Sedimentology and stratigraphy of the sediments from cores drilled by Falconbridge Ltd. in 1994 at Serfat, northern Nuussuaq, West Greenland

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Sedimentology and stratigraphy of the sediments from cores drilled by Falconbridge Ltd. in 1994 at Serfat, northern Nuussuaq, West Greenland

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Abstract

During a mineral exploration programme in the Disko–Nuussuaq region in West Greenland in 1994, the Canadian company Falconbridge International Ltd. drilled 5 holes in a sill complex situated in the Serfat area. Three of the holes penetrated the sill complex and into the underlying sedimentary succession. In one of the holes they penetrated a zone of pressurized gas.

The dinoflagellate cysts and the general understanding of the area suggest a Campanian–Maastrichtian age of the cored sediments. The cored sediments have been divided into five facies associations; 1) mudstone, 2) thinly interbedded mudstone and sandstone, 3) strongly bioturbated thinly interbedded mudstone and sandstone, 4) chaotic beds, 5) medium- to coarse-grained sandstone. The sediments are arranged in coarsening-upward successions, 30–85 m thick, deposited from depositional lobes in a submarine fan environment. It has been possible to correlate two of the wells. This correlation indicates that the coarsening-upward successions and facies associations are laterally continuous over a distance of at least 400 m. Moreover, the correlation indicates that within the drilled area the Serfat sill complex is parallel to the sedimentary bedding and that the regional strike is approximately WNW–ESE, and the dip towards SSW. Finally, the correlation suggests that the zone with a pressurized gas seam, would also have been penetrated in a second well if drilling had been continued for a few more metres.

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INTRODUCTION

During a mineral exploration programme in the Disko-Nuussuaq region in West Greenland in early August 1994, the Canadian company Falconbridge International Ltd. drilled 5 holes in the Serfat area. The purpose of their programme was to test several magnetic, gravity and EM features in the vicinity of and closely associated with the Serfat sill complex. The drilling was performed by Petro Drilling Company Ltd., Canada. A wire-line diamond drilling outfit (Fly-In model 38 Longyear with a Deutz engine) was retrieved. A total of 1076.25 m of core with a recovery close to 100% was sampled in the 5 holes, and is now stored at the Geological Survey of Denmark and Greenland in Copenhagen. The hole diameter is 60 mm (2 23/64 inches; BQ rods), and the core diameter 36.5 mm (1 7/16 inches). All technical data from the drilling programme are presented in Olshefsky *et al.* (1995). The locations of the drill sites are shown in Fig. 1. Three of the drill holes penetrated the sill complex and into the underlying sedimentary succession (FP94-11-02, FP94-11-04, FP94-11-05) (Olshefsky *et al.*, 1995). In two of the holes the drillers locally reported gas bubbles in the sedimentary succession while the cores were emptied from the core tube (FP94-11-02 and FP94-11-04), and close to the bottom of the latter hole they penetrated a zone of pressurized gas (Fig. 2). Christiansen *et al.* (manuscript) have summarized the main results of the organic geochemistry of gas and migrated bitumen from the cores. The aim of the present report is to present the sedimentological and palynostratigraphic data from the cores and establish a correlation between the wells.

GEOLOGICAL SETTING

The Serfat area is situated 3-5 km west of the major Saqqaq-Ikorfat fault zone which separates basement (occasionally with a thin cover of non-marine Upper Cretaceous-Lower Paleocene sediments or Tertiary volcanics) to the east from thick Cretaceous-Tertiary sedimentary successions overlain by Tertiary volcanics to the west. Movement along this fault zone took place during several episodes in the Cretaceous and Tertiary with a total vertical displacement of more than 1 km.

The Serfat area, in contrast to many other localities on the north coast of Nuussuaq, was not studied during the recently completed studies of the sedimentology, biostratigraphy and organic geochemistry of the Upper Cretaceous–Lower Tertiary marine sediments (Christiansen *et al.*, 1994; Nøhr-Hansen, 1994). This was due to the limited number of outcrops and the strong thermal alteration of the sediments in the vicinity of the thick Tertiary sills.

The sill complex at Serfat was studied in detail by Munck (1945). The main sill consisting of quartz dolerite and dolerite is more than 100 m thick and is exposed along the coast and in some gullies along a distance of 2 km. Although irregular in places, the sill seems to have a general dip towards south-west. The sill is overlain and cross-cut by a picritic sill with a thickness between 10 and 25 m; towards west there is a sediment wedge between the sills, towards east a direct contact.

Munck's descriptions of thickness, orientation and petrography of the sills have been confirmed by Falconbridge's drilling programme that penetrated both sills in 3 holes (Figs 1, 2). Moreover, the drilling programme has shown that the sill complex strikes WNW–ESE and is approximately parallel to the bedding (Fig. 2). The sediments in the Serfat area are strongly thermally altered and have a pale colour and greasy appearance (Munck, 1945). Farther west the sedimentary succession is relatively well exposed, especially in the Kangilia–Annertuneq area where it consists of marine shales of Late Campanian to Early Paleocene age with some sandstone and one impressive conglomerate previously known as the Danian basal conglomerate (Henderson *et al.*, 1976; Rosenkrantz, 1970). This conglomerate is now known to have been deposited during the Late Maastrichtian and is associated with a major fall in relative sea-level (Dam & Sønderholm, 1994).

The sediments along this part of the north coast of Nuussuaq seem to have a shallow dip. The Late Campanian *I. Cooksonia* dinoflagellate interval described by Nøhr-Hansen (1994) has probably only a slightly lower position (max. 100–200 m) close to Serfat compared to Annertuneq, suggesting that the contact metamorphic sediments at sea-level at Serfat are Late Campanian in age.

PALYNOLOGY AND BIOSTRATIGRAPHY

Palynological examination of 11 samples from the Serfat well FP94-11-4 (GGU 393001).

The samples 393001-43 (150 m below surface (bls)), -42 (163 m bls), -41 (185 m bls), -40 (210 m bls), -39 (227 m bls), -38 (247 m bls), -36 (267 m bls), and -35 (278 m bls) contain no identifiable dinoflagellate cysts.

One fragmented specimen of an *Isabelidinium* species (maybe *I. cooksoniae*) has been observed in sample 393001-34 (298 m bls). One fragmented specimen of a *Chatangiella* species has been observed in sample 393001-33 (317 m bls) and one fragmented specimen of a *Spiniferites* species has been observed in sample 393001-32 (340 m bls). The presence of the genera *Chatangiella* and *Isabelidinium* suggests a post-Cenomanian to pre-Paleocene age for the lower part of the well. However, since sediments of Turonian to Santonian age have not previously been recorded west of the Ikorfat Fault zone on the north coast of Nuussuaq (Nøhr-Hansen, 1994; in press), the most likely age of the cored sediments is Campanian to Maastrichtian, like the sediments outcropping between Ikorfat and Niaqornat on the north coast of Nuussuaq.

David J. McIntyre, from the Geological Survey of Canada, has examined the organic material from samples at 167, 185, 294 and 335 metres bls in well FP94-11-4. He comments that the material is very poorly preserved and consists mostly of black organic fragments. He did not record any identifiable species at 167 and 294 m bls. At 185 m there are rare probable bisaccates and indeterminate spores, and one *Cicatricosisporites australiensis*. At 335 m bls. *C. australiensis* and *C.* cf. *C. potomacensis* are present. Pollen and spores are rare and apart from the above and some probable *Alisporites* and *Podocarpidites,* they are not identifiable. The TAI values have been estimated to 3 to 3.5 or more. Age determination based on the recorded pollen has not been possible.

FACIES DESCRIPTION

The sedimentary succession underlying the Serfat sill complex was cored in three of the Falconbridge wells: FP94-11-02 (215.15 m-221.8 m, 223-233.2, 246-422.75 m); FP94-11-04 (105.85-340.45 m); FP94-11-05 (31.05-92.8 m, 203.95-223.1 m, 228.3-230.8 m) (Fig. 2). Five facies associations have been recognized; these are: 1) mudstone, 2) thinly interbedded mudstone and sandstone, 3) strongly bioturbated thinly bedded mudstone and sandstone, 4) chaotic beds, 5) medium- to coarse-grained sandstone (Fig. 2).

Facies association 1: Mudstone

Description. This facies association is especially common in the lowermost part of wells FP94-11-04 and FP94-11-02, and the uppermost part of FP94-11-05 (Fig. 2). The association consists of grey parallel laminated mudstone containing less than 10% sandstone laminae. The mudstone is present in intervals up to 52 m thick. Upwards, the mudstones grade into moderately or strongly bioturbated thinly interbedded mudstone and sandstone of facies association 3. The sandstones occur in thin graded laminae composed of fine-grained sandstone. The laminae have sharp bases and are only a few mm thick. Calcite concretions, occasionally surrounding calcite shells, and highly disintegrated plant remains are common. Fragmented bivalves occur throughout the cored mudstones, especially fragments that can be assigned to *Inoceramus* sp. The association in well FP94-11-02 and FP94-11-04 is characterized by very little or no bioturbation.

The mudstone interval in well FP94-11-05 is strongly thermally altered. The sedimentary succession in this well appears strongly bioturbated with *Chondrites* isp.; however, this may also be a trace-fossil-like feature that has appeared due to the strong thermal alteration of the sediment. In this well the mudstone is occasionally calcite-cemented and sulphide minerals occur along fractures.

Interpretation. The lamination of the mudstone in wells FP94-11-02 and FP94-11-04 suggests deposition from suspension and the absence of benthic dwelling invertebrates. If correctly identified, the very large density of *Chondrites* isp. in well FP94-11-05 represents a complex burrow system which was created by animals that systematically mined the sediment for food in one particular place. This type of trace fossil association suggests a restricted oxygen that was exploited thoroughly by a population of opportunist animals that could eke out a living in euxinic sediments without abundant oxygen being available in interstitial waters (cf. Ekdale & Mason, 1988). The interbedded thin sandstone streaks were probably deposited from distal low-density turbidite currents. The presence of floating clasts in the sharply based calcite conglomerate suggests deposition from a high density turbidite current. The presence of *Inoceramus* sp. is generally associated with marine pelagic environments (C. Heinberg, pers. comm., 1995).

Facies association 2: Thinly interbedded sandstone and mudstone

Description. This association is very common in wells FP94-11-02 and FP94-11-04 (Fig. 2). It consists of sharply based graded laminae and beds of fine- to coarse-grained sandstone, capped by grey parallel laminated mudstone (Facies D of Mutti & Ricci Lucchi, 1972; Facies F of Mutti, 1992). The sandstone laminae are generally less than 2 cm in thickness, but in the more coarse-grained intervals beds with thicknesses up to 40 cm occur. The laminae and beds show sharp bases and poorly developed normal grading. Sorting is poor, and small mudstone rip-up clasts frequently occur throughout the laminae and beds. Granules may occur along the base of the graded beds. Sedimentary structures are frequently indistinct due to the poor sorting and disturbance of the sediments, but parallel lamination and cross-lamination have been observed. In the thicker beds the structures are more clear. These beds are normally graded and have sharp flat bases. They are structureless in their lowermost part, and parallel-laminated and cross-laminated in their upper part. Other beds are massive and composed of muddy sandstones with scattered shell fragments, rip-up mudstone clasts, granules and plant debris. There is a well-developed systematic upward increase in thickness of the sandstone laminae and beds, associated with an increase in grain size (Fig. 2). Occasionally pyrite and calcite concretions, finely disseminated plant remains and bivalve fragments occur. Some of the bivalves have been identified as *Inoceramus* sp. The sediments are weakly to heavily bioturbated, but the only identifiable trace fossil is *Planolites* isp. that occurs in large densities. Escape burrows have also been observed.

Interpretation. The thinly interbedded sandstones and mudstones are interpreted as deposits of traction and fall-out processes associated with various stages of sedimentation from waning low-density turbidity currents. The presence of sharp, flat based, normally graded, massive sandstones with laminated tops suggests that some of the sandstones were deposited from sand-rich turbulent flows (T_a, T_b transitional to S_3 of Lowe, 1982). The massive muddy sandstones with floating clasts were deposited from debris flows. The upward thickening of sandstone laminae and beds is interpreted as representing shallowing-upward cycles with distal turbidites beds overlain by more proximal turbidites.

Facies association 3: Strongly bioturbated thinly interbedded mudstone and sandstone
Description. The mudstones and thinly interbedded mudstones and sandstones of the two previous facies associations frequently pass into strongly bioturbated thinly bedded mudstone and sandstone (Fig. 2). The bioturbated intervals are up to 44 m thick and consist of 30–80 % sandstones, the rest being mudstones. The grain-size of the sands range from fine- to coarse-grained. In some intervals it is possible, in spite of the strong bioturbation, to see that the sediments were deposited as heteroliths. In other intervals the lithologies are completely homogenized due to bioturbation. The only identifiable trace fossil is *Planolites* isp. that can be very densely distributed. However, other, unidentifiable, trace fossils also occur. The *Planolites* isp. occur as unlined, straight to gently curving unbranching burrows with smooth or slightly irregular walls. They are circular to elliptical in cross-section, and less than 1 cm in diameter. They are subparallel to the bedding. The burrow fill is composed of structureless sand. Disseminated coal fragments, plant debris and shell fragments frequently occur.

Interpretation. Planolites isp. was probably produced by infaunal organisms combining the activities of deposit-feeding and locomotion, thus producing endostratal pascichnia burrows. The dominance of these burrows suggests that the interstitial environment must have been characterized by at least some oxygen to allow respiration. The high degree of bioturbation of the sediment indicates relatively slow sedimentation, little physical reworking and abundant food supplies. The close association with the two previous facies associations suggests a similar depositional environment.

Facies association 4: Chaotic beds

Description. This facies association occurs in well FP94–11–05 (Fig. 2). It consists of homogenized mudstones with evenly scattered sand grains and granules, calcite concretions and bivalves (mainly *Inoceramus* sp.). The sand may also occur in stringers together with mudstone clasts. The beds are up to 14 m thick and have sharp bases. The beds may pass into contorted beds showing slump folds.

Interpretation. The contorted beds and homogenized mudstones are interpreted as formed by downslope displacement of semi-consolidated sediments. The homogenized mudstones were probably deposited from debris flows.

Facies association 5: Medium- to coarse-grained sandstone

Description. This facies association tops the coarsening-upward successions in the lower part of well FP94–11–04 (Fig. 2). The association consists of amalgamated sandstone beds, occurring in units up to 4 m in thickness. Each bed is less than 0.5 m thick, sharply based and composed of ungraded to graded medium- to coarse-grained sandstone. The sandstones are poorly sorted, and mud clasts and finely dispersed coal fragments are common. Some sandstone beds are massive, while others are cross-bedded or cross-laminated. Mudstones drapes occasionally occur along foresets. The graded sandstone beds are commonly separated by thin discontinuous mudstone drapes or thinly interbedded mudstone and sandstone. The sandstones are weakly to moderately bioturbated and escape burrows are common.

Interpretation. The massive sandstones overlying scoured surfaces are attributed to rapid suspension deposition from a sandy, high-density turbidity current (S_3 of Lowe, 1982). The cross-bedded and cross-laminated sandstones are attributed to low-density turbidity currents.

LATERAL CORRELATION AND DEPOSITIONAL ENVIRONMENT

During the Campanian-Early Maastrichtian the Serfat area was characterized by deposition in a turbidite system. The greater part of the deposits consists of thinly bedded sandstones and mudstones that together with the mudstones and the bioturbated thinly interbedded sandstones and mudstones can be divided into a number of major coarsening-upward units, 30-85 m thick (Fig. 2). Each of these units can be divided into a number of smaller coarsening-upward successions, 2-10 m thick. An ideal major coarsening-upward unit consists of mudstone (facies association 1) grading upward into thinly interbedded sandstone and mudstone (facies association 2). A well-developed systematic upward increase in bed thickness of the sandstone laminae and beds, associated with an increase of sand content and grain size occur in the coarsening-upward units. The coarsening-upward units generally show an upward increase in degree of bioturbation, and the thinly interbedded sandstone and mudstone deposits pass upwards into heavily bioturbated thinly interbedded sandstone and mudstone. The coarsening-upward units may be topped by medium- to coarse-grained sandstone. The top of each of the CU-units is not sharp, but shows a fining-upward tendency over 5 m.

Based on the major CU-units it has been possible to make a correlation between wells FP94-11-02 and FP94-11-04. They both penetrate a thick sedimentary succession and is located 400 m apart (Fig. 2). As a basis for the correlation a large concentration of the bivalve *Inoceramus* sp. present in the lowermost part of the two wells is used (Fig. 2).

The main characteristics of the turbidite system that have been recognized can be summarized as follows:

- The major coarsening-upward units are laterally continuous between the two wells and the thickness of the units varies only a few metres between the wells.

- The cycles are dominantly composed of thinly interbedded sandstone and mudstone deposited from waning low-density turbidity currents. The facies are laterally continuous for more than 400 m and show no major thickness variations.

- The coarsening-upward units show no indications of channelling.
- The coarsening-upward units occur above a basal mudstone.
- Bioturbation increases towards the top of the coarsening-upward units.

Based on the above characteristics, the major coarsening-upward units are interpreted as deposited from depositional lobes in a submarine fan environment (cf. Mutti & Ricci Lucchi, 1972; Ricci Lucchi, 1975; Mutti, 1977, 1985; Mutti & Normark, 1987; Shanmugam & Moiola, 1991). Such lobes are considered to develop at or near the mouths of submarine fan channels, and are developed primarily in active-margin settings (Shanmugam & Moiola, 1988). The mudstones were deposited in the lobe fringe area and the thinly interbedded sandstones and mudstones on the outer and lower part of the fans. The upward-thickening trend suggests that the lobes were constructed by vertical aggradation rather than basinward progradation (cf. Ricci Lucchi & Valmori, 1980). The minor thickening-upward successions that cannot be correlated between the two wells are considered to represent compensation features. The compensation cycles were probably produced by progressive smoothing of the depositional relief as a result of lobe build-up or aggradation (cf. Mutti & Sonnino, 1981).

The large degree of bioturbation in the upper parts of the successions is not common in other ancient examples of depositional lobes. It indicates relatively slow sedimentation, little physical reworking, and abundant food supplies in an environment that became progressively more oxygenated as early thickening-upwards unit was built up. This together with the large terrestrial imprint in the palynology and the general geological setting of the area suggests that these lobes are not deep-sea lobes in a strict sense, but could have been deposited at shallower depths.

Moreover, the correlation between wells shows that the sill complex is approximately parallel to the sedimentary bedding over a distance of 400 m. Combining the data from the three holes that penetrate the sill complex and the assumption that the sill complex is parallel to the bedding, it is suggested that the strike in the area is approximately WNW-ESE and the dip towards SSW.

Finally, the correlation shows that the zone with a pressurized gas seam that was penetrated in well FP94-11-04 would probably also have been penetrated in well FP94-11-02, if drilling had continued for a few more metres. This conclusion is supported by the drillers observation that gas bubbles locally were liberated from the sedimentary successions in both the wells (Olshefsky *et al.*, 1995).

IMPLICATIONS FOR EXPLORATION

Due to the very limited exposures and the strong thermal alteration of the sediments in the vicinity of the thick Tertiary sills the Serfat area was not studied during the recently completed studies of the sedimentology, biostratigraphy and organic geochemistry of the Upper Cretaceous-Lower Tertiary marine sediments (Christiansen *et al.*, 1994; Nøhr-Hansen, 1994). The exploration perspective of the Serfat area is therefore very uncertain and is based on knowledge on the regional geology and data from the cores drilled in this area by Falconbridge and described in this report.

Based on the organic geochemic studies of the gas from the pressurized gas seam that was penetrated in well FP94-11-04, Christiansen *et al.* (manuscript) concluded that the gas is "wet" suggesting a thermogenic origin and a close association with either a condensate or crude oil. Moreover, there is geochemical evidence of a typical clastic marine source rock deposited under anoxic conditions with only limited terrestrial input. Based on the regional knowledge and thermal maturity data the best candidate as source rock is mid-Cretaceous marine shales, probably of Cenomanian-Turonian age, which are expected to be present 0.5-1.5 km deeper in the succession.

No really good reservoirs are expected deeper in the succession, but poorly sorted turbidite sandstones intercalated with mudstones, very similar to the present succession, are likely to continue down to a possible mid-Cretaceous source rock. Cleaner Early Cretaceous fluvial and deltaic sandstones may be present below the source rock interval, but these probably occur below the oil-window.

The dip and strike of the sill complex indicate that the succession dips towards SSW, suggesting that a possible structural closure may occur towards NNE, possibly in offshore areas. This implies that future drilling not should take place farther south than the five Falconbridge wells.

CONCLUSIONS

Based on the sedimentological and palynological analyses of the cores drilled by Falconbridge International Ltd. in the Serfat area, the following main conclusions can be drawn concerning sedimentology and stratigraphy of the Serfat cores.

* The dinoflagellate cysts include *Isabelidinium* sp., *Chatangiella* sp., and *Spiniferites* sp., that together with the general understanding of the area suggest a Campanian-Maastrichtian age of cored sediments.

* The cored sediments can be divided into a number of coarsening-upward units 30 - 85 m thick, dominantly composed of thinly interbedded sandstone and mudstone deposited from waning low-density turbidity currents. The sediments were deposited from depositional lobes in a submarine fan environment.

* It has been possible to correlate wells FP94-11-02 and FP94-11-04 that are situated 400 m apart. Both wells penetrate a thick sedimentary succession, and the correlation shows that the coarsening-upward units and facies associations are laterally continuous for more than the distance between these wells.

* The correlation indicates that the Serfat sill complex is parallel to the sedimentary bedding over a distance of 400 m and that the regional strike is approximately WNW-ESE, and the dip towards SSW.

* The correlation suggests that the zone with a pressurized gas seam that was penetrated in well FP94-11-04, would also have been penetrated in well FP94-11-02 if drilling had been continued for a few more metres.

* Reservoir sandstones of better quality than those already cored are not expected within that part of the succession that occurs above or within the oil window.

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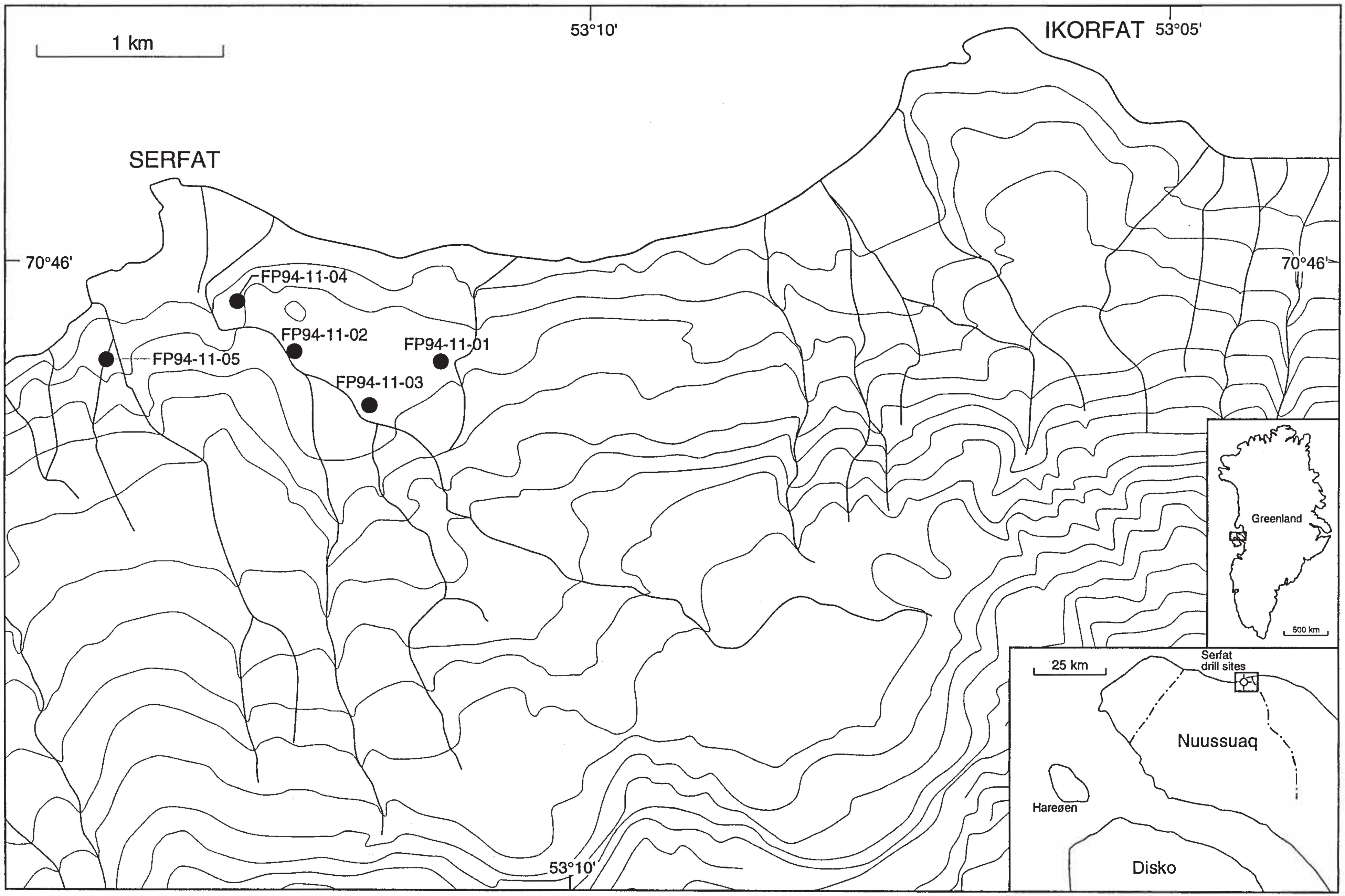

Fig.1 Locations of the five wells drilled by Falconbridge Ltd., Canada in 1994 at Serfat on the north coast of Nuussuaq.

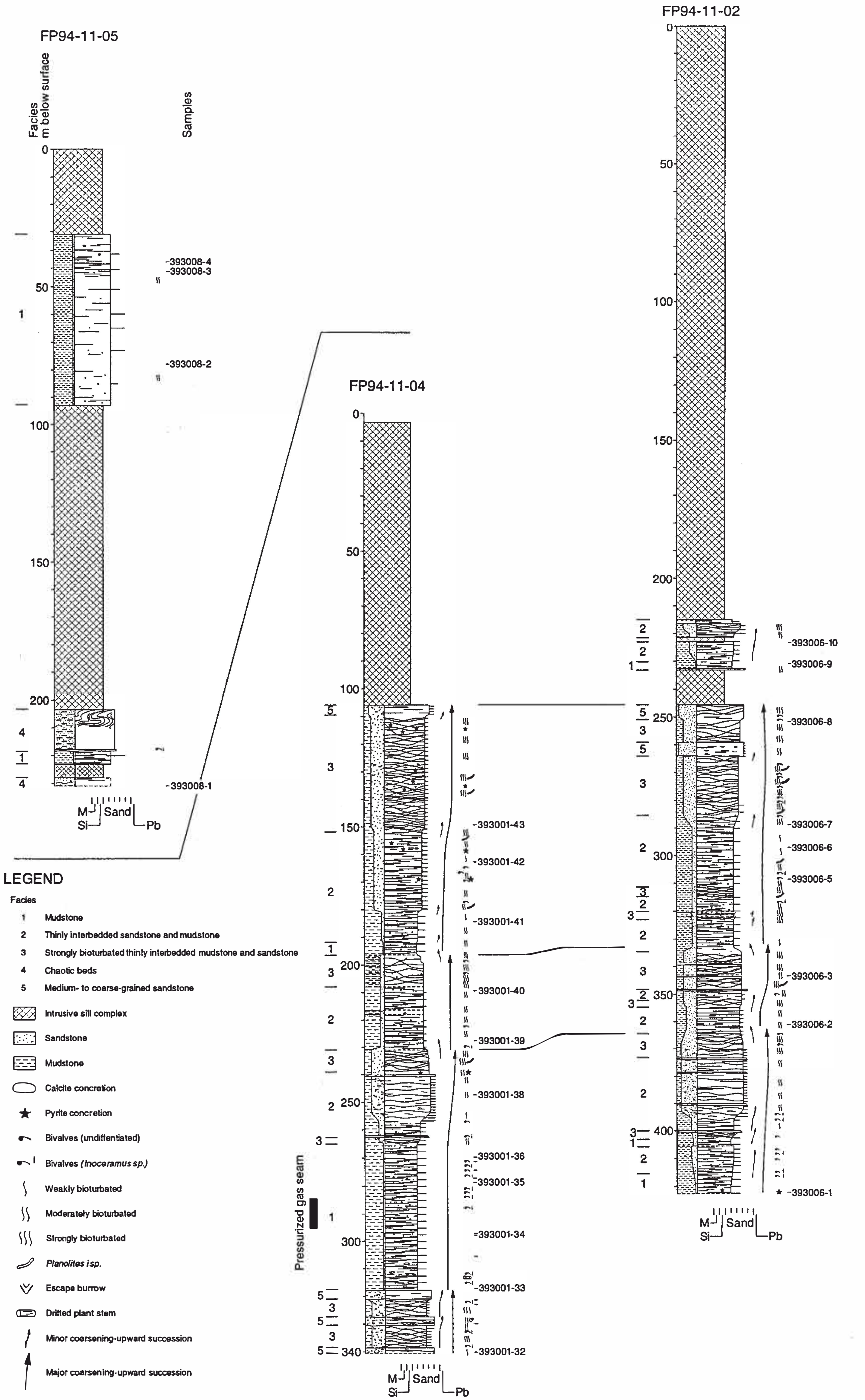

Fig.2 Sedimentological logs from the three wells that penetrated the sedimentary succession underneath the intrusive sill complex at Serfat.

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