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The Ilugissoq graphite andesite volcano, Nuussuaq, central West Greenland

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Abstract

The Ilugissoq graphite andesite volcano on Nuussuaq belongs to the Asuk Member of the Paleocene Vaigat Formation. It is the largest eruption site within the Vaigat Formation and is recognized as the source of the majority of the graphite andesite tuffs found in marine sediments in central Nuussuaq.

The volcano consists exclusively of pyroclastic rocks containing a diverse lithic assemblage including sediment xenoliths. The primary pyroclastic fragments consist of magnesian andesite with several weight percent of graphite, which formed when mafic magma established a shallow-level magma reservoir beneath the eruption site, and within older clastic sediments from the Nuussuaq Basin. Magma-modified mudstone is completely dominant in the xenolith assemblage and attests that the graphite andesite originated through prolonged high-temperature assimilation of mudstone. The eruptions took place on a marine shelf consisting of picritic hyaloclastites and subaqueous crater mounds. The volcano consists of four overlapping crater cones aligned along a more than 4 km long NNW–SSE oriented fissure system; two cones barely reached sea level whereas the other two reached up to 200 m above the sea. The morphology of the pyroclastic rocks demonstrates that the volcano evolved through phreatomagmatic activity, which diminished with time. The magma never degassed sufficiently to reach a subaerial lava stage. A moderate primary gas pressure well in excess of 100 bars in the graphite andesite magma facilitated the phreatomagmatic explosions, which created the Ilugissoq volcano. The rocks of the volcano are rich in graphite and contain little or no native iron. In comparison, the contemporaneous and chemically similar subaerial lavas and breccias from Disko and Nuussuaq contain less graphite and more iron. The differences are considered to be due to the extremely pressure-dependent redox-sensitivity of carbon–oxygen equilibria in the range 1 bar (the lavas) to 500 bars (the Ilugissoq volcano). Eruptions in the Ilugissoq volcano must have been accompanied by intense CO and CO_2 emanations, which would have represented a lethal hazard for all animal life in the volcano's surroundings.

Keywords: Andesite; Graphite; Volcano; Paleocene; Nuussuaq Basin; Greenland

1. Introduction

The southern part of the Nuussuaq Basin in central West Greenland and in particular the island of Disko is known for its large and diverse assemblage of strongly reduced volcanic rocks and xenoliths formed through

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the interaction of Paleocene picritic magmas and Mesozoic to Paleocene carbonaceous clastic sediments (e.g., review in Sjögren, 1916; bibliography in Bøggild, 1953; Clarke and Pedersen, 1976; Pedersen, 1981; Goodrich and Bird, 1985; Ulff-Møller, 1985, 1990; Pedersen and Rønsbo, 1987).

The crustally contaminated rocks occur as dykes, necks, craters, lava flows and tuffs, and their distinctive lithology, petrography and geochemistry has made them invaluable marker horizons within the two large Paleocene volcanic formations (the Vaigat and the Maligât Formations, Hald and Pedersen, 1975). It is now known that four of the crustally contaminated successions have regional extensions from 3000 km^2 to more than 10 000 km^2 and three of these successions contain strongly reduced rocks with native iron (Pedersen, 1977a,b, 1985a,b; Larsen and Pedersen, 1989, 1992; Pedersen et al., 1996). Each of the successions was erupted from a number of shallow-level magma chambers situated within the upper crust, and the distribution of magma modified sediment xenoliths shows that most of these chambers were in contact with clastic carbonaceous sediments.

Pedersen (1978a) described a succession of tuffs within the marine sediments of the Abraham Member from Agatdalen in central Nuussuaq. The majority of the tuffs consist of magnesian andesites rich in disseminated graphite and high in Cr. Similar beds of this exotic rock type were later found as a marine horizon within a succession of subaerial picrite lavas from the Vaigat Formation west of Ilugissoq on Nuussuaq by Pedersen et al. (1989), who also found a thin tuff of the same rock type within the volcanic rocks of the Asuk Member (Pedersen, 1985a) at Asuk on Disko. This has allowed unequivocal stratigraphic correlation between the crustally contaminated volcanic rocks of the Asuk Member on Disko, the tuffaceous rocks of the Vaigat Formation on Nuussuaq and the marine sediments of the Abraham Member.

Based on the abundance and thickness of the graphite andesite tuffs in Agatdalen, Pedersen (1978a) predicted the presence of an eruption centre for the tuffs on Nuussuaq and also concluded, based on graphite–oxygen fugacity barometry, that the tuffs were probably quenched from a "moderate pressure, e.g., 0.5 kbar". The eruption centre has finally been located in the Ilugissoq valley in central–western Nuussuaq.

This paper describes the Ilugissoq graphite andesite volcano, which is the largest individual eruptive centre known from the Vaigat Formation. The pyroclastic rocks of the volcano contain several weight percent of disseminated graphite and represent a rock type that is very rare on Earth.

2. Geological setting

The Nuussuaq Basin (Fig. 1), which forms part of the Cretaceous to Palaeogene West Greenland Basin, is a rift basin on a continental margin (Henderson et al., 1981; Chalmers et al., 1999). From Late Albian to Early Campanian, sandstones and shales were deposited in a fluvial to deltaic environment in eastern Disko and central Nuussuaq. Towards northwestern Nuussuaq, the delta fanned into deeper water (Pedersen and Pulvertaft, 1992). Several tectonic phases from the Campanian to the Early Paleocene affected the basin and eventually created an uplifted rift margin of Precambrian gneiss in eastern Nuussuaq and a gneiss ridge in central Disko (Chalmers et al., 1999; Dam et al., 2000; Dam, 2002). Prior to the initiation of Paleocene volcanism, a regional uplift related to the North Atlantic mantle plume has been inferred (Dam et al., 1998).

The Paleocene volcanic succession is dated at 59.5–61 Ma (Storey et al., 1998) and consists of two formations. The Vaigat Formation consists of picritic pahoehoe lavas and hyaloclastites, interlayered with a number of horizons of crustally contaminated lavas and hyaloclastites. The overlying Maligât Formation consists of voluminous flood basalts and contains two extensive successions of crustally contaminated volcanic rocks in its upper part (Clarke and Pedersen, 1976). A combination of field work, multi-model photogrammetry (Dueholm, 1992; Dueholm and Pedersen, 1992), detailed geochemistry and petrography (e.g., Pedersen et al., 1996; Larsen and Pedersen, 2000), radiometric dating (Storey et al., 1998) and palaeomagnetic stratigraphy (Riisager and Abrahamsen, 1999) has enabled us to construct a number of sections through the volcanic rifted margin of the Nuussuaq Basin (Pedersen et al., 1993, 2002a, 2003, 2005), and hence to trace the evolution and facies changes of the volcanic and sedimentary units with time.

The Vaigat Formation was characterized by very high eruption rates, rapid volcanic aggradation, fast basin subsidence, active tectonic movements along faults and rapid facies changes, where early volcanic islands rose on a marine shelf, then merged into a lava plateau and filled a marine basin from the west towards the east (Pedersen et al., 2002b). Eventually, a large lake was dammed up against a basin margin of Precambrian gneisses (Pedersen et al., 1996, 1998).

3. The Vaigat Formation at the Asuk Member stage

The Asuk Member (Pedersen, 1985a) was originally defined as a succession of crustally contaminated volcanic rocks on Disko, which includes the earliest native-iron-bearing rocks of the Vaigat Formation. They form a subaerial lava succession, up to ca. 150 m thick, which covers more than 500 km^2 in northern and northeastern Disko. At the base of the Asuk Member, scattered tree trunks are found engulfed by the first

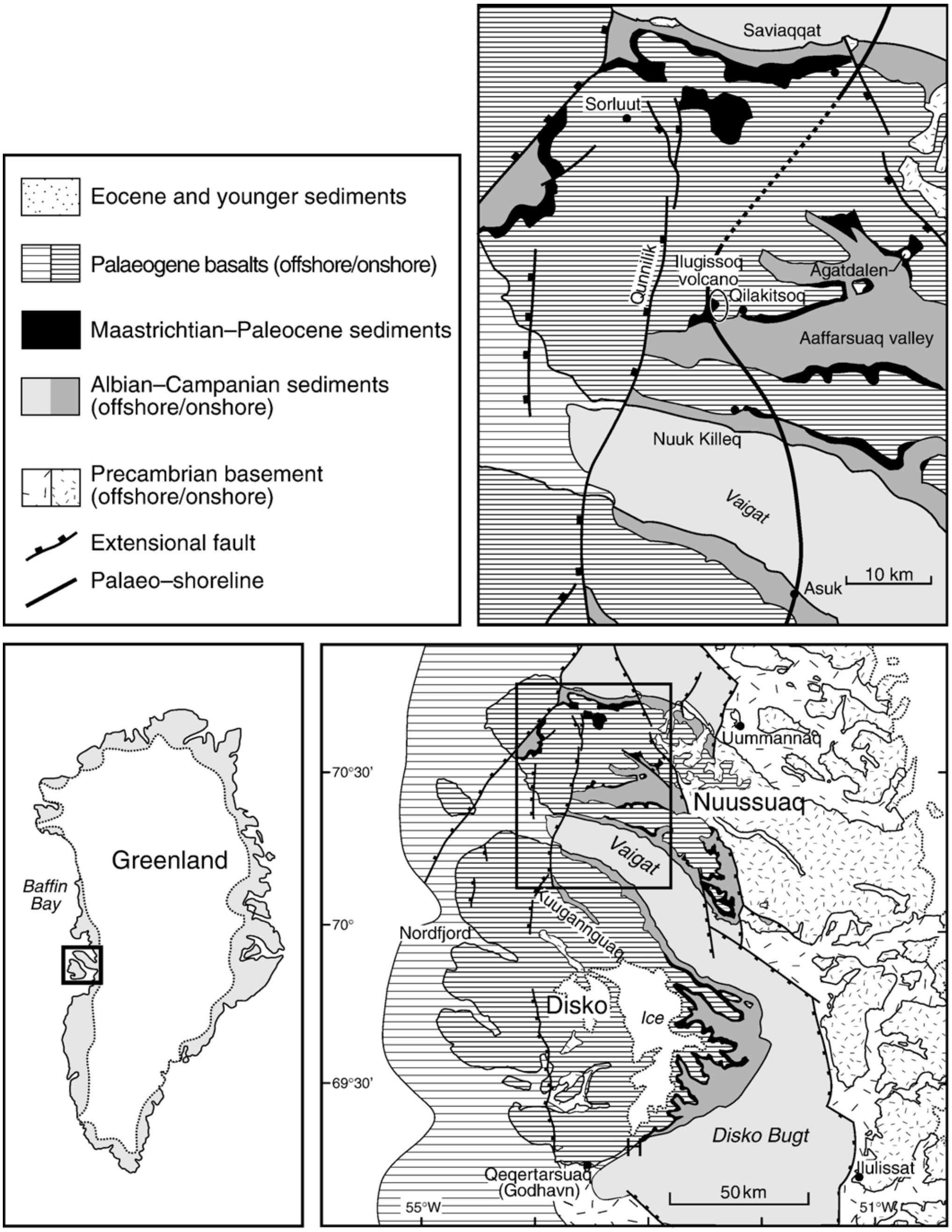


Fig. 1. Geological maps of Disko and Nuussuaq showing localities mentioned in the text. The enlarged map of Nuussuaq and northern Disko also shows the shoreline separating the growing lava plateau in the west from the narrowing marine basin in the east at the early stage of the volcanism of the Asuk Member. An ellipse shows the position of the Ilugissoq volcano.

lavas, and there is also a thin tuff sequence of contaminated basalt and graphite andesite tuff. At Asuk, the lowermost lava flows entered a shallow sea to form subaqueous breccias and pillow lavas.

Later work has extended the Asuk Member to include a small lava succession in northern Kuugannguaq on Disko, a native-iron-bearing andesite lava at Nuuk Killeq on the south coast of Nuussuaq (Steenstrup, 1882; Larsen and Pedersen, 1988), the Ilugissoq graphite andesite volcano and its tuffs on Nuussuaq and finally a contemporaneous but compositionally independent lava succession with native iron on northern Nuussuaq, centered around Saviaqqat (Ulff-Møller, 1991).

The palaeogeography of the Nuussuaq Basin at the start of formation of the Asuk Member comprised a western lava plateau, probably fairly close to sea level (Fig. 1). A narrow marine embayment was situated between the lava plateau and the uplifted eastern basin margin of eroded gneisses. An irregular shore and shelf separated the lava plateau from the sea, which was up to several hundred metres deep. The shelf was either a steeply sloping Gilbert-type delta or a surface peppered by hyaloclastite mounds where numerous eruption sites emerged on the slope itself. The largest of these eruption sites was the Ilugissoq graphite andesite volcano.

4. Structural setting of the Ilugissoq volcano

Chalmers et al. (1999) recognized a number of N–S to NW–SE trending faults within the sedimentary basin, which were active once or several times during the extensional history of the Nuussuaq Basin. A detailed analysis of the structural constraints imposed by a number of volcanic marker horizons within the Vaigat Formation has revealed that several older structural features were reactivated as syn-volcanic and post-volcanic faults and that these features were actively channeling magma from deep sources into shallow-level crustal magma chambers and further upwards to form eruption sites. Two of these features, the Kuugannguaq–Qunnilik Fault and Fault P of Chalmers et al. (1999, Fig. 4 and Foldout 2), which are well displayed on the south coast of Nuussuaq and which also appear on seismic sections covering the offshore region in the Vaigat strait, converge in the area between the Qunnilik, Ilugissoq and Qilakitsoq valleys in central Nuussuaq. In this area, a considerable number of volcanic eruption sites have been located, representing several volcanic units of the Vaigat Formation (Pedersen et al., 2002a).

5. The Ilugissoq graphite andesite volcano

The volcano consists of a row of at least four pyroclastic cones, which extend NNW–SSE for at least 4.2 km on the eastern side of the Ilugissoq valley in central Nuussuaq (Fig. 2). The volcano erupted on a marine slope consisting of foreset-bedded picritic hyaloclastites and local hyaloclastite mounds that mark eruption sites on the sea floor.

The northern part of the volcano is concealed beneath glaciers and moraine, and the northwestern part is covered by younger Vaigat Formation lavas. The southern part of the volcano has been eroded and may have extended south into the Aaffarsuaq valley, but not far because no feeder bodies occur hereabouts (Pedersen et al., 2002a). The Ilugissoq volcano is estimated to have covered at least 19 km^2, based on extrapolation of existing exposures where the thickness of the pyroclastic rocks exceeds 100 m, to include buried, eroded or unexposed parts of the volcano. The volume of the pyroclastic rocks is just above 5 km^3 including areas with more than 10 m of graphite andesite tuffs.

Two volcanic cones A and B are well exposed in the northern part of the volcano (Figs. 2 and 3). They extruded through picritic hyaloclastite at a palaeo water depth of several hundred metres and the cones just barely reached above sea level. Their flanks are covered by younger picritic hyaloclastite and their eroded tops are buried by a few subaerial picritic pahoehoe lava flows.

The two southern cones C and D (Figs. 2 and 4) both reached well above sea level. The southernmost cone D beneath Point 1350 m may once have reached about 200 m out of the sea. Before being buried by younger lava flows, it was levelled by erosion and the top surface is 160 m above the palaeo sea level. The flanks of the cone are onlapped by subaerial lava flows from three consecutive volcanic members, and the poorly exposed contact between the pyroclastic rocks and the flows contain lateritized pyroclastic fragments indicating prolonged exposure to subaerial weathering before the volcano was buried.

The western part of the southern cone D rests on a few subaerial picrite lava flows above 400 m of picritic hyaloclastite, which indicate that the infilling of the marine basin had just been completed at this site before the eruption of the volcano (Fig. 5). A few hundred metres eastwards the picrite flows transform into hyaloclastite facies and their surface defines a 240 m deep shelf. The lava flows are covered by horizontal lapilli beds and small mass flows from the volcano, and these beds have also filled up part of the marine basin

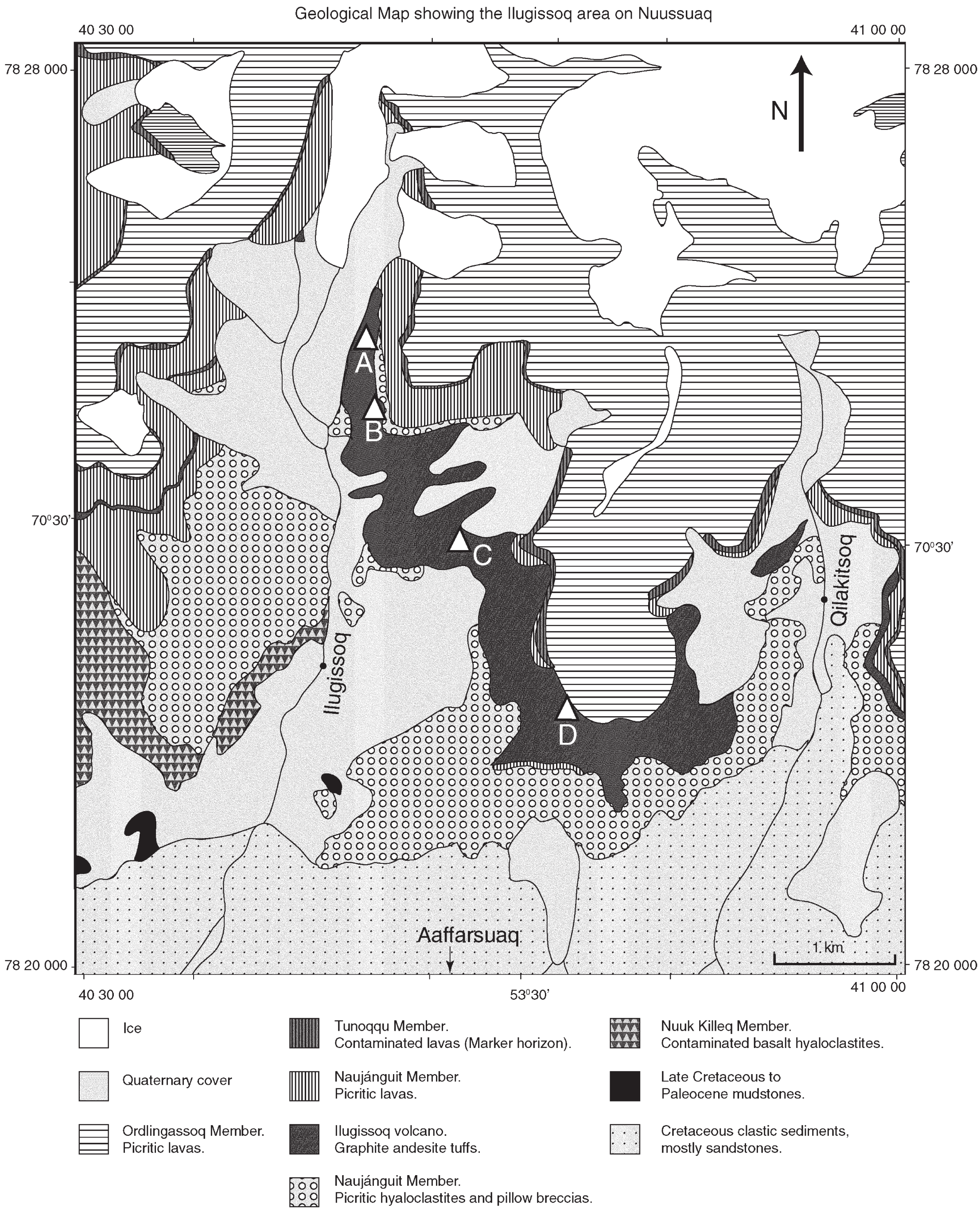


Fig. 2. Geological map showing the Ilugissoq area on Nuussuaq. The pyroclastic cones A to D, which define the feeder system of the Ilugissoq volcano, are shown as triangles.

causing a progradation of the shore zone towards the east (Pedersen et al., 2002a).

Despite the well-defined row of cones, no unequivocal feeder bodies are exposed within the volcano. In a small gully between cones B and C occurs a very compact and very well-preserved pyroclastic rock which resembles a dyke rock and which may be part of a feeder body, and beneath cone C bodies of pyroclastic rock from the volcano form irregular intrusives into older hyaloclastite.

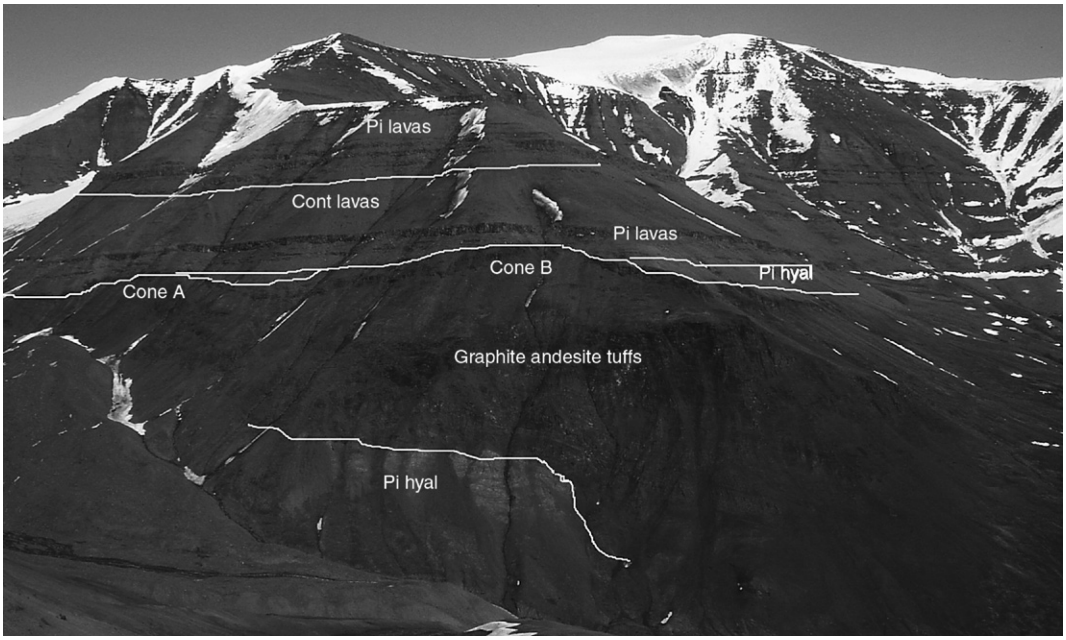


Fig. 3. The northern part of the Ilugissoq volcano with cone A and cone B, seen from the west. A part of the original shelf composed of picritic hyaloclastites (Pi hyal) is cut and overlain by the Ilugissoq volcano. A thin partial cover of picritic hyaloclastites on the top of the volcano shows that the cones just reached sea level. Younger lava flows (picrite lavas and contaminated lavas) cover the whole volcano. East side of the Ilugissoq valley; height of section shown is approximately 700 m.

The volcanic system of the volcano may be linked to the iron-bearing andesite lava and its associated graphitic scoria at Nuuk Killeq 11–12 km to the south, described below.

5.1. Tuffs on Nuussuaq

Graphite andesite tuffs derived from the Ilugissoq volcano occur continuously, where exposed, along the

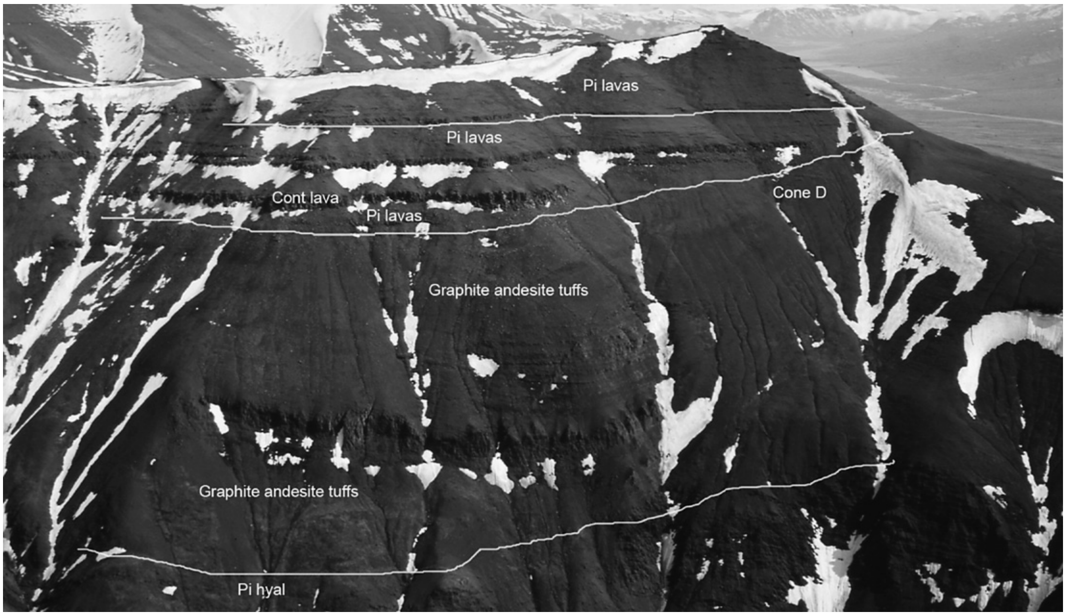


Fig. 4. The southern part of the Ilugissoq volcano with cone D, seen from the west. Cone D extended well above sea level and was onlapped by younger subaerial lava flows. The top of cone D is eroded and the volcano formed a distinct topographic feature for some time before it was buried. East side of the Ilugissoq valley; height of section shown is approximately 550 m.

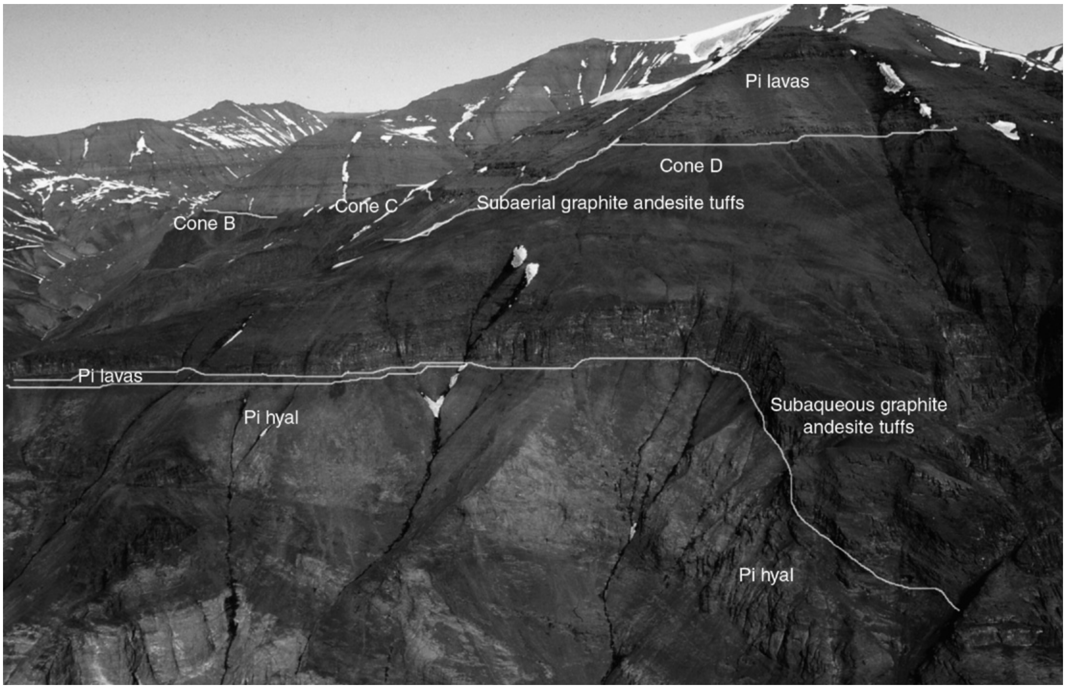


Fig. 5. The southern part of the Ilugissoq volcano as seen from the south. The pyroclastic rocks of cone D cover a few older subaerial lava flows in the west and fill out a marine basin in the east. Cone D is eroded on the top. Northern slope of the Aaffarsuaq valley, with the Ilugissoq valley to the left. Height of section shown is approximately 600 m.

northern part of the Aaffarsuaq valley in central Nuussuaq from the west side of the Qunnilik valley through both sides of the Ilugissoq valley to the east side of the Qilakitsoq valley (Pedersen et al., 2002a) (Figs. 1 and 2). In the west, the tuffs form a weathered horizon a few decimetre thick, interlayered with subaerial picrite lavas. On the west side of the Ilugissoq valley, the tuffs have grown to a thickness of 35 m (Pedersen et al., 1989) and are still interlayered between subaerial picrite lavas, but they contain minor intercalations of mudstone with marine dinoflagellates (Piasecki et al., 1992) indicating a minor marine transgression. East of the Qilakitsoq valley, the graphite andesite tuffs are part of a succession of Paleocene marine sediments overlying Campanian mudstones and sandstones (Dam et al., 2000), which again are separated by an unconformity from Upper to Mid Cretaceous sandstones and heteroliths from the Atane Formation (Pedersen and Pulvertaft, 1992).

In the Agatdalen area of central Nuussuaq, graphite andesite tuffs identical to the tuffs from the Ilugissoq volcano form the main part of a tuff succession within marine Paleocene mudstones from the Abraham Member (Rosenkrantz, 1970; Henderson et al., 1976; Pedersen, 1978a). Within the lower part of the tuffs occur several spherule tuff beds with native iron and magma modified sediment xenoliths and xenocrysts characteristic of the native-iron-bearing rocks well known from Disko (Pedersen, 1978a; Robin et al., 1996). Some authors (e.g., Jones et al., 2005) have argued that the spherule tuffs were formed by a meteorite impact. Spherule tuffs have not yet been located within the Ilugissoq volcano; however, a spherule tuff bed has been found overlying picritic lava flows at the base of the Asuk Member in the Sorluut valley in western Nuussuaq.

5.2. A possible satellite to the Ilugissoq volcano

At Nuuk Killeq on the steep mountain wall facing the Vaigat strait (Figs. 1 and 6), the Vaigat Formation contains a succession of subaerial lava flows. The flows are mainly picritic but the succession also contains a unit of contaminated basalt lava flows including an up to 45 m thick andesite lava with disseminated native iron and graphite (Larsen and Pedersen, 1988; Pedersen et al., 1993). The thick andesite lava extends for just 1 km. At the basal part of the flow and just east of it occurs heaps of poorly exposed and weathered scoria of an andesitic, strongly vesiculated rock rich in graphite and with abundant xenoliths of magma-modified mudstone. The pyroclastic rocks and the thick andesite lava flow

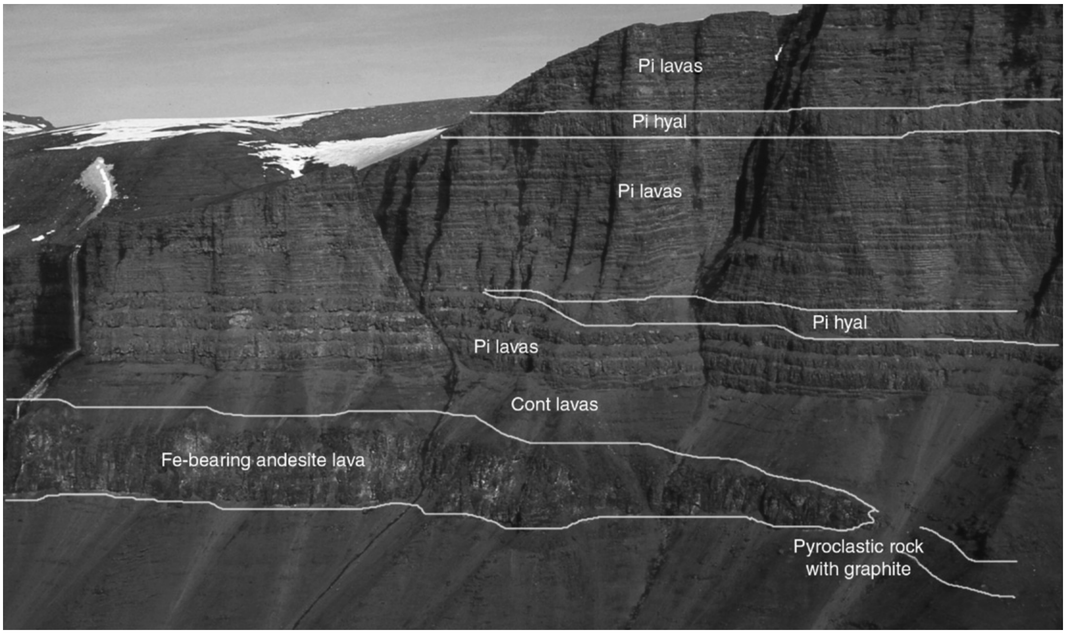


Fig. 6. Thick, short iron-bearing andesite lava flow and poorly exposed graphite-rich scoria sandwiched between subaerial lava flows (Pi lavas) on the steep mountain slope above Nuuk Killeq on the south coast of Nuussuaq. Two younger horizons of picritic hyaloclastite (Pi hyal) were formed during transgressive stages of the Naajaat lake system (Pedersen et al., 1998). Height of section shown is approximately 300 m.

mark a subaerial eruption site established shortly after a lava frontier filled the marine basin. Because of the strong lithological similarity to the Ilugissoq rocks, this occurrence is considered to be a satellite centre to the Ilugissoq volcano.

6. Volcanic lithologies

The Ilugissoq volcano is entirely composed of pyroclastic rocks, which can be characterized as coarse tuffs and lapilli tuffs (Schmid, 1981). No subaerial lava flows, or even pillow lavas, have been found. The pyroclastic rocks are dominated by a single and exotic rock type: magnesian andesite with disseminated flakes of graphite. Additional components are an assemblage of magma-modified sediment xenoliths and xenocrysts (size range for xenoliths <1 mm to 8 cm), cognate fragments of graphite-poor andesite or contaminated basalt (size range <1 mm to 2 cm, rarely up to 10 cm), and various picritic clasts including hyaloclastite, vitric fragments, pillow fragments and crystalline fragments (size range <1 mm to 2 cm, very rarely up to 10 cm).

6.1. Petrography

The *graphite andesite* forms clasts consisting of a colourless glassy to partly crystalline rock with scattered microphenocrysts of orthopyroxene (Fig. 7). The individual clasts carry abundant small spherical vesicles, nearly all of which enclose flakes of graphite, which obviously was a major local source of gas. Minute globular bodies of iron monosulphide with traces of Cu and Ni sulphides occur but are only well preserved in a few very fresh rocks. Xenocrysts of plagioclase containing graphite and rare magnesian spinels are found within some andesite clasts and also as separate clasts. The graphite andesite from Ilugissoq is petrographically identical to the main graphite andesite tuff from Agatdalen on Nuussuaq (Pedersen, 1978a) and to an andesite tuff from a small marine basin at Asuk, Disko (Pedersen, 1985a, Fig 9).

The cognate fragments of *andesite or contaminated basalt* are very fine-grained vesiculated rocks with up to millimetre-sized orthopyroxene phenocrysts which are mostly pseudomorphosed by carbonate, and these rocks are invariably extensively affected by low-temperature alteration (Table 1, no. 5). A few carry xenoliths of mudstone.

The sediment xenoliths which make up a few per cent of the total volume of the volcano are of three types, of which *magma-modified mudstone* is completely dominant (>95%). A few of the mudstones are very fine-grained and show little sediment–magma interaction, and these may represent accidental near-surface xenoliths. However, the great majority show evidence of extensive reaction between basaltic magma and

Fig. 7. Tuff clast of graphite andesite from the root zone of the Ilugissoq volcano. The clast is composed of clear glass with microphenocrysts of orthopyroxene (Opx) and abundant flakes of graphite (Gr) that partly form linings on vesicles. Note the angular outline of the clast. Sample GGU 400286.

mudstone, and there is a considerable range in textures and mineralogies. Most of the xenoliths are composed of graphite, plagioclase, red magnesian spinel and sometimes corundum, and several xenoliths display a characteristic relict stellate texture of magnesian spinel enclosed in plagioclase. In one xenolith, which is less magma modified, are preserved stellate clusters of mullite needles and traces of cordierite in addition to spinel and plagioclase, which are replacing the earlier phases. This shows that the graphite–plagioclase–spinel rocks originated as bodies of silicate melt with graphite, mullite, cordierite and sulphide, derived from high-temperature sediment–magma interaction. Fig. 8A shows a magma modified xenolith from the Ilugissoq volcano compared with a graphite–glass–mullite–cordierite buchite from a dyke intrusion on Disko (Fig. 8B). Magma modified graphite–plagioclase–spinel xenoliths are known from all native-iron-bearing occurrences on Disko (e.g., Törnebohm, 1878; Melson and Switzer, 1966; Pedersen, 1978b, 1979), whereas they are absent from the uncontaminated volcanic rocks from the Nuussuaq Basin. Very similar lithologies, except for the graphite and hence different redox conditions, are described from xenoliths in basic sheets on the Island of Mull (Thomas, 1922; Preston et al., 1999).

A few quartz-rich *sandstone* xenoliths have been discovered but these are so rare that psammitic lithologies, such as dominate the Cretaceous Atane Formation exposed beneath the volcano, cannot have been part of the magma chamber walls of the Ilugissoq volcano.

The third type of xenolith is very rare and consists of very fine-grained *limestones* which have not become decarbonated because of a very short-lived contact to the graphite andesite magma. One such xenolith includes a fragment of lithified wood with very well-preserved tree rings and cellular structure (Fig. 8C). These limestones are very similar to the carbonate-cemented concretions, which are characteristic of Late Cretaceous to Early Paleogene marine mudstones from the Kangilia Formation of northern Nuussuaq (Rosenkrantz, 1970).

The smallest *picrite* clasts are fragments of yellow basaltic glass which may enclose crystals of olivine (often pseudomorphed) and chromite and small crystallites of plagioclase. Larger clasts include crystalline picrite and basalt of variable textures. The largest clasts include picritic pillow fragments, which tend to be extensively altered.

The pyroclastic rocks are invariably affected by zeolite facies metamorphism (see Neuhoff et al., 2006-this volume), which has resulted in widespread formation of smectite, agate and some zeolites. The metamorphism is much more pervasive in the porous rocks from the subaerial upper part of the volcano than in the compact pyroclastic rocks from the root zone.

6.2. Structure and texture of the pyroclastic rocks

In addition to the macroscopic bedding of the pyroclastic rocks, they display a considerable variation in texture and grain size. Two end members are the compact rocks from the volcanic root zone and the well-bedded pyroclastic fall deposits from the subaerial upper parts of the volcanic cones.

The compact pyroclastic rocks from the root zone, as exemplified by sample 400287 (Fig. 9A, Table 1, no. 2) are characterized by a general fine clast size with few clasts exceeding 3 mm and with a clast morphology showing many surfaces produced by shattering. The good preservation of glass, some of which has preserved fresh immiscible iron monosulphide blebs, and the relative scarcity of smectite make these rocks the best approximation to the magma that produced the volcano.

In contrast, the fall deposits exemplified by sample 400281 (Fig. 9b, Table 1, no. 4) show a larger clast size with many clasts exceeding 7 mm. The individual clasts are strongly vesiculated and show many lobate surfaces produced by aerodynamic quenching of melt particles. These rocks have a higher porosity than the basal rocks, have only preserved little glass and contain much more smectite. Additional variations are imposed by secondary sorting in a shallow sea and the activity of mudflows, which affected the cones and the shore zones.

6.3. The volcanic satellite at Nuuk Killeq

The main part of the native-iron-bearing andesite lava flow at Nuuk Killeq is exemplified by sample 340772 (Fig. 10A, Table 1, no. 6). It is a very fine-grained rock, which shows distinct flow lamination marked by inhomogeneity in grain size and in content of opaques. It carries phenocrysts of orthopyroxene and

Table 1
Chemical analyses of volcanic rocks and xenoliths from the Ilugissoq volcano and its satellite at Nuuk Killeq compared to related rocks from the Nuussuaq Basin

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Sample no.	400310	400287	400285	400281	400291	340772	113518	113291	400296	264208	113450	8034	264206	264206
SiO_2	45.67	50.44	51.81	48.28	37.41	56.47	54.06	56.22	45.07	56.92	51.03	54.82	57.1	48.95
TiO_2	0.91	0.84	0.83	0.89	0.63	0.97	0.87	1.06	0.54	1.13	0.87	1.05	1.03	1.51
Al_2O_3	11.67	13.85	13.52	12.73	11.11	15.01	14.40	14.44	26.52	26.04	25.91	15.06	15.36	14.87
FeO*	10.68	8.03	7.86	8.96	6.89	6.22	6.17	4.28	3.06	3.54	6.80	7.96	7.32	10.12
Fe metal						+	+	3.00		+				
MnO	0.17	0.10	0.09	0.11	0.32	0.12	0.09	0.16	0.04	0.02	0.04		0.09	0.13
MgO	16.63	6.89	7.23	8.55	7.86	5.10	6.48	7.13	3.74	1.23	0.91	7.99	6.93	8.32
CaO	9.91	6.10	5.28	5.10	18.39	6.59	6.14	7.07	7.67	0.52	0.81	8.28	7.38	13.12
Na_2O	1.44	1.15	1.09	0.86	1.30	2.06	1.74	1.97	0.77	1.55	2.65	2.19	2.05	1.94
K_2O	0.075	0.988	0.868	1.237	0.556	0.656	0.455	0.900	0.408	1.150	1.360	0.94	1.13	0.17
P_2O_5	0.062	0.104	0.114	0.083	0.328	0.158	0.099	0.160	0.030	0.050	0.240		0.14	0.11
Volatiles	2.52	9.72	10.07	11.76	14.22	5.78	8.87	2.51 [a]	12.03	7.60 [a]	9.03 [a]			
Sum	99.74	98.21	98.77	98.56	99.01	99.13	99.37	98.90	99.87	99.75	99.65	98.29	98.53	99.24
Volatile species analysed														
CO_2		0.00	0.10	0.20	2.89	0.00	0.24			0.13				
C (TOC)		2.43	2.11	1.88	1.80	2.84	4.20	0.07	8.83	2.62	4.07			
S		0.73	0.57	0.54	0.20	0.84	0.02	0.42	0.03	0.16	3.05			
Less O (≡S)		−0.37	−0.29	−0.27	−0.10	−0.42	−0.01	−0.21	−0.02	−0.08	−1.52			
H_2O+								2.23		4.77	3.43			
Trace elements in ppm														
Cr	1294	679	709	788	524	387		583	521	276	177			
Ni	460	451	445	650	419	1477			47	29	102			
Co		50	55	72	41	135			15	15	34			
Cu	130	148	158	202	128	426			31	47	51			
Zn	80	63	63	67	62	6			84	16	110			
V	241	177	175	185	133	163			128	149	170			
Sc		25	25	28	17	22			10	26	25			
Ga		17	16	16	19	18			27	33	38			
Rb		29	30	36	7.3	25			14	66	60			
Ba		273	427	222	100	344			229	385	391			
Pb		6	8	6	9	5			1	10	17			
Sr	117	188	200	195	182	216			298	85	197			
La		15	16	13	16	18			18	62	55			
Ce		33	37	32	31	40			36	113	130			
Nd		17	18	14	15	23			15	48	48			
Y		18	18	17	16	21			9	32	30			
Th		4	4	6	6	6			7	22	17			
Zr		120	126	107	97	143			120	220	136			
Nb		5.9	5.2	4.6	4.7	7.5			7.2	21	16			

cognate orthopyroxene–plagioclase glomerocrysts, and xenocrysts derived from magma-modified mudstone, notably plagioclase with graphite and spinel. The groundmass of the rock contains disseminated native iron, troilite and flakes of graphite. The rock contains about 2.8 wt.% carbon as graphite.

The rock forming the small scoria deposit east of the andesite lava flow (sample 113518, Table 1, no. 7) is a highly vesicular rock with a shining grey surface coating of graphite. The rock contains skeletal phenocrysts of orthopyroxene and xenocrysts of plagioclase and reddish spinel. Magma-modified mudstone xenoliths are scattered through the rock. The groundmass consists of plagioclase, orthopyroxene, ?pigeonite, scattered native iron and troilite, and has a reticulate texture caused by the distribution of the abundant graphite flakes (Fig. 10B). The rock contains 4.2 wt.% carbon as graphite, which is even higher than the main graphite andesite tuff rock of the Ilugissoq volcano.

6.4. Volcanic lithologies underlying the volcano

The volcanic rocks underlying the volcano consist of a range of picritic to less magnesian olivine microphyric basalt. These rocks form pillow breccias and hyaloclastites and originated either from subaerial lava flows that ran into the marine basin or as pyroclastic mounds at submarine eruption sites. Some of these sites have cores of solid picritic rocks. The general petrography of these rocks is given by Larsen and Pedersen (2000). The hyaloclastites are composed of shattered clasts of yellow-green glass with olivine phenocrysts most of which are pseudomorphosed by smectite, which is also present in abundance in the altered matrix. Partially crystalline picrite fragments are angular to slightly rounded pillow fragments with partial glass rims. The pillow breccias and hyaloclastites underlying the volcano are the likely source of the widespread lithic component of picrites that is found in the graphite andesite tuffs even at distant locations.

7. Chemistry

Representative analyses of the rocks of the Ilugissoq volcano and the satellite at Nuuk Killeq are shown in Table 1. For comparison, Table 1 also includes an analysis of the underlying picrites, which represent the composition of the magma before the contamination event (Table

Notes to Table 1:

FeO*: total iron as FeO except in 113291.+: Fe metal present but not analysed for.

Volatiles: loss on ignition corrected for uptake of oxygen due to oxidation of iron, except for three samples explained below.

Notes to analysed samples; all sample numbers are GGU numbers.

(1) 400310, subaqueous picritic feeder body slightly older than the Ilugissoq volcano. North wall of the Aaffarsuaq valley, Nuussuaq, shown in Pedersen et al. (2002a) at 22.2 km, altitude 600 m.

(2) 400287, fine-grained black pyroclastic graphite andesite from the root zone of the Ilugissoq volcano between crater cones B and C. Small canyon cut into the east side of the Ilugissoq valley, altitude 690 m.

(3) 400285, fine-grained black pyroclastic graphite andesite, same general locality and altitude as 2.

(4) 400281, pyroclastic graphite andesite from the upper northwestern part of cone D in the Ilugissoq volcano. Eastern side of the Ilugissoq valley, altitude 1030 m.

(5) 400291, cognate inclusion, 12 cm in size, of extensively altered contaminated basalt or andesite with orthopyroxene phenocrysts (pseudomorphosed by carbonate) in pyroclastic graphite andesite from the upper part of cone C. Eastern side of the Ilugissoq valley, altitude 1025 m.

(6) 340772, native-iron-bearing andesite with graphite from 1 m above the base of 45 m thick andesite lava at Nuuk Killeq, south coast of Nuussuaq, shown in Pedersen et al. (1993) at 18.4 km, altitude 880 m.

(7) 113518, graphite-rich magnesian andesite scoria from Nuuk Killeq, south coast of Nuussuaq. Loose block from the scree beneath the same locality as 6.

(8) 113291, native-iron-bearing magnesian andesite from subaqueous breccia in Asuk Member. Asuk, northern Disko, altitude 2 m. Pedersen (1978b, Table 1 no. 1).

(9) 400296, magma-modified mudstone xenolith with graphite, plagioclase, magnesian spinel and corundum. Upper part of cone C of the Ilugissoq volcano, east side of the Ilugissoq valley, altitude 1130 m.

(10) 264208, black mudstone xenolith with magnéli phases, preserved vitrinite fragments and small droplets of native iron. Xenolith in rock 8, Asuk, northern Disko. Pedersen and Rønsbo (1987, Table 1 no. 1).

(11) 113450, buchite xenolith with graphite, cordierite, mullite, pyrrhotite and glass, in basaltic contaminated dyke from Nordfjord Member. Inner part of north coast of Nordfjord, northwestern Disko, shown in Pedersen et al. (2005) at 20.9 km, altitude 2 m.

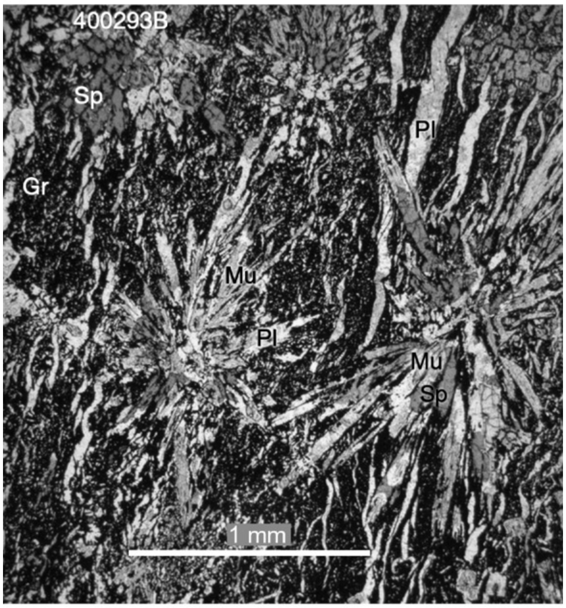
(12) 8034, microprobe analysis of glass in graphite andesite glass grain with orthopyroxene microphenocryst. Major tuff horizon no. 3 in Qaarsutjægerdal, central Nuussuaq. Sampled by A. Rosenkrantz. Pedersen (1978a, Table 3 no. 8).

(13) 264206a, microprobe analysis of glass in graphite andesite glass grain in 1 cm thick tuff in marine mudstone in Asuk Member, overlying rock 8. Asuk, northern Disko.

(14) 264206b, microprobe analysis of yellow basaltic glass with enclosed chromite grain. Same tuff as 13.

[a] Volatiles calculated by summation of the individual volatile species.

A


400293B
Sp
Gr
Pl
Mu
Pl
Mu
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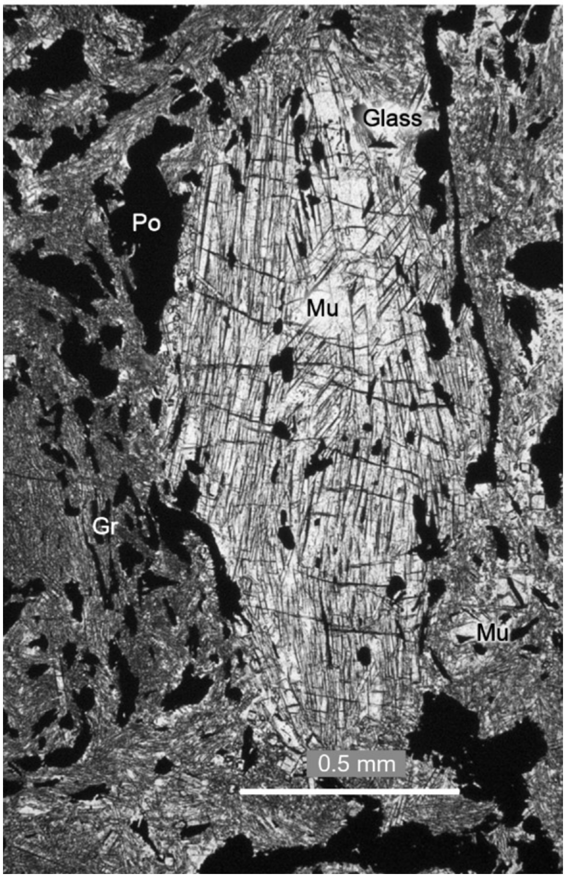
B


Glass
Po
Mu
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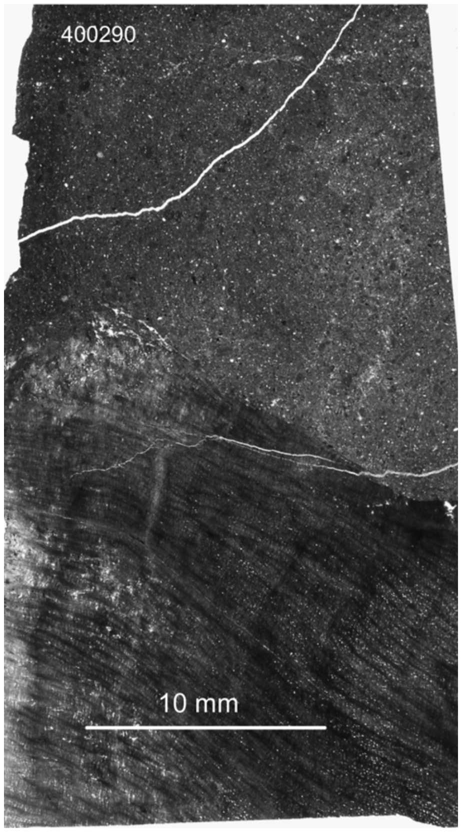
Mu
0.5 mm

C


400290
10 mm

1, no. 1). The freshest pyroclastic rocks of the core zone of the volcano (Table 1, no. 2 and 3) are magnesian andesites, which are notably high in Mg, Cr and Ni relative to Si, indicating that they are derived by contamination of a picritic parent. Their most unusual feature, however, is their very high content of total organic carbon (TOC, measured as non-carbonate-bound carbon) of up to 2.4 wt.% and their high content of sulphur (0.6–0.8 wt.% S), both of which are considered derived from the marine mudstone contaminant.

The cognate clasts of orthopyroxene porphyritic basalt or andesite from the upper part of the volcano (Table 1, no. 5) also carry graphite (1.8 wt.% TOC), but they are extensively carbonate impregnated (2.9 wt.% CO_2) and their original composition cannot be accurately assessed.

The iron-bearing andesite lava from the satellite at Nuuk Killeq (Table 1, no. 6) has a high TOC (2.84 wt.%), high total sulphur (0.82 wt.%) and is generally very similar, but not identical, to the Ilugissoq rocks. The same is true for the graphitic scoria from the same site (Table 1, no. 7), which is the most graphitic igneous rock of the province (4.20 wt.% TOC), but which has lost its sulfur due to degassing (0.02 wt.% S). The subaqueous andesite with native iron from Asuk (Table 1, no. 8) is very similar to the Ilugissoq rocks, the main difference being its native iron and low content of carbon, discussed later.

The magma-modified mudstone xenolith from Ilugissoq (Table 1, no. 9) may be compared to a slightly modified mudstone xenolith from Asuk (Table 1, no. 10) and to an allegedly chemically unmodified graphite buchite from Nordfjord (Table 1, no. 11). The element exchanges (relative gain of Mg, Ca and Cr, and loss of Si, Ti, K and many LIL elements) during the sediment–magma reactions are similar to the processes described in rocks from Disko (e.g., Melson and Switzer, 1966; Pedersen, 1978b, 1979).

Graphite andesite glass analyses from Agatdalen on Nuussuaq and Asuk on Disko (Table 1, no. 12 and 13) are similar in chemical and petrographical details to the Ilugissoq rocks. Also the vitric picrite clasts found associated with graphite andesite tuffs at all three localities are mutually very similar; they are here exemplified by a clast from Asuk (Table 1, no. 14).

8. Discussion

The pyroclastic graphite andesite rocks from the Ilugissoq volcano are probably the most graphite-rich volcanic rocks known from Earth. All our observations, described above, suggest that the carbon-enrichment is a high-temperature phenomenon. There are many known examples of pyroclastic cones which would have high overall carbon content because the volcanic component is intermingled with abundant mudstone clasts as a result of late-stage interaction between magma and unconsolidated mudstone (e.g., Hanson and Hargrove, 1999; Elliot and Hanson, 2001; Lorenz et al., 2002; Skilling et al., 2002). Such an example from the Nuussuaq Basin is the subaqueous rootless cone field from the Assoq lake in southern Disko (Larsen et al., 2006-this volume). If analysed for organic carbon compounds, pyroclastic rocks with unmetamorphosed organic-carbon-rich mudstone intermingled at a late stage would reveal immature hydrocarbon compounds, which might even show up as identifiable biomarkers. Samples of pyroclastic rocks and a magma modified mudstone xenolith from the Ilugissoq volcano have been analysed for hydrocarbons and TOC as part of a regional assessment of oil migration. The results showed that these rocks are conspicuously barren of immature hydrocarbon compounds (J. Bojesen-Koefoed, pers. com., 2004). This strongly supports the petrographical evidence from the pyroclastic rocks and their xenoliths, that the graphite andesites were derived by very extensive and prolonged sediment–magma reactions around a subsurface magma reservoir emplaced within a mudstone succession.

The volume of erupted graphite-rich andesite rock (ca. 5 km^3) shows that very large sediment volumes were involved in the process. A large volume of hot (>1200 °C) picrite magma which formed the parental magma fed into the shallow-level chamber were available as a substantial heat source. If the pyroclastic rocks have a mean concentration of 2 wt.% TOC and a density around 2.5, and hence an erupted mass of ca. 250×10^6 tons of TOC as graphite, and if the likely contaminant is a marine Cretaceous mudstone with a mean TOC of 5 wt.% (Christiansen et al., 1996,

Fig. 8. (A) Magma-modified mudstone xenolith from the Ilugissoq volcano. The rock contains stellate clusters of mullite (Mu) that is being replaced by plagioclase (Pl) and red magnesian spinel (Sp). Note the abundance of graphite (Gr, black). Sample GGU 400293. (B) Xenolith from Disko: a pyrometamorphosed marine mudstone which has escaped extensive magma-modification but is heavily recrystallised to an aggregate of graphite (Gr), mullite (Mu), glass (Glass), sulphide (Po) and cordierite (not seen in this field). Sample GGU 113450. (C) Limestone xenolith with lithified wood fragment from the Ilugissoq volcano. The rock is largely unaffected by pyrometamorphism and magma-modification and was originally a concretion in marine Late Cretaceous to Early Paleocene sediments on Nuussuaq. Sample GGU 400290.

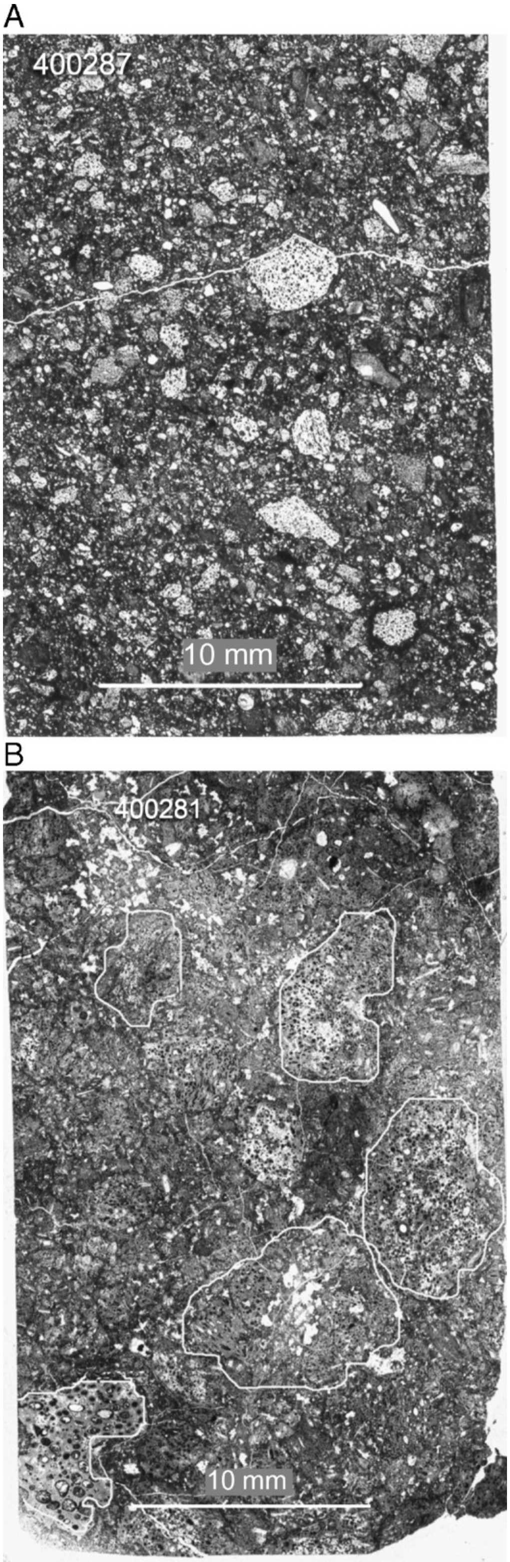


Fig. 9. (A) Compact pyroclastic graphite andesite rock from the root zone of the Ilugissoq volcano between cones B and C. The rock consist of angular clasts of graphite andesite, sediment xenoliths, fragments of picrite and basalt, and matrix (see Fig. 7a). Sample GGU 400287. (B) Pyroclastic graphite andesite rock from the upper part of cone D of the Ilugissoq volcano. The individual clasts are much larger than in the root zone and many clasts have air-quenched lobate outlines. The matrix of the rock is extensively altered to smectite, zeolites and silica phases. Individual clasts are outlined in white. Sample GGU 400281.

1999), then a minimum of 2 km^3 of sediment must have been completely scavenged of carbon and hence have been assimilated by the magma. Add to this that only a minor part of the graphite andesite ever reached within proximity of the Earth's surface.

The mechanism of the assimilation cannot be observed directly, as the Ilugissoq magma reservoir is not exposed, but it can be inferred from observations elsewhere. McClintock and White (2002) have described the formation of coal peperite resulting from the interaction of basic magma from the Ferrar Supergroup and coal-bearing clastic sediments at Coombs Hills, Antarctica. It is highly likely that peperite formation at the front of the expanding Ilugissoq magma reservoir greatly helped in the formation of the very carbon-rich andesite magma.

8.1. Significance of the eruptive environment

A comparison of the geological setting and morphology of the three eruptive areas with carbon-bearing magnesian andesites from the Asuk Member within the Nuussuaq Basin reveal significant differences.

In central Nuussuaq at Ilugissoq, the environment was shallow marine to partly emergent and the volcanism was explosive.

On the south coast of Nuussuaq at Nuuk Killeq, the dominant lithology is a thick subaerial lava flow underlain by a local few metre thick scoria heap of graphitic andesite (Larsen and Pedersen, 1988).

On Disko, the magnesian andesites form up to 40 m thick subaerial lava flows and a subaqueous brecciated body that formed when a flow entered a shallow marine basin (Pedersen, 1985a). The only traces of explosive volcanism on Disko are a decimetre thick tuff succession at the base of the lava succession and a number of up to a few centimetre thick tuff layers (one of which originated from the Ilugissoq volcano) within a local, metre thick, shallow-marine mudstone lens.

Based on these differences, it is concluded that the primary gas pressures of the erupting andesite magmas were only moderate, so that eruption in a subaerial environment predominantly led to formation of coherent lava flows. In support of this, very similar native-iron-bearing magnesian andesites from the younger Maligât Formation on Disko occur as non-vesiculated volcanic necks and shallow-level intrusions (e.g., Ulff-Møller, 1977). The difference between the subaerial and subaqueous eruption morphologies implies that if the Ilugissoq volcano had erupted on land and not on a shelf in a marine basin, then the volcano would have appeared as a row of small scoria cones focussed around one or several voluminous lava flows similar to the one exposed at Nuuk Killeq.

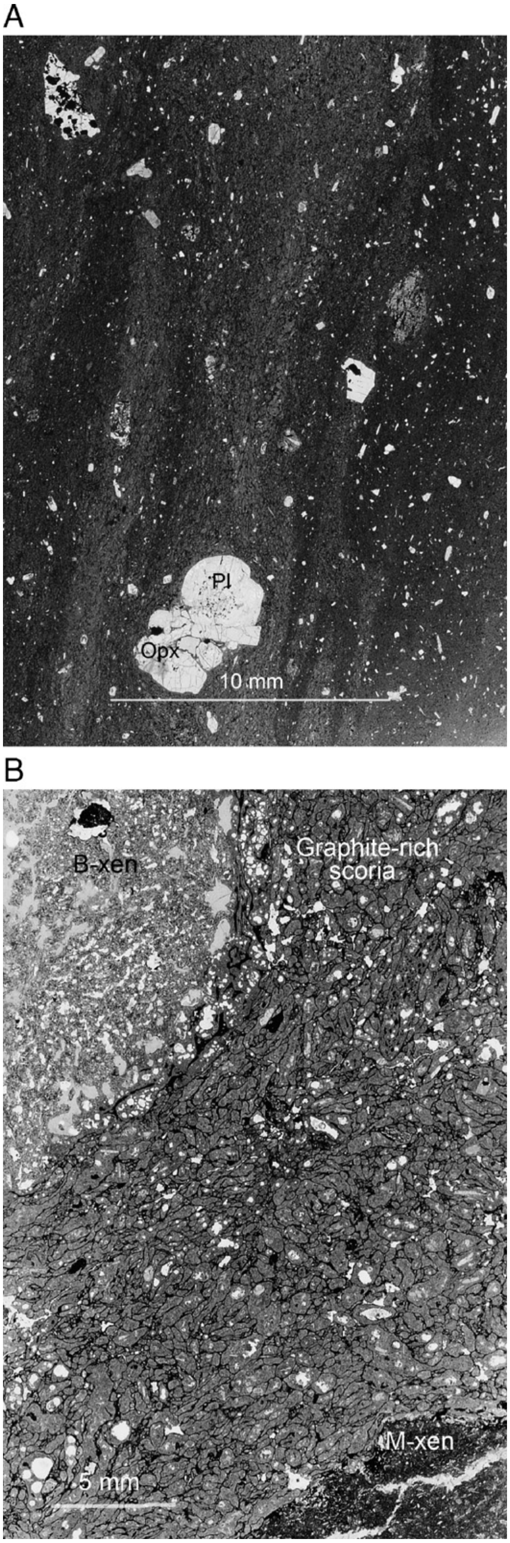


Fig. 10. (A) Native-iron-bearing andesite lava with a fine-grained, distinctly flow laminated groundmass with disseminated iron and graphite. The rock contains phenocrysts of orthopyroxene (Opx) and plagioclase (Pl) and xenocrysts of plagioclase with graphite. Sample GGU 340772, Nuuk Killeq. (B) Graphite-rich scoria clast from the pyroclastic rock at Nuuk Killeq. The graphite (4.2 wt.%) defines a reticulate texture in the groundmass. Xenoliths of basalt (B) and magma-modified mudstone (M) are seen in the section. Sample GGU 113518.

Why, then, did the volcano become so violently explosive as to form the largest eruption site of the Vaigat Formation? The answer must be a combination of moderate internal gas pressure and an external gas source, i.e., hydrovolcanic processes.

The uncontaminated picrites and basalts of the Vaigat Formation did not produce noticeable pyroclastic rocks when they erupted subaerially. Even when they erupted in the same marine shelf environment as the Ilugissoq volcano, quite different volcanic features resulted: an abundance of subaqueous picritic eruption sites slightly older than Ilugissoq volcano occur in the vicinity of the volcano and in a more or less identical setting (Pedersen et al., 2002a), and these form mounds of hyaloclastite and pillow lava very different from the pyroclastic graphite andesite cones. The picrite magmas were characterized by very low though not negligible gas pressures (e.g., Jamtveit et al., 2001), small individual eruption volumes and thin fissure feeder systems, which together did not allow active hydrovolcanism to take place.

Although the primary gas pressure of the graphite andesites of the Asuk Member, when erupted on dry land, was insufficient to generate a large explosive eruption, the gas pressure was clearly higher than that characterising the regional picrites of the Vaigat Formation. All well-preserved glass grains of graphite andesite from Ilugissoq, both from the root zone and from the highest levels of the volcano, show that a free gas phase evolved around the abundant graphite flakes at the time of quenching. This moderate primary gas pressure must have led to rapid expansion of the magma as it approached surface levels, and combined with a higher eruption rate compared to the picrites this must have facilitated the entry of sea water into the volcanic feeder system which probably was a non-continuous fissure wider that the picrite eruption fissures.

The Ilugissoq volcano was distinctly affected by phreatomagmatic fragmentation processes and the four well-bedded crater cones differ markedly from the picritic breccia mounds. The pronounced shattering of the individual glass grains in the compact, fine-grained pyroclastic rocks of the root zone, which is typical of phreatomagmatic activity (Heiken, 1974; Heiken and Wohletz, 1985), shows that phreatomagmatic explosions took place in the conduit beneath the sea floor level which was situated 300–400 m below the sea level. The upward change in structure to the rocks of the upper part of cones C and D, which are characterized by larger particle sizes and a higher proportion of grains with lobate air-quench surfaces, indicates a diminishing importance of steam explosions as the cones built above sea level. The eruptions of the Ilugissoq volcano are probably best characterized as Surtseyan (e.g., Kokelaar, 1983; Moore, 1985). The analogy to Surtsey Island itself (Thorarinsson, 1967) is however imperfect as the Ilugissoq volcano never developed a late subaerial lava stage.

8.2. Significance of the graphite

Pedersen (1978a) compared the then newly discovered graphite andesite tuffs from Agatdalen in Nuussuaq with the magnesian andesites from Asuk Member on Disko and noted that, whereas the tuffs are rich in graphite and poor in or free of native iron, the lavas at Asuk have much less graphite and more native iron. He suggested that the difference in metal contents could be due to the strong pressure dependence of the graphite–oxygen equilibrium (French and Eugster, 1965; French, 1966), implying that the tuffs were quenched at moderate pressures (envisaged as 0.5 to 1 kbar), whereas the andesite lavas and breccias on Disko were equilibrated at surface pressure. The issue of carbon–oxygen equilibria in the context of iron metal formation in West Greenland has later been discussed by Bird et al. (1981), Pedersen (1981), Goodrich and Bird (1985), Ulff-Møller (1985), Pedersen and Rønsbo (1987) and Solovova et al. (2002), and it has been demonstrated that iron-bearing assemblages span at least four log fO_2 units in T–fO_2 space, the most reduced rocks being lava flows and subaqueous breccias, which experienced carbon reduction close to atmospheric pressure. Some iron-bearing rocks record changing fO_2 equilibria with pressure reduction during the flow from crustal reservoirs towards the surface (Pedersen, 1981) or during the degassing of hydrocarbon sources in xenoliths (Pedersen and Rønsbo, 1987).

The discovery of the Ilugissoq volcano as a source for the majority of the tuffs in the Agatdalen region confirms the original interpretation of Pedersen (1978a) that the source of the tuffs was on Nuussuaq and that the tuffs were quenched at a "moderate" pressure. The geology of the Ilugissoq volcano suggests that this pressure was in excess of 100 bars, corresponding to ca. 300 m of rock equivalent.

The eruptions of the Ilugissoq volcano and the Asuk Member andesite lavas must have represented major environmental hazards within the local area. Solovova et al. (2002) calculated the equilibrium gas composition of a contaminated basaltic magma from Disko at the upper range of iron stability (iron–wüstite fO_2 buffer) in equilibrium with troilite and carbide at 1175–1200 °C and in the pressure range 0 to 500 bars. At pressures below 100 bars, CO is a dominant gas species. An eruption of a magma such as that of the Ilugissoq volcano would therefore, as the degassing progressed, have saturated the near surroundings in CO and CO_2. No victims in the form of higher vertebrates have yet been found.

9. Conclusions

The Ilugissoq graphite andesite volcano on Nuussuaq belongs to the Asuk Member of the Vaigat Formation. It is the largest eruption site within the Vaigat Formation and is the source of the majority of the graphite andesite tuffs found in marine sediments in central Nuussuaq.

The volcano erupted on a marine shelf consisting of picritic rocks underlain by sediments of the Nuussuaq Basin. The volcano consists of four overlapping crater cones aligned along a more than 4 km long NNW–SSE oriented fissure system; two cones barely reached sea level whereas the other two reached up to 200 m above the sea. The volcano covered at least 19 km^2 and the volume of the pyroclastic rocks was just above 5 km^3.

The Ilugissoq volcano consists exclusively of pyroclastic rocks, volcaniclastic fragments and sediment xenoliths. The primary pyroclastic fragments consist of magnesian andesite with several weight percent of graphite. The graphite andesite magma formed when mafic magma established a shallow-level magma reservoir within older clastic sediments in the Nuussuaq Basin. Magma-modified mudstone is completely dominant in the xenolith assemblage, indicating that the graphite andesites originated through prolonged high-temperature assimilation of mudstone. The minimum amount of assimilated mudstone is calculated at 2 km^3.

The morphology of the pyroclastic rocks indicates that the volcano evolved through phreatomagmatic activity which diminished with time. The magma never degassed sufficiently to reach a subaerial lava stage. A moderate primary gas pressure in excess of 100 bars in the graphite andesite magma facilitated the phreatomagmatic explosions, which created the volcano.

The graphite-rich rocks of the Ilugissoq volcano contain little or no native iron. In comparison, the contemporaneous and chemically similar subaerial lavas and breccias from Disko and Nuussuaq contain less graphite and more iron. The differences are suggested to be due to the extremely pressure-dependent redox-sensitivity of carbon–oxygen equilibria in the range 1 bar (the lavas) to 500 bars (the Ilugissoq volcano) (e.g., French, 1966; Eugster, 1977; Sato, 1979).

Eruptions in the Ilugissoq volcano must have been accompanied by intense CO and CO_2 emanations, which would have represented a lethal hazard for all animal life in the volcano's surroundings.

Acknowledgements

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