	1	—	—	2
-12	60	Ser-Qtzite	28	—	—	—	—	—	—	—	—

mineral data.

?		Metamorphic																
Apatite				Tourmaline														
Clear	Dusky, inclusions	Epid-clinoz-zoisite	Hornblende	Green-pink	Green-colorless	Blk-red brown	Green-lt.green	Black-pink	Black-tan	Blue-green	Total tourmaline	Garnet	Sillimanite	Diopside	Rutile, red	Rutile, yellow	Sphene	Miscellaneous
1	14	1	4	11	—	—	—	—	—	—	11	4	—	×	×	7	—	
—	2	—	98	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
1	1	1	91	×	—	—	—	—	—	—	×	—	—	—	—	1	4	
1	8	2	4	32	—	—	12	—	—	—	44	1	—	×	—	1	—	
2	7	3	6	23	—	—	9	—	—	—	32	1	—	1	—	2	—	
—	7	36	55	—	—	—	—	—	—	—	—	—	—	—	—	×	×	
2	18	2	2	22	—	—	5	—	—	—	27	1	×	1	—	4	—	
3	2	6	1	—	17	—	6	—	—	—	23	—	2	×	3	13	—	Anatase-×
1	×	13	2	2	—	—	—	—	—	—	2	1	1	2	×	×	—	
—	3	—	—	—	—	—	—	—	—	—	—	97	—	—	—	—	—	
1	6	6	26	—	—	—	—	—	—	—	14	—	—	—	—	—	—	
19	6	7	5	—	—	4	2	1	1	—	8	—	—	×	—	—	—	
×	18	6	42	—	—	×	1	—	—	—	1	×	—	×	—	—	—	
1	29	8	18	—	—	2	×	—	4	—	6	3	—	1	—	—	—	
1	59	1	22	—	—	—	—	—	—	—	—	2	—	3	—	—	×	
5	28	6	22	—	—	—	—	—	—	—	4	—	—	—	—	—	—	
×	52	1	9	8	—	—	—	—	—	—	8	—	—	—	—	—	—	
×	1	2	7	85	—	—	—	—	—	—	85	—	—	—	—	—	—	
2	45	2	2	23	—	—	1	—	—	—	24	×	—	—	—	—	—	
6	26	6	17	1	—	—	—	—	—	—	1	3	—	—	—	—	—	
1	22	—	1	10	—	—	1	—	—	—	11	—	1	—	—	—	—	
3	19	1	4	26	—	×	2	—	—	—	28	19	×	×	—	—	—	
1	47	2	4	2	—	1	1	—	—	—	4	1	1	1	—	—	—	
—	43	3	2	31	—	3	×	—	—	—	34	—	—	1	—	—	—	
2	80	—	1	5	—	—	×	—	—	—	5	—	—	—	—	—	—	
7	17	2	14	21	—	—	4	—	—	—	25	5	3	1	—	—	—	
3	42	1	4	2	—	3	×	—	—	—	5	—	—	—	—	—	—	
2	36	2	6	—	—	—	—	—	—	—	21	—	—	—	—	—	—	
×	19	54	4	11	—	—	5	—	—	—	16	—	4	2	—	—	—	
×	28	4	4	13	—	—	—	—	—	—	13	—	6	—	—	11	—	
×	21	2	1	64	—	—	10	—	—	—	74	—	—	—	—	—	—	
×	14	1	—	78	—	—	6	—	—	—	84	—	—	×	—	—	—	
×	×	5	1	56	—	—	6	—	—	—	62	—	1	2	—	1	—	
2	20	48	15	6	—	—	—	—	—	—	6	—	2	—	—	—	×	
6	53	2	3	8	—	—	×	—	—	—	8	1	3	—	—	9	—	
1	22	17	4	—	—	—	—	—	—	—	38	—	—	—	—	—	—	
—	48	×	6	8	—	—	×	—	—	—	8	×	—	×	—	—	—	
—	34	1	24	×	—	—	—	—	—	—	×	×	—	—	—	—	—	
—	3	2	4	2	—	—	×	—	—	—	2	—	×	—	—	×	—	
—	6	1	2	—	34	—	—	—	—	—	34	1	1	1	1	25	—	

Table 3.

Section and sample number	Estimated meters above base	Metamorphic rock type	Detrital								
							Tourmaline				
			Zircon	Sphene	Rutile, yellow	Rutile, red	Blue-purple	Black-green	Blue-pink	Dark blue-blue	Brown-yellow
PV- 8	40	Ser-Qtzite	59	—	—	—	—	—	—	1	—
- 6	10	Ser-qtz-Schist	63	—	—	—	—	—	—	—	—
- 3	2	Gneiss frag-mica-Schist	26	—	—	—	—	—	—	—	—
Averages	—	—	48	—	—	—	—	—	—	—	—
Kiihtelysvaara											
KI-11	375	Ser-feld-Qtzite	80	×	—	—	—	—	—	4	—
- 9	325	Ser-Qtzite	84	—	—	—	—	—	—	×	—
- 6	225	Ser-Qtzite	38	—	—	—	—	—	×	—	1
- 4	150	Feld-ser-Qtzite	47	×	×	—	×	×	1	×	—
- 3	110	Feld-ser-Qtzite	45	—	—	—	—	—	—	—	—
- 2	50	Quartz pebble-Conglom	22	—	—	—	—	—	—	1	—
- 1	1	Gneiss pebble-Conglom	4	—	—	—	—	2	1	2	—
-gneiss	—	Basement biotite Gneiss	22	—	—	—	—	—	—	—	—
-T.granite	—	Basement tourm.Granite	—	—	—	—	—	—	—	—	—
Average (Not includ. basement)	—	—	46	—	—	—	—	—	—	—	—
Leskelenvaara											
LV-6	100?	Weath.biot.gneiss Basem.	32	—	—	—	—	—	—	—	—
-5	75?	Weath.biot.gneiss Basem.	56	—	—	—	—	—	—	—	—
-3	25?	Weath.biot.gneiss Basem.	21	—	—	—	—	—	—	—	—
-1	5?	Weath.biot.gneiss Basem.	27	—	—	—	—	—	—	—	—
-A	—	Fresh biot.gneiss Basem.	26	—	—	—	—	—	—	—	—
Averages	—	—	32	—	—	—	—	—	—	—	—
East Karelia											
Paduin	?	Ser-Qtzite	80	—	—	—	—	—	—	—	—
Koikari cong.	?	Granite & Qtz pebb Cong.	27	—	×	—	—	—	—	×	—
Koikari 520/43	?	Ser-Qtzite	1	—	—	—	—	—	—	1	—
Averages	—	—	36	—	—	—	—	—	—	—	—
Kuopio Area											
Kuopio	?	Sillimanite Qtzite	4	—	—	—	—	—	—	—	—
Sotkuma	?	? Qtzite	3	—	—	—	—	—	—	—	—
Nilsiä	?	Qtzite	76	—	—	—	×	—	—	1	×
Timovaara	?	Feld-Qtzite	2	—	—	—	—	—	—	—	—
Outokumpu	?	? Qtzite	—	—	—	—	—	—	—	—	—
Averages	—	—	15	—	—	—	—	—	—	—	—
North Lapland											
Muonio	?	? Qtzite	6	11	—	—	—	—	—	—	—
Kolari	?	? Qtzite	24	—	—	—	—	1	—	×	—
Kittilä	?	? Qtzite	49	—	—	—	—	—	—	—	—
Sodankylä	?	? Qtzite	76	—	—	—	—	—	—	—	—
Averages	—	—	39	—	—	—	—	—	—	—	—

× = denotes trace amount

Cont.

?		Metamorphic																
Apatite				Tourmaline														
Clear	Dusky, inclusions	Epid-clinoz-zoisite	Hornblende	Green-pink	Green-colorless	Blk-red brown	Green-lt.green	Black-pink	Black-tan	Blue-green	Total tourmaline	Garnet	Sillimanite	Diopside	Rutile, red	Rutile, yellow	Sphene	Miscellaneous
—	3	4	4	—	16	—	—	—	—	—	16	—	2	×	—	11	—	
—	12	4	1	—	—	—	—	—	—	—	—	—	×	1	—	6	—	
—	59	2	10	×	—	—	—	—	—	—	×	4	1	14	—	—	—	
—	14	2	7	—	—	—	—	—	—	—	9	—	—	—	—	—	—	
—	—	3	7	3	—	×	—	—	—	—	3	1	×	1	—	—	—	
—	—	4	3	3	—	×	—	—	1	—	4	1	×	×	—	3	—	
×	×	1	25	3	—	24	1	—	—	—	28	5	1	—	—	—	—	
2	27	6	3	7	4	—	—	—	—	—	11	×	1	×	—	—	—	
43	6	1	1	2	1	—	1	—	—	—	4	—	—	—	—	—	—	
32	1	2	5	30	—	3	—	—	—	—	33	1	2	×	—	1	—	
33	—	3	4	51	—	—	—	—	—	—	51	×	—	—	—	—	—	
56	—	8	12	—	—	—	—	—	—	—	—	1	—	×	—	1	×	
—	—	—	—	33	—	31	—	9	24	3	100	×	—	—	—	—	—	
16	7	3	9	—	—	—	—	—	—	—	19	—	—	—	—	—	—	
—	22	33	10	—	—	—	—	—	—	—	—	—	—	—	2	1	—	
—	28	—	1	1	—	—	—	—	—	—	1	—	—	—	1	13	—	
47	15	2	×	—	—	—	—	—	—	—	—	1	—	—	1	13	—	
—	58	1	4	—	—	×	—	—	—	—	×	—	—	—	3	7	—	
—	65	2	4	1	—	×	—	×	—	—	2	1	—	—	—	×	—	
—	47	7	3	—	—	—	—	—	—	—	×	—	—	—	—	—	—	
2	7	—	1	3	—	1	1	—	—	—	5	—	3	—	—	×	—	
8	41	3	19	—	—	1	—	—	—	—	2	—	—	×	—	—	—	
1	7	×	4	7	—	77	—	—	—	—	85	1	—	—	—	—	—	
4	18	1	8	—	—	—	—	—	—	—	30	—	—	—	—	—	—	
4	36	1	—	—	—	—	—	—	—	—	—	—	50	×	2	3	—	
1	1	34	53	×	—	—	—	—	—	—	×	—	2	5	—	—	—	Kyanite-×
1	1	3	3	3	—	—	—	—	—	—	3	—	1	—	1	9	—	
—	×	93	1	1	—	×	—	—	—	—	1	—	—	×	—	—	—	
—	×	6	91	—	—	—	—	—	—	—	—	—	—	2	—	—	—	
1	7	27	29	—	—	—	—	—	—	—	1	—	—	—	—	—	—	
7	1	70	4	—	—	—	—	—	—	—	—	—	×	×	—	—	—	
63	2	3	1	3	—	2	—	—	—	—	6	×	—	×	—	—	—	
×	4	5	8	4	—	25	4	—	—	—	33	—	1	×	—	—	—	
3	1	18	1	×	—	—	—	—	—	—	×	—	1	×	—	—	—	
18	2	22	3	—	—	—	—	—	—	—	10	—	—	—	—	—	—	

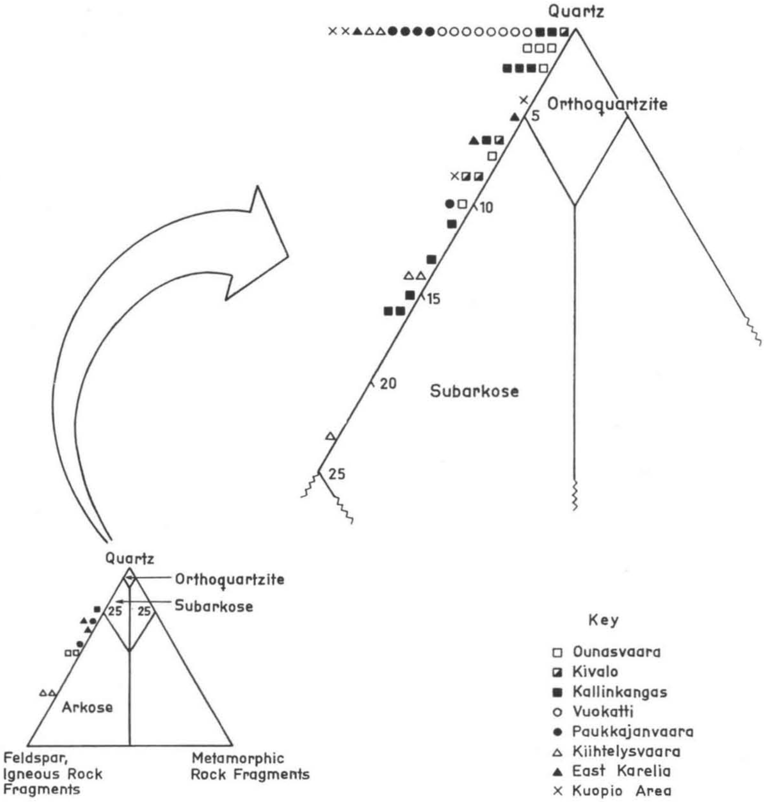


Fig. 16. Generalized classification of pre-metamorphism Jatulian sandstones. Classification after Folk, 1954; however, gneiss rock fragments have been placed on the feldspar plus igneous rock fragment pole.

ROCK TYPES

As all the samples studied contain mica and more than two-thirds contain feldspar, only a few of the samples are fairly pure quartzites. A modifying term is thus added to the rock name for each component, other than quartz, which comprises more than five percent of the rock (Tables 2 and 3). Samples with more than 30 percent mica are arbitrarily called schists rather than quartzites; however, most samples possess some degree of schistosity and the transition from quartzite to schist is gradual. Most of the rocks are thus sericitic quartzites, sericitic-feldspathic quartzites, or sericite-quartz schists.

Determination of the original pre-metamorphism rock types was attempted, assuming that the mica roughly represents the original clayey matrix. Folk's (1954) classification, in which clay is considered a textural rather than a mineralogical component, was used to classify the rocks (Fig. 16): 28 of the rocks are clayey orthoquartzites, 18 are clayey subarkoses, and 9 are clayey arkoses. Fourteen of the subarkoses are mineralogically nearer to orthoquartzites than to arkoses, and would be clayey feldspathic quartzites after Hubert (1962). The plots show that the sandstones constitute a »main-line maturity sequence» from arkoses to feldspathic sandstones to orthoquartzite sandstones (Hubert, 1960; 1962). According to Pettijohn's (1957) classification, 31 of these rocks, by virtue of their clay content (more than 15 percent) would be graywackes. After Gilbert (1954), 38 of the rocks are wackes (more than 10 percent clayey matrix) and 17 are arenites (less than 10 percent clayey matrix).

HEAVY MINERALS

The heavy minerals of the quartzites were studied to obtain evidence on the source rocks and the amount of reworking which the detritus has undergone. Seven basement samples and 59 samples from the quartzites (46 from the 6 thick measured sections and 13 from scattered points in East Karelia, the Kuopio area, and northern Lapland) were crushed to a particle size of 0.29 mm in a mechanical crusher. Many grains of metamorphic origin were crushed due to their large size, but virtually all detrital heavy minerals are smaller than 0.29 mm and are not affected by this procedure. The crushed samples were washed in water, with repeated decanting, until all the clay-size particles were eliminated. The heavy residue was then separated by means of bromoform (S.G. = 2.88 ca) in separatory funnels. Magnetite was removed with an A-C hand magnet. »Shaking» on an inclined surface (Hutton, 1950, p. 645) allowed the separation of much biotite from the residue, and centrifuging with Clerici solution removed additional biotite as well as quartz grains with hematite inclusions and staining.

Each heavy mineral residue was then repeatedly split with a sample microsplitter (in order to assure a random sample in terms of grain size, shape, and density) until the correct amount was obtained for mounting in Canada balsam. The unmounted and mounted portions were then studied with binocular and petrographic microscopes. Some mineral identifications were checked by X- ray by Dr. Atso Vorma.

Three hundred non-opaque heavy mineral grains were counted on each mount (Table 3). In order to facilitate further study of zircon and apatite after determining their abundance in the heavy fraction, they were concentrated by means of a Frantz electromagnetic separator (0.8 amps, slope 15°, tilt 15°). The heavy mineral suite consists of several metamorphic species and only a few detrital species. Grains which may have been inclusions in the detrital quartz and rock fragments and were liberated by the crushing process could not be distinguished from other heavy mineral grains. Study of the associated thin sections was very useful, for at least a few grains of each heavy mineral species were usually present and could be assigned a sedimentary or metamorphic origin on the basis of size, shape, and relation-

Table 4. Minor heavy mineral descriptions

Diopside . . . . Color varies from very light green to deep yellow-green, with some deep green grains (chromian) from Outokumpu. Metamorphic origin from calcareous material.

Epidode-clinozisite-zoisite . . . . Counted together due to similarity of origin and composition and difficulty in distinguishing species in many instances. Metamorphic origin by alteration of feldspars and other silicates and/or calcareous materials.

Garnet . . . . Pale pink, N = 1.82 ca, non-manganese-bearing (probably almandine) in sample OV-A. Clear or pink in most other samples, rarely orange or green. Metamorphic origin.

Hornblende . . . . Predominantly green; deep green in KI-6, OV-19, OV-21; brown variety present at Kivalo, Ounasvaara, and Paukkajanvaara. Pleochroic with absorption in greens, yellow-greens, and browns. Brown grains at Kivalo commonly in close association with diopside (X-ray identification), appearing fibrous and failing to extinct. Dark inclusions very common. Metamorphic origin, possibly from calcareous material.

Opaques . . . . Magnetite, ilmenite, hematite, »limonite», pyrite, chalcopyrite, and unidentified sulfide grains.

Rutile . . . . Commonly light to deep yellow, less commonly red. Metamorphic rutile generally in small euhedral crystals, often in swarms in thin section, some attached to large opaque grains. Red, well-rounded grains occur in very small amounts in ten samples and may be detrital.

Sillimanite . . . . Colorless, long slender prisms; dusky fibrolite noted in Paduin samples. Metamorphic origin from Al-rich clay matrix?

Sphene . . . . Metamorphic origin, surrounding rutile in thin section OV-19. Well-rounded and detrital (?) in Muonio sample and as traces in several other samples.

Spinel . . . . Jet black and shiny (oblique illumination), isotropic; when crushed, small pieces are brown in transmitted light, indicating a chromian variety. Only in Kuopio and PV-20 samples.

Tremolite-actinolite . . . . Very light green in hand specimen, generally quite colorless in transmitted light; X = 1.63 ca. Commonly noted in field at Ounasvaara. Metamorphic origin from calcareous material.

---

ship to other grains. Apatite, tourmaline, and zircon, the three most abundant heavy minerals (Table 3), are described below. Brief descriptions of the other heavy minerals are presented in Table 4.

APATITE

Two main types of apatite are present (Fig. 17); one is clear to light gray and generally free of inclusions whereas the other is dusky gray or brown and is commonly loaded with fine lines of black inclusions aligned parallel to the c-axes. X-ray study of the latter grains showed traces of mica. Both types occur as angular euhedral or highly irregular grains; a few are more rounded. They are commonly too large to be hydraulic equivalents of associated quartz and zircon grains. On the basis of their large size and on thin section observations, it seems probable that all of the dusky grains and many of the clear grains were formed during metamorphism of the quartzites. Some of the small clear euhedral prisms may have been detrital or more probably, may have been separated from within quartz grains during crushing. In the Muonio sample, a few clear, pale greenish-blue (reflected light), perfectly euhedral hexagonal prisms with pinacoidal bases are present. Several apatite

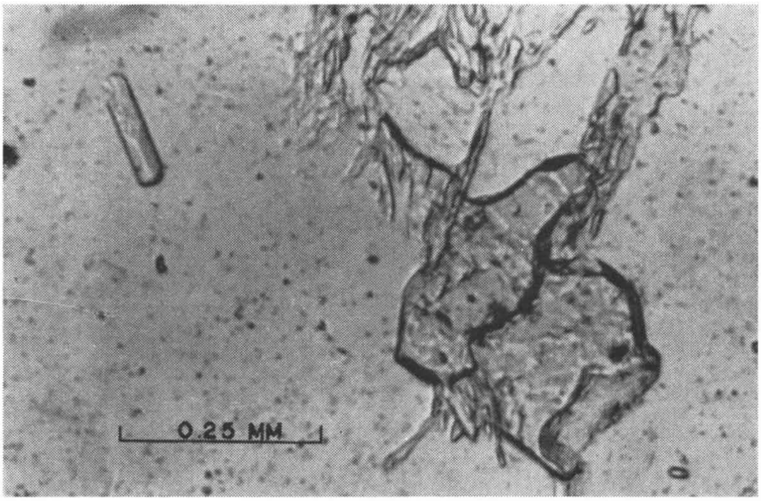


Fig. 17. Apatite grains in thin section of quartzite sample KV-12, from Kivalo. The small elongate prism at upper left in an inclusion is a quartz grain and may be igneous in origin. The large, irregularly shaped grain in the center is apatite which formed in the quartzite during metamorphism. The rest of the field is quartz and sericite. Plane polarized light. Photo by Halme.

grains from quartzites of many widely separated localities, and from basement gneiss as well, all had indices of $N_o = 1.636$ ca and $N_e = 1.630$ ca, indicative of fluorapatite (Winchell and Winchell, 1959, p. 198).

TOURMALINE

The tourmaline generally occurs as angular idiomorphic prisms (Figs. 18 and 19) with the following colors (absorption $0 > E$):

One nicol	Reflected light
Green to pink	Pinkish-gray, light greenish-gray
Green to light green	.. ..
Green to colorless	Light gray or greenish-gray
Black to reddish-brown	Pinkish or reddish-brown
Black to pink	.. ..
Black to tan	.. ..

Most of the prisms are slightly paramagnetic and were separated at 0.8 amps (Frantz) indicating an iron content or iron-bearing inclusions. Fine black inclusions and air vacuoles are common. Many prisms, especially at Kallinkangas, contain red commonly rounded cores (probably detrital) which are dichroic from black to red; the outer portions of these prisms are dichroic from green to pink (Fig. 20). The outer portions of this type of grain have

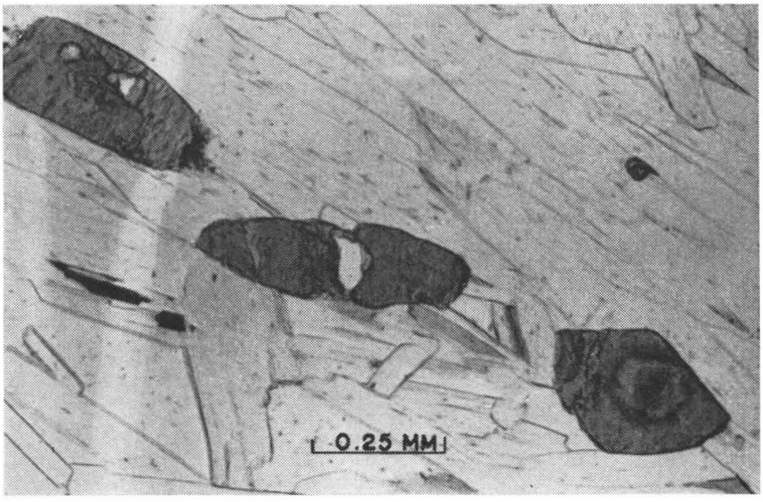


Fig. 18. Metamorphic tourmaline prisms in thin section of mica schist sample VK-14 from Vuokatti. Note fractures. Plane polarized light. Photo by Halme.

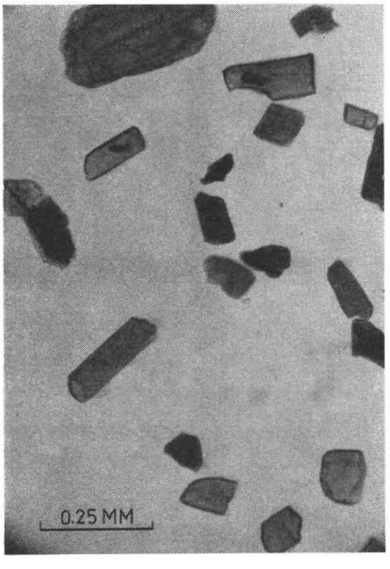


Fig. 19. Metamorphic tourmaline prisms in heavy mineral fraction of quartzite sample VK-15 from Vuokatti. Plane polarized light.

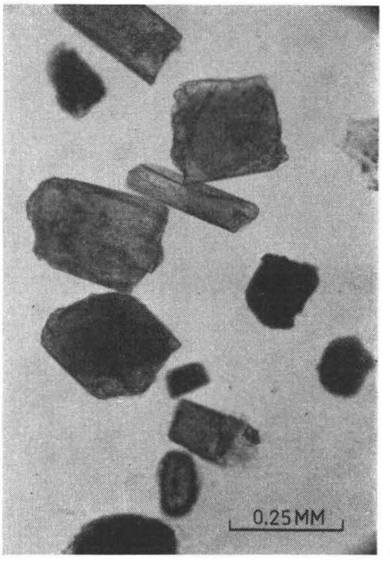


Fig. 20. Tourmaline prisms in heavy mineral fraction of sample KK-13 from Kallinkangas. Each prism has a rounded core, probably a relict detrital grain. The cores are dichroic from black to red, whereas the metamorphic outer shells are dichroic from green to pink. A single rounded zircon grain is at left. Plane polarized light.

commonly been interpreted as authigenic or low-grade metamorphic overgrowths (e.g., Potter and Pryor, 1961). The large size of the overgrowths relative to the cores, and the presence in the same samples of prisms showing the same dichroism (green to pink) but not possessing cores as above, indicates that both the prisms and the overgrowths were formed in the quartzites during metamorphism. (See Metamorphism end Metasomatism pp. 58—60.)

»Detrital tourmaline» occurs as rare rounded to well-rounded grains with the following colors under one nicol (absorption 0 > E): black to green; blue to pink, light blue, or purple; and brown to yellow.

»Basement tourmaline» from the basement tourmaline granite at Kiihtelysvaara is black in hand specimen but exhibits the following colors (absorption 0 > E) under one nicol:

Blue to light blue	33 %
Black to red brown	31 »
Black to pink	9 »
Blue green to pink	24 »
Blue to green	3 »

The tourmaline in samples KI-1 and KI-2 may have been partially derived from the basement.

ZIRCON

Zircon is the only abundant heavy mineral in the quartzites which can be classified with certainty as detrital. However, the zircon percentages, because of the abundance of metamorphic heavy minerals, do not indicate the volumetric importance of zircon in the original sandstones.

The zircon grains are very commonly brownish in color, evidently largely due to staining by iron oxide. Some are clear or yellow. The pink (hyacinth) variety is present in small amounts in many samples, and large well-rounded hyacinths are especially abundant in the Nilsiä sample. The zircons are apparently all metamict.

After concentration with a Frantz separator, one hundred zircon grains were counted in each of 45 mounts and placed in one of three roundness-shape categories (Table 5):

(1) Well-rounded, subspherical to elongate
(2) Subrounded, prismatic
(3) Angular, idiomorphic prismatic

These categories can theoretically be related to the amount of abrasion which the zircon grains have undergone: angular idiomorphic grains indicate

Table 5. Percentages of zircon types based on roundness and shape

Locality	No. of samples	Well-rounded subspherical to elongate	Subrounded prismatic w/pyramids	Angular idiomorphic prismatic	
				No »Shells»	With »Shells»
Ounasvaara	6	84	16	0	0
Kivalo	2	81	18	1	0
Kallinkangas	10	80	18	1	1
Vuokatti	4	77	20	0	3
Paukkajanvaara	7	65	31	2	2
Kiihtelysvaara	6	42	45	8	5
East Karelia	2	40	44	11	5
North Lapland	4	52	31	14	3
Nilsiä	1	84	14	2	0
Basement:					
Kiihtelysvaara gneiss (KI-gn)	1	7	39	46	8
Leskelenvaara gneiss (LV-3)	1	30	50	16	5

direct derivation from igneous or metamorphic rocks and little or no effective abrasion, providing authigenic overgrowths have not caused the angular euhedral shapes; subrounded prismatic grains may indicate moderate abrasion; and well-rounded grains may be indicators of long abrasion (Fig. 21). Admittedly, rounded and subrounded zircon grains can form in igneous rocks and can be derived directly from metamorphic rocks; however, when supplemented by other data such as an abundance of rounded quartz grains in the sandstones in which they are found, their use as an abrasion index is probably valid.

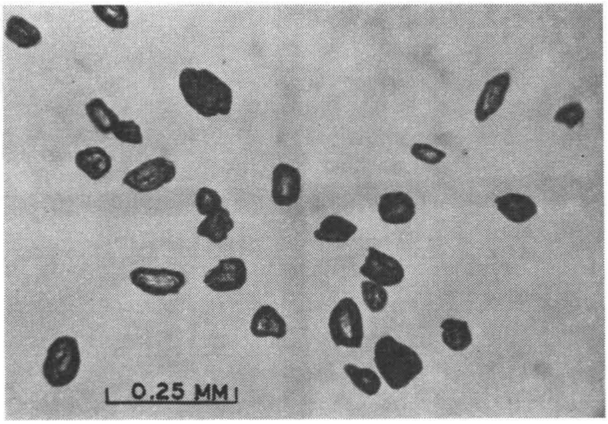


Fig. 21. Well-rounded subspherical to elongate zircon grains from heavy mineral fraction of nearly feldspar-free quartzite sample OV-9 from Ounasvaara. The roundness of the grains indicates long abrasion in the Jatulian Sea. Note aggregate grain at upper left. Plane polarized light.

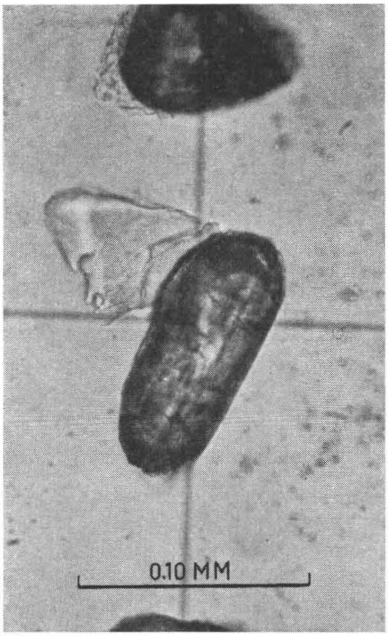


Fig. 22. Rounded zircon grain showing zircon shell on rounded core. Shell probably formed on a detrital zircon grain during transformation of pre-Jatulian sediments into paragneisses. Such grains were later eroded, abraded, and deposited in the Jatulian sediments, where they have since remained unaltered. Sample KK-28 from Kallinkangas. Plane polarized light.

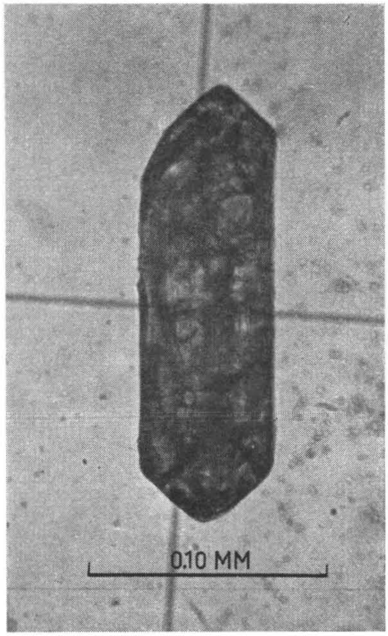


Fig. 23. Angular idiomorphic zircon grain. The angularity indicates little abrasion. There are some indications of a shell on a rounded core. Sample KI-11 from Kiihtelysvaara. Plane polarized light.

The idiomorphic zircon grains were counted in two categories: those which show a thin »shell» on a darker, commonly zoned and rounded core (Fig. 22) and those which lack such a shell (Fig. 23). The latter variety is assumed to be of igneous origin, whereas the shelled type has a more complicated history. The shells are not the protruding type which results from authigenic growth in sediments, as illustrated for example, by Butterfield (1936). Instead, they generally appear rounded under low magnification but commonly show numerous small crystal faces under higher power. Grains with shells, similar to those in the quartzites, also occur in the basement gneiss samples (Fig. 24) indicating that the shells were formed on the rounded cores (relict sedimentary zircons) by the metamorphic processes which formed the gneiss. A zoned zircon is shown in Figure 25. Small aggregate crystals are also present. The grains with shells and the aggregate crystals appear to be

Fig. 24. Angular idiomorphic and subrounded zircon grains showing zircon shells on rounded cores. These grains from basement gneiss sample LV-3 from Leskelenvaara are very similar to zircons in the quartzites (Fig. 22). Apatite grain at right. Plane polarized light.

Fig. 25. Angular idiomorphic grain from basement gneiss sample KI-gn from Kiihtelysvaara. Grain is zoned and does not have the type of shell shown in Figs. 22 and 24, suggesting that it has an igneous origin. Other grain in photo is clear apatite. Plane polarized light.

very similar to zircons extracted from non-intrusive granites by Poldervaart and Eckelmann (1955). Wyatt (1954) described zircon grains with numerous faces which are visible only under high power, and attributed them to recrystallization during granitization. Eckelmann (1962) reported metamorphically generated shells on relic sedimentary zircons. Reynolds (1936) described unaltered zircons from quartzites which underwent intense thermal metamorphism and metasomatism, and evidence that zircons are unaffected by metamorphic intensities below the pyroxene-hornfels facies has been presented by Taubeneck (1957).

Preston (1954, p. 16—21) studied the zircons in the gneisses of the Kuopio area and distinguished between paragneisses and orthogneisses on the basis of zircon rounding and elongation. Rounded zircons are mixed with abundant idiomorphic zircons in the gneiss samples from Leskelenvaara and Kiihtelysvaara (Table 5), suggesting a sedimentary-igneous origin (i.e., migmatized sediments) for these gneisses as well. Perhaps the abundance of rounded zircons in the quartzites reflects a dominantly paragneissic source, as well as abrasion of the detritus.

SEDIMENTATION

The thin (50—100 m) predominantly gneiss-pebble basal Sariolian conglomerates have been interpreted as river valley deposits (Simonen, 1960 b; and others). Their sporadic occurrence and generally poor sorting are indicative of fluvial, rather than beach, deposits. The rounding of the pebbles would have been easily achieved during a few miles of river transport (Krumbein, 1941).

The Jatulian Sea probably transgressed eastward, in general, and deposited quartz-rich sand upon the crystalline basement and, locally, upon the basal conglomerates. Remnants of this ancient little-known surface suggest that it was a regional peneplain with scattered small residual hills (monadnocks) which stood as islands contributing feldspathic detritus to the sea. For example, post-quartzite black schists rest directly upon the weathered basement gneiss at Leskelenvaara, attesting to the existence of a small topographic high here during deposition of the quartz sands.

The thicknesses of the quartzite formation (Fig. 2) indicate a possible thinning towards the east. This would be compatible with an eastern source, as such shallow marine deposits commonly thicken basinward. However, many additional accurate measurements, especially in East Karelia, are necessary to verify this trend.

PALEOCURRENT INTERPRETATION

The paleocurrent pattern (Fig. 13) shows a dominant current movement toward the west-northwest and a secondary but prominent movement toward the south-southwest. Pettijohn (1957, p. 167 and 581; 1962, p. 1473) said that broad regional trends indicate movement of currents down a paleoslope, apparently normal to the trend of the shoreline. Allen (1963 a, p. 226) however, suggested that preferred dip directions represent currents parallel to coasts, are independent of regional slope, and that preferred current and sediment source directions are probably unrelated. T. Mikkola (1960) suggested the very plausible interpretation that currents in the Jatulian Sea were moving from the foreland towards deeper water, as well as parallel to the shoreline.

As the two dominant current directions are situated at about right angles to each other, it seems logical to assume that both longshore currents and currents normal to the shore were active. Which of the two maxima reflects the trend of the shoreline is speculative; it trended either west-northwest or south-southwest. The relationship of the current and sediment source directions can be at least partially determined; even assuming no direct relationship, sources to the northwest, west, and south can be quite safely ruled out because the currents were moving toward these directions. Eastern and/or northern sources seem likely. An analysis of cross-bedding in the quartzites on the Russian side of the frontier would add much to the regional interpretation.

NATURE OF THE SOURCE ROCKS

Some generalized statements can be made about the source rocks:

(1) They contained microcline, orthoclase, and plagioclase. A survey of the literature and the observation of nearly two hundred thin sections indicate local variations in the feldspar types of both the quartzites and the pre-Karelian basement rocks. Orthoclase and plagioclase are more abundant in the basement samples from Leskelenvaara and Kiihtelysvaara than in the overlying quartzites, and microcline is virtually absent in these basement samples. The basement gneisses, dominantly paragneisses, of the Kuopio area contain oligoclase but little microcline and the quartzites here contain no detrital microcline (Preston, 1954). On the other hand, Kharitonov (1960) reported pre-Sariolian microcline granites, and microcline granite pebbles in the Sariolian conglomerate, in East Karelia. Eskola (in Preston, 1954, p. 100) noted microcline granite pebbles in the Sariolian conglomerates near Joensuu in eastern Finland, and (1963, p. 155 and 158) reviewed the evidence for pre-Karelian K-feldspar granites. Although microcline is more resistant to chemical weathering than are orthoclase or plagioclase (Pettijohn, 1957, p. 125 and 502; Folk, 1959, p. 82), the presence of microcline in the source rocks, especially in East Karelia, suggests that this difference in stability is not the only reason that microcline is the dominant feldspar in the quartzites.

(2) The source rocks yielded sand grains and pebbles of both polycrystalline and unit quartz (Table 2). The abundant unit quartz grains may have been derived from either granites, gneisses, or quartz veins. Polycrystalline sand grains are derived from both plutonic and metamorphic rocks (Blatt and Christie, 1963). The apparent great preponderance of gneisses in the basement complex denotes them as the logical sources for most of the quartz grains.

The literature contains more than a dozen references to quartzite pebbles in the Sariolian conglomerate and Jatulian quartzite of Finland and East Karelia, and quartzite pebbles were observed in this investigation as well. They are of two main types, one containing sericite or relict grain boundaries, and the other not containing either (monomineralic). Pebbles of the first type were noted in the Koikari sample; fine crushed quartz is present along the boundaries of seemingly rounded individuals which comprise the white or pink pebbles.

A. Mikkola (1943) reported sericitic quartzite pebbles in which pigment rings show rounded outlines, and Hackman (1918, p. 57) reported pebbles in which individual grains are separated by sericite. It is difficult to name a source, other than the Jatulian quartzite itself, for these pebbles; the only pre-Jatulian non-migmatized quartzites reported in Finland are in the Tuntsa-Savukoski Series of northern Lapland (E. Mikkola, 1941, p. 159). However, Kharitonov (1960) stated that in East Karelia and on the Karelian Massif, the Sariolian conglomerates rest discordantly upon iron quartzites and gneisses, sericitic-quartz schists, schistose phyllites, keratophyre-spilite effusives, and meta-effusives of the Himolian and Bergaulian Series; all of these rocks are thus possible sources.

Numerous reports, notably Hausen's (1930), describe monomineralic quartzite pebbles. Pebbles of this type are scattered in the quartzites at Paukkajanvaara (Fig. 5); their presence amid sand-sized sediment suggests a nearby source. Several origins are possible: (A) the original quartz clastics of the paragneissic pre-Jatulian basement (Väyrynen, 1933; Preston, 1954; Matisto, 1958; Simonen, 1960 a) probably supplied both polycrystalline sand and pebbles; the weathered basement gneiss at Leskelenvaara contains quartz concentrations from a few millimeters to a few centimeters in diameter (Fig. 26) and in the gneiss at Kiihtelysvaara, concentrations up to 2 mm in diameter are very common. (B) Penecontemporaneous erosion of partially- or fully-lithified Jatulian sands, due to local uplift, could have resulted in the deposition of rounded sandstone pebbles in the quartz sand of the adjacent sea (Hausen, 1930, p. 40; Preston, 1945, p. 90; Matisto, 1958, p. 52). (C) Quartz veins could have yielded monomineralic pebbles, with the pebbles perhaps inheriting the recrystallized texture from the vein or receiving it during metamorphism of the beds in which they were deposited. Thin conglomerates composed primarily of vein quartz pebbles are common in Finland and East Karelia (e.g., Eskola, 1948), but such pebbles are less important in the immature Sariolian conglomerates where the more abundant gneissic pebbles mask them. (D) Tuominen (1944, p. 23 and 31) suggested that chalcedonic amygdules and quartz secretions in volcanics of the pre-Karelian basement in East Karelia were a source.

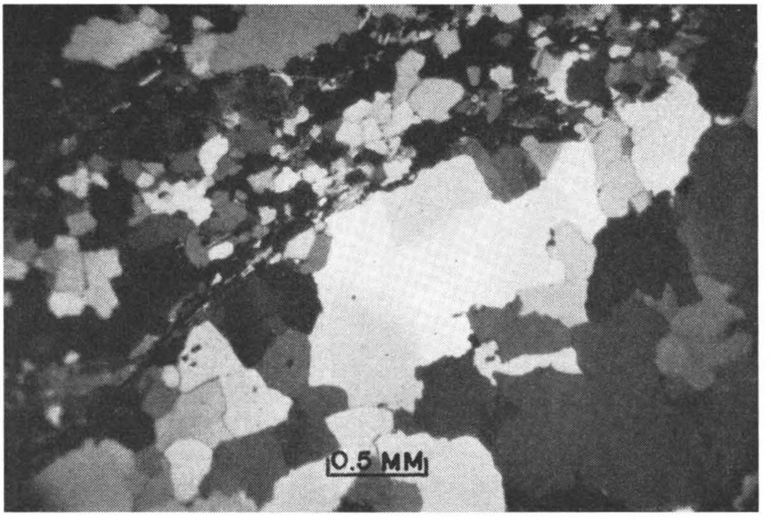


Fig. 26. Photomicrograph of large and small quartz concentrations in weathered basement gneiss sample LV-6 from Leskelenvaara. They are probably sedimentary relicts. Such concentrations are likely sources for the polycrystalline quartz grains of tha quartzites and for some »quartzite» pebbles. Crossed nicols.

(3) The zircon grains in the quartzites are very similar to those in the basement para- and orthogneisses, from which they were evidently derived. Preston (1954) noted a similar relationship at Kuopio. Paragneisses seem to have been the most important.

(4) The basal Sariolian conglomerates reportedly contain clasts of granites, gneisses, amphibolites, other altered basic rocks, vein quartz, and quartzite. At Kiihtelysvaara, and at Kontiolahti 40 km to the north, biotite-gneiss and tourmaline granite clasts in the conglomerates are very similar to the underlying gneiss and granite, suggesting a possible local derivation. The presence of scattered fuchsite pebbles in conglomerate near the Kiihtelysvaara section shows that some pre-Jatulian fuchsite-bearing metamorphic rocks were exposed in the source area.

(5) High-grade metamorphic minerals such as kyanite, andalusite, and garnet are not present as detrital components. It must be concluded that they were either not present in the source area or were effectively removed by abrasion and/or weathering. This further suggests that the garnet-, staurolite-, and cordierite-bearing schists and gneisses in Lapland (the Tuntsa-Savukoski Series of E. Mikkola, 1941) may not have supplied much material to the quartzites studied in this investigation.

In general, rocks of a granitic composition provided most of the detritus to the Jatulian Sea. What the proportion of granitic gneisses to true granites was cannot be reliably determined; the pre-Jatulian basement has been so altered by post-Jatulian granitization that the recognition of pre-granitization rocks has proved difficult (Härme, 1949, p. 56; Eskola, 1963, p. 157).

CLIMATE OF THE SOURCE AREA

The immature Sariolian conglomerates formed under conditions in which mechanical weathering dominated over chemical weathering. Moderate relief in the source area, even in a climate favoring intense chemical weathering, would have resulted in relatively rapid erosion and the formation of such conglomerates in river valleys and other topographic lows. Locally, slightly longer exposure to chemical weathering caused disintegration of the granitic source rocks or the granitic pebbles into arkosic sand. An analogous origin for basal conglomerates and arkoses beneath Upper Cambrian orthoquartzite sandstones has been described from Missouri in central United States, where the monadnocks which supplied much of the arkosic detritus are exposed (Ojakangas, 1963).

However, most of the peneplaned crystalline surface could have been subjected to longer chemical decay, producing the ultimate weathering products of quartz sand and clay. Kaolinite beds have been reported in the Jatulian Series at several localities in Finland. If the clay has survived the metamorphism and is shown to be kaolinite, a climate with rainfall sufficient enough for leaching and removal of Ca, Na, K, Mg, and Fe from the original rock would have been necessary (Keller, 1956). Should these beds prove to be montmorillonite or illite, less precipitation or poorer drainage during the formation of the clay would be indicated. Eskola (1963, p. 166—170) discussed this problem in detail.

Altered and fresh feldspar grains, dominantly microcline, occur together in many quartzite samples; these can be explained as the products of a dissected source area in which streams were eroding through the weathered surface layer into fresh rock and then transporting the mixed detritus to the sea. The fresher feldspar also could have been supplied by less-deeply weathered, more rapidly-eroded monadnocks. Deep pre-Jatulian (premetamorphism) weathering of the gneissose basement is evidenced, for example, at Leskelenvaara by a gradual vertical change in composition of the basement rock; the quartz content increases higher in the section as the feldspar becomes weathered and decreases in amount (Table 2). It has also been suggested that the »bottom schists» of the conglomerates and quartzites are metamorphosed soils (Eskola, 1932, p. 28). Although an *in situ* origin cannot be applied to any of the Jatulian quartzites, such deep weathering was undoubtedly a prime factor in the origin of the large supply of quartz sand. A warm, humid climate would have readily resulted in decomposition of the basement rocks, and a temperate climate over a longer period of time could have also achieved this end. Eskola (1932) pointed out that the lack of vegetation, even in a humid climate, would result in desert conditions. The weathered condition of much of the feldspar in the quartzites, and the presence of a thick weathered zone of basement rocks, argues against a completely arid climate; it is possible, however, that seasonal dry periods might have existed.

MATURITY OF THE JATULIAN SANDS

Jatulian-type quartz-rich sands require that tectonically stable conditions existed in the source area (long exposure to weathering) and/or the site of deposition (extensive reworking), or that the sand has gone through several cycles of sedimentation and erosion (Pettijohn, 1957, p. 300). No petrographic evidence for a multicycle origin was noted in this study, although such evidence would be extremely difficult to find in metamorphosed sandstones. Generally stable tectonic conditions (a stable shelf) evidently prevailed.

Well-rounded and commonly subspherical quartz and feldspar grains are recognizable in those quartzites which have not undergone recrystallization or extensive shearing (Figs. 14 and 27). As the Jatulian Sea transgressed upon the peneplaned landmass, the *in situ* clayey, quartz-rich surface layer of the weathered landmass, as well as much more abundant similar detritus being supplied concurrently by streams from the unsubmerged part of the craton, was reworked in the shallow littoral and neritic zones of the sea. With the certain lack of vegetation on land during the formation of these Precambrian sands, they were quite probably also reworked by wind (Väyrynen, 1928). It is even possible that wind abrasion did most of the rounding of the grains.

The detrital heavy mineral fraction provides a measure of mineralogical maturity. The fact that zircon, chemically and mechanically the most stable of the common heavy minerals, is virtually the only clearly detrital non-opaque heavy mineral present indicates that other detrital species were eliminated during weathering and/or abrasion; however, they may have been remobilized and redeposited during metamorphism, or may have been unimportant in the source rocks. The roundness of the zircon grains (Table 5) is also indicative of the amount of abrasion the sands have undergone. The highest amounts of angular idiomorphic and subrounded grains and the lowest amounts of well-rounded zircons occur at Kiihtelysvaara, East Karelia, and northern Lapland; at least part of the original sands here were evidently subjected to less reworking than those at Vuokatti, Kivalo, Kallinkangas, and Ounasvaara which contain more well-rounded grains (Table 5). These results are generally consistent with the percentages of feldspar and rock fragments (Table 2).

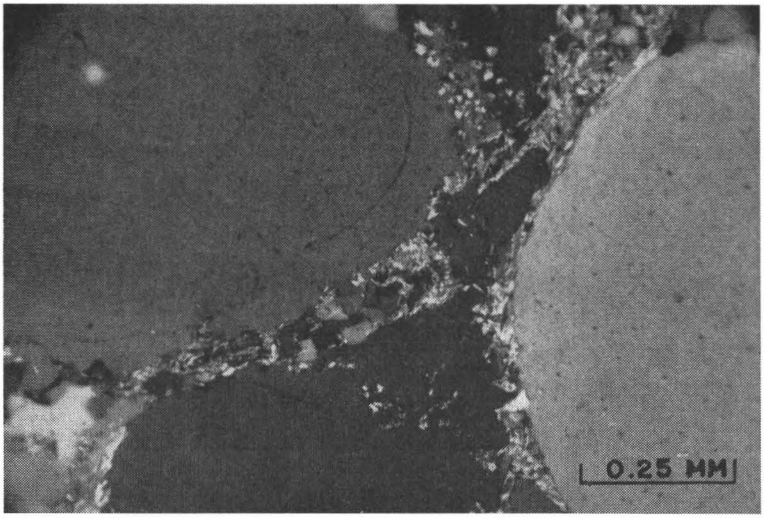


Fig. 27. Photomicrograph of quartzite from Paduin, East Karelia, showing well-preserved, well-rounded quartz grains with optically continuous overgrowths of silica, presumably formed in the original sandstone. Note fine granulation and sericitization. Crossed nicols.

The detrital feldspar content of the quartzites also provides an index of mineralogical maturity of the original sandstones (Table 2). The Vuokatti section and most of the Paukkajanvaara section contain no detrital feldspar and hence the Jatulian sediments in this region were subjected to a thorough chemical weathering and/or to effective abrasion. Rocks at the other studied localities contain differing amounts of feldspar, with some zones feldspar-free, thus indicating variable intensity or duration of the maturing processes and/or the influence of local feldspar-shedding monadnocks. However, the presence of thick, coarse-grained, poorly sorted, immature feldspathic quartzites immediately above the thick feldspar-free quartzites at Paukkajanvaara and Koli suggests an important change of conditions. Erosion by streams of nearby upthrown fault blocks, such as occurred on a much larger scale during deposition of the thick Triassic arkoses of Connecticut (Krynine, 1950) is a possible interpretation. The feldspathic quartzites may be evidence of the advent of folding or faulting on the flanks of the geosyncline or the advent of a more rapid subsidence in the basin (thereby not allowing long reworking and removal of the feldspar), signaling the end of the stable pre-geosynclinal stage. A vertical transition from feldspar-free to feldspathic quartzites is also evident at Kivalo, Kallinkangas, and Kiihtelysvaara (Table 2).

ENVIRONMENT OF DEPOSITION

The quartzites contain appreciable amounts of mica, interpreted as recrystallized clayey matrix. Vertical variations in the amount of matrix are present at all localities and great lateral variation over a short distance is evident near Kemi where the Kivalo section, originally composed of clayey arenaceous beds, is located only 10 km east of the Kallinkangas section in which similar units are interbedded with originally highly argillaceous units. The Jatulian sands present somewhat of a paradox in that they were clayey, suggestive of a rather rapid submergence and hence little reworking, and yet were rounded and mineralogically mature, theoretically reflecting a multicycle derivation (ruled out on the basis of petrography and regional geology) or extensive reworking in a high-energy environment in which clays would have been instantaneously removed by winnowing. The maturity of the sands seems to rule out rapid burial of the detritus in a rapidly transgressing sea. Clay and quartz-rich sand are the end products of the chemical weathering of granitic rocks; although the original texture of the total sediment is thus inherited from the source, the texture of the sediment at any point in the basin of deposition is the result of several factors. Clean sands normally occur in nearshore high-energy environments whereas clayey beds occur in low-energy environments such as lagoons or deeper waters below wave base. A mixture of clay and well-rounded sand thus constitutes a »textural inversion» and may indicate, in a marine or lacustrine environment, mixing of the products of two energy levels (e.g., barrier and lagoon) by either normal or storm processes (Folk, 1959, p. 103).

Fluvial processes also produce clayey sands. Yeakel (1962) thought that the Silurian Tuscarora Quartzite in the Central Appalachians is composed of a succession of channel sheet sands deposited by a series of laterally migrating stream systems which were distributed over an area of about 400 by 200 miles; these rocks commonly contain recrystallized detrital matrix as well as rounded quartz, rock fragments, and feldspar, and a multicycle derivation from earlier sandstones was suggested. Widespread clayey immature sands in the Upper Triassic Chinle Formation in southwestern United States have also been assigned a fluvial origin (Stewart, 1961). Deltaic clayey sands are evidently common along recent coastlines.

Modern clayey sands occur on the Guiana Shelf (Nota, 1958, p. 79). Doeglas (1950, in Kruit, 1955, p. 396) has noted clayey well-sorted sands in tidal flat deposits, and Kruit (1955, p. 458) reported clayey sands near the mouth of the Rhone River. Probably the most intensively studied modern environment which in a general way compares with that which may have existed during deposition of the Jatulian sediments is the Gulf of Mexico. (However, the Pleistocene-Recent history of sea level change and the high clay and silt load of the Mississippi River — Russell and Russell, 1939 — may mean that the Gulf is an atypical environment.) The framework consists of a broad open basin, a large hinterland, shallow water, and a strong prevalence of depositional over tectonic features (Van Andel and Curray, 1960). Waves and longshore currents have resulted in separation of the sand and clay in much of the area, but clayey sands are present in the marginal zone of the Mississippi Delta where marine processes are subordinate and burial is more rapid (Van Andel and Curray, 1960, p. 353), in bays of the Central Texas coast where mixing and deposition of sands from barriers and clay from the rivers occurs (Shephard and Moore, 1960, p. 117), and in the »non-depositional facies» of the shelf where mixing is common (Van Andel, 1960, p. 54; Van Andel and Curray, 1960, p. 353). Half of the surface sediments of the northwest Gulf of Mexico are polymodal mixtures, with the mixing accomplished by burrowing organisms, producing irregularly interlayered and mottled sands and muds, and by bottom currents and strong wave action associated with storms, producing a more homogeneous mixture (Curray, 1960, p. 221 and 236). Sand barriers several miles wide, with muddy sediments on both sides, fringe much of the northern Gulf of Mexico; both longshore currents and local wave action seem to be important in their formation (Shepherd, 1960, p. 197 and 214). Shepherd also pointed out the common present-day worldwide occurrence of barriers along coastal lowlands with numerous estuaries and active sedimentation, particularly on the flanks of large deltas, and suggested that barriers may have been common in the past as well.

Several characteristics of the Jatulian quartzites suggest that they were deposited in a marine rather than a fluvial or lacustrine environment: (1) They form a relatively thin sheet over a wide area. (2) Channels or argillaceous channel plugs are not present. (3) Most of the cross-bedding is the planar or simple type rather than the trough type which might be expected to be more common in fluvial environments. (4) The cross-bedding pattern shows two main current directions, one perhaps normal to the shoreline and one parallel to it, whereas a fluvial or deltaic pattern would probably show a more even distribution of cross-bedding dip directions over a portion of the compass, as noted by Yeakel (1962). (5) Locally the quartzites are overlain by dolomite, as north of Lake Ladoga (Metzger, 1924; Timofejev, 1955; Kharitonov, 1960) and at Kuopio (Preston, 1954); a quartz sand-carbonate association is characteristic of a widespread shallow marine environment (Pettijohn, 1957, p. 612).

Data on the Jatulian sands are inadequate to resolve their complete sedimentary history; the conclusions are necessarily tentative. Possibly the clayey sands were produced by a slow marine advance over a lowland coast, along which several rivers supplied abundant sand-clay sediment derived from the weathered and peneplaned landmass. Wave and current action in the shallow sea and wind action on beaches and barriers would have reworked and winnowed the sediment, imparting a more advanced maturity to the sediment which may have already been abraded by eolian processes on the barren landmass. Thorough mixing of clayey and sandy facies by high-energy waves and currents in some areas (e.g., Kiihtelysvaara and Paukkajanvaara) and incomplete mixing in other areas (e.g., Kallinkangas, Ounasvaara, and Vuokatti) may have followed. The burrowing activity of organisms cannot be safely called upon as an important factor in reworking because of the great antiquity of the deposits.

Perhaps comparisons with modern environments are only partially valid; the conditions during deposition of the Jatulian sands more than 1800 million years ago were quite different from those prevailing today. As eolian abrasion was probably an important process (at least seasonally) over much of the vegetation-free, sediment-supplying landmass, the production of clayey, well-rounded mature sands and their subsequent dumping by streams into a rapidly transgressing sea in which sorting would have been inhibited may have been commonplace and may have produced a great thickness of clayey sands.

Compaction of the clayey matrix and local precipitation of minor silica and carbonate in some units (Fig. 27 and Metzger, 1924, p. 26) resulted in lithification of the argillaceous sands.

The presence of carbonate-rich strata simply signifies a lack of clastic sediments. Streams draining the low-lying landmass during Late Jatulian time may have carried calcium and clay rather than quartz sand, or perhaps carbonates and clayey beds were being deposited in the study area at the same time as quartz sands were being deposited further east in the transgressing sea.

The Jatulian transgression with its resultant quartzose sandstones seems to have been a pre-geosynclinal peneplanation stage, followed by the deposition of a great thickness of immature geosynclinal-type sediments to the west (Simonen, 1960 a, p. 9). These geosynclinal-type sediments have not been found in East Karelia (Simonen, 1960 b, p. 148), presumably due to non-deposition. A period of volcanism evidently began soon after the deposition of the quartzites (Härme, 1949; Preston, 1954, p. 56) as might theoretically be expected in the early stages of geosynclinal development (Turner and Verhoogen, 1951, p. 201). Intense orogenic activity (intrusion and metamorphism) followed the deposition of the geosynclinal-type sediments.

RELATIVE AGES OF THE QUARTZITES

Suggestions have been made that not all of the Karelian quartzites are the same age, and older mapsheets show both Jatulian and younger Kalevian

Fig. 28. »Quartzite-pebble conglomerate» along road at Timovaara. The pebbles have been previously interpreted as detrital Jatulian quartzite pebbles. However, relationships in the area suggest that they may be a result of shearing of thin quartzite beds in argillaceous material. See Fig. 29.

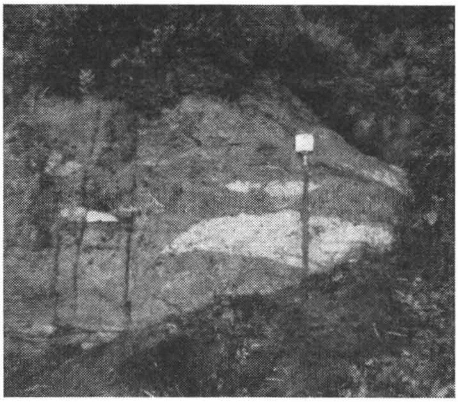


Fig. 29. »Quartzite pebbles» at Timovaara, stratigraphically above those of similar origin in Fig. 28. Note elongate angular nature of the »pebbles».

quartzites. Quartzites at Timovaara (Väyrynen, 1939, p. 43), Nilsiä (Wilkman, 1938, p. 168) and some at Kuopio (Preston, 1954, p. 96) have been designated as younger than the main quartzite belt to the east, and Väyrynen (1939) proposed the existence of a major unconformity above the Jatulian quartzites. Väyrynen (1933, 1939) described quartzite pebble occurrences in North Karelia at the top of the Jatulian quartzite sequence which he felt were of Jatulian type and were evidence of this unconformity. The quartzite-pebble conglomerate at Timovaara (Figs. 28 and 29) was investigated in this study. Comparisons of thin sections of both pebbles and stratigraphically higher bedded quartzite were inconclusive. Recrystallization and introduction of K-feldspar has occurred, but it seems likely that these »pebbles» might be a result of shear, either penecontemporaneous with deposition or tectonic, which broke up beds of relatively pure quartz sandstone and rotated the fragments in the argillaceous interbeds. However, quartzite pebbles in post-Jatulian phyllites and schists at Taivalkoski Rapids north of Kemi (Härme, 1949, p. 22) and in the Kumpu-Oraniemi conglomerates which overlie the Jatulian in Lapland (E. Mikkola, 1941, p. 184) quite probably were derived from the Jatulian sandstones.

During the course of this investigation it was hoped that evidence either for or against two ages of quartzites might be uncovered, but neither cross-bedding trends, thin sections, or heavy minerals revealed any diagnostic similarities or differences which could not be explained by variations in metamorphism or current regimen. Eskola (1963) emphasized that an almost continuous zone of quartzite follows the irregular quartzite-basement boundary line from the Koli area to the Kuopio area, and that the quartzites, though strongly tectonized, are similar to the Jatulian type. He further stated (1963, p. 185) that no geologic evidence of a difference in age has been found between the sedimentary formations of Karelia, Kainuu, and Lapland. E. Mikkola (1941, p. 181 and 187) felt that the quartzites of the Kumpu-Oraniemi Series of Lapland are younger than, but conformable and gradational with, the Lapponian (Jatulian) quartzites.

However, one paleogeographic observation can be made. The cross-bedding trend implies that the foreland lay, in general, to the east or northeast. Therefore, deeper water (that which eventually received geosynclinal sediments), rather than another landmass, would have been located to the west of the quartzite belt of southern and central Finland. The crystalline basement to the west would thus have been covered by sediment early in the eastward transgression of the sea; a younger quartzite would then necessarily have been derived from the east, as were the Jatulian quartzites. If a younger quartzite is present, it should then be manifested as a second quartzite belt situated west of the westward-dipping quartzite belt of central and southern Finland and also be expressed in East Karelia; this, however, is not the case. Furthermore, at the western quartzite localities of Sotkuma and Kuopio, for example, the quartzites rest on the gneissic basement and it must be concluded that these quartzites are very likely correlative with the main quartzite belt to the east which also overlies gneissic basement.

An eastward-transgressing sea infers that the westernmost quartzites (e.g., at Kuopio) are somewhat older than those to the east, deposited before the sea reached as far as the main outcrop belt; however, they are lithologic facies equivalents and for general purposes they can all be considered about the same age. The formation of the quartz-rich sands required a certain environmental framework which existed through a limited span of geologic time, and when this framework changed with the advent of geosynclinal conditions, quartz-rich sands were no longer formed. That is, even if two quartzites are present, they would have formed as a result of the same environmental conditions and their difference in age would be, geologically speaking, of little consequence.

8 6443—64

METAMORPHISM AND METASOMATISM

The grade of metamorphism in rocks of eastern and central Finland increases from east to west (Simonen, 1960 b, p. 151; Eskola, 1963). There is a notable lack of abundant minerals diagnostic of metamorphic grade in the quartzites and interbedded schists, but the accessory minerals provide some evidence. Most of the mineral assemblages from the studied areas contain epidote minerals and hornblende, and commonly sillimanite and/or diopside (Table 3). In many samples, biotite also occurs with these minerals. At Ounasvaara, cordierite occurs in sample OV-24 with biotite, hornblende, and epidote minerals; almandine garnet and biotite are present in sample OV-19 and OV-21, and plagioclase (An_{30-40}) is abundant (Table 2). Kyanite occurs at Koli. These minerals and assemblages are suggestive of the amphibolite facies (Ramberg, 1952). The general paucity of chlorite may rule out the greenschist facies.

K-feldspar metasomatism in the form of microscopic microcline veinlets and irregular, microcline patches was noted in quartzite samples from Kallinkangas, Ounasvaara, Vuokatti, and Timovaara (Table 2). At the latter two localities, some samples contain up to 10 percent introduced microcline. Pegmatite and quartz veins, typical of the Karelian belt, are rather closely associated with these units (Fig. 3).

Fluorine redistribution is suggested by the abundance of large, irregular apatite grains in the quartzites (see Apatite, p. 39).

The abundance of angular idiomorphic unabraded prisms of tourmaline in the quartzites and related rocks, its presence at all studied localities, and numerous references to it in the literature on the Karelian belt, suggest that boron redistribution was a widespread process during metamorphism of the Jatulian sandstones. The variations in color of the prisms from locality to locality, within individual samples, and even within single prisms, indicate slight variations in composition. The dominant green and pink varieties suggest an alkali plus lithium composition (Deer and others, 1962, p. 313), with the green color possibly due to ferrous iron.

Argillaceous sediments may contain sufficient B_2O_3 to form tourmaline in mica schists; the clayey fraction of the Jatulian sands and the clayey in-

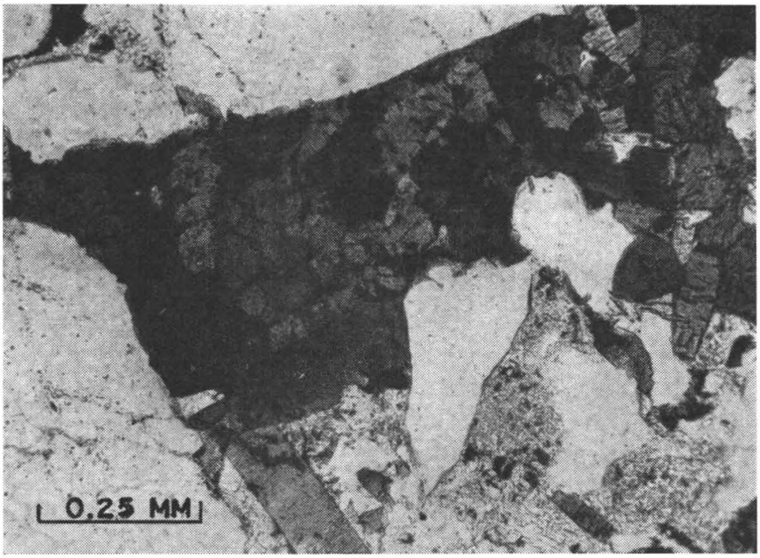


Fig. 30. Tourmaline in thin section of quartzite sample 520/43 from Koikari, East Karelia, collected by Tuominen in 1943. The introduced tourmaline occurs in masses near intrusive diabases (Tuominen, 1943). Quartz grains and sericitic matrix comprise the rest of the field. Plane polarized light.

terbeds are thus possible sources. A comparison of Tables 2 and 3 shows that in at least some cases (as at Kivalo), there is a direct relationship between the percentages of mica (orginally clayey matrix) and tourmaline; however, the very high mobility of boron would probably allow local movement of boron from bed to bed. Another possibility is that the boron may have been remobilized from detrital tourmaline grains; this would also partially explain the crystals with rounded cores (Fig. 20) and the lack of detrital tourmaline in the heavy mineral residues.

The boron in metamorphosed sediments may also be introduced by intrusive igneous activity, as suggested by Hutton (1939) in a study of New Zealand schists. Turner and Verhoogen (1951, p. 491) noted more boron metasomatism and tourmalinization in areas of more intense granitization near granite intrusions, and Brammal and Harwood (1925) showed that as crystallization of the Dartmoor granite proceeded, the magmas became enriched in boron. Ramberg (1952, p. 254), however, felt that tourmaline-bearing pegmatites can be a result of metamorphic differentiation. Pegmatite and quartz veins are abundant throughout the quartzite belt; in this investigation they were noted in the field at Vuokatti, Kallinkangas, and Ounasvaara, and introduced microcline was also noted in thin sections from these localities. Heavy mineral residues from these same localities contain high percentages of tourmaline, and the samples with the highest tourmaline contents are situated relatively close to pegmatite veins (Table 3; Fig. 3). Furthermore, Vuokatti and Ounasvaara are located in areas of granite intrusions which possibly could have supplied the boron or assisted in its mobilization from the sediments. Conversely, veins and introduced microcline were not noted at Kivalo and Paukkajanvaara, where the tourmaline content is low.

A relationship is also apparent between basic sills and lavas of the Karelian belt and tourmaline content of the quartzites. Tourmaline varieties similar to those observed in this investigation were noted by Hackman and Wilkman (1929, p. 65) in cavities of pillow lavas and in the matrix of Karelian conglomerates. Tuominen (1944, p. 23) reported higher tourmaline concentrations near intrusive contacts with diabase (Fig. 30); Koikari sample 520/43 of this investigation was collected by Tuominen. Tourmaline was also reported by Wilkman (1921, p. 82) in metabasalts, by Eskola (1925, p. 55) in veins in East Karelia, by Härme (1949, p. 13) in greenstones near Kemi, and by Meriläinen (1961, p. 8) in veins associated with albite diabases and albitites of Lapland.

Tourmaline crystals in the quartzites are commonly fractured (Fig. 18), with particles sometimes no longer in contact with each other. This was also noted by Berghell and Hackman (1923), Hackman and Wilkman (1929), and Härme (1944). Thus, some deformation took place after the crystals had formed. However, the prisms are frequently aligned parallel to the micas and at Ounasvaara and Vuokatti also have a lineation parallel to the assumed tectonic b-axis, indicating that the crystals probably formed while the rock was being subjected to the main period of deformation.

In conclusion, the tourmaline content may be related to (1) pegmatites and metasomatism, (2) basic igneous activity, or (3) the boron content of the argillaceous fraction of the Jatulian sediments and/or the tourmaline content of these sediments. Further work is necessary to resolve this question.

DEFORMATION

Wegmann (1928, in Preston, 1954) stressed an alpino-type folding in the Karelian belt, recognizing a succession of nappes dipping steeply to the west and separated from each other by major faults. Väyrynen (1939) postulated that nearly horizontal nappes up to 60 km wide in southeastern Finland overrode these older nappes from the northwest, and cited as evidence the curved strike of the phyllite area and the absence of basal conglomerates at many places due to shearing out. However, he also mentioned the far simpler possibility of nondeposition as an explanation for the absence of conlomerates. There is, however, no doubt that the contact between the Karelian formations and the basement is a highly sheared zone; in this investigation, both field and petrographic observations show that the lower samples from Kivalo, Kallinkangas, Paukkajanvaara and Kiihtelysvaara (Figs. 31 and 32) are more highly sheared and more schistose than stratigraphically higher samples with similar mica contents, and the literature on the Karelian belt of both Finland and East Karelia contains numerous references to evidence of movement on the contact between the basement and the Karelian units.

Unrecrystallized (cataclastic) and recrystallized tectonites are both represented in the Jatulian quartzites, the former at Kallinkangas, Kivalo, Paukkajanvaara, Kiihtelysvaara, and East Karelia (Figs. 31—36). Recrystallization occurred at Ounasvaara, Vuokatti, and in the Kuopio area (Table 2; Figs. 15, 37, and 38), and was probably a result of the increased heat and solutions associated with nearby granite intrusions.

Deformational features of quartz were studied and tabulated from 20 randomly selected grains in each of 48 thin sections (Table 6); the mica percentage (from Table 2) represents the original clayey matrix which would have been a factor in the deformation of associated quartz grains. The five localities with unrecrystallized quartzites were ranked in order of decreasing amount of matrix, and compared with their rank based on the abundance of the individual deformational features. A good direct correlation exists between the percentages of matrix and non-undulose quartz grains. Thus the development of undulosity, the first and most easily formed step in the sequence of quartz deformation (Hietanen, 1938, p. 111), seems to be influ-

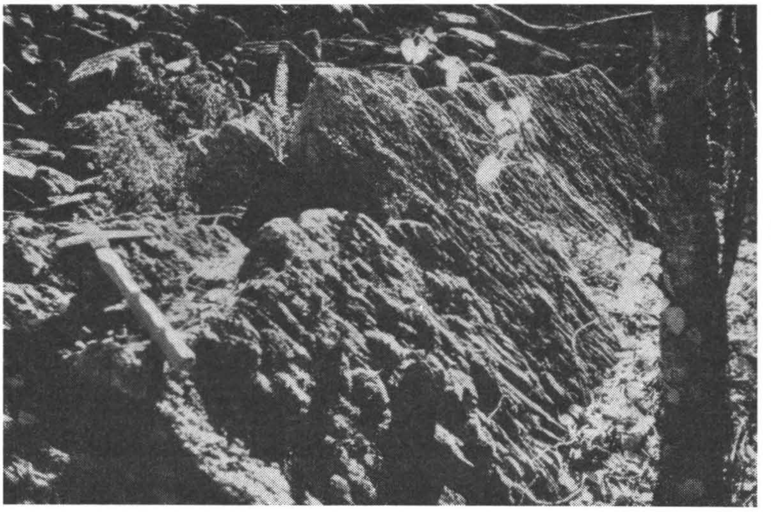


Fig. 31. Highly sheared quartzite in lower part of the quartzite section on the Kivalo Ridge. One thick bed is visible amid field of quartzite boulders, with the bedding trending from lower left to upper right.

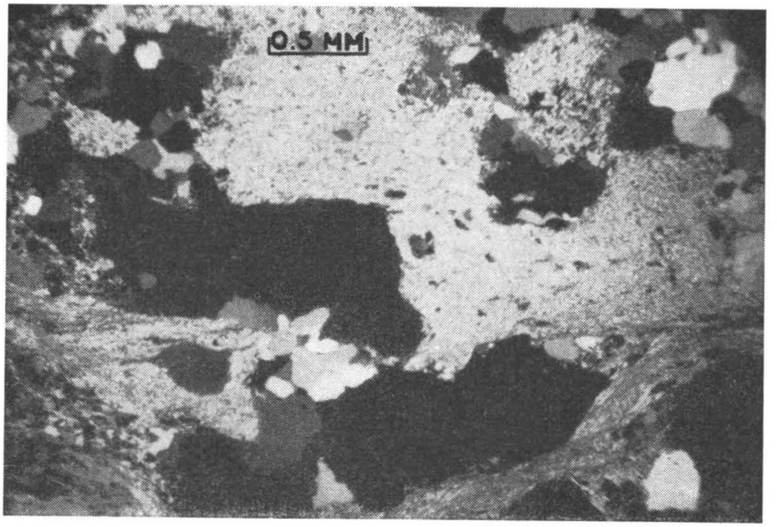


Fig. 32. Photomicrograph of sample PV-3 from the Paukkajanvaara section. Note the highly sheared quartz, the tails on some quartz grains and the abundant sericitic matrix. Crossed nicols.

Table 6. Summary of deformational features of quartz grains in the Jatulian quartzites.

Locality	No. of samples	Ave. % mica (Matrix)	Percentages of quartz grains (20 per sample) which display deformational features						
			Undu-losity	Crush bound-aries	Frac-tured	Tails	Elong-ation	Needles	Lamel-lae
Ounasvaara	8	16	35	0	6	0	43	6	0
Kivalo	4	12	76	80	14	11	6	7	8
Kallinkangas	12	20	61	52	9	3	6	2	8
Vuokatti	8	18	17	0	0	0	17	0	12
Paukkajanvaara ...	6	23	63	40	31	25	32	25	6
Kiihtelysvaara	7	11	87	45	34	1	11	2	1
East Karelia	3	14	72	33	8	0	8	7	0

enced by the matrix which evidently acted as a cushion against weak deformation but which had little effect on stronger deformation, as evidenced by the poor correlations of matrix with the amounts of crush quartz, fractures, lamellae, needles, elongation, and orientation. Argillaceous matrix was also pointed out by Hase (1957) as in inhibiting factor on recrystallization of quartz grains in Upper Huronian (Precambrian) quartzites of Michigan.

Undulose extinction in quartz grains is very abundant in the unrecrystallized quartzites but was also present in the recrystallized samples. The samples from Kiihtelysvaara and East Karelia, areas which apparently underwent less deformation than the other studied areas, contain high amounts of undulose quartz grains, verifying that undulosity can form during mild deformation. In the samples from East Karelia (Figs. 14 and 27), the undulosity of some grains was clearly inherited from the source rock.

Deformation lamellae in quartz, an indication of direct componental movements (Turner and Weiss, 1963, p. 364), were noted in half of the thin sections. They are most abundant at Vuokatti, Kallinkangas, and Kivalo, and least important in unrecrystallized tectonites from Kiihtelysvaara and East Karelia and in the recrystallized tectonites of Ounasvaara (Table 6).

Needle-like units evidently due to fine sets of subparallel cracks developed parallel to the c-axis, commonly occur with and parallel to zones of undulose extinction in quartz grains of the unrecrystallized quartzites. Fellows (1943) felt needles were a late deformational stage between crush quartz and recrystallized quartz; however, their association with zones of undulose extinction in well-rounded, uncrushed grains in the Jatulian quartzites suggests that they formed before crushing. »Selective shattering» of quartz grains (Fellows, 1943), resulting in tails of crushed quartz and fine mica and an even-grained polygonal texture, are present in some unrecrystallized samples (Fig. 32). Grain elongation is most evident in the recrystallized quartzites, but has

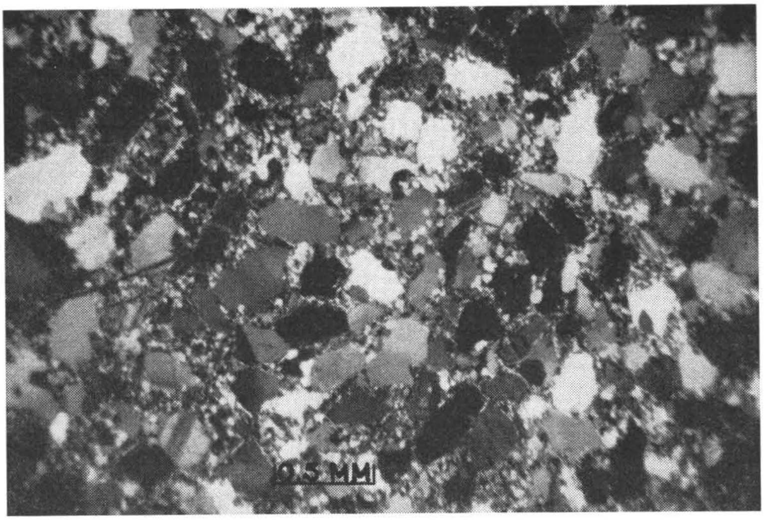


Fig. 33. Photomicrograph of quartzite sample KK-8 from Kallinkangas. Note cataclastic contacts between grains, evidenced by fine crushed quartz. Rounded feldspar and sericitic matrix comprise the rest of the field. Bedding is horizontal in photo. Crossed nicols.

also been formed by shear in unrecrystallized samples. Grains with crushed borders (Fig. 33) are more common than fractured grains.

Orientation of grains, probably a result of granulation and grain rotation, was noted at Kallinkangas (Fig. 34). Obvious optical orientation of quartz grains was noted only in sample OV-H, a coarse recrystallized quartzite near concordant quartz and pegmatite veins. However, a petrofabric study would probably reveal further statistical optic orientations of the quartz lattices; Hietanen (1938) and Preston (1958) noted optic orientation of quartz in quartzites at several localities in eastern Finland. The absence of such a preferred orientation could be attributed to post-tectonic crystallization, under essentially hydrostatic stress (Turner and Weiss, 1963, p. 432).

In the unrecrystallized quartzites, feldspar has survived the deformation with few visible effects (Fig. 35). The original bedding of the quartzites is generally quite well-preserved, and the perfect preservation of cross-beds at Kivalo and Vuokatti, for example (Figs. 7 and 10), is somewhat remarkable in view of the shearing and recrystallization which the rocks at these localities have been subjected to.

Väyrynen (1939) postulated a second period of deformation for eastern Finland, and Hietanen (1938) and Preston (1958) noted petrographic evidence of this. Minor deformation of quartz grains in the completely recrystallized Ounasvaara and Vuokatti sections (Table 6), and cracked metamorphic tour-

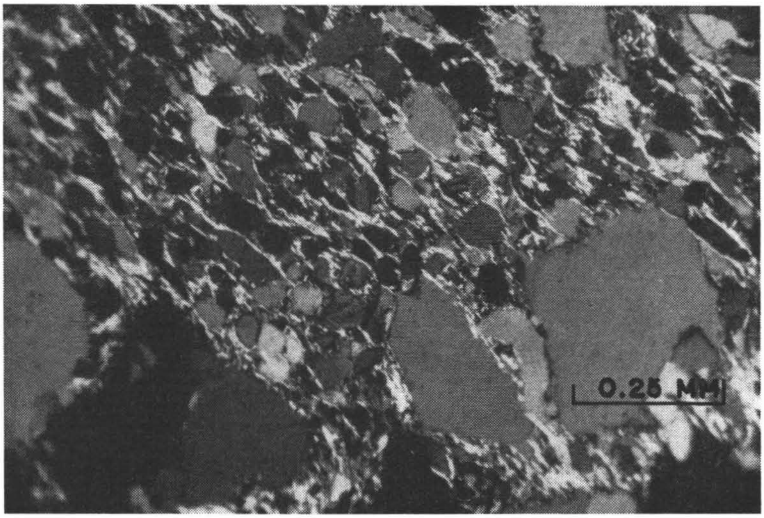


Fig. 34. Photomicrograph of quartzite sample KK-12 from Kallinkangas, showing bedding (horizontal in photo), mica orientation at about 45° to the bedding, and very crude dimensional orientation of the grains. Crossed nicols.

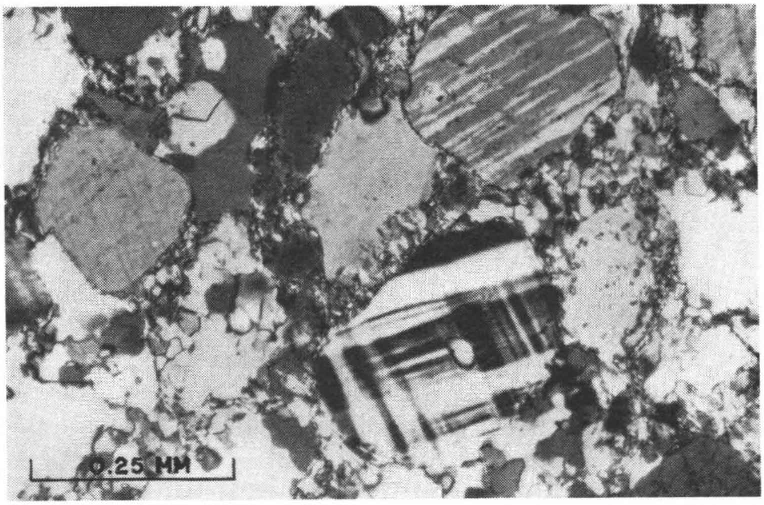


Fig. 35. Photomicrograph of quartzite sample KK-8 from Kallinkangas, showing well-rounded, non-deformed feldspar grains amid highly crushed quartz grains. Note press-solution of quartz at contact of some feldspar and quartz grains. Crossed nicols. Photo by Halme.

9 6443—64

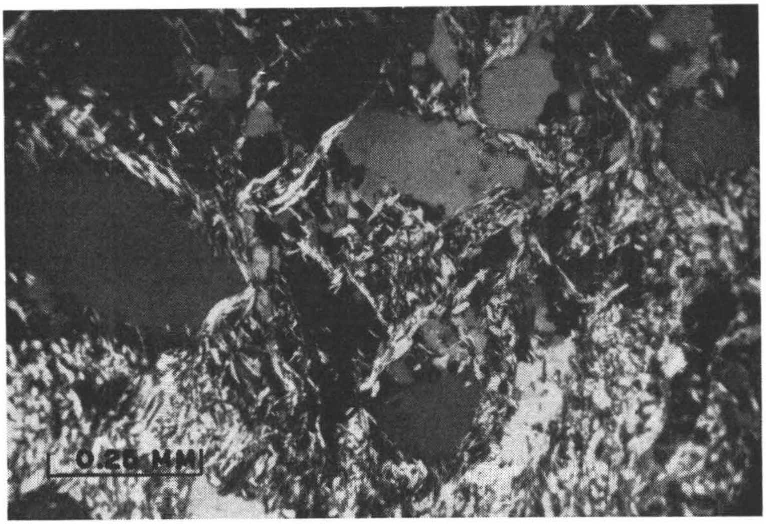


Fig. 36. Photomicrograph of quartzite sample KK-24 from Kallinkangas. Bedding is horizontal in photo. Two mica orientations at 45° to the bedding are present; this is typical of cataclastic quartzites at Kallinkangas, Paukkajanvaara, Kiihtelysvaara, and East Karelia. Crossed nicols.

maline prisms (Fig. 18), also suggest either a second deformation or closing spasms of the original metamorphosing deformation. Turner and Weiss (1963, p. 446) stated that deformation lamellae in quartz (as at Vuokatti) may be due to minor strain in the final phase of deformation.

Schistosity subparallel to the bedding of recrystallized quartzites was noted at Ounasvaara and Vuokatti, whereas transverse schistosity was present at most other localities. The rock samples were not collected with a petrofabric investigation in mind (they are not oriented well enough although all thin sections were cut normal to bedding) but general observations on the fabric, based on microscopic study, are nevertheless possible. There is a remarkable uniformity of mica orientation; in nearly all the unrecrystallized quartzite samples, two s-planes trend at about 45° to the bedding and about 90° to each other (Fig. 36). In the recrystallized quartzites of Ounasvaara and Vuokatti, the primary mica orientation seems to be parallel to the bedding although orientations similar to that in the unrecrystallized quartzites are also detectable (Fig. 15); a lineation of tourmaline prisms parallel to the bedding and normal to the other two mica s-planes is present in a few samples (Fig. 37). Syn- and post-tectonic crystallization of mica is primarily controlled by existing s-surfaces (Turner and Weiss, 1963, p. 442). De Sitter (1956, p. 103) cited the presence of schistosity parallel to bedding in Precambrian rocks, and stated that it may be due to recrystallization of the kind which

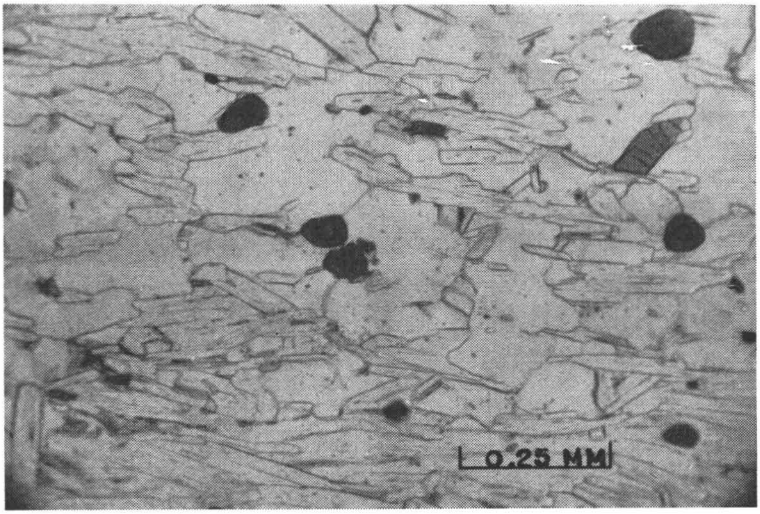


Fig. 37. Photomicrograph of schist sample VK-14 from Vuokatti, showing tourmaline prisms oriented parallel to the bedding which is horizontal in photo. Only the ends of most prisms are visible Note the darker-colored cores. Mica orientations similar to those in Fig. 36 are present but less well developed. Plane polarized light.

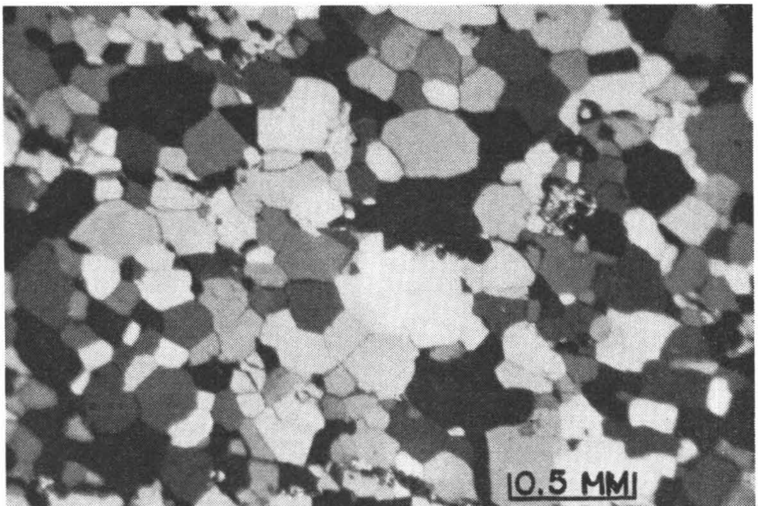


Fig. 38. Photomicrograph of completely recrystallized quartzite from Nilsiä. Very little mica is present. Crossed nicols.

develops on slip planes in concentric folding, augmented by syntectonic intrusion. Shear transverse to bedding seems common in Precambrian rocks with steep dips (Turner and Verhoogen, 1951, p. 560).

The similarity of the mica orientation at all studied localities, regardless of strike of the beds, seems to indicate at least a partial common genesis of the mica at all localities. A simple horizontal compression could theoretically result in pure shear with two sets of shear planes developing at about 90° to each other and each oriented about 45° to the bedding. Whether the mica orientation parallel to bedding at Ounasvaara and Vuokatti could be a result of flexural slip due to the same compression is difficult to say; perhaps doming related to intrusion is a factor. Turner and Weiss (1963, p. 125) noted that intersecting foliations are not necessarily of different ages, and cited the case of closely spaced slip surfaces which develop between widely-spaced conjugate slip surfaces. In only one sample (KK-28) was the mica of one s-plane clearly later than the mica of the other s-plane.

The observations thus seem to suggest compressive forces in general acting toward the east (toward the craton) and creating large north-south trending folds and two cleavages, but varying in direction (as in the north) and complicated somewhat by other mechanisms which may or may not have been contemporaneous.

CONCLUSIONS

1. Erosional remnants of Jatulian quartzites are present at widely-separated points in southeast, central, and northern Finland, as well as in East Karelia (U.S.S.R.) and northern Norway and Sweden. The original Jatulian sandstones once covered an area of more than 400.000 km^2 and attained thicknesses of several hundred meters.

2. Cross-bedding analyses indicate that the major current movement in the Jatulian Sea of Finland was toward the west-northwest, with a secondary but prominent current movement toward the south-southwest. This trend is evident at several individual localities as well, indicating that a similar current regimen existed over a wide area in the shallow epicontinental sea.

3. The Jatulian sandstones were deposited on the crystalline basement and locally upon fluvial (?) Sariolian conglomerates which occupied depressions on the peneplaned surface. The pre-Jatulian surface was evidently a tectonically stable peneplain characterized by deep but incomplete chemical weathering which yielded altered feldspar, unit and polycrystalline quartz, and clay. Fresher feldspar in the formation may have been derived from monadnocks or from local deep erosion into unweathered rocks; however, thick arkosic units overlying the quartzites at Koli and Paukkajanvaara may be evidence of initial folding or faulting on the flanks of the geosyncline which developed to the west of the present quartzite belt.

4. The available information on the Jatulian sands is inadequate to resolve the complete sedimentary history; the conclusions are necessarily tentative The transgressing Jatulian Sea extensively reworked these residual, probably wind-abraded products, as well as more abundant similar detritus supplied by streams draining the landmass to the east, further reducing their feldspar content and further rounding the quartz and feldspar grains. Most reworking seems to have occurred at Ounasvaara and Vuokatti and in some portions of other sections. The quartzites contain appreciable amounts of mica, mainly sericite, which is interpreted as the metamorphosed clayey matrix of the original sandstones. The clay was probably carried in with the sand, separated by current and wave action, and then again mixed with sand prior to burial. However, if all the rounding of the grains was accom-

plished by wind abrasion on the vegetation-free landmass, it is possible that sorting was minimal and that a more rapid burial occurred.

5. The source rocks were mainly granitic (microcline-bearing) with indeterminate proportions of granites and gneisses. Zircon varieties indicate the presence of both para- and orthogneisses, with the former the most important. The source area also contained minor amounts of vein quartz, quartzites, amphibolites, and metavolcanics.

6. Minor K-feldspar metasomatism of the quartzites, evidenced by microscopic stringers and patches of microcline, was noted at several localities. Metamorphic activity produced several accessory heavy minerals, notably tourmaline and apatite. Some of the minor heavy minerals verify that the quartzites were formed under conditions of the amphibolite facies with the degree of metamorphism increasing from east to west.

7. The quartzites at Ounasvaara, Vuokatti, and in the Kuopio area are completely recrystallized, perhaps due to the proximity of granitic intrusions. The quartzites at Kallinkangas, Kivalo, Paukkajanvaara, Kiihtelysvaara and East Karelia are cataclastic in texture, showing extensive shear but little recrystallization. Mica orientation is similar in most samples, with mica on two s-planes formed at about 45° to the bedding and at about right angles to each other. Shear was strongest in the lower portions of the quartzite formation.

REFERENCES

ALLEN, J. R. L. (1963 a) Asymmetrical ripple marks and the origin of waterlaid cosets of cross-strata. Liverpool and Manchester Geol. J., Vol. 3, pp. 187—236.

—»— (1963 b) The classification of cross-stratified units with notes on their origin. Sedimentology, Vol. 2, pp. 93—114.

BERGHELL, H. and HACKMAN, V. (1923) Der Quartzit von Kallinkangas, seine Wellenfurchen und Trockenrisse. Bull. Comm. géol. Finlande 59.

BLATT, H. and CHRISTIE, J. M. (1963) Undulatory extinction in quartz of igneous and metamorphic rocks and its significance in provenance studies of sedimentary rocks. J. Sedimentary Petrology, Vol. 33, pp. 559—579.

BRAMMAL, A. and HARWOOD, H. (1925) Tourmalinization in the Dartmoor Granite. Min. Mag., Vol. 20, pp. 319—330.

BUTTERFIELD, J. A. (1936) Outgrowths on zircon. Geol. Mag., Vol. 73, pp. 511—516.

CUMMINS, W. A. (1962) The greywacke problem. Liverpool and Manchester Geol. J., Vol. 3, pp. 51—72.

CURRAY, J. R. (1960) Sediments and history of Holocene transgression, Continental Shelf, Northwest Gulf of Mexico. *In* Recent Sediments, Northwest Gulf of Mexico. (API project 51), Am. Assn. Petroleum Geologists, Tulsa, Oklahoma, pp. 221—266.

DEER, W. A., HOWIE, R. A., and ZUSSMAN, J. (1962) Rock forming minerals. Vol. 1., Longman, Green, and Co., London.

ECKELMANN, F. D. (1962) Zircon paragenesis in Precambrian crystalline rocks of the Teton Range, Wyoming (Abs.). Geol. Soc. America, Abstracts for 1962, p. 143.

ESKOLA, P. (1925) Petrology of eastern Fennoscandia. Fennia 45, pp. 1—92.

—»— (1932) Conditions during the earliest geologic times as indicated by the Archean rocks. Ann. Acad. Scient. Fennicae, Ser. A, 36.

—»— (1948) Über die Geologie Ost-Kareliens. Geol. Rundschau, Bd. XXXV, 2, pp. 154—165.

—»— (1963) The Precambrian of Finland. *In* The Precambrian, edited by Kalervo Rankama; Vol. 1. Interscience Publishers and John Wiley and Sons, New York.

ESKOLA, P. and NIEMINEN, E. (1938) The quartzite area of Tiirismaa near Lahti. Bull. Comm. géol. Finlande 123, pp. 31—45.

FELLOWS, R. E. (1943) Recrystallization and flowage in Appalachian quartzites. Bull. Geol. Soc. America, Vol. 54, pp. 1399—1432.

FOLK, R. W. (1954) The distinction between grain size and mineral compositions in sedimentary rock nomenclature. J. Geol., Vol. 62, pp. 344—359.

—»— (1959) Petrology of sedimentary rocks. Hemphills, Austin, Texas.

GAFAROV, F. A. (1961) Structure of the Precambrian basement in the northern part of the Russian platform. Izvestiya of the Academy of Sciences of the USSR, Geologic Series No. 1, English translation by the Am. Geol. Inst., pp. 46—57.

GILBERT, C. M. (1955) *in* Petrography, by H. Williams, F. J. Turner and C. M. Gilbert; W. H. Freeman and Co., San Francisco.

HACKMAN, V. (1910) Pre-Quaternary rocks, Sheet C 6, Rovaniemi. General Geological Map of Finland, 1 : 400 000. Helsinki.

—»— (1918) Vuorilajikartan selitys C6 — B5 — B6, Rovaniemi — Tornio — Ylitornio. General Geological Map of Finland, 1 : 400 000. Helsinki.

HACKMAN, V. and WILKMAN, W. W. (1929) Kivilajikartan selitys D6, Kuolajärvi. General Geological Map of Finland, 1 : 400 000. Helsinki.

HÄRME, M. (1944) Karjalaisista muodostumista Tsobinan-Kumsan alueella. Pro Gradu Thesis, Univ. of Helsinki.

—»— (1949) On the stratigraphical and structural geology of the Kemi area. Bull. Comm. géol. Finlande 147.

HASE, D. H. (1957) Upper Huronian sedimentation in a portion of the Marquette Trough, Michigan. J. Geol., Vol. 65, pp. 561—574.

HAUSEN, H. (1930) Geologie des Soanlahti-Gebietes im südlichen Karelian. Bull. Comm. géol. Finlande 90.

HIETANEN, ANNA (1938) On the petrology of Finnish quartzites. Bull. Comm. géol. Finlande 122.

HUBERT, J. F. (1960) Petrology of the Fountain and Lyons Formations along the Colorado Front Range. Colorado School of Mines, Quart. Bull., Vol. 55, No. 1.

—»— (1962) A zircon-tourmaline-rutile maturity index and the interdependence of the composition of heavy mineral assemblages with the gross composition and texture of sandstones. J. Sedimentary Petrology, Vol. 32, pp. 440—450.

HUTTON, C. O. (1939) The significance of tourmaline in the Otago Schists. Royal Soc. New Zealand, Trans., Vol. 68, pp. 599—601.

—»— (1950) Studies of heavy detrital minerals. Bull. Geol. Soc. America, Vol. 61, pp. 635—716.

KELLER, W. D. (1956) Clay minerals as influenced by environments of their formation. Am. Assn. Petroleum Geologists, Bull, Vol. 40, pp. 2689—2710.

KHARITONOV, L. J. (1937) Geologic description of the Chiobino-Pokrouskeye district. XVII Int. Geol. Congress guidebook to the northern excursion (The Karelian ASSR) USSR, pp. 59—77.

—»— (1960) Stratigraphy of the Proterozoic rocks of Karelia, Kola Peninsula, and the adjacent countries of the Baltic Shield and its structural subdivision. Moscow. (XXI Int. Geol. Congress, Russian geologists presentation, Vol. LX, Questions). (Translated to Finnish with English summary by Geol. Survey of Finland.)

KOUVO, O. (1958) Radioactive age of some Finnish Precambrian minerals. Bull. Comm. géol. Finlande 182.

KRUIT, C. (1955) Sediments of the Rhone Delta: I — Grain size and microfauna. Kon. Nederlands Geol. Mijnbouwk Gen. Verhand., Vol. 15, pp. 357—499.

KRUMBEIN, W. C. (1941) Measurement and geological significance of shape and roundness of sedimentary particles. Sedimentary Petrology, Vol. 11, pp. 64—72.

KRYNINE, P. D. (1950) Petrology, stratigraphy, and origin of the Triassic sedimentary rocks of Connecticut. Connecticut Geol. Survey Bull., Vol. 73.

MATISTO, A. (1958) Kivilajikartan selitys D5, Suomussalmi. English summary. General Geological Map of Finland, 1 : 400 000. Helsinki.

MCKEE, E. D. and WEIR, A. W. (1953) Terminology for stratification and cross-stratification. Bull. Geol. Soc. America, Vol. 64, pp. 381—390.

MERILÄINEN, K. (1961) Albite diabases and albitites in Enontekiö and Kittilä, Finland. Bull. Comm. géol. Finlande 195.

METZGER, A. A. Th. (1924) Die Jatulischen Bildungen von Suojärvi in Ostfinnland. Bull. Comm. géol. Finlande 64.

—»— (1959) Svecofenniden und Kareliden; eine kritische Studie. Acta Acad. Aboensis, Math. et Phys. XXI, 16.

MIKKOLA, A. (1943) Paateneen-Selkien ja Maaselän karjalaiset muodostumat. Pro Gradu Thesis, Univ. of Helsinki.

MIKKOLA, E. (1941) Kivilajikartan selitys B7 — C7 — D7, Muonio — Sodankylä — Tuntsajoki. English summary: Explanation to the map of rocks. General Geological Map of Finland, 1 : 400 000. Helsinki.

MIKKOLA, T. (1953) Peruskalliogeologian näköaloja. Geologi, Vol. 5, p. 29.

—»— (1955) Sedimentary transportation in Karelian quartzites. Bull. Comm. géol. Finlande 168, pp. 27—29.

—»— (1960) Sedimentation of quartzite in the Kemi area, North Finland. XXI Int. Geol. Congress, Copenhagen, Pt. IX, pp. 154—161.

—»— (1961) Sediment groups, particularly flysch, of the Precambrian in Finland. Bull. Comm. géol. Finlande 196, pp. 51—65.

NOTA, D. J. G. (1958) Sediments of the western Guiana Shelf. Reports of the Orinoco Shelf Expedition, Vol. II. H. Veenman and Zonen, Wageningen, Netherlands, 98 p.

OJAKANGAS, R. W. (1963) Petrology and sedimentation of the Upper Cambrian Lamotte Sandstone in Missouri. J. Sedimentary Petrology, Vol. 33, pp. 860—873.

PETTIJOHN, F. J. (1957) Sedimentary rocks. 2nd ed., Harper and Bros., New York.

—»— (1962) Paleocurrents and paleogeography. Am. Assn. Petroleum Geologists, Bull., Vol. 46, pp. 1468—1493.

POLDERVAART, A., and ECKELMANN, F. D. (1955) Growth phenomena in zircon of authochthonous granites. Bull. Geol. Soc. America, Vol. 66, pp. 947—948.

POTTER, P. E. and others (1958) Chester cross-bedding and sandstone trends in the Illinois Basin. Am. Assn. Petroleum Geologists, Bull., Vol. 42, pp. 1013—1046.

POTTER, P. E., and PRYOR, W. A. (1961) Dispersal centers of Paleozoic and later clastics of the Upper Mississippi Valley and adjacent areas. Bull. Geol. Soc. America, Vol. 72, pp. 1195—1250.

PRESTON, J. (1954) The geology of the Precambrian rocks of the Kuopio district. Ann. Acad. Scient. Fennicae, ser. A, III, 40.

—»— (1958) Quartz lamellae in some Finnish quartzites. Bull. Comm. géol. Finlande 180, pp. 65—77.

RAMBERG, H. (1952) The origin of metamorphic and metasomatic rocks. Chicago University Press, Chicago.

REYNOLDS, D. L. (1936) Demonstrations in petrogenesis from Kiloran Bay, Colonsay. I. The transfusion of quartzite. Min. Mag. Vol. 24, pp. 367—407.

RUSNAK, D. A. (1957) A fabric and petrological study of the Pleasantview Sandstone. J. Sedimentary Petrology, Vol. 27, pp. 41—45.

RUSSELL, R. J., and RUSSELL, R. D. (1939) Mississippi River Delta sedimentation. *In* Recent marine sediments, edited by Parker Trask, Am. Assn. Petroleum Geologists, Tulsa, Oklahoma, pp. 153—177.

SAKSELA, M. (1933) Die Kieserzlagerstätte von Karhunsaari. Geol. Fören i Stockholm Förh, Bd. 55, pp. 29—58.

SEDERHOLM, J. J. (1932) On the geology of Fennoscandia with special reference to the Precambrian. Explanatory notes to accompany a general geological map of Fennoscandia. Bull. Comm. géol. Finlande 98.

SHEPHARD, F. P. (1960) Gulf Coast Barriers. *In* Recent Sediments, Northwest Gulf of Mexico. (API project 51), Am. Assn. Petroleum Geologists, Tulsa, Oklahoma, pp. 197—220.

SHEPHARD, F. P. and MOORE, D. G. (1960) Bays of Central Texas Coast. *In* Recent Sediments, Northwest Gulf of Mexico. (API project 51), Am. Assn. Petroleum Geologists, Tulsa, Oklahoma, pp. 117—152.

SIMONEN, A. (1960 a) Pre-Quaternary rocks in Finland. Bull. Comm. géol. Finlande 191.

—»— (1960 b) Precambrian stratigraphy of Finland. XXI Int. Geol. Congress, Copenhagen, Section IX, p. 141—152.

SITTER, L. U. de (1956) Structural geology. McGraw-Hill, New York.

STEWART, J. H. (1961) Stratigraphy and origin of the Chinle Formation (Upper Triassic) on the Colorado Plateau. Unpub. PhD thesis, Stanford University, California, 196 p.

TAUBENECK, W. H. (1957) Zircons in the metamorphic aureole of the Bald Mountain Batholith, Elkhorn Mountains, Northeast Oregon (Abs.). Bull. Geol. Soc. America, Vol. 68, pp. 1803—1804.

TIMOFEJEV, T. (1935) Geologie von Karelien. Leningrad. (German translation from Russian. Geol. Survey of Finland).

TUKEY, J. W. (1954) Phi-square test of orientation. Comment # 1A, Earth Sciences Panel Review Group, CSPS-ASA unpub. communication.

TUOMINEN, H. (1944) Koikarin seudun kallioperästä. Pro Gradu Thesis, Univ. Helsinki.

TYNI, M. (1962) Paukkajanvaaraan uraanikaivoksen geologiasta. Geologi, Vol. 14, pp. 24—27.

TURNER, F. J. and VERHOOGEN, J. (1951) Igneous and metamorphic petrology. McGraw-Hill, New York.

TURNER, F. J. and WEISS, L. E. (1963) Structural analysis of metamorphic tectonites. McGraw-Hill, New York.

VAN ANDEL, T. H. (1960) Sources and dispersion of Holocene sediments, Northern Gulf of Mexico. *In* Recent Sediments, Northwest Gulf of Mexico. (API project 51), Am. Assn. Petroleum Geologists, Tulsa, Oklahoma, pp. 34—55.

VAN ANDEL, T. H. and CURRAY, J. R. (1960) Regional aspects of modern sedimentation in the northern Gulf of Mexico and similar basins and paleogeographic significance. *In* Recent Sediments, Northwest Gulf of Mexico. (API project 51), Am. Assn. Petroleum Geologists, Tulsa, Oklahoma, pp. 345—364.

VÄYRYNEN, H. (1928) Geologische und petrographische Untersuchungen im Kainuugebiete. Bull. Comm. géol. Finlande 78.

—»— (1933) Über die Stratigraphie der Karelischen Formationen. Bull. Comm. géol. Finlande 101, pp. 55—78.

—»— (1938) Notes on the geology of Karelia and Onega region in the summer of 1937. Bull. Comm. géol. Finlande 123, pp. 64—80.

—»— (1939) On the geology and tectonics of the Outokumpu ore field and region. Bull. Comm. géol. Finlande 124.

WILKMAN, W. W. (1921) Vuorilajikartan selitys D4, Nurmes. General Geological Map of Finland, 1 : 400 000. Helsinki.

—»— (1938) Kivilajikartan selitys C3, Kuopio. English summary. General Geological Map of Finland, 1 : 400 000. Helsinki.

WINCHELL, A. N. and WINCHELL, H. (1959) Elements of optical mineralogy, part 2. John Wiley and Sons. New York.

WYATT, M. (1954) Zircons as provenance indicators. Amer. Mineralogist, Vol. 39, pp. 983—990.

YEAKEL, L. S., Jr. (1962) Tuscarora, Juniata, and Bald Eagle paleocurrents and paleogeography in the Central Appalachians. Bull. Geol. Soc. America, Vol. 73, pp. 1515—1540.