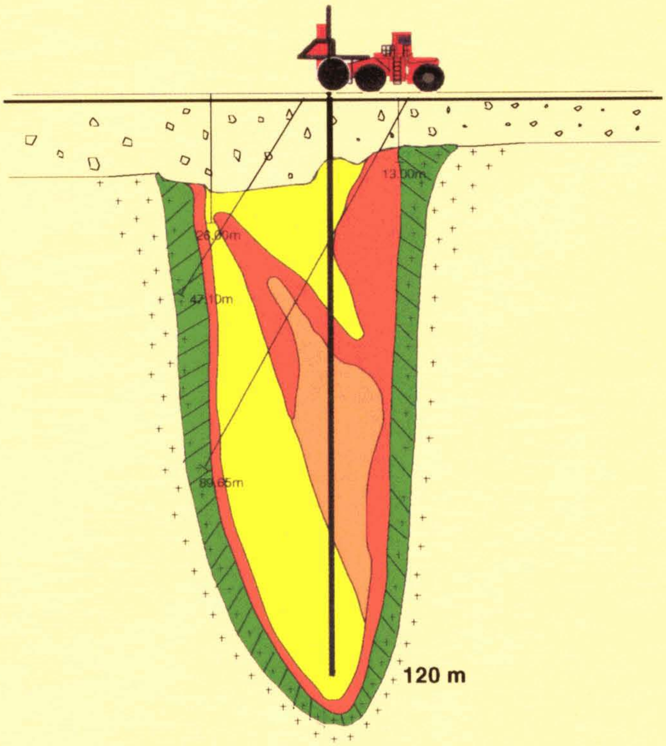
Proterozoic primary kaolin deposits at Virtasalmi, south-eastern Finland

Synopsis

Olli Sarapää



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Cover picture: Cross section of Eteläkylä kaolin deposit.

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by
Olli Sarapää

ACADEMIC DISSERTATION

in Geology and Mineralogy

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Kaolin deposits at Virtasalmi, southeastern Finland, formed as a result from *in situ* chemical weathering of quartz-feldspar gneiss, tonalite, mica gneiss and amphibolite in a warm and humid climate. Potassium-argon dating of authigenic illite from the Litmanen kaolin deposit indicates that the age of kaolinization is 1180 Ma. Further evidence of Proterozoic kaolinization at Virtasalmi was found in the impact structure of Iso-Naakkima, where kaolinitic sediments contain microfossils that lived 650-1000 Ma ago. The sediments lie unconformably on weathered Paleoproterozoic mica gneiss. Based on recent paleomagnetic measurements, Fennoscandia was at or near the Equator during the kaolinization at Virtasalmi.

The kaolin deposits occur, in an area 20 km x 5 km, on the southwestern side of the Raahe-Ladoga Zone. The bedrock comprises Svecofennian schists and plutonic rocks (ca. 1900 Ma). The erosion surface of the kaolin deposits is 77-93 m a.s.l., below a 20-30 m thick Quaternary overburden. The individual kaolin deposits are 0.5-2 km long and 50-400 m wide and the thickness of the deposits is usually 30-40 m, 100 m at most. The fractures, joints, structures and lithology of bedrock control the occurrence and quality of kaolin. The white kaolin was usually derived from quartz-feldspar gneiss, tonalite or mica gneiss and coloured kaolin from amphibolite or mica gneiss. There is a gradual transition zone between kaolin and its parent rock that, together with relict parent rock texture, indicates the primary origin of kaolin.

The kaolin from different deposits averages 40-75% kaolinite and 20-30% quartz. In some drill cores, from Litmanen, Ukonkangas and Eteläkylä, the kaolinite content reaches 100%. Usually, the silt and clay fractions are almost entirely kaolinite. There remains some feldspar and mica in the lower parts of deposits, where the clay fraction also contains smectite and illite. Coloured kaolin contains some goethite or haematite; ilmenite and occasionally graphite are other staining components.

During kaolinization, alkalies and alkaline earth metals have been completely removed from the parent rock with 50% decline in silica content and more than 70% decline in iron. The behaviour of rare earth elements is similar to that in recent tropical weathering profiles and differs from that of hydrothermal kaolin. Based on chemical changes, the Proterozoic kaolinization atVirtasalmi was more thorough than Mesozoic or Tertiary kaolinization elsewhere in Europe. This may have been due to a high concentration of CO_2 in the Proterozoic atmosphere, which strengthened a greenhouse effect that resulted in global warming and provided optimal conditions for kaolinization over a considerable span of time.

The kaolin was presumably covered by Neoproteroterozoic sediments, which protected it from Neoproterozoic and later glacial erosion, at least until the beginning of the Tertiary, and, thus, the Mesozoic kaolinization had probably no influence on the kaolin deposits buried under the sediments. Subsequently, erosion removed the sedimentary cover and most of the kaolin; kaolins in deep fractures were, however, preserved.

Key words (GeoRef Thesaurus, AGI): kaolin deposits, mineralogy, geochemistry, mineral deposits, genesis, kaolinization, absolute age, K/Ar, illite, Proterozoic, Mesoproterozoic, Virtasalmi, Finland

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Vammalan Kirjapaino Oy 1996

To Lea,
Eveliina, Jukka and Tommi

CONTENTS

INTRODUCTION

This doctoral thesis deals with the Virtasalmi kaolin deposits that are situated in an area, 20 km x 5 km, on the southwestern side of the Raahe-Ladoga Zone in SE Finland. The bedrock consists of highly metamorphosed Svecofennian schists and plutonic rocks (ca. 1900 Ma). The Neoproterozoic sedimentary rocks discovered in the Iso-Naakkima impact crater are the youngest rocks in the area. The kaolin deposits occur in a quartz-feldspar gneiss - amphibolite - carbonate rock (marble) belt. The belt also contains several copper-sulphide occurrences.

In northern Finland, in Kainuu and Lapland, there are several small kaolin occurrences that have been known for a long time (Pekkala and Sarapää 1989). In southern Finland kaolin appears to be rare. This stems from the fact that glacial erosion was stronger in the south and that exploration has been limited in the poorly exposed areas.

Unmetamorphosed sedimentary rocks are rare in Finland and Quaternary deposits usually lie directly on Paleoproterozoic and Archean rocks. Sporadic sedimentary rock areas indicate regions where the erosion has been low and, thus, the preservation of previous kaolin may have been possible. The common association of old impact craters with preserved sedimentary rocks also indicates a low intensity of erosion. The 1300-1400 Ma Jotnian sediments have been preserved in the downfaulted Satakunta and Muhos blocks and at Lake Ladoga near the Finnish border (Simonen 1980; Kohonen et al. 1993). Mesoproterozoic pre-impact sediments have been preserved in the eastern slope of the Lappajärvi crater (77 Ma) (Uutela 1990; Pipping 1991). Neoproterozoic Vendian (600-650 Ma) sediments occur in small basins at Hailuoto and Taivalkoski (Tynni and Uutela 1985). Younger Cambrian quartz-sandstones and shales have been found in western Finland at Lauhanvuori (Simonen and Kouvo 1955) and in the impact crater of Söderfjärden (Simonen 1980; Lehtovaara 1990). The sediments of Lappajärvi, Hailuoto and Taivalkoski all contain a considerable amount of kaolinite. Chemically mature Cambrian quartz-sandstones at Lauhanvuori and a kaolin weathering crust under Cambrian sediments in Estonia also indicate Proterozoic kaolinization (Jørgensen 1995).

In 1986 the Geological Survey of Finland (GSF) started kaolin exploration in southern and Central Finland (Pekkala and Sarapää 1989) due to the rapidly increasing demand for kaolin by the Finnish paper industry. During the preliminary study all geological, geochemical and geophysical material were carefully reviewed, including checking of several tens of drill cores stored at GSF. Several drill cores from the Virtasalmi area indicated extensive core loss and intense weathering and also contained white kaolin clay fragments (Sarapää 1987). Accordingly, the main effort was concentrated on the Virtasalmi area, where an extensive geological and geophysical database, particularly gravity maps (Siikarla 1967; Hyvärinen 1969), provided a sound foundation for ultimately successful exploration. Between 1986 and 1992, ten kaolin deposits were located and studied by the GSF in the Virtasalmi area. Six of the deposits may have economic value as sources of raw material for paper coating and filling. At present, the Kemira Company is evaluating the mining potential of two deposits.

This thesis describes the mineralogy, geochemistry, origin and age of the Virtasalmi kaolin deposits. Technical properties and possible uses will be also discussed and kaolin exploration methods and potential targets areas briefly summarized. It is hoped that this work inspires further scientific and technical studies of all the material available on the Virtasalmi kaolins and encourages exploration for new domestic pigment resources to meet with the increasing needs of the Finnish paper industry.

REVIEW OF THE PAPERS

This doctoral thesis comprises three papers:

1) **Elo, S., Kuivasaari, T., Lehtinen, M., Sarapää, O. and Uutela, A. 1993.** Iso-Naakkima, a circular structure filled with Neoproterozoic sediments, Pieksämäki, southeastern Finland. Bulletin of the Geological Society of Finland 65, part 1, 3-30.

2) **Sarapää, O., Kuivasaari, T., Niemelä, M., Pekkala, Y. and Reinikainen, J.** Kaolin deposits in the Virtasalmi area, southeastern Finland; geology, technical properties and possible uses. In: Pekkala, Y. (ed.), The kaolin deposits in Finland. Geological Survey of Finland, Special Paper, in prep. 39 p.

3) **Sarapää, O.** Genesis and age of the Virtasalmi kaolin deposits, southeastern Finland. In: Pekkala, Y. (ed.), The kaolin deposits of Finland. Geological Survey of Finland, Special Paper, in prep. 66 p.

Paper 1. This paper describes the Iso-Naakkima impact structure and its sedimentary rock sequence and microfossils. It also gives a minimum age for kaolinization in the Virtasalmi area.

During kaolin exploration by the GSF, an impact crater filled with kaolinitic sediments was found in the gravity low of Lake Iso-Naakkima, 8 km northwest of the Montola kaolin deposit. The microfossil assemblage of the kaolinitic sediments is as old as Neoproterozoic (Late Riphean). The circular structure of Iso-Naakkima was first recognized on the regional gravity map, as a minimum of -4 mGal with a half-amplitude width of 2 km. The drilling record covers a 100 m thick sequence of shale, siltstone, quartz sandstone, kaolinitic clay and conglomeratic sandstone. These unmetamorphosed sedimentary rocks rest unconformably on a weathered Paleoproterozoic mica gneiss. The Quaternary cover is 40 m thick. Planar deformation features in the quartz of conglomeratic sandstone and in the mica gneiss are the best evidence for shock metamorphism. The kink banding of mica and the occurrence of dike breccia in mica gneiss also point to an impact. Much of the bedrock affected by the impact has subsequently been eroded leaving only minor traces of shock metamorphism.

Kaolinization in a warm and humid climate preceded the deposition of the Iso-Naakkima sediments and probably continued during their sedimentation. This is indicated by the underlying weathered basement and kaolinitic clay (50% kaolinite), pure mature quartz-sandstone with minor white kaolin interbeds, as well as kaolinite-bearing siltstone and shales in the Iso-Naakkima sequence. The quartz-sandstone and siltstone are interpreted as fluvial sediments, and shales as transgressive lacustrine or lagoonal deposits. The microfossil assemblage in the sediments (sphaeromorphs of acritarchs) is from Late Riphean (650-1000 Ma). Postdepositional relative subsidence of the Iso-Naakkima basin protected the sequence from further erosion. The subsidence and the nature of the sedimentary sequence indicate that the sediments once covered a much larger area.

The impact structure of Iso-Naakkima has been recorded as the fourth oldest by Grieve et al. (1995). Small impact structures of Precambrian age are rare on the earth because they are prone to erosion. In the Iso-Naakkima impact structure, kaolinitic sediments, dated from microfossils as Neoproterozoic, unconformably overlie weathered Paleoproterozoic (1.9 Ga) mica gneiss, indicating Proterozoic kaolinization.

Paper 2. This paper describes the kaolin deposits from the area of Virtasalmi, their geology, and genesis, technical properties and possible uses.

The kaolin deposits at the Virtasalmi area, Litmanen, Eteläkylä, Vuorijoki, Ukonkangas, Montila, Niittylampi, Kahdeksaisiensuo, Hyväjärvi and Montilanlampi, are located in a NW-trending, 20 km x 5 km zone. The kaolin deposits occur in smoothly undulating terrain, where the erosion surface of kaolin is 77-93 m a.s.l. and the Quaternary overburden is 20-30 m thick.

The kaolin deposits were found by drilling and from 1.0 - 2.0 mGal gravity lows. They are magnetically neutral, but give a weak electrical anomaly discernible on regional scale airborne electromagnetic maps.

The kaolin deposits are hosted by quartz-feldspar gneiss, mica gneiss, amphibolite and tonalite, and are often closely associated with metamorphic carbonate rocks. The distribution of deposits is also controlled by the NW-trending Virtasalmi fracture, apparently related to the Raahe-Ladoga Zone. In the latter, tectonic movements have probably occurred during younger orogenic events. The deposits are lenticular in shape, 0.5-2 km long, and 50-400 m wide. Their thickness averages 30-40 metres, but reaches over 100 metres in some places. The quality of kaolin reflects on the mineralogy of the parent rock. White kaolin grades gradually into quartz-feldspar gneiss or tonalite. Coloured kaolin often derives from amphibolite or mica gneiss.

At Virtasalmi the mineral composition of quartz-feldspar gneiss and tonalite is ideal for the formation of high quality kaolin. The plagioclase content is high, about 50%, while the amounts of K-feldspar (5-10%) and mafic minerals (10-15%) are low. In contrast, the high content of mafic minerals of the amphibolites favoured the formation of coloured kaolin. The typical structural features of the bedrock of the Virtasalmi area, such as steep axial plane schistosity, banding and jointing, provided space for kaolinization solutions to percolate through the rocks.

White kaolin contains on average 40-75% kaolinite, 20-30% quartz and some feldspar and mica. Additional minerals in coloured kaolin are goethite or haematite. Other staining components in both kaolin types are ilmenite, anatase and graphite. The < 20 µm and <2 µm fractions are composed almost entirely of kaolinite and only traces of quartz; smectite and illite have been identified occasionally. The proportion of the <2 µm fraction in the kaolin deposits is 30% and that of the <20 µm fraction 60%. The particle size distribution of the < 20 µm fraction is quit similar to that of imported filler grades. Because the < 20 µm fraction is pure kaolin, further grinding increases the recovery of the coating grade kaolin (< 2 µm). The quality of processed white kaolin at Virtasalmi meets the requirements of paper kaolin. Comparison with commercial kaolin products shows that some of the refined Virtasalmi kaolin has an even better brightness than many commercial kaolins, probably because of its lower iron content. Further, the resources 18 Mt of white kaolin are satisfactory. Both kaolin types could also be used in ceramics.

Tectonic features have controlled both the genesis and preservation of the Virtasalmi kaolins. Fracturing opened cracks in the parent rocks for kaolinizing agents. An exceptionally high kaolinite content, a low iron content and the fact that the deposits are thick indicate strong leaching over a long period at several occasions.

Paper 3. This paper describes the mineralogy, geochemistry, genesis and age of the Virtasalmi kaolin deposits.

Material for the study was selected from the drill cores of the Litmanen, Ukonkangas, Vuorijoki and Eteläkylä deposits, which are the best known among the deposits discovered at Virtasalmi. The kaolin profiles developed from various rock types in eight cross sections were studied. The transition from kaolin into a parent rock is gradual and marked by changes in texture, mineralogy and chemical composition. For example, the content of kaolinite decreases and that of quartz increases with depth in the kaolin profiles. This is strong evidence for the residual origin of the kaolin. Frequently, the parent rock texture has been well preserved in the kaolin.

The kaolin derived from quartz-feldspar gneiss is white and consists of kaolinite and quartz. Dioctahedral mica and feldspar may occur in the basal part of the kaolin profile. Kaolin derived from mica gneiss is either white, grey or coloured and typical mineral assemblages are kaolinite-quartz, kaolinite-quartz-mica-(pyrite-graphite) and kaolinite-quartz-goethite (rarely haematite), respectively. Kaolin derived from amphibolite is mostly coloured and consists of kaolinite, kaolinite-goethite and, in the basal part of the kaolin profiles, kaolinite-smectite. Kaolin derived from tonalite is mostly white and consists of kaolinite and quartz. Small amounts of ilmenite, anatase and pyrite are often present in all kaolin types. The mineralogical composition is typical for a residual kaolin deposit; hydrothermal kaolin minerals - halloysite, dickite and nacrite - are totally lacking.

According to mass balance calculations, the kaolinization process has been very intense, because Mg, Ca, Na and K have been dissolved. Losses of SiO_2 and Fe_2O_3 are over 50% and 70% of the original amounts in the parent rock, and also quartz has been partially dissolved. The volume decrease is estimated to be 20-30%, even though the texture of the parent rock has been retained. The behaviour of major and trace elements, especially that of the rare earth elements, is similar to that described in recent weathering crusts, but differs from hydrothermal deposits. The heavy rare earth elements have been depleted over the light rare earth elements in kaolin in relation to the parent rock and enriched in the basal part of the weathering profile. Mass balance calculations based on the silica loss in the Eteläkylä deposit suggest that the development of a 70 m thick kaolin deposit takes at least about 15 million years in a warm and humid climate. Comparison to other kaolin deposits in

Europe shows that the Virtasalmi kaolin deposits are thicker, richer in kaolinite, higher in alumina and lower in iron. Due to subsequent erosion, they also cover smaller areas than the residual deposits of Central Europe.

During the formation of the Virtasalmi kaolin deposits, acidity of groundwater caused by oxidation of sulphide minerals and solution of CO_2 in water (H_2CO_3), derived from the atmosphere with a high concentration of CO_2 accelerated kaolinization of aluminium-bearing silicates. A high content of relatively decomposing plagioclase and a low content of more stable K-feldspar resulted in the high kaolinite content. The small amount of biotite in quartz-feldspar gneiss, in turn, favoured a white end product. Fractured gneisses with steep schistosity and easily soluble carbonate rocks provided an ideal drainage system for intense leaching and kaolinization, necessary for origin of a high quality kaolin.

Independent isotopic and palaeontological data suggest that the Virtasalmi kaolin deposits are Proterozoic in age. The K-Ar age of authigenic illite from the Litmanen kaolin is 1180 Ma. Kaolinite-bearing sediments of the Iso-Naakkima sequence that lie unconformably on the weathered and kaolinized mica gneiss have a Neoproterozoic (650-1000 Ma) microfossil assemblage. The Mesoproterozoic kaolin was presumably covered by Neoproteroterozoic sediments, which protected it from subsequent Neoproterozoic glacial erosion and later erosion for a long time. The intense Mesozoic kaolinization may not have affected the kaolins atVirtasalmi as they were buried by the sedimentary cover. Most of the kaolins, except those in deep fractures, were probably removed by later erosion. The present deposits are only the remnants of an extensive kaolinitic crust.

CONCLUDING DISCUSSION

The preservation of several kaolin deposits and an unmetamorphosed sedimentary sequence in the Virtasalmi area indicate that erosion has been unusually weak in the study area during the last 1200 million years. During the last glaciation, Virtasalmi was situated in the area of active ice flow, but despite this the last glacial erosion did not affect much the kaolin deposits in fractures. Kaolin may have acted either as sliding surface, after the loose upper part of the kaolin was removed during several glacial cycles, or the kaolin deposits were protected from erosion by older till layers and the rock hills on their proximal side. (Lintinen 1995; Nenonen 1995). The most prolonged periods of glaciation in Earth history took place during the Neoproterozoic, from which the closest example is Varanger tillite in northern Norway (Windley 1995). At that time the intensity of erosion was presumably strongest at Virtasalmi, however the kaolin deposits were probably preserved in a downfaulted block in which the Neoproterozoic sediments protected kaolin from erosion.

This is similar to the situation of kaolin deposits in Central Europe, which are mostly preserved under sedimentary cover in downfaulted blocks (Störr et al. 1978; Kuzvart 1980). All kaolin deposits in the Virtasalmi area are found on the southwestern side of the Raahe-Ladoga Zone, which may represent a crustal block downfaulted during the 1.2-0.9 Ga Sveconorwegian orogeny, concurrent with kaolinization at Virtasalmi. It is also possible that some other blocks on the southwestern side of the Raahe-Ladoga Zone may have been similarly downfaulted and thus have potential for the preservation of kaolin.

Based on this study the following criteria and methods are useful in exploration of areas with good kaolin potential:

1) the occurrence of unmetamorphosed sedimentary rocks or weathering crust (indicating low intensity of erosion)

2) gently undulating terrain where fracture zones are not directly visible (weathering products have filled fractures, such terrains can be identified from contour line maps)

3) favourable parent rock lithology (quartz-feldspar gneiss, tonalite) and structures (fractures, jointing)

4) chemical composition of till (high Al, Ti, V, Cr, Ni Cu, Ga and very low Mg, Ca, Na, K, Rb), assuming that kaolin has mixed with till, which is not the case at Virtasalmi

5) electromagnetic anomalies in deep gravity lows (1-2 mGal)

Although kaolinite is a very common clay mineral, the development of a thick kaolin deposit requires extraordinary conditions. Prolonged kaolinization, favourable parent rock lithology, high annual precipitation, warm climate and efficient leaching may result in a deep kaolin crust without humid acids. The Mesoproterozoic kaolinization at Virtasalmi was clearly more thorough than younger kaolinization events elsewhere in Europe. In the Mesoproterozoic, the global climate was probably more favourable for extensive kaolinization. The higher CO_2 levels of the ancient atmosphere could have strengthened the greenhouse effect (Kasting 1986; Holland 1993), and, at Virtasalmi, acids generated by sulphide oxidation also promoted deep weathering.

The kaolinization at Virtasalmi was followed by downfaulting and sedimentation. An extensive kaolinitic weathering crust on the southwestern side of the Raahe-Ladoga Zone was covered by Meso- and Neoproterozoic sediments derived from adjacent uplands, which became the site of erosion. The remnants of sediments are still in situ at the Iso-Naakkima impact site and also at several other places in southern Finland (Lappajärvi, Muhos, Ladoga and Satakunta; Kohonen et al. 1993). The Iso-Naakkima impact structure is probably roughly contemporaneous with the main kaolinization stage at Virtasalmi. The tentative paleomagnetic age of the impact is 1.2 Ga, and that of the Iso-Naakkima sediments 0.9-1.1 Ga (Järvelä et al. 1995). At Virtasalmi, the buried kaolin deposits escaped erosion for a long time, probably also from later Carboniferous, Mesozoic and Tertiary kaolinization events reported elsewhere in Europe (Störr et al. 1978; Bristow 1995).

The study suggests that the following events took place at Virtasalmi after the Svecofennian orogeny sequence (Fig. 1):

1) weathering, erosion and denudation of the Svecofennian mountain belt and formation of a peneplain (1.9-1.6 b.y. ago)

2) intensive Mesoproterozoic kaolinization (main stage at ca. 1180 m.y. ago),

3) the Iso-Naakkima impact (1.2 b.y. ago)

4) weathering, erosion (impact breccia) and deposition of fluvial quartz sands and kaolin at Iso-Naakkima

5) downfaulting of the Virtasalmi area and the sedimentation of clays of the Iso-Naakkima sequence (ca. 1.0 b.y. ago)

6) subsidence of the Iso-Naakkima basin → tilting of sediments

7) Cenozoic erosion of sediments and kaolin

8) deposition of Quaternary glacial till on the kaolin

The main results of this study are:

1) the identification and interpretation of kaolin profiles, several tens to 100 metres thick, of Mesoproterozoic age at Virtasalmi, and

2) recognition of a new impact structure at Iso-Naakkima filled with kaolinite-bearing sediments of Neoproterozoic (1000-650 Ma) age.

No high quality white primary kaolin deposits of Mesoproterozoic age have been reported earlier and therefore the Virtasalmi kaolin is among the oldest soft kaolin deposits in the world - most kaolin deposits in Europe are Mesozoic or younger. To the author's knowledge, this is the first time residual kaolin has been dated by the K/Ar -method from illite that was formed during the kaolinization. The Proterozoic age of Virtasalmi kaolinization was confirmed by stratigraphical observation of post impact sediments in the Iso-Naakkima structure and it also matches well with paleomagnetic data (cf. Pesonen et al. 1989; Elming et al. 1993) that suggest that Fennoscandia was then near the Equator. So far the Meso- and Neoproterozoic geological record in Finland has been very scarce. This study sheds further light on the geological evolution of Finland after the Mesoproterozoic.

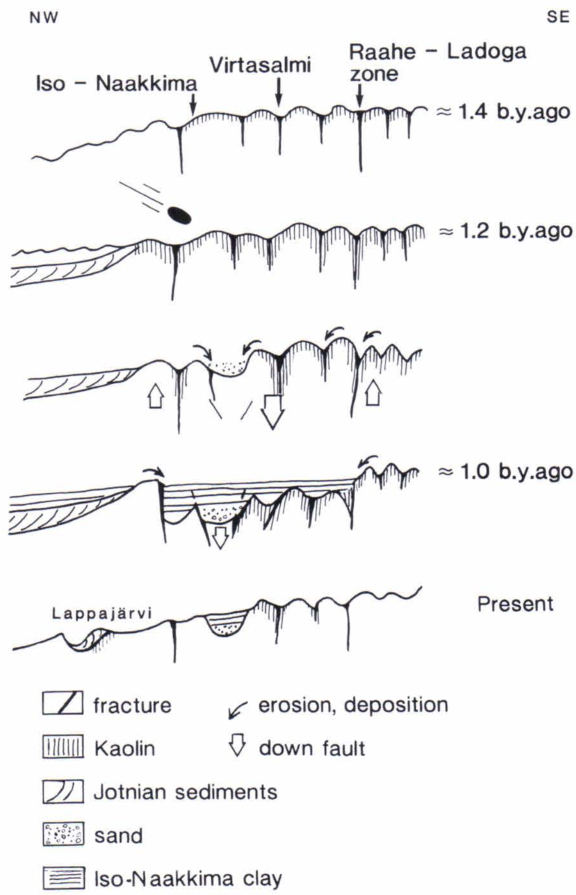

Fig. 1. Schematic model of main events at Virtasalmi from Mesoproterozoic to present. (not in scale).

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