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Subglacial to Emergent Volcanism at Shield Nunatak, Mt. Melbourne Volcanic Field, Antarctica

By G. Wörner and L. Viereck*

Summary: Sections through Shield Nunatak volcano, an alkali basaltic subglacial table-mountain from the Mt. Melbourne Volcanic Field, are described. Resting on a base of older lava flows and a fossile tillite layer, the volcano is formed mainly by massive ash and lapilli (mass flow) deposits while pillow lavas are absent. The recurrent stage of emergence from subglacial to subaerial conditions is characterized by development of tuff rings from explosive interaction between magma and melt water, complex ash- and lapilli deposits, including lava flows brecciated by water-interaction and a subaerial basaltic ash-flow deposit. The sequence is capped by subaerial tuff rings, lava flows, scoria cones and reworked tephra. Available data on subaquatic explosive volcanism indicate that early Shield Nunatak basaltic lavas erupted under less than 300 m of ice cover; later lavas erupted under shallow-water and subaerial conditions. Shield Nunatak probably formed during a glacial period (possibly the last) when the ice thickness in the Mt. Melbourne area must have been at least 200 m greater than at present. The volcano has suffered only minor glacial erosion and still almost has its original shape.

Zusammenfassung: Es werden Profile beschrieben durch einen alkalibasaltischen subglazialen Vulkan (Shield Nunatak) im Mt. Melbourne Vulkanfeld. Die Unterlage des Vulkans wird von einer Serie subaerischer Lavaströme intermediärer Zusammensetzung (Mugearit) gebildet. Über einer Lage von Paleo-Till bilden massive Aschenablagerungen die Basis der subglazialen Sequenz. Kissenlaven fehlen. Der Wechsel von subglazialen (subaquatischen) zu subaerischen Eruptionsbedingungen, d. h. das Stadium in dem der Vulkanbau über den Wasserspiegel hinausreichte, wird gekennzeichnet durch Tuffring-Ablagerungen, brecciierte Lavaströme und einen Aschenstrom. Diese vulkanischen Lockerprodukte entstanden durch die explosive Wechselwirkung zwischen flachem Wasser und Lava. Die Eruptionsfolge wird abgeschlossen durch subaerische Oberflächeneruption von Basaltschlacken und Lavaströmen. Betrachtungen über die explosiven Fragmentierungsprozesse in Abhängigkeit verschiedener Parameter (Magmatyp, Wassertiefe, etc.) deuten an, daß die Paleo-Eisdicke zur Zeit der Eruptionen des Shield Nunatak (möglicherweise während der letzten Vereisungsphase) mindestens etwa 300 Meter betragen haben muß, ca. 200 Meter höher als heute. Der Vulkanbau hat nur wenig glaziale Erosion erlitten und hat heute noch nahezu seine ursprüngliche Ausdehnung.

1. INTRODUCTION

Volcaniclastic deposits from submarine and subglacial volcanoes are similar in many ways though surrounding environment and geologic setting, origin and composition of the lavas erupted may be quite different. Observations on submarine pillow formation by MOORE (1965) and the evaluation of factors governing the nature of submarine volcanism by McBIRNEY (1963) first addressed questions of subaquatic volcanism and the effects of variable water depths. Studies on island volcanoes like Surtsey (JACOBSSON & MOORE 1980), uplifted seamounts such as LaPalma island (STAUDIGEL & SCHMINCKE, 1984) as well as subglacial volcanic formations e. g. on Iceland provide insight into styles and mechanisms of subaquatic explosive volcanism. Investigations of subglacial volcaniclastic sequences (JONES 1966, 1969, 1970; JONES & NELSON 1970; ALLEN 1980) resulted in a generalized subglacial sequence that typically is characterized by a basal pillow complex. The pillows show upwardly increasing vesicularity and grade into massive fine-grained, glassy ash deposits (hyaloclastites). The sequence may be capped by subaerially erupted lava flows and associated flow-foot breccias which result from lava flows entering shallow melt water.

Here, a well exposed sequence of volcaniclastic rocks from an emerging subglacial volcano, Shield Nunatak, of the Mt. Melbourne Volcanic Field (Antarctica) is described. The discussion is focussed on the origin of massive hyaloclastites as well as the transition from subglacial/subaquatic to subaerial eruptive conditions. It is emphasized, that water depth has important control on explosive subaquatic volcanism irrespective of the fragmentation process involved. Our observations will be used to deduce age and glacial history of Shield Nunatak in the Mt. Melbourne volcanic field.

* Dr. Gerhard Wörner and Dr. Lothar Viereck, Institut für Mineralogie, Ruhr-Universität, D-4630 Bochum.

2. GEOLOGICAL SETTING

Shield Nunatak (Nunatak = ice-free mountain) forms a flat-topped complex of eruption centers, rising to 300 m above present day sea level within the south-eastern part of the Mt. Melbourne volcanic field (Fig. 1). The field belongs to the Cenozoic McMurdo Volcanic Group in Victoria Land which comprises several volcanic provinces (KYLE & COLE 1974) between the Transantarctic Mountains and the Ross Sea basin. Regional normal faulting of pre-volcanic age with a relative downward displacement of the crust in the Ross Sea area by at least 2000 m is inferred from the regional topography of the metamorphic basement (Fig. 1). Bathymetric and seismic data from the Ross Sea area (COOPER & DAVEY 1985) document an extensive sediment-filled trough along the Transantarctic Mountains with a possible total vertical displacement of 14 km. Recent small scale normal faulting is apparent from subaerial lavas extending below present day sealevel (e. g. at Cape Washington, Fig. 1). Young isostatic uplift and continued regional tectonic movements, are indicated by Holocene marine terraces which are exposed some 20—40 m above sea level in the Mt. Melbourne area. The volcanoes in the field were thus erupted in a tectonically rather unstable environment making interpretations of paleo-ice thicknesses and sea level changes difficult.

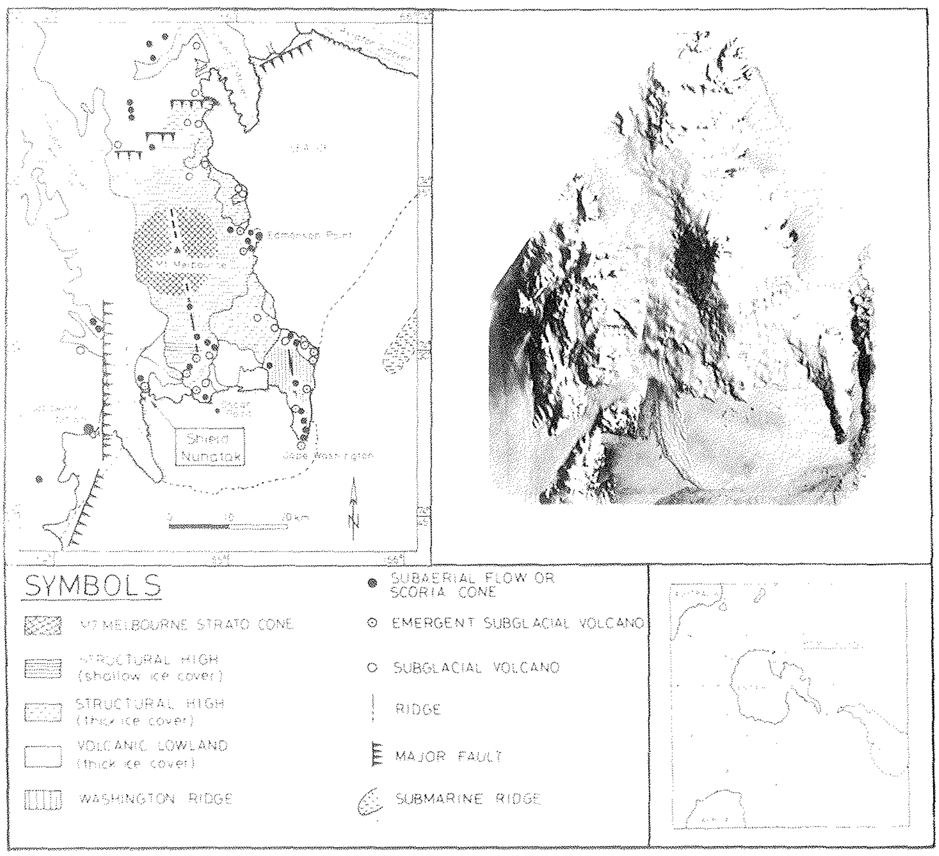

Fig. 1: The Mt. Melbourne volcanic field: Structural and morphological features. Eruptive centers are distinguished for eruption from under ice, emerging sub-glacial/subaerial and purely subaerial conditions. Satellite image for comparison with the morphological features portrayed above. The satellite image is courtesy of Dr. B. Lucchitta, USGS, Flagstaff. Index map for orientation.

Abb. 1: Das Mt. Melbourne Vulkanfeld: Eruptionszentren, Tektonik und Morphologie. Subglaziale, subaerische und Eruptionszentren am Übergang subaerisch/subglazial sind unterschieden. Das Satellitenphoto wurde dankenswerterweise vom USGS in Flagstaff (Dr. B. Lucchitta) zur Verfügung gestellt.

The Mt. Melbourne volcanic field comprises about 60 exposed, and probably many more ice covered, Pleistocene to Recent eruption centers of alkaline basaltic to intermediate composition, which surround the central trachytic to trachybasaltic Mt. Melbourne stratovolcano (2732 m). NATHAN & SCHULTE (1968) and later KEYS et al. (1983) noted evidence for recent eruptions and active fumaroles in the summit area of Mt. Melbourne. K-Ar ages for a non-representative set of samples range from > 3 to 0.19 m. a. for the volcanic field and are even younger (up to recent) for rocks from the Mt. Melbourne summit area (ARMSTRONG, 1978; KREUTZER & WÖRNER, unpubl. data). An estimated total volume of 0.15 km^3 of alkali-basaltic magma was erupted at Shield Nunatak. The basalts are moderately to highly phyric (plagioclase, clinopyroxene, olivine) and sometimes cumulus textured. There is no systematic petrographic and chemical variation throughout the stratigraphic section.

3. SECTIONS AND ROCK TYPES AT SHIELD NUNATAK

3.1 *The basement*

Shield Nunatak volcano (Fig. 2) was constructed upon an irregular basement dipping at a minimum angle of about 8° to the east. The base is exposed as glacial erosion surface on top of a sequence of at least 7 subaerial mugearite lava flows along the western cliff at about 100 m elevation (Figs. 3 and 4). Individual flows are between 1.5 and 6 m thick and show columnar jointing and scoriaceous flow tops. Abundant xenoliths of such mugearite are present in all volcaniclastic deposits of Shield Nunatak and indicate that the flows underlie most of Shield Nunatak volcano. The flows are locally overlain by a 0.3 m thick tillite layer with paleo-ice fragments and a thick dark brown, sandy layer a few cm thick, possibly a paleo soil. A poorly stratified, fine-grained, well sorted and palagonized volcaniclastic sediment, about 3 m thick, may represent eolian reworked ash that lies on top of tillite and soil. Contacts to the overlying Shield Nu-

Fig. 2: Shield Nunatak table mountain at 164° 30' E / 74° 34' S, 300 m high, 2,2 km wide, as viewed from ESE (Cape Washington) at ca. 28 km distance. Subaerial lavas of Markham Island and Oskar Point at sea level in the foreground.

Abb. 2: Shield Nunatak subglazialer Tafelberg (164° 30' E / 74° 34' S): 300 m hoch, ca. 2,2 km breit. Sicht von ESE (Cape Washington) aus 28 km Entfernung. Subaerische Laven von Markham Island und Oskar Point auf Meereshöhe im Vordergrund.

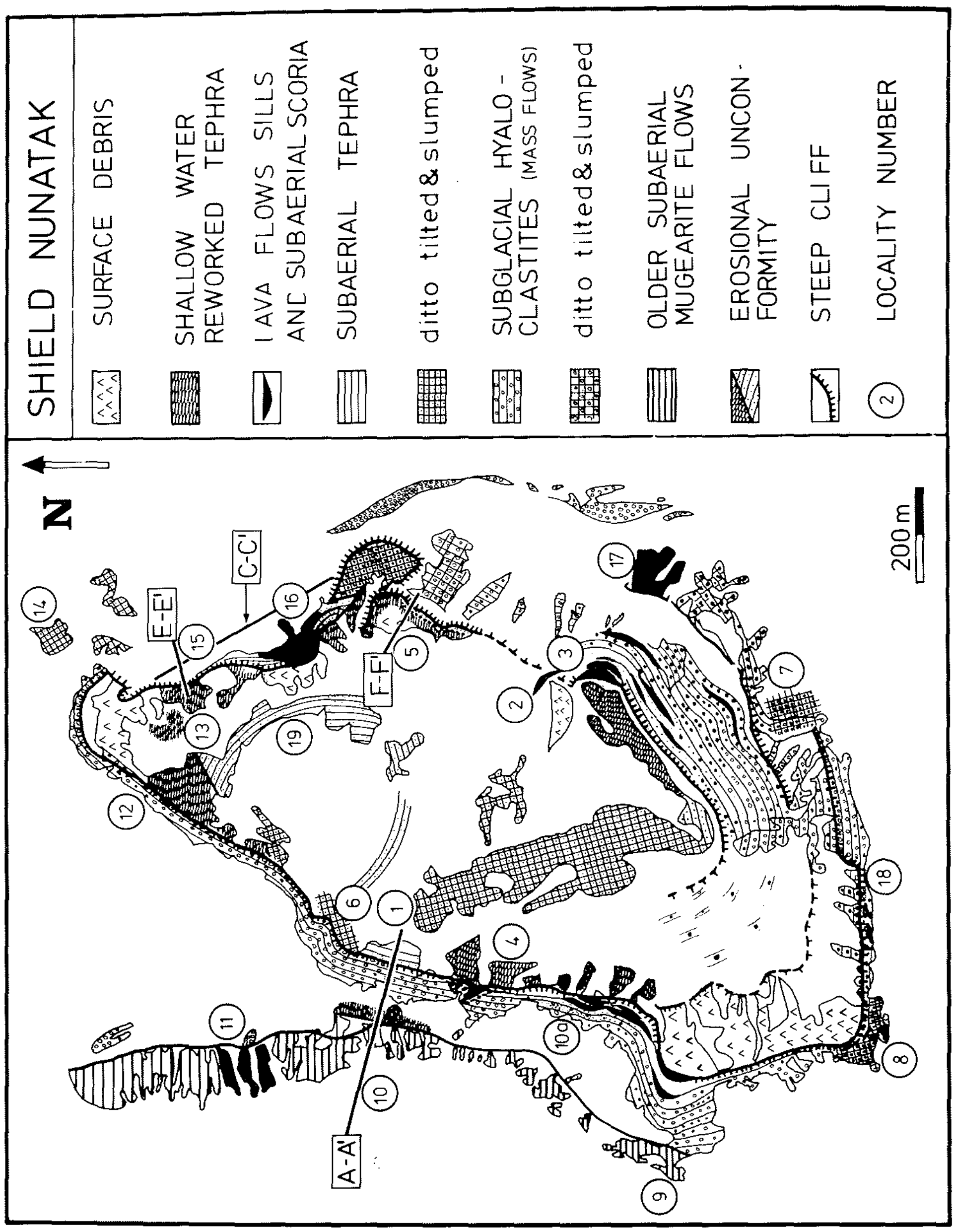

Fig. 3: Geological map of Shield Nunatak. A-A ' and other heavy lines represent profile-lines some of which are discussed in the text.

Abb. 3: Geologische Karte von Shield Nunatak. A-A ' und andere Linien repräsentieren Profilschnitte.

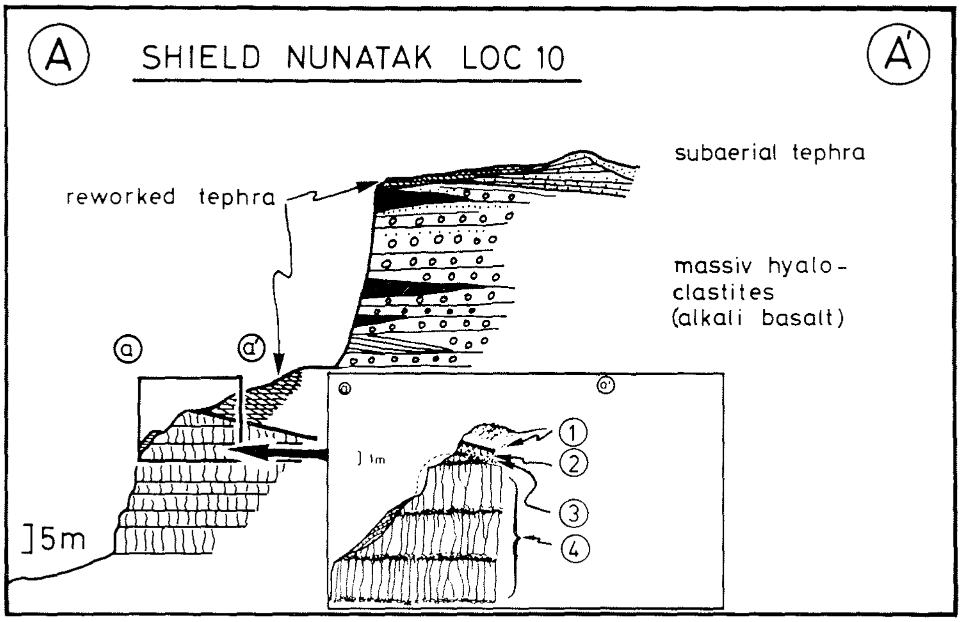

Fig. 4: Schematic section through the western cliff of Shield Nunatak with its base exposed. From top to base: reworked pyroclastics, and tuff ring deposit, lava flows (black) with intercalated hyaloclastites and tuff ring deposits, reworked tuff, erosional unconformity, basal subaerial lava flows. Symbols as in Fig. 3. Enlarged inset shows details of the erosional unconformity with tillite, paleo-soil and overlying aeolian reworked ash. Note the steeply dipping erosional unconformity towards the valley of Campbell glacier. It suggests that prior to the formation of Shield Nunatak, the glacier took a similar course. Inset: (1) = massive, well sorted (fine silt) hyaloclastite (aeolian reworking of ash?), (2) = pebbles, ventifacts with glacial striations, fragments from underlying lava flows in fine-grained matrix cemented by pedogenic processes, (3) = angular blocks from underlying flows on smooth erosional surface, (4) = mugearite lava flows.

Abb. 4: Schematisches Profil durch die Westwand von Shield Nunatak. Von oben nach unten: Umgelagerte Tuffe, Tuffring-Ablagerungen, Lavaströme (schwarz), zwischengelagerte massige Aschenablagerungen, Erosionsdiskordanz, basale Lavastromserie. Symbole wie in Abbildung 3. Das Inset zeigt Details des Erosionshorizontes: (Wind-) umgelagerte Asche, Paleoboden, Tillit. Man beachte die steil nach W zum heutigen Campbell Gletscher abfallende Erosionsfläche. Dies mag bedeuten, daß der Gletscher vor der Eruption des Shield Nunataks eine ähnliche Richtung genommen hat. Inset: (1) massive gut sortierte Asche (Feinsilt, windumgelagert?), (2) Gerölle, Windkanter mit glazialen Striemen, Bruchstücke des unterlagernden Lavastroms in feinkörniger Aschematrix, die durch die Bodenbildung zementiert ist, (3) Blöcke des unterlagernden Lavastroms über glatter Erosionsfläche, (4) Mugearit Lavaströme.

natak subglacial rocks are not exposed due to cover with scree. This contact, however, must be closely located upsection. Notably, no pillow lavas have been observed.

3.2 *Massive subglacial hyaloclastites*

Cliffs comprising most of Shield Nunatak up to 200 meters high are composed mostly of palagonized hyaloclastites and breccias deposited by mass flows of primary (i. e. volcanic) and secondary (i. e. reworked) origin. Intercalated in the upper parts are shallow water to subaerial tuff ring deposits (described below). Younger sill- or plug-shaped intrusions are abundant. The massive hyaloclastites ranges from fine ash ($<$ 1 mm) to coarser-grained, matrix supported lapilli tuffs some of which contain angular, non-vesicular basaltic fragments larger than 10 cm in size. Individual mass flow units may be separated by layers of fine-grained ($<$ 0.1 mm), laminated hyaloclastite up to several tens of cm in total thickness. These indicate quiet subaquatic sedimentation between eruptions. There is abundant evidence for post-depositional slumping and convolution of mass flow layers at scales from centimeters to several meters as well as major collapse structures (Fig. 5). Deformation and collapse may be caused by (a) dewatering of sediment, (b) forceful intrusion of basalt into wet hyaloclastite or, most likely (c), retreat of ice walls supporting the subglacial volcano and melt water lake.

3.3 *Tuff ring deposits*

Tuff ring deposits occur throughout the upper half of the Shield Nunatak sequence. They are best expo-

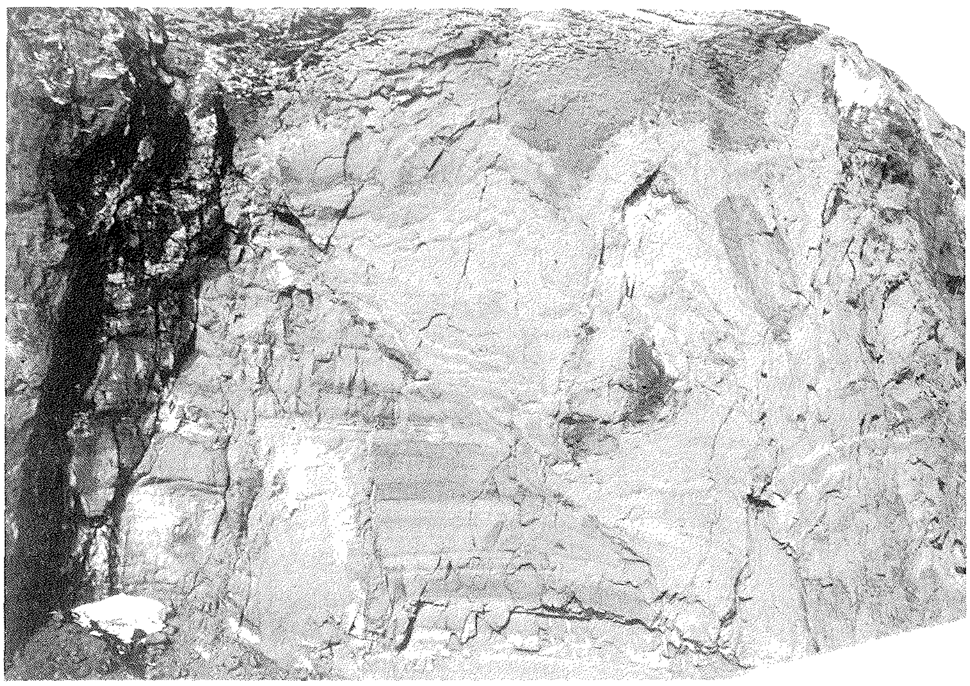

Fig. 5: Massive glass tuffs (hyaloclastites) at the northern cliff of Shield Nunatak. Height of cliff approximately 150 m. Note the slumping plane cutting through the section from the upper right to the lower left and other vertical faults. These finer-grained massive hyaloclastites belong to a more distal facies because coarse blocks of basalt are absent and finelayering is abundant.

Abb. 5: Massives Tuffkliff (Hyaloklastit) im Nordteil von Shield Nunatak, ca. 150 m hoch. Man beachte die 45° Versatzfläche, entlang der das Kliff abgerutscht ist. Deformationen deuten daraufhin, daß die Bewegungen in nassem, synsedimentärem Milieu erfolgten. Die feine Schichtung und die Abwesenheit von Basaltblöcken zeigen eine schlotferne Ablagerung an.

sed along the western cliff (Figs. 3 and 6) where they are represented by laminated lapilli tuffs displaying the following features: a) steep erosional surface dipping inward towards the eruptive center, b) outward-dipping layers (Fig. 6), c) lapilli tuff layers from a few mm to 10 cm thick and poorly sorted have maximum particle size ranging from mm up to about 50 cm, d) dominantly dense juvenile lapilli, e) larger blocks (> 20 cm) without impact sags are plastered on one side by wet ash resulting from horizontal transport, f) common occurrence of mantled lapilli, and, more rarely, accretionary lapilli (concentrically accreted ash particles, evidence for wet eruption clouds), g) cm-sized and larger comagmatic bombs with impact sags.

These deposits are found underlying subaerial scoria and lava flows. They mark the transition from subaquatic/subglacial hyaloclastite formation to shallow water/subaerial phreatomagmatic (water-magma) explosions as described by JACOBSSON & MOORE (1980) and KOKELAAR (1983). Tuff ring deposits of this type, strongly faulted and tilted into almost vertical position, also forms the central ridge of Shield Nunatak (Fig. 3). This indicates large-scale block slumping, prior to the late subaerial stage of the volcano. Tilting probably followed a widening by melting of the glacial "ice-bowl" due to migration of subglacial eruptions. A young tuff ring structure is recognized on the northern plateau of Shield Nunatak (Fig. 3, loc. 19) and probably marks a late stage of volcanic acitivity at Shield Nunatak. Tuff rings of similar morphology with typical permafrost patterns are common on top of ridges north of Oscar Point (Fig. 1), where they probably also represent top exposures of emerging subglacial volcanoes of similar age.

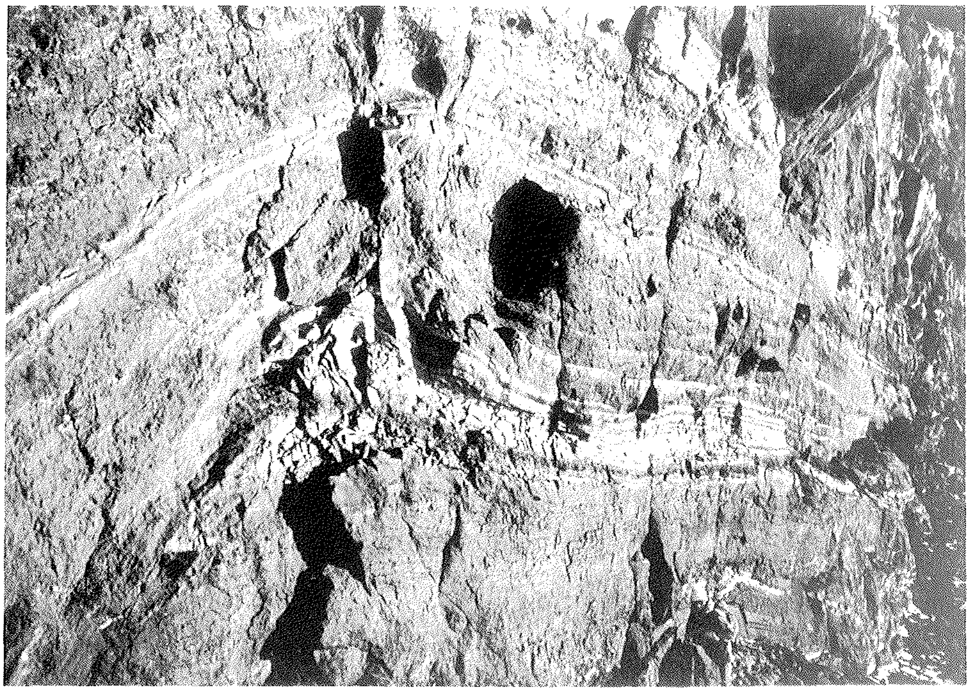

Fig. 6: Subaerial tuff ring deposits at locality 10a (Fig. 3), person for scale. Note the fine banding and strong grain-size contrast between different lapilli layers. There is an erosional crater rim unconformity in the left center of the picture with tuff layers dipping towards the eruptive center.

Abb. 6: Subaerischer Tuffring, Lokalität 10a (Abb. 3). Person (1.81 m) als Maßstab. Man beachte die feine Bänderung und die starken Korngrößenkontraste zwischen den Schichten. Eine Kraterranddiskordanz ist im linken Bildteil zu sehen, an der die Tuffschichten nach links zum Eruptionszentrum einfallen.

3.4 *Lava flows, scoria and hydroclastic breccias*

Aa-type lava flows with brecciated base and irregular scoriaceous top, columnar jointing and of lensoid to tabular shape are common along cliff tops at Shield Nunatak. Typically, they overly the emerging subglacial to subaerial transitional sequence and are themselves overlain by shallow-water reworked ash and lapilli (Fig. 7). Thicknesses of the flows range from a few meters up to 10 meters. They appear to have flowed for no more than about 100 m and contribute to the flat-topped shape of Shield Nunatak. Welded scoria deposits and funnel-shaped feeders identified at least two eruption centers for such subaerial lavas.

One complex eruption center is exposed along the north-eastern cliff (loc. 16, Fig. 3). Subaerial phreatomagmatic to strombolian eruptions excavated a crater into surrounding massive hyaloclastites and built an asymmetrical scoria cone. To the south, a scoria layer, a lava flow, and a subaerially deposited tuff layer, which is described below as a basaltic ash flow are exposed. To the north, basaltic lava and breccia layers are interstratified with fine-grained tuffs (loc. 15, Figs. 3 and 8). The center is cut by a flat-lying erosional unconformity which is overlain by fluvially reworked volcaniclastic material comprised of laminated fine-grained sediments with abundant ripples and erosion channels.

The brecciated scoria layers, 1 to 2 m thick (Fig. 8), are distinct from typical subaerial deposits by abundant fine ash matrix (Fig. 8). Particle size ranges from less than 1 mm to more than 10 cm in diameter. At their base, these breccias intrude and mix with the underlying water-saturated sediment. Disintegration of the lava is observed into lapilli- and ash-sized droplets of variable vesicularity and smooth surfaces immersed in the fine-grained hyaloclastite tuff. Sedimentary structures of the tuff are destroyed and there is

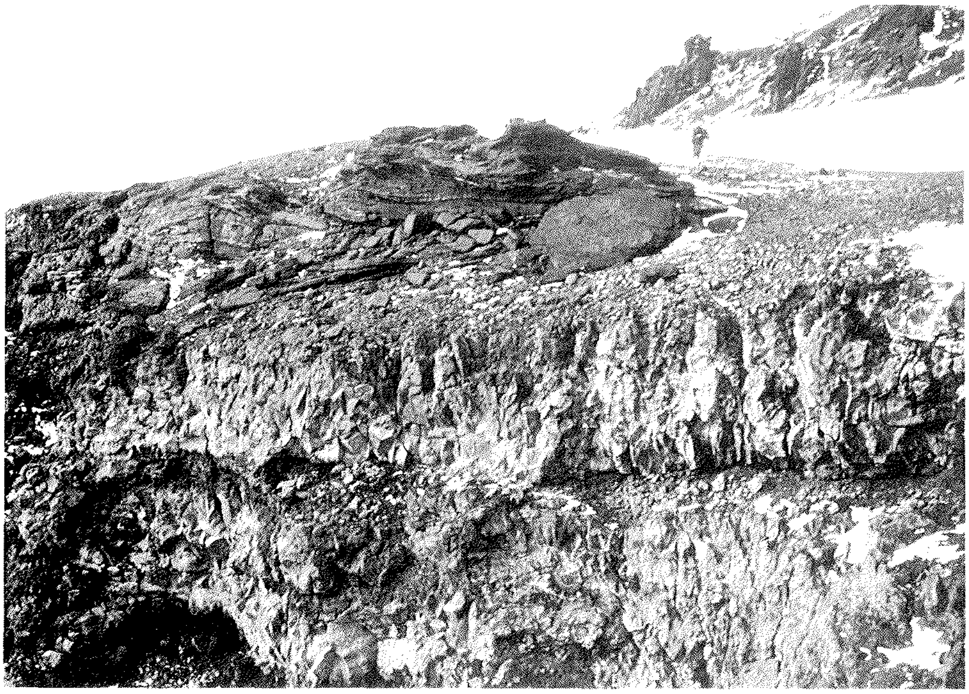

Fig. 7: Subaerial lava flows capping the subglacial and tuff ring sequence. Columnar structures from cooling are very irregular in some flows which may have brecciated flanks very similar to matrix free hydroclastic lava flows (Fig. 8). This suggests, that some of the lower flows entered shallow melt water ponded on top of the hyalaoclastite and tuff ring sequence. Person for scale.

Abb. 7: Subaerische Lavaströme überlagern die Tuffringablagerungen und massigen Tuffe. Abkühlsäulen sind unregelmäßig und Lavaströme können an ihrer Seite in hydroklastische Breccien übergehen. Dies deutet an, daß einige dieser Ströme in flaches Wasser und/oder nasse Tuffe geflossen sind.

no thermal effect on the hyaloclastite matrix. In addition, there are degassing pipes emanating from larger clasts as well as mud-filled cracks and large cavities. Towards the exposed eruption center, these layers grade into scoria-rich aa-flows. With increasing distance, they grade into ash-rich, poorly sorted deposits that show matrix supported larger dense blocks with chilled margins and scoria clasts. The sequence of breccias resembles those described by KOKELAAR (1982) and probably formed by hydroclastic processes (lava-water interaction). It thus represents layers of degassing aa-type breccias that flowed into and under shallow water and invaded and mixed by fluidization with soft sediments. Different degrees of sorting and variable contents of fine ash reflect proximal and distal facies with respect to the eruptive center. Intrusion and mixing of lava with sediment may be a particularly common fragmentation process in ice-contained subglacial eruption centers because, in contrast to oceanic islands where fine-grained hyaloclastites may be easily removed from the eruption centers by gravity flows.

3.5 *A basaltic ash flow at Shield Nunatak*

At locality 16 described above (Fig. 3), an unusual massive tuff deposit is intercalated between a subaerial scoria layer and a subaerial aa-lava flow (Fig. 9). It is thus most likely that it also was erupted and deposited subaerially. Underlying topography of an aa-flow is smoothed out by this up to 3 m thick layer. Four units are characterized by grain size changes and interlayered fine ash. This deposit is distinctive in that:

a) it is intercalated with subaerially erupted lava, yet it represents a laterally continous layer rich in coarse ash and lapilli.

Fig. 8: Hydroclastic breccias (subaquatic aa-flows) at loc. 15, north-eastern cliff (Fig. 3). Note the different facies with variable amount of fine-grained matrix between the brecciated scoria clasts and variable thickness of still-water deposited finely laminated ash (''background'' sedimentation during and between lava flow activity). Author for scale.

Abb. 8: Hydroklastische Breccien (subaquatische Aa-Ströme), Localität 15 (Abbildung 3). Man beachte die unterschiedlichen Fazies von stark variablem Aschengehalt der Breccie. Feinlaminierte, umgelagerte Aschen repräsentieren Stillwasserablagerungen zwischen den Lavaströmen. Author als Maßstab.

b) degassing (lapilli-) pipes occur and cut across flow unit boundaries

c) basaltic scoriaceous clasts with slightly chilled margins are abundant and have distinctively high vesicularity (brown ''pumiceous scoria'')

d) the bulk of the layers is depleted in fine ash and has a medium grain size of around 0.5—1 cm close to the eruption center

e) horizontal trains of coarser (> 5 cm) juvenile pumiceous clasts and accumulations in lenses of dense, blocky alkali-basalt fragments mark the base of individual units.

About two hundred meters further south (loc. 5, Fig. 3), a similar deposit is found extending over half of the top of the eastern cliff of Shield Nunatak. It is also formed by 4 individual layers that are conspicuous for their basaltic pumiceous lapilli and bombs (< 10 cm in size).

These observations suggest that this compound volcaniclastic unit represents a horizontally transported flow deposit, i. e. a primary basaltic ash flow deposit that formed from a hot, wet and dense collapsing eruption column such as those described by KOKELAAR (1983, 1986).

The observation of such rocks is notable because pyroclastic flows rarely form from basaltic eruptions

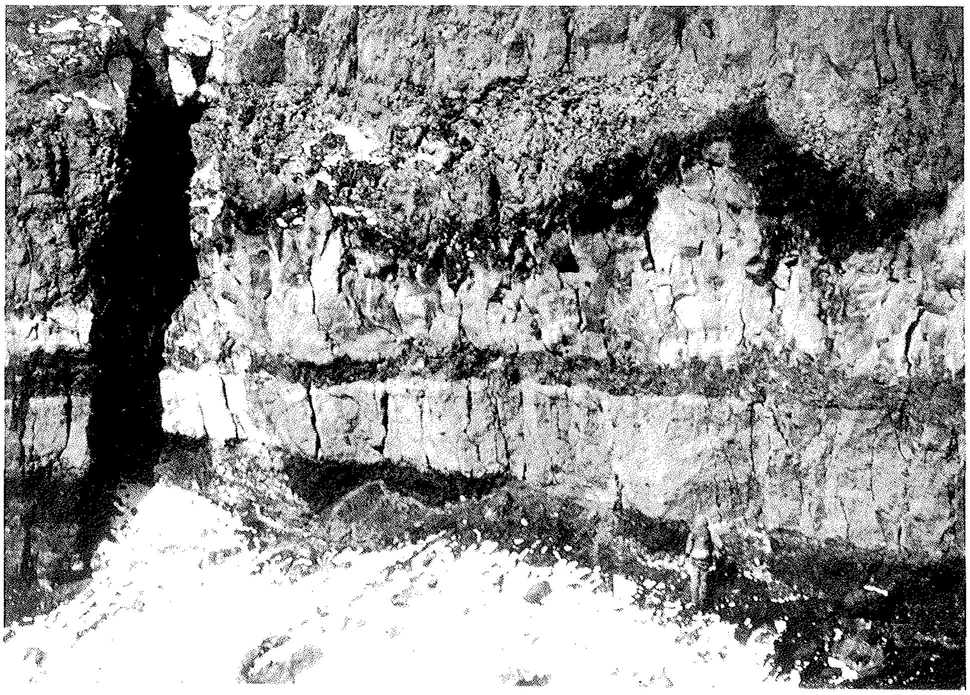

Fig. 9: The basaltic ash flow in proximal facies (locality 16) intercalated between subaerial scoria and an aa-lava flow. Author for scale.

Abb. 9: Der basaltische Aschenstrom nahe des Eruptionszentrums (links), eingeschaltet zwischen subaerischen Schlacken (unten) und einem Aa-Lavastrom (oben).

and descriptions are scarce (WILLIAMS & CURTIS 1964; TAYLOR 1979).

4. DISCUSSION

4.1 *Subglacial volcanism at Shield Nunatak*

Figure 10 schematically summarizes principal rock types and structures at Shield Nunatak from its basal massive hyaloclastites to breccias and overlying tuff ring deposits, younger intrusions and late capping tuff rings and lava flows. The absence of pillow lavas, which have been frequently observed in Icelandic subglacial volcanoes, is noteworthy at Shield Nunatak. In order to interpret the emerging subglacial volcaniclastic sequence at Shield Nunatak we will first summarize possible fragmentation processes and discuss eruptive behaviour of volatile-poor (tholeiitic) and volatile-rich (alkali-basaltic) magma under variable water depths.

Physical processes of melt-water interaction have been investigated theoretically and experimentally, partly with respect to possible nuclear reactor accidents ("fuel-coolant interaction") (DULLFORCE et al. 1976; CORRADINI 1981; WOHLETZ & McQUEEN 1984). Processes of explosive interaction between magma and water were discussed by WOHLETZ (1986) and KOKELAAR (1986, and reference therein). Resulting types of fragments and their clastic deposits are described by WOHLETZ (1983) and HEIKEN & WOHLETZ (1985). As the principal processes of magma fragmentation by interaction with water, KOKELAAR (1986) identified 1) explosive release of magmatic volatiles, 2) explosive expansion and collapse of steam formed at magma-water contact, 3) explosive expansion of steam following enclosure of water in magma, and 4) cooling contraction. KOKELAAR stressed that a) vesiculation (1) is not

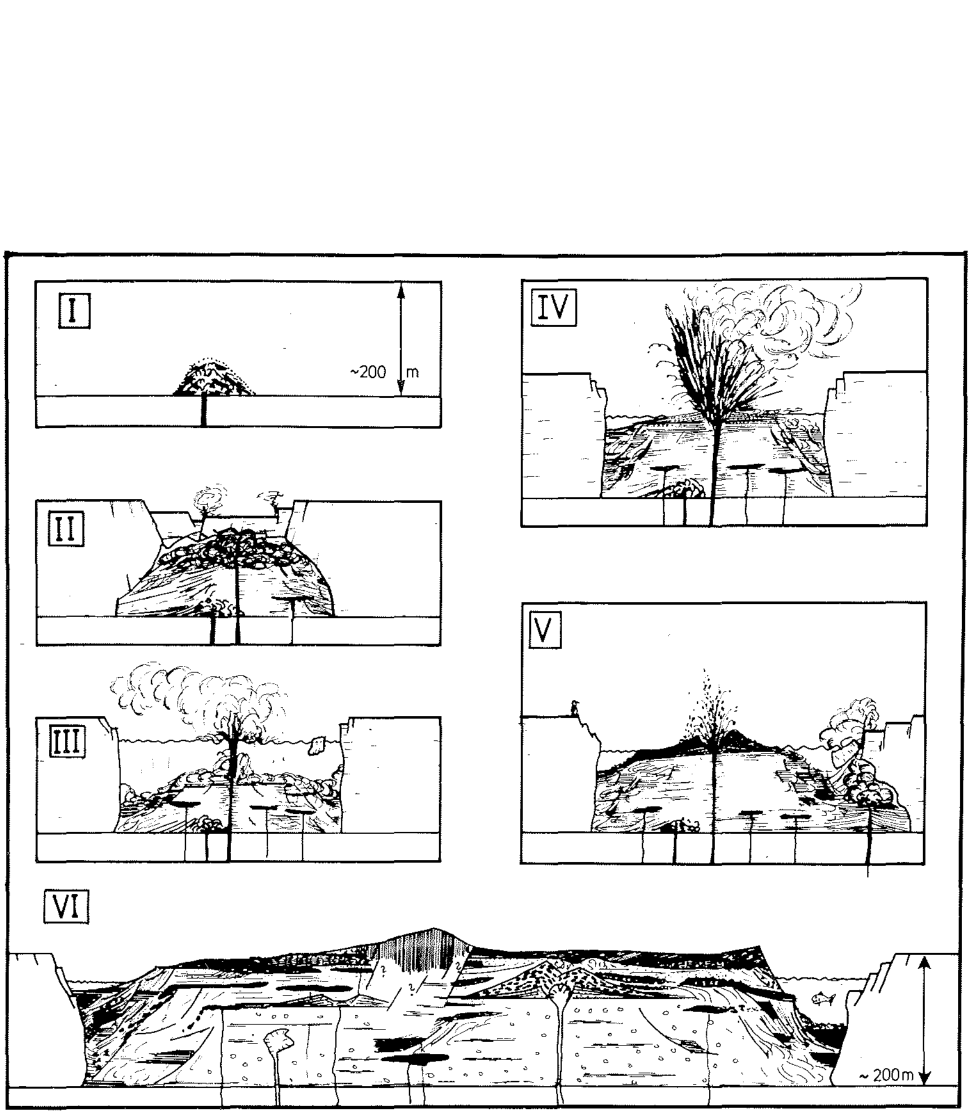

Fig. 10: Evolution of Shield Nunatak summarized highly schematically in six stages: (I) Initial eruption under ca. 200 m ice cover, built up of a subglacial dome, deposition of breccias and massive hyaloclastites. (II) Collapse of the glacial roof, venting through cracks, continued eruption of hyaloclastites. (III) Eruptions from under a melt water lake, intrusions of sills and plugs. (IV) Drainage of the lake and/or built up of the volcanic edifice resulting in emergent phreatomagmatic eruptions (tuff rings). (V) Subaerial eruptions, formation of scoria cones, lava flows and invasive flows into wet, soft hyaloclastites, retreat of supporting ice walls, formation of new eruption centers collapse of tuff cliffs. Stage VI represents present day Shield Nunatak.

Abb. 10: Die Entwicklung des subglazialen Shield Nunatak Vulkans: (I) Initialstadium, Eruption unter ca. 200 m Eis, Ausbildung eines subglazialen „Domes", Produktion von massigen Glas/Lapillituffen (Hyaloklastite) durch Magma-Wasser Wechselwirkung. (II) Kollaps des Eisdaches, Dampferuptionen durch Risse im Eis, kontinuierliche Produktion von Hyaloklastiten. (III) Eruption in und durch einen Schmelzwassersee, Intrusionen von Gängen und Sills in feuchte, weiche Tuffe, (IV) Abfluß des Schmelzwassers durch Risse und an der Unterseite des Gletschers. Weiterer Aufbau des Vulkans bis zu subaerischen Tuffen. (V) Subaerische Eruptionen von Lavaströmen und Schlacken. Fließen von Lavaströmen in seichtes Wasser und Vermischung mit nassen, weichen Tuffen (hydroklastische Breccien). Schmelzen des Eises, Verlagerung des Eruptionszentrums, Erweiterung des Schmelzsees, Kollaps großer Tuffkliffs. (VI) Schemazeichnung des heutigen Shield Nunatak Vulkans.

necessarily the cause for (the onset of) magma fragmentation and b) volatile control on the depth of fragmentation can be poor. At Shield Nunatak, however, we are not concerned with deep-water (> 1000 m) processes. Explosive eruptions at Shield Nunatak will be governed mostly by magmatic degassing (1) enhanced by processes (2) and (3) of KOKELAAR. Figure 11 compiles information relevant to explosive versus effusive subaquatic eruptions from various sources (KENNEDY & HOLSER 1966; McBIRNEY 1963; MOORE 1965; BISCHOFF & ROSENHAUER 1984).

During ascent of *tholeiitic* magma (0.5 wt % H_2O, minor CO_2) through the crust, CO_2 will degas continuously and produce small vesicles. At around 200 b (2000 m water resp. ice depth), H_2O-saturation is reached and H_2O filled bubbles will start to form. Subaquatic eruptions at such depths will result in formation of pillows or sheetflows of low vesicularity (depending on magma viscosity and discharge rate,

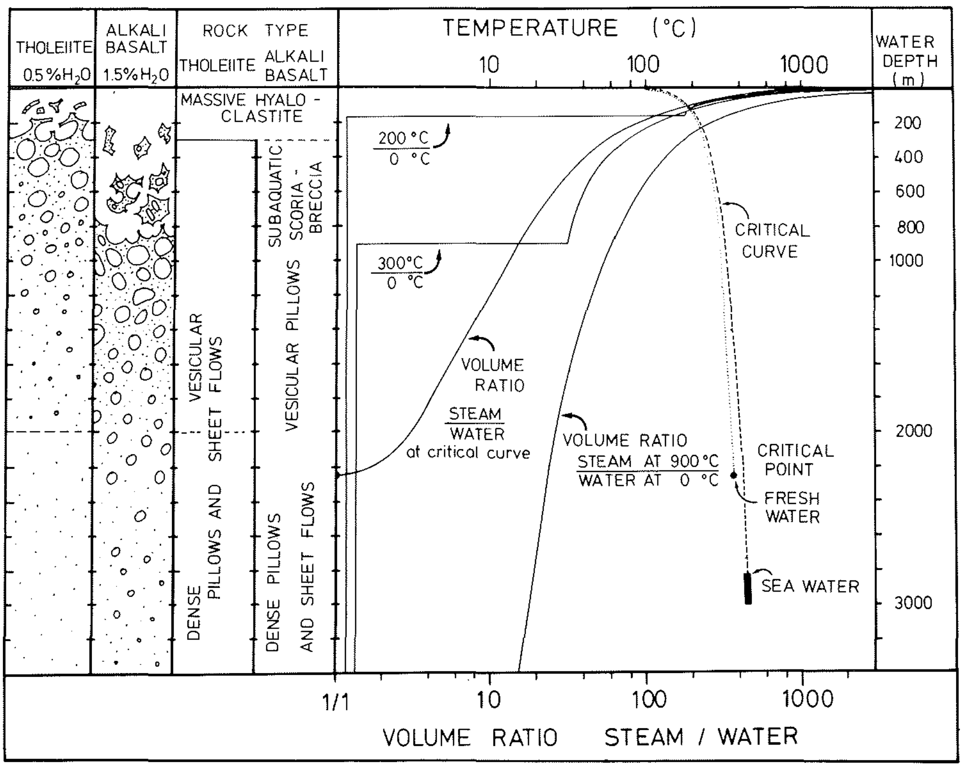

Fig. 11: A summary of physical data relevant to subaquatic eruptions. Data for the vesicularity of lavas with depths from MOORE (1965), water data from KENNEDY & HOLSER (1966), critical curve of water from Llandold Bernstein Tables. Critical Point of sea water from BISCHOFF & ROSENHAUER (1984). Curves labeled 0° C/200° C, 0° C/300° C, 0° C/900° C show volume increase of steam over water (bottom scale) for different degrees of heating (0° C to 200, 300, 900° C) and along the critical curve (from the critical temperature to 0° C) as a function of water depth. The temperature scale (top) relates only to the critical curves (for water and sea water). The temperature increase from 0° C to 200° C represents the most realistic case for subaquatic eruptions.

Abb. 11: Zusammenfassung von P-V-T Daten von Wasser und Salzwasser relevant für subaquatische Eruptionen. Daten über Pillowblasigkeit von MOORE (1965), Wasserdaten nach KENNEDY & HOLZER (1986). Kritische Kurve von reinem Wasser nach Llandold Bernstein Tabellen. Kritischer Punkt von Salzwasser (Meerwasser) von BISCHOFF & ROSENHAUER (1984). Die Kurven (0° C/200° C, 0° C/300° C, 0° C/900° C) stellen den Volumensprung zwischen Wasser und Dampf dar (untere Skala) für unterschiedliche Heizgrade (0° C bis 200, 300, 900° C) in Abhängigkeit der Wassertiefe. Der Temperaturanstieg auf 200° C ist für subaquatische Eruptionen vermutlich am realistischsten. Die Temperaturskala (oben) bezieht sich lediglich auf die kritischen Kurven (Wasser und Meerwasser).

MOORE 1965) (Fig. 11). Bulk steam explosivity will be unimportant (KOKELAAR 1986) and an explosive flashing into steam therefore is not to be expected. Build-up of a pillow pile towards shallower water depths will produce pillows with increasing vesicularity (JONES 1969; MOORE & SCHILLING 1973). However, the volatile fragmentation depth (VFD, FISHER & SCHMINCKE 1984), where disruption of magma by magmatic volatiles occurs (> 60 vol.-%, SPARKS 1978), is shallower than 200 m for a typical tholeiite. Fragmentation will be very efficient due to the large expansivity of the generated steam. For a given volume of water at 0° C that is heated to 200° C, the 0°/200° C volume change (of water over steam) shows a step function at around 200 m water depth due to the phase change at the critical curve (Fig. 11). Towards even shallower water depths, the steam shows a further exponential volume increase. The 200—300 m water depth thus appears to represent an important pressure threshold. Any water heated to 200° C or more at this and shallower depths will explosively flash into steam and cause further disruption of magmatic particles. This "depth of flashing" (DOF) appears to be especially critical for tholeiitic magmas because it coincides with disruption of magma caused by exsolution of juvenile gas. For tholeiitic magmas, we can expect a *rapid transition over a narrow depth range* (some 10 meters) from slightly vesicular pillows into fine-grained glass shards forming massive hyaloclastite deposits during subaquatic eruptions.

The situation may be quite different for more volatile-rich *alkali basalts* (water content 1.0—1.5%, some CO_2) as it probably applies to Shield Nunatak, vesicular pillows will form at water depths < 2000 m. At the volatile fragmentation depth (VFD, FISHER & SCHMINCKE 1984), somewhat deeper than the depth of flashing (DOF, i. e. > 200 m), more volatile rich lavas will tend to disintegrate into scoriaceous or (pumiceous) fragments and form subaquatic breccia flows. Any steam generated from water will *not* be orders of magnitude more voluminous at such depth. Abundant fine ash therefore is not expected and further fragmentation of scoria is dominated by cooling contraction (KOKELAAR 1986).

In contrast to tholeiitic magmas, there will be a gradational variation from brecciated scoria to fine-grained hyaloclastite as the DOF is approached towards shallower water levels for alkali basaltic magmas. Glass shards constituting these hyaloclastites will tend to be larger sized and more vesicular.

The general problems of emerging subaquatic eruptions into subaerial conditions have been studied during the activity of Surtsey (JACOBSSON & MOORE 1980) and have been discussed in great detail by KOKELAAR (1983, 1986).

The major difference between emerging subglacial and submarine eruptions is the lack of an extensive surrounding water body and resulting wave erosion. There also is a possibility of melt water draining (so-called Jökulhaups in Iceland) from and recurrent partial flooding of the system during subglacial eruptions. Therefore, transitions between subaquatic hyaloclastite formation and subaerial phreatomagmatic activity grading into magmatic eruptions may be more distinct and *recurrent* in subglacial volcanoes. This may be the reason for intercalations of subaerial and subaquatic deposits at Shield Nunatak.

It is further interesting to speculate that a steam-filled subglacial dome may have formed at Shield Nunatak by melting of the glacier from below which could have lead to "subaerial"-type steam and phreatomagmatic eruptions below ice. Such a situation is similar to conditions of eruption into a subaquatic steamfilled cupola described by KOKELAAR & DURANT (1983).

4.2 *Implications for paleo-ice thickness and age*

Subglacial volcanism at Shield Nunatak commenced with the formation of large volumes of poorly-sorted massive hyaloclastites, up to 200 m thick, on a gently dipping basement of distinctly older glacially eroded mugearite lava flows. Consideration of subaquatic eruption processes and the absence of pillow lavas at Shield Nunatak and subaerial deposits at around 200 m above present day sea level (i. e. 100—200 m above the pre-existing base) suggests, that Shield Nunatak lavas erupted under ice (water) cover less than about 200—300 m. Comparison with other subglacial and subaerial volcanoes in the Mt. Melbourne field supports this conclusion (WÖRNER & VIERECK 1987). Most of the centers exposed along two major ridges north of Cape Washington (Washington Ridge) and Oscar Point (Oscar Ridge) expose emergent subglacial/subaquatic sequences similar to those studied in more detail at Shield Nunatak. Glacial debris and features of glacial erosion are completely absent on top of these volcanoes and also at Shield Nunatak. Undissected surface exposures suggest that glaciation never advanced over these volcanic surfaces. Two observations indicate, that Shield Nunatak volcano still almost has its original shape and volume: a) collapsed cliffs and lava flows flowing into shallow water are exposed and most likely were deposited near the original margins of the volcano. b) almost vertical debris cliffs a few meters thick, wallpapered against a primary hyaloclastite cliff, represent gully-fill between the volcano and the surrounding ice. The eruption of Shield Nunatak was thus only followed by ice retreat and minor erosion around the margins.

SUIVERS et al. (1981) observed moraines related to the peak of the last glaciation ("Younger Drift", 0.021 to 0.017 m. y. ago) reaching an almost constant elevation of 360 m above present day sea level in the Terra Nova Bay area. Washington Ridge, 25 km to the east of Shield Nunatak (> 3 m. y., KREUTZER & WÖRNER, unpubl. data) has an elevation of over 400 m and thus should not have been affected on its top exposures by the "Younger drift". The ridge also shows steeply eroded cliffs on its seaward side and thus may be significantly older than Shield Nunatak and Oskar Ridge volcanoes. Shield Nunatak, however, reaches an elevation of only 300 m, yet it appears to be unaffected by the "Younger Drift". Two interpretations are possible: a) Shield Nunatak erupted through the most recent ice sheet and thus may be as young as 0.021—0.017 m. y. Alternatively b), Shield Nunatak sits on a recently down-faulted block. In this case it could be of somewhat older, however, unknown age.

5. CONCLUSIONS

1) Shield Nunatak is an example of shallow (< 300 m) subglacial to emergent volcanism of *alkali basaltic* lava compositions.

2) Lack of glacial erosion and detritus ontop of Shield Nunatak makes an eruptive age as young as 0.021—0.017 m. a. possible.

3) The temporal evolution of a typical subglacial volcano in an environment of shallow ice cover such as at Shield Nunatak is sketched in six stages in Fig. 11.

4) Observations made at Shield Nunatak to some extent also apply to emerging *submarine* alkali basaltic volcanoes. However, the recurrent change between formation of massive hyaloclastites and shallow water/subaerial phreatomagmatic deposits described here, represent the principal difference between submarine and subglacial volcanic sequences.

5) Volatile-poor (tholeiitic) and volatile-rich (alkaline basaltic) lavas will theoretically tend to show a quite different transition from deep to shallow water hydroclastic eruptions, tholeiites should show a rapid change from pillows to fine-grained hyaloclastite. Alkali-basalts, in contrast, should evolve with decreasing water depth from vesicular pillows through subaquatic scoria breccias into coarse-grained hyaloclastite breccias and ash-sized hyaloclastites (e. g. LaPalma seamount, STAUDIGEL & SCHMINCKE 1984).

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