Shallow-water, eruption-fed, mafic pyroclastic deposits along a Paleoproterozoic coastline: Kangerluluk volcano-sedimentary sequence, southeast Greenland

W.U. Mueller a,*, A.A. Garde b, H. Stendal b

a Sciences de la Terre, Université du Québec à Chicoutimi, 555, Blvd de l’Université, Chicoutimi, Québec, Canada G7H 2B1
b Geological Survey Denmark and Greenland, Thoravej 8, DK-2400 Copenhagen NV, Denmark

Abstract

The 200–300 m thick, volcano-sedimentary sequence at Kangerluluk is part of the psammitite zone, one of four major zones, which constitute the 1.8 Ga Ketilidian orogen in south Greenland. Three lithofacies are emphasized in the study: (1) the conglomerate-sandstone; (2) the volcanic; and (3) the pyroclastic lithofacies. The 2–40 m thick conglomerate-sandstone lithofacies represents a subaerial to subaqueous fan-delta deposit. Matrix- and clast-supported conglomerates are interpreted as debris flow and longitudinal gravel bar deposits. Erosive-based conglomerate channel fills attest to stream incision. Trough crossbedded sandstone, interpreted as lunate megaripples, planar-bedded sandstone indicative of upper flow regime bar-top sands, and small-scale trough crossbeds reflecting ripples follow up-section, form collectively with the conglomerate, 0.40–2.50 m thick fining-upward sequences. The sandstone-dominated unit, up-section from the conglomerates and composed of planar and low-angle crossbeds, minor ripples and graded beds as well as mudstone is indicative of a lower shoreface deposit below normal wave base. The clastic sedimentary rocks are suggestive of a fan-delta setting. The 100–200 m thick volcanic lithofacies, composed of pillowed and pillow brecciated lava flows, is consistent with shallow-water deposition. Interstratification of lava flows with both conglomerate-sandstone and pyroclastic lithofacies, intrusion of dykes into volcanioclastic rocks, and peperite formation accentuate contemporaneity between volcanism and sedimentation and is a common feature of island arcs. The 1–50 m thick, pyroclastic lithofacies with sharp depositional contacts to the overlying volcanic and underlying conglomerate-sandstone lithofacies, was emplaced in a subaqueous setting. The lithofacies is divided into a planar- to crossbedded tuff-lapilli tuff and a bedded lapilli tuff breccia, whereby both deposits are inferred to result from shallow-water surtseyan-type eruptions. The 5–15 m thick, bedded lapilli tuff breccia with abundant bomb sag structures and graded beds is considered a result of subaqueous eruptions strong enough to form an insulating steam cupola characterized by ballistically emplaced bombs that rapidly collapsed allowing for transport via mass flow processes. The deposits are considered proximal to the vent. The 2–50 cm thick, planar- to crossbedded tuff-lapilli tuff featuring abundant euhedral and broken crystals of feldspar (≤ 2 cm) and minor pyroxene (≤ 1 cm), are massive, graded, crossbedded and stratified. The planar but laterally discontinuous beds, characterized by abundant low-angle scours, are interpreted as low- to high-concentration sediment gravity flows produced directly from subaqueous
tephra jets that collapsed due to massive water ingestion. Local breccia-size pyroclasts disrupting beds are interpreted as bomb sags. The mafic, eruption-fed, Surtseyan-type deposits, postulated to be a subaqueous counterpart of cold, subaerial base surges, originate from subaqueous tuff cones formed along a rugged volcanic-dominated shoreline featuring high-energy fan-deltas. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Proterozoic; Greenland; Surtseyan eruptions; Pyroclastic; Subaqueous; Bounding lithofacies; Sedimentology; Volcaniclastic apron; Sediment gravity flows

1. Introduction

A significant component of emergent and submergent arc volcanoes is represented by tephra and reworked counterparts (Sigurdsson et al., 1980; Smoot, 1988; Bloomer et al., 1989). Recognizing primary pyroclastic deposits without heat retention structures in the subaqueous realm, still remains a highly contentious issue in both modern as well as ancient volcanic-volcaniclastic sequences (Cas and Wright, 1991). Pyroclastic debris is especially prominent on shoaling volcanic centres (Moore, 1985; Sohn, 1995; Fiske et al., 1998) or with coastal volcanic edifices (Kano, 1990; Cole and DeCelles, 1991) and complexes (Sewell et al., 1992) because of the constant interaction with sea water. Abundant tephra, derived from paroxysmal volcanic island eruptions in the form of airfall, surge and pyroclastic flow products, is deposited in adjacent basins, as documented in modern (Klein, 1985; Carey and Sigurdsson, 1984; Mandeville et al., 1996) and ancient settings (Lowman and Bloxam, 1981; Hanson and Schweikert, 1986; Houghton and Landis, 1989). Unconsolidated tephra is readily mobilized and transported in a subaerial environment (Suthern, 1985) by hyperconcentrated flood flows (White and Robinson, 1992) or is transported from shallow-water volcaniclastic aprons into deep water (Cole and Stanley, 1994) via cold-state, mass-flow processes (Cas, 1979; White and Busby-Spera, 1987).

Abundant pyroclastic debris is retained on volcaniclastic aprons surrounding volcanoes (Fisher and Schmincke, 1984; p. 276; Suthern, 1985; Orton, 1995), as documented on the Lesser Antilles arc islands of Dominica (Whitham, 1989) and during the 1996–1997 eruptions on Montserrat (Montserrat Volcano Observatory Team, 1997). Volcaniclastic aprons are therefore an ideal locus to elucidate the dynamics of effusive volcanic (Busby-Spera, 1987) and pyroclastic processes (Mandeville et al., 1996). These dynamics are especially crucial at the air-water interface because transport processes and the ambient medium change. Sedimentologically, subaerial fluvial or braided stream systems, affected by traction-currents, yield to marine wave- storm- and/or tide-induced processes. Similarly, volcaniclastic deposits are considerably affected at the coastal air-water interface. Pyroclastic flows generally disintegrate at the shoreline because phreatic explosions occur upon contact with water (Cas and Wright, 1991), but if pyroclastic flows continue in a subaqueous milieu and are not disrupted, they transform from hot gas- to cold water-supported products (Cas and Wright, 1987; p. 283). In contrast, Sparks et al. (1980) and Mandeville et al. (1996) contend that pyroclastic flows entering the sea can maintain their physical integrity. Identification of ancient subaqueous pyroclastic flows with welding and eutaxitic textures deposited at moderate depths (> 150 m; Kokelaar and Busby, 1992), well below normal wave-base (Schneider et al., 1992), or below storm wave-base (Fritz and Stillman, 1996; White and McPhie, 1997), indicate unequivocally that hot pyroclastic flows develop in a subaqueous setting. Non-welded products are still difficult to identify.

The Kangerluluk study area in southeast Greenland displays subaqueous eruption-fed, mafic rocks of pyroclastic origin deposited along a Paleoproterozoic shoreline. The volcaniclastic rocks may have originated from shallow-water or subaerial eruptions or even be syneruptive re-
worked pyroclastic deposits. A twofold approach is conducted to elucidate the deposits along the Kangerluluk Fjord: (1) documentation of the bounding facies to constrain the depositional environment; and (2) proper identification of pyroclastic rocks, including textural components and sedimentary structures. Modern and ancient pyroclastic deposits at the air-water interface or in high-energy, nearshore volcanic settings have a low preservation potential so that documenting non-welded pyroclastic deposits in such a dynamic environment is novel.

2. Geology, stratigraphy and terminology

2.1. Regional geology

The southern tip of Greenland (Fig. 1) is a complex 1.8 Ga Paleoproterozoic mobile belt referred to as the Ketilidian Orogen (Allaart, 1976). Extensive field mapping (1992–1996) by the Geological Survey of Greenland and Denmark (GEUS) enabled reinterpretation of the Ketilidian event. The principal divisions, as recommended by Garde and Schønwandt (1995), Chadwick and

Fig. 1. Location of the Kangerluluk volcano-sedimentary sequence and principal divisions of the Ketilidian Orogen (adapted from Garde and Schønwandt, 1995) in southern Greenland. Most of the orogen is concealed by Inland Ice which is not shown on figure.
Garde (1996) and Garde et al. (1998), are: (1) an Archean foreland composed of high-grade gneisses serving as a basement to the volcano-sedimentary successions of the Paleoproterozoic; (2) an Archean border zone affected by the Ketilidian orogen; (3) a magmatic arc represented by the 30,000 km² polyphase, calc-alkaline Julianehåb batholith and numerous volcano-sedimentary sequences; (4) a psammite zone composed of highly deformed and commonly migmatized, clastic sedimentary and local volcanic rocks; and (5) a pelite zone with highly deformed and migmatized turbidite-dominated sedimentary rocks. Recognition of distinct divisions enabled Chadwick and Garde (1996) to propose a new coherent geodynamic model: a magmatic arc with an extensive forearc. Large rafts of volcano-sedimentary successions, commonly preserved as keels in magmatic arcs and dissected synvolcanic plutons, are observed in the polyphase Julianehåb batholith. Structural and lithotectonic studies of the orogen (Chadwick et al., 1994; Chadwick and Garde, 1996; Garde et al., 1997), as well as local volcanology (this study), massive sulfide stringer mineralization (chalcopyrite-epidote-garnet of Stendal et al., 1997; Stendal, 1997) and an arc-related geochemistry of the Kangerluluk volcanic and plutonic rocks (Mueller and Dostal, unpublished data) support a proposed mature ocean or continental arc-type setting. The study area, located near the contact of the Julianehåb batholith with the psammite zone (Fig. 1), represents the transition from magmatic arc to forearc. Regional mapping indicates that remnant volcanic sequences are preserved near this interface. Abundant intrusions of younger plutonic suites characterize the psammite and pelite zones.

The 4 km² remnant supracrustal sequence (Fig. 2), initially evaluated for its mineral potential (Stendal et al., 1997; Stendal, 1997), is a preserved dissected volcanic arc segment. Probable on-strike equivalents of the study area are exposed in vertical section at ‘Sorte Nunatuk’ (Fig. 1). The volcano-sedimentary succession at Kangerluluk is in sharp contact with the polyphase Julianehåb batholith (Fig. 3a), which can be either depositional or faulted. Conformable, unconformable, and faulted contacts, common to dynamic arc settings (Mueller et al., 1989), occur contemporaneously in regions with significant basin subsidence, volcano-tectonic uplift and abundant synvolcanic faults.

Mapping and related facies analysis was conducted at a scale of 1:2500 with selected stratigraphic sections mapped in detail at 1:20. The generally shallow (15–50°), northwest-dipping, NE-SW trending sequence youngs towards the NW and is folded into small tight folds that are locally overturned (Fig. 2). Fold hinges are m-scale and asymmetric with a subhorizontal long limb facing NW and a vertical to overturned short limb. Detailed facies analyses are facilitated in prominent flat-lying beds because of numerous fault scarps transecting the strata. The amphibolite grade of metamorphism destroyed delicate primary pyroclastic textures such as tuff-size, scoria or vitric ash, but primary sedimentary features in pyroclastic and sedimentary units, such as crystals, amygdules, or bedding styles, as well as lava flow forms, are easily recognized. Eriksson et al. (1988) demonstrated that sedimentary rocks, even under regional high-grade metamorphic conditions without penetrative deformation fabrics or shear zone influence, are valid for detailed facies analysis. The prefix ‘meta’ is omitted to simplify rock description.

2.2. Kangerluluk volcano-sedimentary sequence

The 200–300 m thick volcano-sedimentary succession at Kangerluluk (Fig. 2) is the best exposed and accessible volcano-sedimentary succession along the east Greenland coast. Four principal lithofacies, defined by textures, sedimentary structures, composition, and contact relationships, are recognized: (1) a 2–40 m thick conglomerate-sandstone lithofacies; (2) a 1–50 m thick pyroclastic lithofacies; (3) a 2–100 m thick volcanic lithofacies; and (4) a 1–30 m thick peperite lithofacies. The first three lithofacies define the depositional setting and are considered in detail, whereas the peperite lithofacies is briefly discussed with respect to contact relationships. Dykes intruding the sequence are (i) contemporaneous with volcanism; and (ii) related to folding and late faulting.

The composite stratigraphy (Fig. 4) reveals a lower conglomerate-sandstone lithofacies interstratified with pillowed flows and intruded by numerous dykes. Conglomerate strata constitute
Fig. 2. Geology of the Kangerluluk volcano-sedimentary sequence with four identified lithofacies, a batholith phase and various sills. The feldspar-pyroxene sill/dykes are coeval with the volcano-sedimentary sequence, whereas the feldspar-magnetite sill is related to the deformation phase. A, B and C indicate sections mapped in detail (1:20).
Fig. 3. Contact relationships between lithofacies and characteristics of synvolcanic dykes. Large arrow indicates top in all photographs. (A) Contact between Kangerluluk (KL) sequence and Julianehåb batholith (JB). Scale, 120 m between three arrows. (B) Sharp depositional contact between pillowed to pillow breccia units of the volcanic lithofacies (VL) and crystal rich graded beds of the pyroclastic lithofacies (PL). A locally inverse-graded, felsic volcanic breccia (Vbx) is observed. Scale, pen 15 cm. (C) Sharp depositional contact between pillows (P) and pillow breccia, and pyroclastic lithofacies (PL). Volcanic breccia (Vbx) of pyroclastic lithofacies is used as a marker horizon. Scale pen, 17 cm (arrow). (D) Highly irregular contact (arrows) between peperite (Pe) and pyroclastic lithofacies. Scale, field book 17 cm (small arrow). (E) Irregular-shaped fragment of the pyroclastic lithofacies interacting with magma (M) producing a peperite. A well-defined altered margin (AM) is observed around pyroclastic fragment (pf). Scale, pen 15 cm. (F) Grey, feldspar-phyric dyke (D) locally intruding parallel (arrows) to pyroclastic lithofacies (PL). Scale pen, 17 cm (next to D). (G) Grey, amygdale-rich, feldspar-phyric dyke (D) with well-defined chilled margins cross-cutting the pyroclastic lithofacies which is composed of laminated (L) and graded beds (gb), as well as crossbeds (cb). Scale, pen 17 cm (arrow). (H) Grey, feldspar-phyric dyke (D) intruding pillow breccia (Pbx) which is interstratified with the pyroclastic lithofacies (see Fig. 2). Scale, field book 17 cm (arrow).

the base, whereas sandstone is prevalent up-section. A zone of high strain generally masks the basal pluton-conglomerate contact but a local erosional contact can be inferred. Similarly, faulting with sulfide mineralization and folding characterize the upper contact between the conglomerate-sandstone lithofacies and pyroclastic or volcanic lithofacies, but a sharp depositional contact is observed at several localities.

The pyroclastic lithofacies is prominent in the central part of the Kangerluluk area (Fig. 2) and exhibits a sharp depositional contact with the overlying pillowed and pillow breccia flows of the volcanic lithofacies (Fig. 3b, c) as well as a sharp but highly irregular contact with the peperite lithofacies (Fig. 3d, e). An inverse graded volcanic breccia composed of felsic angular to subrounded clasts in the mafic pyroclastic lithofacies (Fig. 3b, c), just below the depositional contact with the volcanic lithofacies, serves as a marker
horizon facilitating reconstruction of the stratigraphy.

The volcanic lithofacies (Fig. 4), containing feldspar-phyric and feldspar-pyroxene-phyric flows, constitutes the principal component of the remnant Kangerluluk supracrustal sequence. Both flow types are phenocryst-rich and mafic, with SiO₂ ranging from 45–50% (Mueller and Dostal, unpublished data). Pervasive synvolcanic hydrothermal alteration composed primarily of epidote with subordinate garnet and sulfide mineralization (Stendal, 1997) characterizes the pillowed and pillow breccia flow units.

The 30 m thick peperite lithofacies (Figs. 2 and 3d, e) is an unusual combination of unconsolidated pyroclastic deposits interacting with mafic dykes. The water-saturated pyroclastic sedimentary clasts, ranging from cm- to decimeter-scale and irregular or amoeboid in form, display highly altered rims due to the interaction with magma (Fig. 3e). The mixing of magma and sediments producing peperites is common to volcanic arcs and arc-related settings (Busby-Spera and White, 1987), in which sedimentation and magmatism is coeval (Klein, 1985).

Dykes attest to a complex intrusive sequence of this magmatic arc. Grey feldspar-phyric dykes were injected into the wet, unconsolidated pyroclastic lithofacies (Fig. 3f, g) or intrude pyroclastic breccia (Fig. 3h). Well-defined chilled margins with an abundance of amygdules (and weathered out amygdules) characterize both the grey, mafic, feldspar-phyric dykes (Fig. 3f, g) and black pyroxene-phyric dykes (Fig. 2). The feldspar-pyroxene-phyric dykes or sills are compositionally similar to the mafic lava flows, suggesting contemporaneity. The prominent feldspar-magnetite dykes/sills (Fig. 2) of andesitic composition (Mueller and Dostal, unpublished data) are emplaced late during deformation of the supracrustal sequence. Late aplitic and appinite dykes cut the supracrustal sequence, and the Julianehåb batholith (Fig. 2).
2.3. Terminology of volcaniclastic rocks

Rocks containing fragmental volcanic material irrespective of their origin, environment or proportion are referred to as volcaniclastic deposits (Bates and Jackson, 1987, p. 715), as initially proposed by Fisher (1961). Generally, it is used to imply that the volcanic component is prominent. ‘Volcaniclastic’ is therefore an umbrella term for pyroclastic (hydroclastic), autoclastic or epiclastic rocks, but differentiating between the three in the ancient rock record remains problematic. Depending on the school of thought, unconsolidated, but remobilized pyroclastic debris may be considered either epiclastic or pyroclastic so that a major problem in semantics may arise (see review by Orton, 1996; p. 526–528). The volcanic rock classification can be based on: (i) the grain size and constituents of volcanic origin (Fisher, 1961, 1966), or (ii) the primary volcanic process with respect to eruption or fragmentation mechanism as well as transport medium (Cas and Wright, 1987, p. 34, 1991; McPhie et al., 1993). Herein lies the major point of contention. The nomenclature problem is especially evident for pyroclastic debris or tephra deposited in the subaqueous realm. Pyroclastic, hydroclastic, autoclastic and epiclastic processes represent fragmentation mechanisms producing particles of all sizes. Transport agents such as wind and water cannot for example trans-
form the initial origin of the particle from pyroclastic to epiclastic (Fisher and Schmincke, 1984, p. 89; Fisher and Smith, 1991). Consequently, remobilized unconsolidated pyroclastic debris transported downstream via mass or stream flow processes or transported via sediment gravity flows in a subaqueous setting with preserved pyroclastic components may be referred to as pyroclastic in origin.

Recognition of pyroclastic debris in extensively deformed and altered modern and ancient rocks is difficult because delicate volcanic textures and sedimentary bedforms are destroyed. Pumice shreds, vitric shards, broken or euhedral crystals, and vesicular to non-vesicular, angular lithic fragments (Fisher and Schmincke, 1984; p. 89–90; Stix, 1991) are constituents consistent with a pyroclastic origin. Individual constituents are diagnostic of numerous types of eruption. Autoclastic flows may have components similar to pyroclastic deposits and their reworked equivalents so that associated lithofacies are important in final assessment of the deposit. The term pyroclast is now defined as a fragment produced as a ‘direct result of volcanic action’ rather than ‘generated by disruption during volcanic eruptions’ (Schmid, 1981). The change in definition has far reaching implications: pyroclasts may also be formed by non-explosive thermal granulation. Hydroclastic fragments derived either from hydroexplosions (Fisher and Schmincke, 1984, p. 231) or hydrovolcanic (Wohletz, 1983) eruptions are considered a ‘variety of pyroclast formed by steam explosions at magma-water interfaces, and also by rapid chilling and mechanical granulation of lava that comes in contact with water or water-saturated sediments’ (Fisher and Schmincke, 1984, p. 89). The term hyaloclastite becomes equivocal because glassy fragments can be produced during auto-brecciation or by thermal granulation due to interaction of lava with water. Fragments produced by thermal granulation processes and generating hyaloclastite deposits represent a type of pyroclast according to the definition of Schmid (1981). Phreatic, phreatomagmatic, submarine, and littoral explosions are four distinct categories of hydroclastic eruptions (Fisher and Schmincke, 1984, p. 233) that produce pyroclasts.

The standard granulometric classification scheme of Fisher (1961, 1966) for indurated pyroclastic rocks associated with explosive and non-explosive fragmentation processes is employed in this study because it is more appropriate for Precambrian rocks: (1) tuff, <2 mm; (2) lapilli, 2–64 mm; and (3) block or breccia, >64 mm. Volcanic breccia (clasts >2 mm) and volcanic sandstone (grain size <2 mm) are general terms referring to all volcanic rocks composed predominantly of lithic fragments (Fisher and Schmincke, 1984; p. 92; Cas and Wright, 1987; p. 356, 360; McPhie et al., 1993). If the origin is evident and/or contact relationships between coherent lava flows and brecciated counterparts are observed, genetic terms such as hyaloclastite breccia, lobe-hyaloclastite breccia, flow breccia, pillow breccia, or flow-top breccia, indicating autoclastic fragmentation processes, are employed.

3. Bounding lithofacies

The depositional setting of pyroclastic deposits in many stratigraphic successions is problematic, so that it becomes imperative to properly define the bounding volcanic or sedimentary facies (Cas and Wright, 1987; p. 270; Fritz and Howells, 1991). In contrast to many stratigraphic successions, a complete but complicated stratigraphy is observed for the Kangerluluk volcano-sedimentary sequence. The depositional setting of the pyroclastic lithofacies is constrained by the bounding conglomerate-sandstone and volcanic lithofacies.

3.1. Conglomerate-sandstone lithofacies

The 2–40 m thick conglomerate-sandstone lithofacies (Fig. 4; Table 1) is divided into a basal conglomerate-dominated and upper sandstone unit (Fig. 5a, b). Approximately 60% of the lithofacies is composed of 0.8–2 m thick matrix- and 0.2–1 m thick clast-supported, conglomerate beds (Fig. 6a). Sandstone is prevalent at the interface with the pyroclastic lithofacies. Matrix-supported conglomerates are massive and disorganized with local outsized 1.1 × 0.8 m large boulders (Fig.
<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Facies, structure, characteristics</th>
<th>Origin, process, deposit</th>
<th>Setting, locus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Volcanic</strong></td>
<td>Dominant mafic pillowed and pillow breccia flows with minor massive flow units; amygdale content highly variable (0–30%); amygdules common in pillow flows</td>
<td>Calm effusive lava flow with brecciation caused by flow velocity exceeding internal yield strength of laminar viscous flow</td>
<td>Lava flows on subaqueous part of volcaniclastic apron; dissected arc milieu</td>
</tr>
<tr>
<td>Thickness: 100–200 m</td>
<td></td>
<td>Abundance of phenocrysts suggests viscous flow</td>
<td>A shallow water depth is assumed based on bounding facies (&lt;100 m depth)</td>
</tr>
<tr>
<td>Interstratified with pyroclastic and conglomerate-sandstone lithofacies</td>
<td>Flows are: (i) feldspar; and (ii) feldspar-pyroxene-phyric</td>
<td>Prominence of pillows is consistent with small volume flows and low effusion rates</td>
<td>Pillow flows and stratigraphic succession indicate rapid drowning of volcaniclastic apron</td>
</tr>
<tr>
<td><strong>Pyroclastic</strong></td>
<td>a) Laterally discontinuous 10–50 cm thick planar to wavy bedforms with abundant euhedral and broken feldspar and minor pyroxene crystals; angular lithic volcanic clasts subordinate</td>
<td>Pyroclastic deposits resulting from subaqueous Surtseyan-type eruptions; tephra jets creating steam envelope with rapid collapse due to water ingestion</td>
<td>Shallow-water volcaniclastic apron between lower shoreface and proximal offshore; below normal wavebase; probable depths 10–40 m</td>
</tr>
<tr>
<td>Thickness: 1–50 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interstratified with volcanic lithofacies</td>
<td>Beds are normal (S₁- bed) to rarely inverse graded (S₁⁻ bed)</td>
<td>Subaqueous sediment gravity flows with erosive power forming S₁⁻, S₂ and S₂⁻ beds; S₂⁻ beds, rapid fallout from pyroclastic suspension cloud; S₂⁻beds, traction carpet deposits with internal shear stress producing dispersive pressure; S₃⁻beds, planar beds or crossbeds from unsteady high-to low-concentration turbulent flows. Deposits strikingly similar to base surges but not gas-supported; deposition under cold water-laden conditions</td>
<td>Pyroclastic deposits associated with submergent tuff cones along a Paleoproterozoic shoreline of a dissected arc volcano</td>
</tr>
<tr>
<td>a) Planar- to crossbedded tuff-lapilli tuff (1–30 m thick)</td>
<td>Principal bedforms: planar- to crossbedded with abundant low-angle or channels-shaped scours; internal stratification and fine-laminations with grading common; lateral change over 0.5–2 m from planar beds to low-angle crossbeds grading back into planar beds (S₂⁻ bed) Angular to subangular lapilli- and breccia-size pyroclasts disrupt bedforms, and cause synsedimentary deformation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 1 (Continued)

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Facies, structure, characteristics</th>
<th>Origin, process, deposit</th>
<th>Setting, locus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>b) Bedded lapilli tuff breccia</strong>&lt;br&gt;(5–15 m thick)</td>
<td>b) Laterally discontinuous 10–60 cm thick planar to slightly wavy beds; massive to graded beds rich in 0.3–2 cm size euhedral to broken feldspar and minor pyroxene crystals Round pyroclasts (locally vesicular) disrupt fine-grained tuff beds; tuff beds mold around clast Complete bed: basal subunit with round pyroclasts and feldspars grading upward into massive to faintly laminated coarse-and fine-grained tuff</td>
<td>Pyroclastic deposits resulting from subaqueous Surtseyan-type eruptions; pyroclasts disrupting beds considered bomb sag structures Graded beds represent high-to low-particle sediment gravity flows ($S_t$) beds Eruption produces steam cupola permitting deposition of ballistic ejecta.; collapse of steam envelope due to water ingestion resulting in subsequent mass flow deposition</td>
<td>Shallow-water volcaniclastic apron between lower shoreface and proximal offshore; below normal wavebase; probable depths 10–40 m Deposits associated with submergent tuff cones along a Paleoproterozoic shoreline of a dissected arc volcano</td>
</tr>
</tbody>
</table>

| **Conglomerate-Sandstone** | a) Facies sequence<br>Thickness: 2–40 m<br>Interstratified with pillowled and pillow breccia flows of the volcanic lithofacies<br>a) Conglomerate-dominated unit<br>(2–30 m thick)<br>b) Sandstone unit (1–10 m thick) | Bedforms in facies sequence the result of fluvial transport during high- to low-energy flood discharge: Gms, mass or debris flow; Gm, sheet gravel or longitudinal gravel bar; Gt, high-energy channel fill; St, matrix-supported conglomerate; Gm, massive to crudely stratified clast-supported conglomerate; Gt, massive to stratified conglomerate-filled troughs; St, isolated or trough crossbedded sandstone in cosets; Sh, planar bedded sandstone; Sr, small-scale trough crossbeds; Fl, laminated mudstone, siltstone or fine-grained sandstone | Volcaniclastic apron: subaerial portion of fan-delta around dissected arc volcano |

| **Conglomerate-Sandstone** | | Prevalent sand grain size indicates lower energy conditions; wave-dominated bedforms with sporadic storm and/or stream controlled processes. Low energy wave-induced dunes and ripples Wave-induced sheet sands from high wave surge or storms Wave-induced bottom currents with prominent suspension sedimentation | Volcaniclastic apron: subaqueous portion of fan-delta and proximal offshore influenced by wave, flood and storm activity Shoreface setting of fan-delta Lower shoreface setting of fan-delta; below normal wavebase Lower shoreface to proximal offshore setting; below normal wavebase |
Fig. 5. Stratigraphic sections of the Kangerluluk volcano-sedimentary sequence. See Fig. 2 for locations. (A) Coarse clastic sedimentary sequence composed of conglomerate and sandstone. Sedimentary facies code of Miall (1978, 1992) indicated by Gms, Gm, St, Sh, Sr, and Fl is employed. See text and Table 1 for explanations. Detailed sections exhibit 50–250 cm thick, fining-upward sequences. (B) Coarse clastic sedimentary sequence in abrupt depositional contact with fine-to-coarse-grained tuff of the pyroclastic lithofacies. Fining-upward sequences, 20–150 cm thick, characterize to the basal part of the section.
5a, Fig. 6a) randomly dispersed. In contrast, the clast-supported conglomerate beds, containing smaller clasts, are massive to stratified and in some places display a channel-shape and basal scour (Fig. 6b). Erosive contacts are ubiquitous with conglomerate commonly incising into the underlying sandstone (Fig. 5a; at 4 m). Stratification is best developed in the channel-shaped beds, where single pebble trains develop preferentially on high-angle foresets of tangential crossbeds (Fig. 6c). Angular to rounded plutonic and volcanic clasts of pebble to boulder size are prominent. Locally, smaller clasts aggregate behind larger boulders. Small- (Fig. 6d) to medium-scale trough crossbeds, 10–50 cm thick (Fig. 6e), and 5–30 cm thick planar sandstones (Fig. 6d), collectively 10–100 cm thick and generally occurring as cosets, are interstratified with the conglomerates. Minor parallel laminated, very-fined grained sandstone to mudstone caps the 0.4–2.5 m thick, conglomerate-sandstone (Fig. 5a, b).

Fig. 6. Characteristics of the conglomerate-sandstone and volcanic lithofacies. Large arrow indicates top in all photographs. (A) Matrix-supported conglomerate (facies Gms) overlain by a series of trough crossbedded sandstone (St) and clast-supported conglomerate (Gm). Three fining-upward sequences (see Fig. 5a at 1–5 m). Scale, field book 17 cm (arrow). (B) A well-developed fining-upward sequence commencing with facies Gt followed by cosets of trough crossbedded sandstones, locally pebbly (facies St), interstratified with planar beds (facies Sh) and small-scale trough crossbeds (facies Sr, indicated by pen). Channeled bedform with an erosive base indicates facies Gt. Scale, pen 17 cm. (C) Pebble trains (Pt) on foresets of trough crossbeds (facies Gt), followed up-section by facies St. Scale, pen 17 cm. (D) Small-scale trough crossbeds erode planar beds (facies Sh). Scale, pen 17 cm. (E) Medium-scale trough crossbedded sandstone (facies St) and trough crossbedded pebble conglomerate (facies Gt). Scale, pen 15 cm. (F) Planar-bedded (laminated) sandstone truncated by low-angle planar-bedded sandstone (Pcb). Note ripples (r) capping planar beds (Pb). Scale, pen 15 cm. (G) Feldspar (white)-pyroxene (dark)-phyric pillow with concentric flow-oriented phenocrysts. Scale, coin 1.8 cm in diameter. (H) Feldspar-phyric pillowled flows with cm-thick chilled margins overlain by graded bedded pyroclastic deposits. Scale, clipboard 35 cm (arrow).
The sandstone unit is composed of very fine-to very coarse-grained sandstone, 5–20 cm thick, with discontinuous pebble lags developed at the base of thicker sandstone beds (Fig. 5b). The presence of quartz and plutonic grains, as well as an absence of euhedral pyroxene crystals and light grey weathering colour distinguish the sandstones from the dark grey to black weathering pyroclastic lithofacies. Small- to medium-scale trough crossbeds and planar beds, 2–30 cm thick, and ripples characterize the facies. Collectively, these bedforms develop 0.2–1 m thick fining-upward sequences. Medium to very fine-grained sandstone beds featuring parallel laminated bedforms to low-angle planar beds, low-angle trough cross-beds, local ripples, and minor mudstone beds are common in proximity to the pyroclastic lithofacies (Fig. 5b; 7–11 m). Beds are locally poorly graded.

3.2. Hydrodynamic process and setting

The conglomerate-sandstone lithofacies (Fig. 5a, b) is characteristic of coarse clastic, streamflow and mass flow processes on alluvial fans (Galloway and Hobday, 1983; Mack and Rasmussen, 1984) or fan-deltas (McPherson et al., 1987; Horton and Schmitt, 1996). A submarine fan setting with in-channel products could be a possibility, but is discounted because of (1) the prominence of traction-current to wave-induced structures; (2) lack of graded turbidite beds; (3) absence of shale interbeds or Bouma T<sub>de</sub> or T<sub>e</sub> sequences common to submarine channels; (4) characteristic fluvial fining-upward cycles; (5) the overall lithofacies association, and (6) the unconformable contact with an arc batholith. The facies code of Miall (1978, 1992; see Table 1) is employed, but as pointed out by Collinson (1996), p.61), the code should be used with caution. Mas-
sive matrix-supported conglomerate beds with outsized boulders (facies Gms) are considered cohesive mass flow deposits (Schulz, 1984; Nemec and Postma, 1993). The massive clast-supported conglomerates (facies Gm) with erosive bases are interpreted as high-energy, traction-current structures, representing either coalescing sheetflood gravel deposits (Ballance, 1984; Nocita and Lowe, 1990) or longitudinal gravel bars (Eriksson, 1978). Trough crossbedded conglomerates, characterized by channelized bedforms and pebble lags alternating with sandstone on foresets, are bedload structures in a traction current-dominated flow regime and are interpreted as in-channel gravel bars (fa-

Fig. 7. Detailed stratigraphic section of the planar to crossbedded tuff-lapilli tuff unit (column C in Fig. 2) in the Kangerluluk volcano-sedimentary sequence. The upper sharp contact with the pillowed and pillow breccia flows constrains the depositional setting of the pyroclastic lithofacies. Numerous synvolcanic dykes with chilled margins, and abundant amygdules and vesicles intrude the pyroclastic sequence.
cies Gt). Pebble avalanching on foresets is attributed to fluctuating flow energy conditions, a common feature in alluvial systems during flooding. Clast angularity in conglomerate, the result of limited transport distance, and concentration of clasts in pockets behind larger boulders or cobbles, support bedload processes with diminishing flow energy conditions (Mueller and Dimroth, 1987). Planar-bedded sandstone (facies Sh) overlying conglomerate (facies Gt) is indicative of migrating in-channel lunate megaripples (Eriksson, 1978). Small-scale trough crossbeds (facies Sr) are considered low-energy dunes that developed during waning flood conditions. Pebble lags (facies Gm) are commonly found at the base of trough crossbeds, indicating the beginning of fining-upward cycles (Fig. 5b). Laminated fines (facies Fl) indicate waning energy conditions characteristic of overbank or residual flood suspension deposits.

The sandstone unit represents a lower energy regime than the conglomerates and interstratification with pillow and pillow breccia indicates a subaqueous setting (Fig. 2; close to section B). Minor pebble trains and trough crossbeds is suggestive bedload-dominated processes possibly reflecting either fluvial (Orton, 1995) or storm influence (Mueller and Dimroth, 1987). Thin-bedded, planar and low-angle planar beds are considered bedforms influenced by wave-action and a beachface to foreshore setting may be envisaged, but local interstratified mudstone and fine-grained sandstone favours a lower shoreface setting (Reinson, 1984) just below normal wave base. Lower shoreface deposits feature the characteristics of suspension and wave-induced sedimentation (Reinson, 1984). Planar beds with local ripples may be high concentration subaqueoussheetflood deposits (Dam and Andreasan, 1990), a counterpart of fluvial sheetfloods before entering the sea (Orton, 1995). Parallel laminated beds are common to marine-influenced shorefaces with high wave surge or storm activity (Tunbridge, 1983). Local rippled horizons are considered a product of high wave surge or waning storm activity.

The conglomerate-sandstone lithofacies is interpreted as a fan-delta along a high-energy, rugged, volcanic-dominated shoreline. Metre-scale fining-upward cycles (Fig. 5a, b) represent a succession of bedforms interpreted as the response to autocyclic flood sequences. A complete facies sequence of $\pm Gms + Gm + Gt + St + Sh + Sr + Fl$ is typical of alluvial fans (Rust and Koster, 1984) or subaerial parts of fan-deltas (Orton and Reading, 1993; Horton and Schmitt, 1996). A rapid decrease in grain size and prevalence of sandstone units occupy the subaqueous portion of the fan-deltas resulting in the formation of low gradient fan-delta fronts (Orton and Reading, 1993). The sandstone unit represents the subaqueous segment of the fan-delta system below normal wave base and Collinson (1996) suggests that conglomerate and pebble lag deposits are still an integral component. In this study, the decrease of fining-upward sequences and the prominence of fine-grained sandstone support the change from subaerial to subaqueous setting (Fig. 5b).

### 3.3. Volcanic lithofacies

The 100–200 m thick volcanic lithofacies (Figs. 1 and 2) is composed of two phenocryst-rich lava flow units that are divided into (i) feldspar-phyric flows with up to 5% pyroxene; and (ii) feldspar-pyroxene-phyric flows (Fig. 6g). Plagioclase, 0.5–3 cm size and pyroxene 0.2–2 cm size, constitute between 20–50% of the flows (Fig. 6g). The feldspar-phyric flows are prominent at the base of the volcanic lithofacies and are locally interstratified with the pyroclastic lithofacies. Three flow morphologies including pillowed, pillow breccia and massive, were recognized. Mafic flows (Fig. 6h) contain pillows ranging between 0.2–3 m in diameter (av. 60–80 cm). The abundance of cm- to mm-scale quartz and/or calcite amygdules, which are commonly weathered out, leaving voids similar to vesicles, are observed in feldspar-phyric flows and are minor in the feldspar-pyroxene-phyric flows. Interpillow hyaloclastite debris is subordinate in both types. Flow orientation of phenocrysts is especially well developed in the pillowed facies (Fig. 6g). Rare massive flows, up to 5 m thick, grade up-section and laterally into pillowed units, which in turn change into pillowed breccia. Pillow breccia (Fig. 3b), up to 10 m thick,
is readily recognized by pillowed fragments and complete pillows set in a hyaloclastite matrix now altered pervasively to epidote. Pillow breccias are generally disorganized and massive, but locally a crude low-angle stratification is discernible. Up-section, the pillowed unit becomes more prominent whereas the brecciated flows and massive flows disappear.

3.4. Volcanic process and setting

The volcanic lithofacies represents primary lava flows deposited in a subaqueous setting (Macdonald, 1972; Williams and Mc Birney, 1979) whereby a shallow-water setting is implied because of the close association with the conglomerate-sandstone lithofacies. Prominence of pillowed and pillow breccia flows suggests limited flow volume and reduced extrusion rates. High phenocryst content is consistent with viscous lava flow (Macdonald, 1972; Gill, 1981) and local abundance of amygdules in flows indicate an elevated gas content. Pillow breccias and associated hyaloclastites are considered the result of autobrecciation with water-lava interaction generating thermal granulation products or small littoral eruptions when entering the sea (Fisher and Schmincke, 1984; p. 233). The massive to disorganized pillow breccias formed during autobrecciation with little or no reworking, whereas the locally stratified counterparts are considered remobilized debris at the front or margin of the flow (Dimroth et al., 1978; McPhie et al., 1993). Collectively, these deposits may be referred to as pillow-fragment breccias (Fisher and Schmincke, 1984; p. 270) and are commonly constrained to shallower water depths (Staudigel and Schmincke, 1984). The lateral and vertical change of flow morphology, massive to pillowed to pillow breccia followed by massive to stratified hyaloclastite breccia is characteristic of subaqueous mafic flows (Dimroth et al., 1978; McPhie et al., 1993).

4. Pyroclastic lithofacies

The pyroclastic lithofacies (Fig. 2), up to 50 m thick, is located between the lower shoreface sandstones of conglomerate-sandstone lithofacies and the pillowed flows of the volcanic lithofacies (Fig. 4), so that a subaqueous emplacement of the pyroclastic lithofacies is convincing. Two distinct depositional units, based on sedimentary characteristics and grain-size, were recognized and include: (i) planar- to crossbedded tuff-lapilli tuff; and (ii) bedded lapilli tuff breccia.

4.1. Planar- to crossbedded tuff-lapilli tuff

The 1–30 m thick planar- to crossbedded tuff-lapilli tuff is composed of 2–50 cm thick fine-grained tuff to fine lapilli tuff beds (Fig. 8a, b). Euhedral to broken feldspar crystals, up to 0.2–2 cm in size, constitute the prevalent crystal component, whereas 0.2–1 cm pyroxene crystals (< 15%) and lapilli-sized (up to 3 cm) lithic volcanic fragments (< 15%) are subordinate pyroclast constituents. Crystal and pyroclast size is commensurate with bed thickness, although outsized fragments which represent < 5%, are not unusual. The hornblende-quartz-albite groundmass, probably initially vitric, exhibits a dark grey to black colour on weathered surface. The 10–30 cm thick bedforms, continuous on metre-scale but discontinuous over 10's of m (20–30 m), display ubiquitous normal graded bedding with crystal- and lithic volcanic-rich bases and parallel laminated, coarse to fine-grained tuff tops. Inverse graded beds were seldom identified. Weathering colour grading from shades of grey to black emphasize the change in grain size and indicate subsets in beds. Bedding contacts are generally sharp, erosive and distinct, but diffuse contacts are prominent between thick massive, crystal-rich, lapilli tuff beds. Planar to wavy beds exhibit a prevalence of planar bedding with low- to medium-angle cross-beds. Lateral changes in the same bed are recorded over 0.5–2 m, where planar beds grade into low-angle crossbeds, which in turn grade into planar beds (Fig. 8c, d). Low- to high-angle tangential crossbeds are developed in the shallow channels and planar beds (Fig. 8e). Individual laminae or layers, thicken in the channel-shaped part of the laterally continuous beds. Scouring is accentuated at the base of crossbeds, but is also
Fig. 8. Salient characteristics of the planar to crossbedded tuff-lapilli tuff and disruptively bedded lapilli tuff breccia. Large arrow indicates top in all photographs. (A) Graded bedded (arrows), laterally continuous planar beds. Scale, pen 17 cm (outlined arrow). (B) Two tuff-lapilli tuff beds. Basal bed displays Bouma T n or S n–T s sequence of Lowe (1982) with a lower crystal-rich massive graded and an upper laminated segment. Upper bed is stratified to laminated as well as graded suggesting a modified S 1-type bed. Scale, pen 17 cm. (C) Wavy bedform with a shallow scour channel (ssc), strikingly similar to U-shaped surge channels. Diffusely laminated to stratified (S 1-type bed), but well-graded tuff-lapilli tuffs (S 3) are prominent above and below channel structure. Scale, pen (arrow) 17 cm. (D) Close-up of shallow scour channel shown in C with laminae draping (Dr) on left side and scouring (s) right side of channel margin. Well-defined graded tuff-lapilli tuffs (S 3) are evident below channel. Scale, pen 17 cm. (E) Tangential crossbed with grain-size and colour changes on foresets of crossbed. Underlying tuff-lapilli tuff bed is graded to laminated. Scale, pen 17 cm. (F) Angular breccia-size pyroclast disrupting graded, laminated and stratified beds. The interpreted bomb sag displays a slightly asymmetric shape and synsedimentary deformation (sd). Arrows shows assumed apparent angle of bomb entrance which is based on synsedimentary deformation. Fine lapilli are associated with the infilling of the bomb sag. Scale, pen 17 cm. (G) Field view of bedded lapilli tuff breccia. Scale, jacket 70 cm long (arrow). (H) Round feldspar-phyric pyroclast (bomb). Scale, coin, 2 cm in diameter. (J) Numerous round pyroclasts (bombs) disrupting fine-grained laminated tuff (Lt). Scale, coin, 2 cm in diameter (arrow). (K) Three graded beds of the bedded lapilli tuff breccia (indicated by numbered arrows) commencing with abundant bombs followed by a massive to poorly graded crystal-rich segment grading abruptly into fine- to coarse-grained laminated tuffs. Scale, pen 17 cm.

evident as subtle but omnipresent, low-angle scours at the base of planar (parallel laminated) beds (Fig. 8c). In addition to well-defined massive graded (Fig. 8b) or massive beds, internal stratification may be prominent either throughout or in the summital segment of the bed (Fig. 8b, c). Lapilli-size crystal-rich layers, 0.5–3 cm thick, alternating with 0.2–2 cm thick fine- to coarse-grained tuff layers within a bed, accentuate internal stratification. Similarly, crossbeds may show compositional changes on foresets (Fig. 8e).

Numerous angular to subangular lapilli- and breccia-size pyroclasts disrupt individual bedforms or transect bedding planes of several beds.
Tuff beds underlying the large pyroclasts may locally mold around the fragments. Several large pyroclasts display well-defined, in part asymmetric, underlying sag structures and synsedimentary deformation, subsequently infilled by fine lapilli-sized clasts (Fig. 8f). Load casts develop locally where crystal-rich coarse-grained tuff and lapilli tuffs overlie fine-grained tuffs.

4.2. Interpretation

The planar- to crossbedded tuff-lapilli tuff (Fig. 7) is a complex process-response deposit combining the salient characteristics of inferred subaqueous pyroclastic surge-like products (Kano, 1990; White, 1996) and base surge deposits (Sohn and Chough, 1989; Chough and Sohn, 1990) with high-density turbidity currents (Lowe, 1982, 1988). These deposits are considered to be an explosive counterpart of the interstratified feldspar-phryic lavas as indicated by the abundance of euhedral and broken crystals. The ambient medium, water, not only affected the eruption process, but also influenced transport and deposition of pyroclastic material, whereby bedload or sediment gravity flow deposits occurred next to fine-grained pyroclastic debris which settled through the water column. The well-defined massive to graded portion of the tuff-lapilli tuff represents rapid suspension fallout from high particle concentration flows (T_s or S_3-bed of Lowe, 1982), whereas the laminated upper portions of the bed is best explained by reduced suspended fallout rates and decreasing velocities (Bouma T_b; Lowe, 1988). Local inverse graded beds (S_2 bed of Lowe, 1982, 1988) are considered bedload traction carpets resulting from incipient collapse of particle congested pyroclastic clouds. High internal shearing rates within the suspension cloud can

Fig. 8. (Continued)
generate the dispersive pressure required to develop inverse grading (Chough and Sohn, 1990). Well- to poorly-developed stratification and lamination in planar beds (Fig. 8b) or crossbeds probably result from unsteady high-to low-concentration turbulent flows, respectively (S₁-bed of Lowe, 1982; Chough and Sohn, 1990).

The crossbedded tuff and lapilli tuff (Fig. 8d, e) are interpreted as current structures dominated by traction processes (Chough and Sohn, 1990; White, 1996). At the base of crossbeds and planar beds, local abundance of broad low-angle scour suggests that these non-confined, subaqueous, high-concentration flows have erosive capacity, which in turn supports traction-dominated processes. The observed lateral change in bedform from planar- to crossbedded, reverting back to planar-bedded is similar to subaerial pyroclastic surge deposits (Fisher, 1982), but the subaqueous setting of these rocks makes a direct comparison tenuous. Local wave reworking of tuff cones at the shoreline has been suggested for low- to high-angle crossbeds of the Songaksan tuff ring (Chough and Sohn, 1990), but these crossbeds are incised bedforms that do not grade into planar structures, whereas wave reworking for the Kangerluluk deposits seems improbable.

A subaqueous mechanism producing such structures must be considered. Wave-action induced by an eruption (White, 1996), radial waves emanating from the vent due to paroxysmal subaqueous hydroclastic eruptions (this paper) or thermal eddies associated with a submarine eruption (Cas et al., 1989) can account for these structures occurring in the same bed. The sedimentary structures in the well-bedded, broadly scoured coarse ash and lapilli deposits described by White (1996) for Pahvant Butte are strikingly similar. They result from unchannelized, dilute and unsteady aqueous current flows with erosive power, whereby flow turbulence caused erosion.

In contrast to density current emplacement, the minor lapilli to breccia-size pyroclasts disrupting beds or causing contorted bedding are interpreted as ballistically emplaced bombs (Fig. 8f). Bomb sag structures display synsedimentary deformation and locally asymmetric shapes possibly due to inclined entrance of a bomb (Fisher and Schmincke, 1984, p. 245-247; Sohn and Chough, 1989). The latter is consistent with a shallow water setting and/or possibly a subaqueous emplacement, but under subaerial conditions.

4.3. Bedded lapilli tuff breccia

The 5–15 m thick, bedded lapilli tuff breccia (Fig. 8g), located above section B in Fig. 2, represents a series of 10–60 cm thick laterally discontinuous planar-bedded to slightly wavy beds. Beds are massive to graded with abundant euhedral to broken, 0.3–2 cm large feldspar crystals and sub-
ordinate lithic grains. Pyroxene crystals are minor (< 5%). Ubiquitous round to subround (Fig. 8h), locally vesicular (weathered amygdules?), lapilli-to breccia-size pyroclasts, indent or disrupt beds (Fig. 8j). Commonly, the upper tuff beds are distorted by the emplacement of large pyroclasts, but they are also an integral part of a thick bed. Numerous clasts appear to have thin films of fine-grained tuff. A complete bed, reflecting one depositional event, displays a basal 20–30 cm thick massive subunit composed of feldspar-phyric pyroclasts, feldspar crystals, and angular lithic volcanic grains grading upward into massive to faintly laminated coarse- (10–20 cm thick) and subsequently a fine-grained tuff (5–20 cm thick; Fig. 8k). The change of weathering colour from dark grey to black facilitates identification of individual beds and shows recurrence of these beds throughout the section (Fig. 8k). The feldspar-phyric pyroclasts are identical to the interstratified feldspar-phyric lava flows on strike with the bedded lapilli tuff breccia (Figs. 2 and 4).

4.4. Interpretation

The bedded lapilli tuff breccia represents another process-response combination in which deposits controlled by subaqueous mass flow processes interact with ballistically emplaced ejecta governed by explosive mechanisms. The round pyroclasts disrupting lower fine-grained tuffs (Fig. 8j) and causing laminae to mold around are clasts characteristic of bomb sags (Cas and Wright, 1987 p. 121; White, 1996). The presence of bomb sags, an abundance of liberated feldspar crystals and angular lithic volcanic grains support a primary explosive origin, although pyroclastic heat retention structures were not observed. Internal structuring of beds from massive to graded lapilli tuff breccia, to coarse crystal-rich tuff into laminated fine-grained tuffs (Fig. 8k) suggest deposition from high- to low-particle sediment gravity flows (Lowe, 1982, 1988). Disruption of beds by bombs or formation of bomb sags within individual graded beds as well as their recurrence (Fig. 8k) argue for explosive activity contemporaneous with subaqueous mass flow deposition. Deposits with strikingly similar features were observed in the lithofacies M2 of White (1996). Thin films around pyroclasts suggest wet ash adhering to the bomb, but the metamorphic grade discounts unmistakable identification as armored lapilli. The recurrence of graded beds and bomb sag structures within the sequence favours numerous explosive pulses in which water was an important transport modifier.

5. Discussion

The interpretation of the Ketilidian orogen as a magmatic arc with an extensive forearc (Chadwick and Garde, 1996) is supported by the Kangerluluk volcano-sedimentary sequence, but on a much smaller scale. The studied sequence displays the attributes of a small remnant arc volcano located in the psammite zone in proximity to the synvolcanic Julianehåb batholith (Fig. 1). The three principal lithofacies attest to a fundamental change in depositional setting on a volcaniclastic apron of an arc volcano. The depositional context is discussed to explain the processes and eruptive mechanism responsible for the formation of the pyroclastic lithofacies.

5.1. Kangerluluk depositional setting

The composite sequence at Kangerluluk exhibits a distinct stratigraphy (Figs. 2 and 4) featuring a basal conglomerate-sandstone lithofacies followed by a medial pyroclastic lithofacies (and minor peperite lithofacies), which is conformably overlain by the volcanic lithofacies. The volcano-sedimentary rocks in unconformable contact with the synvolcanic Julianehåb batholith support the notion of a dissected arc setting (Figs. 4 and 9a). Similarly, an unconformable contact has been documented between the synvolcanic arc pluton and clastic fan-delta deposits of the Stella Formation in the Abitibi greenstone belt (Mueller and Dimroth, 1987) and elucidates the close temporal relationship between arc volcanism, and uplift and erosion of arc plutons. Additionally, the volcano-sedimentary succession displays the initial
stages of transgression coupled with a rapidly subsiding marginal basin, a common feature of dissected arcs (Mueller et al., 1989).

The conglomerate-sandstone lithofacies represents coarse clastic subaerial to subaqueous deposits along a high-energy coastline. The conglomerate-dominated unit is considered the subaerial part of the fan-delta, whereas the sandstone-dominated unit is allocated to the subaqueous segment. Significant topographic relief may be inferred based on the presence of matrix- and clast-supported conglomerate with local large boulders (Fig. 5a). Fan-deltas are an integral portion of the volcaniclastic apron surrounding the volcano. Volcanic clasts are predominant in conglomerate beds, but the presence of boulder-size plutonic clasts derived from the Julianehaab batholith, is consistent with erosion of the arc pluton. Well-defined upward-fining sequences (Fig. 5a, b, Fig. 6a, b) reflect a stream-dominated setting (Galloway and Hobday, 1983; Rust and Koster, 1984) with inferred mass flow products.

Fig. 9. (A) Paleogeographic reconstruction of the shoreline at Kangerluluk during the Ketilidian Orogen (ca. 1.8Ga). A dissected arc volcano, represented by polyphase Julianehaab batholith, is bordered by coarse clastic shoreline deposit characterized by alluvial fan, fan-delta and braidedplain deposits. Material is derived from the arc pluton and volcanoes. Numerous mafic-dominated volcanoes straddle the subaerial to subaqueous interface. In the foreground, an erupting shallow-water volcano is observed. The subaqueous Surtseyan-type eruption displays the violent interaction between water and magma. Other volcanoes along the shoreline are either being eroded by continual wave-activity after cessation of volcanic activity or have lava flows emanating from central vents and prograding into the sea (top of figure). (B) A possible model of a shallow-water Surtseyan-type eruption based on the Kangerluluk area. Numerous tephra jets emanate from a central vent in which water-magma interaction is violent. The jets may break the water surface or collapse in the subaqueous realm due to ingestion of water and continue as cold-water sediment gravity flows. Continual jetting may help develop a subaqueous eruption column of limited duration that forms a steam cupola. Gas cavities will collapse because of the hydrostatic pressure. Bomb sags may develop in such an environment and are deposited close to the vent. The two principal lithofacies are (I) bedded lapilli tuff breccia and (II) planar- to crossbedded tuff-lapilli tuff and reflect the direct result of a subaqueous eruption. Proposed model based on mapping of the Kangerluluk area and integrating work from Kokelaar (1983, 1986), Kokelaar and Durant (1983), Moore (1985), and White (1996).
(Fig. 5a, b), possibly indicating more proximal fan reaches (Mack and Rasmussen, 1984). The subaqueous part of the fan-delta is characterized by planar-bedded, sheet-type sandstones with small low-angle scours and local pebble lags (Fig. 5b, Fig. 6f). Up-section, pebble lags and grain-size diminish, suggesting increasing water depth. A lower shoreface, below normal wave base or proximal offshore setting with increased suspension sedimentation is proposed (Reinson, 1984). High-energy shorelines, as suggested by the presence of gravelly fan-deltas, generally have steep slopes (Howard and Reineck, 1981). Assessing the depth of water is problematic, but based on studies of high- and low-energy wave controlled shorelines by Heward (1981), and Howard and Reineck (1981), as well as theoretical wave modeling of large wave ripples in volcaniclastic sediments by Fritz (1991), a depth range between 10–40 m for the lower shoreface deposits seems appropriate.

The pyroclastic lithofacies, intercalated between lower shoreface sandstone + mudstone units (Fig. 5b) and pillow to pillow breccia flows, was deposited in a submarine setting. Interstratification of feldspar-phyric, pillowed and pillow breccia flows (Fig. 3h) with the pyroclastic lithofacies (Fig. 2) is an additional argument favouring subaqueous emplacement of pyroclastic material. Dykes that intrude the unconsolidated pyroclastic rocks (Fig. 3g) producing peperites and graded bedded tuff-lapilli tuffs indicative of subaqueous sedimentary gravity flow processes, are supplementary indicators of coeval sedimentation and volcanic activity in a subaqueous volcaniclastic setting.
The over 100 m thick volcanic lithofacies offers conclusive evidence of drowning of the volcaniclastic apron. Pillowed and pillow breccia flows are unequivocal indicators of a subaqueous setting and interstratified pyroclastic rocks (Figs. 4 and 6) accentuate coeval evolution. It is envisaged, based on the local stratigraphy and regional mapping, that small mafic tuff cones straddled the Ketilidian paleoshoreline or erupted subaerially (Fig. 9a). Tuff cones at the margins of volcanic islands in the Japan Sea (Chough and Sohn, 1990; Sohn, 1995), as well as littoral cones on the island of Hawaii (Fisher, 1968) would be analogous.

5.2. Significance of the pyroclastic lithofacies

Documentation of pyroclastic deposits adjacent to a high-energy fan delta system is rare in the ancient rock record. In addition, deposits related to shallow-water eruptions are poorly documented. The bedded lapilli tuff breccia and planar- to crossbedded tuff-lapilli tuff help elucidate the dynamics of Surtseyan-type eruptions. The pyroclastic lithofacies displays numerous sedimentary structures and volcanic textures which enable comparison with tephra deposits derived directly from explosive volcanic activity. These criteria are important, because subaqueous pyroclastic debris is generally considered cold mass flow deposit (Cas, 1979; Cas and Wright, 1991). The pyroclastic rocks at Kangerluluk are considered the direct result of an eruption, but rather than being hot, cold and wet conditions appear dominant. Base surge deposits associated with Surtseyan eruptions form under similar conditions (Cas and Wright, 1987; p.115). The Kangerluluk eruption-fed subaqueous products are compared to the mafic pyroclastic deposits at Surtsey (Thorarinsson, 1967)Kokelaar, 1983, 1986), Surtla (Kokelaar and Durant, 1983) and Pahvant Butte, Utah (White, 1996) that were governed by violent hydroclastic fragmentation.

5.2.1. Bedded lapilli tuff breccia

The bedded lapilli tuff breccia represents a combination of subaqueous sediment gravity flow processes and eruption driven ballistically emplaced ejecta (Fig. 8h, j, k). Considering the subaqueous setting of the deposits, few possibilities accommodate ballistic or gas-driven transport with submarine sediment gravity flows. They include: (1) a steam cupola developed around a subaqueous eruption column of limited duration (Kokelaar, 1983, 1986); (2) violent and strong submarine tephra jetting (White, 1996); (3) continuous subaqueous uprush explosions creating a vapour-gas dominated zone (Moore, 1985); or (4) large subaerial pyroclastic flows entering the sea (Mandeville et al., 1996). Restricted bed thickness, limited distribution of the lapilli tuff breccia (Fig. 2), grading of beds, absence of thick massive flow units of pyroclastic debris, and bounding lithofacies favour a subaqueous eruption, presented as possibilities 1, 2 and 3. The eruption must have been sufficiently strong to create a steam envelope in which ballistic material had time to be deposited, but not voluminous enough to develop thick pyroclastic flow deposits with heat retention structures. If the amoured lapilli interpretation is correct then a wet steam-rich cupola can be inferred. Large subaerial pyroclastic flows deposited subaqueously are discounted because they are generally felsic in composition, characterized by metre-thick, massive, sediment gravity flow deposits and recorded in the succession. None of these criteria apply for the deposits of the pyroclastic lithofacies. In addition, mafic pyroclastic debris does not originate from large column-directed eruptions, but rather from small volume hydroclastic explosions of limited extent.

The graded nature of the subaqueous lapilli tuff breccia beds indicate a sediment gravity flow process, which adds to the complexity of the eruption. Water was definitely an important transport and sorting agent. Pyroclastic deposits which display the attributes of both ballistic and mass flow transport in a submarine setting requires special consideration. Few eruption models can incorporate these two contradictory aspects. A sufficiently strong subaqueous eruption column or shallow-water tephra jet eruption can create an insulating steam cupola that subsequently collapses rapidly due to water ingestion during decrease in eruptive energy. Both mechanisms can explain the ballistic as well as mass flow aspects of the Kangerluluk
deposits. As pointed out by Moore (1985), if individual explosions or tephra jets occur at rates in excess of 12 per minute, a phase of continual uprush explosions ensues. Subaqueous eruptions of this nature favour the formation of steam envelopes which permit ballistic emplacement of tephra in a subaqueous setting (Fig. 9b). Abundant tephra jetting, common to Surtseyan eruptions (Kokelaar, 1983, 1986; White, 1996), probably coincided with column formation and implosion as well as controlling the transport and deposition (e.g. White, 1996) of the graded beds in this study. Recurrence of these beds within the pyroclastic sequence implies an abundance of small-scale eruptions that were strong enough to generate steam envelopes. An intermittent magma supply is inferred, and pulsating eruptions of this nature characterize basalts with low effusion rates (Kokelaar, 1983). The bedded lapilli tuff breccia is considered an eruptive product formed by tephra jetting adjacent to the vent area (Fig. 9b). Surtla, a satellite volcano near Surtsey, which did not breach the surface (Kokelaar and Durant, 1983), probably has abundant deposits of this character.

5.2.2. Planar- to crossbedded tuff-lapilli tuff

The planar- to crossbedded tuff-lapilli tuff has the attributes of both subaerial surge and subaqueous mass flow deposits. Local abundance of ballistically emplaced ejecta with asymmetric sag structures (Fig. 8f) requires an eruption capable of producing a steam cupola. In some cases, the insulating steam envelope may have collapsed prior to impact of the projectile causing it to settle in part through the water column, but the pyroclasts had still sufficient gravitational energy to disrupt beds in the unconsolidated pyroclastic debris. The planar graded bedded and stratified to laminated deposits represent suspension- and traction-dominated sediment gravity flows, respectively, but the crossbedded tuff-lapilli tuffs (Fig. 8c, e) require special attention. The co-existence of planar beds and crossbeds in the same bed necessitates an event or mechanism capable of generating such energy conditions. Tephra jetting, inherent to subaerial (Kokelaar, 1983; Moore, 1985) and subaqueous (White, 1996) hydrovolcanic Surtseyan eruptions, best explains the observed complex bedform relationship. The high velocity jets are low concentration turbulent gas-vapour flows with local scouring power that, due to water ingestion and high-velocity shearing within the medium, develop planar stratified and laminated beds as well as low-angle crossbeds. As the flow decelerates, additional water is ingested and turbulence is increased, creating an abundance of low to high-angle crossbeds which erode underlying tuff-lapilli tuff. The change from a gas-vapour to water-supported medium is complete with the formation of abundant crossbedded structures. The stacking of beds is interpreted as recurrent tephra jetting and collapse.

White (1996) argued in similar fashion for the development of planar stratified to laminated tuff-lapilli tuff at Pahvant Butte, but contented that crossbeds were wave-generated structures produced by the eruption and superposed on the outward flowing sediment gravity portion of the flow. The result was a form-discordant, dune-like bedform (White, 1996). Both interpretations can explain the observed sedimentary structures at Kangerluluk. If the contention of White (1996) is correct, then the combined ‘pyroclastic’ sediment gravity flow and wave-generated oscillatory current deposits may well be a pyroclastic counterpart of storm-generated hummocky cross-stratified beds (Dott and Bourgeois, 1982; Walker, 1984).

The planar- to crossbedded tuff-lapilli tuff in comparison with subaerial surge (Sohn and Chough, 1989) and subaqueous surge-like structures (White, 1996) is directly related to an explosion, but transport and deposition were controlled by aqueous processes. The deposits are best described as eruption-fed, surge-like products, because they are the results of tephra jetting. Ingestion of water in subaqueous pyroclastic flow or surge deposits causes transformation into cold subaqueous sediment gravity flows, but the change of transport medium from gas to water within or during the same flow does not modify the origin of the deposit. The planar- to crossbedded tuff-lapilli tuffs with distinct surge-type sedi-
mentary structures should be considered the sub-
aqueous equivalent of cold base surges.

The planar- to crossbedded tuff-lapilli tuff was
deposited further down-slope than the vent prox-
imal bedded lapilli tuff breccia. Planar stratified
and laminated beds of subaerial surges without
crossbeds are closer to the vent (cf. Sohn and
Chough, 1989), whereas increased ripple and dune
(crossbed) development occurs on the distal por-
tions of tuff rings (M3 lithofacies of White, 1996).
The planar- to crossbedded tuff-lapilli tuff repres-
ents an intermediate position between the two
eruptive deposits. A water depth of 20–50 m for
the M3 lithofacies (and deeper for M1 lithofacies)
of White (1996) compares favourably with 10–40
m depths implied for sandstones of the conglom-
erate-sandstone lithofacies.

5.3. Subaerial versus subaqueous eruption

The pyroclastic lithofacies is a subaqueous de-
posit as indicated by bounding lithofacies, but this
does not preclude a subaerial eruption. High-den-
sity pyroclastic flows may enter a marine setting
without significant change (Cole and DeCelles,
1991; Mandeville et al., 1996), whereas low-den-
sity, gas-driven turbulent surges associated with
Surtseyan eruptions skim the water surface, show
wave reworking, or disintegrate at the air-water
interface (Cas and Wright, 1991). The eruption-
fed mafic pyroclastic rocks at Kangerluluk repre-
sent primary deposits. Emergent Surtsey-type
edifices display half-moon structures facilitating
sea water access and water-induced eruptions
(Kokelaar, 1983; Moore, 1985). The resultant de-
posits would be easily wave-reworked. Wave re-
working of the pyroclastic deposits characterized
by local incision of high-angle crossbeds as de-
scribed by Chough and Sohn (1990) were not
observed.

6. Conclusions

The depositional setting of the pyroclastic litho-
facies is constrained by the bounding subaerial to
subaqueous conglomerate-sandstone and shallow-
water volcanic lithofacies. Fan-deltas along a
rugged high-energy shoreline characterize the vol-
caniclastic apron. Amygdaloidal massive, pillowed
and pillow breccia flows indicate drowning of the
apron. Interstratification of conglomerate-sand-
stone, pyroclastic and volcanic lithofacies indicate
contemporaneity between effusive to paroxysmal
volcanism and sedimentation. The stratigraphy of
the Kangerluluk sequence reflects a rapidly sub-
siding marginal basin adjacent to a partially dis-
sected arc island.

The pyroclastic lithofacies has the salient char-
acteristics of shallow-water Surtseyan eruptions,
with the study area indicating submarine con-
struction of a tuff cone. The planar- to crossbed-
ed tuff-lapilli tuff and bedded lapilli tuff breccia
of the pyroclastic lithofacies represent subaqueous
eruption-fed pyroclastic deposits emplaced by a
combination of sediment gravity flows and ballis-
tically emplaced ejecta. The bedded lapilli tuff
breccia features abundant bomb sags which are
considered to result from a shallow-marine erup-
tions that had sufficient energy to develop a steam
envelope. The graded beds are inferred to result
from sediment gravity flows that formed after
collapse of the steam cupola.

The planar- to crossbedded tuff-lapilli tuff with
local bomb sags is best explained as a product of
recurrent tephra jetting. Tephra jets collapsing in
a subaqueous setting transformed into water-satu-
rated mass flows. The graded bedded, stratified to
laminated beds, as well as crossbedded tuffs and
lapilli tuffs are laterally discontinuous planar to
wavy beds suggesting formation from sediment
gravity flows. The combination of bedforms indi-
cates deposition from high- to low-concentration
traction currents and suspension clouds. The de-
posits result directly from an eruption similar to
base surges; they are not gas-suspended products,
but rather the water-laden counterparts. The pla-
nar- to crossbedded tuff-lapilli tuff may possibly
be considered a subaqueous version of cold base
surge deposits evolving from a gas-dominated
tephra jets into water-laden mass flow deposits.

The lack of fallout deposits or fine-grained tuff
settling through the water column, common to
inferred subaqueous eruptions (e.g. Fiske and
Matsuda, 1964; Cashman and Fiske, 1991) sug-
gests a different eruption style. As pointed out by
White (1996), sustained eruption columns produce abundant fallout material, whereas the Kangerluluk pyroclastic deposits are dominated by sediment gravity flow processes. Tephra jetting, inferred to be the prominent eruption mechanism, is typical of shallow-water basalt eruptions with intermittent magma supply.

Acknowledgements

The senior author would like to thank Drs Adam Garde of GEUS and Brian Chadwick of Exeter University for the introduction into the wonders of Greenland geology. The paper is published with the permission of the Geological Survey of Denmark and Greenland. Everyone from GEUS participating during the summer of 96 in southeast Greenland is thanked for their input and Scandinavian hospitality. Excellent sunny weather made working off the glacier a dream and Dr Hendrik Stendal was a great companion and proficient colleague in the field. Precambrian Research reviewers, Drs C.A. Landis and W. Fritz upgraded the manuscript significantly with their incisive comments. Dr Ken Eriksson, editor of Precambrian Research, is thanked for making this Special Volume possible.

References


Horton, B.K., Schmitt, J., 1996. Sedimentology of a lacustrine fan-delta system, Miocene Horse Camp Formation, Nevada, USA, Sedimentology 43, 133–156.


