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A Rb-Sr investigation of illite-forming events in diagenesis-grade Neoproterozoic shales, Varanger Peninsula, North Norway

NGU
Norges geologiske undersøkelse
Geological Survey of Norway

Geological Survey of Norway
P.O.Box 3006 - Lade
N-7002 Trondheim, Norway
Tel.: 47 73 90 40 11
Telefax 47 73 92 16 20

REPORT

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A Rb-Sr investigation of illite-forming events in diagenesis-grade Neoproterozoic shales, Varanger Peninsula, North Norway

Authors: Gorokhov, I.M., Siedlecka, A., Roberts, D., Melnikov, N.N., Turchenko, T.N., Konstantinova, G.V., Kutyavin, E.P. & Sochava, A.V.	Client: Geological Survey of Norway
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Summary:

In this report we present evidence for the occurrence of at least two generations of authigenic illite in diagenesis-grade Upper Riphean and Vendian shales of the Stangenes, Nyborg and Stappogiedde Formations, Varanger Peninsula, North Norway. Dating of illite subfractions by the Rb-Sr method has yielded ages for redeposited clastic material and for the diagenetic events. As well as dating actual events, an objective of this study has been to contribute to the intense and long-lasting research and discussion on the absolute age of the Riphean - Vendian boundary, and the age ranges of the 'Varangerian glaciation' and the Late Vendian (=Ediacaran) period of time.

The results suggest that the age of the Riphean - Vendian boundary is ≤630 Ma, and that the age of the Early Vendian 'Varangerian glaciation' is bracketed between ≤630 Ma and c. 560 Ma, and perhaps even between ≤ 630 and c. 590 Ma. The age of burial diagenesis at 560±10 Ma may be related to a regional compaction of the sedimentary succession arising from Baikalian deformation which is recognised in NW Russia. The c. 530 Ma minimum age for burial diagenesis of the Stappogiedde Formation does not contradict the location of the Precambrian - Cambrian boundary at the top of this formation. The younger ages, ranging from 440 to 390 Ma, appear to reflect phases of Scandian deformation and uplift.

Keywords: Datering	Berggrunnsgeologi	Prekambrium
Neoproterozoikum	Sedimentær bergart	Fagrapport

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1. INTRODUCTION AND GEOLOGICAL SETTING

Chronostratigraphy of Neoproterozoic to Cambrian sedimentary sequences, including the absolute age of the Precambrian-Cambrian boundary, has been a focus of attention over many years (e.g., Brasier 1992, Brasier et al. 1994). In this work, the approach has been to integrate several stratigraphic methods; biostratigraphy based on microfossils, Ediacara, Platysolenites and trace fossils, combined with chemostratigraphy and radiometric ages (e.g. Sokolov & Fedonkin (eds.) 1985, Asmerom 1991, Bottomley et al. 1992, Brasier et al. 1992, 1994, Narbonne et al. 1994). These investigations have also brought into focus the age range of the Vendian period and the age of the lower boundary of the Vendian which remains controversial (e.g. Chumakov & Semikhatov 1981, Knoll & Walter 1992, Kaufmann et al. 1993, Sokolov 1995) The absolute age of the Varangerian glaciation, its duration and its possible worldwide extent has also been a subject of debate for decades (e.g. Harland 1965, 1983, Chumakov 1981, 1985). Varanger Peninsula in northern Norway contains the type area and type localities of this glaciation, where there are classic sections of glacial deposits, the lithostratigraphy is well established and the biostratigraphy is known in some detail (Føyn 1967, Vidal 1981, Farmer et al. 1992). Radiometric datings, however, are few and remain imprecise for several reasons; e.g. the dating of sedimentary rocks is difficult and so far no volcanic ash beds have been found within the relevant sections; and dolerite dykes which intrude parts of the sections have given only minimum ages which do not entirely solve the problems of either time stratigraphy or tectonic events.

The sections of interest in the present study, embracing Neoproterozoic and Lower Palaeozoic rocks and comprising two levels of Varangerian glacial accumulations, occur in the southwestern part of the Varanger Peninsula called the Tanafjorden-Varangerfjorden Region (TVR). The very low-grade rocks of this region continue westwards into the Digermulen Peninsula where they extend up into the Tremadoc and are gradually more strongly affected by the Caledonian deformation and metamorphism. Illite crystallinity studies have shown that, in general, the rocks of the TVR have been affected only by diagenesis (Bevins et al. 1986, Rice et al. 1989). In southwestern areas of the TVR, however, the metamorphic grade rises to lower or even middle anchizone. Folds with ENE-WSW axes are common in these southwestern districts, especially within the pelitic Nyborg Formation, but they die out southeastwards along the northern shore of Varangerfjorden.

The ages so far determined on the Neoproterozoic sedimentary rocks of the TVR are: (1) Rb-Sr whole-rock isochron ages of 654±7 Ma for the Nyborg Formation and 807±19 Ma for the Klubbnasen Formation (Pringle 1973, Sturt et al. 1975), recalculated using the ^{87}Rb decay constant of 1.42×10^{-11} yr^{-1} (Steiger & Jäger 1977); (2) a poorly constrained ^{40}Ar-^{39}Ar date of c. 635 Ma for Nyborg Formation rocks in the western TVR, interpreted to represent a diagenetically related disturbance (Dallmeyer & Reuter 1989). Based on the Rb-Sr age obtained for the interglacial Nyborg Formation, the approximate date of 650 Ma has been used in various stratigraphic schemes as the age of the lower boundary of the Vendian and of the beginning of the Varangerian glaciation. This age is also the one used by Russian workers for the base of the Vendian (Chumakov & Semikhatov 1981, Sokolov 1995).

In order to try to improve the chronological record for the Neoproterozoic - Lower Cambrian sedimentary succession in the TVR *and also* of the post-depositional (tectonic) events, we decided to attempt to date micron-size fractions of clay minerals from three formations, applying the Rb-Sr method. This approach is based on the fact that minerals of siliciclastic rocks, even as fine-grained as clayey shales, may differ both in age and in origin. The minerals may be redeposited or they may be authigenic, related to separate events post-dating sediment accumulation. An enrichment or even isolation of such non-cogenetic minerals is feasible through separation of the ordinary <2 μm clay fraction into several subfractions (SFs), with the size of particles varying within narrow limits and reflecting separate events which affected the sediment.

The samples of clayey shales collected for isotopic dating are from the following formations:

- Stangenes Formation: Sample # 1008/13, 1:50,000 map-sheet 2435-2, 967 820. This locality is situated in the southeastern part of the TVR. The beds are almost horizontal and have apparently been very little, if at all, affected by the Caledonian deformation.

- Nyborg Formation: Sample # 1004/3 , 1:50,000 map-sheet 2535-2, 726 836. This locality is situated further to the west, not very far from the head of Varangerfjorden. The Nyborg Formation there is sharply overlain by the Mortensnes Formation (tillite). The tillite shows a widely spaced cleavage while small-scale folds are present in parts of the Nyborg Formation (see Siedlecka & Roberts 1992, p. 17 and their Fig. 11).

- Stappogiedde Formation, Innerelva Member: Sample # 1008/3, 1:50,000 map-sheet 2435 2, 042 912. The sampled locality is situated in the northeasternmost part of the TVR in flat-lying, non-cleaved shales which show a good compactional fabric (see Siedlecka & Roberts 1992, p. 21 and their Fig. 18).

The samples were collected in 1993 by A.V. Sochava, D. Roberts and A. Siedlecka. The stratigraphic positions of the sampled formations are shown in Fig. 1.

2. Rb - Sr DATING

2.1 Technique

The <2 μm fractions were extracted by means of the ordinary sedimentation technique. They were separated into six (<0.1, 0.1-0.2, 0.3-0.6, 0.6-1 and 1-2 μm) SFs using centrifugation and ultrafiltration. X-ray diffractometry (XRD) of oriented slides was used to determine the mineral composition of the SFs and the illite crystallinity index (I_k). Leaching with 1N ammonium acetate and Rb-Sr analysis of the untreated SF, leachate and residue enables us to fit a Rb-Sr 'leachochron' to each of these SFs and determine its apparent age and $^{87}Sr/^{86}Sr$ initial ratio.

2.2 Results

The <2 μm fractions of the shales of all the formations are similar in the size distribution of the particles (Fig. 2). The coarser fractions dominate. The content of the finer particles (<0.3 μm) does not exceed 30 per cent.

2.2.1 Mineralogy

The mineralogical data are presented in Tables 1, 2 and 3.

Stangenes Formation (# 1008/13). All the SFs were found to contain only illite. The I_k value (non-calibrated) increases from the coarser to the finer SFs from 0.40° to 0.96° $\Delta 2\theta$ (Fig. 3). The 1-2, 0.6-1 and 0.3-0.6 μm SFs contain $2M_1$ and 1M illite polymorphs. The proportion of $2M_1$ (probably detrial) illite, as compared with the 1M polytype, decreases drastically in the 0.3-0.6 μm SF. The 0.2-0.3 μm SF contains 1M and 1Md polytypes, whereas the 0.1-0.2 and <0.1 μm SFs contain only 1Md illite.

Nyborg Formation (# 1004/3). All the SFs include illite and chlorite. The 1-2 μm SF also contains admixed haematite, feldspar and quartz. As the size of the particles decreases from 1-2 to <0.1 μm, the proportion of chlorite decreases from 10 per cent to just a trace. The lowest I_k value (0.70°) is in the 1-2 μm SF, whereas in finer SFs it varies in the range from 0.90 to 1.02° (Fig. 3). The 1-2 and 0.6-1 μm SFs contain traces of $2M_1$ illite along with the 1M polytype. The 0.2-0.3 μm SF contains 1M+1Md polymorphs. The finer (0.1-0.2 and <0.1 μm) SFs contain only 1Md illite.

Stappogiedde Formation (# 1008/3). All the SFs include illite and chlorite. As the size of the particles decreases from 1-2 to <0.1 μm, the proportion of chlorite decreases from 20 to <5 per cent. The coarser SFs (1-2, 0.6-1 and 0.3-0.6 μm) also contain admixed quartz and traces of feldspar. The I_k value smoothly increases from 0.73° for the 1-2 μm SF to 1.00° for the <0.1 μm SF (Fig. 3). The coarser SFs (1-2 and 0.6-1 μm) contain the mixture of $2M_1$ and 1M illite polymorphs. The proportion of the $2M_1$ polytype sharply decreases in the 0.3-0.6 μm SF. The finer SFs (0.2-0.3, 0.1-0.2 and <0.1 μm) contain only 1 Md illite.

2.2.2 Rb-Sr systematics

On the whole, the Rb-Sr characteristics of the clay particles vary unidirectionally with their size.

Stangenes Formation (# 1008/13)

1. The Rb content in the residues smoothly decreases from 305-308 ppm in the 1-2 and 0.6 μm SFs to 261 ppm in the <0.1 μm SF (Fig. 4). Sr content also decreases in this direction from 326-329 ppm to 151 ppm (Fig. 3). As the size of the particles decreases from 1-2 to <0.1 μm, the $^{87}Rb/^{86}Sr$ ratio in the residues increases from 2.72 to 5.01.
2. The apparent Rb-Sr age value decreases from 931-932 Ma for the 1-2 and 0.6-1 μm SFs to 649±31 Ma for the <0.1 μm SF (Fig. 5).
3. The $^{87}Sr/^{86}Sr$ initial ratio decreases from 0.7141-0.7145 for the 1-2 and 0.6-1 μm SFs to 0.7128 for the 0.1-0.2 μm and 0.7121 for the <0.1 μm SF (Fig. 6).
4. A linear arrangement of data points of the residues on the $^{87}Rb/^{86}Sr$ - $^{87}Sr/^{86}Sr$ (Fig. 7) and 1/Sr - $^{87}Sr/^{86}Sr$ (Fig. 8) diagrams is a sufficient demonstration of the two-component mixing with the end-members presented by the 0.6-1 and 0.1-0.2 μm SFs. The points of the coarsest (1-2 μm) and finest (<0.1 μm) fractions deviate from the straight lines. It is therefore concluded that SFs of the Stangenes shale consist of at least two illite generations (the more or less pure components are presented by the 0.6-1 and 0.1-0.2 μm SFs) and contain them in various proportions. It is highly plausible that the 1-2 and<0.1 μm SFs include two further illite generations.

Nyborg Formation (3 1004/3)

1. The Rb content in the residues increases from 224 ppm (1-2 μm SF) to 261 ppm (0.1-0.2 μm SF) and then decreases in the <0.1 μm SF to 252 ppm (Fig. 9). The Sr content decreases in this direction from 147 ppm (1-2 μm SF) to 41.7 ppm (0.1-0.2 μm SF) and then increases to 44.1 ppm (<0.1 μm SF) (Fig. 9). The $^{87}Rb/^{86}Sr$ ratio in the residues increases from 4.44 (1-2 μm SF) to 18.39 (0.1-0.2 μm SF) and then decreases to 16.75 (<0.1 μm SF) (Fig. 12).

2. The apparent Rb-Sr age values decrease from 572±16 Ma (1-2 μm SF) to 412±5 Ma (0.1-0.2 μm SF) and 388±6 Ma (<0.1 μm SF) (Fig. 10).
3. The $^{87}Sr/^{86}Sr$ initial ratio decreases only slightly from 0.7285 (1-2 μm SF) to 0.7267 (0.1-0.2 μm SF) and then slightly increases to 0.7274 in the <0.1 μm SF (Fig. 11).
4. The data points of all the SFs, except the <0.1 μm SF, lie along the straight lines on both the $^{87}Rb/^{86}Sr$ (Fig. 12) and 1/Sr - $^{87}Sr/^{86}Sr$ (Fig. 13) diagrams. This suggests that the 1-2 and 0.1-0.2 μm SFs represent the end-members of the mixture (two illite generations). It is possible that the <0.1 μm SF includes one more generation of illite.

Stappogiedde Formation (# 1008/3)

1. The Rb content in the residues increases from 145 ppm (1-2 μm SF) to 240 ppm (0.1-0.2 μm SF) and then decreases to 235 ppm (<0.1 μm SF) (Fig. 14). The Sr content decreases in this direction from 43.1 ppm (1-2μm SF) to 10.4 ppm (0.1-0.2 μm SF) and then increases to 13.1 (<0.1 μm SF) (Fig. 13). The $^{87}Rb/^{86}Sr$ ratio increases from 9.8 (1-2 μm SF) to 69.8 (0.1-0.2 μm SF) to 69.8 (0.1-0.2 μm SF) and then decreases to 53.4 (<0.1 μm SF) (Fig. 17).
2. The apparent Rb-Sr age values decrease from 584-589 Ma for the 1-2 and 0.6-1 μm SFs to c. 440 Ma for the 0.1-0.2 μm SF and c. 430 Ma for the <0.1 μm SF (Fig. 15).
3. The $^{87}Sr/^{86}Sr$ initial ratio is 0.7189 in the 1-2 μm SF; it then decreases sharply to 0.7138 for the 0.6-1 μm SF, and thereafter progressively increases to the value of 0.7192 for the 0.2-0.3 μm SF (Fig. 16). Then it decreases again to 0.7190 (0.1-0.2 μm SF) and 0.7168 (<0.1 μm SF).
4. The data points of four SFs (from the 1-2 to the 0.2-0.3 μm SFs) lie along straight lines on both the $^{87}Rb/^{86}Sr$ - $^{87}Sr/^{86}Sr$ (Fig. 17) and the 1/Sr - $^{87}Sr/^{86}Sr$ (Fig. 18) diagrams, but the <0.1 μm SF (and 0.1-0.2 μm SF ?) points deviate from the lines. It is believed that the 1-2 and 0.2-0.3 μm SFs are the end-members of the mixture and represent two illite generations. The finer SFs (<0.1 and possibly 0.1-0.2 μm) appear to contain a third illite generation.

2.3 Geochronology

All the evidence together suggests that the various SFs in each of the samples contain several non-cogenetic illite generations.

Stangenes Formation (# 1008/13). The coarser SFs in this shale sample contain $2M_1$ illite, and their I_k values lie in the range 0.40 to 0.52°. It is believed that this high-temperature illite might be reworked and was thus inherited from some older source. The dates of 931-932 Ma for the 1-2 and 0.6-1 μm SFs therefore correspond to the minimum age of the rocks of the source area (Fig, 19A, B). The most likely age of the authigenic 1Md illite in the 0.1-0.2 μm

SF with I_k=0.86° is ca. 650 Ma. This value appears to be the age of burial diagenesis of the Stangenes shale (Fig. 19E). The <0.1 µm SF with the age of ca. 630 Ma probably crystallised during a later diagenetic event (Fig. 19F).

Nyborg Formation (# 1004/3). The age of burial diagenesis for this shale is probably sandwiched between the values of 572±16 Ma (1-2 µm SF) and 547±15 Ma (0.6-1 µm SF) (Fig. 20A, B). Solely for convenience of description, we will hereafter use the mean value of ca. 560 (±10) Ma. The 1-2 µm SF contains $1M+2M_1$ illite, and its age may therefore be slightly overestimated. The dates of ca. 415 and 390 Ma for the finest SFs (0.1-0.2 and <0.1 µm) appear to correspond to late diagenetic events, probably associated with the Caledonian orogeny (Fig. 20 E, F).

Stappogiedde Formation (# 1008/3). The coarser (1-2 and 0.6-1 µm SFs) contain $2M_1$ illite and despite good I_k values their dates of 584-588 Ma are probably overestimated (Fig. 21A, B). Consequently, the date of ca. 530 Ma for the 0.3-0.6 µm SF may be accepted as a *minimum* age for burial diagenesis for the Stappogiedde shale (Fig. 21C). The real age value for this main phase of diagenesis is probably a little more than that, perhaps 560-570 Ma, but definitely no more thant 584-588 Ma. As for the ages of the younger illite generations, one can only suggest that there were late diagenetic events at ca. 440 and ca. 430 Ma (Fig. 21E, F).

3. DISCUSSION

The various apparent Rb-Sr age values recorded by the different SFs, and noted in sections 2.2.2 and 2.3 above, require interpretation in the light of our current knowledge of the regional geology. For convenience, we consider first the oldest formation, the Stangenes, which by coincidence also records the oldest apparent age of any of the coarser illite SFs.

The Stangenes Formation of the lower Tanafjorden Group contains *Bavlinella faveolata* and other acritarchs of even wider stratigraphic range and is, on palaeontological grounds, considered to be of R4 Terminal Riphean age (Kudashian, named 'Lower Vendian' by Vidal 1981). The age of c. 930 Ma for the detrital anchizone illite in the two coarsest SFs is clearly reflecting inheritance from the source area. This minimum age for the rocks in the source area is not unlike dates recorded by detrital illites from shales in formations of comparable stratigraphic age on the Sredni Peninsula of NW Kola in Russia (Gorokhov et al. 1995). Based on stromatolite assemblages, the youngest preserved formation of the Tanafjorden Group, the Grasdalen Formation, is of Late Riphean (Terminal Karatavian) age (Raaben et al. 1995). Above this there is a low-angle, angular unconformity beneath the Vesterana Group with a hiatus increasing southwards. The hiatus records the greatest event, in space and time, in the Neoproterozoic record of northern Norway, involving uplift, tilting and erosion of an already **lithified** sedimentary sucession. It may therefore be suggested that the c. 650 Ma age reflects the burial diagenesis of the Tanafjorden Group succession with no specific relationship to any particular known event, while the c. 630 Ma apparent age is related to the terminal event recorded by the unconformity. This would imply that the minimum age for the Terminal Riphean would be c. 650 Ma and the maximum age for the Varangerian glaciation c. 630 Ma.

The Nyborg Formation is located stratigraphically between the two Varangerian glacials, the Smalfjord and Mortensnes Formations (Fig. 1). All three formations contain long-range Upper Riphean-Vendian acritarchs, many of them reworked from the underlying formations. The age of the Nyborg Formation was considered Vendian because of the Vendian age of diagnostic microfossils occurring in the underlying and overlying lithostratigraphic units, **and** on the basis of the isotopic Rb-Sr isochron age reported by Pringle (1973).

The mean value of the two illite SFs which we have obtained is around 560 Ma (i.e. for burial diagenesis) but its significance, if we consider the Nyborg Formation in isolation, is uncertain. If it were related to the pre-Mortensnes unconformity (erosional hiatus), the age of the Mortensnes glaciation would be fairly close to the Precambrian - Cambrian boundary at about 540 Ma, and the obtained ages would bracket the 'Varangerian Ice Age' between $\leq$630 Ma and <560Ma. However, both the Nyborg Formation and the post-Varangerian Stappogiedde Formation are part of the same Vestertana Group succession; and both units show roughly the same 'mean' ages for their burial diagenesis, c. 560 Ma. Thus, it is more likely that the Vestertana Group succession as a whole acquired its burial diagenetic fabric c. 560 Ma ago, towards the end of the Vendian period.

The ages of 415 Ma and 390 Ma for the two finest illite SFs in the Nyborg shales are interpreted by us as reflecting what were probably separate fluid-generating events. In this connection, it is natural to consider these events as part of the protracted Scandian deformation and uplift that is known to have affected the Caledonian allochthon and parautochthon in Finnmark. Late-stage thrust movements of the Kalak and Gaissa Nappes, for example, have been radiometrically dated to Early-Mid Devonian time (Roberts & Sundvoll 1990). Comparable dates have also been recorded in several U-Pb lower intercept zircon ages from Archaean crystalline massifs south of Varangerfjorden (Levchenkov et al. 1995). The small-scale folds in the Nyborg and the widely spaced cleavage in the tillite at the sampling locality probably relate to these Late Silurian and Devonian events.

The Innerelva Member of the Stappogiedde Formation is an extensive siltstone and clayey shale dominated unit. It contains several acritarchs of wide stratigraphic range. On the basis of the presence of *Balveolina faveolata* and with the support of correlation with the Dividal

Group, Vidal (1981) suggested a Late Vendian age for this formation. The formation also contains trace fossils (Banks 1970) and Ediacara medusoids (Farmer et al. 1992). On the combined biostratigraphic evidence, including the presence of *Platysolenites antiquissimus* in the overlying Breivika Formation, a Late Vendian age for the Stappogiedde Formation has been confirmed and the Precambrian - Cambrian boundary was placed just above the basal sandstones of the Breivika by Farmer et al. (1992).

The ages of 584-588 Ma obtained by us are believed to be overestimated (presence of $2M_1$ illite, see above) and therefore the 530 Ma age is suggested as a minimum age for the burial diagenesis. We have also pointed out that the **real** age of this main phase of diagenesis may thus be approximately 560 Ma, as in the case of the Nyborg shales. The 440 Ma and 430 Ma dates, as in the case of the Nyborg Formation, are interpreted as reflecting Caledonian terminal events.

Considering the various illite ages reported here in a more regional context, the 560±10 Ma burial diagenetic event that is common to two of the three formations would appear to relate in some way to the Vendian *Baikalian* deformation and very low-grade metamorphism, which affected the Upper Riphean rocks in the Rybachi and Sredni Peninsulas of NW Russia. The age of this event is constrained to around 580-560 Ma (Roberts 1995). Several lines of evidence also suggest that this SW-directed compressive event left its mark in the rocks and structures of northeastern Varanger Peninsula (Roberts 1996). The burial diagenetic event which we have recorded in the illites of the Stappogiedde and Nyborg Formations may thus be interpreted as relating to the compaction of the Vestertana Group succession imposed by the rising fold belt to the northeast, which shed detritus into the 'Vestertana Group Basin' after the Varangerian glaciation had ceased (Banks et al. 1971).

The c. 650 and c. 630 Ma dates recorded in the Stangenes shales appear to have correlatives in data reported in the literature. Dallmeyer & Reuter (1989), for example, have suggested that a diagenetically related disturbance affected the Nyborg Formation rocks in the westernmost TVR at around 635 Ma. Although we do not see this event in our own illite data from the Nyborg, this suggested disturbance may equate with the c.630 Ma authigenic illite generation in the Stangenes. The 630 Ma event, as noted earlier, is also comparable in number to the 620-610 Ma recorded in shales from the Sredni Peninsula; however, in the latter case this was interpreted as the age of the main burial diagenesis, rather than a later diagenetic event.

Several isotopic ages have been generated on a worldwide basis and used for refining the age range of the Early Vendian, and the time when the Varangerian glaciation affected many places on several continents. Similarly, the age range of Late Vendian, or Ediacaran, has been a target of interest. In Newfoundland, the volcanites that immediately underlie the Varangerian tillites were dated by U-Pb on zircons at c. 606 Ma (Krogh et al. 1988) and a date of 602±3 Ma was obtained in Massachusets for volcanites with the same stratigraphic relationship to the tillite (Kaye & Zartman 1980). Also in Newfoundland (at Mistaken Point), volcanic ash interbedded with beds containing Ediacara has been dated to 565±3 Ma (Benus 1988). However, as pointed out by Kaufmann & Knoll (1995) the isotopic systematics have not been published for this date. In the Flinders Ranges in Australia, Ediacara occurs in two horizons: a lower one, comprising only discoidal remains, and an upper unit (in the Rawnley Quartzite) which has a variety of forms inluding *Cyclomedusa* Sprigg 1947, to which the *Cyclomedusa* forms from the Stappogiedde Formation have been compared (Farmer et al. 1992).

As pointed out by Jenkyns (1995), the age reported by Benus (1988) gained credibility when Tucker & Pharaoh (1991) dated the Ercall Granophyre by U-Pb on zircon at 560±1 Ma. The granophyre intrudes the 566±2 Ma old volcanites and is unconformably overlain by strata of Early Cambrian age. The cited datings suggest that the Varangerian glaciation in North America commenced later than c. 600 Ma and that the age of the Ediacara fossils would be c. 565 Ma.

The Neoproterozoic Windermere Supergroup in the Mackenzie Mountains of northwestern Canada comprises two glacial diamictites and abundant Ediacara-type fossils above the upper (Ice Brook) glacials (Narbonne & Aitken 1995). The geochronology of this supergroup, however, is poorly known. Ash beds have not been found and, therefore isotopic dating using the Rb-Sr method on diagenetic illite subfractions would be a challenge in that area.

In the Gariep Complex in Namibia there are two tillites separated from each other by a terrigenous turbidite succession containing dolomites, and the similarity to the succession of the TVR is striking. In Central Namibia in the Witvlei Group, only one (older) tillite is preserved and in both areas there is an unconformity between the tillite-bearing successions and the overlying Nama Group which contains Ediacara fossils. Germs (1995) suggested estimates of 725-700 Ma and 650-600 Ma for the lower and upper tillite, respectively, while Knoll & Walter (1992) have proposed a 'Varanger age' of 610-590 Ma for the upper (Numees) tillite. Germs (1995) estimated the lower time limit of the Ediacara-bearing lower Nama Group at between 620 and 590 Ma and the upper limit at about 550-545 Ma, which is the approximate age of the Precambrian - Cambrian boundary.

The cited data show clearly that the time range of the Early Vendian in general, and of the Varangerian glaciation in particular, is by no means clarified and that estimates vary considerably. Our estimate for the Varangerian glaciation in the type area is in the lower part of the time interval c. 630 to c. 560 Ma which is wider than the 610-590 Ma interval (Knoll & Walter 1992) that appears to be currently accepted by western workers. More interesting and better constrained is perhaps the age of Ediacara fossils, i.e. close to c. 560 Ma and with a lower limit for the Ediacaran at c. 590-600 Ma. If this last time interval is accepted, then the time range for the Varangerian glaciation, at least in the Varanger area, would be ≤630 - c. 590 Ma.

4. CONCLUSIONS

Although the Rb-Sr dating of the illite SFs does not give the actual age of sedimentation, the ages derived from the authigenic illites help to refine the geochronology of Late Precambrian - Cambrian time. Several important points can be made:

1. The ages obtained for the Stangenes Formation confirm the Late Riphean age of this formation and suggest that the age of the Riphean - Vendian boundary is ≤630 Ma.
2. Although the age of the 'Varangerian glaciation' appears to be bracketed between ≤630 and c. 560 Ma, it is more likely to date to the earlier stages of this interval. On the basis of comparisons with data from other comparable sections, an upper limit of c. 590 Ma is suggested.
3. The 530 Ma minimum age for the burial diagenesis of the Stappogiedde Formation does not contradict the location of the Precambrian-Cambrian boundary between the Stappogiedde and Breivika Formations.
4. The c. 560±10 Ma real age of burial diagenesis for both the Nyborg and the Stappogiedde shales may be related in some way to compaction arising from effects of the Baikalian deformation. The coincidence of this number with similar figures for the age of the Ediacara assemblage is uncertain; it may perhaps indicate a change in life conditions, an event not traceable in the sampled section.
5. The ages of the finer, authigenic illite SFs, ranging from 440 to 390 Ma, appear to reflect phases of Scandian deformation and uplift.

5. REFERENCES

Asmerom, Ye., Jacobsen, S.B., Knoll, A.H., Butterfield, N.J. & Sweet, K. 1991: Strontium isotopic variations of Neoproterozoic seawater: implications for crustal evolution. *Geochimica et Cosmochimica Acta 55*, 2883-2894.

Banks, N.L. 1970: Trace fossils from the late Precambrian and Lower Cambrian of Finnmark, Norway. *Geol. Jour. Special Publ.* 4, 19-34.

Banks, N.L., Edwards, M.B., Geddes, W.P., Hobday, D.K. & Reading, H.G. 1971: Late Precambrian and Cambro-Ordovician sedimentation in East Finnmark. *Nor.geol. unders.* 296, 197-236.

Benus, A.P. 1988: Sedimentological context of a deep-water Ediacaran fauna (Mistaken Point Formation, Avalon zone, eastern Newfoundland). *In*: Landing, E., G.M. Narbonne & P.M.Myrow (eds): *Trace Fossils, Small Shelly Fossils, and the Precambrian-Cambrian boundary.* Bull.N.Y.State Mus.,m 463, 8-9.

Bevins, R.E., Robinson D., Gayer, R.A. & Allman, S. 1986: Low-grade metamorphism and its relationship to thrust tectonics in the Caledonides of Finnmark, North Norway. *Nor.geol.unders. Bull. 404*, 33-44.

Bottomley, D.J., Veizer, J., Nielsen, H. & Moczydlowska, M. 1992: Isotopic composition of disseminated sulfur in Precambrian sedimentary rocks. *Geochimica et Cosmochimica Acta 56*, 3311-3322.

Brasier, M.D. 1992: Global ocean - atmosphere change across the Precambrian - Cambrian transition. *Geol. Mag. 129*, 2, 161-168.

Brasier, M.D., Anderson, M.M. & Corfield, R.M. 1992: Oxygen and carbon isotope stratigraphy of early Cambrian carbonates in southeastern Newfoundland and England. *Geol. Mag. 129*, 265-279.

Brasier, M.D., Cowie, J. & Taylor, M. 1994: Decision on the Precambrian - Cambrian boundary stratotype. *Episodes 17*, 3-8.

Chumakov, N.M. 1981: Upper Proterozoic glaciogenic rocks and their stratigraphic significance. *Precambrian Research 13*, 373-395.

Chumakov, N.M. 1985: Laplandian glacial horizons and their analogs. *In*: Sokolov, B.S. & Fedonkin, M.A. (eds.): *Vendian System 2, chapter 7*, 167-198, Nauka (in Russian).

Chumakov, N.M. & Semikhatov, M.A. 1981: Riphean and Vendian of the USSR. *Precambrian Research 15*, 229-253.

Dallmeyer, R.D. & Reuter, A. 1989: ^{40}Ar/^{39}Ar whole-rock dating and the age of cleavage in the Finnmark autochthon, northernmost Scandinavian Caledonides. *Lithos 22*, 213-217.

Farmer, J., Vidal, G., Moczydlowska, M., Strauss, H., Ahlberg, P. & Siedlecka, A. 1992: Ediacaran fossils from the Innerelv Member (Late Proterozoic) of the Tanafjorden area, northeastern Finnmark. *Geol. Mag. 129*, 181-195.

Føyn, S. 1967: Dividal-gruppen (Hyolithus-sonen) in Finnmark og dens forhold til de eokambriske - kambriske formasjoner. *Nor. geol. unders. 249*, 1-82.

Germs, G.J.B. 1995: The Neoproterozoic of southwestern Africa, with emphasis on platform stratigraphy and paleontology. *Precambrian Research 73*, 137-151.

Gorokhov, I.M., Turchenko, T.L., Baskakov, A,V., Kutyavin, E.P., Melnikov, N.N. & Sochava, A.V. 1995: A Rb-Sr study of multistage illite generation in shales of the Pumanskaya and Poropelonskaya Formations, Sredni Peninsula, NW Kola region (Extended abstract). *Nor. geol. unders. Special Publ. 7*, p. 330.

Harland, W.B. 1965: Critical evidence for a great Infra-Cambrian glaciation. *Geol.Rundschau 54*, 1, 45-61.

Harland, W.B. 1983: The Proterozoic glacial record. *Geol. Soc. America Mem. 161*, 279-288.

Jenkyns, R.J.F. 1995: The problems and potential of using animal fossils and trace fossils in terminal Proterozoic stratigraphy. *Precambrian Research 73*, 51-69.

Kaufman, A.J., Jacobsen, S.B. & Knoll, A.H. 1993: The Vendian record of Sr and C isotopic variations in seawater: Implications for tectonics and paleoclimate. *Earth Planet. Sci. Letters 120*, 409-430.

Kaufman, A.J. &. Knoll A.H. 1995: Neoproterozoic variations in the C-isotopic composition of seawater: stratigraphic and biochemical implications. *Precambrian Research 73*, 27-49.

Kaye, C.A. & Zartman, R.F. 1980: A late Proterozoic to Cambrian age for the stratified rocks of the Boston Basin, Massachusetts, USA. *In*: D.R.Wones (Ed.): *Proceedings «The Caledonides in the USA»*. Dept. Geol. Sci. Virginia Polytech. Inst., State Univ.Mem. 2, 257-261.

Knoll, A.H. & Walter, M.R. 1992: Latest Proterozoic stratigraphy and Earth history. *Nature 356*, 673-677.

Krogh, T.E., Strong, D.F., O'Brien, S.J. & Papezik, V. 1988: Precise U-Pb zircon dates from the Avalon Terrain in Newfoundland. *Can. J. Earth Sci., 25*, 442-453.

Levchenkov, O.A., Levsky, L.K., Nordgulen, Ø., Dobrzhinetskaya, L.F., Vetrin, V.R., Cobbing, J., Nilsson, L.P. & Sturt, B.A. 1995: U-Pb zircon ages from Sørvaranger, Norway and the western part of the Kola Peninsula, Russia. *Nor. geol. unders. Special Publ. 7*, 29-47.

Narbonne, G.M. & Aitken, J.D. 1995: Neoproterozoic of the Mackenzie Mountains, northwestern Canada. *Precambrian Research 73*, 101-121.

Narbonne, G.M., Kaufman, A.J. & Knoll, A.H. 1994: Integrated chemistratigraphy and biostratigraphy of the Windermere Supergroup, northwestern Canada: implications for Neoproterozoic correlation and the early evolution of animals. *Bull. Geol. Soc. Am. 106*, 1281-1292.

Pringle, I. 1973: Rb-Sr age determinations of shales associated with the Varanger Ice Age. *Geol. Mag. 109*, 465-472.

Raaben, M.E., Lyubtsov, V.V. & Predovsky, A.A. 1995: Correlation of stromatolitic formations of northern Norway (Finnmark) and northwestern Russia (Kildin Island and Kanin Peninsula). *Nor. geol.unders. Special Publ. 7*, 233-246.

Rice, A.H.N., Bevins, R.E., Robinson, D. & Roberts, D. 1989: Evolution of low-grade metamorphic zones in the Caledonides of Finnmark, N.Norway. *In*: Gayer, R.A. (ed.): *The Caledonide Geology of Scandinavia*, Graham & Trotman, London, 177-191.

Roberts, D. 1995: Principal features of the structural geology of the Rybachi and Sredni Peninsulas, Northwest Russia, and some comparisons with Varanger Peninsula, North Norway. *Nor.geol.unders. Special Publ.7*, 247-258.

Roberts, D. 1996: Caledonian and Baikalian tectonic structures on Varanger Peninsula, Finnmark, Norway, and coastal areas of Kola Peninsula, NW Russia. *Nor. geol. unders. Bull.431*, 59-65.

Roberts, D. & Sundvoll, B.A. 1990: Rb-Sr whole-rock and thin-slab dating of mylonites from the Kalak Thrust Zone near Børselv, Finnmark. *Nor. Geol. Tidsskr. 70*, 259-266.

Siedlecka, A. & Roberts, D. 1992: The bedrock geology of Varanger Peninsula, Finnmark, North Norway: an excursion guide. *Nor. geol. unders. Special Publ. 5*, 45 p.

Sokolov, B.S. 1995: The Vendian System and 'Neoproterozoic-III'. *In*: *Stratigraphy and Geological Correlation 3*, 6, 575-590 (English Translation).

Sokolov, B.S. & Fedonkin (eds.), 1985: *Vendskaya Systema 2, Stratigrafia i geologitcheskye procesy*. Nauka, 237 p.

Steiger, R.H. & Jager, E. 1977: Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology. *Earth Planet. Sci. Lett. 36*, 359-362.

Sturt, B.A., Pringle, I.R. & Roberts, D. 1975: Caledonian nappe sequence of Finnmark, northern Norway, and the timing of the orogenic deformation and metamorphism. *Geol. Soc. Am. Bull. 86*, 710-718.

Tucker, R.D. & Pharaoh, T.C. 1991: U-Pb zircon ages for late Precambrian igneous rocks in southern Britain. *J.Geol. Soc. London 148*, 435-443.

Vidal, G. 1981: Micropalaeontology and biostratigraphy of the Upper Proterozoic and Lower Cambrian sequence in East Finnmark, Northern Norway. *Nor. geol. unders. 362*, 53 pp.

Table 1. Mineralogical data for the sample # 1008/13 (Varanger Peninsula, Stangenes Fm.)

Size of particles µm	Weight proportion in the <2µm fraction per cent	Crystallinity index I_k non-standard. ° $\Delta 2\theta$	Illite polymorph	Illite per cent	Chlorite per cent	Impurities
1-2	22.4	0.40	$1M + 2M_1$	100	-	tr. of quartz
0.6-1	22.4	0.42	$1M + 2M_1$	100	-	-
0.3-0.6	26.3	0.52	$1M > 2M_1$	100	-	-
0.2-0.3	13.2	0.80	1Md + (1M)	100	-	
0.1-0.2	9.2	0.86	1Md	100	-	-
< 0.1	6.5	0.96	1Md	100	-	-

Table 2. Mineralogical data for the sample # 1004/3 (Varanger Peninsula, Nyborg Fm.)

Size of particles µm	Weight proportion in the <2µm fraction per cent	Crystallinity index I_k non-standard . °$\Delta 2\theta$	Illite polymorph	Illite per cent	Chlorite per cent	Impurities	Note*
1-2	20.9	0.70	$1M + 2M_1$	90	10	quartz + hematite + tr. of Fsp	I + I/S
0.6-1	22.9	1.02	1M	93	7	tr. of $2M_1$ illite	I + I/S
0.3-0.6	27.3	1.00	1M	95	5	tr. of hematite tr. of $2M_1$ illite	
0.2-0.3	15.3	0.90	1Md - 1M	> 95	< 5	-	
0.1-0.2	9.6	1.02	1Md	> 95	< 5	-	
< 0.1	4.0	0.92	1Md	100	tr.	-	

* I - illite; S - smectite.

Table 3. Mineralogical data for the sample # 1008/3 (Varanger Peninsula, Stappogiedde Fm.)

Size of particles μm	Weight proportion in <2μm fraction per cent	Crystallinity index I_k non-standard. °Δ2θ	Illite polymorph	Illite per cent	Chlorite per cent	Impurities
1-2	35.3	0.73	$1M + 2M_1$	80	20	quartz, tr. of Fsp
0.6-1	25.6	0.80	$1M + 2M_1$	80	20	quartz, tr. of Fsp
0.3-0.6	22.0	0.80	$1M + (2M_1)$	80	20	quartz, tr. of Fsp
0.2-0.3	5.9	0.90	1Md	90	10	-
0.1-0.2	9.2	0.90	1Md	> 95	< 5	
< 0.1	2.0	1.00	1Md	> 95	< 5	-

Age	Lithostratigraphic units and their thicknesses		
		Formation	Member
VENDIAN – CAMBRIAN – ORDOVICIAN	DIGERMULEN GROUP 1510–1555 m	Berlogaissa 300 m	
		Kistedalen 710–735 m	Grey quartzite 200 m Black shale 200 m Black quartzite 10–35 m Sandstone and shale 200 m Quartzite and shale 100 m
		Duolbasgaissa 500–520 m	Massive bedded quartzite 300 m Thin-bedded quartzite 200–220 m
	VESTERTANA GROUP, 1317–1655	Breivika 600 m	
		Stappogiedde 505–545 m ♦	Manndrapselva 190 m Innerelva 275 m Lillevatnet 40–80 m
		Mortensnes 10–60 m	
		Nyborg 200–400 m ● ♦	
		Smalfjord 2–50 m	

Age	Lithostratigraphic units and their thicknesses		
		Formation	Member
VENDIAN	TANAFJORDEN GROUP 1448–1665 m	Grasdalen 280 m	Upper Lower
		Hanglečærro 200 m	
		Vagge 80 m	
		Gamasfjellet 280–300 m	
		Dakkovarre 273–350 m	Ferruginous sandstone 130 m "k" member 62 m "j" member 46 m "i" member 35 m Quartzitic sandstone 60–80 m
		Stangenes 205–255 m ♦	
		Grønneset 130–200 m	
	VADSØ GROUP, 590–960 m	Ekkerøya 15–190 m	
RIPHEAN		Golneselva 50–135 m	
		Paddeby 25–120 m	
		Andersby 25–40 m	
		Fugleberget 125 m	
		Klubbnasen 50 m ●	
		Veinesbotn 300 m	

Figure 1. Lithostratigraphy of the Tanafjorden Group and the Vadsø Group (mainly after Siedlecka & Siedlecki 1971 and Banks et al. 1974) and of the Digermulen Group and the Vestertana Group (after Reading 1965). Dots indicate stratigraphic positions of datings by Pringle (1973), diamonds show datings presented in this paper.

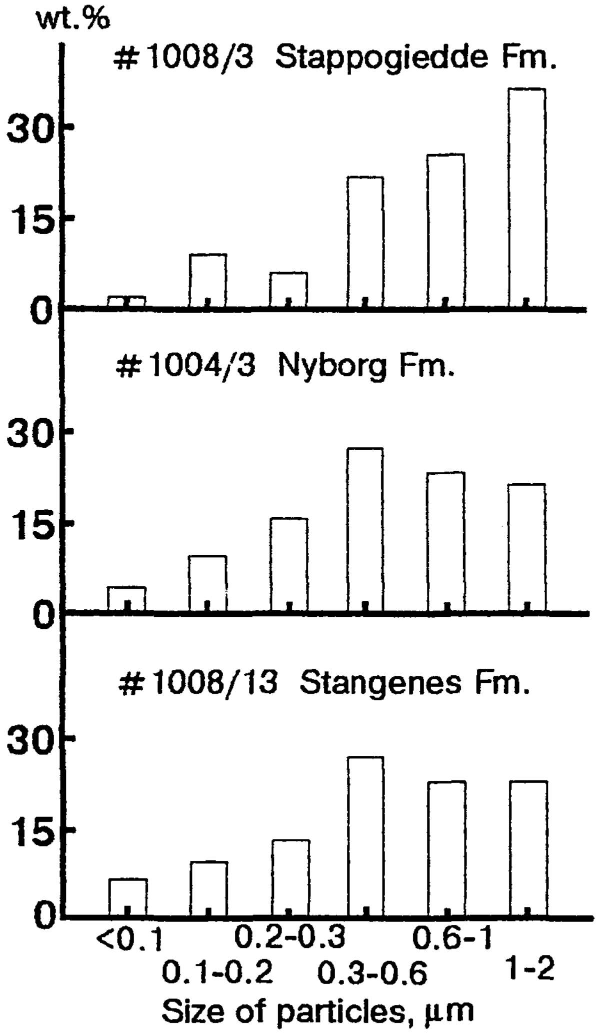

wt.%
#1008/3 Stappogiedde Fm.
30
15
0
#1004/3 Nyborg Fm.
30
15
0
#1008/13 Stangenes Fm.
30
15
0
<0.1
0.1-0.2
0.2-0.3
0.3-0.6
0.6-1
1-2
Size of particles, µm

Figure 2.

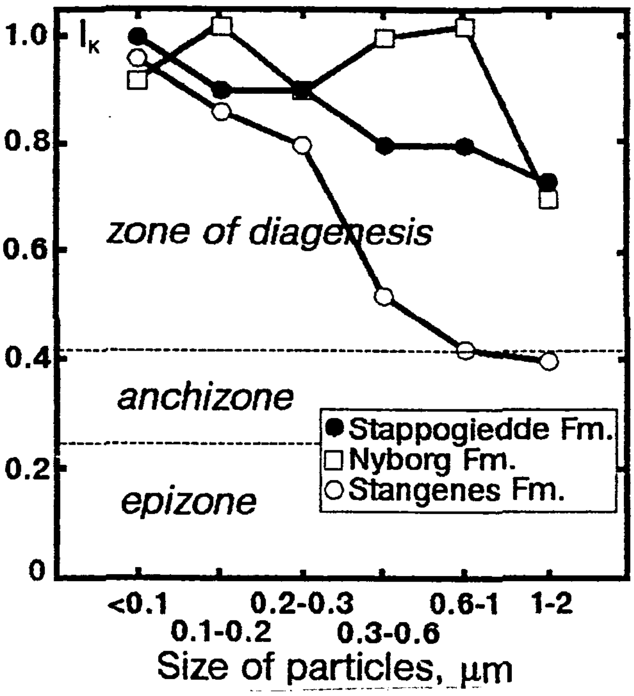
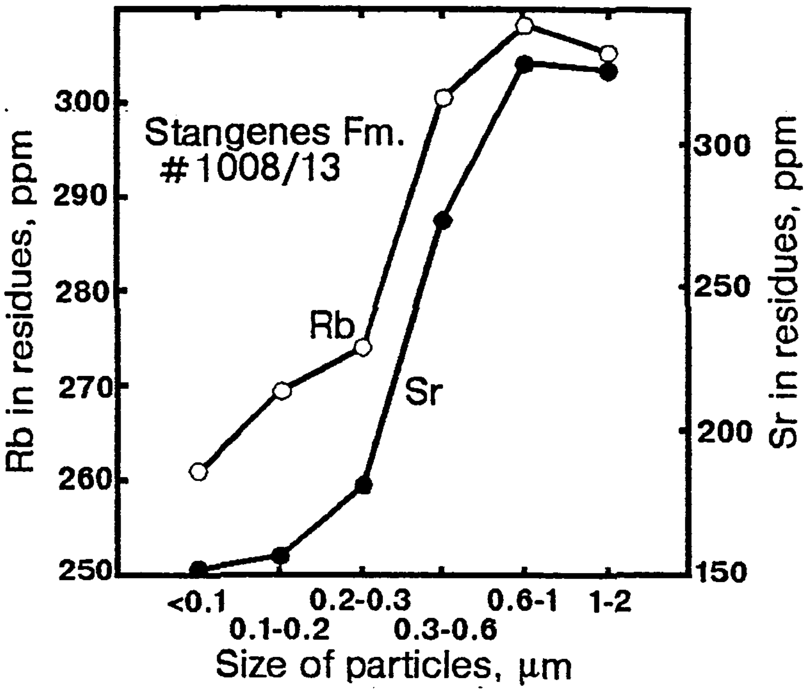


Figure 3.



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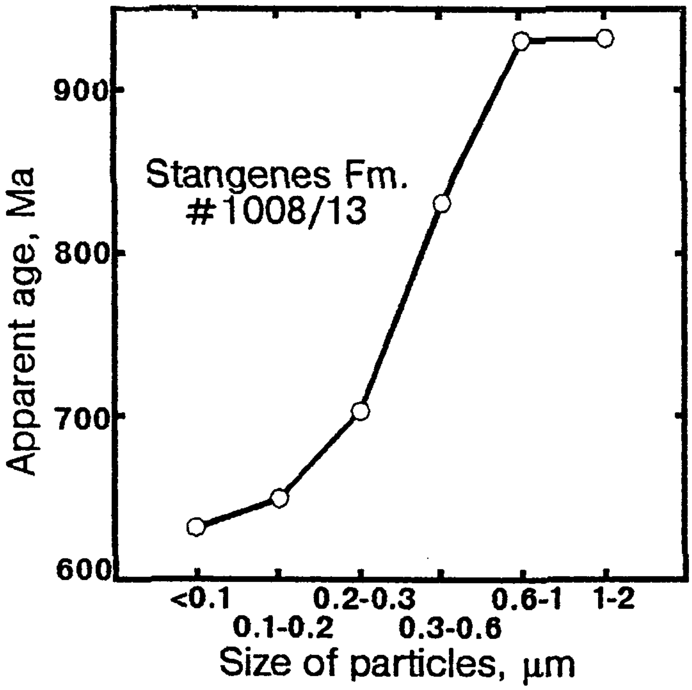


Figure 5.

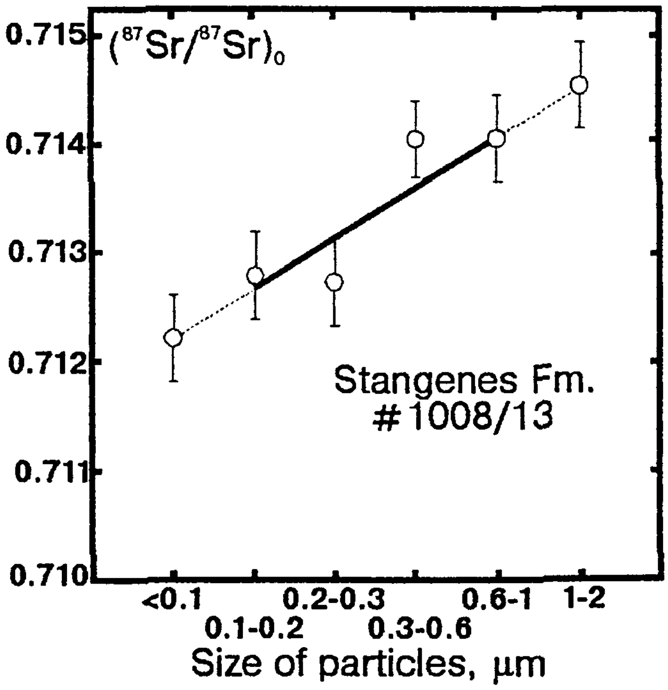


Figure 6.

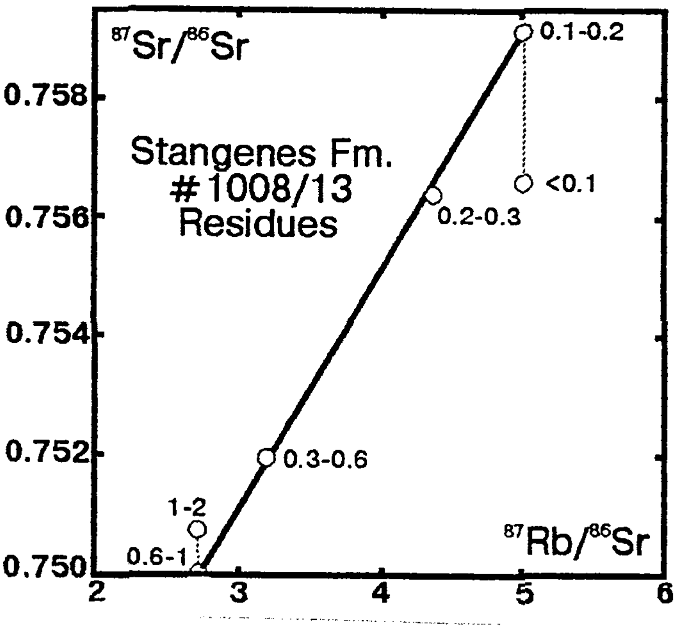


Figure 7.

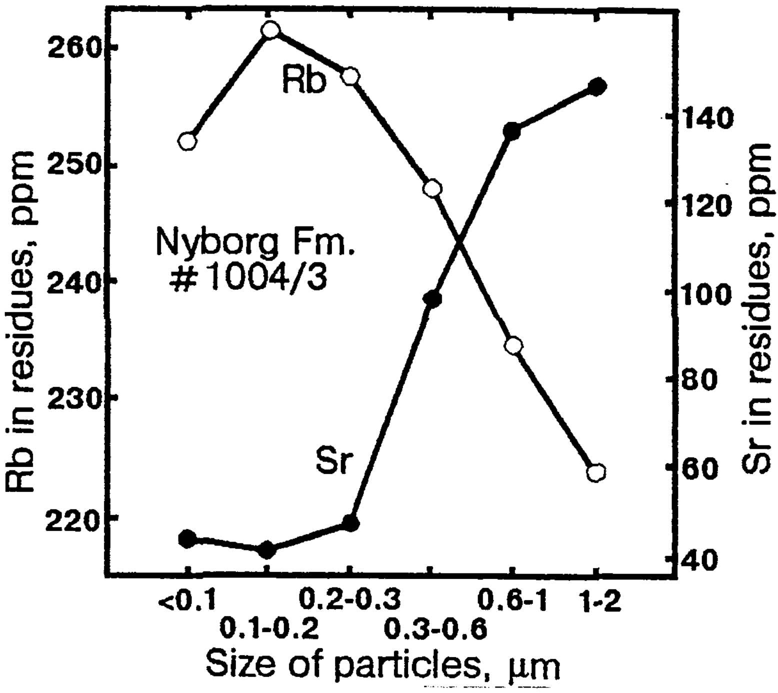


Figure 9.

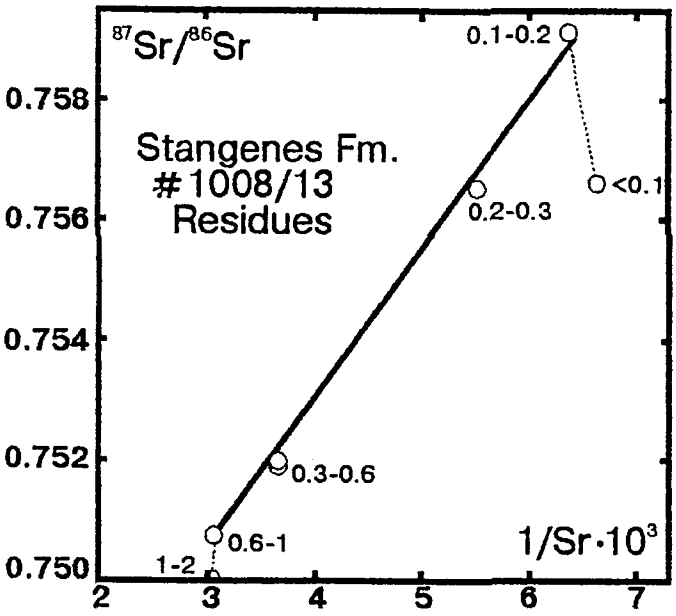


Figure 8.

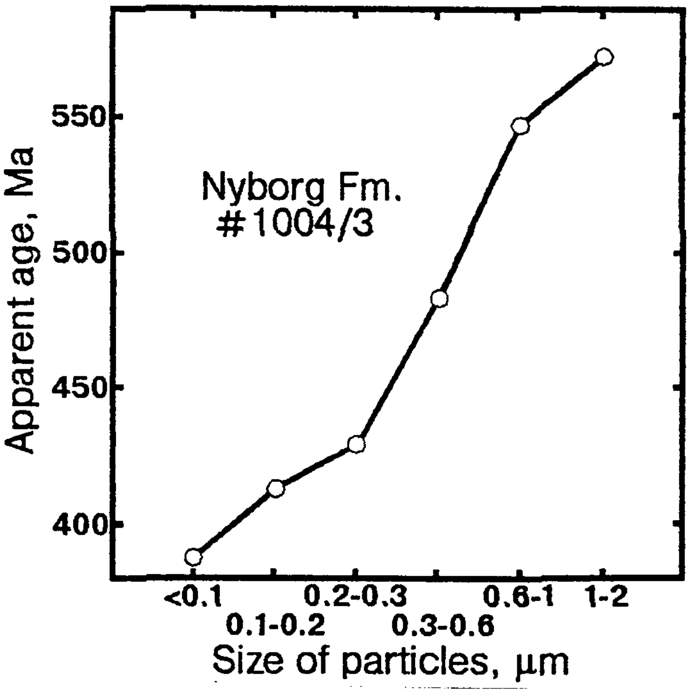


Figure 10.

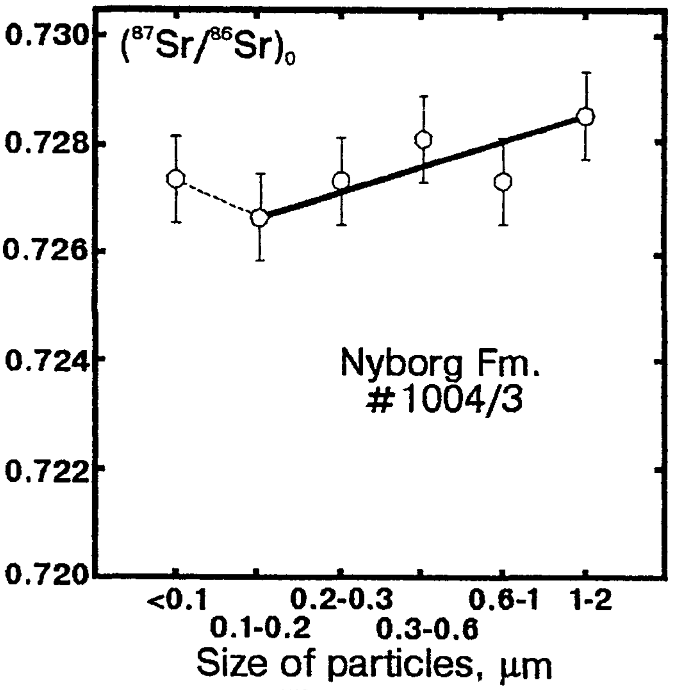
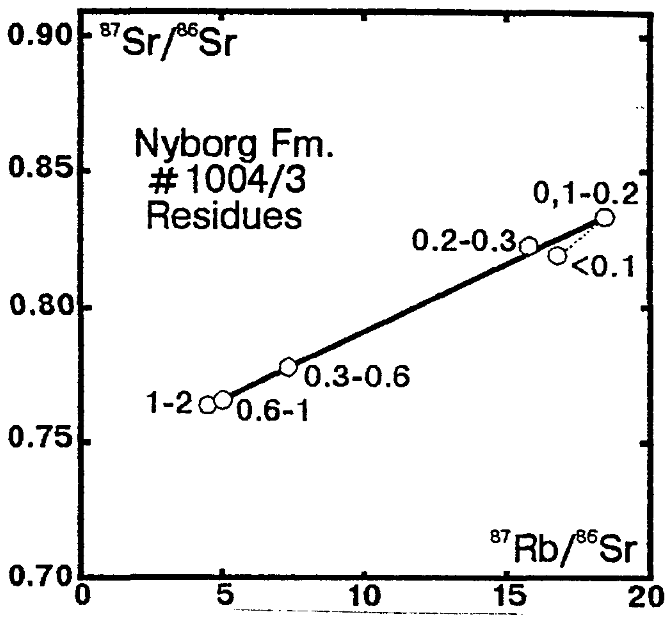


Figure 11.



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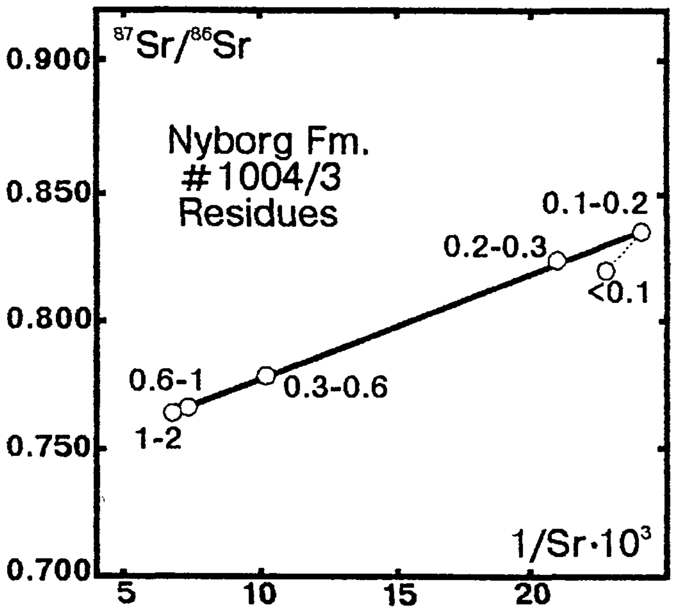


Figure 13.

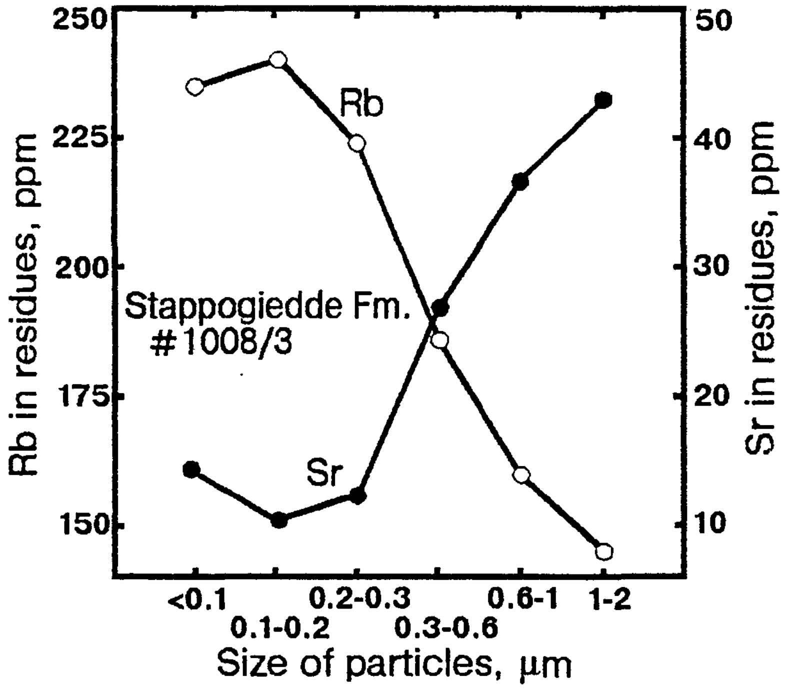
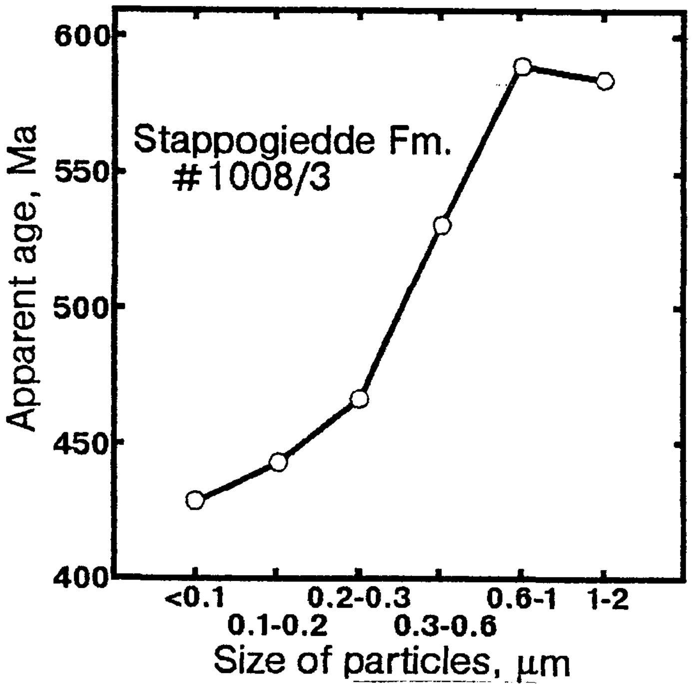


Figure 14.



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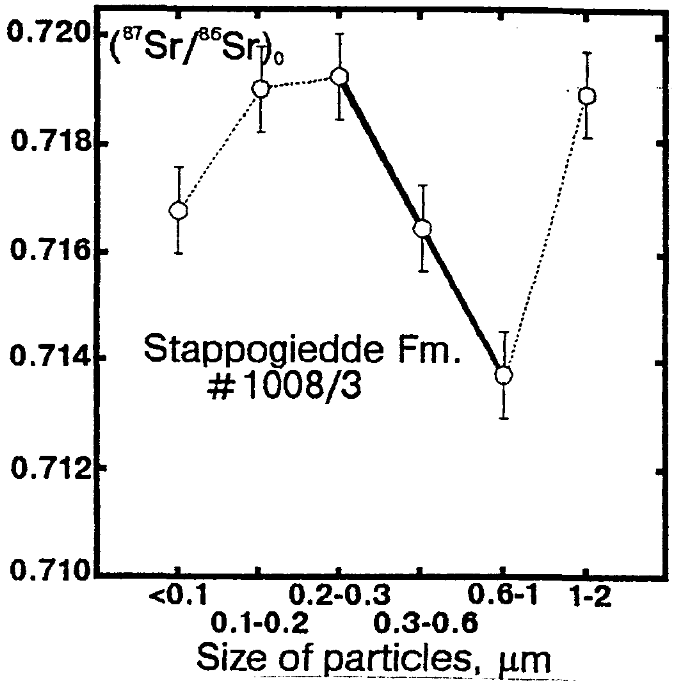


Figure 16.

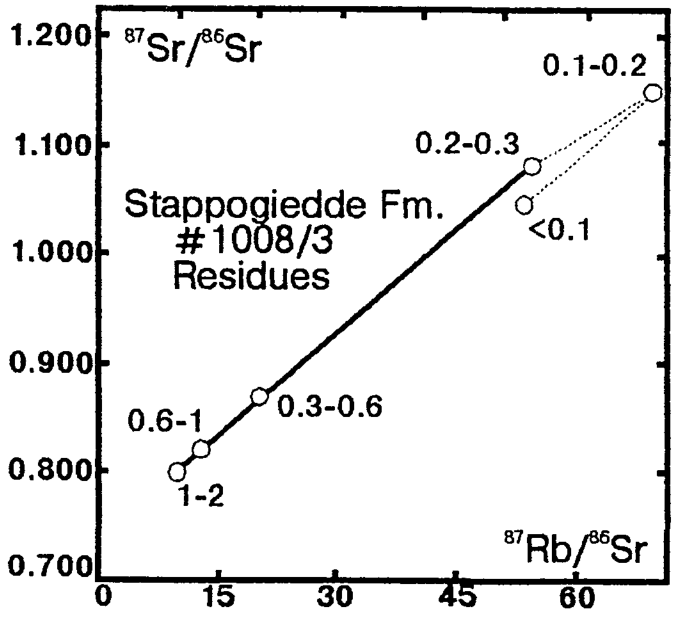


Figure 17.

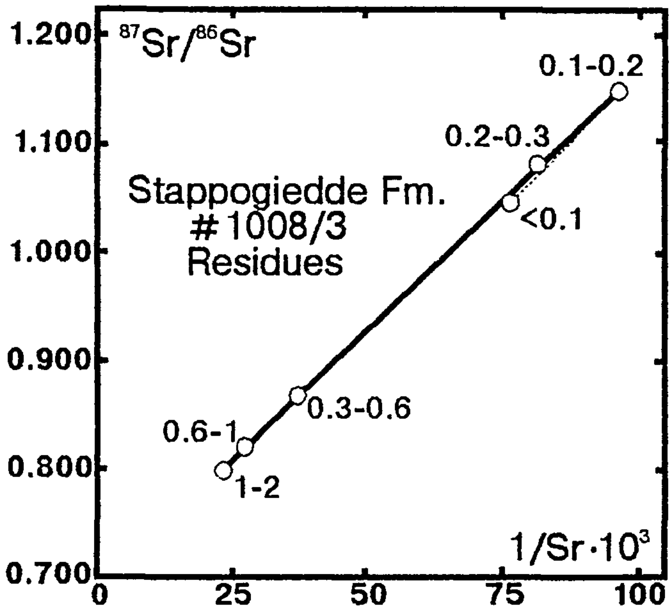


Figure 18.

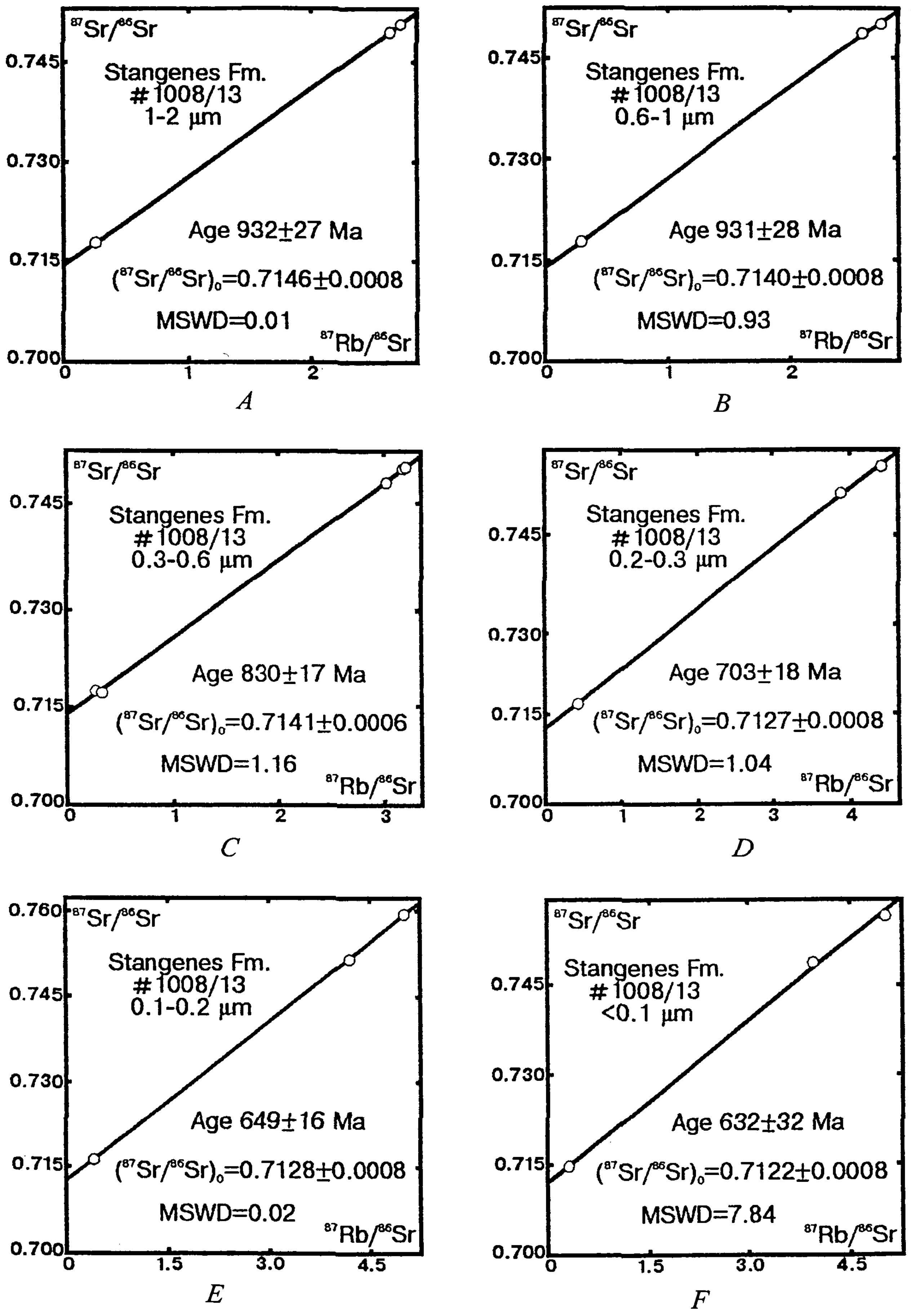

A
87Sr/86Sr
Stangenes Fm.
#1008/13
1-2 µm
Age 932±27 Ma
(87Sr/86Sr)0=0.7146±0.0008
MSWD=0.01
87Rb/86Sr
0.745
0.730
0.715
0.700
0
1
2
B
87Sr/86Sr
Stangenes Fm.
#1008/13
0.6-1 µm
Age 931±28 Ma
(87Sr/86Sr)0=0.7140±0.0008
MSWD=0.93
87Rb/86Sr
0.745
0.730
0.715
0.700
0
1
2
C
87Sr/86Sr
Stangenes Fm.
#1008/13
0.3-0.6 µm
Age 830±17 Ma
(87Sr/86Sr)0=0.7141±0.0006
MSWD=1.16
87Rb/86Sr
0.745
0.730
0.715
0.700
0
1
2
3
D
87Sr/86Sr
Stangenes Fm.
#1008/13
0.2-0.3 µm
Age 703±18 Ma
(87Sr/86Sr)0=0.7127±0.0008
MSWD=1.04
87Rb/86Sr
0.745
0.730
0.715
0.700
0
1
2
3
4
E
0.760
87Sr/86Sr
Stangenes Fm.
#1008/13
0.1-0.2 µm
Age 649±16 Ma
(87Sr/86Sr)0=0.7128±0.0008
MSWD=0.02
87Rb/86Sr
0.745
0.730
0.715
0.700
0
1.5
3.0
4.5
F
87Sr/86Sr
Stangenes Fm.
#1008/13
<0.1 µm
Age 632±32 Ma
(87Sr/86Sr)0=0.7122±0.0008
MSWD=7.84
87Rb/86Sr
0.745
0.730
0.715
0.700
0
1.5
3.0
4.5

Figure 19.

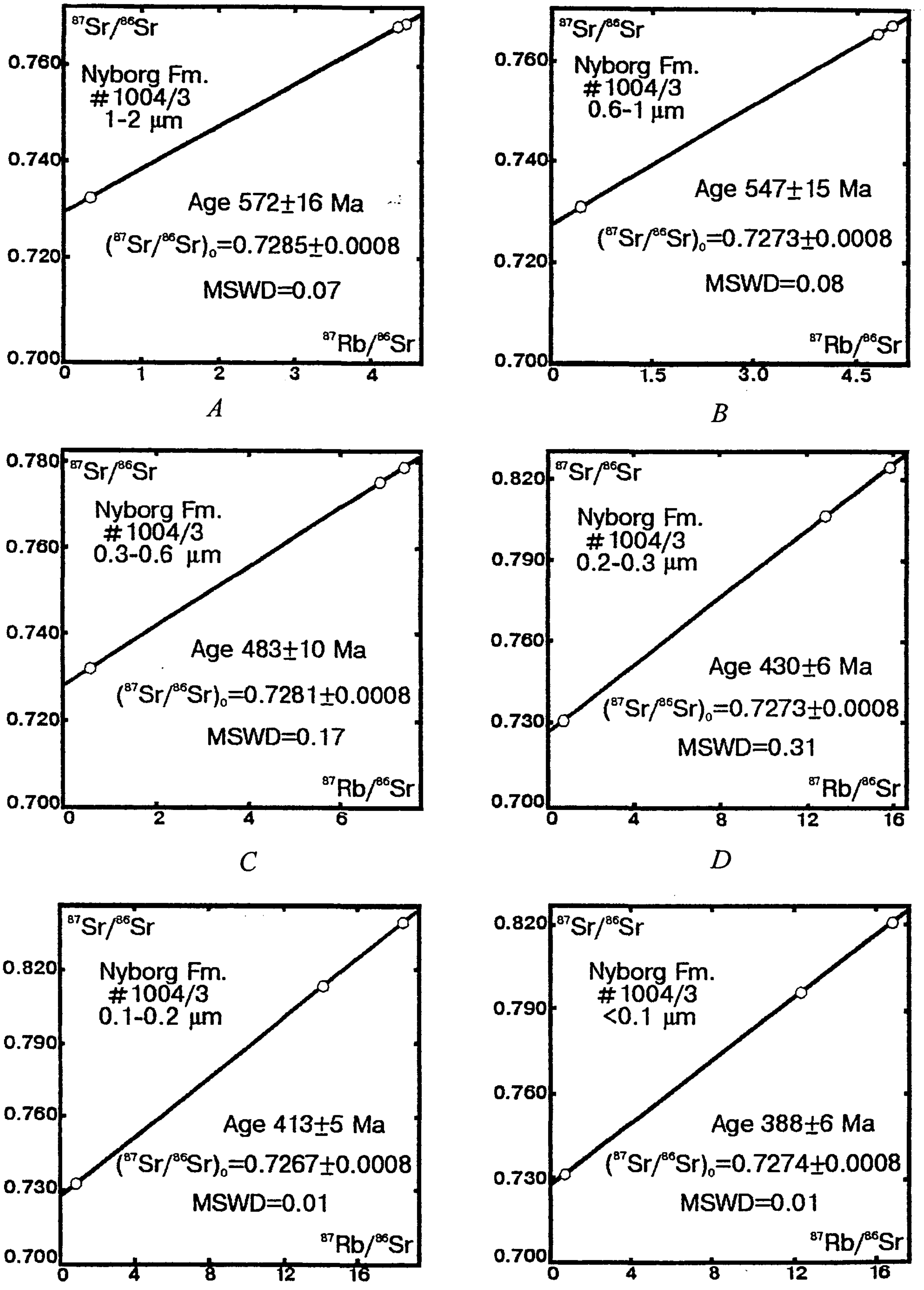
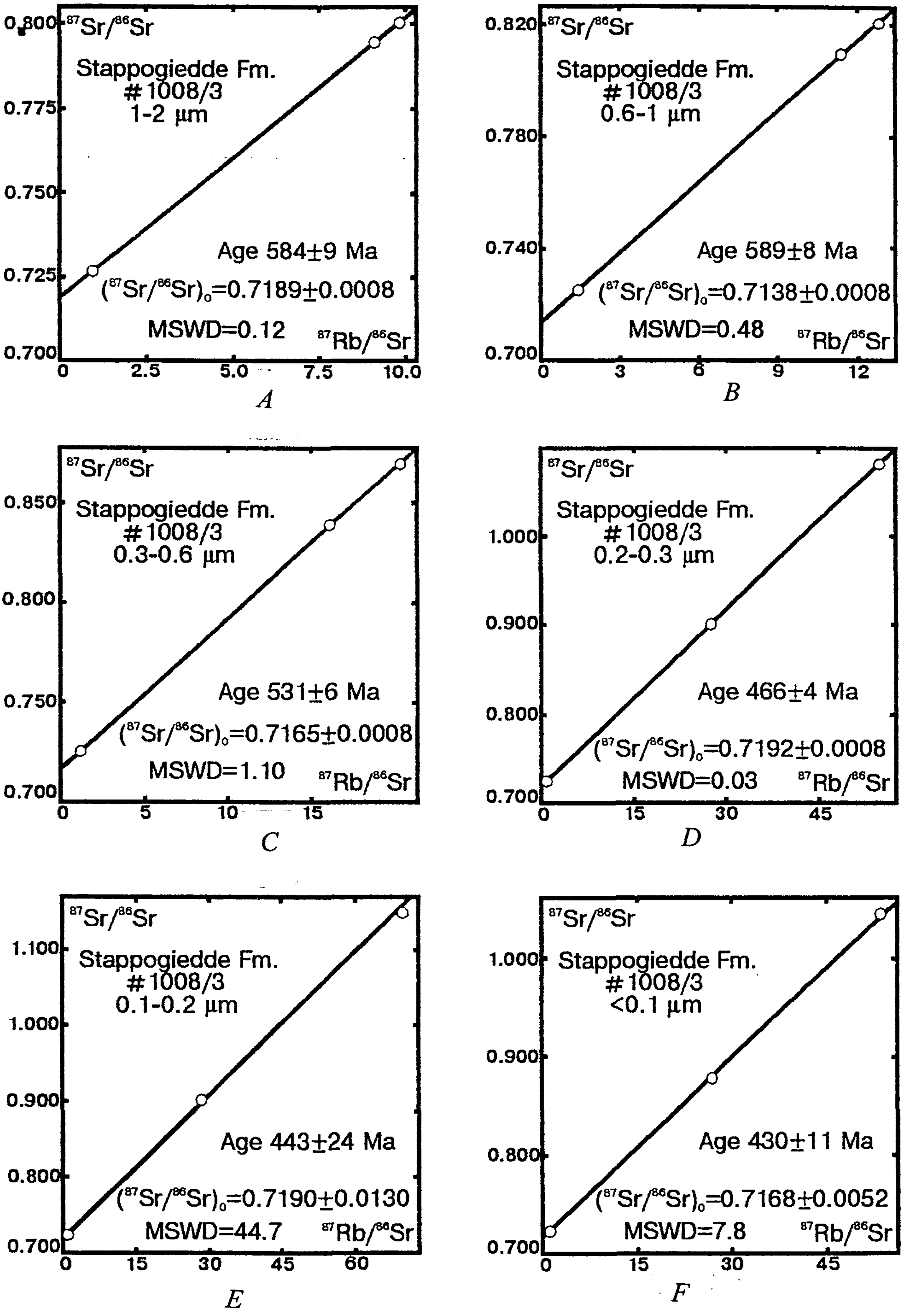

$^{87}Sr/^{86}Sr$
Nyborg Fm.
#1004/3
1-2 µm
Age 572±16 Ma
$(^{87}Sr/^{86}Sr)_0$=0.7285±0.0008
MSWD=0.07
$^{87}Rb/^{86}Sr$
0.760
0.740
0.720
0.700
0
1
2
3
4
A
$^{87}Sr/^{86}Sr$
Nyborg Fm.
#1004/3
0.6-1 µm
Age 547±15 Ma
$(^{87}Sr/^{86}Sr)_0$=0.7273±0.0008
MSWD=0.08
$^{87}Rb/^{86}Sr$
0.760
0.740
0.720
0.700
0
1.5
3.0
4.5
B
$^{87}Sr/^{86}Sr$
Nyborg Fm.
#1004/3
0.3-0.6 µm
Age 483±10 Ma
$(^{87}Sr/^{86}Sr)_0$=0.7281±0.0008
MSWD=0.17
$^{87}Rb/^{86}Sr$
0.780
0.760
0.740
0.720
0.700
0
2
4
6
C
$^{87}Sr/^{86}Sr$
Nyborg Fm.
#1004/3
0.2-0.3 µm
Age 430±6 Ma
$(^{87}Sr/^{86}Sr)_0$=0.7273±0.0008
MSWD=0.31
$^{87}Rb/^{86}Sr$
0.820
0.790
0.760
0.730
0.700
0
4
8
12
16
D
$^{87}Sr/^{86}Sr$
Nyborg Fm.
#1004/3
0.1-0.2 µm
Age 413±5 Ma
$(^{87}Sr/^{86}Sr)_0$=0.7267±0.0008
MSWD=0.01
$^{87}Rb/^{86}Sr$
0.820
0.790
0.760
0.730
0.700
0
4
8
12
16
E
$^{87}Sr/^{86}Sr$
Nyborg Fm.
#1004/3
<0.1 µm
Age 388±6 Ma
$(^{87}Sr/^{86}Sr)_0$=0.7274±0.0008
MSWD=0.01
$^{87}Rb/^{86}Sr$
0.820
0.790
0.760
0.730
0.700
0
4
8
12
16
F

Figure 20.



⁸⁷Sr/⁸⁶Sr
Stappogiedde Fm.
#1008/3
1-2 µm
Age 584±9 Ma
(⁸⁷Sr/⁸⁶Sr)₀=0.7189±0.0008
MSWD=0.12
⁸⁷Rb/⁸⁶Sr
0.800
0.775
0.750
0.725
0.700
0
2.5
5.0
7.5
10.0
A
⁸⁷Sr/⁸⁶Sr
Stappogiedde Fm.
#1008/3
0.6-1 µm
Age 589±8 Ma
(⁸⁷Sr/⁸⁶Sr)₀=0.7138±0.0008
MSWD=0.48
⁸⁷Rb/⁸⁶Sr
0.820
0.780
0.740
0.700
0
3
6
9
12
B
⁸⁷Sr/⁸⁶Sr
Stappogiedde Fm.
#1008/3
0.3-0.6 µm
Age 531±6 Ma
(⁸⁷Sr/⁸⁶Sr)₀=0.7165±0.0008
MSWD=1.10
⁸⁷Rb/⁸⁶Sr
0.850
0.800
0.750
0.700
0
5
10
15
C
⁸⁷Sr/⁸⁶Sr
Stappogiedde Fm.
#1008/3
0.2-0.3 µm
Age 466±4 Ma
(⁸⁷Sr/⁸⁶Sr)₀=0.7192±0.0008
MSWD=0.03
⁸⁷Rb/⁸⁶Sr
1.000
0.900
0.800
0.700
0
15
30
45
D
⁸⁷Sr/⁸⁶Sr
Stappogiedde Fm.
#1008/3
0.1-0.2 µm
Age 443±24 Ma
(⁸⁷Sr/⁸⁶Sr)₀=0.7190±0.0130
MSWD=44.7
⁸⁷Rb/⁸⁶Sr
1.100
1.000
0.900
0.800
0.700
0
15
30
45
60
E
⁸⁷Sr/⁸⁶Sr
Stappogiedde Fm.
#1008/3
<0.1 µm
Age 430±11 Ma
(⁸⁷Sr/⁸⁶Sr)₀=0.7168±0.0052
MSWD=7.8
⁸⁷Rb/⁸⁶Sr
1.000
0.900
0.800
0.700
0
15
30
45
F

Figure 21.