DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2012/102

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Report for Noreco

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DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

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Introduction

The Luna-1 well was drilled in 2012 by Noreco, and a TD core was taken at depths of 2111.35–2123.84 m. The core is of high quality with 100% recovery. The core was described at GEUS in September 2012. The core comprises 12 meters of red epiclastic volcanic conglomerates interpreted to be of Early Permian (Rotliegend) age.

The well is located on the East North Sea High, which may also be regarded as the western part of the Ringkøbing-Fyn High (Fig. 1). The geological map (Fig. 2) shows the presence of Lower Permian igneous rocks, intrusives as well as extrusives, in relatively short distance from the position of the well. Heeremans *et al*. (2004a) has compiled a list of wells with Lower Rotliegend volcanic and/or intrusive rocks in the Southern and Northern Permian Basins.

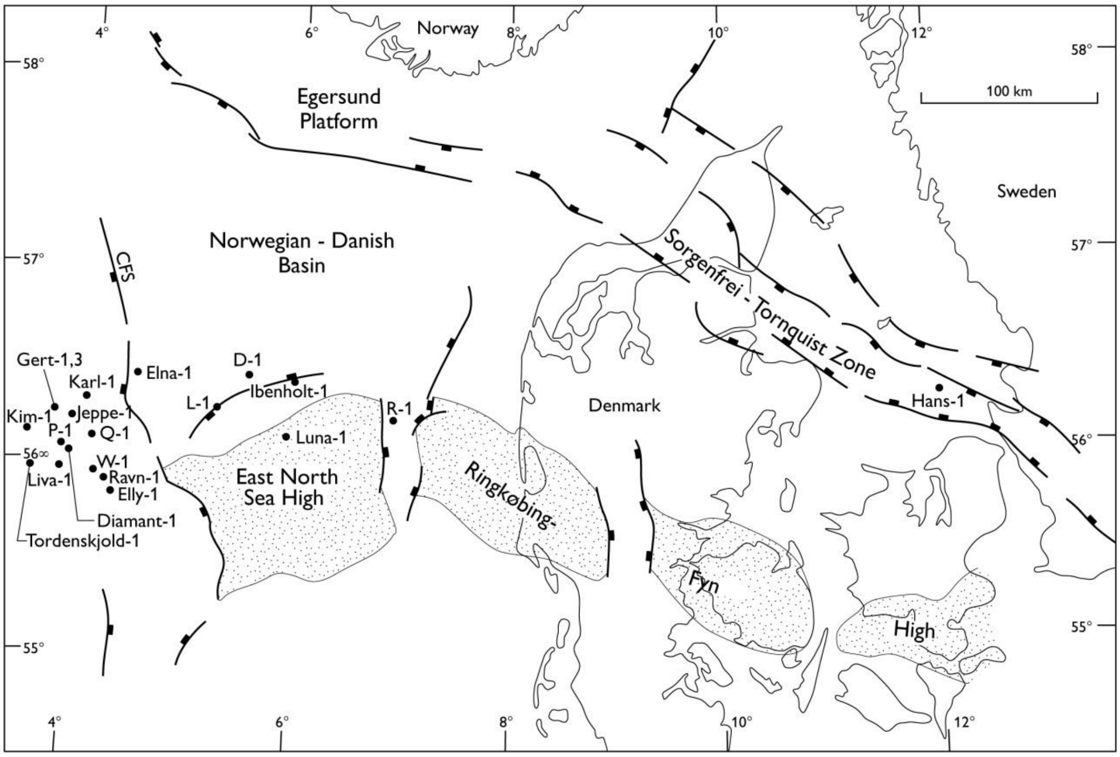

Figure 1. Location map showing the position of the Luna-1well on the Ringkøbing-Fyn High between the Central Graben and the Horn Graben. The map also shows wells in the Danish North Sea containing Rotliegend deposits from the Karl and Auk Formations. From Stemmerik *et al*. (2000).

Geological setting

In the central and northern North Sea, the Permian succession comprises the Rotliegend Group (red, continental siliciclastic sediments and volcanic rocks) and the Zechstein Group (carbonates, evaporites and local siliciclastic rocks). Lower Permian sediments are known from several deep wells (Nielsen & Japsen 1991, Glennie *et al*. 2003, Heeremans *et al*. 2004a), and the Early Permian palaeogeography is interpreted as arid continental deposits, characterized by various red bed facies (Stemmerik *et al*. 2000, Glennie *et al*. 2003). Most Danish successions are Lower Rotliegend, and aeolian sandstones, characteristic of the Upper Rotliegend in the Southern Permian Basin are generally absent, although these sandstones are known from the Elna-1 well.

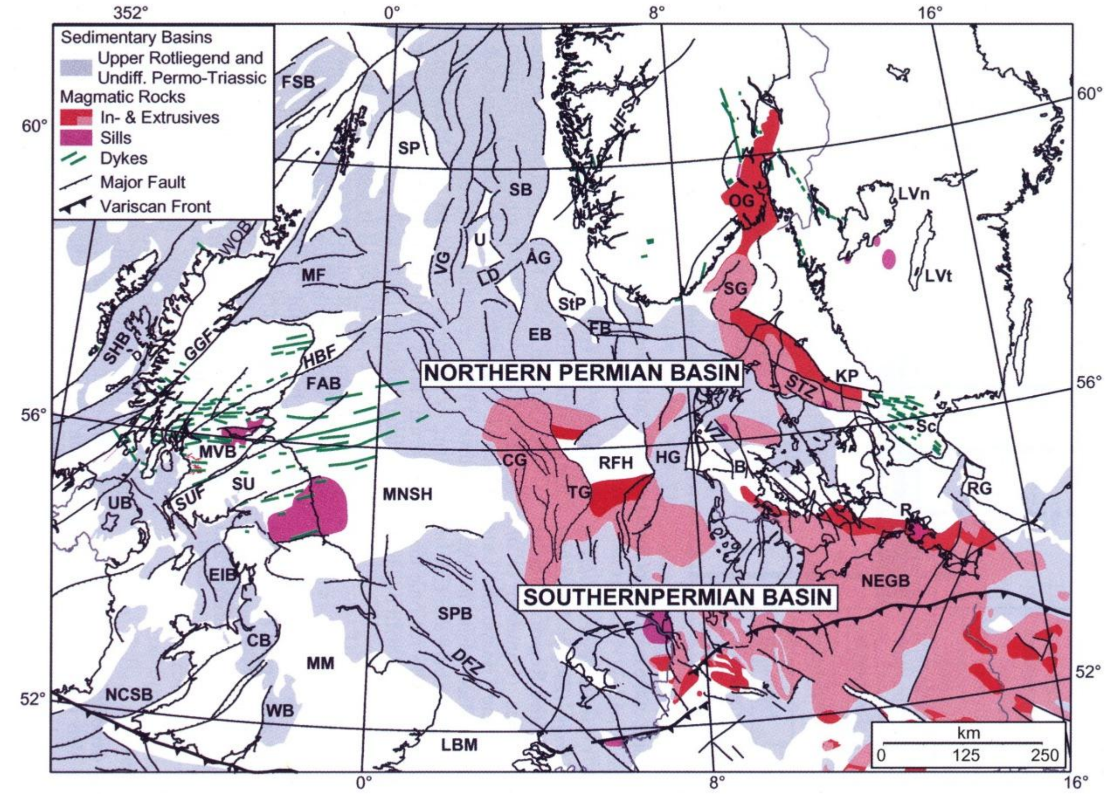

Figure 2. Geological map showing the distribution of Lower Permian volcanic rocks. CG: Central Graben, HG: Horn Graben, MNSH: Mid-North Sea High, RFH: Ringkøbing-Fyn High. From Heeremans et al. (2004a).

The Lower Rotliegend magmatic event started with the emplacement of large volumes of tholeiitic basalts over large parts of Europe at *c*. 300–295 Ma. Following this magmatic event, the North Sea remained an area of non-deposition until Upper Rotliegend continental sediments were deposited in the rapidly evolving Southern and Northern Permian Basins, separated by the discontinuous Mid-North Sea High and the Ringkøbing-Fyn High (Heeremans *et al*. 2004b). Volcanic rocks, referred to the Inge Volcanics Formation, in the well 39/2-4 on the easternmost margin of the Mid-North Sea High have been dated to 299 ± 3 Ma (Heeremans *et al*. 2004b). Data from the Oslo Graben, the NE German Basin, Scania, and the UK show that a widespread voluminous magmatic event took place at *c*. 300 Ma (Heeremans & Faleide 2004, Larsen *et al*. 2008). More Ar–Ar age dating is needed on the basalts of the Karl Formation in the Danish Central Graben to help correlate the timing of volcanism across the region (Heeremans *et al*. 2004b).

Studies in the Oslo Graben and in the Kattegat (the Hans-1 well) have revealed that the *c*. 300 Ma magmatic event was followed by the development of sediment-filled half-grabens (Michelsen & Nielsen 1993, Heeremans & Faleide 2004).These syn-rift deposits consist primarily of volcaniclastic material and probably belong to the Lower Rotliegend.

Lithostratigraphy

The Rotliegend Group in the Danish part of the Northern Permian Basin has been described by Stemmerik *et al*. (2000). They focused on four wells in the Danish part of the Central Graben (Elly-1, Gert-1, Gert-3, Karl-1) and one well, Elna-1, located on the northern Ringkøbing-Fyn High. They established the Karl Formation, which includes the syn-tectonic volcanic, volcaniclastic and sedimentary fill of the Lower Permian half-grabens in the Danish part of the Northern Permian Basin. The Karl Formation is overlain by the Auk Formation. The Karl Formation includes four distinctive lithologies, regarded as members (Stemmerik *et al*. 2000):

Formations	Members	Lithology	Occurrence in selected Danish North Sea wells
Auk		Sandstones and pebbly sandstones deposited in aeolian dunes, fluvial (wadi) channels and shallow sabkha lakes	D-1, Elna-1, Ibenholt-1
Karl	Liva	Basaltic lavas and tuffs classified as alkaline basalts, hawaiites and mugearites. Correlated to the Inge Volcanics Formation	L-1, D-1, R-1, Gert-1, Gert-3, Karl-1, Elly-1, Liva-1, Ravn-1
	Horn Graben Rhyolite	Rhyolitic lava flow(s)	R-1, C-1
	Elly	Redbrown siltstones, shallow lacustrine or sabkha deposits, below or between the volcanic rocks	D-1, L-1, Elly-1, Ravn-1
	Diamant	Volcaniclastic sandstones and conglomerates, Fluvial and alluvial	R-1, Liva-1, Diamant-1, Kim-1

Lithostratigraphy of the Danish North Sea part of the Northern Permian Basin, based on Stemmerik *et al*. (2000). The Auk Formation is known from numerous wells outside the Danish North Sea.

The basaltic volcanics of the Liva Member are more than 300 m thick in the Karl-1 well, whereas the Elly-1 and Gert-3 wells comprises thinner successions of volcanic rocks interbedded with lacustrine siltstones of the Elly Member (Stemmerik *et al*. 2000). Note the distinction between the volcaniclastic sandstones and conglomerates (Diamant Member) and the predominantly siliciclastic sandstones and conglomerates (Auk Formation).

Alluvial fan deposits

Blair & McPherson (1994) discussed the distinction between alluvial fans and rivers, and found that these two depositional systems differ with respect to morphology, hydraulic and sedimentary processes, and facies assemblages. Alluvial fans represent a naturally unique sedimentary environment and their most significant attributes are the semi-conical shape, restricted radial length (generally <10 km), plano-convex cross-profile, and comparatively steep slope (typically 2^o–12^o). Alluvial fans are constructed mainly by catastrophic fluid gravity flows (sheetfloods and incised-channel floods) or sediment gravity flows (rock falls, rock slides, rock avalanche, colluvial slides, and debris flows) generated through failure of bedrock cliffs or colluvial slopes in the drainage basin. It should also be noted that the conical shape on an alluvial fan precludes the development of floodplains (Blair & McPherson 1994). Consequently low-energy deposits are subordinate.

Blair (1999a, b) studied two adjacent modern alluvial fans dominated by sheetflood respectively debris-flow processes. The critical factor causing their dissimilarities in processes and facies is the contrasting lithology of the bedrock in their respective catchment areas. The alluvial fan dominated by sheetfloods represents a catchment area consisting almost entirely of crystalline rocks. The fan has an average slope of 2.6^o, a radius of 9.7 km and an area of 26.9 km^2.

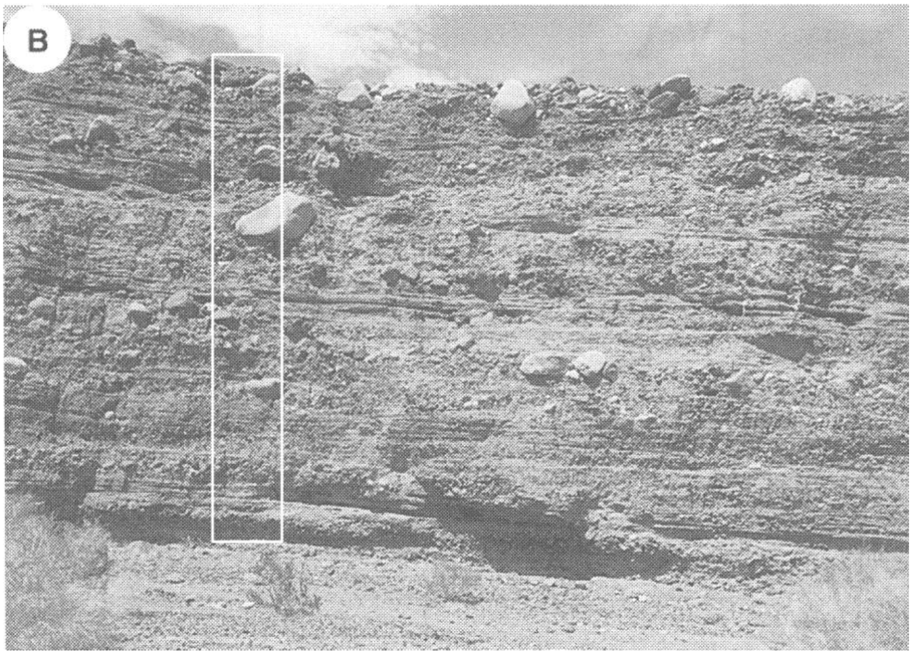

Figure 3. Sedimentary facies in a section at the Anvil Spring Canyon alluvial fan (Blair 199a, his Fig. 6B). The conglomerates show a subhorizontal stratification, and there is a marked contrast in grain-sizes. An out-sized clast is seen in the middle of the photo. The white frame outlines a section roughly comparable to the width of a core, and shows that the stratification is much less easy to recognize here.

The dominance of sheetflood processes, and the virtual absence of debris flows, is ascribed to (1) the lack of clay, and (2) the predominance of very coarse sand, granules and pebbles, because permeability is high and pore-throats are large. As a result the small amounts of fine-grained matrix are infiltrated and thus are not available for formation of debris flows (Blair 1999b). The sheetfloods have deposited poorly sorted, medium to very coarse-grained sand, with a clayey matrix, which is interpreted as infiltrated due to its occurrence as microlaminated grain coats or bridges between grains. Grain-size analysis of six samples show that they consist of 15–55% gravel, 44–71% sand, 0–9% silt and 0–3% clay (Blair 1999a, b). The majority of the conglomerates and pebbly sandstones were deposited by infrequent and catastrophic, upper-flow-regime sheetfloods, while the intervening periods only resulted in minor reworking by aeolian and fluvial processes. The strata have a few degrees dip either down the fan or uphill, but cross-bedding is rarely seen (Fig. 3).

Fluvial deposits

An overview of fluvial deposits is beyond the scope of this report, but it may be stated briefly, that fluvial depositional systems include fluvial channel and floodplain environments. Fluvial channels range from meandering channels with sandy bedforms and stable channel boundaries to braided channels with gravel bars and bedforms, which are transitional to alluvial fans. Depending on the fluvial discharge and climate the floodplain successions derive from overbank depositional processes, formation of palaeosols and accumulation of peat in swamps or shallow lakes (Collinson 1996).

Sedimentology of the Luna-1 core

The Luna-1 core has a length of 12 m and comprises dark red volcaniclastic conglomerates, which are dominated by granule and pebble-size clasts (2–64 mm) (Fig. 4, Enclosure). The largest clasts exceed 128 mm in diameter, but the majority of clasts are less than 32 mm in diameter. Sediments containing a mixture of sand and gravel range from pebbly sandstone (<30% gravel) to sandy conglomerate (30-60 % gravel) and conglomerate (>60% gravel) (Collinson *et al*. 2006, their Fig. 7.2). Most of the conglomerates in the Luna-1 core are clast supported and are divided into seven facies based on their maximum clast size, sorting and sedimentary structures.

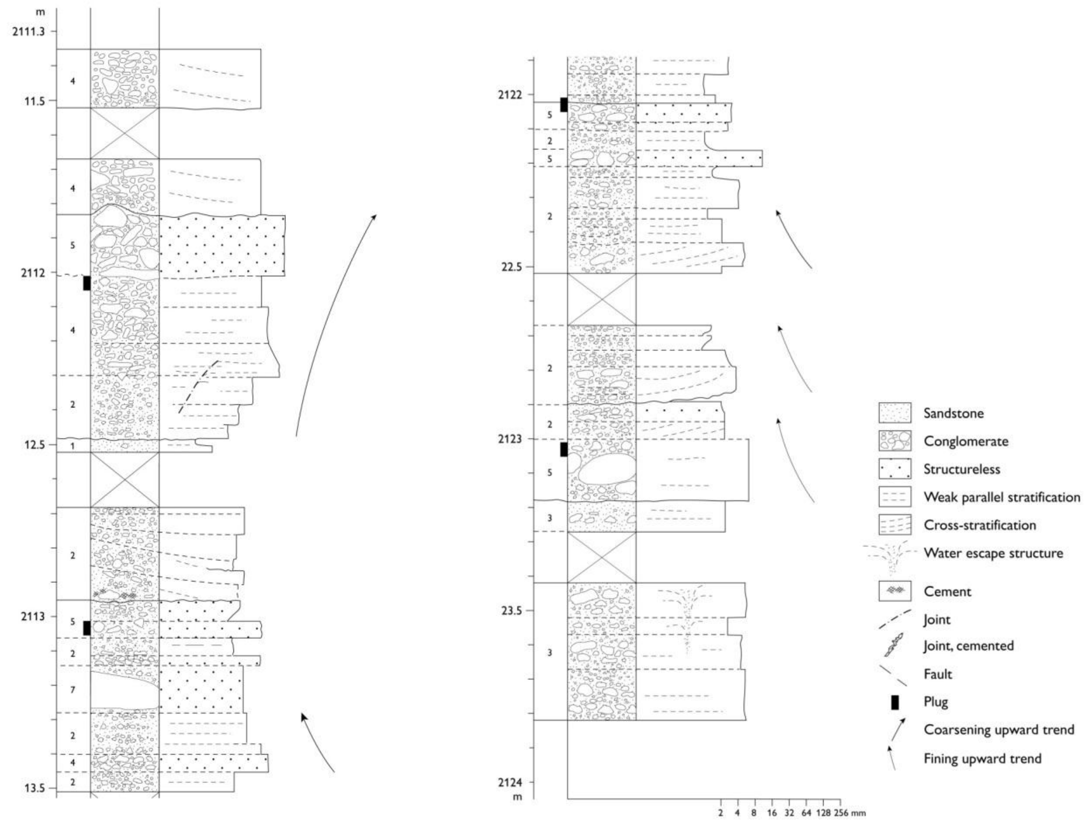

Figure 4. Sedimentological log of the core, which is divided into seven sedimentary facies. The entire log is found as an enclosure.

Grain-size of conglomerates. In the present study the maximum clast size is shown in the sedimentological logs. The maximum clast size in a bed is calculated according to Surlyk (1978): The diameters of the twelve largest clasts are measured, the two largest clasts are omitted, and the average diameter of the remaining clasts is calculated. This method is quick and discards the out-sized clasts. The large solitary clasts are indicated in the sedimentological log but they rarely contribute to the calculated grain-size.

The maximum clast size is a useful means of recording the fluvial energy during deposition (Collinson *et al*. 2006, their Fig. 7.7). The relationship between the largest size of bedload clasts that can be rolled relative to the largest size of particles that can be carried in suspension are shown in Fig. 5. For example a mean shear velocity of 0.25 ms^{-1} may move clasts up to 63 mm as bed-load, while matrix particles up to 1.95 mm may be carried in suspension. These values agree well with observations in the Luna-1 core, where the matrix is dominantly sand.

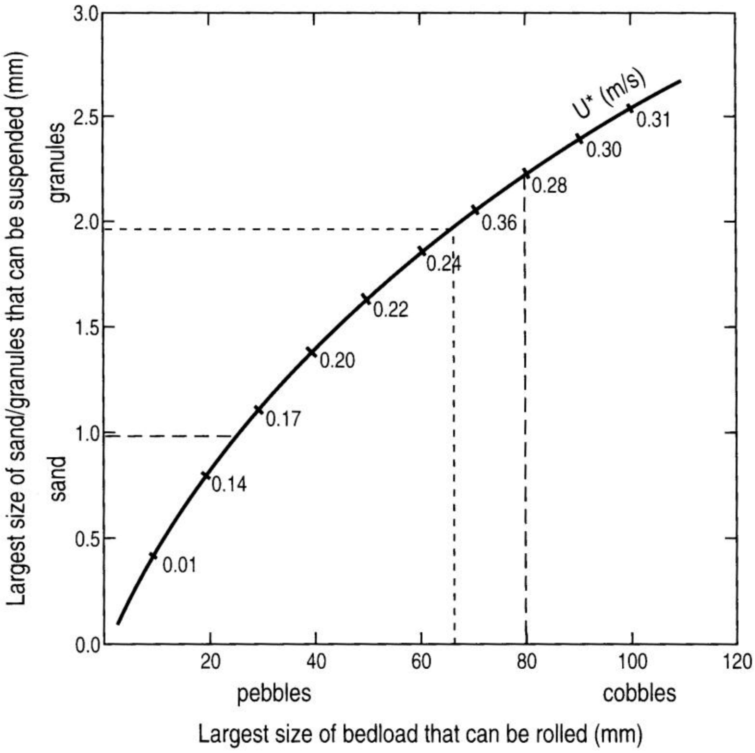

Figure 5. Diagram showing the relationship between largest clast size and particle size of matrix. From Collinson *et al*. (2006).

Clasts. All the clasts appear to be of volcanic origin and to be derived from lava flows. They differ in colour, number of vesicles, and amount and type of phenocrysts, and range from dense, fine-grained lithologies to lavas with numerous vesicles filled by white minerals, possibly zeolites. Some lavas are porphyric with feldspar phenocrysts. The different lithologies indicate a geochemical difference between the lava flows. All the large cobbles, with diameters of more than 128 mm, represent the same lithology: grey lava in which the olivine crystals are weathered and replaced by dark red clay (Fig. 6A). This lithology is intermediate, probably of andesitic composition (Lotte Melchior Larsen, pers. comm. 2012), and appears to be most stable against weathering and erosion. Intermediate igneous rocks are transitional between basic and silicic, generally having a silica content of 54–65 %, such as andesite and trachyte. Characteristic clast lithologies are shown in Fig. 6B. The largest clasts are rounded to well rounded, whereas several of the smaller clasts are subangular. This suggests that the largest clasts were

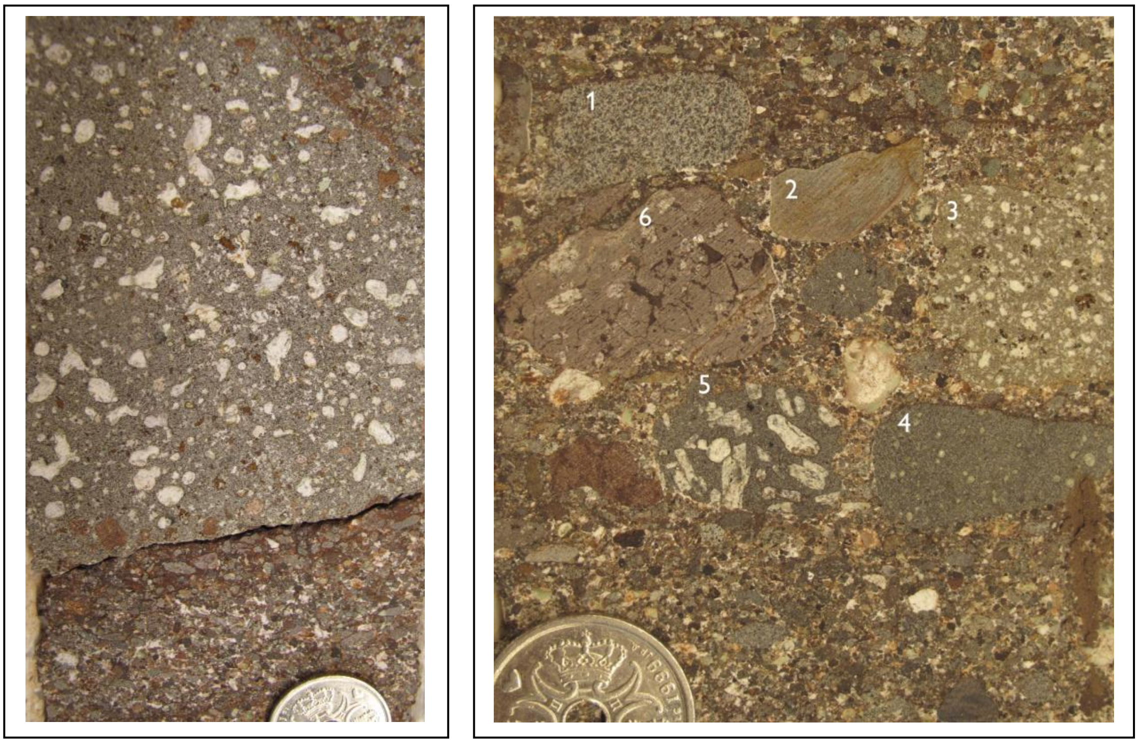

Figure 6. A: The grey lava of intermediate composition, which constitutes the out-sized clasts. Numerous vesicles filled with a white mineral (not determined). Small brown spots are weathered olivine phenocrysts. B: An assemblage of rounded clasts of different volcanic lithologies. Coin for scale, 24 mm in diameter.

Figure 7. Volcanic clasts, derived from Paleocene lavas, on a recent alluvial fan, Qorlortorssuaq, north coast of Disko, West Greenland.

worn effectively during transport (rolling). Figure 7 shows various volcanic lithologies on a modern alluvial fan at Qorlortorssuaq, West Greenland. An aerial view of this alluvial fan (Fig. 8) shows that the fluvial water is red to brown due to a large load of suspended particles.

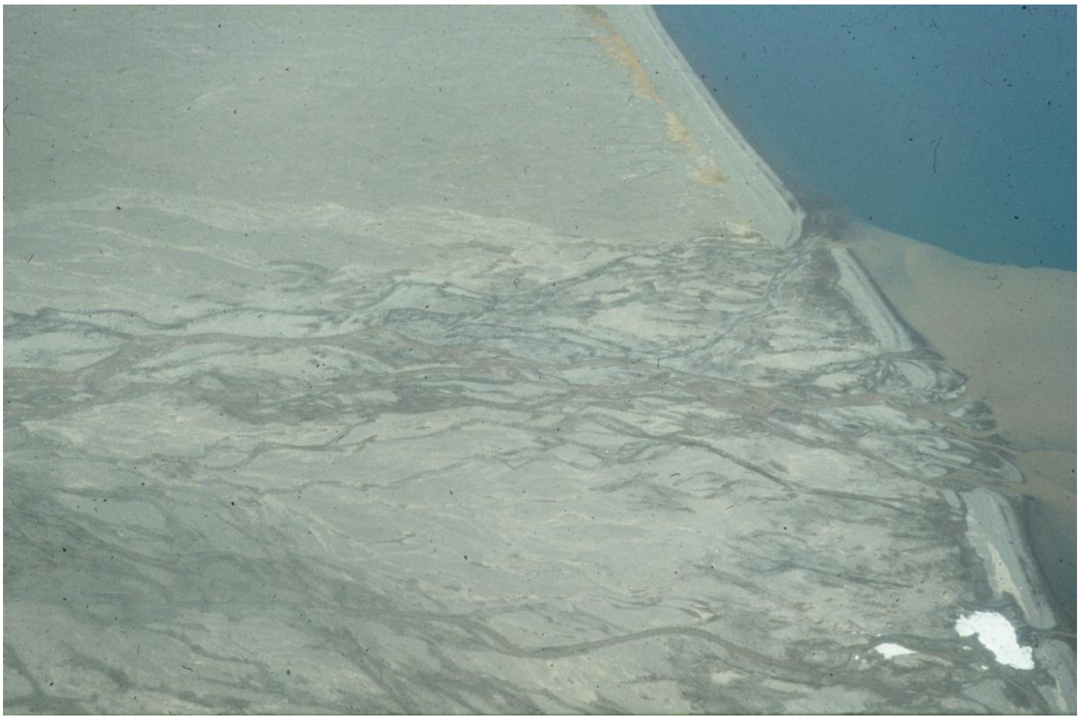

Figure 8. The alluvial fan at Qorlortorssuaq, note that the water in the river is coloured by the large amount of suspended material.

Matrix. The matrix of the conglomerates consists of dark red (coated) sand grains and small rock fragments of 2–3 mm size. The matrix is dark red, and the colour is interpreted as partly derived from red clay carried in suspension and partly from *in situ* weathering and oxidation of iron-bearing minerals.

Grading and bed boundaries. Most beds are moderately well sorted, and boundaries between beds are mostly transitional, and only rarely it is possible to see sharp or erosive boundaries. These features make it difficult to observe normal or inverse grading within the beds, and only few beds do clearly show normal grading. Due to the transitional boundaries it is generally difficult to identify upward fining or upward coarsening successions.

The large grain-size and the relative good sorting indicate deposition by unidirectional currents in water. The scarcity or absence of inverse grading indicates that the sediment was not deposited from debris flows. The clasts and matrix of the conglomerates are interpreted as deposited from bedload and suspended load in traction currents.

Sedimentary facies

The Luna-1 core is divided into seven facies, listed in the table below. The sedimentary facies are also indicated on the sedimentological log (Fig. 4, Enclosure).

Grain-size Class	Clast length (mm)	Rock name	Luna-1	Facies	
Cobble	128–256	Coarse cobble conglomerate		7	Debrisflow with large clasts
	64–128	Fine cobble conglomerate	Dominant grain-sizes	6	Very coarse pebbly conglomerate
Pebble	32–64	Very coarse pebble conglomerate			
	16–32	Coarse pebble conglomerate		5	Coarse pebbly conglomerate
	8–16	Medium pebble conglomerate		4	Pebbly conglomerate
				3	Muddy pebbly conglomerate
	4–8	Fine pebble conglomerate			
Granule	2–4	Granule conglomerate		2	Stratified pebbly sand
Sand	0.5–2	Coarse-grained sandstone			
	0.125–0.25	Fine-grained sandstone		1	Fine-grained sandstone

Sedimentary facies in the Luna-1 core

Facies 1: Fine-grained sandstone. The sandstone is dark red-brown, structureless and may contain some silt as well as a few small clasts. It thus represents the finer particles occurring in the matrix of the conglomerates. Facies 1 occurs only as two thin beds.

Facies 1 is interpreted as deposited from suspension in a low energy environment, possibly a small channel in a braided fluvial system.

Facies 2: Stratified pebbly sand. The sandstone is greyish red and contains varying proportions of small clasts, typically less than 4 mm in diameter (Fig. 9). The sediment is fairly well sorted and a crude horizontal to low-angle cross-stratification is seen. The average grain-size varies between successive beds.

Facies 2 is interpreted as deposited from fluvial processes. The low angle stratification indicates that dunes or cross channel bars were scarce or absent, which suggests that the pebbly sand was deposited by un-channelized flows.

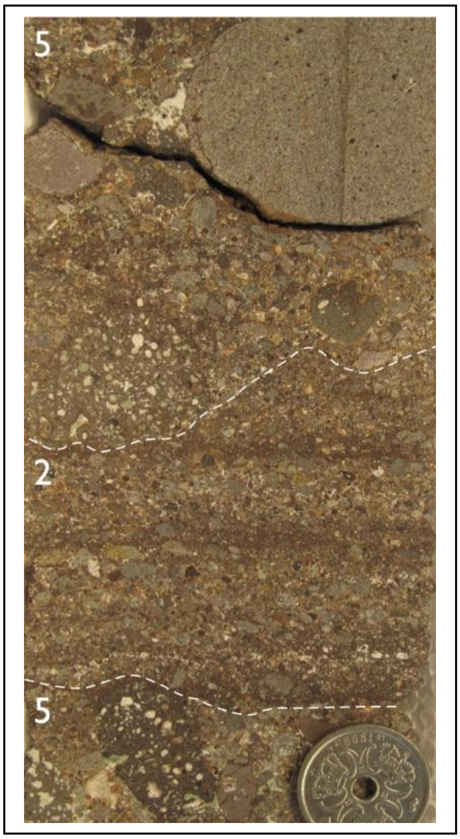

Fig. 9. Stratified pebbly sand, facies 2, interbedded with coarse pebbly conglomerate, facies 5. Coin for scale, 24 mm in diameter.

Facies 3: Muddy pebbly conglomerate. Angular pebbles, moderately sorted, typically 8-12 mm in diameter, are deposited with a dark red muddy matrix. The conglomerate has a vague stratification and is predominantly clast-supported. The conglomerate shows no grading. It occurs only in the basal part of the core, and the stratification is cut by a vertical water-escape structure.

Facies 3 is interpreted as a series of minor debris flows, which redeposited surface deposits of an alluvial fan.

Facies 4: Pebbly conglomerate. Sub-angular to sub-rounded pebbles form a clast-supported conglomerate. In some beds the clasts are elongate and vaguely imbricated. Some conglomerate beds contain very little matrix, and the original porosity is now filled by a white mineral, not calcite but otherwise undetermined (Fig. 11A). Other conglomerate beds are moderately sorted, with a matrix of coarse-grained sand and granules. A faint stratification may be seen in the conglomerates. The pebbly conglomerates of facies 4 show transitional boundaries to facies 2 and facies 5.

Facies 4 is interpreted as deposited by fluvial processes and the clasts were transported as bedload. The lack of sedimentary structures suggests that the conglomerate may have been deposited by ephemeral, un-channelized floods.

Facies 5: Coarse pebbly conglomerate. Sub-angular to rounded pebbles form a clast-supported conglomerate. Few conglomerate beds are almost devoid of matrix, but most beds are moderately sorted, with a matrix of coarse-grained sand and granules (Fig. 9). The original porosity is now filled by a white mineral, which has not been determined. It is not possible to recognize stratification in the pebbly conglomerate in the core.

Facies 5 is interpreted as a fluvial deposit dominated by clasts transported as bedload, and the shape suggests that they rolled. The lack of sedimentary structures suggests that the conglomerate may have been deposited by ephemeral, un-channelized floods.

Facies 6: Very coarse pebbly conglomerate. Sub-rounded to rounded pebbles form clast-supported conglomerates. The large size of the pores between the clasts is filled with matrix and smaller clasts, and consequently this conglomerate appears only moderately sorted. There is a gradual transition between facies 5 and 6. Some of the conglomerate beds show an indistinct normal grading.

Facies 6 is interpreted as a fluvial deposit dominated by clasts transported as bedload, and the shape suggests that they rolled.

Facies 7: Debrisflow with large clasts. The core has penetrated a number of large clasts, which all are surrounded by a few centimeters of sandstone. The size of the clasts is larger than the diameter of the core, and the clasts appear to be solitary (compare Fig. 3). They are rounded and all of them represent the same lithology, a grey volcanic rock with altered phenocrysts of olivine. It should be noted that these out-sized clasts generally are not associated with the very coarse pebbly conglomerate but occur in the finer grained facies 2. The large clasts are all much larger (2-3 times larger) than the clasts in the coarse pebbly conglomerate (facies 6).

Facies 7 is tentatively interpreted as an alluvial fan deposits. Alluvial fans have a higher gradient than braided fluvial channels and the gradient may make the transport of cobbles easier, either if the clasts bounce down the fan or if their transport is assisted by a veneer of sand and mud which reduce the roughness of the surface of the fan.

Depositional environment

Facies 1, 2, 4, 5, and 6 are interpreted as deposited by fluvial processes, as bedload and suspended load. The scarcity of cross-bedding and the poorly developed, upward-fining successions indicate that fluvial bedforms, such as dunes or cross-channel bars, were rare. This suggests that the fluvial channels were poorly developed, and that deposition was characterized by ephemeral floods. Facies 3 and 7 probably represent debris flow deposits. The large clasts in facies 7 suggest that the depositional system may have been an alluvial fan. Facies 1–6 may well have formed part of an alluvial fan.

In an arid climate floodplain deposits would be likely to include fine-grained sandstones or mudstones with desiccation cracks and caliche nodules. Fine-grained sediments are very rare in the core, and caliche nodules have not been observed either *in situ* or as reworked pebbles. It is therefore concluded that floodplain deposits are not present in the Luna-1 core. Their absence supports the interpretation of the depositional environment as an alluvial fan.

The clasts in the conglomerates are all of volcanic origin. Their subangular to rounded shapes indicate that they were transported over some distance. The core demonstrates several volcanic lithologies, most of which indicate an intermediate composition.

The depositional model (Fig. 10) shows that the volcaniclastic deposits of the Diamant Member were deposited in fault-bounded half-grabens (Stemmerik et al. 2000: their Fig. 9). Alluvial fans would fit well into such a depositional setting. It is likely that the volcanic rocks of the Karl Formation provided the volcanic clasts, and the cored succession should be referred to the volcaniclastic Diamant Member of the Karl Formation.

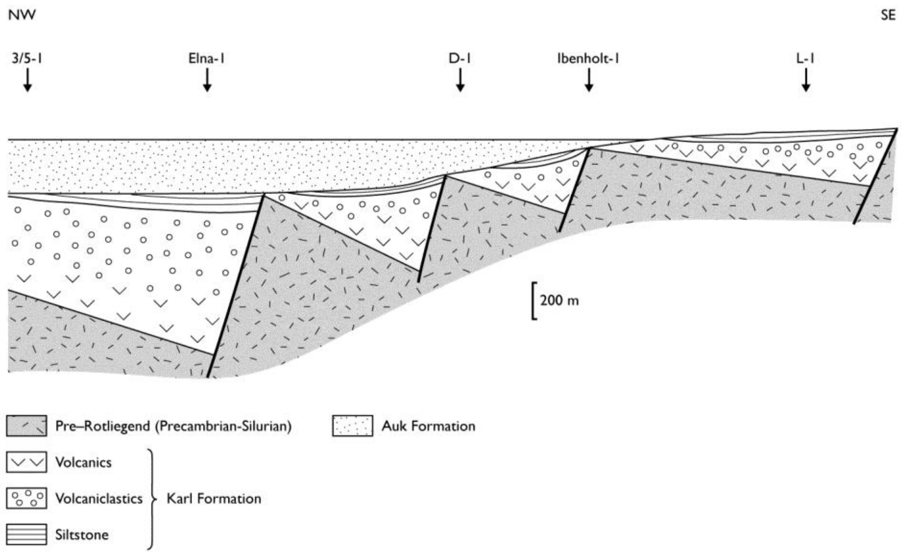

Figure 10. Depositional model for the volcaniclastic sediments referred to the Diamant Member of the Karl Formation. From Stemmerik *et al*. (2000).

Diagenesis

Pore-filling cement is seen in several of the sedimentary facies, but is best developed in well-sorted pebbly conglomerates of facies 5 (Fig. 11A). The pore-filling mineral is not calcite, but the mineral has not been determined.

The core is cut by a few joints, and some of these are filled with a white, coarse-crystalline mineral, which has not been determined (Fig. 11B). The mineral within the vesicles in the lava clasts has not been determined. This mineral may have been precipitated before erosion of the lava flows.

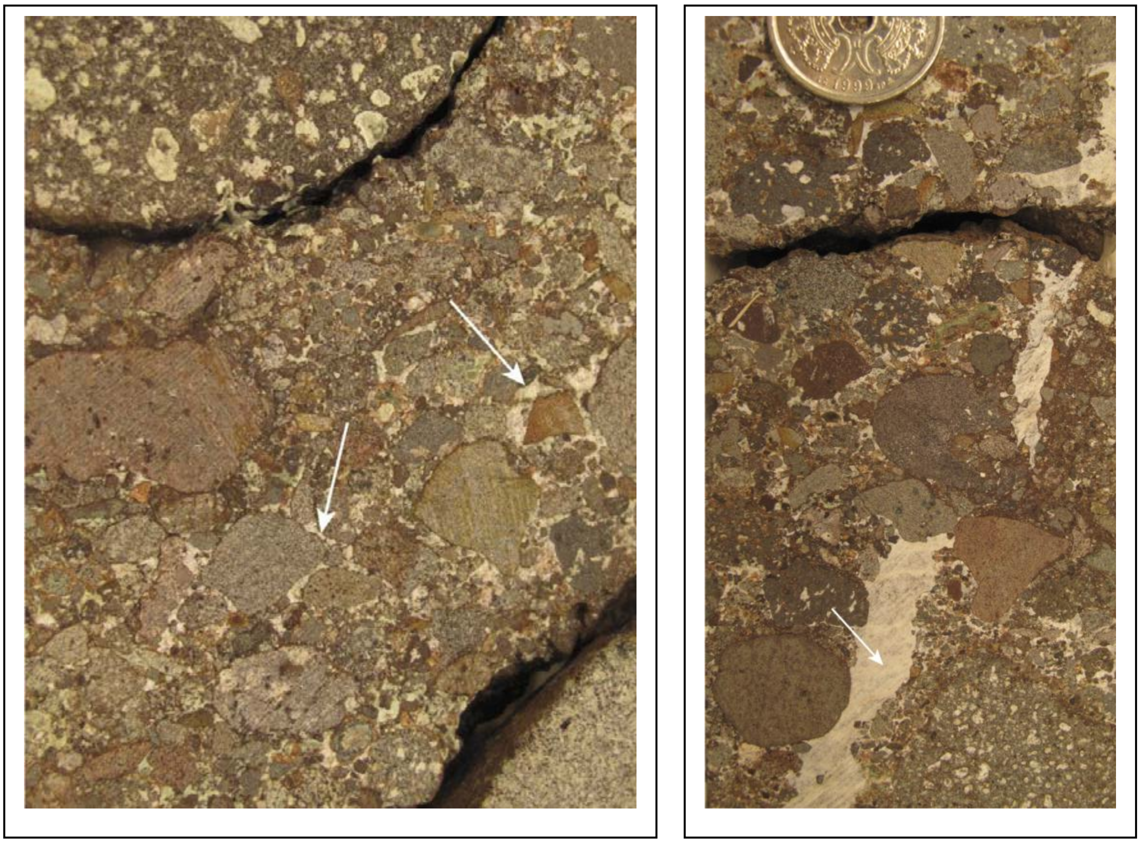

Figure 11. Precipitation of cement. Left: White mineral is precipitated in original pores in the conglomerate (arrows), Right: White mineral precipitated in joints cutting the bedding. Coin for scale, 24mm in diameter.

Summary

The 12 m long core from Luna-1 represents a succession of pebbly volcaniclastic conglomerates, referred to the Diamant Member of the Lower Permian Karl Formation. The coarser-grained conglomerates are all clast supported, and the clasts are rarely imbricated. The sediments are divided into seven facies on basis of maximum grain-size, sorting and stratification. The conglomerates are interpreted as fluvial and alluvial fan deposits. The porosity is low due to matrix as well as precipitation of diagenetic minerals in the pores.

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