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The Early Proterozoic glaciogenic and deep weathering geologic record in northern Karelia, eastern Finland

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Academic Dissertation

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Cover: Koli National Park, core of the study area. In front: typical white aluminous quartzite at Ukko-Koli. Photo: the author.

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Early Proterozoic Sariola and Jatuli Groups have been studied in the Koli-Keltimo area that forms the northeastern part of the North Karelia Schist Belt in eastern Finland. The age of the studied sequence can be bracketed between 2.5 - 2.2 Ga. The study confirms the presence of Prejatulian deposits in the area, and, reports glacial deposits and ancient soil formation. In addition, the origin of quartzites, oxidation-reduction of the paleoatmosphere, causes for drastic climate changes and regional correlations have been studied.

Separated from the Archean Basement by a nonconformity, the Sariola Group (thickness 330m) consists of poorly to moderately sorted arkose and conglomerate, with minor siltstone and argillite. The basal units were deposited in alluvial conditions. These were followed by glaciomarine diamictons, silts and muds with dropstones, turbidites, and finally, by glaciofluvial outwash plain deposits. The whole sequence is correlated with the volcanic-sedimentary rocks of Kainuu, northern Finland and Karelia of Russia that formed during the 2.45 Ga rifting. A penecomtempoanous major glaciation for the Karelia Craton is suggested.

The Jatuli sandstone and conglomerate are generally moderately to well sorted varying in their compositional maturity. The basal units (maximum thickness 300m) underlain by quartz-sericite schist consist of a lower aluminous quartzite, an upper conglomerate and quartz conglomerate and quartzite. The quartz-sericite schist (thickness 80m) is interpreted as a paleosol. The original soil developed on both Archean granitoids and Early Proterozoic glaciogenic rock. Relative to its parents, the paleosol is consistently depleted in ferrous iron, sodium, calcium and magnesium. In the uppermost throughly weathered portions, ferric iron and potassium decrease, in some profiles considerably. Silica and alumina constitute nearly all of the uppermost paleosol; alumina reaches 30%. Chemical reduction characterized the weathering, until shortly before the soil became partially eroded and buried.

The overlying aluminous sediments were derived from paleosol and deposited in braided rivers as proximal poorly sorted aluminous detritus and more distal braidplain sediments. The chemical maturity and great thickness of the paleosol and associated sediments record intense chemical weathering under warm and humid climate, comparable to a modern tropical climate. The deep weathering generated enormous amounts of soil consisting of residual quartz and clay that were reworked and deposited as aluminous sediment. Presented evidence strongly favours a single cycle origin for the quartzite. The deep weathering probably spanned the entire area of the Karelia Craton, because other paleosols associated with quartzite in similar stratigraphic position are scattered across eastern part of the Fennoscandian Shield.

The preserved geologic record indicates a drastic climate change, that is, given climatic zoning, in accordance with recent paleomagnetic studies. Also global climate change may have been involved assuming a causal connection between 2.45 Ga magmatic event, major glaciation and green house effect-type deep chemical weathering. The weathering apparently acted as a sink for carbon dioxide and other reactive aerosols released into the atmosphere during magmatic activity.

Key words (GeoRef Thesaurus, AGI): metasedimentary rocks, lithostratigraphy, paleosedimentology, deposition, chemical weathering, glaciation, paleosols, chemical composition, Proterozoic, Koli, Kaltimo, Finland.

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INTRODUCTION

The study area is called Koli-Kaltimo area and located in the north-eastern part of the Early Proterozoic North Karelia Schist Belt. The two lowermost associations of the craton cover sequence have been studied; the Sariola Group, and, the Hokkalampi Paleosol and the related aluminous, quartzitic metasediments of the Jatuli Group. The age of these units can be bracketed between 2500 ma and 2200 ma, which are the U-Pb ages for the Late Archean granitoids and mafic intrusions in the metasediments, respectively.

This study is based on fieldwork and exploration carried out in the study area during 1980 - 1987. Between 1980 - 1984 the Geological Survey of Finland (GSF) investigated a huge aluminum silicate deposit of the Hokkalampi area. This work was followed by a GSF project for evaluation of paleoplacer gold potential (1985 - 1987) of the study area, and, a simultaneous GSF and University of Oulu joint project related to economic geology.

Sedimentological work was mainly carried out as detailed mapping along profiles across the sedimentary sequences. Despite of deformation and metamorphism the primary features of the excellently exposed rocks are generally well preserved. Environmental interpretations for the sedimentary rocks are based on lithofacies associations, whereas for the paleosol, geological setting, and, mineral and chemical compositions of its profiles were the decisive factors.

The study has been presented in the following papers, which papers deal with stratigraphy, sedimentology, composition and environmental interpretations of the lower Proterozoic Sariola and Jatuli Groups in North Karelia, eastern Finland:


REVIEW OF THE PAPERS

Paper 1 is the first description of Early Proterozoic glaciogenic deposits on the Fennoscandian Shield. The interpretation was based on presence of the association of diamictite and dropstone bearing siltstone-argillite having a gradational contact with each other. The unit was named the Urkkavaara Formation, and, as the formation is overlain by a metaregolith which in turn underlies the Jatuli quartzite, the existence of Prejatulian rocks in the area was confirmed. In the previous studies the lowermost (Gaăil 1964, Piirainen 1968) quartzite had been interpreted as basal Proterozoic sedimentary unit.

Within the Urkkavaara Formation, four informal members that grade into each other were described consisting of three depositional facies, as follows: lower siltstone-argillite member, graded sandstone member, upper siltstone-argillite member and diamictite member.

The up to 60 meters thick Urkkavaara Formation was interpreted as glaciomarine sediments and the model of deposition including the interpreted glacial advance and retreat, was presented. Sedimentation was probably the result of suspension fallout,
turbidity currents, and iceberg rafting in front of a grounded or floating glacier. It was tentatively suggested, that if all of the lonestone-bearing units associated with diamictites in Soviet Karelia, that occur in similar stratigraphic position, prove to be glaciogenic deposits, they may indicate an Early Proterozoic, continent scale glaciation.

In Paper 2, the immature metasediments enveloping the Kontiolahti dome in the north were all interpreted as prejatulian, because the rocks were observed to grade upwards into the metaregolith. The rocks were described, the Sariola Group several hundreds of meters thick was established, through defining the formations included. The lower contact of the Sariola group is a well-defined nonconformity. In addition, the metaregolith was reported, preliminary described and named as the Hokkalampi Formation.

The sporadically exposed basal arkoses and conglomerates overlain by the rocks of the Urkkavaara Formation, were named as the Ilvesvaara Formation. The upper contact is poorly exposed and the thickness of the unit is estimated not to exceed 30 metres. The sediments were interpreted as alluvial deposits related to faulting. The mineral composition sediments of the Ilvesvaara resembles that of the local Archean granitoid, and inferred from sedimentological features and contact relations, the rocks of the Ilvesvaara Formation were deposited proximal to their source.

Three new members deposited on the top of the previously described Urkkavaara Formation were defined and included in the formation. The members total up to 200 meters in thickness. The diamictite member was observed to wedge out towards the north through grading into the upper siltstone-argillite member. In the south, the diamictite member and in the north the upper siltstone argillite member were overlain by the upward coarsening upper graded sandstone member, that gradually turned into the parallel-bedded conglomerate member characterized by inverse to normal grading.
Separated by erosional features at its base, the upward fining crossbedded conglomerate member terminated the glaciogenic sequence. The upper graded sandstone and parallel-bedded conglomerate with abundant subaqueous debris flow deposits were interpreted as turbiditic sediments deposits, whereas the crossbedded unit was deposited as glacial outwash during deglaciation. The clasts in the rocks of the Urkkavaara Formation and the chemical composition of the matrix of the diamictite member suggest a source area consisting of felsic plutonic rocks. The previous model of deposition was complemented to be consistent with the presented new observations.

The sedimentary rocks of the Sariola Group grade upwards over 10 to 15 meters into the quartz-sericite schist lacking internal features. The unit is present throughout the study area and invariably underlies the quartzitic rocks of the Jatuli Group. In the main part of the study area where the Sariola sediments are absent, the quartz-sericite schist grade downward also into the Archean Basement. The thickness of the unit varies from less than ten meters in the north to several tens of meters in the south. When thickest, abundance of aluminum silicates features the upper part. In addition to stratigraphic control, the gradual base due to chemical alteration, clear internal zoning reflected by an upward depletion of alkalies and alkaline earths, upward increase of aluminium and high values for the CIA in its upper part, evidenced in favour of soil origin for the quartz-sericite schist.

The paleosol was interpreted to record an intense chemical weathering in warm and humid climatic conditions corresponding to those prevailing today on low latitudes. Thus the succession in the study area implies a drastic climate change. A tentative correlation of the paleosol with other paleosols of similar stratigraphic position on the Fennoscandian Shield was suggested. Excluding a quite similar paleosol in Kainuu, the other paleosols are generally thin, and, show low to medium values for the CIA.

**Paper 3** is a summary of lithostratigraphy and sedimentation of the Jatuli and Sariola Groups in the study area. Relevant for the present paper are the provenance and paleocurrent study, and, the defining of a new, sedimentary unit belonging to the Sariola Group in the northern part of the study area.
The new unit, the **Hattusaari Formation** was correlated with the Sariola rocks in the south. The correlation based on the observation that it grades upward through alteration into the quartz-sericite schist of the paleosol. This 100m thick immature formation consists of a lower matrix-supported conglomerate with abundant pebbles from the adjacent Archean greenschists, a middle orthoconglomerate, and an upper cross-bedded arkosic unit, that grades upward into the paleosol. Within the conglomeratic unit, the pebbles of felsic plutonic rocks become more abundant upward and, finally, in the middle part of the formation, dominant. For the Hattusaari Formation, a proximal alluvial environment related to faulting was suggested. The relation of the Hattusaari Formation to the Urkkavaara Formation in the south is unresolved. However, the upper crossbedded part of the formation resembles in primary features that of the Urkkavaara Formation.

Paleocurrents indicated a general westward transport for the detritus although considerable variation within the solitary units was observed. For the Sariola sediments, a single cycle origin and a source area consisting mainly of felsic plutonic rocks were suggested. A crucial result regarding the origin of the lower Jatuli sediments, the aluminous conglomeratic Vesivaara and quartzitic Koli Formations, was that they were interpreted to have been derived from the underlying regolith and were deposited as continental, fluviatile deposits (see also Kohonen 1987).

**Paper 4** contains a detailed description of the **Hokkalampi Paleosol** called the Hokkalampi Formation in the previous papers. Interpretation was based on chemical and mineral composition of its protoliths, profiles and relation to the overlying aluminous and quartzitic metasedimentary rocks. In the south and north the paleosol forms a "marker bed" separating the Jatuli and Sariola sediments.

The paleosol consists of quartz-sericite schist with an increasing proportion of kyanite and andalusite, sometimes chloritoid toward the top. The original soil had minimum thickness of 80 meters, but is typically much thinner due to erosion prior to burial. The erosion resulted in the deposition of voluminous aluminous sand and gravel, now aluminous quartzite, metaconglomerate and orthoquartzite.
The soil developed on both the Archean granitoids (middle part of the study area) and Sariola glaciogenic rock (in the south and north). The major protolith for the paleosol, the Archean granitoids mainly consist of tonalitic to granodioritic rocks, with minor green schist. The sedimentary protolith, is dominantly arkosic in composition. The CIA values for the protoliths vary between very low and low, indicating a low degree of chemical weathering. Given the granodioritic-tonalitic sources for the arkosite, the prime difference in the chemical compositions is generally less iron, calcium and aluminum, and, more silica in the sediments.

The Hokkalampi Paleosol clearly grades upward from its parent rocks through zones of increasing alteration. Relative to its parents, the paleosol is consistently depleted in ferrous iron, sodium, calcium and magnesium. In the upper, most thoroughly weathered portions, ferric iron and potassium decrease, in some profiles considerably. Silica and alumina constitute nearly all of the uppermost paleosol; alumina reaches 30%. Estimates of the extent of weathering, based on values for the CIA index are low near the bottom, moderate in the middle, and very high at the top. In the overlying sediments, the values for the CIA vary insystematically between moderate and very high. Chemical composition of the Hokkalampi Paleosol resembles that of the modern kaolinitic soils. The premetamorphic minerals are interpreted to have been kaolinite and residual quartz, given the present chemical and mineral composition of both the paleosol and overlying sedimentary rocks.

The Hokkalampi paleosol is chemically reduced where thickest but slightly oxidized where it became eroded near topographic highs. The overlying aluminous sediments lack ferrous iron and contain abundant hematite. Given that hematite formed within the contemporaneous soil, it record oxidation. The ratio uranium/thorium is much higher in the protoliths than in the overlying sediments that may indicate oxidation associated with sedimentation and chemical weathering. Oxidation of primary magmatic uranium mineral erased from the Archean basement and the subsequent mobilization of uranium may explain the absence of uranium paleoplacers in the study area, the other conditions being favourable. Thus, penecontemporaneous oxisol development cannot be ruled out.
Early Proterozoic paleosol underlies quartz-arenite in the Karelides of the Svecofennian Shield both in Finland and in Karelia of Russia. Paleosol in Kainuu, 300 km north of the study area, is several tens of meters thick and similarly consists of quartz-sericite schist with aluminosilicates and chloritoid-rich units. It resembles the Hokkalampi paleosol in that it also developed on sedimentary rock (of glaciogenic features) and is overlain by aluminous quartzite. In Russia, the paleosols are thin but are also composed of quartz-sericite schist. If all the paleosols and associated quartzite of the Fennoscandian Shield are contemporaneous, the entire area of the Archean Craton (400 000 km\(^2\)) must have experienced a prolonged period of intense chemical weathering.

CONCLUSIVE DISCUSSION

The main results of this study are the reporting of the presence of almost 300 meter thick sequence of Sariola rocks, the recognition of glacial deposits and ancient soil horizons underlying the quartzitic rocks in the study area.

The two Early Proterozoic, extraordinary and strikingly different platformal associations i.e. glacial deposits followed by the products of deep chemical weathering (paleosol and associated aluminous sediments) preserved in the geologic record have retained, despite of greenschist facies metamorphism and deformation, their primary features astonishingly well to allow interpretations of conditions during their origination.

Their geological significance has been approached and discussed from the following angles:

- origin of voluminous quartz sands
- as key units in regional correlation and even intercontinental correlation
- oxidation-reduction of the paleoatmosphere
- potential causes for drastic climatic changes.
The Sariola rocks comprise a purely sedimentary sequence, the immature rocks being first cycle sediments. Instability is recorded by fast rate of sedimentation and rapid burial; the Ilvesvaara and Hattusaari Formations were deposited during a faulting stage.

The Urkkavaara Formation represents a result of glacial cycle, because the lower glaciomarine part was formed during glaciation and the upper part deposited during glacial retreat and deglaciation. For the Urkkavaara Formation, no evidence for a contemporaneous faulting exist. However, the basal part of the Ilvesvaara Formation shows features that may be attributed to ice shattering. Consequently, it appears that the entire Sariola sequence may have been formed in a glacially influenced environment associated with faulting.

The thick Hokkalampi paleosol, and the associated supermature sediments record peneplanation, i.e., stability. The prolonged stability in surficial conditions was featured by a warm and humid climate, or, other conditions causing high rate of weathering. Extensive soils consisting mainly of kaolinite and residual quartz were developed. Composition, textural immaturity, and geological setting of the overlying aluminous sediments show a close genetic relationship with the paleosol. A single-cycle origin for these quartz-rich sediments is evident, the sediments being derived from the contemporaneous soils.

The best preserved profiles of the paleosol record chemical reduction, seen as upward depletion of ferrous iron and even ferric iron in some profiles. On the other hand, eroded profiles and proximal aluminous and hematite-rich sediments show oxidation. This might mean that the oxyatmoinversion may have been underway penecontemporaneously with the deep weathering and deposition of the associated sediments. The absence of paleoplacer uranium deposits may be explained by conditions where primary uranium minerals were chemically decomposed with subsequent mobilization of uranium.
The generation of quartz sands through deep, chemical weathering was interrupted by rifting that resulted in the deposition of the arkosite of the Jero Formation, on the tip of the quartzitic sequence and finally, in the mafic magmatism 2.2 Ga ago (Vuollo, Piirainen & Huhma 1992, Kohonen & Marmo, 1992). Given the minimum age of 2.5 Ga for the Archean Basement Complex in eastern Finland, the time span required for the glaciation, deglaciation and the deep weathering was some 300 million years. Kohonen and Marmo also interpret that the preservation of these continental deposits can be explained by the downfaulting of the rifted Jero Basin. For the Sariolan rocks and the paleosol the best preserved sections occur in the south. The glacial rocks may have also been preserved as remnants of fault bounded basin. For the paleosol, the preferential paleosol preservation was localized in areas of relative subsidence that became the sites of braided river plains.

Early Proterozoic glaciogenic rocks as well as numerous remnants of paleosols associated with quartzite of similar stratigraphic position are scattered across the eastern Fennoscandian Shield. Given that they represent, respectively, contemporaneous deposits, the Karelia Craton underwent a period of major glaciation and subsequent deglaciation, and then the craton experienced a prolonged period of intense chemical weathering.

In Kainuu and Karelia of Russia, glaciogenic rocks are underlain by or associated with volcanic-sedimentary deposits. In Finnish Lapland, glaciogenic rocks have not been reported, the lowermost unit being dominantly magmatic. The magmatic event related to rifting has been dated to about 2.44 Ga. In Kainuu, it appears (Laajoki 1991) that glaciogenic events were associated with this rifting. Assuming that the these basal units including those of northern Karelia are contemporaneous, the rifting was craton wide, but in northern Karelia it apparently did not advanced to a stage of magmatism.

Ojakangas (1988) has proposed a term "megaevent" for extraordinary geologic record, such as major glaciations, that may be useful in intracontinental or even intercontinental correlation. The two Early Proterozoic megaevents, glaciation succeeded by deep weathering reported from the study area also record a drastic
climate change. For the Fennoscandian Shield, recent paleomagnetic studies suggest that the shield drifted toward lower, and, given a climatic zoning toward warmer latitudes during the Early Proterozoic. This is in accordance with the studied geological record. We do not, however, know how long time span was involved in the change and whether the climate change was exclusively due to drifting of continent or were also global climatic changes involved.

For the Phanerozoic, there is evidence of global climate changes triggered by extensive volcanism injecting enormous amounts of SO₂ and CO₂ into the atmosphere. Long term changes in the Earth’s climate, with megacycles of about 30 to 300 Ma have been proposed perhaps to be caused by variations in atmospheric CO₂ due to cyclic global tectonism (Rampino 1991, Fischer 1984, Imbrie and Shackleton 1990). For the early Proterozoic, consequently, there may be causal connection between 2.44 magmatic event, major glaciation and "green house effect"-type accelerated deep weathering.

Green house effect and acid rain, caused by effluents from burning of fossil fuels, and their consequences comprise one of the major challenges for today’s natural science. Deep chemical weathering and associated paleosols could be seen as a carbon dioxide sink, and may thus appear a useful research target in gathering reference data to be utilized in climate change studies.

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