DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2016/22

Excursion guide in the western Maniitsoq impact structure, southern West Greenland

With an introduction on the discovery and geological setting of the impact structure

Adam A. Garde

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
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G E U S

Frontispiece. *Brendan Dyck, Kim Esbensen and Lotta Möller during field work in 2011, resting on a messy outcrop of shock-brecciated supracrustal rock invaded by locally formed granite. South coast of Qerrulik island 5 km east of Talerulik, loc. 2011-74.* AAG 2011-599.

Contents

Plagioclase grain 3 cm across, crystallised at high temperature after impacting. Black and deep red colours due to high iron content. Small island south of Portusoq, loc. 2011-56. AAG 2011-432.

Preface

This field guide is written for a 7-day excursion to the Maniitsoq impact structure in June 2016 with the 12-passenger travelling boat M/S Minna Martek, beginning in Nuuk and ending in Maniitsoq. The excursion is organised by the Geology Department, Ministry of Mineral Resources (Nuuk, Greenland) with participants from this department, the Geological Survey of Denmark and Greenland (GEUS) and industry (North American Nickel Inc).

The main purpose of the excursion is to familiarise the participants with the special features of the Maniitsoq impact structure in the context of the Archaean orogenic evolution in the North Archaean craton, and discuss the impact-related features and their scientific and economic significance. The norite belt in the eastern part of the impact structure with its Ni-Cu mineralisation is not accessible by boat and will not be visited.

The excursion guide begins with an informal account of important steps in the investigation of the impact structure from its discovery in 2009 to May 2016. The idea of an impact structure was conceived in September 2009, and although a great deal of new knowledge has been acquired since then the structure is still poorly known in comparison to other large impact structures on Earth. It is the hope that this introduction will help newcomers appreciate that although the idea of the Maniitsoq impact structure began in a geological office, the structure is now the target of an ongoing research process in many directions, with participants representing different geological backgrounds, and with continuous exposure to the international scene of research in impact processes.

The Maniitsoq impact structure probably represents the remains of the largest currently known impact structure on Earth, but a direct comparison with the sizes of other impact structures is difficult because of their different levels of exhumation.

The author is grateful to Brendan Dyck, Lotta Möller and Leif Johansson (participants in the field work in 2011 that underpins this guide), for commenting and checking up on a near-final version of the manuscript.

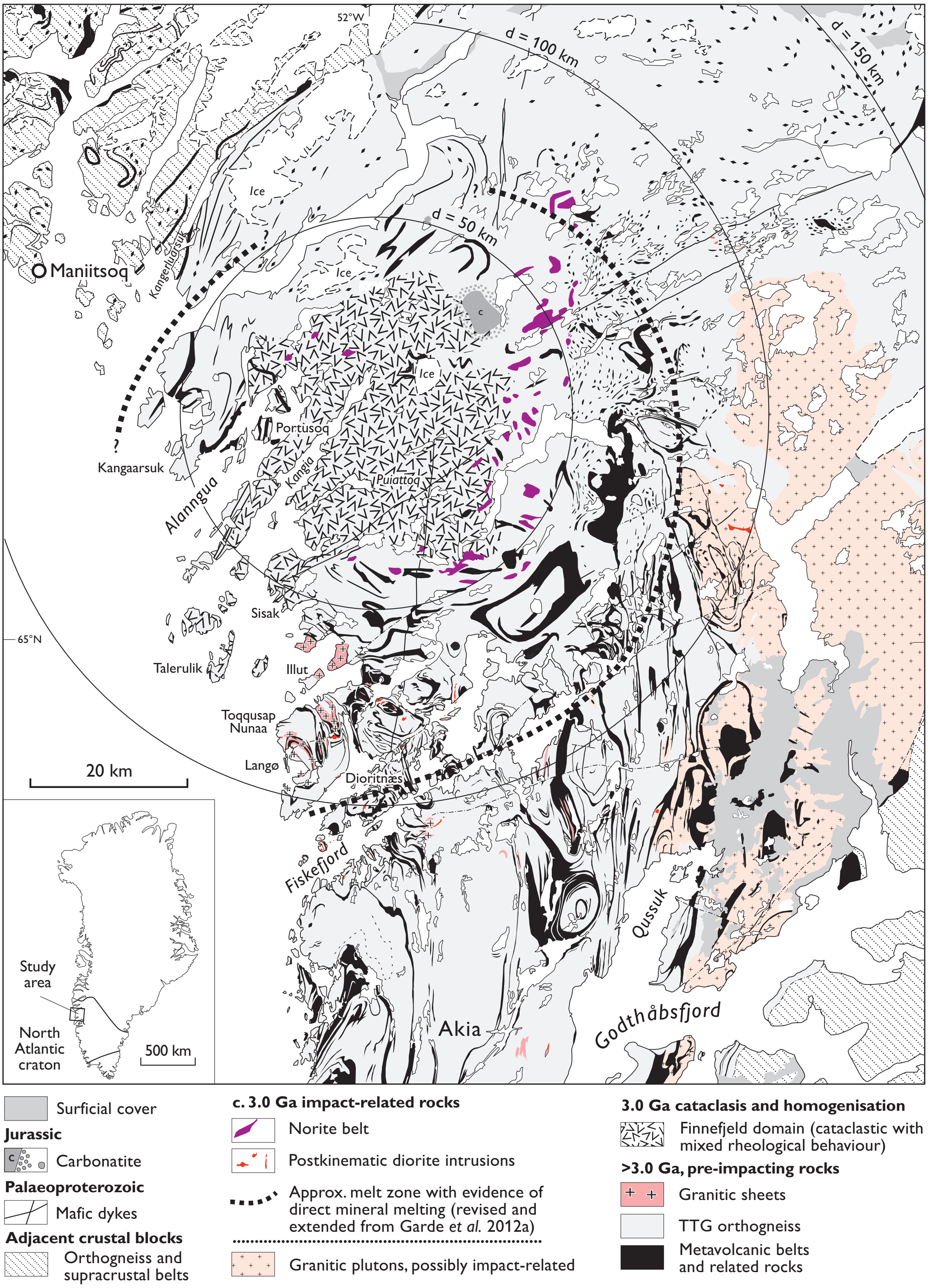


Fig. 1. *Simplified geological map of the Fiskefjord block with Maniitsoq impact structure, bounded by the Godthåbsfjord–Ameralik belt in the south-east and the Maniitsoq block in the north-west. Modified from Garde et al. (2012a).*

Geological setting of the Maniitsoq impact structure and comparison with the Vredefort dome

The extraterrestrial impact that created the Maniitsoq structure took place 3.0 Ga ago (Garde *et al.* 2012a; Scherstén & Garde 2013) in the Mesoarchaean North Archaean craton of southern West Greenland. The impact structure is shaped like a tear drop, and its approximate centre is located at 65°15'N, 51°50'W. The impacting coincided with the waning stage of a convergent plate-tectonic orogeny whereby abundant juvenile continental crust had already been accreted in a large magmatic arc system (Garde 1997, 2007; Windley & Garde 2009). Since the impact took place, the original upper and middle parts of the crust have been removed by uplift and erosion. The remnants of the Maniitsoq impact that are exposed today were thus located in the lower crust, no less than 25 km below the surface that was impacted. In comparison, the second-largest impact structure on Earth, the 2.02 Ga Vredefort dome in the Kaapvaal craton of South Africa, has only been eroded by about 10 km, and upper-crustal rocks are still exposed in the periphery of the latter structure around a central dome.

Due to the different degrees of exhumation and the ongoing orogeny when the Maniitsoq region was impacted, the ambient P-T conditions of the target rocks that are now exposed at Maniitsoq and Vredefort were quite different. Therefore the response to the two impacts in the respective target rocks was also different. The ambient temperature of the rocks now exposed at Maniitsoq was 850–900°C at the time of impacting (B. Reno and B. Dyck, personal communication, 2012; Keulen *et al.* 2015), but only about 350°C in the Vredefort dome (Gibson & Reimold 2008). This difference is highly significant. For instance, the short-lived, shock-induced temperature increase of a few hundred degrees caused direct melting of K-feldspar over a large region in the Maniitsoq structure because K-feldspar will melt directly at c. 1300°C at a pressure of 8–10 kbar, whereas no regional shock melting has occurred at Vredefort. Likewise, the rocks and minerals now exposed at Maniitsoq were hot and ductile, but at Vredefort cold and brittle when the respective impacts occurred. This difference is one of the main reasons why shock lamellae (planar deformation features, PDFs) imposed on minerals such as quartz would be much more prone to rapid subsequent annealing at Maniitsoq than at Vredefort.

These considerations have not taken the relative original sizes of the two structures into account, inasmuch as there is no precise estimate of the original uneroded size of the Maniitsoq impact crater. However, modelling by B.A. Ivanov (in Garde *et al.* 2011) indicates that the kinetic energy of an impact capable of causing direct mineral melting in the lower crust within a diameter of c. 80 km, as in the Maniitsoq structure, would have been an order of magnitude greater than at Vredefort (corresponding to incoming projectiles with diameters of around 30 and 15 km, respectively, if they travelled with the same speed of 20 km/s).

Understanding lower-crustal rocks in the context of impacting

The lower continental crust exposed in the Archaean North Atlantic craton consists of many different rock components that were formed by orogenic crustal processes at different times during the Mesoarchaean and successively emplaced as magmas or tectonically juxtaposed to each other. Most rock components have also been affected by several phases of penetrative Mesoarchaean deformation and metamorphism. Due to the slow nature of the lower-crustal geological processes the rocks and minerals have been equilibrated at high temperature and pressure, and their Archaean structures are of ductile type. The Archaean geological history and geochronological evolution are summarised in a later section.

An extraterrestrial impact, in contrast, is an exceedingly fast event. The pressure increase and relaxation caused by the passage of the initial impact shock and rarefaction waves are instantaneous (Melosh 1989; French 1998), whereas the accompanying temperature excursion lasts for a little longer. The deformation regime in the lower crust deep under the floor of the Maniitsoq crater suddenly changed from being ductile to brittle and back again, and was accompanied by a sharp temperature increase into the field of direct melting of individual minerals, far above the minimum melting temperature for dry granite (Keulen *et al.* 2015). The impacting was also accompanied by intense seismic shaking (Garde *et al.* 2014a) that would only have lasted a few minutes. A 75 km long, curvilinear belt of noritic rocks were emplaced due to localised melting of the mantle and mixing with lower-crustal rocks, and soon after this the lower crust was invaded by extremely hot, percolating aqueous fluids which caused intense hydrothermal alteration of rocks and minerals in large parts of the impact structure – possibly because ocean water flowed into the juvenile crater with access to the deeper crust through impact-induced fractures as suggested by Scherstén & Garde (2013).

In order to understand the effects of the impacting at Maniitsoq it is therefore necessary to recognise and evaluate geological features that would not normally occur or survive in the lower crust, and which are ‘out of place’ in the root zone of a normal mature convergent magmatic arc.

Impact-related features of the Maniitsoq structure (as of May 2016)

Impact-related features in the Maniitsoq structure as the structure is currently known can be grouped into the following categories (see also the 15 points listed in Garde *et al.* 2012a):

(1) Shock-melted minerals;
(2) Intense and thorough cataclasis with complete loss of older rock textures throughout the 35 x 50 km large Finnefjeld domain that forms the central part of the impact structure;
(3) Micro-cataclastic zones and injectites (‘grey dykes’) with interior veins of K-feldspar, observed up to 100 km from the impact centre;
(4) Highly localised brittle deformation features, including fracture cleavage and autobreccias associated with melting, superimposed on the regional, ductile orogenic deformational structures;
(5) A curvilinear deformation pattern displayed by metavolcanic belts south-east of the Finnefjeld domain.
(6) Stocks, plugs and inclined dyke-like intrusions of noritic to dioritic composition, which are post-kinematic with respect to the orogenic deformation history but predate the hydrothermal alteration.

(7) Rocks and minerals (including zircon) with evidence of intense hydrothermal alteration and recrystallisation under high metamorphic P-T conditions. The regional aeromagnetic anomaly shown by Garde *et al.* (2012a) may in part be controlled by this alteration.

(8) As a potential category, quartz and other minerals in rocks that are unaffected by hydrothermal alteration exhibit subplanar trails of fluid inclusions with crystallographic orientations that coincide with those of shock lamellae, and which are likely – but not proven – to represent such lamellae in deformed and altered forms (Garde *et al.* 2012a).

(9) Another potential category is crustal remobilisation of granitoid rocks up to 25 Ma after the impact, perhaps caused by a long-lived, impact-related thermal perturbation of the lower crust (Keulen *et al.* 2015), but this has to be substantiated by further work. The intrusions include the large, dome-shaped, 2995 Ma Taserssuaq tonalite complex in the eastern part of the impact structure and several smaller granitic intrusions in its south-eastern part including the Qugssuk granite and Igánánguit granodiorite, see Table 1 and Garde (1997).

(10) Anomalous compositions of the Palaeoproterozoic, rift-related mafic dykes that cross the impact structure. The dykes are noritic to boninitic (Hall & Hughes 1987) in the impacted area, not tholeiitic as elsewhere in the North Atlantic craton, possibly due to a prevailing chemical anomaly caused by impact-induced mechanical mixing of crust and upper mantle below the impact.

(11) The centre of the impact is also the centre of a swarm of c. 600 Ma kimberlite dykes (Nielsen *et al.* 2009) which were first recognised in the 1960s by Kryolitselskabet Øresund A/S. The location of this kimberlite dyke swarm might just be coincidental, or it might reflect a long-lived, impact-induced anomaly in the underlying lithospheric mantle.

Recognition of impact-related features

In complex geological terrains it is difficult to recognise anomalous rocks as being individually and collectively foreign to the regional geological evolution and geologically 'out of place'. At Maniitsoq the anomalous components and structures are exposed over a region measuring well over 100 x 100 km, but there is no physical crater left to act as a practical or mental frame of reference. It has taken several generations of field geologists who studied the middle and lower continental crust to develop meticulous, state-of-the-art field observation techniques whereby all the rock components, critical mineral assemblages and complex structures are first of all recognised and then recorded and used to establish a relative sequence of events. The absolute time scale is not important in this context. Most endogenic geological processes take millions of years, but the study of the Maniitsoq impact structure shows that the same techniques also work for impact-related processes, where the time scale is initially only seconds or minutes. Thus, the recognition of impact-related features in the deep crust arguably requires a good deal of experience from studies of normal high-grade rocks and structures, and this probably also represents a barrier for geologists with different geological backgrounds who might underrate the complexity of the rocks they are looking at. Otherwise the structure would have been discovered long before 2009 (see below).

Discovery and growing insight

The first geologist to recognise some highly unusual features in the Maniitsoq (Sukkertoppen) area was Berthelsen (1962). He described intense cataclasis but his observations were ahead of their time and became forgotten (see Garde *et al.* 2014a). Hall (1984) described ‘intrusive breccias’ in the north-eastern part of the impacted region during regional geological mapping. Garde (1987, 1989) compiled two map sheets covering the eastern and southern parts of the impact structure and described intense hydrothermal alteration as endogenic metamorphic retrogression (Garde 1990, 1997). The idea of a giant impact structure occurred in September, 2009, prompted by a request by NunaMinerals A/S to the author for an overview of the Maniitsoq region for an upcoming company workshop. The new idea would account for features such as the near-circular shape of the Finnefjeld domain (Allaart 1982), a coincidence of ages of late granites, intense hydrothermal alteration, the curvilinear norite belt, and Palaeoproterozoic dykes with anomalous chemical compositions directly over the proposed impact structure (Hall & Hughes 1987). An aeromagnetic anomaly at the structure was confirmed (Fig. 2), and by October 2009 an abstract for the Nordic Geological Winter Meeting, January 2010 and an application to Carlsbergfondet for field work were submitted.

Thus, the discovery of the Maniitsoq structure was not the result of an active search for impact structures (as is the case e.g. for most Canadian impact structures), but a last resort to account for highly unusual regional geological features that did not fit into the regional Archaean crustal evolution. Some of the supposedly impact-related features were actually misconceived at first which becomes apparent by comparing the first abstract (Garde 2010) with later insight. Despite its shortcomings, this abstract and discussions over a beer or two by participants in a promotion meeting of exploration geologists in Perth, Western Australia, attracted the interest of the highly experienced exploration geologist John Ferguson. He persuaded North American Nickel Inc., to take up a new exploration licence on the Ni-Cu mineralisation in the norite belt which had been found and explored in the 1960s by Kryolitselskabet Øresund A/S. In 2011 the company began its still ongoing exploration.

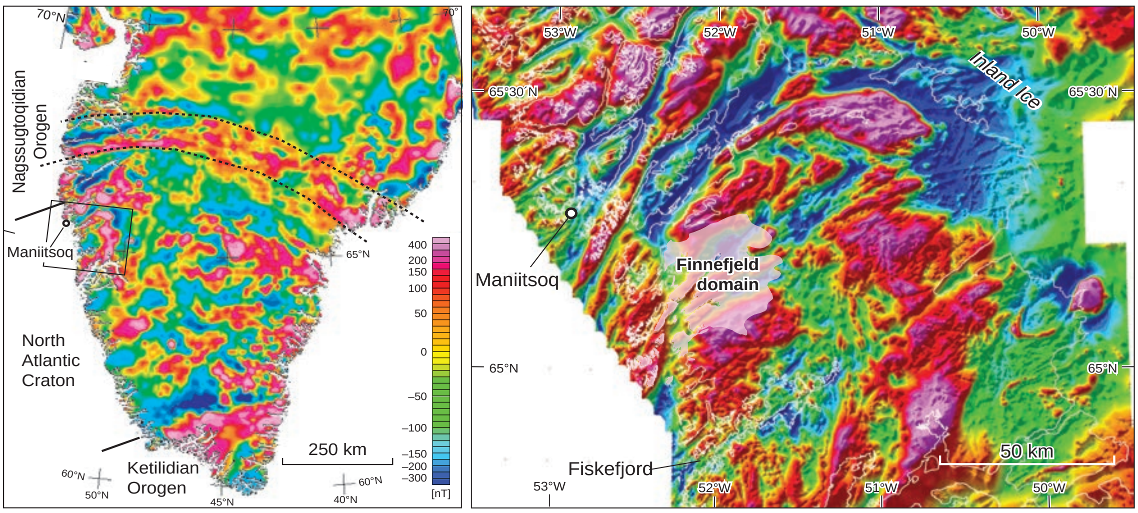


Fig. 2. *Aeromagnetic anomaly over the Maniitsoq impact structure. Modified from Garde et al. (2012a, their fig. 2).*

New field work and the first publication

The new dedicated field work was instrumental in the process towards establishing the impact structure as a fact. Field work in July 2010 (Fig. 3) took place from four fly camps in the eastern part of the structure by the author and Brendan Dyck (Lund University). Subsequent field work in June 2011 by boat (M/S Minna Martek) in the southern and south-western parts of the structure was carried out by Brendan Dyck, Leif Johansson and Lotta Möller (Lund University) and Kim Esbensen and the author (GEUS). Financial support was provided by Carlsbergfondet and GEUS. The summer of 2010 was very dry and little snow remained from the previous winter. Aided by generous helicopter support from NunaMinerals A/S this permitted observations of many excellent, clean outcrops on the high plateau south-east of Maniitsoq, including some very assertive outcrops of highly unusual, micro-cataclastic dykes with ptygmatically folded, *interior* K-feldspar veins. The field work in 2011 was also effective and was characterised by numerous discussions on site.

Fig. 3. *The first attempt to establish the sequence of observed impact-related events in the eastern part of the Maniitsoq structure. Field camp, July 2010.* AAG 2010-622.

Iain McDonald (Cardiff University), who had participated in the NunaMinerals workshop, shared some of his previous insight in cratering and provided analytical data from the norite belt. Help from Thorkild M. Rasmussen with aeromagnetic data and Karsten Secher (GEUS) with information and samples from the norite belt and a long conversation with John S. Spray at the Meteoritical Society conference in Greenwich, U.K. in June 2011 were also important. After two rejections from other journals the first account of the Maniitsoq structure was published in June 2012 in Earth and Planetary Science Letters (Garde *et al.* 2012a).

Determining the age of the impacting

Both the Vredefort (South Africa) and Sudbury (Ontario, Canada) impact structures have been dated by means of authigenic minerals (Kamo *et al.* 1996; Ames *et al.* 1998), but an attempt to do the same by Scherstén & Garde (2013) gave an unexpected result. All the

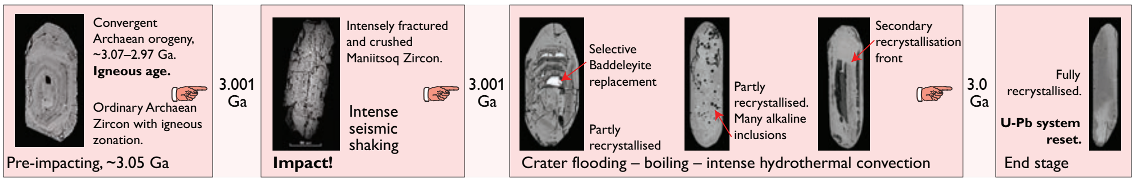


Fig. 4. *Impact-induced hydrothermal alteration of zircon. Based on Scherstén & Garde (2013).*

zircon turned out to be variably and mostly intensely affected by hydrothermal alteration (Fig. 4), presumably by dissolution and reprecipitation in hot, alkaline aqueous fluids. The hydrothermally altered zircon grains collected from five different locations up to 50 km apart all yielded the same age of 3.0 Ga. The pooled, 3001 ± 1.9 Ma age was interpreted as the age of the hydrothermal alteration following massive influx of ocean water into the original impact crater, and which effectively also dates the impacting itself.

Apart from yielding a minimum age of the impact, the age data reported by Scherstén & Garde (2013) also constitute a rare and possibly unique example of pervasive and nearly complete isotopic resetting of zircon during a regional hydrothermal event.

Setting the scene of the Ni-Cu mineralisation in the norite belt

The renewed exploration of the Ni-Cu mineralisation in the norite belt onwards from 2011 by North American Nickel Ltd. prompted a short description of the norite belt in the context of impacting (Fig. 5; Garde *et al.* 2013a) which was coauthored by John Pattison from the company. It is well known that the 1.85 Ga Sudbury impact structure is one of the largest Ni camps in the world, and it is generally believed that its nickel is derived from the impact melt sheet in the crater floor which incorporated local Ni-bearing supracrustal rocks. The ore is mined from the base of the impact melt sheet, where the heavy metal sulphides were settled by gravity. Regarding the mineralisation in the Maniitsoq structure it was important to point out to the public that although the Maniitsoq norite belt is also impact-related, its setting is very different from that at Sudbury. The setting, microstructures, paragenesis and high Ni-tenor of the mineralisation in the norite belt all point to a magmatic origin of the mineralisation, but the norite belt is not part of a former impact melt sheet as at Sudbury but was derived from mantle melting, and the Ni source is most likely mantle olivine. Further preliminary information on the norite belt and its genesis can be found in Kokfelt *et al.* (2013).

Fig. 5. *Nickel-mineralised drill core from 'Imiak Hill' in the norite belt. From Garde et al. (2013a).*

Fig. 6. *M/S Minna Martek against a fjord side of structureless and uniform, mechanically homogenised Finnefjeld domain. AAG 2011-515.*

Revisiting the Finnefjeld domain

The Finnefjeld structure and its boundaries were described next (Garde *et al.* 2014a). This domain is exceedingly uniform and homogeneous. No internal lithological boundaries can be recognised (Fig. 6), and the rocks are structureless except for younger anatectic veins of white granite. In spite of Berthelsen's pioneering study in 1962, it was believed until the new field work that the domain represented a granitoid intrusion. The new study of its western boundary in 2011 showed that the gneissic structure of the orthogneiss has been obliterated over a few metres due to intense cataclasis. The contact zone is also highly compressed, as evidenced by upright accordion-style folds (first described by Berthelsen 1962) that are superimposed on polyphase fold structures of orogenic origin. The field party in 2011 also observed veins of shock-melted K-feldspar and new growth of subhedral black plagioclase in the contact zone. The black colour of the plagioclase is due to numerous tiny inclusions of iron oxide and signals that the plagioclase crystallised at very high temperature.

Detailed evidence of direct melting

Shock melting of individual rock-forming minerals, also called direct melting, proves the passage of a shock wave and hence constitutes diagnostic evidence of impacting (French & Koeberl 2010). Direct melting is an instantaneous phase change of a single mineral species from solid to liquid state. Direct melting takes place without any interference between adjacent mineral grains contrary to normal, 'petrological' melting where different mineral species react with each other. The temperature required depends on the individual melt temperature of the mineral in question, and for rock forming silicate mineral greatly exceeds the crustal temperatures that can be reached during endogenic (non-impacting) geological processes.

The paper by Keulen *et al.* (2015) technically constitutes proof of impacting and the passage of a shock wave at Maniitsoq. The core of the paper is a detailed account of direct melting of K-feldspar in a group of folded granitic sheets that occur intercalated with tonalitic gneisses in the south-western part of the impact structure at and north of Toqqusap Nunaa (Fig. 2). The direct melting of K-feldspar (and biotite) was accompanied by intense cataclasis of plagioclase (which has a higher direct melting point), and by crystal-plastic deformation and disruption of quartz grains into elongate, bifurcating aggregates which are quite unlike ribbon quartz in rocks deformed by normal tectonic processes. The plagioclase and quartz microstructures document intense seismic shaking that took place while the K-feldspar was in a molten state, i.e., the seismic shaking was induced by the impacting.

Seismic shaking: scientific excursions to the Italian Alps and the Vredefort dome in South Africa

The growing evidence of widespread impact-induced seismic shaking in the Maniitsoq impact structure in the form of localised micro-cataclasis without faulting, the thoroughly crushed and mechanically homogenised Finnefjeld domain and the plagioclase and quartz microstructures at Toqqusap Nunaa mentioned above all bear much resemblance to pseudotachylytes. As is well known, pseudotachylytes are dense, black rocks that resemble felsic volcanic glass, which form vein-like bodies in fault zones and in large impact structures such as the 2.02 Ga Vredefort and 1.85 Ga Sudbury impact structures in South Africa and Canada. In fact, the Vredefort dome is the type locality for pseudotachylytes, where they were first described in 1916 by S.J. Shand. However, the Vredefort pseudotachylytes have remained enigmatic ever since they were discovered. The conventional interpretation of pseudotachylytes is that they are formed by frictional melting between moving rock surfaces in faults (Sibson 1975), but there are no large faults associated with the spectacular and voluminous pseudotachylytes in the Vredefort dome, and it has therefore remained difficult to understand how they might have been produced (Shand 1916; Melosh 2005).

Garde *et al.* (2015) discovered that the prominent and well-known pseudotachylytes in the Ivrea-Verbano zone of the Southern Alps, Italy, are not located inside faults as formerly believed, but were formed without lateral displacement in the footwall of the Insubric line, the megafault of Alpine age that separates the European and African plates. He and his coauthors (Fig. 7A) interpreted the pseudotachylytes as results of numerous incidents of seismic shaking released by earthquakes along the Insubric line (no extraterrestrial impacting is implied in the Italian Alps).

The next logical step was to visit the pseudotachylytes in the Vredefort dome and test whether they might also have been produced by impact-induced seismic shaking – and if so, obviously associated with the 2.02 Ga impact. There is no controversy about the Vredefort dome being

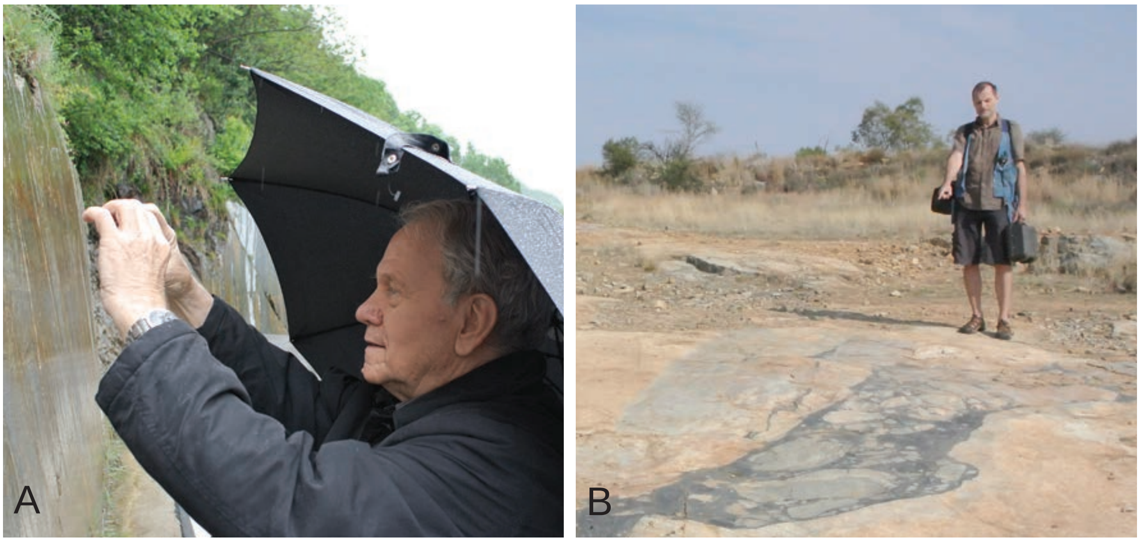


Fig. 7. ***A.*** *Attilio Boriani (University of Milan, Italy) studying seismic shaking at Premosello, Val d'Ossola, in the footwall of the Insubric line.* AAG 2013-404. ***B.*** *Martin Klausen (Stellenbosch University, South Africa) pointing at a pseudotachylyte zone in the Salvamento quarry, Vredefort dome. Vredefort impact structure, South Africa.* AAG 2015-001.

an impact structure, and it was considered that it would be easier to convince the scientific community about impact-induced seismic shaking at Maniitsoq if the process had already been documented at Vredefort. Field work in September 2015 by the author and Martin Klausen, Stellenbosch University (Fig. 7B) confirmed the theory. The new interpretation of the Vredefort pseudotachylytes (Garde & Klausen in press) will be published in the Journal of the Geological Society (London) where Shand (1916) published his original observations. A detailed description of the micro-cataclastic dykes and other features at Maniitsoq interpreted as resulting from impact-induced seismic shaking is under way.

Opposition against acceptance of the Maniitsoq impact structure

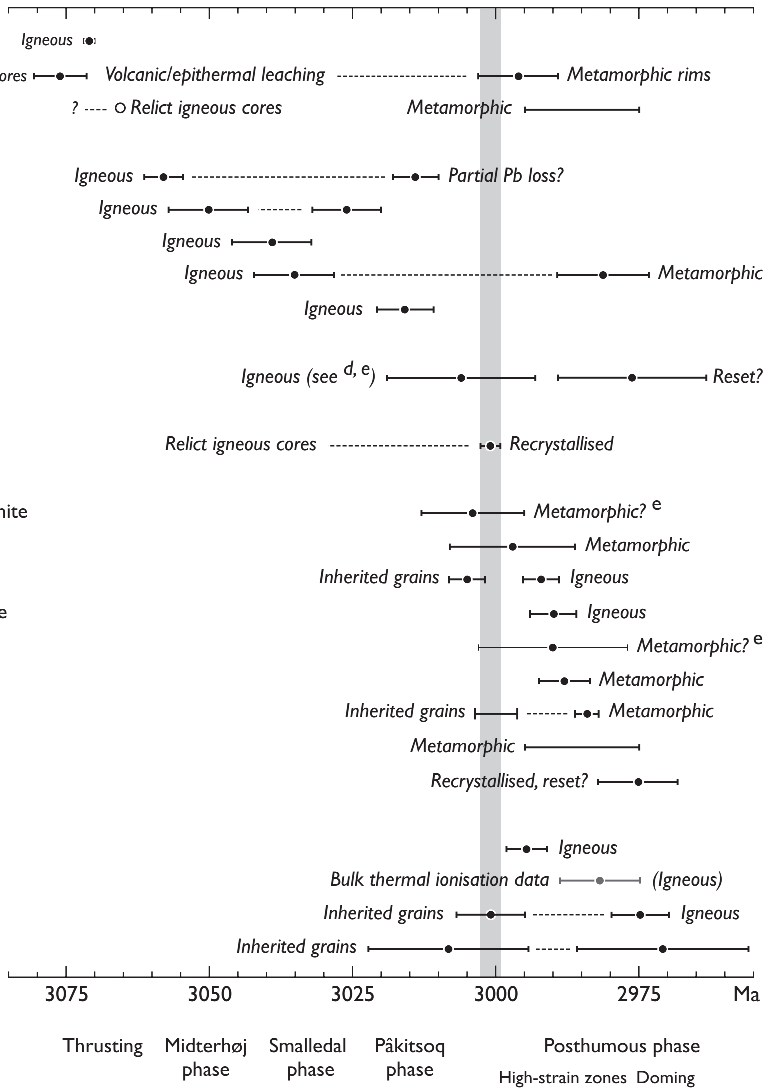
A group of scientists led by Uwe Reimold (Humboldt University, Berlin) and Christian Koeberl (Wien University) has commented on two of our earliest papers, arguing that the Maniitsoq structure is not an impact structure or, at best, highly unlikely to be one (Reimold *et al.* 2013, 2014). Their main argument was the absence of well-preserved and diagnostic shock lamellae in quartz, but they did not present any alternative interpretation that might in any way explain the features exposed in the structure. The Maniitsoq research group agrees with the opponents that unmistakable shock lamellae in quartz have not been found, but they have also explained that this is a logical consequence of the fact that only target rocks from the lower-crustal substructure are exposed today and available for study. These rocks were hot and ductile already when they received the impact, and the impacting was followed immediately by intense seismic shaking. It is therefore highly unlikely that well-preserved shock lamellae would have survived, as their host minerals have been deformed. In the replies (Garde *et al.* 2013b, 2014b) it was also pointed out that direct melting of rock-forming silicate minerals, which is prominent at Maniitsoq, is generally accepted as diagnostic of impacting and has been described from other impact structures, e.g. from the centre of the Vredefort dome in South Africa. The above-mentioned description of shock melting of K-feldspar (and biotite) by Keulen *et al.* (2015) therefore constitutes a robust proof of impacting at Maniitsoq.

Table 1

Mesoarchaean magmatic, metamorphic, hydrothermal and deformational events in the central and south-eastern Maniitsoq structure based on published zircon U-Pb data. Note the change from primary accretion and regional deformation to localised crustal melting and deformation after 3000 Ma. From Garde et al. (2014a).

Early continental nucleus, Nordlandet[a], ~3220–3180 Ma

Sample	Age populations		Area	Description
Magmatic accretion of volcanic rocks				
479827[c]	3071 ± 1		B	Volcano-sedimentary schist
477635[d]	3076 ± 4.6	2996 ± 7	Q	Leached metavolcanic rock
477367[c]	≤3068	~2995–2975	Q	Meta-volcaniclastic andesitic rock
Magmatic accretion of grey gneiss precursors				
477678[d]	3058 ± 3.4	3014 ± 4	Q	Orthogneiss
289246[b]	3050 ± 7	3026 ± 6	F	Orthogneiss, *'retrogressed'*
339223[b]	3044 ± 7		F	Qeqertaussaq diorite, *'retrogressed'*
339199[b]	3035 ± 7	2981 ± 8	F	Orthogneiss, *'retrogressed'*
G94-3[b]	3016 ± 5		M	Orthogneiss, granulite facies
Postkinematic diorite				
339512[b]	3006 ±13	2975 ± 7	F	Postkinematic diorite
Major hydrothermal event				
5 samples[e]	3000.9 ± 1.9		M	Various rocks
Metamorphism / Thermal event				
Unpublished data[g]		3004 ± 9	F	Isoclinally folded feldspathic pyroxenite
477629[d]		2997 ± 11	Q	Metavolcanic rock
477320[c]	3005 ± 3	2992 ± 3	Q	Granite sheet in high-strain zone
477318[c]		2990 ± 7	Q	Granite vein cutting high-strain zone
Grain A[f]		2990 ± 13	F	Single large zircon grain
488103[d]		2988 ± 4.5	B	Metavolcanic rock, Bjørneøen
477352[c]	~3000	2995–2975	Q	Meta-volcaniclastic andesitic rock
477385[c]		~2995–2975	Q	Meta-volcaniclastic andesitic rock
339641[b]		2975 ± 7	M	Finnefjeld 'gneiss'
Crustal remelting				
524261[e]	2994.6 ± 3.4		Q	Taserssuaq tonalite complex
289271[a]		2982 ± 7	Q	Taserssuaq tonalite complex
289177[b]	3001 ± 6	2975 ± 5	Q	Qugssuk granite
278886[b]	3008 ± 14	2971 ± 15	Q	Igánánguit granodiorite



Deformation [h]

All ages are based on U-Pb zircon ion probe data unless otherwise noted. Age populations shown with 2σ errors.
B: Bjørneøen (structural continuity with Qussuk area).
F: Fiskefjord area.
M: Central and northern Maniitsoq structure.
Q: Areas north and east of Qussuk, south-eastern peripheral Maniitsoq structure.
[a]Garde (1997); [b]Garde *et al.* (2000); [c]Garde (2007); [d]Garde *et al.* (2012b); [e]Scherstén & Garde (2013); [f]Nilsson *et al.* (2010); [g]A.P. Nutman in Nilsson *et al.* (2010).
[h]Revised from Berthelsen (1960) and Garde *et al.* (2000) including newest age data.

Regional geology and geochronology

Summary of the regional geological evolution

The regional geological evolution in the southern Fiskefjord block has been summarised in recent papers (e.g. Garde *et al.* 2012a, 2014a). The impact hit the Fiskefjord block in the northern part of the North Atlantic craton (Fig. 1) and affected large parts of the block. Most of this block constitutes the root zone of a convergent Mesoarchaean magmatic arc system (Windley & Garde 2009); modern geological information is scarce in the northern part of the block, but the Fiskefjord area that underlies the southern part of the impact structure is well known. In the north-west the impact structure is truncated by a fossil, south-dipping, *c.* 2.5 Ga subduction zone that also forms the north-western boundary of the Fiskefjord block.

Volcanic and plutonic accretion of the Fiskefjord block occurred at c. 3.07–3.02 Ga around a 3.2 Ga core of dioritic orthogneiss in Akia (Nordlandet, Fig. 1). The oldest recognised component of the main accretional event is andesitic metavolcanic rocks with epithermal gold mineralisation (Garde *et al.* 2012b) and associated mafic, arc-related magmatic rocks. Voluminous tonalitic, trondhjemitic and granodioritic (TTG) magmas were emplaced into the volcanic rocks between c. 3.05–3.02 Ga. It is assumed that the TTG rocks were largely derived from partial melting of subducting oceanic crust. Some of the tonalitic rocks around central Fiskefjord have unusual major and trace-element compositions with enrichment of Mg, P, Ba, Sr and light rare earth elements. According to Steenfelt *et al.* (2005) these rocks owe their unusual composition to a source that not only consisted of subducting oceanic crust but also involved a mantle component contaminated by carbonatite (Steenfelt *et al.* 2005).

The earliest recognisable deformation structures in the Fiskefjord area indicate thrust intercalation of mafic volcanic and tonalitic rocks. As the arc became thicker, large recumbent isoclinal folds were formed in the stacked extrusive and intrusive rocks and were refolded. The youngest regional folds are upright with typical amplitudes and wavelengths of up to a few kilometres. Berthelsen (1960) made a detailed structural analysis of the peninsula of Toqqusap Nunaa (Fig. 1), and his fold phases (shown in Table 1) and general structural evolution were substantiated, re-interpreted in a plate-tectonic context and extended into the larger Fiskefjord region by Garde *et al.* (2000).

The ambient temperature and pressure have been estimated to 800–860 °C, 0.8 GPa from construction of pseudosections in adjacent pelitic rocks (B. Reno and B. Dyck, personal communication, 2012). An older determination from the southern periphery of the Maniitsoq structure on Akia c. 40 km south of the present study area yielded 800 ± 50 °C, 0.79 ± 0.1 GPa, based on mineral pair equilibria (Riciputi *et al.* 1990).

Geochronology

All published geochronological data from the Fiskefjord block were compiled by Garde *et al.* (2014a) and are shown here in Table 1 (references are listed in the table). Most of the geochronological information was obtained from the Fiskefjord and Qussuk areas in the south-eastern and eastern parts of the impacted region, and most of it predates the discovery of the impact structure. The collective data set shows that the structural and tectonic evolution of the region falls into two separate parts (Table 1). The first part, between c. 3075 and 3015 Ma, covers the juvenile volcanic and plutonic crustal accretion in the convergent arc system. The second part, after the impact, began with the emplacement of the norite belt (Fig. 1) and associated post-kinematic diorites after the cessation of penetrative regional deformation. There are no published age data from the norites, and the contemporaneous post-kinematic diorites have not yielded a precise age, although available U-Pb zircon data are compatible with an emplacement close to 3.0 Ga. The intrusion of the norites and diorites was succeeded by the hydrothermal event that caused complete isotopic resetting of zircon east of the Finnefjeld domain at 3000.9 ± 1.9 Ma (Scherstén & Garde, 2013).

A widespread c. 3000–2975 Ma thermal event (Table 1) is recognised in all parts of the Maniitsoq structure where geochronological data exist. It is recorded by metamorphic zircon and metamorphic rims on igneous zircon, monazite growth, and by igneous zircon in crustal melts. The most prominent post-impact intrusion (apart from the norite belt) is the Taserssuaq tonalite complex (Garde 1997) which covers a large region in the eastern part of the impacted area and was emplaced at c. 2995 Ma (Scherstén & Garde 2013). This was followed by the Igánánguit granodiorite and Qugssuk granite in the south-eastern periphery of the Maniitsoq structure. A more detailed overview of zircon and monazite age data from the late intrusions and granitic veins in small shear zones can be found in Garde *et al.* (2014a).

Older whole-rock Rb-Sr, Pb-Pb and bulk zircon data from the Finnefjeld domain are interesting. The earliest attempts to date the Finnefjeld rocks, using Rb-Sr whole rock and U-Pb bulk zircon methods, were unsuccessful *per se* as they failed to yield proper isochrons, however, both methods clearly indicated a protolith age well above 3.0 Ga (all reported dates are with 2σ errors). Two Rb-Sr whole rock errorchrons with reference lines of 3058 ±123 Ma (S. Moorbath, personal communication, 1990) and 3034 ±134 Ma (Garde 1997) were clearly older than they should have been if the Finnefjeld body was really a late-kinematic orogenic intrusion. Also a conventional, multi-grain U-Pb zircon analysis from a sample collected 3 km south of Sisak (Fig. 1) yielded an apparent age that seemed too old (3067 +62/–42 Ma, see Garde 1997). These 'old-fashioned' geochronological data sets clearly support Berthelsen's (1962) interpretation that the Finnefjeld body was transformed from the surrounding rocks, and also happen to be in excellent agreement with the ion probe U-Pb dates well above 3.0 Ga obtained from surviving cores of otherwise thoroughly hydrothermally altered zircon in samples collected east of the Finnefjeld complex (Scherstén & Garde 2013).

In view of the cataclasis and hydrothermal alteration the large errors on the bulk-rock and bulk zircon age determinations are not surprising. Whole-rock Pb-Pb analysis of 12 samples from the island of Talerulik in the south-western part of the Finnefjeld complex by Paul N. Taylor (see Garde 1997) gave a best fit line of 2700 +380/-350 Ma (model $\mu 1 = 7.59$). Garde *et al.* (2000) obtained a U-Pb zircon ion probe age of 2975 ± 7 Ma from a homogeneous sample with finely dispersed biotite collected 2 km north of Sisak close to the south-western margin of the Finnefjeld complex (Fig. 1). The zircon is prismatic with magmatic-type oscillatory zonation. A revisit to the sample locality in 2011 revealed that the sample might represent a local melt phase that postdates the main body, and is conceivably related to the widespread, post-3000 Ma thermal event (Table 1).

Hydrothermal alteration

Hydrothermal alteration has been mentioned several times in the previous sections and is indeed a prominent feature of the impacted region. It is therefore described separately here. It was considered to be an endogenic feature, although an enigmatic one, until the discovery of the impact structure, and was previously referred to as high-grade retrogression from granulite-facies metamorphism.

Much of the Archaean bedrock exposed in the Fiskefjord region and elsewhere in the impacted area has been altered by intense hydrothermal processes, whereby original granulite-facies parageneses have been partially or wholly altered to intermediate amphibolite facies parageneses. This has resulted in rocks with a characteristic spotted ('blebby') texture of mafic minerals as well as a centimetre-scale, reticular network of pale veinlets with very indistinct boundaries (Figs 8, 9). The hydrothermally altered rocks are thoroughly recrystallised. In the widespread tonalitic orthogneisses original pyroxene has been altered to spongy amphibole-quartz intergrowths ± biotite, and biotite has crystallised (or recrystallised) into centimetre-sized, sheaf-like clots consisting of radiating individual grains. A similar mineral texture can also be found e.g. where sheets of granulite-facies orthogneisses have been thrust over lower-grade gneisses, and has colloquially been known in the North Atlantic craton of southern West Greenland as 'blebby texture' (e.g. McGregor 1993, his fig. 29).

Fig. 8. *Hydrothermally altered orthogneiss. 'Blebby' texture with centimetre-sized aggregates of mafic minerals and net-veining. Inland locality 2010-110. AAG 2010-604.*

The transformation from anhydrous mafic minerals to hydrous equivalents was first interpreted as high-grade metamorphic retrogression by metamorphic fluids expelled from more deeply located gneisses undergoing progressive dehydration (Garde 1990, 1997). Although this process might actually take place, the author gradually realised that the alteration in the Fiskefjord area was much more thorough and intense than in any other high-grade metamorphic terrain he had visited in Greenland, or read about from similar high-grade

Fig. 9. *Net-veined 'blebby' texture in hydrothermally altered orthogneiss. The small black spots are lichens. Inland locality 2010-109. AAG 2010-606.*

regions worldwide. The transformation is now re-interpreted as impact-related and caused by influx of seawater into the young impact crater and formation of a crustal-scale hydrothermal cell extending deep into the middle or even lower crust (Scherstén & Garde 2013).

Apart from the above mentioned zircon study by Scherstén & Garde (2013) and a pilot study of amphibole and biotite compositions in unaltered and hydrothermally altered ('retrogressed') amphibole and biotite reported by Garde (1990, 1997), the hydrothermal alteration has not been studied in detail. For instance, the exact range of P-T conditions under which the alteration took place has not been determined. The altered rocks might potentially also contain chemical and isotopic information about the origin and composition of the hydrothermal fluid (and hence, potentially, the composition of seawater at the time of impacting). An example of thoroughly silicified rocks along a 20 m wide alteration zone is shown in Fig. 10.

Fig. 10. *Intensely silicified orthogneiss in 20 m thick hydrothermal alteration zone. Inland locality 2010-20, eastern Maniitsoq structure. AAG 2010-082.*

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Fig. 11. *Rhodiola rosea, roseroot, a common flowering plant along the coasts of the Finnefjeld domain. It is thought to have positive medicinal effects against stress. Loc. 2011-48, AAG 1011-353.*

Field localities

Maniitsoq impact structure. The field localities presented on the following pages are intended for a 6-day excursion by boat to the western part of the Maniitsoq impact structure beginning in Nuuk and ending in Maniitsoq. The selection is based on localities visited during ship-based field work in 2011 by Lotta Möller, Leif Johansson and Brendan Dyck (Lund University) and Kim Esbensen and the author (GEUS), Fig. 11. The localities are shown in Fig. 12 and listed in Table 1. Impact-related features occur in all parts of the Maniitsoq structure within the 'melt zone' (Fig. 1), but are expressed in different ways. It is likely that equivalent or even better localities could be found in the western part of the structure if it was surveyed in detail. An advantage of the selected localities is that the field observations are supported by microstructural studies.

Corundum locality. The last locality at the head of the fjord Kangerluarsuk south-east of Maniitsoq is an ultrabasic lens and aluminous, kyanite-bearing metasedimentary rocks in the fossil, 2.5 Ga subduction zone that separates the Fiskefjord and Maniitsoq blocks of the North Atlantic craton (Dyck *et al.* 2015). A black micaceous rock in the contact zone of the ultrabasic lens contains blue-red, barrel-shaped corundum crystals up to several centimetres in size. The locality was visited by Mogens Marker and the author in 1987 but is not addressed further in this excursion guide as it is unrelated to the Maniitsoq structure. The reader is referred to the short description by Garde & Marker (1988).

Fig. 12. *The 2011 field team on board M/S Minna Martek: from left to right Brendan Dyck, Kim H. Esbensen, Adam A. Garde, Lotta Möller and Leif Johansson.*

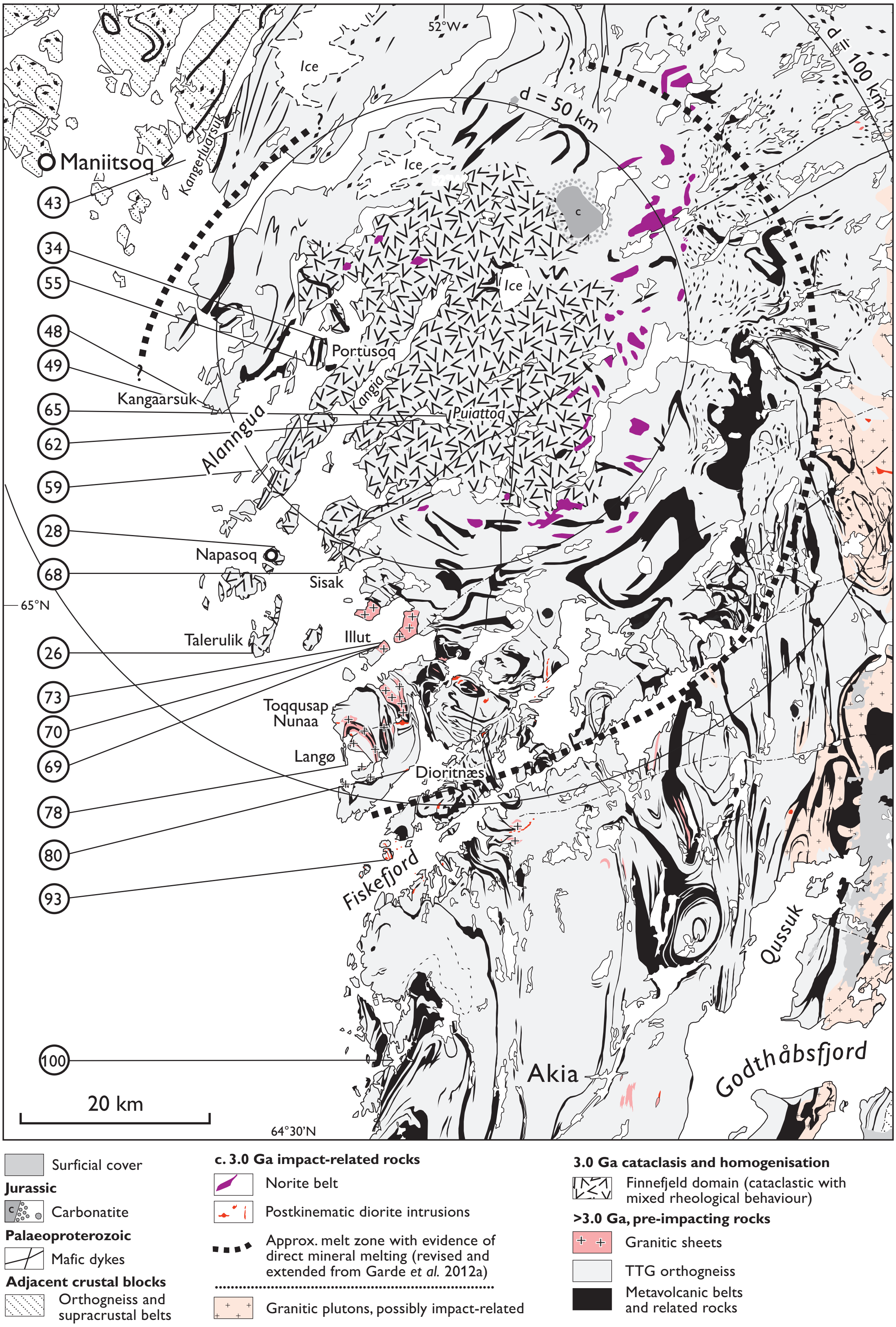

Fig. 13. *Excursion map of the south-western part of the Maniitsoq impact structure. Numbers of described 2011-localities shown in circles.*

Table 2

Excursion plan for 13– 19 June 2016

12 June **Nuuk to Toqqusap Nunaa** (mouth of Fiskefjord)

Locality		Degree-minute.decimal		Exposure
13 June	**Toqqusap Nunaa** (mouth of Fiskefjord)			
2011-100	Akia (Nordlandet)	64°35'.3	-52°05'.3	Granulite facies orthogneiss
2011-80	Dioritnæs, Toqqusap Nunaa	64°51'.0	52°03'.9	Orbicular post-tectonic diorite (~60 m a.s.l.)
2011-93	Mouth of Fiskefjord	64°45'.8	-52°06'.6	Postkinematic diorite - plagioclasite
2011-78	Langø, southern tip (Sydkap)	64°51'.2	-52°11'.9	Fracture cleavage
	Anchorage at Toqqusak			
14 June	**Toqqusap Nunaa– Puiattoq**			
2011-69	Illut, north coast A	64°57'.8	-52°08'.5	Dunite breccia. Orthogneiss with ghost structure
2011-73	Illut, north coast B	64°58'.1	-52°07'.7	Purple gneiss
2011-73	Illut, north coast C	64°58'.1	-52°07'.7	Orthogneiss, incipient 'grey dyke' formation
2011-26	Talerulik	64°57'.2	-52°24'.3	Homogenisation and melting, black plagioclase
2011-68	Sisak	65°02'.2	-52°12'.9	Mechanical homogenisation of amphibolite
	Anchorage at Puiattoq			
15 June	**Puiattoq –Alanngua and east coast of Sdr. Isortooq**			
2011-62	Puiattoq	65°10'.8	-52°02'.2	'Grey dykes' with K-feldspar veins in cataclastic rock
2011-65	Puiattoq	65°11'.2	-51°59'.2	Mechanical mixing of mafic and felsic rocks
2011-64	Puiattoq	65°11'.2	-52°00'.1	Younger brittle/ductile shear zone
2011-59	Island, outer Alanngua	65°07'.8	52°25'.2	Cataclastic melange
	(Naajannguit W of new becaon)			
	Anchorage behind Uummannaq island			
16 June	**Alanngua**			
2011-28	Napasoq	65°03'.3	-52°22'.4	Pseudotachylyte in late shear zone (reference outcrop)
2011-55	Portusoq	65°14'.0	-52°18'.3	Accordion folding at contact to Finnefjeld domain
2011-34	Portusoq	65°15'.4	-52°15'.6	Annihilation of gneissic structure, Finnefjeld contact
	Anchorage behind Uummannaq island			
17 June	**Alanngua**			
2011-48	Kangaarsuk	65°11'.6	-52°31'.3	Melt veins, black plagioclase
2011-49	Kangaarsuk	65°11'.0	-52°30'.3	Melt veins, black plagioclase, orthogneiss bulk melting?
	Portusoq-Kangaarsuk area			Black high-T plagioclase and hydrated red plagioclase
	Anchorage behind Uummannaq island			
18 June	**Reference outcrops and blue-green corundum locality. Not impact-related**			
2011-43	Island, mouth of Kangerluarsuk	65°25'.6	-52°35'.0	Orthogneiss unaffected by impacting.
1987	Head of Kangerluarsuk	65°33'.9	-52°23'.9	Metapelite, Archaean subduction zone. Corundum loc.
	Anchorage at head of Kangerluarsuk			

19 June **Kangerluarsuk–Maniitsoq, Maniitsoq–Nuuk**

Loc. 2011-100. Dioritic gneiss, Akia/Nordlandet

Dioritic orthogneiss at granulite-facies grade in north-western Akia/Nordlandet, with age c. 3.2 Ga (Garde 1997). Non-impacted reference locality.

The metamorphic grade is high (Riciputi *et al.* 1990; B. Reno, personal communication, 2012) and the orthogneiss is restitic after loss of a felsic melt component by partial melting. Boundaries between rock units are diffuse due to the partial melting and recrystallisation, and the rock components appear blurred (Figs 14, 15). Occasional thin pegmatitic veins. likewise with diffuse margins, are present. Such granulite-facies pegmatites typically contain quartz, plagioclase and hornblende.

Fig. 14. *Dioritic orthogneiss, outer coast of Akia/Nordlandet. Note granular texture and refolded tight fold, outlined by thin pegmatite veins.* AAG 2011-859.

Fig. 15. *Granular, granulite-facies texture in dioritic orthogneiss. Note dark grey plagioclase. Diameter of coin 2.8 cm.* AAG 2011-860.

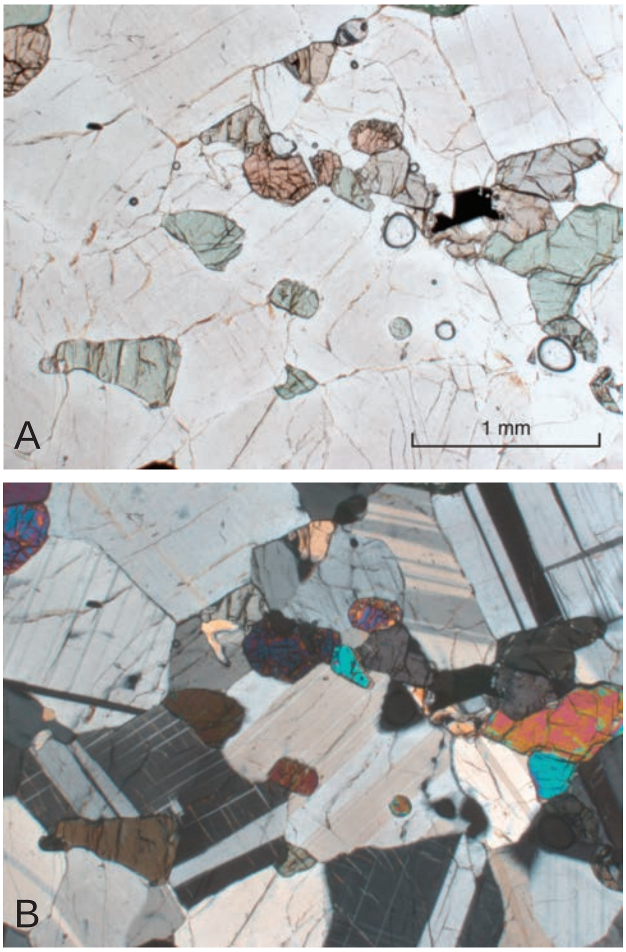

Fig. 16. *Equant grains of plagioclase and orthopyroxene with common triple junctions, typical of granulite-facies rocks. The plagioclase is 'dusty' due to tiny inclusions of Fe-oxide.* **A**: *Transmitted light.* **B**: *crossed polarisers.* Sample GGU 525380.

Due to the blurred boundaries between the individual components and the recrystallisation it is difficult to recognise and study the tectonic structure, although a tight recumbent fold is visible in Fig. 13. The map-scale structure is complex and more easily recognisable in the amphibolite-facies gneiss terrains in other part of the Fiskefjord map area (Garde 1989), and as demonstrated particularly well on the peninsula of Toqqusap Nunaa north of the head of Fiskefjord (Fig. 1; Berthelsen 1960).

In thin section the orthogneiss is granular, with typical 120° triple junctions between equant mineral grains (Fig. 16).

Dark plagioclase in orthogneiss. The dark appearance of the orthogneiss is due to its dark grey plagioclase, which is 'dusted' by tiny inclusions of iron oxide (Fig. 17). such inclusions were probably originally dissolved in the crystal lattice and witness crystallisation at high temperature (see e.g. Johansson 1992).

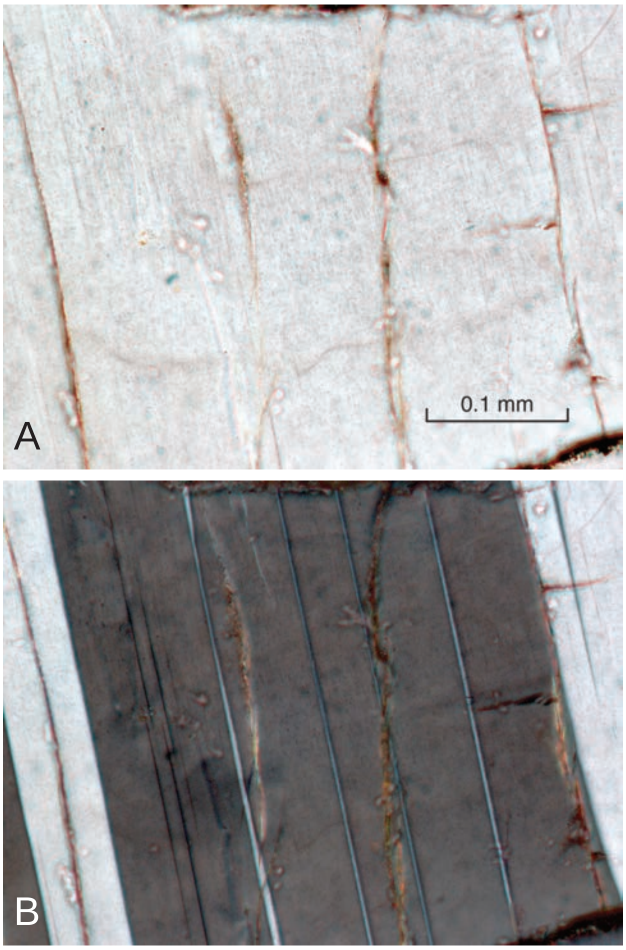

Fig. 17. *'Dusty' plagioclase viewed at high magnification. The 'dusting' is due to numerous tiny specks of iron oxide (probably exsolved from Fe^{2+} in the plagioclase lattice and oxidised to hematite). This suggests that the plagioclase crystallised at high temperature.* **A***: Transmitted light.* **B***: crossed polarisers.* GGU 525380.

Plagioclasite micro-intrusion. Vein-like micro-intrusions of coarse-grained, almost monomineralic plagioclasite can be observed on clean coastal outcrops of northern Akia (Fig. 18). The plagioclase is dark grey to almost black.

Such small intrusions and veins seem to be common in northern Akia, but are not a normal constituent of high-grade orthogneiss terrains. They have never been studied in detail, and their petrogenesis is not well understood.They almost certainly belong to the family of impact-related, post-kinematic diorites and norites, see loc. 2011-93. There are no chemical analyses of the plagioclasites, and it is therefore not known if they possess an ultramafic signature like the post-kinematic diorites and norites. They might stem from remobilised shock-induced melts of local rocks where plagioclase had the lowest direct melt temperature of the phases present, or they might be derived from a deeper source.

Fig. 18. *Intrusive vein of dark-grey, coarse-grained plagioclasite. Contact below coin (d = 2.8 cm) near top of photo.* AAG 2011-863.

Loc. 2011-80. Orbicular diorite , Dioritnæs

Introduction. Berthelsen (1960) was the first geologist to recognise the small dyke- and plug-like post-kinematic intrusions of diorite in the Fiskefjord block. He thought they were replacive, which is partially correct as they commonly have up to several metres wide magmatic hybrid zones against the country rocks. Some of the country rock has been adsorbed and mixed with the intruding magma, which must therefore originally have been mafic or ultramafic, not dioritic in composition.

These diorites, which were emplaced after the cessation of the regional deformation, can be found as scattered plugs and inclined sheets of most of the Fiskefjord map area (Garde 1991). They have very high Mg, Cr, Ni and V contents for rocks with dioritic bulk compositions and are thought to contain a significant mantle component (Garde 1991).

The post-kinematic diorites have been likened to the norite belt (Garde 1991) and are considered to be impact-related (Garde *et al.* 2012a). They have clearly been emplaced after the impacting as they do not possess any shock-related features such as fracture cleavage or micro-cataclastic dykes. U-Pb geochronology of inherited and new zircon in a post-kinematic diorite from central Fiskefjord is compatible with emplacement at 3.0 Ga (see Garde *et al.* 2012a and Scherstén & Garde 2013).

Observations. One of the many diorites on Toqqusap Nunaa crops out at sea level at Dioritnæs (named so by Berthelsen 1960). At 60 m elevation there is a typical crumbling, weathered outcrop with proto-orbicular texture: large skeletal crystals of plagioclase with interstitial orthopyroxene and sometimes concentric growth rings (Figs 19–20). The orbicular texture is probably related to fast plagioclase crystallisation from a small number of crystal nuclei.

Although the post-kinematic diorites weather easily they commonly form small topographic highs in the glaciated landscape. This may reflect their homogeneity, as they do not possess internal lithological heterogeneties or regular joints that would lend themselves to plucking by the moving ice, in contrast to orthogneiss and amphibolite which commonly form roches moutonnées. The larger noritic intrusions of the norite belt in the eastern part of the impact structure display similar topographic features.

Fig. 19A. *Gravelly outcrop of post-kinematic diorite with loose orbicules up to 10 cm large Coin (d = 2.8 cm) for scale.* AAG 2011-658.

Fig. 19B. *Orbicules in place. Coin (d = 2.8 cm) for scale.* AAG 2011-659.

Fig. 20. *Section of orbicule from the norite belt. Central radiating and outer concentric crystallisation structure. Width of orbicule 6 cm.* Sample 257527 (KSE).

Loc. 2011-93. Post-kinematic diorite and plagioclasite dyke

This locality is a arge area of post-kinematic intrusive dioritic rock with indistinct outer boundaries and many indistinct, presumably partially digested inclusions of host rocks (Fig. 21). The dioritic mass is granular and homogeneous and devoid of tectonic foliation or regional deformation. It is cut by thin granitic/pegmatitic veins, commonly with rather sharp margins unlike granulite-facies pegmatites such as observed at Akia (loc. 2011-100). The veins are also typically straight and have several directions with large angles between them, as if they might have been emplaced along temporary joints.

The post-kinematic diorites have many features in common with the norite belt, including their hybrid margins to country rocks and lack of tectonic deformation features, see also loc. 2011-80 (Dioritnæs).

Plagioclasite. A dyke-like 'intrusion in the intrusion' of almost black plagioclasite several metres wide, is younger than the post-kinematic diorite itself but interpreted as closely related to it (Figs 22–24). A close-up (Fig. 24) shows that the plagioclasite is coarse-grained and structureless and contains minor orthopyroxene. The occurrence of the plagioclasite inside the post-kinematic intrusion of course indicates that it was emplaced after the diorite, but the two components could be penecontemporaneous.

Fig. 21. *Dark grey, plagioclase-rich dyke cutting pale, Homogeneous, brownish-coloured post-kinematic diorite and related, dark plagioclasite dyke. Lotta Möller (Lund University) for scale. AAG 2011-811.*

Fig. 22. *Plagioclasite with enclave of the main post-kinematic diorite. AAG 2011-813.*

Fig. 23. *Close-up of Fig. B. The brownish enclave of post-kinematic diorite contains slivers of presumed host rock amphibolite (white arrow). AAG 2011-814.*

Fig. 24. *Plagioclase-rich, opx- bearing post-kinematic rock. AAG 2011-816.*

Loc. 2011-78. Fracture cleavage, 'grey dykes' and hydrothermal alteration, Langø

The southern part of Langø at the west side of Toqqusap Nunaa contains both pre-, syn- and post-impacting features.

Pre-impact amphibolite-orthogneiss relations. A raft of compositionally layered, foliated and isoclinally folded amphibolite of likely volcanic origin is seen in Fig. 25. It is cut by thin tonalitic sheets similar to the regional orthogneisses, which have been ductilely deformed together with the amphibolite after their emplacement. This is a perfectly normal relationship seen in most of the Fiskefjord block, showing that the amphibolite is older than the orthogneiss.

Fig. 25. *Normal endogenic magmatic-tectonic relationship between amphibolite (older) and orthogneiss (intrusive, younger), with subsequent ductile deformation. Coin d=2.8 cm. AAG 2011-649.*

Fracture cleavage. In parts of this locality the rocks contain numerous steep, closely spaced fractures without any displacement. The fracture spacing is typically about 1 cm (Fig. 26). Such fractures would normally never be formed in the lower crust, where crystal-plastic deformation prevails. In order to produce fracturing in the lower crust a very high strain rate is needed, much higher than occurs in endogenic (non-impact-related) tectonic environments. The fracture cleavage is unrelated to faulting or thrusting but appears to have been variably annealed by recrystallisation during subsequent intense hydrothermal alteration (Fig. 26) that has affected much of the impacted region. It follows that the fracture cleavage was formed in the lower crust, not during the brittle Palaeoproterozoic deformation that resulted in e.g. the Fiskefjord fault.

Fig. 26. *Fracture cleavage (arrow), partially annealed by recrystallisation during intense hydrothermal alteration. AAG 2011-643.*

Comment on the fracture cleavage. Fracture cleavage has been observed in different parts of the Maniitsoq impact structure and is interpreted as due to impact-induced seismic shaking. Fracture cleavage is a well-known feature in terrestrial impact structures (e.g. Vredefort, Sudbury and Gosses Bluff in South Africa, Canada and Australia, respectively). However, it has generally been interpreted as a result of the direct shock wave, inasmuch as the process of seismic shaking has not previously been given due attention in terrestrial impacting (see Garde & Clausen in press).

Fig. 27. *Vein-like micro-cataclastic zones ('grey dykes') at white arrows, closer view of Fig. 26. Their margins and the host rock have been affected by hydrothermal alteration with hydration of pyroxene to amphibole and biotite and thorough recrystallisation of quartz and feldspar. This has partially annealed the fracture cleavage (black arrow). Coin d=2.8 cm. AAG 2011-644.*

Vein-like micro-cataclasites (**'grey dykes')**: Micro-cataclastic, dyke-like zones typically a few centimetres wide (Figs 27–30), formed *in situ* or injected from close by, are a common feature in the impacted area. They were described already by Bridgwater *et al.* (1976) under the name of 'grey dykes' and were believed to be small magmatic intrusions. The thicker zones are commonly lined by centimetre-thin veins of K-feldspar (originally described as pegmatite), which may also form internal veins in the cataclastic material. The micro-cataclasites are composed of finely fractured plagioclase, ductilely deformed stringers of quartz, very fine-grained biotite, and undeformed patches and microveins of K-feldspar).

Interpretation. The micro-cataclastic zones were formed by impact-induced seismic shaking. They are closely related to pseudotachylyte, which can also be produced by seismic shaking – both along major tectonic faults as in the footwall of the Insubric line in the Italian Alps (no impacting; Garde *et al.* 2015), and in the Vredefort impact structure South Africa (Garde & Klausen in press), the type locality for pseudotachylyte.

Hydrothermal alteration. In addition to features formed in direct response to the impact (fracture cleavage, 'grey dykes'), the Langø locality is also a good example of recrystallisation under hydrous conditions at high metamorphic grade, resulting in a microstructure known in Southern West Greenland as 'blebby texture'. In the Maniitsoq structure such hydrothermal alteration and recrystallisation is both very intense and widespread and interpreted as due to massive influx of sea water into the crater floor of the young impact structure (Scherstén & Garde 2013). 'Blebby texture' can also be formed by endogenic retrogression from granulite to amphibolite facies.

Fig. 29. *Interfingering relationship between micro-cataclastic material (interpreted as produced in situ by intense impact-induced seismic shaking) and less affected orthogneiss. Small lenses of less comminuted material occur inside the cataclastic area (arrow). Diameter of coins 2.8 cm. AAG 2011-648.*

Fig. 28. *Fracture cleavage and micro-cataclastic, bifurcating 'grey dyke'. The fracture cleavage is better developed, more regular and more closely spaced in the orthogneiss than in the micro-cataclasite. The two features are interpreted as contemporaneous results of impact-induced seismic shaking. Diameter of coin (arrow) 2.8 cm. AAG 2011-645.*

Fig. 30. *Hydrothermally altered orthogneiss with recrystallised micro-cataclasite. The 'blebby' texture' in the orthogneiss is due to intense, static hydrothermal alteration at amphibolite-grade in the middle/lower crust shortly after the impacting. Also the micro-cataclasite has been recrystallised, which has coarsened its grain size and given it a sugary appearance. AAG 2011-647.*

Loc. 2011-69. Ultrabasic breccia, Illut

The orthogneisses and granitic rocks of the archipelago north of Toqqusap Nunaa contain belts, rafts and enclaves of mafic metavolcanic rocks, as well as lenses of dunite (probably of cumulate origin and derived from the root zone of the former magmatic arc). Such enclaves are in themselves perfectly normal constitutents in most parts of the North Atlantic craton.

Fig. 31. *Dunitic breccia with granitic matrix. Brendan Dyck for scale.* AAG 2011-577.

Fig. 32. *Close-up of dunitic breccia in Fig. 31 with granitic matrix (black arrow). The margins of the dunitic clasts have been hydrothermally altered (white arrow).* AAG 2011-579.

Fig. 33. *Dunitic breccia with coarse-grained granitic matrix (lower right) and orthogneiss at left margin (black arrow). The dunitic clasts have been hydrothermally altered. with serpentinised mantles and serpentinisation along former interior fractures (white arrow). The intense foliation of the orthogneiss wraps around the breccia. This is interpreted as due to impact-related rather than tectonic deformation (see loc. 2011-73).* AAG 2011-557.

Some of these remnants of amphibolite and dunitic rocks form the main component of highly unusual and spectacular breccias in the vicinity of the Finnefjeld domain. One of these breccias at loc. 2011-69 comprises equant, decimetre-sized fragments of dunite embedded in a granitic matrix (Figs 31, 32). The dunitic fragments are commonly affected by hydrothermal alteration (Figs 32, 33).

Fig. 34. *Detail of contact between dunitic breccia and orthogneiss. The foliation of the orthogneiss is bulging inwards between the ultrabasic clasts (black arrow), as if it had been pressed into an interstice from the outside.* AAG 2011-558.

Probably the most unusual property of these breccias is that they have been formed *in situ*, *not* as composite intrusions where a magma has transported xenoliths of another rock type, and *not* as parautochthonous intrusion breccias where a local wall rock has been incorporated into the marginal part of an intrusion.

Bulging orthogneiss contact. The bulging margin of a strongly foliated orthogneiss against one of the breccias and is particularly interesting (Fig**.** 34). A bulge is displayed in the orthogneiss at the contact to the breccia, as if the low-pressure zone now occupied by granite between the dunitic fragments (below the black arrow) had been exploited by the orthogneiss. If this observation is correct, it indicates a late compressional stage whereby the orthogneiss that surrounds the breccia was pressed up against it after the brecciation.

Field interpretation of the breccias. The competent component of these breccias (in this case the dunite) appears to have been subjected to cataclasis *in situ*. Part of the local rock volume around them has melted and now fills the space between the 'exploded', originally coherent fragments.

Interpretation of the breccias as impact-related. The brecciation of the competent component is considered to have formed by impact-induced seismic shaking, as the initial shock wave was transformed into elastic seismic waves.

Impact-induced seismic shaking is very short-lived and probably only lasts for a couple of minutes even if it is induced by a very large impact. Such seismic shaking is an established process which was described from the Moon already in the 1970s, but this important process has hardly previously been been considered in the context of terrestrial impact structures. See further discussion in Garde & Klausen (in press).

The precise timing and mechanism of formation and emplacement of the granitic breccia matrix is not fully understood at present. Was it a shock melt that was squeezed out of the surrounding orthogneiss during the seismic shaking?

Loc. 2011-70. Purple gneiss, Illut

Continuing by foot along the north coast of Illut, there are exposures of anonymous-looking, fine-grained, purplish-grey granitoid rocks and grey tonalitic orthogneiss (Figs 35, 36). Berthelsen (1960) called these rocks 'purple gneiss'. They probably owe their unusual colour to very finely dispersed K-feldspar and mesoperthite (see below). Superficially these rocks appear dull and uninteresting, but a detailed study by Keulen *et al.* (2015) has revealed that their microstructures are highly unusual and exceedingly complex due to a combination of direct (shock) melting of K-feldspar and seismic shaking.

Fig. 35. *Purple gneiss on the north coast of Illut with complex, ghost-like polyphase structure. The rock is thoroughly affected by impacting: both shock melting and seismic shaking.* AAG 2011-591.

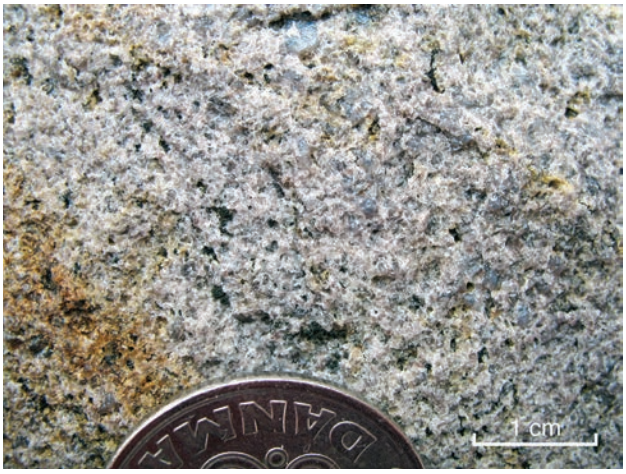

Fig. 36. *Detail of apparently homogeneous purple gneiss. North coast of Illut (site of sample 525360). Diameter of coin 2.8 cm.* AAG 2011-583.

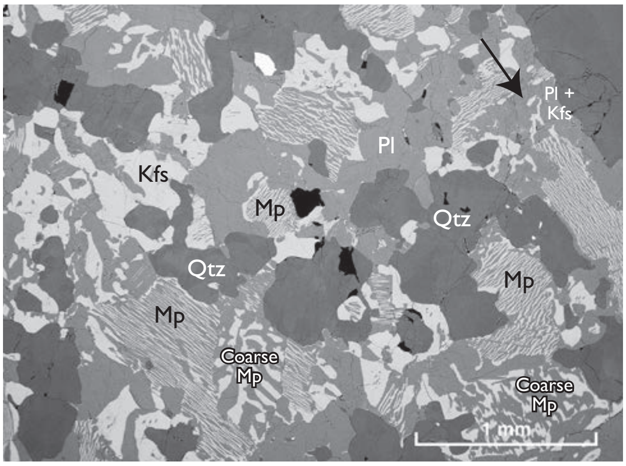

Fig. 37. *Complex microstructure of three-feldspar granitic rock with albitic plagioclase (Pl), K-feldspar (Kfs, microcline), mesoperthite (Mp), coarse mesoperthite and quartz. Backscattered electron scanning electron microscope (BSE-SEM) image from Keulen et al. (2015, their fig. 2B).* *GGU 525360.*

Feldspar shock melt microstructures. The paragenesis in sample 525360 shown in Fig. 37 and in other samples with three coexisting alkali feldspars is highly unusual. The mesoperthite represents an original ternary alkali feldspar, with a locally recrystallised, coarser variety. Mesoperthite as such is normal in high-temperature metamorphic rocks, but never together with both albitic plagioclase and K-feldspar touching each other.

As explained by Keulen *et al.* (2015) this paragenesis is 'impossible' for an endogenic granitic rock, as three different phases of alkali feldspar cannot coexist in endogenic granitic systems.

Keulen *et al*. (2015) explained the paragenesis and feldspar textures as follows. The rock volume was momentarily heated to above 1300°C by the passage of the impact shock wave. The temperature excursion was very short-lived, and did not allow sufficient time for the normal chemical reactions between coexisting mineral phases which lead to normal cotectic or eutectic melting. At lower-crustal pressure the melting temperature of K-feldspar is about 1300°C, a little higher for albitic plagioclase, and close to 2000°C for quartz (see compilation of melt temperatures in Keulen *et al.* 2015).

The sequence of events was interpreted as follows: (a) Shock melting of K-feldspar above 1300°C, (b) partial mixing with adjacent plagioclase which was shattered and penetrated by microscopic veins of molten K-feldspar, (c) formation of intermediate ternary feldspar melt patches where the mixing was effective, (d) solidification without feldspar re-equilibration, (e) exsolution of the ternary feldspar during slow cooling (a normal phenomenon), and (e) incipient coarsening of the mesoperthite in the presence of small amounts of hydrous fluid (but insufficient to cause full re-equilibration and recrystallisation of the whole rock).

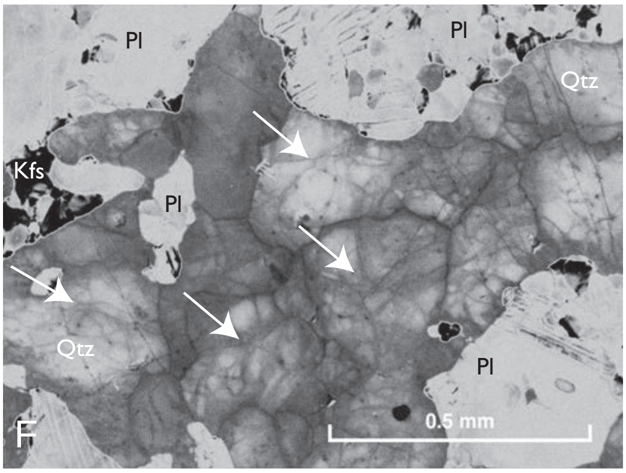

Fig. 38. *Cathodoluminescence scanning electron image of quartz subgrains in a sample from southern Toqqusap Nunaa. The quartz grains have an internal, radiating microstructure, interpreted as due to the initial shock wave or impact-induced seismic shaking. From Keulen et al. (2015, their fig. 9F).* *GGU 278816.*

Quartz microstructures. The quartz in these rocks also displays highly anomalous impact-related microstructures but did not melt.

The quartz in the purple gneiss (sample 525360) shown in Fig. 37 consists of chains of rounded subgrains that form irregular, branching and anastomosing patterns, as well as single, spherical grains that appear to have been constricted from the chains. Related quartz microstructural details in another sample can be seen in Fig. 38. See the full description in Keulen *et al*. (2015).

The quartz chains are interpreted as transformed former normal individual quartz grains. The quartz was much softer and more ductile than plagioclase and were battered into their present shapes during the seismic shaking, sitting between cataclastic plagioclase and single-mineral alkali feldspar melts.

Loc. 2011-73. Orthogneiss and incipient 'grey dykes', Illut

Tonalitic orthogneisses on the north coast of Illut contain other impact-related structures which are probably more or less ubiquitous but not necessarily recognised by the uninitiated observer, even on close inspection. The island of Illut and adjacent islands islands were mapped by the author in 1986 without discovering the significance of the unusual rock fabrics and microstructures in the orthogneisses.

The special nature of the apparent planar rock fabrics seen in n Figs 39–40 is revealed by the BSE-SEM images in Fig. 41 where the distribution of the quartz areas (dark) and small patches of direct K-feldspar melts (light grey) stand out. There are no microstructures that can be related to normal shear strain such as observed in tectonically deformed rocks. The microstructures are the results of shock melting of K-feldspar, cataclasis of plagioclase and ductile, pure-strain deformation of quartz during seismic shaking. A detailed account of these microstructures is in preparation.

Fig. 39. *Orthogneiss with apparent tectonic foliation consisting of interfingering zones of more and less intensely cataclastic zones.Diameter of coin 2.8 cm.* AAG 2011-570.

Fig. 40. *Orthogneiss with apparent normal tectonic foliation (arrows), which actually consists of micro-cataclastic zones due to seismic shaking rather than tectonic deformation. Note the interfingering nature of the dark (micro-cataclastic) and light (less comminuted) zones in the left. Site of GGU sample 525358 (Fig. 41).* AAG 2011-569.

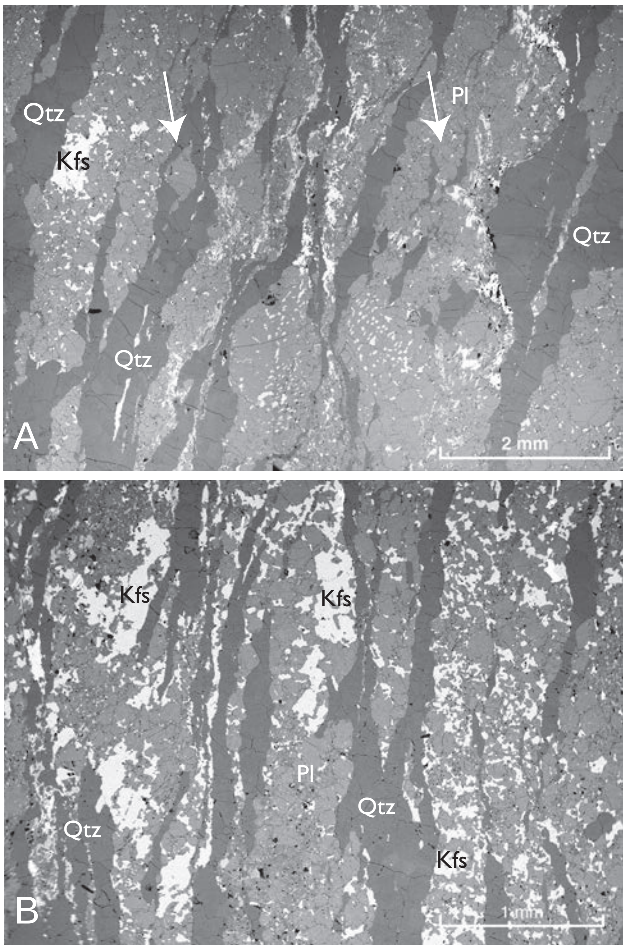

Fig. 41. *BSE-SEM images of branching quartz belts and feldspar zones with transverse patches of shock-melted K-feldspar (especially in right part of image).* GGU 525358.

Loc. 2011-26. Melt-related(?) homogenisation of orthogneiss, Talerulik

The southern tip of the island Talerulik exposes folded orthogneisses and a supracrustal belt of garnet-biotite paragneiss and metavolcanic amphibolite.

The most interesting rocks of this locality are probably the polyphase tonalitic orthogneisses with angular, recumbent folds at the eastern contact to the supracrustal belt. The gneisses have a peculiar and highly unusual, diffuse and penetrative microstructure which affects the whole rock volume (Fig. 42). The individual components of orthogneiss are granular and homogeneous, and although the individual, layers are folded and possess different shades of grey they do not have any obvious foliation, and mafic minerals such as biotite and/or hornblende are not present. The plagioclase in these rocks is not colourless but grey to dark grey, and in places almost black, as also observed in a melt patch in the adjacent supracrustal belt (Fig. 43).

Comment and interpretation. In ordinary, tectonically deformed polyphase orthogneisses the different grey colours would be due to different contents of e.g. biotite, which would also typically have a preferred orientation that would impose an S fabric to the rock. The microstructure at loc. 2011-26 is thus not a normal high-grade gneissic texture. It is also very different from the 'blebby' texture characterised by clusters of biotite sheaves observed at loc. 2011-78 on Langø. In fact, the Talerulik outcrops appear to be altogether unaffected by hydrothermal alteration.

There are no thin sections from this particular locality, but partial breakdown and more or less complete disappearance of biotite has been observed in several thin sections of rocks from this part of the impact structure.

The granular rock texture, the absence of biotite and the grey to dark grey colour of plagioclase are interpreted as due to impact-induced heating, breakdown of biotite and incorporation of Fe^{2+} in the new-formed plagioclase, which was subsequently exsolved from the plagioclase crystal lattice as tiny particles of iron oxide. It is uncertain at this locality if most or all of the plagioclase melted or if iron could was incorporated during recrystallisation at high temperature. The melt patch shown in Fig. 43 is interpreted as shock-induced.

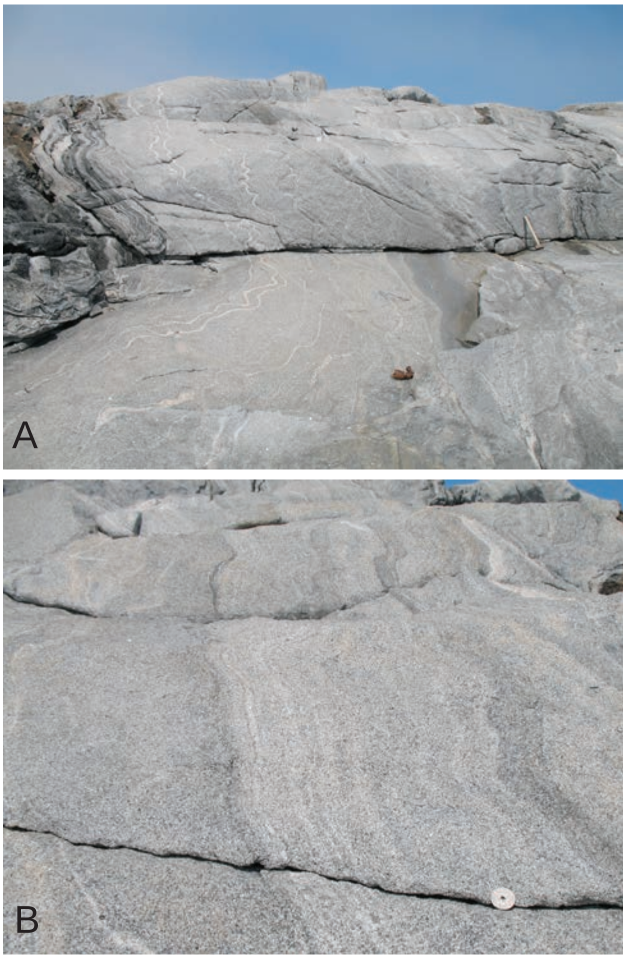

Fig. 42. *Progressive closer views of polyphase tonalitic orthogneiss with blurred and nebulitic microstructures. Hammer 45 cm long, coin 2.8 cm in diameter.* AAG 2011-181 and 184.

Fig. 43. *Dark grey plagioclase (e.g. arrows) in diffuse melt patch in orthogneiss, adjacent to an inclusion of amphibolite. Pair of gloves for scale.* AAG 2011-180.

Loc. 2011-68. Mechanical homogenisation, metavolcanic belt and orthogneiss, Sisak

This key locality at the point Sisak north-east of Napasoq village (Fig. 1) illustrates how a metavolcanic belt many metres wide has been split up, crushed and 'disappeared' at the contact to the Finnefjeld domain (Figs 44, 45).

The locality illustrates that the Finnefjeld contact is not intrusive but of cataclastic nature. This is a type of contact that is completely unknown from lower-crustal orogenic settings, and which has not been described in the literature except from the Maniitsoq structure. In the opinion of the author geological quality of this locality is such that it deserves the status of a World Natural Heritage Site.

Inside a narrow boundary zone, almost the entire mass of the Finnefjeld domain is devoid of visible metavolcanic or metasedimentary components (Garde *et al.* 2014a). Such belts simply disappear at its contact. However, as mentioned in the introduction (p. 13) the Finnefjeld domain is not an intrusive rock but cataclastic, as recognised already be Berthelsen (1962).

Remnants of the metavolcanic belt now constitute 'enclaves' in the contact zone (Fig. 44). Breccia-like mixtures of small and large amphibolite fragments sit in a matrix of new-formed granitoid rock and K-feldspar (Figs 46, 47) and both components are surrounded by cataclastic material of the Finnefjeld domain.

When the Sisak locality was visited by the author and his research group in 2011, the transition between the metavolcanic belt and the Finnefjeld domain was considered enigmatic. It is now known to be due to intense, impact-induced seismic shaking.

Fig. 44. *Several remnants of metavolcanic amphibolite (arrows) at the margin of the Finnefjeld domain. The exposure is c. 10 m high.* AAG 2011-536.

Fig. 45. *Metavolcanic amphibolite 'dissolved' by fragmentation into homogeneous, cataclastic rocks of the Finnefjeld domain. Both the amphibolite and Finnefjeld material are cut by white granitic dykes. The upright folds outlined by these dykes document subsequent lateral shortening.* AAG 2011-537.

Fig. 46. *Fragments of metavolcanic amphibolite in a granitoid matrix, surrounded by cataclastic material of the Finnefjeld domain (upper part of image) and possibly also veins of directly melted K-feldspar.* AAG 2011-549.

Fig. 47. *Broken remnants of metavolcanic amphibolite in cataclastic rock. A ptygmatically folded vein of K-feldspar (lower left by arrow) is interpreted as formed by direct melting of this mineral followed by lateral compression.* AAG 2011-541.

Fig. 48. *Cataclastic Finnefjeld rock with dyke- or inclusion-like areas of micro-cataclasite, 'grey dykes' (arrows). A thin vein by the ink pen, possibly composed of K-feldspar, curves around the far side of the finely ground body and is presumed to be impact-related. A straight, c. 4 cm thick, anatectic granitic vein (left) is younger and of endogenic (non-impacting) origin.* AAG 2011 -544.

'Grey dykes'. The degree of comminution in the cataclastic material is variable, giving rise to micro-cataclasites ('grey dykes'). Such components (Fig. 48) are common in the Finnefjeld domain.

K-feldspar direct melt veins. Two other kinds of veins or dykes are also exposed. White to pink, commonly ptygmatically folded veins composed of only K-feldspar are always restricted to within or marginal to particular, small areas of intense cataclasis ('grey dykes').

Interpretation. The K-feldspar rims and ptygmatically folded veins were formed by direct melting. Most or all of the K-feldspar may have been melted by by shock melting by the passage of the shock wave and segregated out of the cataclastic material during the phase of seismic shaking in the first couple of minutes after the impacting. Alternatively, some of the K-feldspar reached the temperature necessary for direct melting by frictional heating during the subsequent seismic shaking.

Anatectic granitic veins. The cross-cutting veins of white granite (Figs 45–48) are younger than the Maniitsoq impacting, cataclasis and K-feldspar direct melt veins. They are ordinary magmatic veins of local anatectic origin. They contain numerous small prismatic zircon grains which are being dated at the time of writing. The upright folds of the white veins indicate NNW–SSE-oriented crustal shortening subsequent to the impacting and its directly related processes. It is hoped that the ongoing zircon geoghronological study will provide a maximum age for the crustal shortening.

Loc. 2011-62. Cataclasis, 'grey dykes' and K-feldspar melt veins, Finnefjeld domain, Puiattoq

The cataclastic deformation of the Finnefjeld domain has led to the formation of an apparently homogeneous body which was for many years assumed to be a late-kinematic granitoid intrusion (e.g. Garde 1997). It is unfortunately still depicted as such in some recent publications (e.g. Dyck *et al.* 2015). However, as initially described by Berthelsen (1962) the Finnefjeld gneiss (his nomenclature) consists of a thoroughly cataclastic variety of the same rock types (mainly tonalitic orthogneiss) that surround the domain. The younger, white granitic dykes of anatectic origin that occur in most parts of the Finefjeld domain (e.g. the Sisak locality, 2011-68) are likely to have been a confusing factor, as it constitutes a mental bridge to the late-magmatic leucocratic veins that are common in many endogenic granitoid intrusions.

At locality 2011-62 one can observe effects of the impact-induced seismic shaking that formed the Finnefjeld domain, but only by close and unbiased inspection. The results of this deformation were described by Garde *et al.* (2014a) as "differential rheological features", namely cataclasis of plagioclase and ductile deformation of quartz, besides shock-induced direct melting of K-feldspar.

A homogenised former orthogneiss is shown in Fig. 49. It has traces of impact-induced fracture cleavage which has locally been intensified into elongate zones of intensely comminuted material.

A close-up (Fig. 50) depicts such a comminuted body, which owes its dark colour to fine grain size; the material is the same as in the surrounding rock. Larger bodies of finely comminuted rock have commonly been mobilised and injected as fluids into adjacent fratures that were presumably momentarily open during the seismic shaking.

In Fig. 51 angular, partially crushed fragments representing cores of former plagioclase phenocrysts or porphyroblasts can be seen, surrounded by pale or white rims of finer-grained cataclastic plagioclase. The white 'rims' are not metamorphic rims of chemically zoned grains as might be assumed. Further documentation for this can be found in Garde *et al.* (2014a).

Fig. 49. *Homogenised Finnefjeld rock with traces of fracture cleavage (white arrow) and slivers of comminuted dark, fine-grained material (black arrows). Coin 2.8 cm across.* AAG 2011-484.

Fig. 50. *Intensely comminuted, dark, incipient 'grey dyke' in cataclastic, mechanically homogenised Finnefjeld rock. The dark colour is due to fine grain size, not a different composition.* AAG 2011-497.

Fig. 51. *Surviving, unbroken cores of cataclastic plagioclase surrounded by pale 'rims' of crystal fragments (white arrows). Coin 2.8 cm across.* AAG 2011-498.

'Grey dykes' and K-feldspar direct melt veins. Zones of very fine-grained, cataclastic material produced in situ or injected from nearby during seismic shaking are a characteristic feature of the Maniitsoq impact structure and at loc. 2011-62.

The 'grey dykes' at Maniitsoq are equivalent to pseudotachylytes in less exhumed impact structures (Garde & Klausen in press), see also discussion under loc. 2011-78. Their traditional name, 'grey dykes' (Bridgwater *et al.* 1976), is an appropriate field name although the bodies are neither igneous nor intrusive. In fact, most of them probably occur as autochthonous bodies precisely where they were produced.

A typical, well-developed 'grey dyke' is shown in Fig. 52. It constitutes a very fine-grained, dull grey zone of finely comminuted cataclastic material about 1 m thick with a rather sharp contact against less comminuted material; both components are derived from orthogneiss (Garde *et al.* 2014a).

A conspicuous, 3–10 cm thick, ptygmatically folded but non-cataclastic vein of coarse-grained K-feldspar occurs in the 'grey dyke'. Such K-feldspar veins are commonly seen either along the margins of or inside 'grey dykes'. In the latter case thay invariably display ptygmatic folds. The K-feldspar veins superficially resemble folded pegmatite veins but are entirely different.

- The veins only contain K-feldspar.
- The veins are confined to the 'grey dykes'.
- The veins do not cut the host rocks.
- The veins are not cataclastic.
- Interior K-feldspar veins are invariably ptygmatically folded.

Interpretation. The five features above marked with bullets, taken together, imply that the K-feldspar veins were formed during seismic shaking from the cataclastic material itself while it was being comminuted. The K-feldspar melted due to shock heating, possibly aided by frictional heating during the cataclasis. The K-feldspar melts were segregated into temporary low-pressure zones in the 'grey dyke' interiors and/or at their margins, and solidified after cessation of the shaking. The ptygmatic folds furthermore show that the 'grey dykes' and their K-feldspar veins were compressed after the shaking.

Mobilised melt veins with black plagioclase. In addition to direct melt veins of pure K-feldspar, loc. 2011-62 and other localities in the interior part of the Maniitsoq structure also expose a different kind of melt veins which are composed of black plagioclase, K-feldspar and quartz but no mafic minerals. Most of these melts form diffuse patches with gradational boundaries to their hosts, indicating melting *in situ*, as well as veins and patches with discordant boundaries to their hosts, as shown in Fig. 53.

Fig. 52. Micro-cataclasite *('grey dyke') with ptygmatically folded internal vein of K-feldspar. To the left the 'grey dyke' is bounded by less comminuted rock. Coin 2.8 cm across. AAG 2011-489.*

Black plagioclase in the Maniitsoq structure was briefly discussed by Garde *et al.* (2014a) and in this report at loc. 2011-26 (Talerulik island). The grains are sub- to euhedral and are interpreted as having crystallised from a melt. It is therefore likely that more extensive rock melts might have formed as an additional result of the impacting besides direct melting of K-feldspar.

Fig. 53. *Mobilised melt vein with black plagioclase and discordance to the comminuted Finnefjeld host rock. Coin 2.8 cm across (arrow). AAG 2011-490.*

Loc. 2011-65. Mechanical mixing of felsic and mafic rocks, Finnefjeld domain, Puiattoq

This outcrop is one of the few places in the interior Finnefjeld domain where several rock components can be recognised (Fig. 54A), although there are no clear boundaries between them and all components are strongly affected by cataclasis (viz. different rheological behaviour, Garde *et al.* 2014a, see loc. 2011-62). During the field work in 2011 five compositional varieties were recognised and collected at this locality, see Fig. 54B. A relatively dark variety with fragments of hornblende is shown in Fig. 55.

Fig. 54. *Felsic and intermediate to mafic, cataclastic Finnefjeld rock components without mappable boundaries.* **A.** *Overview with Kim Esbensen for scale.* AAG 2011-517. **B.** *Five rock samples illustrating the large compositional variation at loc. 2011-65. From Garde et al. (2014a).* Photo: Kim Esbensen, GEUS.

Fig. 55. A. *Cataclastic, mechanically homogenised Finnefjeld rock of intermediate composition. Coin 2.8 cm across (at arrow).* AAG 2011-518. **B.** *Detail of Fig. 55A with up to centimetre-sized hornblende crystals (arrows). Coin 2.8 cm across.* AAG 2011-519.

Discussion. The recognition of several components with different compositions but without clear delineations and boundaries, begs the question how the different components of the basement rocks in the surrounding regions (mainly in- and extrusive members of the supracrustal belts, and successive phases of orthogneiss) were transformed into their present homogeneous state.

Was seismic shaking sufficient to produce the cataclasis and mechanical mixture observed at this and other localities in the Finnefjeld domain? Alternatively, computational modelling of impact structures comparable to Maniitsoq in size (B.A. Ivanov in Garde *et al.* 2011; modelling images shown in Garde & Haack 2013) suggests that during the rebounce phase of the impacting, even deep-crustal parts of the target are lifted up into the atmosphere and fall back into the crater. This would surely create very effective mixing.

Loc. 2011-59. Cataclastic mélange, margin of Finnefjeld domain. Skerry, Alanngua

The small skerry of Naajanngiut (just west of new beacon) at the head of Alanngua exposes a cataclastic mélange at the boundary of the Finnefjeld domain with partially crushed fragments of amphibolite and hornblendite (Fig. 56). A supracrustal belt and orthogneiss affected by cataclasis are exposed on the adjacent small island, and it is assumed that the precursor rocks at loc. 2011-59 were similar or identical lithologies.

The quartzo-feldspathic matrix, mainly plagioclase and quartz, likewise appears to be thoroughly cataclastic, and the exposure is thus not interpreted as an intrusion breccia. A clast of foliated and migmatised tonalitic orthogneiss is shown in Fig. 57, outlined by white dots. It is hardly discernible on the photograph and illustrates the close mineralogical similarity with the cataclastic matrix around it.

The shapes and orientations of mafic clasts can be seen in Fig. 56B. Some have thin mantles with pinkish colour that might represent direct K-feldspar melts (white arrow). Most of the clasts are elongate (black arrows) but in spite of some degree of their preferred orientation the clasts do not have lensoid or sigmoidal shapes such as formed during ductile tectonic shear deformation. On the contrary, clasts with different shapes and orientations commonly abut against each other.

Fig. 56. *Cataclastic mélange with supracrustal and orthogneiss clasts showing preferred orientation, possibly due to cataclastic flow.* **A.** *Overview.* AAG 2011-455. **B.** *Cataclastic mélange. Supracrustal clasts (black arrows) have mantles of (?K-feldspar) melt (white arrow). Coin 2.8 cm across.* AAG 2011-461.

Interpretation. The cataclastic mélange is interpreted as due to seismic shaking, which may or may not have been accompanied by cataclastic flow.

It is conceivable that the shaking would have terminated with overall compression in a pure stress field, when the ambient lithostatic pressure became effective again after the wild kinetic and pressure oscillations of the seismic shaking had ceased. Depending on the shape and orientation of the zone affected by the cataclasis, the observed crude clast alignment might have occurred during final compaction of the loose particles.

Lateral compression following seismic shaking is witnessed by the ptygmatically folded K-feldspar veins in 'grey dykes', and it is suggested that it is an inherent final deformational phase following intense shaking.

Fig. 57. *Cataclastic mélange with partially crushed clasts of orthogneiss (arrow) and melt seams and patches (of K-feldspar?). Coin 2.8 cm.* AAG 2011-458.

Loc. 2011-28. Late shear zone with pseudotachylyte, near Napasoq village.

Introduction. One of the common characteristics of meteorite impact structures preserved in the upper crust is the occurrence of thick and prominent pseudotachylyte zones. The best developed impact-induced pseudotachylytes occur in the Vredefort dome, South Africa, which is also the type locality for pseudotachylyte (Shand 1916). In the Maniitsoq structure, the equivalents of impact-induced pseudotachylytes are the micro-cataclastic zones and 'grey dykes' lined with veins of K-feldspar (see e.g. loc. 2011-62), which are never quite as fine grained as pseudotachylytes. Pseudotachylyte is also known from fault and brittle/ductile shear zones worldwide of endogenic origin, related to seismic events.

The region affected by the Maniitsoq impact also hosts typical, 'normal' pseudotachylytes. The locality north-east of Napasoq is an excellent place to observe them and pin down their relationship with both impact-related and orogenic features.

Observations. The bedrock at loc. 2011-28 is strongly deformed tonalitic orthogneiss with foliation-parallel, millimetre- to centimetre-thick migmatitic veins of leuco/neosome due to regional, endogenic anatexis (Fig. 58). A characteristic undeformed, coarse-grained melt patch with indistinct margins (in which all feldspar and possibly also quartz was melted) and dark grey to black plagioclase is also seen. Similar strains of melting mimick some of the leucosome layers.

Fig. 58. *Melt patch with black plagioclase (interpreted as impact-related) in orthogneiss with a strong S fabric acquired during regional orogenic deformation prior to impacting. Coin 2.8 cm across.* AAG 2011-189.

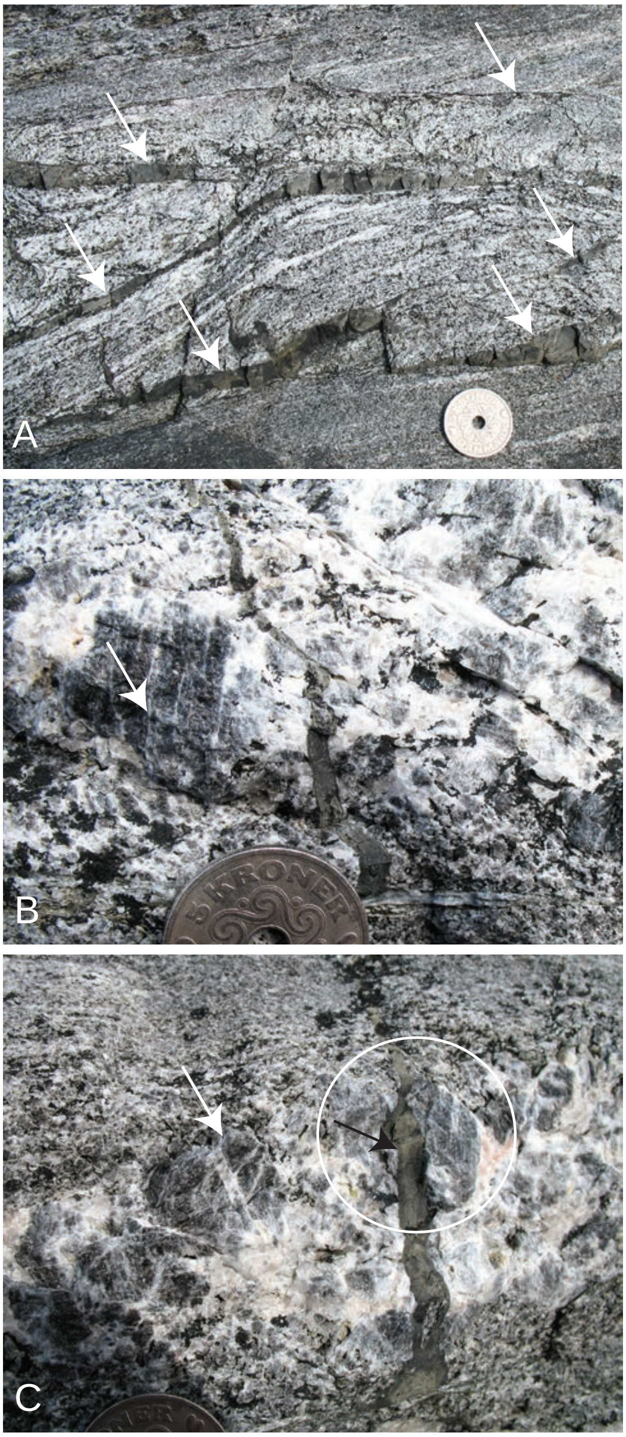

Fig. 59. *Brittle deformation zone with thin veins of pseudotachylyte (**A**, arrows). The tonalitic host has a strong S fabric from regional deformation (see Fig. 58). Undeformed melt patches with dark plagioclase postdate the S fabric (**B**, **C**). Plagioclase megacrysts are bleached by hydrothermal alteration along microjoints (arrows). The Pseudotachylyte veins cut the melt patches with dark plagioclase (**C**, circle, arrow) and are thus younger than the growth of dark plagioclase and hydrothermal alteration.* AAG 2011-194, 193 and 192.

Such melt patches are interpreted as induced by the Maniitsoq impact, see also localities 2011-26, -34, -48, -49, -55 and -62.

The pseudotachylytes at loc. 2011-28 are narrow (less than about 2 cm) and confined to localised, brittle-ductile shear zones with evidence of simple shear deformation in the form of common sigmoidal fabric elements (Fig. 59A). The veins commonly have dark margins and brownish interiors, either due to chilling or due to formation in two strages.

The pseudotachylytes cut the hydrothermally altered plagioclase megacrysts (Fig. 59 B, C) and are hence younger than the melt patches themselves as well as the hydrothermal alteration that affected their dark grey to black plagioclase crystals. There are no radiometric age determinations of the pseudotachylytes. Their age is thus unknown. They might be late Archaean, or more likely Palaeoproterozoic and contemporaneous with the NE-trending Fiskefjord fault and other, NE-trending and WNW-trending conjugate faults and semibrittle shear zones adjacent to the Fiskefjord fault north of outer Fiskefjord (see Berthelsen 1962 and Garde 1997).

Related, late brittle/ductile shear zone in the Finnefjeld domain, superimposed on cataclasis. The NE-trending fjord of Kangia that cuts into the central part of the Finnefjeld domain opposite the village of Napasoq is the locus of a similar, late shear zone superimposed on the cataclastic Finnefjeld domain. Observations from a small island in central Kangia at loc. 2011-21 (65°15'.0 N, -51°04'.5 E) are shown here to supplement observations at loc. 2011-28. The shear zone along Kangia also contains pseudotachylyte and was briefly described by Garde *et al*. (2014a). Like the brittle/ductile deformation zone near Napasoqit is unrelated to impacting. A field photograph and a photomicrograph of a cataclastic rock with superimposed ductile deformation forming sigmoidal plagioclase is shown in Figs 60A and 60B, and a photomicrograph of a pseudotachylyte, likewise with evidence of simple shear in the wall rock, is shown in Fig. 60C. Several sigmoidal fabric elements are visible (arrows and dotted lines).

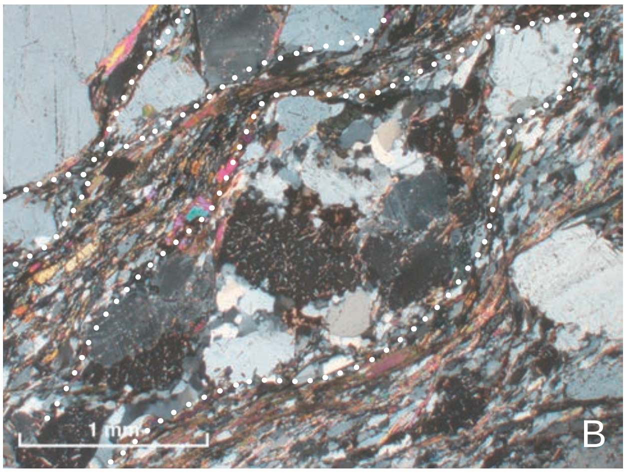

Fig. 60B. *Sigmoidal lenses consisting of several cataclastic plagioclase grains (outlined by dotted lines) in brittle/ductile shear zone superimposed on cataclastic fabric. Loc. 2011-21. Crossed polarisers. From Garde et al. (2014a).* GGU 525318.

Fig. 60A. *Cataclastic orthogneiss with sigmoidal plagioclase fragments, caused by ductile simple shear superimposed on the cataclastic deformation in the central part of the Finnefjeld domain. Loc. 2011-21. Diameter of coin 2.8 cm.* AAG 2011-142.

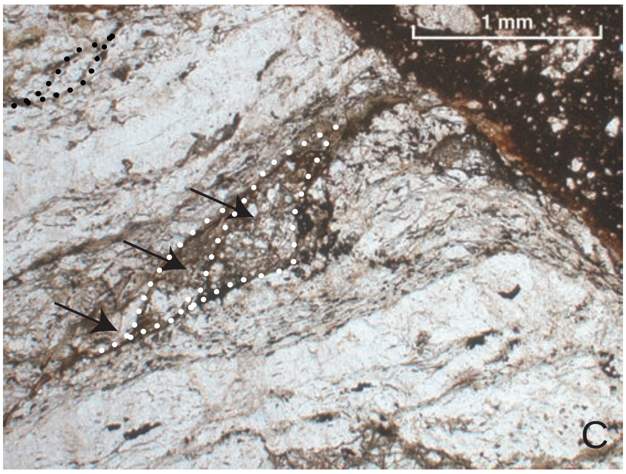

Fig. 60C. *Photomicrograph of pseudotachylyte with asymmetric, sigmoidal, partly comminuted clasts indicating a significant component of simple shear during the pseudotachylyte-forming deformation. From Garde et al. (2014a). Loc. 2011-21.* GGU 525319.

Loc. 2011-55. Accordion folding, margin of the Finnefjeld domain, Portusoq

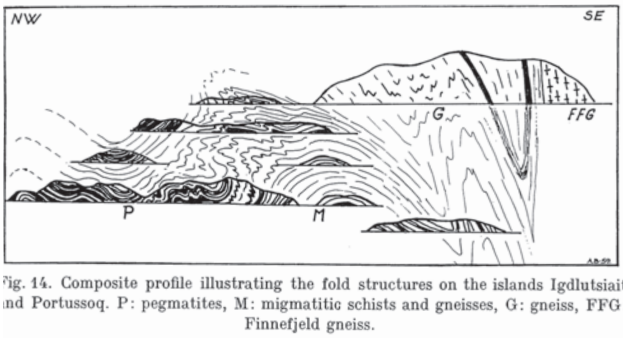

Fig. 61. *Berthelsen's (1962) conceptual sketch of lateral compression at the margin of the Finnefjeld domain (his Finnefjeld gneiss, FFG), superimposed on regional deformation structure with flat-lying, multiply folded, recumbent folds.*

Introduction. Some of the most mind-boggling structural and microtextural features that can be observed at this locality were already described by Berthelsen (1962), see also Garde *et al*. (2014a). He described an increasing, localised lateral pressure towards the margin of the cataclastic 'Finnefjeld gneiss' that was superimposed on the regional deformation.

Observations. The resulting accordion-style, simple upright folds in orthogneiss with enclaves of amphibolite are shown at increasing detail in Fig. 63. It can also be seen that the contacts between the individual components of the polyphase orthogneiss are blurred and have an apparent granular texture, much like the observations at loc. 2011-26, Talerulik. The orthogneiss does not contain biotite or hornblende, but the plagioclase is dark. This is considered highly significant, see p. 49.

K-feldspar direct melt veins. The rocks also contain numerous veinlets of pink K-feldspar (not pegmatite), some of which are marked with arrows in Fig. 63. These are interpreted as direct melt veins, indicating a short-lived, shock-induced temperature increase to above 1300°C (the direct melting temperature of K-feldspar at mid- to lower crustal pressure, see Keulen *et al.* 2015).

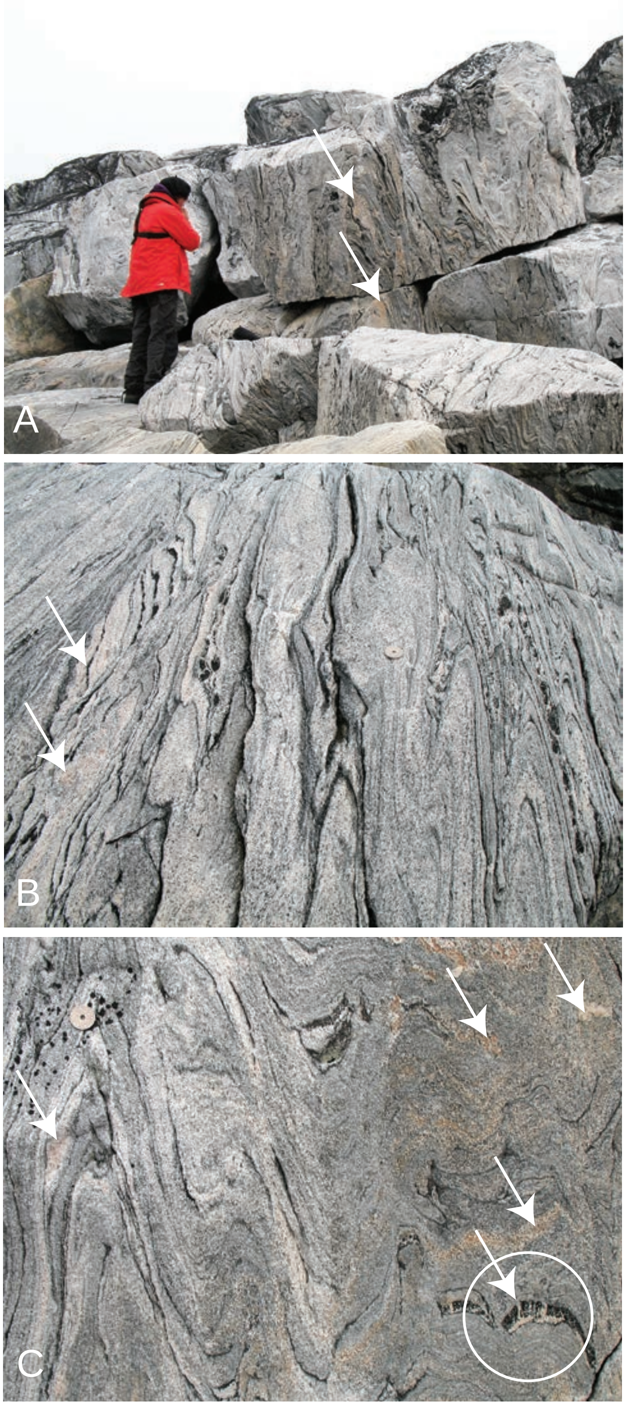

Fig. 62. *Accordion-style, simple, upright folds in polyphase orthogneiss with enclaves of amphibolite at the margin of the Finnefjeld domain, and ubiquitous K-feldspar direct melt veins (arrows). One of the most obvious direct melt veins (circle) is seen in the lower right of Fig. 62C. Modified from Garde et al. (2014a). AAG 2011-407, 420 and 410.*

Melt veins with black plagioclase. A close-up image of another type of melt veins, which are also characteristic and unusual, is shown in Fig. 63. These melt veins have indistinct, gradational boundaries to their hosts and are of local origin, i.e., some of the rock volume melted in situ. The veins contain dark grey to black, subhedral to euhedral plagioclase crystals which have clearly crystallised from melts (Fig. 64). In contrast to the direct K-feldspar melt veins these veins have at least two melt components, K-feldspar and plagioclase, whereas it is highly uncertain if quartz was also melted; contrary to the plagioclase the quartz grains display evidence of crystal-plastic deformation with lattice-controlled slip domains (arrow in Fig. 64).

Fig. 63. *Diffuse plagioclase-K-feldspar (?-quartz) melt vein with black plagioclase (arrows) in orthogneiss. Coin is 2.8 cm across.* AAG 2011-415.

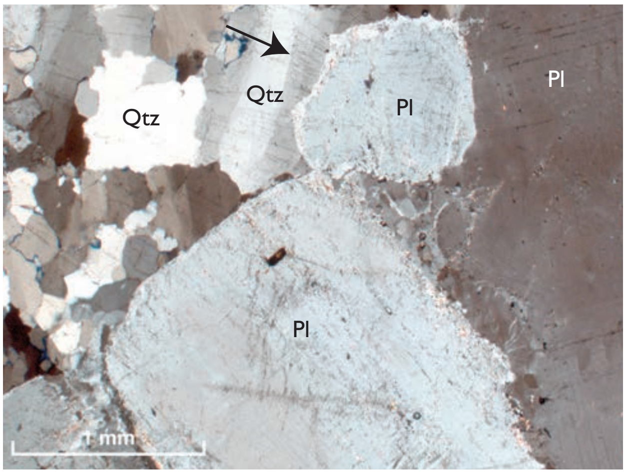

Fig. 64. *Subhedral plagioclase grains crystallised from a melt. The larger plagioclase grain is 'dusted' with fine particles of iron oxide which give the plagioclasee a red-brown tint in thin section. Crossed polarisers. Modified from Garde et al. (2014a).* GGU 525348.

A close inspection of the host rocks to these diffuse veins will reveal that also the host orthogneisses contain numerous small grains of black plagioclase, suggesting that much of the rock volume was melted.

Comment. Irrespective of whether quartz was melted or not along with the two feldspars, the melt veins with black plagioclase are extraordinary. They are not partial melts as very commonly found in the regional high-grade orthogneisses, where a leucocratic component was melted during anatexis by reactions between different minerals.

Contrary to such endogenic migmatite veins the veins described here must be the result of either direct melting of the feldspar components (both K-feldspar and plagioclase), or wholesale melting (if quartz was also melted). The temperature required to do this greatly exceeds the temperature of regional thermal granulite facies metamorphism as determined by Riciputi *et al.* (1990) in Akia.

Low-grade, brittle/ductile shear zone. As shown in Fig. 65, the exposures are cut by brittle/ductile lateral shear zones which were formed much later at low-metamorphic conditions where chlorite was stable. The exposed surface is horizontal, and the shear zone is sinistral and trends 040°. It is interpreted as Palaeoproterozoic in age and unrelated to the impacting and its aftermaths.

Fig. 65. *Young chlorite-bearing, brittle/ductile tectonic shear zone with sigmoidal shape fabric, indicating sinistral displacement. Horizontal surface. The shear zone is probably Palaeoproterozoic.* AAG 2011-413.

Loc. 2011-34. Annihilation of gneissic structure, contact to Finnefjeld domain, Portusoq

Portusoq island is located at the western boundary of the Finnefjeld domain. On its northern coast a ‘complete’ gradual transition over a few metres can be observed between orthogneiss preserving part of its pre-impacting migmatic and fold structure and mechanically homogenised rocks that have lost all previous structure (Fig. 66). The transition is not full, inasmuch as the orthogneiss shown in the left part of the transect (Fig. 66A) is already strongly affected by cataclasis. However, some of the pre-impacting migmatitic structure can still clearly be seen.

Feldspar melt veins with black plagioclase and a syn- crystallisation compressional fold are shown in Figs 66B–C. The Finnefjeld rock in Fig. 66D has lost all previous gneissic structure, but contains younger, pale anatectic veins (compare loc. 2011-68 at Sisak). The younger age of the latter anatectic veins can be ascertained by comparing them to those at the other end of the traverse. The vein margins in the homogenised Finnefjeld rock have sharp boundaries, whereas those of the older veins at the other end of the traverse have been partially wiped out. The great significance of the melt veins with black plagioclase (Fig. 66B) was discussed at loc. 2011-55 on the preceding pages.

Another example of partial annihilation of pre-impacting orthogneiss structures and black plagioclase (indicating bulk feldspar melting) are shown in Figs 67 and 68 (following page). The large black plagioclase grains superficially appear to be fragmented, with parts of the crystals separated by ‘foreign’ white material (arrows). This observation led to confusion during the field work in 2011 because the other observations at loc. 2011-34 showed that the black plagioclase postdates the cataclasis and homogenisation of the orthogneiss. Later investigation by L. Johansson (pers. comm., 2013) has shown that the white material is simply parts of the plagioclase crystals that have lost their black colour due to hydrothermal alteration along microscopic fractures.

Fig. 66A. *Exterior margin. Relict gneissic structure in orthogneiss, partially destroyed by seismic shaking.* AAG 2011-224.

Fig. 66B. *Mobilised melt vein in marginal zone. Black plagioclase (arrow), K-feldspar (and possibly quartz) were melts. No mafic minerals.* AAG 2011-228.

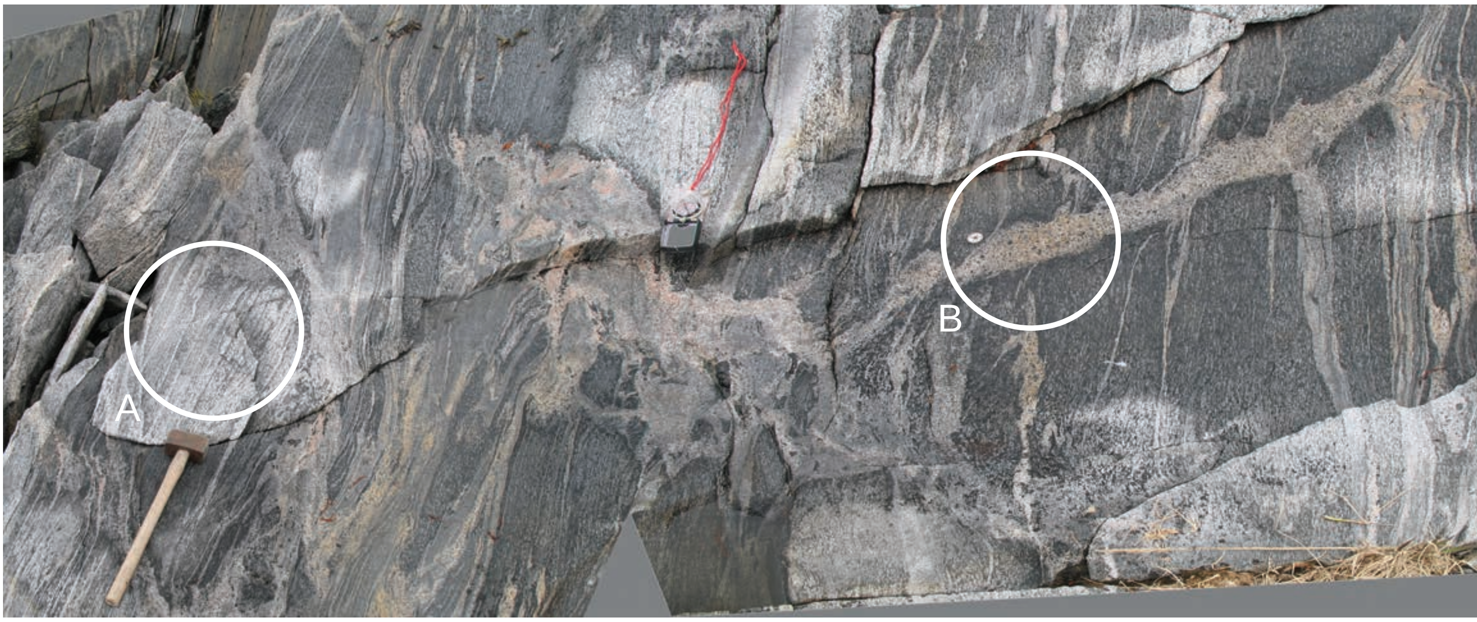

Fig. 67. *Partially annihilated, pre-impacting gneissic structure with tight folds (dotted lines) in orthogneiss, and an undeformed, autochthonous melt vein with black plagioclase. . AAG 2011-231.*

Fig. 68. *Detail of black plagioclase in Fig. 67. The black plagioclase crystals superficially appear to be cataclastic. However, the white zones (arrows) are due to bleaching by hydrothermal fluids along thin fractures, and the plagioclase is not cataclastic. AAG 2011-232.*

Fig. 66C. *Mobilised melt vein in marginal zone as in Fig. 66B, with compressional fold. Compression apparently predated solidification. AAG 2011-229.*

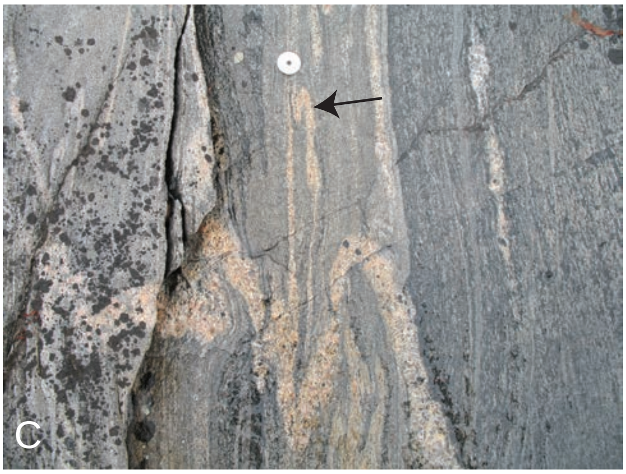

Fig. 66D. *Inside the margin. Complete transformation to cataclastic Finnefjeld rock. Younger, ordinary anatectic veins marked by arrows. AAG 2011-230.*

Loc. 2011-48. Melt veins with black plagioclase, Kangaarsuk

This locality on the headland west of Alanngua provides a large, well-exposed area where one can become familiarised with the impact-induced transformation of orthogneiss.

Dispersed melting of plagioclase, K-feldspar and possibly quartz is shown in Fig. 69. The melt zones are considerably more coarse-grained than the parts where the folded gneissic structure of normal, tectono-magmatic origin is preserved. Some melt zones mimick the folded leucosome in the pre-impacting gneissic structure. Other melt zones are massive and patchy or form discordant veins with diffuse boundaries. K-feldspar seems to be minor or absent in the exposure shown in Fig. 69.

A 25 cm thick melt vein is shown in Fig. 70. It consists of black plagioclase (arrow), abundant patchy K-feldspar, and quartz. Biotite and hornblende are absent. A detail of dark plagioclase with partial beaching along hairline fractures is shown in Fig. 71. This initially gave rise to some confusion as discussed under loc. 2011-34, because the pale zones in the dark plagioclase may give the observer the wrong impression that the plagioclase is cataclastic.

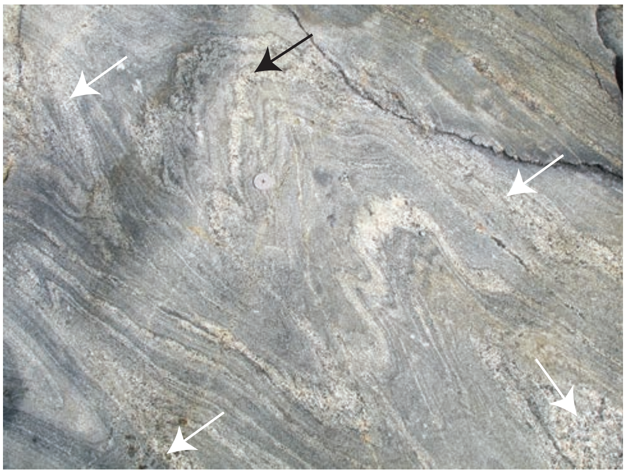

Fig. 69. *Melt zones in tonalitic orthogneiss along pre-impacting migmatite seams (black arrow) and as discordant, massive areas (white arrows).* AAG 2011-364.

Fig. 70. *25 cm thick melt vein with black plagioclase (arrow) and patches of pink K-feldspar direct melt. The vein is not a pegmatite.* AAG 2011-359.

Fig. 71. *Pale, hydrothermally altered zones in dark plagioclase, superficially giving the impression of plagioclase cataclasis.* AAG 2011-356.

Loc. 2011-49. Orthogneiss with secondary magmatic mineral texture and melt veins, Kangaarsuk

This locality on the headland west of Alanngua displays essentially the same features as loc. 2011-48.

Decimetre-sized patches with complete melting of feldspar and crystallisation of black plagioclase can be seen in Fig. 72. The transition between the obvious melt patches and their host is shown in Fig. 73. The transition is gradational, and small black plagioclase crystals can also be seen in the host. Biotite, which is an almost ubiquitous constituent of most normal felsic to intermediate, upper amphibolite- to granulite- facies orthogneisses, is absent both in the melt patches and veins and in the host. Hornblende and proxene are also absent.

Discussion. The observations of black, 'magmatic' plagioclase both in obvious melt patches and in the adjacent groundmass of tonalitic orthogneiss suggest that most of the rock reached a (probably short-lived) stage following the impacting during which plagioclase melted throughout the rock volume – resulting in

orthogneiss with a secondary magmatic mineral texture, as distinguished from

orthogneiss with evidence of a new migmatitic event that would be found in endogenic tectonothermal contexts.

At the time of writing it remains uncertain if the black plagioclase is a result of direct, shock-induced melting or not. Direct melting of plagioclase in tonalitic orthogneiss (andesine–oligoclase) would have required a shock-induced temperature excursion up to around 1450°C or beyond (Keulen *et al.* 2015).

Fig. 72. *Widespread melting in situ of tonalitic orthogneiss, in part mimicking previous endogenic migmatisaion.* AAG 2011-367.

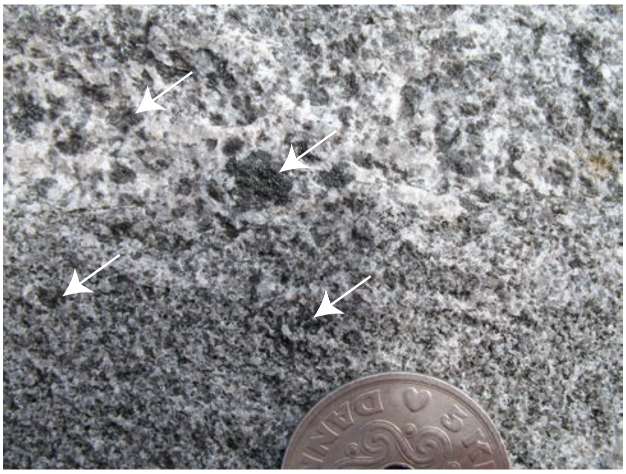

Fig. 73. *Gradational boundary between coarse-grained, fully recrystallised melt patch with black plagioclase and orthogneiss host, likewise with black plagioclase (arrows). No biotite.* AAG 2011-369.

Fig. 74. *Widespread, almost ubiquitous remelting of orthogneiss.* AAG 2011-372.

Loc. 2011-43. Orthogneiss without impact-related features, mouth of Kangerluarsuk

This small island in the Maniitsoq block of Windley & Garde (2009) north of the impacted region is underlain by orthogneiss and amphibolite which are unrelated to the Maniitsoq impact structure.

This locality was included in the excursion programme as a 'reference locality' for comparison with the previous, highly anomalous localities – that is, localities that are anomalous in an endogenic context and for those visitors who are unfamiliar with the deep-crustal testimony of a giant meteorite impact.

The main lithology at the locality is high-strain orthogneiss with subordinate, likewise highly strained layers and lenses of amphibolite. There is no fracture cleavage, micro-cataclasis, no direct melts of K-feldspar and no sub- to euhedral black plagioclase.

Fig. 75. *High-strain orthogneiss and amphibolite.* *AAG 2011-317.*

Fig. 76. *Tight fold in high-strain, migmatised orthogneiss with a thin layer of amphibolite which is also folded. No fracture cleavage. No micro-cataclasis. No K-feldspar seams. No sub- to euhedral black plagioclase.* *AAG 2011-315.*

Epilogue

The release of kinetic energy by extraterrestrial impacting leads to short-lived pressure and temperature excursions that far exceed those occurring in endogenic terrestrial geological settings. Some of the resulting geological processes are extremely fast and specific for impacting, for instance direct mineral melting. Nevertheless, impact-related processes involve rocks and minerals and can be studied using familiar geological techniques, if the observer puts superficial observations and ensuing habitual interpretations aside and uses his or her skills without bias.

Some of the rocks and structures that can be found in the Maniitsoq impact structure have been studied in detail by the authors of the currently available publications, while other aspects such as the hydrothermal alteration have not. Important aspects of the impact structure remain largely unexplored, including a better linkage between hydrocode modelling of giant impact structures and the features observed in the field at Maniitsoq, such as the central cataclastic domain and seismic shaking. Also the petrogenesis of the potentially economically important norite belt is currently poorly constrained.

The author of this guide hopes that the exposures described here can help visitors to certify that a grey gneiss is not just a grey gneiss but can contain a wealth of unexpected information about its geological history. Impacting geology is total geology. Observation at all scales is the first key to understand it, along with theoretical insight made accessible to ordinary geologists by specialists in planetary science.

Fig. 78. *Brendan Dyck studying generation and interference of waves by oblique impacts on a water surface. AAG 2010-694.*

Check list

This check list is meant for use on the outcrops to help the observer recognise and distinguish the many different geological features, and to promote discussion.

Locality	2011-26 Melting, black plagioclase	2011-28 Pseudotachylyte	2011-34 Finnefjeld contact	2011-43 Orthogneiss	2011-48 Melt veins	2011-49 Melt veins	2011-55 Accordion folding	2011-59 Cataclastic mélange	2011-62 ‘Grey dykes'	2011-64 Brittle/ductile shear zone	2011-65 Mechanical mixing	2011-68 Homogenisation	2011-69 Dunite breccia	2011-73 Purple gneiss	2011-73 Incipient 'grey dyke'	2011-78 Fracture cleavage	2011-80 Orbicular diorite	2011-93 Plagioclasite	2011-100 Granulite facies gneiss
Felsic veins *sensu lato*:																			
Orthogneiss vein in amphibolite																			
Leucosome (regional anatexis)																			
Granulite facies pegmatites, blurred margins																			
Pegmatites with sharp margins																			
K-feldspar veins within or along ‘grey dykes’																			
Ptygmatically folded K-feldspar veins																			
Melt patches with black plagioclase																			
Discordant melt veins with black plagioclase																			
Plagioclasite																			
Granitic matrix in breccia																			
White granitic veins cutting cataclasite																			
Minerals and mineral textures																			
Black plagioclase																			
K-feldspar patches																			
Proto-orbicular texture																			
Purple gneiss																			
Blebby texture																			
Bleaching of black plagioclase along microjoints																			
Annealing of fracture cleavage																			
Breccias:																			
Dunite breccia with granitic matrix																			
Amphibolite brecia with granitic matrix																			
Cataclastic mélange																			
Brittle deformation:																			
Fracture cleavage																			
Mechanical mixing, different rock components																			
Mechanical homogenisation of orthogneiss																			
Relict plagioclase cores in cataclasite																			
Incipient, interfingering 'grey dyke' formation																			
‘Grey dykes'																			
Brittle/ductile tectonic deformation:																			
Brittle/ductile, low-T shear zones																			
Sigmoidal (simple shear) fabric elements																			
Pseudotachylyte																			