CHEMICAL AND ISOTOPIC REDISTRIBUTION IN ZONES OF DUCTILE DEFORMATION IN A DEEPLY ERODED MOBILE BELT

Part I

CHEMICAL REDISTRIBUTION

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Introduction

Faulting, volcanism, and hydrothermal activity are surface and near-surface manifestations of regional crustal instability represented at greater depth by ductile deformation, magma intrusion and magma genesis, metamorphism and migration of fluids. The purpose of the present note is to summarise the evidence for changes in the chemical composition which take place at depth when old continental crust is involved in younger tectonic and thermal activity since these changes must influence the physical properties of the rocks in which they occur. Three types of redistribution are considered:- changes in chemistry related to passage of fluids along fissures during retrograde metamorphism, redistribution of Rb and Sr as a guide to more regional changes, and generation of magmas at depth by partial melting of the crust. The examples described come from the Nagssugtoqidian mobile belt of East Greenland (Bridgwater 1976, Bridgwater & Myers, in press), however the features appear to be common to other deeply eroded zones of tectonic reworking in the crust. The main advantages of the Nagssugtoqidian mobile belt for this study are the lack of younger cover sequences and the almost complete exposure through the belt which allows the identification of units in a pre- and post tectonic state. The present erosion surface within the mobile belt corresponds to a section between 10 and 30 km deep in the mid-Precambrian crust, that is below the level at which brittle deformation took place. Both magmatism and the more diffuse migration of fluids within the mobile belt are intimately related to regional and local structural control. The converse must also be true since the structural properties of the rocks must also have changed in response to changes in bulk chemistry, recrystallisation and the local transfer to heat during the movement of magmas.

Regional setting

The Nagssugtoqidian mobile belt in East Greenland is part of a larger zone of tectonic activity, extending at least from NW Scotland through East and West Greenland to Baffin Island and Labrador. In this zone Archean rocks were affected by several phases of Proterozoic tectonic and magmatic activity. The overall crustal control of this tectonic activity is still a matter of speculation. As far as the Greenland-Labrador section is concerned the most convincing comparison to a modern plate tectonic regime is that put forward by Watterson (1978). He suggests that the Nagssugtoqidian tectonic activity represents deformation within a continental mass up to 1000 km in front of a major collision zone, perhaps comparable to present day tectonism in China resulting from the indentation of India into Asia along the line of the Himalayas.

In East Greenland the Nagssugtoqidian mobile belt (Figs. 1 and 2) is restricted to a 240 km wide zone of deformation trending approximately E-W, flanked to the north and south by Archean gneisses (Bridgwater et al., 1978). The belt was established approximately 2600 m.y. ago by the formation of vertical shear zones with transcurrent movements. These zones occur throughout the Archean North Atlantic craton. They show a marked increase in numbers and width of individual shear zones within the area which became the Nagssugtoqidian mobile belt. The transcurrent movements were accompanied by the intrusion of basaltic dykes. Within the mobile belt these now outcrop as irregular podded and branching intrusions of garnet-bearing metadolerite; the forms, internal structures and distribution of which suggest that dyke injection at depth was concentrated along active zones of deformation. Traced southwards into the Archean craton the dykes show a progressive change to more regular bodies less intimately associated with individual shear zones and probably emplaced at a higher level in more stable crust. Dyke injection and movements along transcurrent faults continued in the Archean craton from circa 2600 through to about 1900 m.y. (Kalsbeek et al., 1978). Calc-alkaline plutonic magmatism occurred near the centre of the mobile belt approximately 2300-2400 m.y. ago.

The mobile belt was affected by a second major phase of tectonic activity approximately 1800-1900 m.y. ago characterised by thrusting of Archean rocks from the north over the area previously affected by a concentration of transcurrent movements. The thrusts are marked by zones of deformation dipping 10°-15° to the north with a marked linear fabric parallel to the supposed movement direction (generally NW-SE). In the southern part of the mobile-belt the low-angle thrust zones are sharply defined, tens to a few hundreds of metres in width with knife-sharp margins against the unmodified Archean gneisses and dykes. The fabric within the shear zones suggests extreme deformation with feldspar augen in a finely comminuted ground mass of quartz, feldspar and epidote. Towards the centre of the mobile belt the thrust zones become broader, more diffuse and show recrystallisation under amphibolite facies conditions. In the northern part of the mobile belt overfolding rather than thrusting dominates the structures formed during this second phase of Proterozoic movement within the Nagssugtoqidian mobile belt. This change from sharply defined narrow zones of intense deformation through to less well defined deformation zones and folding are thought to reflect the depth now exposed at the present erosion surface.

The piling-up of thrust slices lead to considerable crustal thickening. Granulite facies metamorphic conditions were reached in the centre of the mobile belt where hypersthene-bearing gneisses form a broad aureole surrounding syntectonic norite and charnockite intrusions. The aureole rocks locally become mobilised forming a series of garnet granites. Post-tectonic intrusions of mixed acid-basic suites were emplaced in the thickened crust near the centre of the mobile belt between 1500 and 1600 m.y. ago.

Chemical and isotopic mobility in the mobile belt

Extreme deformation and tectonic dislocation makes it impossible to follow individual units on a regional scale. Studies on possible changes of chemistry during deformation therefore have either to be done using a massive statistical approach or on an outcrop scale where there is a chance to maintain control of which units are studied. A strictly statistical approach would be irresponsible in an area like the Nagssugtoqidian since the logistics of collecting and analysis would be impossibly expensive. Furthermore as different levels of Archean crust are preserved within and outside the belt even when complete one could never be certain that the populations sampled were originally the same. In this study the emphasis is therefore on restricted parts of the mobile belt chosen to represent different degrees of tectonic and chemical reworking. Chemical and isotopic results are presented from one locality in which retrogressed Archean granulite facies gneisses are affected by shearing accompanied by further retrogression. As a measure of general mobility within the mobile belt isotopic results are presented from three other localities to show the degree of isotopic re-equilibration which occurs at depth in an area of tectonic activity and crustal thickening (Pedersen and Bridgwater, in press).

Chemical and isotopic mobility along early Nagssugtoqidian shear zones

The northern half of Store (locality 1, fig. 2) consists of Archean hypersthene-bearing tonalitic gneisses which are interlayered and intrude earlier sequences of supracrustal rocks (basic volcanic, pelites, minor amounts of quartzites, ultrabasic masses and layered meta-gabbros). Away from the contacts with the supracrustal horizons the tonalites are fairly homogeneous on outcrop scale and show the same general chemical and lithological characters as the granulite facies rocks of the Archean craton extending for 250 km to the north. Both supracrustal rocks and the tonalites were affected by granulite facies metamorphism and yield a Pb-Pb whole rock age of 2750 ± 150 m.y. (Taylor in Bridgwater et al., 1978), comparable to that from granulites in the main areas of Archean granulite south of the mobile belt (Black et al., 1973). The Archean granulite facies gneisses on Store are preserved as part of a lens flanked on either side by Nagssugtoqidian shear belts in which a marked fabric is impressed on the rocks and in which amphibolite facies minerals are developed. In the field the granulites weather brown due to the breakdown of magnetite while the amphibolite facies weather white. On mountain side exposures the shear zones are seen to be surrounded by transitional areas up to several hundreds of metres wide in which the granulites are retrogressed along a network of fracture planes without marked deformation of earlier fabrics.

The southern end of Storø is composed of amphibolite facies gneisses formed by retrogression of earlier granulite facies assemblages either in shear zones or in more diffuse zones associated with the shearing. The shear zones vary from broad belts several hundreds of metres across to minor structures less than a metre wide. Three small shear zones were chosen for detailed analysis. These trend at approximately 130°/V at a high angle to earlier layering. Each has a central zone approximately 10 cm wide in which the original fabric of the host rock is completely obliterated, surrounded by a 50 to 100 cm zone in which the original fabric is rotated (see fig. 3). Strain measurements calculated (J. Watterson) from the rotation of the lithological banding are shown in fig. 4.

The gneisses surrounding the shear zones consist of slightly foliated tonalite and granodiorite gneisses with a restricted range in chemistry on the outcrop scale and virtually homogeneous on a scale of 15-20 cm^2, the surface area of individual samples. Occasional trondhjemite veins cut the unsheared gneiss. In the 50 to 100 cm zone on either side the shear zones the country gneisses become markedly less homogeneous. Ill defined light and dark layers are developed parallel to the rotated earlier foliation. In the shear centres there is a 10 cm zone of highly deformed rock with a linear fabric and marked inhomogenuity with feldspathic blebs and schlieren. The bulk composition of the centre is identical with the outer zones of the shears and there is no evidence for material injected as magmas along the shear planes.

Eighteen samples were collected from the shear zones and their immediate country rocks. Twelve of these were cut from elongate blocks collected at right angles to the shear zones and extending outwards for up to 1 m from the shear centres (at which distance no rotation is seen in the pre-shear fabric). Five samples were collected along the strike of the shears to control possible variations in composition of the most highly sheared rocks. Five samples of country rock and one pre-shear trondhjemite vein were collected from 5 to 20 metres away from the shears. Individual samples weighed over ten Kilograms before crushing. The sampling was meant to cover the area in which the maximum changes in chemistry from unsheared rock were expected to take place. I thought this should occur in the same rocks in which major changes in structure occurred, that is within a metre of individual shear zones. As will be shown from the results described later the zone of chemical change is much wider than anticipated and the transition between unaltered and altered rock occurs between one and five metres from the shears, in parts of the outcrop not sampled.

Petrology of the samples

The dominant country rock five metres or more from the shear zones is a tonalite with a very poorly developed foliation in the field and in hand sample. In thin section no preferred orientation is seen. Mafic minerals (biotite, magnetite, hornblende and garnet) are concentrated in patches about 5 mm in diameter separated from each other by 10 to 15 mm in a ground mass of quartz and plagioclase feldspar. The mafic minerals are intergrown with each other and with quartz and feldspar. This texture is common in granulite facies rocks which have been retrogressed without developing a new fabric (Collerson and Bridgwater, 1979). Quartz and feldspar show considerable variation in grain size thought to be due to grain size reduction during strain. Many of the quartz and feldspar grains show strain. Whether the grain size reduction and strain seen in the quartz and feldspar was developed in these rocks at the same time as the shear zone was formed is not known.

The rock-forming minerals in the country rocks are quartz, plagioclase, biotite, hornblende, magnetite with ilmenite lamella, and garnet. Typical mineral analyses are given in table 1. K-feldspar is generally restricted to antiperthitic blebs in plagioclase and a few interstitial grains. Small patches of secondary alteration with muscovite occur locally, zircon is a common accessory mineral. Both subhedral and rounded grains are present. Preliminary fluid inclusion studies (J. Konnerup-Madsen, Institute of Petrology, Copenhagen University) show C02 in fluid inclusions from the country rocks. This is in agreement with the textural evidence that the rocks have been in granulite facies.

Rocks from the centres of the shear zones show a marked foliation and linear fabric. In thin section there is a marked preferred orientation seen in all major minerals. Quartz and feldspar form ellongate strings made of several grains. The grain size is variable, there appears to have been considerable annealing particularly in the centres of the shears.. Biotite, hornblende and garnet are commonly slightly more iron rich than those seen in the minerals from the surrounding country rocks, plagioclase is more sodic. There is a marked increase in K-feldspar which is found as independant grains of microcline. Scapolite and muscovite are locally rock forming minerals. Hematite or altered hematites are the only opaque minerals. Zircons are common as an accessory mineral. Preliminary studies of separated grains has not revealed major differences in morphology of zircons from the shear zones and from the unsheared rocks.

Preferred orientation is not so marked in the rocks within 10–100 cm from the shear zone centres. The mineral compositions from the gneisses 1–100 cm from the shears are in the same range as those found in the shear centres. Fluid inclusions are small and contain water plus halite.

Chemistry of the gneisses

The chemistry of five representative samples is given in table 2. The results from all the samples analysed are illustrated as histograms in which the five rock samples away from the shear zone are contrasted with the sheared rocks and their immediate country rocks (Fig. 5). Assuming that the sampling was not biased in any way it is clear that there are major differences between the shear zones and their immediate country rocks as one group and the country rocks 5-20 metres away. There are no consistent differences between the centres of the shear zones and the country rocks up to a metre from the shear centres.

The shear zones and their immediate country rocks show a marked increase in K and Rb also seen in the increase in potash feldspar and an increase of biotite compared to other mafic minerals. The increase in Rb is sporadic, material from one of the shear zones shows on average an increase of four times that seen in the country rocks and twice that found in the other shears. Ba and Pb show a overall increase but a greater spread in the sheared rocks. Abundance of both these elements are thought to be controlled by the amount of potash feldspar which varies considerably in the sheared gneisses. There is a marked increase in Cl, and S as sulphate both of which enter scapolite in the sheared rocks. Sulphur as sulphide decreases, accompanied by marked loss of Cu and possibly Ni. Zn remains constant, probably indicating that this element is not concentrated in a sulphide phase. Calcium decreases in the shear zones, presumably related to the breakdown of the more calcic plagioclases found in the shears and the formation of scapolite. Sodium and aluminium show a less marked decrease. Zr decreases markedly. It has not been possible to show whether this is due to a decrease in modal zircon or whether it could be due to changes in Zr content of, for example, the amphiboles or biotites. Although zircons are generally regarded as highly refractory minerals zirconium is soluble in halogen-rich peralkaline fluids and was presumably removed during the passage of Cl and K rich solutions. There is an apparent loss in total volatiles as measured by loss on ignition corrected for oxidation of iron. No consistent change from ferrous to ferric iron was noted from the analyses inspite of the mineralogical change seen from magnetite to hydrated ferrous oxide.

One of the most marked features of the study was the sporadic nature of the changes associated with shearing. This is particularly true of trace elements which show a considerably greater spread in values in the shear zones and their immediate surroundings compared to their country rocks. The sporadic nature of redistribution of trace elements seems to be a general feature of sheared rocks and results in very poor inter-element correlation (cf. Beach and Tarney, 1978). Presumably local factors both in the availability of a particular element, the nature of the transporting fluid and in suitable sites to capture the element play a much more important role in metasomatic processes than they do in igneous crystal fractionation.

Correlation between the gneisses on southern Stora with any particular unit within the unretrogressed Archean granulite facies gneisses in the northern part of the island or elsewhere is not demonstrable in the field. There are no distinctive marker horizons on a regional scale and although the quartzo-feldspathic gneisses are remarkably homogeneous there can be local variations as large as any differences which could be the result of retrogression. Any comparison must therefore be based on the assumptions that the collection of material from the granulite facies rocks was not biased and that the rocks from southern Stora represented part of the normal range of granulite facies gneisses before they were retrogressed. I have no reason to doubt these assumptions, Fig, 5 shows the major chemical and available trace element data from 8 samples of granulite facies gneisses from the high graa enclave of which Stora forms the southern margin. Seven of the sampled gneisses are markedly more basic than any of the retrogressed gneisses from Stora. The only rock which overlaps with the Storø gneisses in chemistry is a banded gneiss with pegmatitic layers which is clearly migmatitic and which cannot be regarded as a likely parent for the essentially homogeneous country rocks surrounded the Storø shear belts. Granted the assumption that granulites and retrogressed granulites once formed part of a single population it is apparent that retrogression was accompanied by very considerable changes in composition. The retrogressed country rocks from the same outcrop as the shear zones on southern Store appear to represent approximately halfway stages in a much larger change from granulites with stable orthopyroxene, andesine, quartz and magnetite as major minerals through to the shear zone rocks. Changes in the order of the addition of 2% K_2O and 2.5% SiO_2 and a loss of 1% FeO, 0.5% MgO and 0.8% CaO can be suggested (neglecting corrections due to components adding to 100%). These changes are close to those suggested by Ramberg (1951) from the Nagssugtoqidian of West Greenland and Beach (1973, 1976) from the Lewisian of Scotland, except that there is little consistent chemical evidence in the present study for increase in total volatiles or oxidation of iron. If these figures are even approximately correct then the amount of material moved during retrogression is enormous. One cubic metre of granulite facies gneiss gains on average between 100 and 120 kilograms SiO_2 plus K_2O while about 50 kg FeO plus CaO and MgO are lost. Retrogression results in a decrease in density between 2 and 4%, which in turn would have considerable effects on the tectonic stability of the region.

In summary the main changes which take place during retrogression and shearing are due to movement of alkalies, silica and halogens. The movement of this material must have involved very large amounts of fluids (cf. Beach and Fyfe, 1972). At the erosion level studied the fluids deposited K, Rb, Cl, Si and possibly Ba and Pb. They removed Ca, Na, Mg, Zr, heavy metals from sulphides, and oxidised S and Fe_3O_4. Redistribution of material was sporadic and although there is a general change from unretrogressed granulites through to the sheared rocks for the changes outlined above some elements, for example Na and Mg, show major changes during the first regional stages in retrogression while others show more marked changes in close proximity to shear zones. The derivation of the fluids, which are probably the most important factor in controlling the retrogression and addition or redistribution of the various elements, is not known. There is no evidence in the area studied for large masses of water-bearing crustal material being tectonically emplaced beneath the Archean granulites (cf. Beach and Fyfe, 1972). Water could be derived from underlying granulites by a process of further dehydration possibly related to emplacement of mantle-derived magmas, but it seems rather unsatisfactory to explain the hydration of one group of granulites by the dehydration of a second without good cause. In spite of the oxidising nature of the fluids I prefer a mantle source simply on the grounds of the enormous volume necessary. Whatever the source, passage of chemically active fluids through the crust during periods of active deformation must play a very important role in controlling the type of deformation. It cannot be assumed that recrystallisation along shear planes is isochemical. The rate at which many of the most abundant minerals such as feldspar and quartz recrystallise will depend to a large degree on the chemical properties of the intercrystal fluids. The depth at which the transition between ductile and brittle fracture takes place in any shear zone should be controlled by the ease at which recrystallisation occurs. In a modern context it would perhaps be interesting to see whether there is correlation between depth of earthquake centres and hydrothermal activity in areas of transcurrent faulting. One might expect a shallower cut-off of seismic activity in areas where there is evidence for upward migration of fluids along fault controlled features.

Part II

Rb-Sr ISOTOPIC STUDIES

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Isotopic studies of rocks from areas of crust of one age which have been involved in later tectonism can give considerable information about the extent of element mobility at depth during metamorphism, metasomatism and magma genesis. The degree to which Rb-Sr systems re-equilibrated in a deeply eroded mobile belt such as the Nagssugtoqidian should give an indication about what may be happening 30 km below the present surface in areas of recent tectonism, for example, western America.

Four suites of rocks have been studied (Pedersen and Bridgwater, in press) the results of which are summarised below.

Rb-Sr STUDIES ON GNEISSES FROM THE STORØ SHEAR ZONES

Rb-Sr data from the shear zones, their immediate country rocks and unsheared amphibolite facies material approximately 2 km away all fall close to the same 2630 m.y. isochron (fig. 6). There is no detectable difference between sheared and unsheared rocks in spite of the evidence of considerable Rb addition in the shear zones. This implies that the Rb addition and therefore the shearing took place at about 2600 m.y., soon after the regional granulite event, unless ^{87}Sr was added in the same proportions to individual samples as Rb. We cannot completely dismiss this possibility. Recent work on metamorphosed basic dykes intruded into earlier tonalites (Bridgwater, Collerson and Pedersen, in prep.) has shown that there was a marked increase in the $^{87}Sr/^{86}Sr$ ratio at the dyke margins. This took place during recrystallisation of earlier assemblages of intermediate feldspar to sodic feldspar with the formation of epidote and scapolite, comparable to the mineralogical changes reported in the Storø shear zones.

Rb-Sr studies on gneisses affected by Proterozoic granulite facies events

A series of garnet-bearing granitic gneisses is found near the centre of the mobile belt (fig. 2, locality 2), formed by the recrystallisation of a mixed group of Archean metasediments and tonalitic intrusions in the granulite-facies thermal aureole surrounding a norite-charnockite complex. The Archean rocks maintain their gross lithological layering on a scale of tens to hundreds of metres but on outcrop scale show considerable signs of remobilisation and partial melting. Available information from other parts of the Archean craton suggest that mixed sequences such as this show a common age and Sr initial ratio of about 2800 m.y. and 0.701 although rocks making up the complex are of very different provenance.

Samples were taken across strike from five localities at distances between 8 and 3 km from the norite complex at the present erosion level. The Rb-Sr results show considerable scatter about a 1950 m.y. reference isochron (fig. 7). The samples furthest away from the norite-charnockite complex show the worst fit to the isochron. The results show that Sr isotopic homogenisation is imperfect on the scale sampled. As the intrusion is approached the regional homogenisation became better possibly reflecting Sr mobility on a larger scale. This data gives some indication of what degree of Sr isotope homogenisation is taking place in a thermally active area 30-40 km below present day tectonic zones.

Archean tonalites with basic inclusions from the centre of the mobile belt

The third group of samples is taken from a single outcrop of Archean gneisses 20 x 10 m on the west side of Angmagssalik Ø (fig. 2, locality 3). The rocks in this area can be assumed to have been under conditions approaching granulite facies metamorphism at 1900 m.y. although very few show marked signs of recrystallisation apart from local annealing. There is no evidence of strong late tectonic movements at this locality, or obvious sources of local heating from late intrusions. The gneisses at locality 3 are strongly banded rocks with dark and light layers representing tonalitic intrusive material and inclusions of earlier basic material. They are assumed before involvement in the Nagssugtoqidian to have had a common Rb-Sr age and Sr-initial ratio of 2800 m.y. and 0.701 respectively. The Rb/Sr ratios are low, averaging about 0.036 so that the amount of radiogenic Sr developed between 2800 and 1900 m.y. ago is not large. Ten samples each weighing over 5 kilograms were collected. These were halved at right angles to the foliation and one half treated as a whole rock sample, the other half was split into individual layers. The resulting Rb-Sr diagram is shown in fig. 8. Data points scatter about a 1875 m.y. reference isochron. Samples weighing above 1 kg fall above the isochron but do not define an older age line. Smaller samples lie closer to the reference isochron. The data suggests that quartzo-feldspathic gneisses may not respond completely to a younger thermal event on a scale larger than a few centimetres unless they are strongly recrystallised either under partial melting conditions or in zones of intense tectonic movement.

Rb-Sr isotopic studies on a post tectonic intrusion

The rocks studied are taken from a mixed acid-basic intrusion Prom the northern part of the Angmagssalik area (fig. 2, locality 4). The samples range from hornblende-gabbros through to potash-rich granites. There is field and chemical evidence that two magmas were involved, a basic presumably mantle derived component and an acid component of unknown origin. The Rb-Sr determinations give an age of 1583 ± 27 m.y. for these rocks and Sr initial ratio of 0.7035 (fig. 9).

The data from both acid and basic components fall on the same isochron within experimental error and there is thus no isotopic evidence of a crustal component involved. However the Rb/Sr ratios of the gneiss complex forming the country rock are low (less than 0.04) and it is doubtful whether 2800 m.y. basement rocks remobilised at 1550 m.y. would be distinguishable from mantle derived magmas by Rb-Sr methods. The geological setting of the plutons in an area of previous crustal thickening and the petrological evidence that the acid and basic components crystallised from different magmas strongly suggest that there may be crustal material involved in the formation of granitic parts of these intrusions.

Summary

The Rb-Sr studies on the Nagssugtoqidian of East Greenland suggest that homogenisation of Sr isotopes in areas of older crust during younger tectonic and metamorphic events is limited. The only rocks which show Sr isotope homogenisation on a scale of more than a few centimetres are those in which there has been appreciable partial melting or major transport of fluids (such as suggested during the retrogression of granulite facies rocks). The results from East Greenland are comparable to those obtained during parallel studies from the West coast Nagssugtoqidian [Kalsbeek and Zeck, 1978, Hickman, in press).

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References

(combined Bridgwater and Bridgwater & Pedersen)

Beach, A. 1973: The mineralogy of high temperature shear zones at Scourie, NW Scotland. J. Petrol., 14, 321-248.

Beach, A. 1976: The interelationships of fluid transport, deformation, geochemistry and heat flow in early Proterozoic shear zones in the Lewisian complex. Phil Trans. R. Soc, London, A280, 569–604.

Beach, A. & Fyfe, W.S. 1972: Fluid transport and shear zones at Scourie, Sutherland: evidence of overthrusting? Contr. Mineral. and Petrol. 33, 227–231.

Beach, A. & Tarney, J. 1978: Major and trace element patterns established during retrogressive metamorphism of granulite-facies gneisses, NW Scotland. Precambrian Res. 7, 325-348.

Black, L.P., Moorbath, S., Pankhurst, R.J. & Windley, B.F. 1973: ^{207}Pb/^{206}Pb whole rock age of the Archaean granulite facies metamorphic event in West Greenland. Nature, phys., Sci., vol. 244, 50-53.

Bridgwater, D. 1976: Nagssugtoqidian mobile belt in East Greenland. In Escher, A. & Watt, W.S. (edit.) Geology of Greenland. Copenhagen, 97–103. Geological Survey of Greenland.

Bridgwater, D., Davies, F.B., Gill, R.C.O. Gorman, B.E., Myers, J.S., Pedersen, S. & Taylor, P. 1978: Precambrian and Tertiary geology between Kangerdlugssuaq and Angmagssalik, south-eastern Greenland. Rapp. GrOnlands geol. Unders. 83, 17 pp.

Bridgwater, D. & Myers, J.S. 1979: Outline of the Nagssugtoqidian of East Greenland. In Korstghrd, J. (edit.) Nagssugtoqidian geology. Rapp. Grsnlands geol. Unders., in press.

Bridgwater, D.. Collerson, K.D. & Pedersen, S. in preparation: Sr isotope and trace element redistribution within an Early Archean amphibolite dyke, from Saglek, Labrador.

Collerson, K.D. & Bridgwater, D. 1979: Metamorphic development of Early Archean tonalitic and trondhjemitic gneisses: Saglek area, Labrador. In Barker,.F. (edit.) Trondhjemites, dacites, and related rocks. Elsevier.

Hickman, M.H. 1979: A Rb-Sr age and isotope study of the Ikertoq, Nordre Strsmfjord, and Evighedsfjord shear belts, West Greenland. Outline and preliminary results. In Korstghrd, J. (edit.) Nagssugtoqidian geology. Rapp. Grønlands geol. Unders. in press.

Kalsbeek, F. & Zeck, H.P. 1978: Preliminary Rb-Sr whole-rock data for Archaean and Nagssugtoqidian rocks from the Søndre Strsmfjord area, West Greenland. Rapp. Grsnlands geol. Unders. 90, 129–134.

Pedersen, S. & Bridgwater, D. 1979: Isotopic re-equilibration of Rb-Sr whole rock systems during reworking of Archaean gneisses in the Nagssugtoqidian mobile belt, East Greenland. In Korstghrd, J. (edit.) Nagssugtoqidian geology. Rapp. Grsnlands geol. Unders. in press.

Ramberg, H., 1951: Remarks on the average chemical composition of granulite facies and amphibolit.e to epidote amphibolite facies gneisses in West Greenland. Medd. Dansk geol. Foren. 12, 27–34.

Watterson, J. 1978: Proterozoic intraplate deformation in the light of South-east Asian neotectonics. Nature, London 273, 636–640.

Table 1.

Representative mineral analyses from the shear zones Storø.

Mineral compositions Storø.

	Amphiboles		Biotite	
	Country rocks	Shear	Country rocks	Shear
	226836	226840	226836	226840
SiO2	41.89	38.00	37.73	35.20
TiO2	1.24	0.93	4.94	4.32
Al2O3	12.12	12.42	15.08	15.04
FeOT	17.55	24.62	16.92	23.20
MgO	10.56	5.97	11.95	9.33
MnO	0.11	0.25	0.03	0.19
CaO	11.23	10.74	ND	0.0
K2O	1.69	2.60	9.73	9.48
Na2O	1.33	1.45	ND	ND
MgO/FeO+MgO	0.52	0.30	0.56	0.42

(FeOT = total iron as FeO)

	Garnet		Opaque minerals		
	Country rock	Shear. (10 cm from centre)	Country rocks		Shear
	226836	226846	226836^{x}	226836^{xx}	226847
SiO2	39.98	38.59	0.00	0.00	0.00
TiO2	0.0	0.02	19.25	42.87	0.03
Al2O3	21.32	21.20	0.11	0.05	0.29
FeO	26.82	26.76	74.55	54.35	96.72
MgO	6.02	4.45	0.12	0.31	0.03
MnO	1.49	2.43	0.07	0.26	0.07
CaO	5.88	8.73	0.00	0.04	0.00
MgO/Mg+FeO	0.28	0.14			

x) 10 μ raster
"Magnetite" ground mass with fine exsolution.
xx) "Ilmenite" lamella.

	Plagioclase		K-feldspar		Scapolite	Muscovite
	Country rock	Shear.	Country rock	Shear	Shear	Shear
	226836	226840	226836	226840	226846	226848
SiO2	66.36	63.46	64.60	63.61	50.51	46.19
TiO2	ND	ND	ND	ND	0.0	0.86
Al2O3	20.96	22.75	18.48	18.76	24.6	33.87
FeOT	0.06	0.06	0.01	0.01	0.07	2.95
MgO	ND	ND	ND	ND	0.02	0.08
MnO	ND	ND	ND	ND	0.01	0.01
CaO	4.92	4.08	0.00	0.00	13.50	0.00
Na2O	6.58	8.82	0.68	1.43	5.6	0.22
K2O	0.23	0.34	15.74	14.66	0.43	10.74
BaO	ND	0.01	ND	0.95	ND	ND
S	ND	ND	ND	ND	0.3	ND
	An29 (mol)	An20(mol)	516			
	Or 2	Or 3				

Table 2 Chemistry of gneisses, Storø

Sample No.	226836	226837	226833a	226840	226848	226902
SiO_2	68.89	70.06	70.83	71.62	70.94	68.16
TiO_2	0.32	0.28	0.50	0.22	0.27	0.46
Al_2O_3	16.31	15.49	14.91	14.96	15.01	15.99
Fe_2O_3	0.59	1.07	0.17	0.39	0.82	1.55
FeO	1.47	1.25	1.83	1.03	1.02	1.42
MnO	-	0.03	0.03	-	-	-
MgO	0.83	0.78	0.78	0.50	0.53	0.92
CaO	3.54	2.87	1.92	2.30	2.27	3.81
Na_2O	5.09	4.74	3.94	4.56	4.19	4.72
K_2O	1.52	2.49	4.36	3.05	3.26	1.05
H_2O(L.O.I.)	0.71	0.63	0.50	0.36	0.44	0.68
P_2O_5	0.08	0.12	0.09	0.05	0.08	0.13
ppm F	280	-	-	1230	-	
Cl	200	340	450	1520	820	
S	320	120	40	120	70	
% Sulphide	45	25	0	0	0	
Rb	9	24	-	33	64	3
cu	37	19	7	9	5	
Sr	670	658		674	583	811
Ba	812	1692	-	1449	1500	
Zn	42	39			44	
Zr	343	387	173	179	156	
Pb	5	15		12	22	
Cr	3	11		3	5	
co	25	10		21	13	
Ni	3	3		3	3	
	Country rocks			Shear centres	Shear margin	Granulites

Text to figures (Bridgwater and Bridgwater & Pedersen)

Fig. 1. Position of Nagssugtoqidian mobile belt.

Fig. 2. Sketch map across the Nagssugtoqidian mobile belt, East Greenland to show main structural divisions and localities discussed in text (from Bridgwater and Myers, 1979).

Fig. 3. Field sketch to show sampling localities across early Nagssugtoqidian minor shear zones, Storø.

Fig. 4. Strain diagram calculated from rotation of earlier foliation across one of shear zones in fig. 3 (after Watterson, this volume).

Fig. 5. Histograms of major and minor element distribution across shear zones on Storø compared to regional granulite facies gneisses.

Fig. 6. Rb-Sr isochron from Storø shear belt (locality 1, fig. 2).

Fig. 7. Rb-Sr isochron from garnet gneisses Angmagssalik (locality 2, fig. 2).

Fig. 8. Rb-Sr isochron from Archean grey gneisses near centre of mobile belt (locality 3, fig. 2).

Fig. 9. Rb-Sr isochron from post-tectonic granites (locality 4, fig. 2).

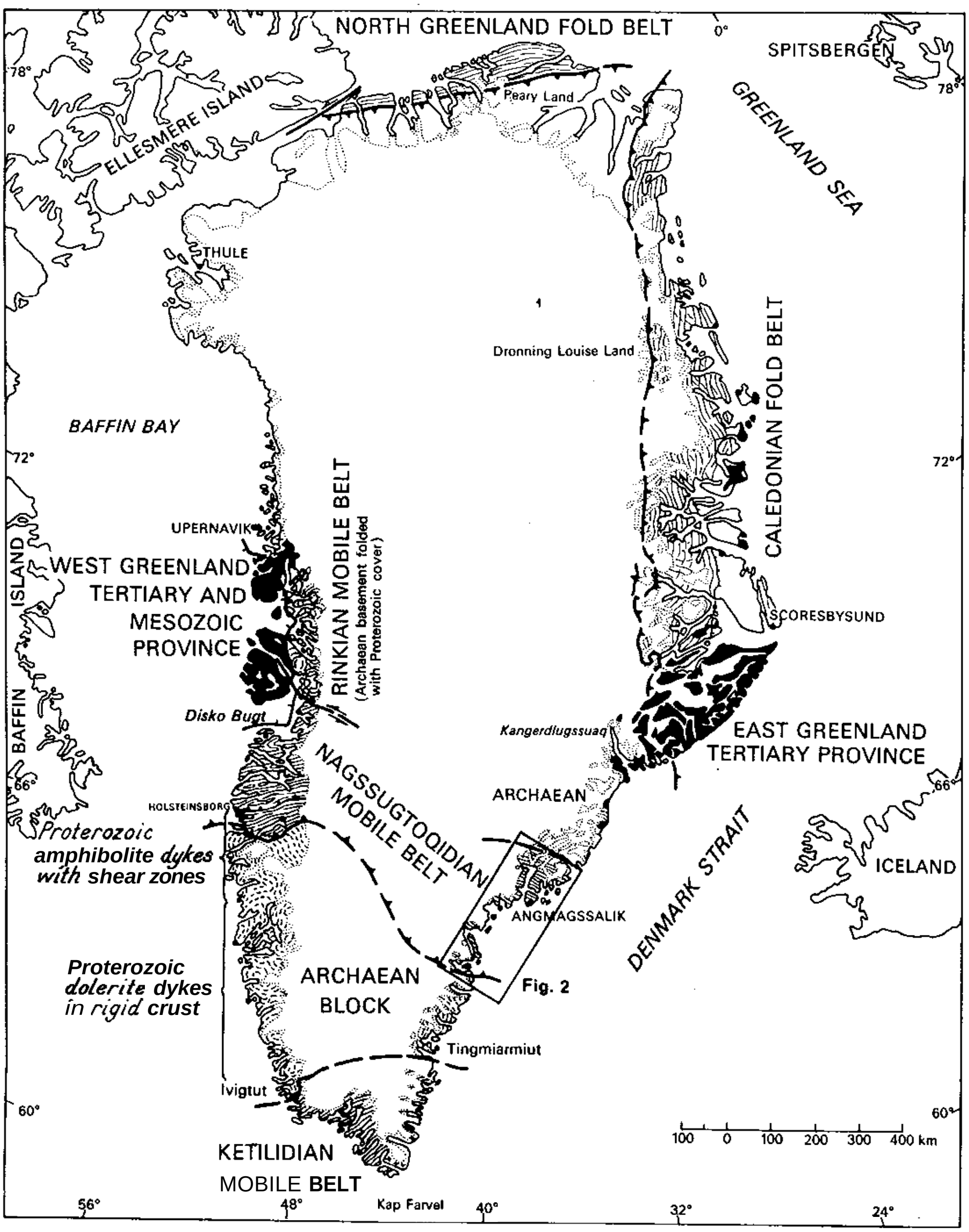
NORTH GREENLAND FOLD BELT
0°
SPITSBERGEN
78°
78°
Peary Land
ELLESMERE ISLAND
GREENLAND SEA
THULE
1
Dronning Louise Land
CALEDONIAN FOLD BELT
BAFFIN BAY
72°
72°
UPERNAVIK
RINKIAN MOBILE BELT
(Archaean basement folded with Proterozoic cover)
BAFFIN ISLAND
WEST GREENLAND TERTIARY AND MESOZOIC PROVINCE
SCORESBYSUND
Disko Bugt
Kangerdlugssuaq
EAST GREENLAND TERTIARY PROVINCE
NAGSSUGTOQIDIAN MOBILE BELT
66°
66°
ARCHAEAN
HOLSTEINSBORG
Proterozoic amphibolite dykes with shear zones
DENMARK STRAIT
ICELAND
ANGMAGSSALIK
Proterozoic dolerite dykes in rigid crust
ARCHAEAN BLOCK
Fig. 2
Tingmiarmiut
Ivigtut
60°
60°
100 0 100 200 300 400 km
KETILIDIAN MOBILE BELT
56°
48°
Kap Farvel
40°
32°
24°

Figure 1

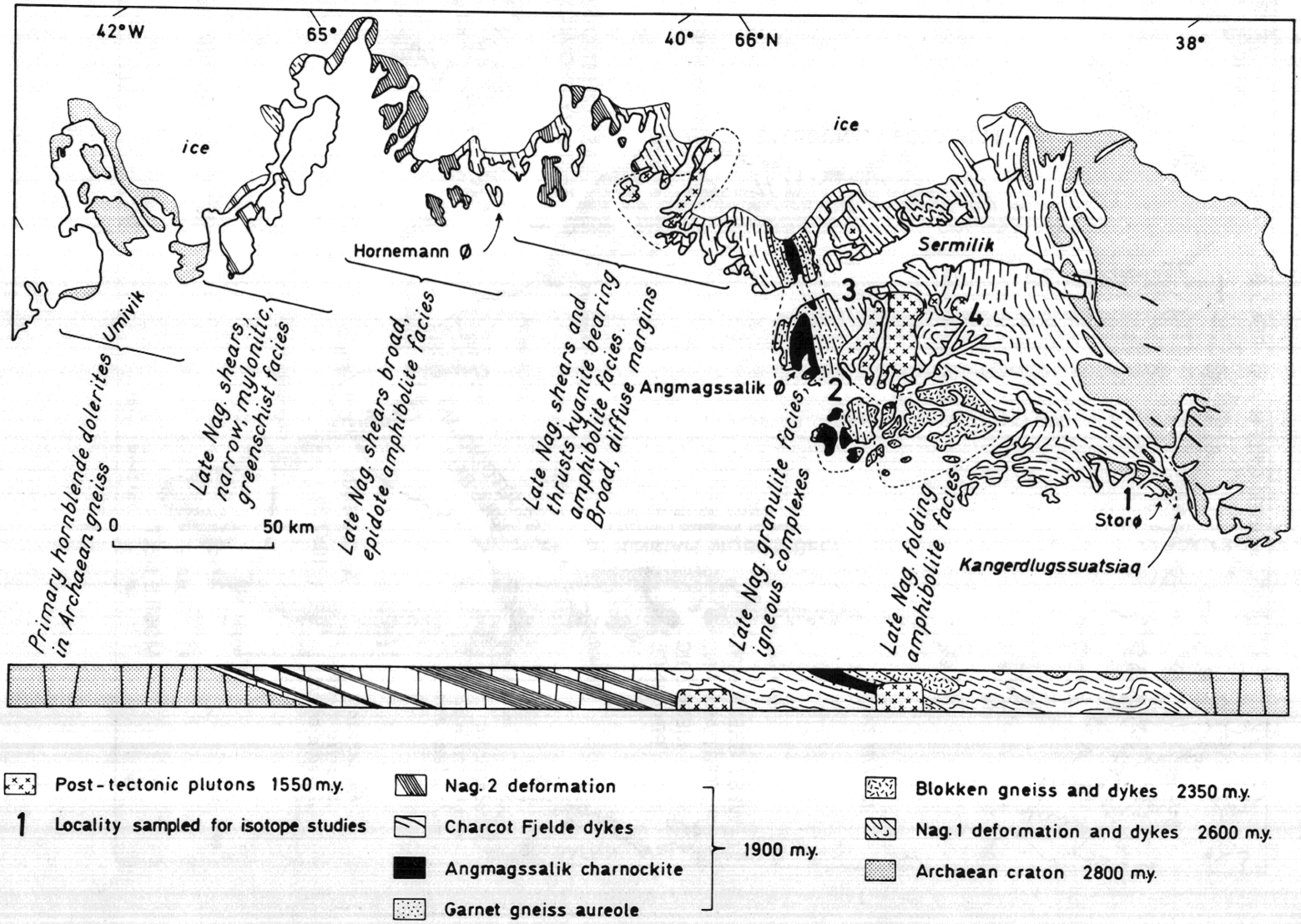
42°W
65°
40°
66°N
38°
ice
ice
Umivik
Hornemann Ø
Sermilik
Angmagssalik Ø
Storø
Kangerdlugssuatsiaq
1
2
3
4
0
50 km
Primary hornblende dolerites in Archaean gneiss
Late Nag. shears, narrow, mylonitic, greenschist facies
Late Nag. shears broad, epidote amphibolite facies
Late Nag. shears and thrusts kyanite bearing amphibolite facies. Broad, diffuse margins
Late Nag. granulite facies, igneous complexes
Late Nag. folding amphibolite facies
Post-tectonic plutons 1550 m.y.
Locality sampled for isotope studies
Nag. 2 deformation
Charcot Fjelde dykes
Angmagssalik charnockite
Garnet gneiss aureole
1900 m.y.
Blokken gneiss and dykes 2350 m.y.
Nag. 1 deformation and dykes 2600 m.y.
Archaean craton 2800 m.y.

Figure 2

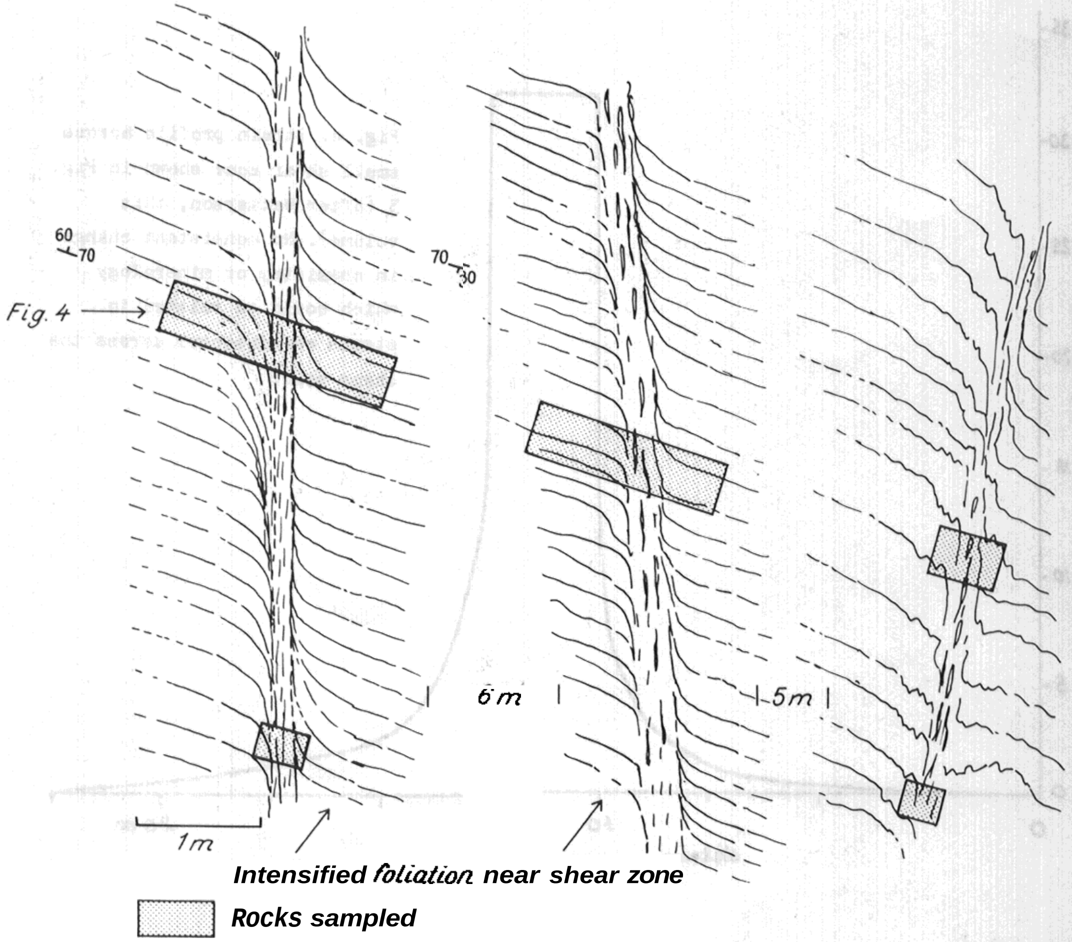
60
70
Fig. 4
70
30
6m
5m
1m
Intensified foliation near shear zone
▨ Rocks sampled

Figure 3

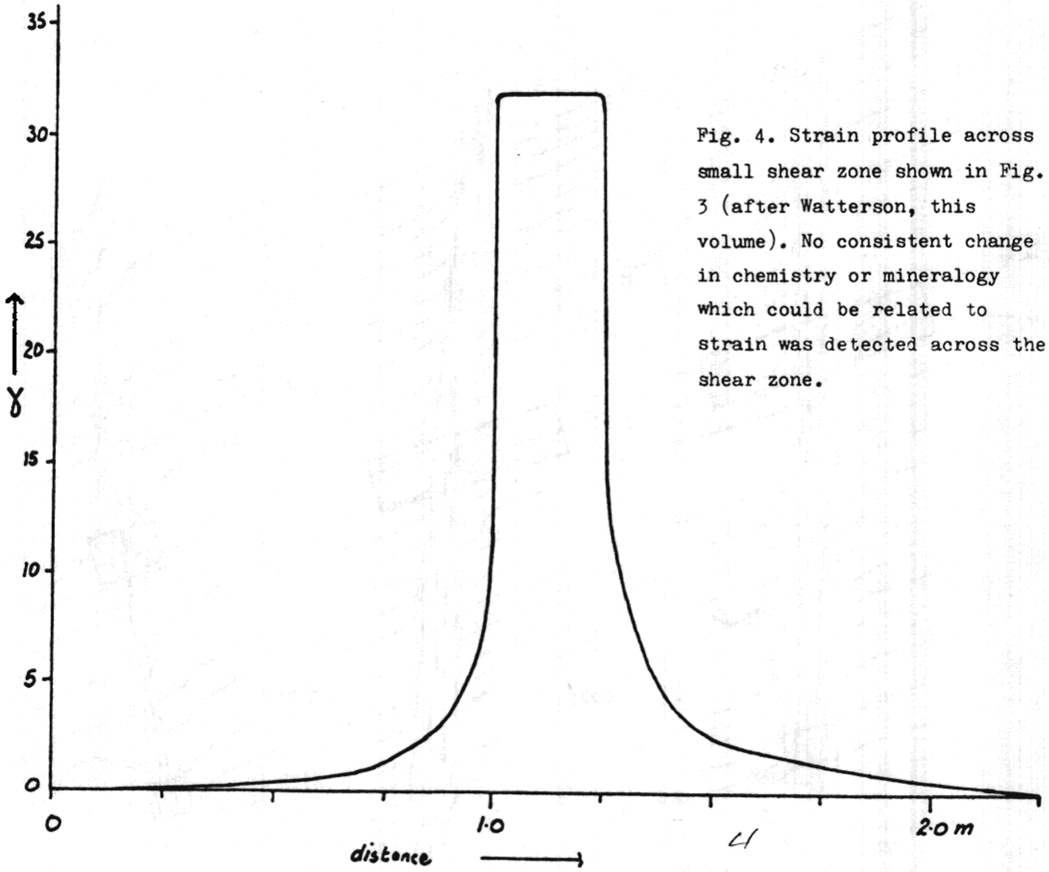

Fig. 4. Strain profile across small shear zone shown in Fig. 3 (after Watterson, this volume). No consistent change in chemistry or mineralogy which could be related to strain was detected across the shear zone.

Figure 4

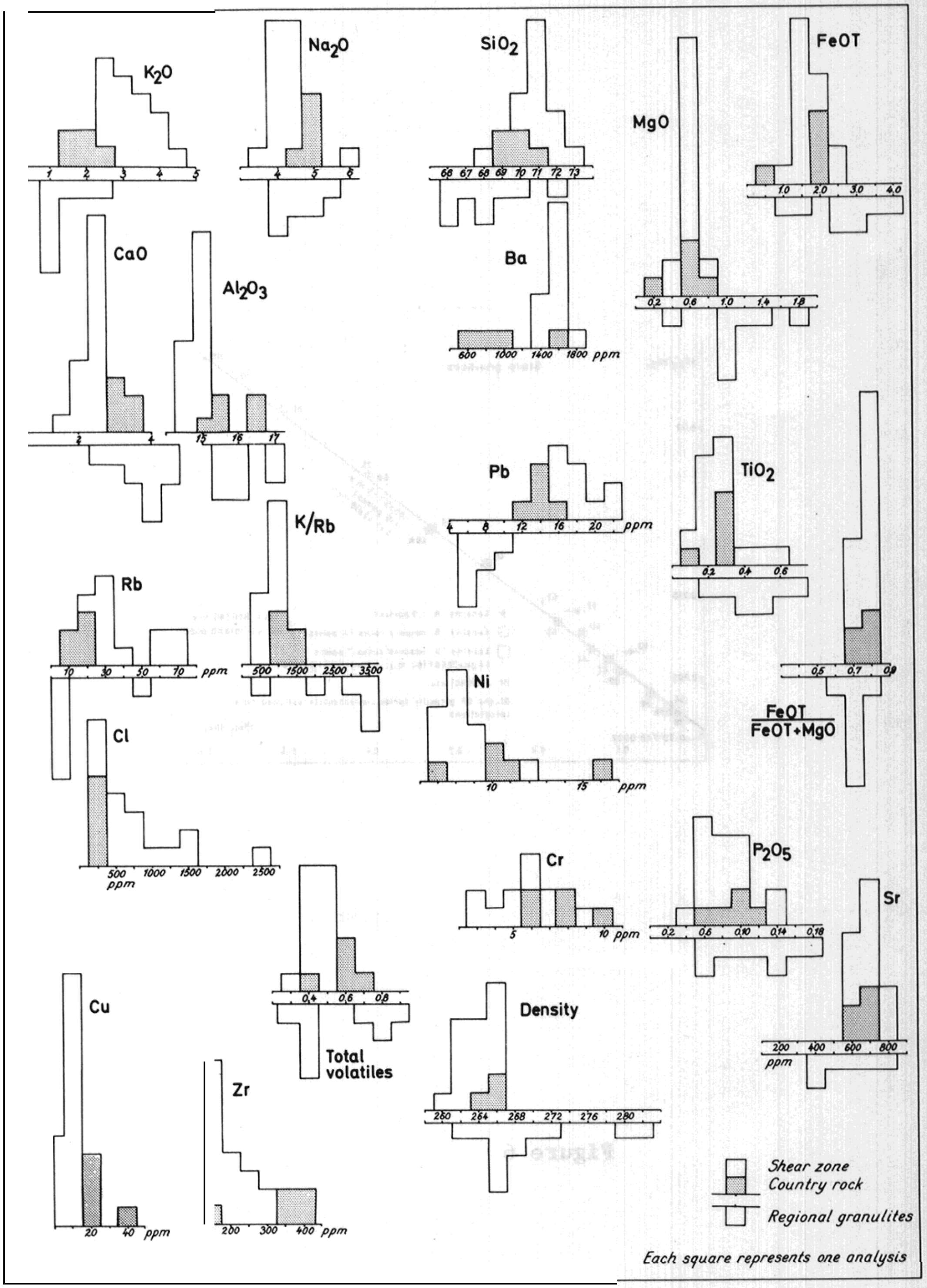
K2O
1 2 3 4 5
Na2O
4 5 6
SiO2
66 67 68 69 70 71 72 73
MgO
0.2 0.6 1.0 1.4 1.8
FeOT
1.0 2.0 3.0 4.0
CaO
2 4
Al2O3
15 16 17
Ba
600 1000 1400 1800 ppm
Pb
4 8 12 16 20 ppm
TiO2
0.2 0.4 0.6
K/Rb
500 1500 2500 3500
Rb
10 30 50 70 ppm
0.5 0.7 0.9
FeOT/FeOT+MgO
Ni
10 15 ppm
Cl
500 1000 1500 2000 2500
ppm
P2O5
0.2 0.6 0.10 0.14 0.18
Cr
5 10 ppm
Sr
200 400 600 800
ppm
Cu
20 40 ppm
Total volatiles
0.4 0.6 0.8
Density
260 264 268 272 276 280
Zr
200 300 400 ppm
Shear zone
Country rock
Regional granulites
Each square represents one analysis

Figure 5

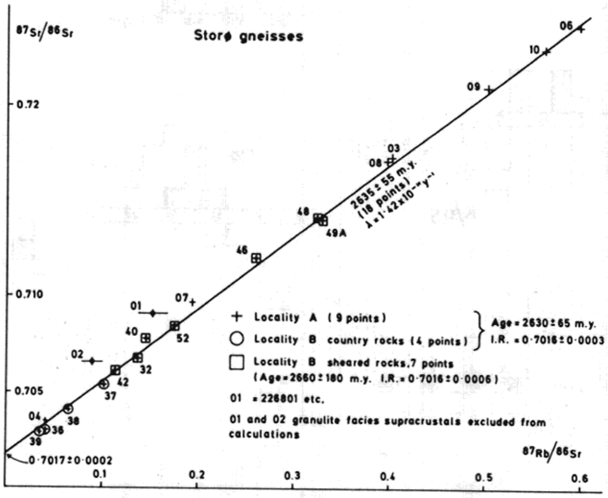
$^{87}Sr/^{86}Sr$
Storø gneisses
0.72
0.710
0.705
06
10
09
03
08
2635 ± 55 m.y.
(18 points)
λ = 1·42x10⁻¹¹y⁻¹
48
49A
46
01
07
40
52
02
32
42
37
38
04
36
39
0·7017 ± 0·0002
+ Locality A (9 points)
○ Locality B country rocks (4 points)
Age = 2630 ± 65 m.y.
I.R. = 0·7016 ± 0·0003
☐ Locality B sheared rocks, 7 points
(Age = 2660 ± 180 m.y. I.R. = 0·7016 ± 0·0006)
01 = 226801 etc.
01 and 02 granulite facies supracrustals excluded from calculations
$^{87}Rb/^{86}Sr$
0.1
0.2
0.3
0.4
0.5
0.6

Figure 6

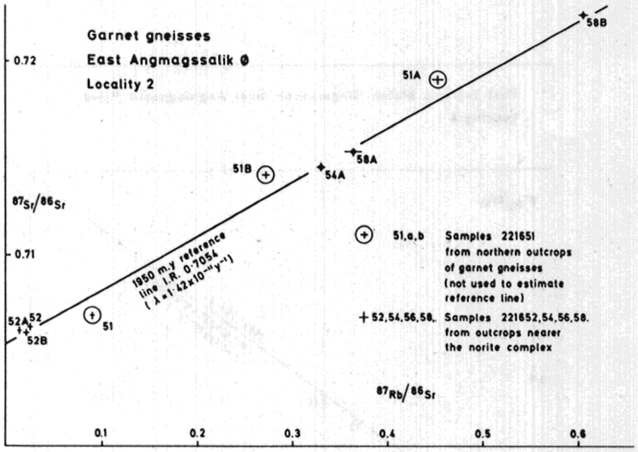
Garnet gneisses
East Angmagssalik Ø
Locality 2
0.72
0.71
$^{87}Sr/^{86}Sr$
$^{87}Rb/^{86}Sr$
0.1
0.2
0.3
0.4
0.5
0.6
58B
51A
58A
54A
51B
51
52A
52
52B
1950 m.y reference line I.R. 0·7054 ($\lambda = 1{\cdot}42 \times 10^{-11} y^{-1}$)
51,a,b Samples 221651 from northern outcrops of garnet gneisses (not used to estimate reference line)
+ 52,54,56,58. Samples 221652,54,56,58. from outcrops nearer the norite complex

Figure 7

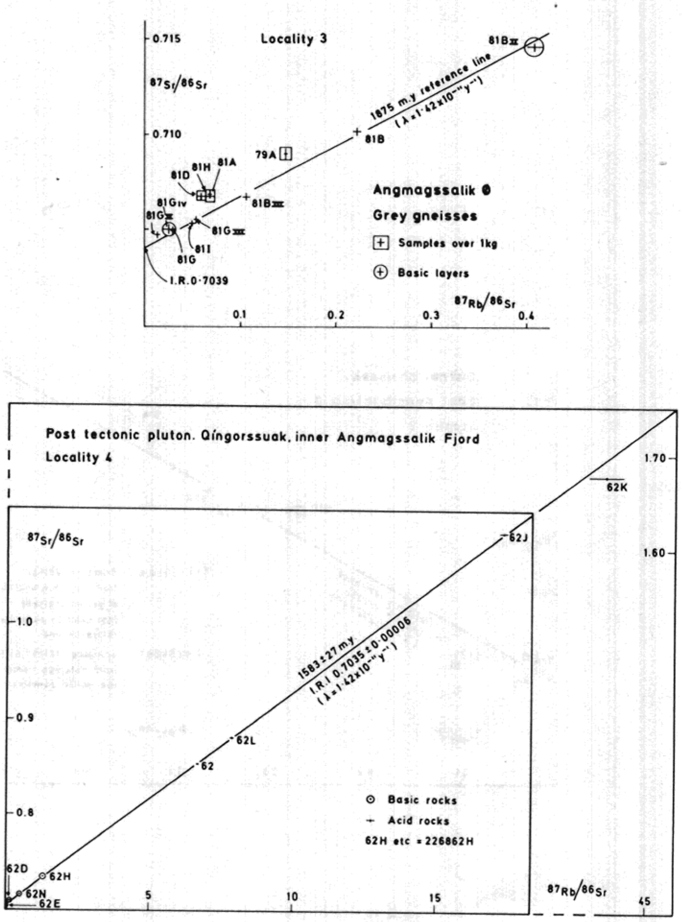

Figure 8 and 9