SUPPLEMENTARY MATERIAL VOLCANICA

Supplementary Material for:

The episodic onset of explosive and silicic-dominated volcanism in a continental rift; insights from the Permian Oslo Rift, Norway

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Whattam et al. (2024) should be cited if this material is used independently of the article. Refer to maintext for references to figures and tables.

Phase 1

Descriptions

Kringlefjell basalts Four basaltic lava flows crop out in the far west of the area, and were mapped (Figure 2A) and logged (Figure 3 and 4) collectively as the Kringlefjell basalts. These flows are invariably underlain by intrusive syenite. Although classical tripartite flow divisions of vesicular or brecciated base, dense core, and rubbly flow top [sensu Thordarson and Self 1998] were not clearly visible, an overall step-like morphology [i.e. traps: Svensen et al. 2019] and sparse exposures of rubbly lava tops were observed. Individual flows are distinguished by differing phenocryst content, with changes consistent with the topographic steps. The first and third flows are coarse porphyritic to glomerophyric basalt, with abundant plagioclase phenocrysts typically of 4–6 mm length, whereas second flow is aphanitic to finely-porphyritic (very sparse <1 mm plagioclase phenocrysts). The uppermost flow (Figure 5A) is distinct, comprising two discrete parts; (1) a non- to marginally-vesicular aphyric to sparsely-porphyritic basalt, hosts (2) enclaves of highly-porphyritic (ca. 25–60 % phenocrysts) basalt with 1.5 mm to 13 mm tabular plagioclase phenocrysts (dominantly >10mm). The porphyritic basalt enclaves have sharp, cuspate to irregular margins with the aphyric host. Phenocrysts in the enclaves show alignment and flow textures near enclave boundaries (Figure 5A), with more chaotic orientations observed away from enclave boundaries. Phenocryst exchange from enclave to host is not observed (i.e. the host basalt has no large phenocrysts), although some incipient break-out lobes are observed (Figure 5A).

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Breisjøhogdene basalt The preserved thickness of the Breisjøhogdene basalt is unknown as no base has been observed, however, a large exposures give a minimum thickness of >10 m. It is the base of the logged succession in the middle to eastern side portion of the field area, although we find no clear link between this and the basal units to the west (i.e. the Kringlefjell basalts and Kringlefjell tuff breccia). The deposit is varies between coherent (i.e. lacking obvious clastic texture) porphyritic and porphyritic clastogenic textures. Coherent areas are poorly- to moderately-vesicular with plagioclase phenocrysts of <0.5 mm to ~6mm. Clastogenic portions are dominated by poorly vesicular, slightly to moderately porphyritic clasts, with subordinate scoria and angular to subangular breccia, with rare moderately vesicular basalt, in an ash-sized groundmass. Porphyritic clasts have rounded to irregular shapes and are often slightly to moderately elongated whereas angular clasts are more equant. The groundmass comprises fine-lapilli size basaltic fragments surrounded by glassy material.

Kringlefjell tuff breccia This unit (Figure 2) overlies the Kringlefjell basalts in the west, although the absolute lower contact was not observed. The unit comprises clasts of porphyritic and slightly vesicular aphanitic basalt within a fine-ash groundmass. Clasts are typically 2–10 cm, rounded to sub-rounded, with occasional indented to cuspate margins (amoeboid shape). Porphyritic clasts have abundant <2 mm to >1 cm plagioclase phenocrysts, whilst subordinate vesicular aphanitic clasts have small (<~3-4mm) vesicles, and typical vesicularities of ~5–25 %. The groundmass comprises small plagioclase phenocrysts (<3-4mm), with sparse large plagioclase phenocrysts (~8–12 mm) and fine basaltic lapilli. Particle size distribution appears roughly continuous from fine-ash to

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fine-bombs, although there is a lesser abundance of clasts in the range of ~1–3 cm.

Lachmansfjell basalt The Lachmansfjell basalt is typically poorly exposed but is observed to overlie the Kringlefjell (Figure 2) in the west of the field area, separating this units from the very similar Linderudkollen tuff breccia (described below). A lower contact has not been observed and only the upper few metres of this unit crop out. However, we estimate a thickness of ~10–15 m based on a topographic step below good exposures of this unit in the west, below the hilltop Lachmansfjell. The unit is a non-vesicular to poorly-vesicular porphyritic basalt, with plagioclase phenocrysts of ~1 mm to 7 mm, with a glassy to micro-crystalline groundmass. No internal structure is observed in the small outcrop exposures.

Linderudkollen tuff breccia The Linderudkollen tuff breccia (Figure 2) is underlain by the Lachmansfjell basalt in the west and east, and intruded by syenite in the north and south. The contact with syenite is sharp with fine veins of syenite protruding into the tuff breccia; the lower contact with the Lachmansfjell basalt has not been observed. Typical exposures comprise an ash rich groundmass hosting lapilli-to bomb-sized (typically <~0.5 m, rarely ~1–1.5 m) porphyritic basalt clasts. Rarely, bedding can be seen defined by clast alignment and elongated scoriaceous lenses (Figure 3E). The groundmass is very-fine to fine ash (Figure 3D) with sparse (⩽ ~10 %) of medium to coarse ash, comprised of whole and fragmented crystals and fragments of basalt. Clasts are dominantly porphyritic (Figure 3D, 3F), with uniform phenocryst populations within clasts, but varying between clasts, and typically have rounded and irregular to cuspate (embayed) margins. Comparatively sparse aphyric to aphanitic vesicular basalt clasts also occur, with vesicularities of ~10–20 % and vesicles from sub-millimetre up to approximately 4–5 mm, and rare vesicular silicic clasts (white to pinkish-white groundmass with k-feldspar phenocrysts) occur in the upper few metres of the unit. Particle size distribution is bi-modal, with one mode represented by large blocks of ca. >0.4 m and another mode covering the range of ash, lapilli, and clasts up to ca. ~20 cm. Disaggregation of basaltic clasts, evinced by the distribution of clast fragments, crystals, and crystal fragments around clast boundaries (Figure 3F), is evident in most outcrops. Disaggregation is more evident in porphyritic than vesicular basalt clasts, and the rare silicic clasts show no evidence of disaggregation, with an upwards gradation of decreasing clasts and increasing clast disaggregation throughout the unit. The uppermost exposure of this unit (at Merramyrhogda, Figure 1A) contains a thin layer (15–25 cm thick) of spatter clasts 20–40 cm wide and 5–10 cm thick. The Linderudkollen tuff breccia is overlain by a fine grained sedimentary unit in a few rare instances but is too poorly preserved for detailed description (see supplementary information 1 for additional details).

Interpretation The lower three Kringlefjell basalts appear to be simple rubbly pāhoehoe type [e.g. Duraiswami et al. 2008; Barreto et al. 2014] with minor intra-flow stratification. Correlations between topography (i.e. flow tops) and phenocryst content variation implies these are distinct flows rather than a time-varying component within a single flow. As phenocryst size and abundance does not change successively, we interpret the variation as representing eruptions tapping distinct magma reservoirs rather than decompression crystallisation [e.g. Kuritani 1999] or crystal growth within a single magma batch. Whilst magma mingling and mixing is relatively common, visibly mingled components are typically compositionally distinct (i.e. rhyolite and basalt) and mixing results in hybrid intermediate deposits with mineralogy or chemistry indicating the two initial components [Gibson and Walker 1963; Charreteur and Tegner 2013; Gogoi and Saikia 2019; Morgavi et al. 2022]. That notwithstanding, we find no literature mentioning basalt-basalt mingling comparable to the uppermost Kringlefjell basalt. However, general theories of magmatic mingling from other examples is likely still valid for this occurrence given the expected differences in viscosity and rheology between a highly- and sparsely-porphyritic magma [Costa et al. 2009; Petford 2009; Vona et al. 2011]. Protrusions from enclaves into the aphyric host are in line with observational and experimental data for systems where a less viscous magma was injected into a more viscous magma [Perugini and Poli 2005]. The abundant crystal alignment within porphyritic enclaves, cuspate margins, protrusions, and lack of visible phenocryst exchange suggest reactivation and erosion of a crystal mush from the magma chamber walls by a remnant melt-fraction, or by an injection of fresh basalt, forming a two phase magma [e.g. Browne et al. 2006; Paterson et al. 2016; Marzoli et al. 2022]. The breakup of a mush into smaller enclaves likely indicates a relatively quickly turbulent and/or rapid process [Turner and Campbell 1986; Marzoli et al. 2022] with minimal residence time for substantial mechanical and/or chemical mixing prior to the final eruption.

The Breisjøhogdene basalt has features suggestive of varied eruptive and depositional processes although the shortage of continuous vertical exposures means placing the various textures in a confident stratigraphic order is impossible. For example, we cannot accurately determine if the vesicular regions are one continuous horizon, relate to different parts of a single flow, or relate to similar horizons (e.g. a vesicular basal zone) across several flow units. Nevertheless, in outcrops with several metres of lateral and vertical exposure we do see coexistence of both coherent-porphyritic and clastogenic textures, with suggesting that individual eruptions involved transitions between pāhoehoe and ʻaʻā styles. Flow transitions have been documented in both recent [e.g. Polacci et al. 1999] and ancient [e.g. the Deccan Traps, Duraiswami et al. 2014] but are not diagnostic of a single process. Flow and/or effusion rate variance is oft cited as the driver of lateral transitions between pāhoehoe and ʻaʻā, wherein low flow- or effusion-rate would lead to pāhoehoe type lavas and vice-versa [Duraiswami et al. 2014]. basalt flows encountering an sudden slope angle increase (i.e. arriving at a slope crest) could thus transition almost instantaneously from a pāhoehoe type flow to an ʻaʻā type flow; a feature seen in the 2014–2015 Holuhraun lava flow-field in Iceland [Voigt et al. 2021].

The apparent chaotic and regular lateral transitions with short length-scales in the Breisjøhogdene basalt likely results from reworking of two components (ʻaʻā and pāhoehoe) however and does not indicate whether topographic variability or effusion rate is the driving process. Moderate to high vesicularity throughout the Breisjohogdene basalt, often with partial or complete secondary filling (i.e. amygdules) is notable when compared to the extremely limited vesicularity of the Kringlefjell basalts. A coupled volatile phase would explain textural differences between the Kringlefjell basalts (simple pāhoehoe) and Breisjøhogdene basalt (mixed pahohoe and ʻaʻā) whereby a coupled volatile phase would promote greater volatile overpressure and increased ascent and effusion rates (and vice-versa). Variable, but overall faster effusion rate may thus explain lateral and vertical transitions between pāhoehoe and ʻaʻā textures, although outcrop quality inhibits accurate determination of this in Alnsjø.

Several basaltic tuff breccia units have been mapped through the field area, distinguishable based on clast and groundmass textures. Collectively, these units appear to represent similar, but separate eruption and depositional episodes, and form a common surface over which the younger stratigraphy was deposited. Previous interpretations suggested the basaltic tuff breccias were localised regions of reworked basaltic material [i.e. sediments: Sæther 1962; Naterstad 1978]. However, although ambiguity is manifest in many outcrops, we note several key features attest to volcanic origins. Predominantly cuspate to amoeboid clast shapes and a paucity of brittle fracture or brecciation textures (i.e. sharp, angular clast edges) imply that clasts behaved in a plastic manner (i.e. high temperature) during deposition. Additionally, disaggregation textures preserved around larger clasts allude to syn-depositional breakdown (i.e. disaggregation during transport within a flow). Deposition from a debris or hyperconcentrated flow could be invoked to explain a fine, clay-poor groundmass, matrix support, poor sorting, and possibly syn-depositional disaggregation [Fisher and Schmincke 1984; Smith 1986; Benvenuti and Martini 2002]. However, the disaggregation textures in combination with evidence for ductile deformation of clasts, and spatter bombs near the top of the deposit suggest primary volcanic deposition.

Although rarely observed, stratification orientations in the basaltic tuff breccias are consistent with those in overlying mudstones (see 4.2 and 4.3). Assuming essentially horizontal deposition of the mudstones, we infer approximately horizontal deposition of the basaltic tuff breccias, which implies a depocentre away from the ultra-proximal volcano flank. Conversely, basaltic spatter, the result of deposition from lava fountaining, is generally inferred to indicate vent-proximal locations, although rafting on flow tops can transport these deposits several kilometres from source [e.g. Karhunen 1988; Brown et al. 2014]. A proximal to medial (~0.5-3km) depocentre is therefore inferred. Shallow dipping volcanic aprons around small to moderate size scoria or agglutinate cones [sensu Brown et al. 2014] are consistent with proximal and roughly horizontal deposition, and are commonly associated with deposition of spatter, scoriaceous material, blocks, and bombs. Furthermore, brittle fracture can occur during eruptions in these settings either through interaction with water (i.e. ground- or surface-water), or by shattering solidified or partially solidified material in the upper edifice (cone walls) or conduit cap [Alvarado and Soto 2002; Yamamoto et al. 2005; Miyabuchi et al. 2006]. The similarity of phenocrysts in the groundmass and clasts suggests a common magmatic source for each unit, possibly with minor lithic contributions. If a substantial lithic contribution was present (e.g. fragmented cone wall or loose clasts from flank or apron regions) we might observe a greater disparity between clast and groundmass components, or greater clast variability. The relative sparsity of vesicular clasts in all basaltic tuff breccias suggests that eruptions lacked adequate heat and/or volatile content to undergo substantial syn-eruptive vesiculation. Moreover, basaltic magma is difficult to fragment or fracture at typical eruption temperatures [Papale 1999] without invoking anomalously low eruption temperatures, high crystallinity, rapid decompression, or phreatomagmatism [Giordano and Dingwell 2003]. Accordingly, we suggest explosive basaltic eruptions formed these deposits, generating larger clasts and domains through breakup of partially crystallised conduit caps [e.g. basaltic variants of conduit tuffisite: Schipper et al. 2021; Unwin et al. 2021] or lava-lakes [Miyabuchi et al. 2006], with column collapse providing additional ash components to the flow, possibly in combination with comparatively minor flank collapse [also providing lithic components e.g. Alvarado and Soto 2002], and subordinate contributions from proximal lava fountaining. The Lachmansfjell basalt may indicate that occasional lava flows were also produced at this time, possibly from the same scoria cone vents. Variations between explosive and effusive behaviour has been reported for basaltic scoria cones elsewhere [Pioli et al. 2009]. Alternatively, this unit may represent a volcanic plug or lava-dome related to the eruption of the Linderudkollen tuff breccia. The similarity in phenocryst assemblage at least suggests a magmatic source with similar properties but further detailed study would be required to address this relationship. We lack enough outcrop detail to construct a meaningful description and interpretation of the fine-grained unit overlying the Linderukollen tuff breccia; however, we infer that the partial occurrence is indicative of an erosional period between the deposition of the Linderudkollen tuff breccia and the overlying units (see 4.2 below).

Phase 1a

Alnsjø tuff Two exposures of the Alnsjø tuff are known, in both cases overlying the Breisjøhogdene basalt, and in turn overlain by the Svartkulp ignimbrite. The unit is comprised of a red, ash rich groundmass with common fine-lapilli, planar stratification defined by variations in fine-lapilli content, distinct horizons of coarse-lapilli to block/bomb sized clasts within an ash-rich groundmass, occasional fiamme, and typically poor vesicularity.

Sedimentary deposits Several occurrences of poorly preserved sediments occur at a common stratigraphic level across Alnsjø. They overly variable mafic units of Phase 1, are dominantly composed of basaltic clasts and grains, and are overlain by silicic units (where erosion has not removed these overlying units). The Linderudkollen siltstone is a fine-grained ca. 0.5–3 m thick deposit sometimes found to occur at the top of the Linderudkollen tuff breccia. Extremely limited outcrops with poor quality mean this unit is only described from hand samples. Where observed, it separates the upper Linderudkollen tuff breccia from the overlying Linderudkollen ignimbrite, but is only found in the W to SW portion of the study area whereas the underlying and overlying units have more widespread distributions and can be found in direct contact elsewhere. It is dark-grey in all hand-samples, fine grained with sparse clasts and no obvious crystal cargo, and has faint planar stratification. In the east, small outcrops of conglomerate (Alundammen conglomerate), sandstone (Ammerud Sandstone) are found, and sparse mudstone occurrence is observed in single outcrops (i.e. not mappable) in a quarried area near Grorud. Outcrops of the Alundammen conglomerate are mostly flat-lying veneers (i.e. thin <1 m thick cover) and therefore do not provide any information on stratification features. The unit is dominantly matrix-supported with sparse small (ca. 2–3 m) areas of clast-support, with common basaltic and sparse trachy-andesite (rhomb-porphyry) rounded to well-rounded clasts. The Ammerud Sandstone forms one continuous outcrop ca. 2 × 30 m and is comprised of medium to coarse sand with thin to very-thin (ca. 5–15 cm) parallel stratification.

Rhomb Porphyry Although we do not focus on intrusive components in this study it is necessary to mention the occurrence of a Rhomb Porphyry (trachy-andesite) intrusion that cuts through the former sedimentary units and the Breisjøhogdene basalt. Contacts with host rocks are vertical to sub-vertical (ca. 70-90 degrees) and sharp to somewhat peperitic or brecciated. Texturally, the unit is more comparable to a lava than a dike, with a variably glassy to granular groundmass, clastogenic zones, large (ca. <20mm) phenocrysts, and localised zones of breccia to peperite type textures along contacts. We cannot link this intrusion with a specific extrusive deposit but prior workers suggest that it is from high in the lava stratigraphy (RP13, of a possible 16 flow units across the rift).

Interpretation The lithologies and distribution of units in Phase 1a implies that a period of erosion, sedimentary deposition, and trachy-andeiste eruptions occurred, with subsequent erosion removing much of these deposits prior to the onset of Phase 2. Although prior interpretations sugest the rhomb-porphyry was a lava flow deposits, the cross-cutting relationship with the Ammerud sandstone and the Breisjøhogdene basalt strongly suggest an intrusive rather than extrusive origin although we cannot entirely rule out lava-infilling of a channel or small topographic depression. Nevertheless, we interpret the combination of textural features as indicating a lava-feeding conduit, likely emplaced somewhere within a few hundred metres from the paleo-surface. The overlying stratigraphy is correlatable over this surface, implying that the absence of the Phase 1a sediments and trachy-andesite units in some areas is not a late-stage erosional feature.

Phase 2

Kringlefjell ignimbrite The Kringlefjell ignimbrite occurs as a single outcrop in the far west of the field area, and is thought to overly the Kringlefjell tuff breccia, although no contact is observed. The unit is a moderately to heavily welded lapilli tuff, with flow lamination, rotated lapilli, and wrapping of flow-laminae.

Svartkulp ignimbrite

Description This unit underlies variably overlies the Breisjohogdene basalt and Alnsjø ignimbrite with a sharp, slightly undulating lower contact. Key characteristics are high-density, diffuse stratification (Figure 4B), glassy groundmass, and abundant k-feldspar phenocrysts. High to extremely-high (lava-like) degrees of welding are present throughout the unit. The lower 1–1.5 m exhibits a high degree of welding with strongly flattened, elongated, and aligned fiamme in a welded tuffaceous groundmass, with a subordinate component of moderately flattened fiamme, and some convolute flow banding defined by fiamme deformation. Welding from ~1.5 m to the unit top is extremely-high, with only subtle remnants of fiamme in places, and no visible vesicularity. Diffuse stratification is defined by phenocryst alignments and concentrations, with with subtle slightly undulating and occasional convolute flow-banding visible within the glassy groundmass (Figure 4A). Abundant, typically well aligned, acicular k-feldspar crystals (Figure 4A, 4B), are present in all observed outcrops, but are less abundant in the lower 1–2 m of the unit. Sparse small (ca. <3 cm) rounded to sub-rounded lapilli (Figure 4A), and extremely sparse angular fragments are present, and subtle flow banding and crystals show alignment and wrapping around these clasts. Rounded to sub-rounded clasts are pale-brown to light-pink, slightly to heavily elongated (with larger clasts often showing greater elongation), and dense to very poorly vesicular. Rare angular clasts are brown to light-brown, dense, and have no discernible internal structures or crystal contents.

Linderudkollen ignimbrite

Description The Linderudkollen ignimbrite is a variably welded ignimbrite overlying the Linderudkollen tuff breccia (or partial sedimentary cap of this unit) with a sharp and slightly undulating lower contact (Figure 4C). The ignimbrite is heavily welded in the lower ~10m, with a progressive decrease in welding intensity to a slightly welded upper portion. The basal 20–30 cm (Figure 3C) comprises a highly vesicular glassy groundmass with minor phenocrysts, no visible clasts. Many vesicles are coalesced and elongated (up to ~4 cm long), with a lesser proportion of non-coalesced vesicles typically 3-4 mm long. The following 0.5–1 m comprises a lava-like zone ,with rare discernible clasts, a glassy groundmass with scattered k-feldspar phenocrysts, and highly elongate (ca. 0.5–2 cm length) vesicles. This lava-like zone transitions to a highly-welded, rheomorphic portion (although the absolute transition is not observed) characterised by pronounced flow laminations (including convoluted eddy-like or flow-fold structures), minor (~10 %) clast content, and sparse k-feldspar phenocrysts. Flow bands are commonly folded or warped [i.e. flow-folds sensu Branney et al. 1992], sometimes around clasts (with minor indicators suggesting clast rotation), with fold wavelengths of millimetres to several centimetres. Clasts typically range in size between ~1–5 cm, with rare ⩽25 cm clast, are rounded, have cuspate or amoeboid shapes, and generally contain larger phenocrysts (~0.5–1 cm, including some glomerocrysts) than the surrounding groundmass (~1–2 mm). The upper ~10 m of the ignimbrite is moderately to slightly welded (Figure 3E), lacking clear flow banding or vesicles, has a pink groundmass with sparse phenocrysts, and is clast rich. Clasts are mostly small (<0.5–2 cm) and occur as rounded, elongate, and angular fragments; all clasts are dense and dark brown to black with no discernible internal structure or crystallinity. Elongate clasts show a common alignment, with orientation consistent with elongate vesicles and flow banding lower in the unit.

Gruvevei ignimbrite

Description This unit (previously mapped as rhyolitic breccia) is only present in the eastern portion of the field area (Figure 2A), and overlies the Svartkulp ignimbrite, with a poorly exposed but generally thin (~2–5 cm) gradational lower contact. The comprises stratified to diffuse stratified lapilli tuff, with a fine-grained, slightly vesicular groundmass. It is typically clast rich (especially in the basal zone: Figure 4F), groundmass supported (locally clast supported), with upwards decreasing clast abundance and becoming ash rich with clast-rich interbeds (Figure 5A) in the upper 3–5 m. The groundmass is grey to white, poorly sorted ash and fine lapilli, with rare lenses of fine-ash. Clasts in the basal 1–3 m (Figure 4F, 4G) are black to grey, dense to incipiently vesicular, typically angular to sub-angular clasts with subordinate sub-rounded clasts, and well to moderately-well sorted. Clasts though the middle of the unit are mostly sub-rounded and spherical to elongate, and generally moderately (10–30 %) vesicular. In the upper few metres, dense clasts are present in the finer fraction (ca. <2–3 cm) whereas the larger clasts are moderately vesicular, elongate clasts. Stratification and lensoidal features are clear in the upper 3–5 m with subtle large-scale diffuse stratification apparent in the middle of the unit where large enough exposures are found (Figure 5A).

Interpretation Differentiating between heavily welded ignimbrites and silicic lavas is eminently difficult [Brown and Bell 2013], even with a substantial body of literature on the subject [Metz and Mahood 1991; Branney et al. 1992; Sumner and Branney 2002; Branney et al. 2008; Brown and Bell 2013]. However, there is a general agreement that lavas will typically exhibit a degree of autobrecciation in the basal zone due to the shear stresses caused by cooling lava (i.e. viscosity increase) in contact with underlying strata, and continued viscous flow overtop [Bonnichsen et al. 1987; Henry and Wolff 1992]. We observe no basal breccias in any outcrops of units interpreted as heavily welded ignimbrites. Lava-like ignimbrites are only expected to exhibit an upper autobreccia zone [Brown and Bell 2013], with pyroclastic textures possibly better preserved in basal zones due to lack of secondary flow in this zone [Henry and Wolff 1992]. In the Svartkulp ignimbrite we observe a minor upper brecciated zone, and a diffuse contact with the overlying Gruvevei ignimbrite (see below) in line with expectations for lava-like ignimbrites. Where obvious and relatively undeformed clasts are present there is a clear difference in the phenocryst content, with clasts containing smaller and fewer phenocrysts than the surrounding groundmass. Although the Svartkulp ignimbrite lacks unambiguous pyroclastic textures, the fragmented crystals, minor flow-folds, and rotated crystals, and lack of an auto-brecciated base testify to pyroclastic origins [Brown and Bell 2013; Vezzoli et al. 2023]. Other characteristic features for distinguishing silicic lavas from lava-like ignimbrites [such as topographic relationships, distal thinning, and flow-front morphology: Henry and Wolff 1992; Vezzoli et al. 2023] are either not visible or preserved in the Svartkulp rhyolite. Although equal in stratigraphic position to the Svartkulp rhyolite, welding and textural gradations in the Linderudkollen ignimbrite clearly distinguish the two ignimbrites. The pumiceous base, flow-folded flow laminations, ductile clast deformation, eutaxitic fabrics, and glassy fragments all clearly establish pyroclastic flow deposition [Branney et al. 1992; Branney and Kokelaar 2002]. Textural gradations in the Linderudkollen ignimbrite are comparable to examples such as the Bad Step tuff [Branney et al. 1992] and the 'TL' ignimbrite in Gran Canaria [Sumner and Branney 2002], although the lava-like and rheomorphic textures are not as intensely developed. The pumiceous basal zone with faint clast outlines may represent a thin pre-ignimbrite Plinian air-fall deposit [i.e. layer 1 of Sparks et al. 1973] that has undergone deformation, welding, and vesiculation during deposition of the main ignimbrite body.

Vertical gradations from dense, high-grade to clast rich, low-grade welding has been ascribed to both syn- and post-depositional processes [Schmincke and Swanson 1967; Branney et al. 1992; Branney and Kokelaar 1992; Sumner and Branney 2002; Branney et al. 2008], although the more recent publications favour syn-depositional processes [Branney et al. 2004; Andrews et al. 2008; Andrews and Branney 2011]. Lessening degrees of welding can be attributed to changing source conditions, leading to variations in flow characteristics and particle concentrations [Branney and Kokelaar 1992]. High eruptive mass flux combined with low eruption columns emanating from wide vents (either fissures or wide point sources) has been suggested as a likely mechanism for extensive heavily welded ignimbrites [Sumner and Branney 2002; Branney et al. 2008; Lenhardt et al. 2017]. Furthermore, these ignimbrites typically have thin or non-existent pre-ignimbrite fall deposits (refs). Given the general consensus that the Oslo Rift was dominated by fissure fed eruptions [Larsen et al. 2008] it is conceivable that these same vents fed the earliest silicic eruptions, prior to construction of central volcanoes. Additionally, the absence of the Linderudkollen ignimbrite in the eastern field area suggests topographically controlled deposition, likely combined with erosion during build up to and earliest deposition of the overlying Gruvevei mudstone (described below).

Ash rich groundmass and lenses, stretched and deformed vesicular clasts, and occasional fiamme all point to deposition of the Gruvevei ignimbrite from a pyroclastic flow. Clasts in the basal zone of the Gruvevei ignimbrite are dissimilar to the underlying Svartkulp rhyolite, so although the contact appears slightly gradational we infer that these are distinct units rather than a vertical grading as seen in the Linderudkollen ignimbrite. Lateral and vertical stratification and clast gradations in ignimbrites are thought to signify deposition through progressive aggradation and are common features of massive to poorly stratified lappili tuffs [Branney and Kokelaar 2002]. Decreasing clast abundance and increasing clast size through lower to middle portions of the ignimbrite can be interpreted as waxing (increased clast transport distance) or waning flow (reduced particle support), or increasing clast availability at the source [Branney and Kokelaar 2002]. The angular clasts in the lower portion of the ignimbrite have similar colour, phenocryst abundance, and vesicularity to adjacent rounded and elongate clasts, therefore we assume angular to sub-angular clasts are cogenetic fragments (as opposed to lithic) brecciated during transport. In a pyroclastic density current, angular to sub-angular clasts may form as a result of attrition and breakage during transport in the pyroclastic flow [Branney and Kokelaar 2002]. Dense angular to sub-angular juvenile clasts in the Adeje Formation, Tenerife have been ascribed to waxing flow conditions, with varying eruption dynamics and magma residence time in the conduit also contributing [Dávila-Harris et al. 2013]. However, deposits of well-sorted, often angular to sub-angular and roughly equidimensional juvenile clasts with limited accidental lithics are also attributed to pre-ignimbrite Plinian air-fall deposition [Rosi et al. 1999; Branney and Kokelaar 2002], although these deposits lack abundant ash sized material [Branney and Kokelaar 2002]. Reworking and incorporation of a pre-ignimbrite fallout deposit could account for the angular relatively well sorted clast population, with the rounded lapilli and ash size groundmass accumulating from a combination of clast attrition and rapid deposition in the flow boundary zone. The latter explanation is supported by the presence of ash-rich lenses in the lower parts of the ignimbrite that may represent erosive incorporation and re-working of a pre-ignimbrite ash deposit. Observed gradation profiles in clast size, shape, abundance, and vesicularity likely reflects waxing flow conditions, whereby greater carrying capacity transports larger clasts, reduces rates of clast deposition, and increased shear at the depositional boundary [Branney and Kokelaar 1992], whereas the ash rich, clast poor upper ignimbrite is indicative of waning flow conditions (flow indicated by elongate pumiceous clast), possibly in combination with co-ignimbrite ash deposition [Branney and Kokelaar 2002]. Thus, we interpret the Gruvevei ignimbrite as an incipiently to non-welded ignimbrite related to a sub-Plinian to Plinian eruption with a reworked pre-ignimbrite fallout in the basal zone.

Phase 2a

Gruvevei mudstone Whilst previous [Naterstad 1978] show mudstone across the Alnsjø area as a single lithological unit, field relationships show that there are two distinct mappable mudstone bodies, partially separated by volcanic deposits. The Gruvevei mudstone is older (stratigraphically lower) and volumetrically subordinate to the Storhaug mudstone (described below). In the eastern section (Figure 2) the Gruvevei mudstone is stratigraphically separated from the Storhaug mudstone stratigraphically by a basaltic lava (the Gruvevei basalt; described below), and separated in the west by the Kapteinsmyra ignimbrite (Figure 2 and Table 1). In all other locations there is continuous deposition of mudstone from the Gruvevei mudstone into the Storhaug mudstone, although the two units are still generally divisible based on distinct stratification in the Gruvevei mudstone. The Gruvevei mudstone can be found in most areas, at least in small outcrops, and therefore acts as an important stratigraphic marker bed. The unit is approximately 2–3 m thick with a sharp, slightly undulating lower contact. Along the southern field area boundary it overlies the Linderud tuff breccia, in the west, north-west, and south-west it overlies the Linderud ignimbrite, and in the east it variably overlies the Gruvevei ignimbrite and Kavringen basalt (Figure 1).

The mudstone is black in northern exposures but a rust-red colour in southern exposures (see white dashed line line in Figure 1A; also applicable to the Storhaug mudstone described below). A discrete contact between the red and black mudstone has not been observed but tracing outcrops from north to south indicates the transition occurs rapidly, within a few metres laterally. Clay to silt size sediment is dominant, but beds of fine to very-fine sand with occasional outsized clasts (up to ~2 cm) occur. In addition, discontinuous beds or lenses of volcaniclastic material (fine lapilli and diffuse scoriaceous material) occur in the upper 0.5 m of most outcrops. Outsized clasts appear pumiceous but the fine interbeds are too thin and fine-grained to permit detailed description. In the upper ~50 cm the unit becomes stratified with thin to medium volcaniclastic beds, including scoriaceous clasts. Stratification is present throughout, typically sparse lower in the unit becoming progressively more common vertically, and consists of planar to wavy laminations (possibly with slight asymmetry to the ripples) and very-fine to fine interbeds with occasional tabular cross-stratification (Figure 5C). Where volcaniclastic beds are present they are typically accompanied by minor indications of soft sediment deformation (rip-up clasts and deformed laminations) of the silliciclastic sediments.

Kapteinsmyra ignimbrite The Kapteinsmyra ignimbrite is a ash and crystal (k-feldspar) rich tuff with sparse very fine lapilli that overlies the Gruvevei mudstone in the south-west of the field area with a peperitic basal zone over 20–40 cm. Subtle parallel stratification can be seen in some outcrops but only ca. 2 m of the basal portion of the ignimbrite is preserved.

Gruvevei basalt The Gruvevei basalt is a moderately to slightly vesicular, aphyric to micro-porphyritic basalt with a peperitic basal zone (Figure 5G), dense core, and scoriaceous clastogenic top (Figure 5D). It is approximately 20 m metres thick and has a small areal extent (ca. 0.2 km^2; Figure 1A), although this is almost certainly not the entire original extent. It invariably overlies the Gruvevei mudstone (Figure 5B, 5E), with the contact comprised of a 0.5 to 1 m thick zone of peperite comprised of angular to sub-rounded moderately vesicular basalt clasts in a matrix of mudstone. Flow structures are visible in the mudstone and vesicles in the basalt have been partially infilled with mudstone (Figure 5G). It is also important to note the it is invariably overlain by the Storhaug mudstone, and that south of Gruvevei in the Disenbakken area continuous mudstone deposition from the Gruvevei mudstone into the Storhaug mudstone is observed. Although extremely poorly exposed, small outcrops indicate the core region of the lava is dense and aphyric. However, any large-scale internal stratification or flow structures would be missed. The upper approximately ? metres is comprised of a scoriaceous breccia. Scoria clasts (Figure 5G) range from <1 cm up to ~5 cm, are sub-angular to sub-rounded, typically elongate in profile view, invariably green and slightly to moderately vesicular, with a general trend of larger clasts having higher vesicularity than smaller clasts.

Interpretation Outcrops of the Gruvevei mudstone show both vertical and lateral variations in lithology and stratification, and a general upwards increase in volcaniclastic material. Unstratified to poorly stratified mudstone in the lower 0.5–1 m with no indications of sub-aerial exposure or bioturbation, and absent of clear grain-size variations suggests low-energy deposition, likely from suspension fall-out, with consistent water cover [Newell et al. 1999; Araújo et al. 2016]. Silty to very-fine sandy beds with subtle asymmetrical ripples and occasional tabular cross-stratification suggests a slight increase in depositional energy and unidirectional flow of water. Sandy layers with occasional outsized clasts likely reflect both increased flow in small, shallow distributory channels [Pakzad and Fayazi 2007] and periodic increases in availability of tuffaceous material as a result of small ash jetting episodes from cinder-cones. The lateral gradation from black to red, and notable lack of stratification in the red mudstone indicates a lateral variation in sedimentation conditions. Whilst the red colour is typical oxidising conditions and subaerial to shallow water conditions [e.g. White and Youngs 1980; Benison and Goldstein 2001], the absence of subaerial exposure textures (i.e. desiccation cracks) suggest shallow water conditions or relatively consistent water input in a subaerial setting [Van Houten 1973], and the lack of stratification suggests calm water. Lacustrine deltas occur at the fluvial to lacustrine transition often record varying transport energy but with typically fine grain-size deposits, especially in the pro-delta to delta-front regions, whereas shoreline to mudflat settings often have red to brown colour mudstones, a poor preservation of stratification [Tye and Coleman 1989]. The features in the Gruvevei mudstone are thus considered to represent varying transport energy in lacustrine pro-delta to delta-front (black, stratified mudstones) and the adjacent shoreline to natural-levee [i.e. partially subaerial delta overbank: Tye and Coleman 1989] or mudflat (red, unstratified mudstones) settings during early lake development with occasional influx of volcanic material representing small scoria cone eruptions leading up to the eventual eruption of the Gruvevei basalt (following section).

This basalt is interpreted as a small, locally restricted lava flow, erupted from a scoria cone or similar small eruptive vent [e.g. the agglutinate cones of Brown et al. 2014], possibly emanating from the same eruptive vents that produced the earlier pyroclastic basaltic products (e.g. the Linderudkollen tuff breccia). Scoria cones are common in many volcanic settings, including continental rifts, and are typified by either simultaneous or alternating explosive and effusive eruptions, often of mafic compositions [Wood 1980; Pioli et al. 2009]. The ash and fine volcaniclastic material observed in the underlying and overlying mudstones may then be the result of smaller precursor and successor eruptions. The thickness of the peperitic basal zone is related to both sediment characteristics (e.g. degree of consolidation, grainsize, water content) and magmatic properties [e.g. temperature, flow velocity, flow volume: Skilling et al. 2002; Waichel et al. 2007], and although it is typically associated with the interaction of magma and wet sediments, magma interaction with dry sediments has also been shown to produce peperite [Jerram and Stollhofen 2002]. Nevertheless, the peperitic basal zone and continuous mudstone deposition where the basalt is not present both unequivocally indicate contemporaneity of the sedimentary and volcanic environments at this time, and the lack of subaerial exposure features in underlying mudstone (e.g. desiccation cracks or paleosols) suggests peperite formation through interaction with wet sediments. The continuity of mudstone deposition surrounding the Gruvevei basalt, and no indication of volcanogenic conglomerate anywhere else further indicates that the basalt is a single depositional unit [i.e. not a basaltic lava and overlying conglomerate as indicated by Naterstad 1978] that likely represents deposition over a period of days to weeks. Thus, the scoriaceous clastogenic top is inferred to represent small volumes of explosive ejecta from the vent transported with other pyroclastic ejecta (e.g. ash) in the waning stages of the eruption. Lapilli erupted from scoria cone vents commonly includes fluidal, angular, and rounded scoria [McGetchin et al. 1974], all of which are seen in the upper 2–3 m of the Gruvevei basalt. Auto-brecciation could be invoked to explain clastogenic flow tops [e.g. rubbly flow tops: Duraiswami et al. 2008; Murcia et al. 2014] but the distinct difference between clasts and groundmass do not fit with brecciation of a relatively uniform lava crust; ergo, we favour the former interpretation. Transport away from an eruption site is indicated by the lack of proximal deposition features (e.g. bombs). Earlier erupted lapilli and bombs they may have been included in the lava have presumably been completely assimilated.

Phase 3

Storhaug mudstone The Storhaug mudstone is a purple-black to rust-red coloured argillitic mudstone unit with a stratigraphic thickness of approximately 135 m (Figure 2) covering the central portion of the field area (Figure 1A). The change from purple-black to rust-red is a lateral rather than vertical gradation (as in the Gruvevei mudstone) and the approximate boundary is shown in Figure 1A. The absolute point of this change has not been observed but it appears to occur rapidly, over 5–10 m laterally. Syenitic intrusions cross-cut the mudstone through the logged section, possibly accommodating some offset within the mudstone. Repetition of a key feature (i.e. the carbonate nodule beds described below) is not observed but as the unit is largely unstratified a lack of obvious repetition is not a strong diagnostic finding, thus the measured thickness should be considered a maximum. This unit is the continuation of the Gruvevei mudstone and deposition of these units is often uninterrupted, however the two mudstones are separated by both the Gruvevei basalt and the Kapteinsmyra ignimbrite (see additional units section).

The basal section is variable, but typically contains three distinct carbonate nodule beds at approximately 3-5m (Figure 6A), but where it overlies the Gruvevei basalt there is also a 1–3 m thick zone of occasionally brecciated mudstone with fine scoria lapilli, and ash beds (Figure 5H) that underlies the carbonate nodule beds. Although outcrop exposures small and rare, these carbonate nodule beds appear to be a consistent feature of the lowermost portion of the unit. The beds show variability between small (2–6 cm) isolated nodules and amalgamated or longer (30–50 cm) semi-continuous lenticular forms, but never occur as continuous beds. Fine beds of sand occurring throughout the lower mudstone have been mentioned by previous workers (ref); we find no presence of sand beds in the lower parts of the unit. We speculate that the mention of sand beds in the lower portion of the mudstone may refer to the beds in the the Gruvevei mudstone, as these mudstones were previously mapped as a single unit. Above the carbonate nodule beds, from ~10 m to 115 m the mudstone is dominantly featureless with extremely sparse isolated carbonate nodules. At 120m isolated pumice clasts (4–15 cm) are observed within the mudstone, and the next 15m of the mudstone unit comprises a transition zone of mudstone with increasingly common isolated pumice clasts, sandy laminations and interbeds (Figure 6B), and volcaniclastic interbeds (Figure 6C). Stratification of mud, silt, and sandy layers in this upper 15m is commonly observed to be disturbed and deformed where thicker (~>5 cm) volcaniclastic interbeds occur (Figure 6B, 6C), whereas isolated pumice clasts lower in the unit are entrained within unstratified mudstone with no signs of deformation (e.g. impact sags under clasts). Thicker (roughly >5 cm) volcaniclastic beds are observed to have variably sharp to diffuse lower contacts, with deformation (e.g. impact sags) and cross-cutting of the underlying sediments, and incorporation of thin mudstone laminae and lenses into the main volcaniclastic deposit.

Interpretation The key interpretation from the majority of this unit is that it represents protracted volcanic quiescence, at least locally. Preservation of volcaniclastic beds in both the underlying Gruvevei mudstone and upper portion of the Storhaug mudstone indicate a high-likelihood of at least partial preservation of volcanic activity. The complete lack of any visible primary or reworked volcaniclastic beds through the majority of the Storhaug mudstone therefore suggests little availability of volcaniclastic material in the proximal to medial source regions, either as reworked material from older ignimbrites or from fresh eruptions. Cryptotephra may be present but would be indicative of distal (100s to 1000s of km distance) eruptive activity [Lowe 2011]. No other correlated mudstone units are known within the rift so inferring a rift-wide period of volcanic quiescence would be extremely speculative. That notwithstanding, there are several (3–4) interpreted caldera structures within 20–30 km (and an additional ~5 within 80 km) distance of the Alnsjø succession generally thought to have been active at similar times [Corfu and Larsen 2020] that could have been tephra sources if eruptions occurred during the deposition of the Storhaug mudstone, thus implying a broader volcanic quiescence.

In modern lake systems carbonate deposition is controlled by hydrology, sediment input, and temperature, and is deposited everywhere from the palustrine (wetland) region to the profundal (deepwater) region [Gierlowski-Kordesch 2010]. Weathering of basaltic rocks is an obvious source for calcium but given the carbonate nodules are extremely sparse and only occur in a narrow zone the supply of calcium to the lake system was clearly subordinate to the silliciclastic supply. Nodular carbonates in the Olduvai Paleolake (Tanzania), a lacustrine to fluvial setting with similar volcanic and climatic conditions as the Oslo Rift, are suggested to represent water level lowsands and deposition near lake margins [Bennett et al. 2012; Stanistreet et al. 2020]. We infer that the nodular carbonates in the Storhaug mudstone represent a similar depositional variation during the early stages of lake development. This is supported by subtle bedding defined by small grain size variations occasionally observed in the lower few metres of the Storhaug mudstone and more commonly in the underlying Gruvevei mudstone, in line with a maturing lake system in which the sediment delivery system (i.e. streams) was retreating as the lake expanded. Furthermore, an absence of sedimentary features indicative of subaerial exposure (e.g. desiccation cracks) suggests a perennial lake and the lateral colour gradation (purple-black to rust-red) is indicative of a water line where typical conditions changed from oxic to anoxic. Sedimentary red-beds are generally inferred to have been deposited in subaerial to shallow water conditions [e.g. White and Youngs 1980; Benison and Goldstein 2001], therefore it is suggested that the lateral gradation in the Storhaug mudstone represents the lake margin to floodplain or overbank region adjacent to a lake. The unit is situated roughly 3–5 km from a main rift fault [e.g. Figure 1 Larsen et al. 2008] which would likely provide a topographic slope where the lake shallowed away from the rift valley floor and eventually transitioned to alluvial depositional environments. This is further supported by the reported occurrence of fluvial sandstone deposits in the far east (i.e. closer to the rift fault) of the Alnsjø area [Sæther 1962; Naterstad 1978].

Phase 5

Storhaug ignimbrite The Storhaug ignimbrite was briefly mentioned in a field excursion guide [stop 15, Naterstad 1978] but was only shown as a thin sliver on the west side of Storhaug and has not been shown on any other geological map; mapping has shown this to be a far more extensive (Figure 1A) 7–8 m thick unit. An outcrop in the Linderudseter area (Figure 2A) exposes a complete sequence of upper Storhaug mudstone, Storhaug ignimbrite, and lowermost

Storhaug conglomerate. The lower contact of the Storhaug ignimbrite is slightly undulating with a thin (ca. 5–20 cm thick) zone of fluidal peperite comprised of the underlying mudstone and overlying ignimbrite (Figure 6D). The ignimbrite is variably coloured with fresh surfaces typically light pink to grey-white, dotted with green (altered) and brown slightly- to non-vesicular lapilli (Figure 6E). Slight to moderate development of fiamme and moderate to strong alignment of pumiceous lapilli (Figure 6E) is observed (although a paleo-flow is ambiguous with limited 3D exposures) and visible groundmass crystals are present but are sparse and are mostly less than 0.5 mm in length. Rare well- to sub-rounded moderately vesicular basaltic clasts (Figure 6F) are found in the upper ca. 1–2 m alongside a decrease in fiamme and lapilli alignments and an increase in rounded juvenile clasts.

Storhaug conglomerate The 42 m thick Storhaug conglomerate (Figure 3) is the uppermost unit observed in the Alnsjø field and is found in the central portion of the field area (Figure 2A). The lower contact with the Storhaug ignimbrite is not clearly resolved but appears to be a gradational change over several metres. Overall, the Storhaug conglomerate consists of repeated moderately to weakly stratified, rapidly upward fining beds ranging from 20 cm to 1m thick. Although lateral continuity of outcrops is very limited, attempts to follow individual beds suggests that most are laterally discontinuous down dip over distances of 10 to several 10s of metres. Stratigraphically lower beds are typically thicker, overall finer grained, and less clearly stratified, with a general coarsening of maximum and average grain size and increase in stratification features upwards from ~10 m into the unit. Bed contacts are often sharp and occasionally show evidence of scour, but some gradational contacts also occur with gradations over ca. 2–10 cm. Typically, beds have a fine to medium pebble, clast supported base, fining rapidly upwards with normal coarse tail grading to fine to medium pebble matrix supported conglomerate or pebbly sandstone. Rarely, coarse pebble to cobble sized clasts are observed, and very rarely, thin (1–3 cm thick) inversely graded basal sections of sandstone to very fine pebble conglomerate occur, although overall rapid fining and normal coarse-tail grading are retained. Beds consistently show poor sorting (Figure 6H) of both clast and matrix components with a few exceptions of moderately well sorted sandstone. Occasionally, elongate lenses of coarse pebbles are present in the upper, sand-rich portions of beds. Throughout the unit the matrix typically consists of poorly sorted very fine to medium sand with subordinate silt to clay size material, whilst medium to coarse sand occasionally comprises a minor, and rarely a dominant component of the matrix. K-Feldspar is the dominant matrix component, with quartz, plagioclase, and oxides comprising the remainder. Clasts are sub-angular to well rounded (typically sub-rounded to rounded), fine to coarse pebble size (typically fine) with rare cobbles (Figure 6H, 6I), although brecciated and deformed sub-angular to angular clasts are observed in beds of the lower 2–3 m (Figure 6F). Clast composition is dominantly bi-modal (Figure 6H) with vesicular and porphyritic basalt and felsic pumice and ignimbrite fragments, however very rare clasts of rhomb-porphyry lava and syenite are also present. Notwithstanding the absence of a systematic clast composition study, the unit notably lacks clasts of the underlying Storhaug ignimbrite or Storhaug mudstone units, and the pumiceous felsic and vesicular basalt clasts do not have a textural equivalent within the Alnsjø succession. Elongate clasts are typically orientated plane parallel to basal bed contacts, but sub-horizontal to sub-vertical clast orientations were also observed on occasion. Paucity of clear 3D clast exposure restricted possibilities for measuring clasts orientation and imbrication; elongate clasts commonly had a-axes alignment where measurable, but imbrication was rarely observed and palaeo-flow direction was ambiguous.

Interpretation The peperitic basal zone implies contemporaneity of ignimbrite deposition with active lacustrine to fluvial deposition, and as previously stated, the characteristics of a peperite layer are related to both sedimentary and magmatic properties. The very thin but fluidal nature of the basal peperite is here inferred to indicate partial consolidation of the underlying mudstone along with a relatively low temperature and volume of the deposited ignimbrite; low-temperature and low-volume ignimbrites would be unable to sustain and transfer as much heat to the sediment resulting in a thinner peperite layer. The minor fiamme and more common deformed pumice and glassy material in the lower 2–3 m indicate slight to moderate welding and lack of obvious welding textures in the remaining 5–6 m additionally supports a low depositional temperature [sensu Mundula et al. 2009]. Changes in welding intensity through a single ignimbrite can be linked to compositional, volatile, temperature, and grain-size properties, and lithic clast content, which in turn relate to changing eruption conditions [Branney and Kokelaar 2002]. The presence of sparse basaltic clasts in the upper ignimbrite indicates a marginal increase in lithic components, coincident with decreasing welding grade, which can be linked to both waxing and waning eruption conditions or availability of lithic clasts at the source [Branney and Kokelaar 1992; 2002]. Waning flow conditions, possibly in connection with a change in lithic availability is suggest by the coincidence of lithic clasts with declining welding textures.

The brecciated, deformed clasts in the lower few metres and the gradational lower contact is interpreted as indicating mixed volcanic and sedimentary processes, but this remains ambiguous due to limited outcrop. A possible scenario is the deposition of small volume ash-flows into a developing alluvial system where rapid cooling and continued flow led to brecciation or quench-fragmentation of the flow, with rapid erosion leaving small remnants of this feature preserved. Based on classification schema of Lowe [1979], Smith [1986], and Benvenuti & Martini [2002], typical bed morphology for the remainder of the unit indicates deposition from cohesionless fines-poor debris flows and hyperconcentrated flows, with comparatively minor contribution from normal stream flow. Hyperconcentrated flows can occur both as a standalone flow, or as the downstream transition of a debris flow as flow velocity and clast carrying capacity decrease [Pierson and Scott 1985; Benvenuti and Martini 2002]. Debris flow deposits and hyperconcentrated flow deposits are distinguished based on key characteristics of grading (uncommon, reverse and coarse-tail vs frequent, distribution normal), stratification (none vs some horizontal stratification), and conglomerate framework (typical matrix support vs common clast support), whilst both flow deposits typically show poor to minor imbrication and flow-parallel clast alignment [Smith 1986]. Beds in the Storhaug conglomerate dominantly display these features but commonly show stratification and grading that is transitional between the two classifications of Smith [1986]. Clast supported basal zones represents peak-flow, possibly becoming clast supported due to loss of matrix through subsequent flow. The upper pebbly sand and coarse tail grading in units represents waning flow conditions but with relatively high sediment loads able to support outsize clasts. Although there are wide variations in debris flow compositions (on a spectrum between fines-rich and fines-poor), fines-poor (i.e. cohesionless) debris flows are a particularly common occurrence in volcanic regions where the debris is derived from relatively fresh volcaniclastic material [Fisher and Schmincke 1984; Benvenuti and Martini 2002]. Pebbly sand to sandy beds imply lower overall transport capacity and flow velocity and are suggested to represent background stream-flow processes with comparatively poor preservation due to the recurrence of high energy flows causing erosion and reworking of finer material in channels.

The absence of a clear source unit for the the vesicular mafic and silicic clasts in addition to a notable paucity of clasts from underlying mudstone unit implies limited local erosion and possible input of younger volcaniclastic material (i.e. continued eruptions), although detailed clasts studies are required to confirm this. The ignimbrite clasts are typically welded and crystal rich varieties but are too small to resolve further, they do not appear to be a match for the Storhaug ignimbrite however. During deposition of the Storhaug conglomerate syenite would likely only have been present in sub-surface magma chambers and possibly as crystallising sub-surface intrusions, and therefore the syenite clasts are not thought to directly relate to erosion of the major syenitic bodies exposed in the present day rift. Inclusions of syenite clasts in the Linderudkollen ignimbrite offer a potential source, although substantial burial of the Linderudkollen ignimbrite and limited signs of local erosion under the Storhaug conglomerate imply that the source was an unknown ignimbrite (i.e. not recorded within the Alsnjo succession) at a higher stratigraphic level that had similar syenitic inclusions. Rare rhomb porphyry clasts indicate partial exposure of the upper rhomb porphry sequence, possibly in relation to uplift on a border fault. Therefore, we interpret the Storhaug conglomerate as an alluvial fan dominated by cohesionless debris flow and hyperconcentrated flow deposition, sourcing most clastic components from relatively fresh eruptions in a source area external to the Alnsjø Succession stratigraphy. Construction of topography in the proximal to medial region is suggested by the underlying Storhaug ignimbrite and basal volcaniclastic layers of the Storhaug conglomerate. Both increased local topography and abundance of fresh volcaniclastic material led to a change in the sedimentary system from lacustrine to alluvial dominated.

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