Calibration of spectral gamma-ray logs to deltaic sedimentary facies from the Cretaceous Atane Formation, Nuussuaq Basin, West Greenland

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Gamma-ray logs are widely used as a lithology indicator in wells as part of standard petrophysical interpretations. In cored wells, gamma-ray logs should always be calibrated to the lithology in order to correct the petrophysical model. Gamma radiation is emitted from three elements, K, Th and U (potassium, thorium and uranium) which occur in minerals such as feldspar, mica, glauconite, clay minerals, zircon, titanite and apatite as well as in organic complexes. Organic-rich mudstones usually have high gamma-radiation values and quartz-rich sandstones low values. In many places, upward-coarsening successions are recognisable from the gamma log. The gamma log records the sum of radiation from K, Th and U, and their relative contributions are measured in a spectral gamma-ray log. The present case study focuses on spectral gamma-ray characterisation of the deltaic Atane Formation which shows well-developed, upward-coarsening delta-front deposits in outcrops (Fig. 1C).

Geological setting

The Nuussuaq Basin is a rift basin, which contains the only exposures of Cretaceous and Paleocene sediments along the west coast of Greenland. The siliciclastic sediments are overlain by a thick pile of volcanic rocks (Chalmers *et al*. 1999; Dam *et al*. 2009). During Late Cretaceous, Greenland was characterised by a warm and probably humid climate. The sediments range from alluvial fans overlying deeply weathered Precambrian basement through marginally marine deposits to marine deep-water deposits, all referred to the Nuussuaq Group (Dam *et al*. 2009). The floodplains and delta plains had a rich flora, recorded in well-preserved plant

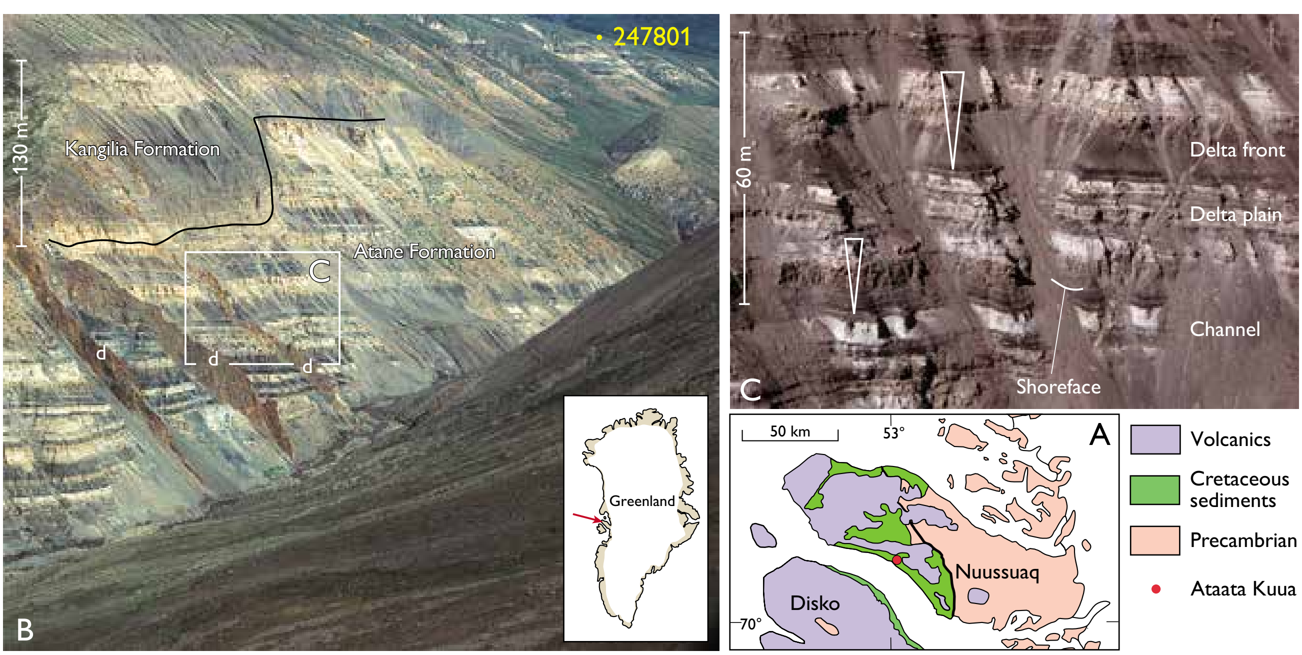

Fig. 1. **A:** Geological map of central West Greenland showing the location of Ataata Kuua on the south coast of Nuussuaq. **B:** The Atane Formation is erosionally overlain by the Kangilia Formation in the western slope of Ataata Kuua. The yellow dot marks the drilling site of borehole 247801, **d**: dyke. Height of section *c.* 500 m. The frame shows the position of Fig. 1C. **C:** The Atane Formation with depositional environments indicated. Note the distinct coarsening-upward successions (triangles). Height of section *c.* 100 m.

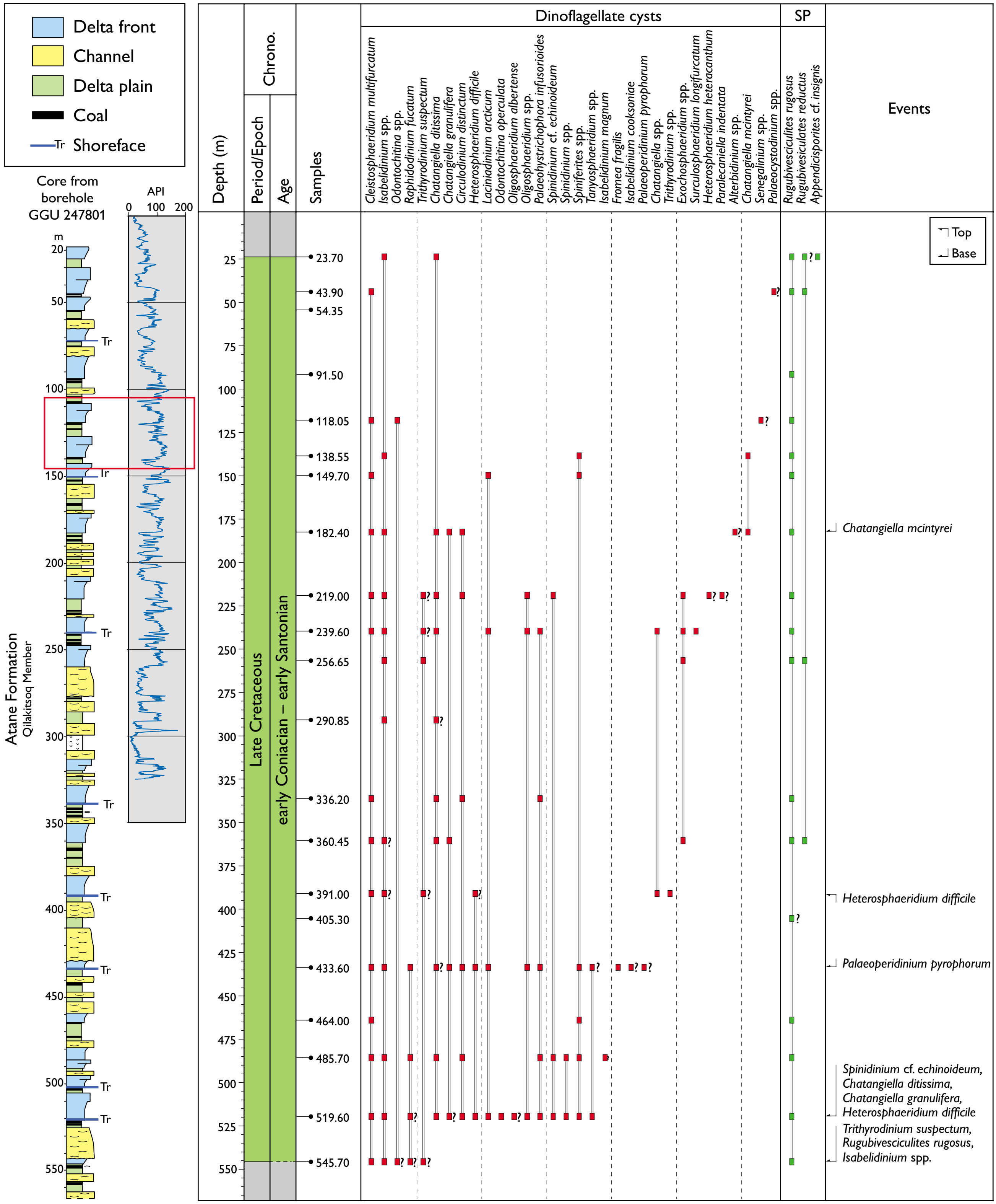

Fig. 2. Data from borehole 247801: a simplified sedimentological log of the entire core (566 m), a gamma log measured in the borehole to a depth of 320 m, and the new range chart for the dinoflagellate cysts in core samples. **API:** American Petroleum Institute units. GGU 247801 is located at 70°19.87′N, 52°55.8′W. The framed interval is shown in Fig. 3. The drill site is shown in Fig. 1B.

macrofossils and abundant comminuted plant debris. A huge volume of non-marine to shallow marine deposits constitutes the Cretaceous Atane Formation, which is well exposed along 65 km of the south coast of Nuussuaq from sea level to altitudes of 500–800 m. Seismic data indicate a minimum thickness of 3000 m for the formation (Dam *et al*. 2009).

Ataata Kuua – A narrow fluvial valley at Ataata Kuua, on the south coast of Nuussuaq (Fig. 1), shows the deltaic Atane Formation erosively truncated and overlain by the turbiditic, Paleocene Kangilia Formation (Dam *et al*. 2009). In 1980, the Geological Survey of Greenland drilled a 566 m deep borehole (GGU 247801) at Ataata Kuua as part of a regional study of the composition and distribution of coal in the Atane Formation. The entire succession was cored, with 100% recovery, and a gamma log was measured in the upper 320 m of the borehole. This gamma log as well as a simplified sedimentological log of the entire core are shown adjacent to the new biostratigraphical range chart in Fig. 2.

Biostratigraphy – In recent studies of 21 delta-front mudstone samples from core 247801, palynomorphs have been examined (Fig. 2). The diversity and density of dinoflagellate cysts, spores and pollen are very low, but the presence of *Chatangiella granulifera*, *Heterosphaeridium difficile* and *Spinidinium* cf. *echinoideum* in the lower part and *Chatangiella mcintyrei* and *Spinidinium* cf. *echinoideum* in the middle to upper part indicates an early Coniacian age or younger. An early Santonian minimum age of the upper part of the core is indicated by the presence of *Rugubivesciculites* spp., the absence of Campanian marker species and by the presence of *Heterosphaeridium difficile, Laciniadinium arcticum* and *Spinidinium* cf. *echinoideum* in a sample from the Ataata Kuua 2004-3 section situated immediately above the site of borehole 247801. The relatively uniform dinoflagellate assemblage recorded throughout the core (Fig. 2) supports the interpretation of a relatively high sedimentation rate.

Sedimentology – The delta deposits of the Atane Formation represent four depositional environments: delta front, distributary channel, delta plain and shoreface (Figs 1C, 2, 3). The delta-front deposits include mudstones, heterolithic sandstones with wave-generated sedimentary structures and well-sorted sandstones, all with comminuted plant debris. The distributary channel deposits are mostly cross-bedded, medium- to coarse-grained sandstones with some feldspar grains. The delta-plain mudstones are interbedded with coal beds or thin sandstone beds. The thin shoreface sandstones contain abundant marine trace fossils and overlie erosive surfaces. The delta-front deposits and the overlying fluvial sandstones form distinctly upward-coarsening units (Figs 1C, 2, 3), interpreted as formed during delta progradation. The shoreface sandstones are interpreted as deposited during a transgression. A detailed log of the core is shown in Dam *et al.* 2009 (fig. 43).

The dominant minerals in the mudstones are quartz and kaolinite, neither of which contain more than traces of K. Small amounts of K-feldspar and mica result in a K content about 1.3–1.8% K_2O, significantly lower than the 2.7% K_2O of average mudstones (Rider 1990). All mudstones and many sandstones in the Atane Formation contain comminuted debris from higher land plants. Total organic carbon (TOC) values of the non-marine delta-plain mudstones range from 3 to 15% and include thin coal beds with 50–65% TOC (Pedersen *et al*. 2006). The marine delta-front mudstones contain 6–14% TOC, with the highest values in the fine-grained, lower part, which includes a flooding surface and had a low sedimentation rate. Despite this, marine organic particles, such as dinoflagellate cysts, only form a small part compared to terrestrial organic matter.

The gamma log obtained in the borehole shows, as expected, low values for the fluvial sandstones whereas the mud-dominated delta-front and delta-plain deposits are difficult to identify from the gamma log alone (Fig. 2). In order to document the contributions of K, Th and U to the total gamma radiation we measured the spectral gamma radiation (Fig. 3). K is mainly located in feldspar, mica and glauconite; Th and U are hosted in zircon, titanite, and apatite. Clay minerals may contain small amounts of Th, and organic complex compounds may contain U.

Spectral gamma-ray characterisation

Core scanning – The core interval was scanned at the core laboratory at the Geological Survey of Denmark and Greenland using a set-up which allows simultaneous spectral gamma-ray and density measurements. The spectral gamma-ray analysis is carried out using two 15 cm NaI (Tl) crystals and the bulk density is determined using a caesium source. The scanning speed was 1 cm/min., corresponding to a vertical resolution of approximately 2 cm for the density log. The scanning data thus supply high resolution data to support sedimentary and geochemical data from the core, as exemplified in Fig. 3.

Results – The upward-coarsening successions, which are clearly seen in the field and in the core (Figs 1C, 2, 3), are difficult to identify on the total readings of the spectral gamma log (Fig. 3). The grain-size trends are, however, reflected in the Th and K logs, which are negatively correlated. The mudstones have high Th and low K contents, whereas the sandstones have high K and low Th contents. No distinct

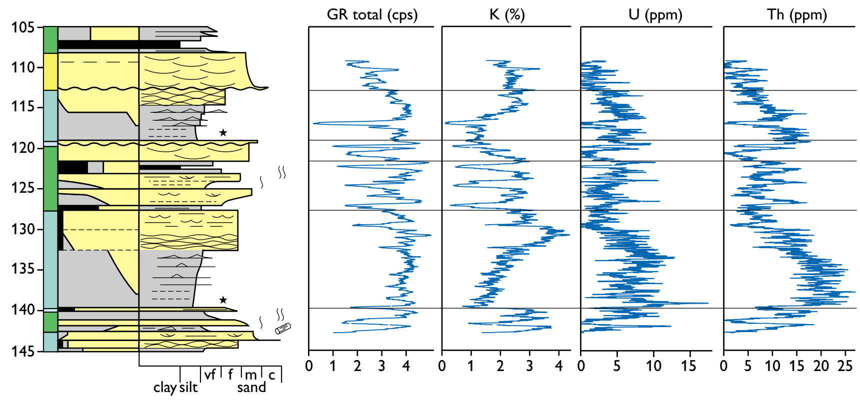

Fig. 3. Spectral gamma logs from 40 m of the core from borehole 247801. Note the difficulty in interpreting the total gamma radiation log, the negative correlation between K and Th content, and the absence of maxima on the U log. The core section is located in Fig. 2. Yellow: sandstone, grey: mudstone, black: coal or plant debris, black stars: pyrite. **cps**: counts per second. The total gamma radiation (**GR**) may be compared to the radiation measured in the borehole (Fig. 2).

relationship between high U content and mudstone grain-size is seen.

Ruffell *et al.* (2003) presented a model for the flux of K, U and Th in different weathering systems at basin scale. One of their scenarios is a basin with a low-relief hinterland and a humid climate, which applies to the depositional setting of the Atane Formation. The model predicts that chemical weathering dominates and that K and U are removed in solution to sea water, while Th is concentrated in detrital clay. This model may explain the relatively high Th radiation in the detrital mudstones of the Atane Formation. K-feldspar is a minor constituent of the sandstones but contributes significantly to the K-radiation in the sandstones. The model further predicts that K and U are enriched in authigenic minerals in the basin. Such enrichment of U is not observed in the Atane Formation, possibly due to the relatively high sedimentation rate. The low U content may also reflect the predominance of land plants (type III kerogen) that generally contain small amounts of U in organic complexes compared to marine organic material. A comparison of sedimentological logs from delta-front successions with their total gamma radiation in a case study from Ireland also indicates that the delta-front successions are difficult to identify from the gamma log alone (Davies & Elliott 1996).

Summary

The present study demonstrates the importance of calibrating petrophysical logs to core data. The cyclicity which characterises the Atane Formation in outcrops and cores (Figs 1, 2), and which would be a means of identifying the Atane Formation in an un-cored well, is obscured in the total gamma-ray log. This fails to resolve the grain-size variation in the Atane Formation because the presence of K-poor kaolinite, despite enrichment by Th, provides a 'cleaner' signature of the mudstones while the presence of sand-sized K-feldspar gives a 'dirtier' signature of the sandstones. The Th log can, to some degree, resolve the lithological variation but the energy is too small to be reflected in the total gamma-ray signal. The high sedimentation rate and the predominance of terrestrial organic material precluded the development of a characteristic U signature in the marine mudstones. The gamma log thus shows the variations in elements which occur in small amounts, because the bulk of the sediment (quartz, kaolinite and terrestrial coal debris) contributes very little to the gamma-ray radiation.

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