Photogrammetric mapping of fluvial channel sand-bodies in the Atane Formation at Paatuut, Nuussuaq, central West Greenland

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Upper Cretaceous deltaic sediments from the Atane Formation are well exposed in a series of steep-sided gullies at Paatuut on the south coast of Nuussuaq. The large exposures within the gullies allowed a large-scale sedimentological investigation of delta stratigraphy, sand-body geometry and fluvial style of the distributary channels.

Multi-model photogrammetry was applied in several ways. Photogrammetric mapping of good exposures within the area produced accurate vertical sections up to 2 km long and 0.5 km high. A bed to bed stratigraphy of the delta cycles was established and the sand-bodies within each cycle correlated. The horizontal extent of the sand-bodies was subsequently mapped photogrammetrically using the already orientated stereomodels. This mapping allowed a three-dimensional interpretation of the sand-body geometry. Cross-sections of the sand-bodies and the sand-body geometry formed the basis for the interpretation of the fluvial style of the distributary channels.

Using the three-dimensional photogrammetric data the width/thickness ratio, the sinuosity and the shape of sand-bodies as well as of palaoechannels are described. These data are useful when modelling the reservoir geometry in deltaic hydrocarbon fields.

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Detailed descriptions of the three-dimensional geometry of distributary channel sand-bodies are very rare in the literature (Dreyer, 1990). The deltaic Atane Formation is therefore interesting because large sandy channel fills from distributary channels can be studied in outcrop. This paper illustrates how the multi-model photogrammetric method (Dueholm, 1992) was used in a survey of the three-dimensional sand-body geometry and discusses the value of the method applied to this type of sedimentary deposits.

The sedimentological investigations within the Paatuut area were mainly concerned with fluvial facies analysis which serves to interpret the channel morphology and fluvial style of the palaeoriver. The variability shown by modern rivers proves that vertical facies analysis using sedimentological logs must be regarded with caution (Jackson, 1978; Miall, 1985). A promising approach is the fluvial architecture element analysis described by Allen (1983) and Miall (1985, 1988). However, the best and most convincing interpretations of fluvial style can only be made where the three-dimensional geometry of the sand-bodies and the channel forms within them can be observed. Exhumed channel belts in subarid climates provide such examples (e.g. Puidefabregas, 1973; Smith, 1987). As illustrated in this paper, three-dimensional photogrammetric mapping of fluvial sand-bodies in steep terrain is a good alternative to such rare outcrops.

Geology

Good exposures of the Upper Cretaceous Atane Formation occur on eastern Disko and along the Vaigat sound (Fig. 1). The Atane Formation represents the deposits of a large delta complex (Koch, 1964; Schiener, 1975; Pedersen, 1989; Pedersen & Midtgaard, 1990; Olsen, 1991b).

One of the most extensive areas with exposures from the Atane Formation is found in the 8 × 3 km area around Paatuut where sections can be mapped in a

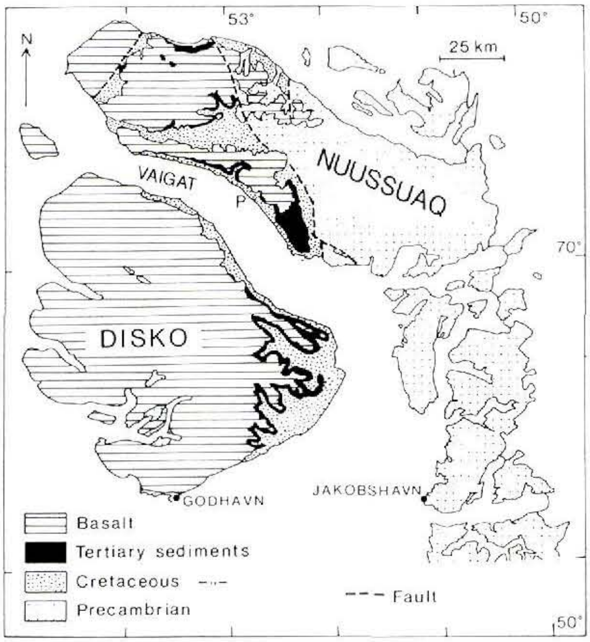

Fig. 1. Location map. The Paatuut (Pautût) area is found on the south coast of Nuussuaq adjacent the P. Almost all of the Cretaceous sediments on Disko and the south coast of Nuussuaq belong to the Atane Formation.

series of steep sided gullies (Fig. 1 & 2). Good exposures of the Atane Formation are seen between 200 and 300 m above sea level and up to *c.* 750 m. In the eastern part of the area an up to 300 m deep trough-shaped depression has been eroded down into the top of the Atane Formation. In the depression sandstone belonging to the Tertiary Quikavsak Member of the Upper Aternikerdluk Formation can be seen. Above 750 m a 400–500 m thick package of Tertiary hyaloclastites occurs which in turn is succeeded by plateau basalts up to 1900 m (Clarke & Pedersen, 1976).

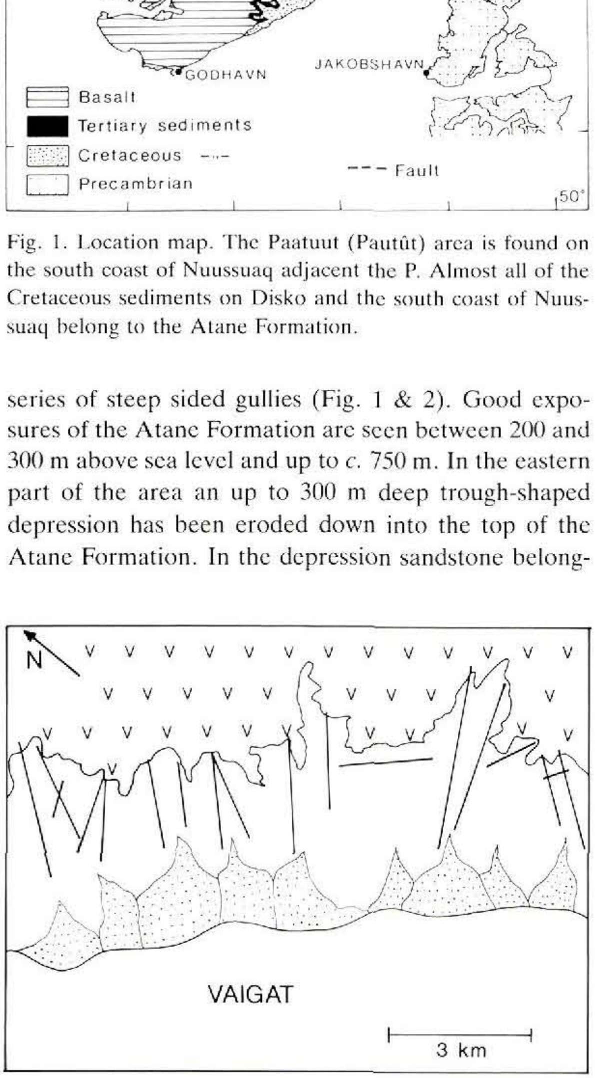

Fig. 2. Simplified geological map of the Paatuut area showing the projection planes used for the vertical sections. Active fan deltas occur at the mouth of the gullies and Tertiary volcanics are seen to the north-east. The palaeotransport direction was towards the north-west.

Palaeocurrent data show that the palaeoflow direction was towards the north-west and thus generally at a right angle to the sections (Fig. 2). However, as the investigated area has a NW–SE elongation (Fig. 2) most sand-bodies can be observed in several adjacent gullies, some for distances of up to 8 km.

The cyclic nature of the deltaic deposits is very pronounced at Paatuut and in all 32 cycles have been identified. Delta cycles are on average 20 m thick and are initiated with a coarsening-upward delta front sequence. Individual sequences are uniform in thickness across the area and were used in the correlation of the delta cycles. They are capped with fine-grained delta plain sediments including numerous coal seams and widespread thin (0.1–1 m) crevasse splay sand layers. Fluvial sand-bodies occur intercalated with the delta plain deposits or are eroded down into the top of the delta front sequences. The sand-bodies are 3–30 m thick and consist of white and yellow, medium- to coarse-grained sand. The top of a cycle is often marked by a thin layer of rapidly fining-upward transgressive sand. This pattern of deposition is described and discussed in detail by Midtgaard & Olsen (1989), Olsen (1991a) and Olsen & Pedersen (1991).

The Atane delta was wave influenced but fluvial dominated and debouched into a marine basin (Olsen, 1991a; Olsen & Pedersen, 1991). Low numbers of marine fossils (bivalves and echinoids) in the lower part of the delta front sequences date the sediments at Paatuut to the transition between Santonian and Campanian (Olsen & Pedersen 1991). The total stratigraphic thickness of 630 m observed at Paatuut was probably deposited within a limited time span (*c.* 1 million years) (Olsen, 1991a).

Vertical sections

Vertical sections were compiled using the multimodel photogrammetric method. The sections were mapped from 60 × 60 mm colour dias taken from a helicopter window using a Hasselblad SWC camera equipped with a 40 mm wide angle lens. A strip of 16 photographs covering the Paatuut area was taken parallel to the coast in 1987 by F. Ulf-Møller and have a picture scale of 1:50 000 at the coast decreasing to as little as 1:150 000 in the back of the gullies. In 1988 an additional 6 strips were taken by A. K. Pedersen, this time flying in and out of the gullies. These strips are on

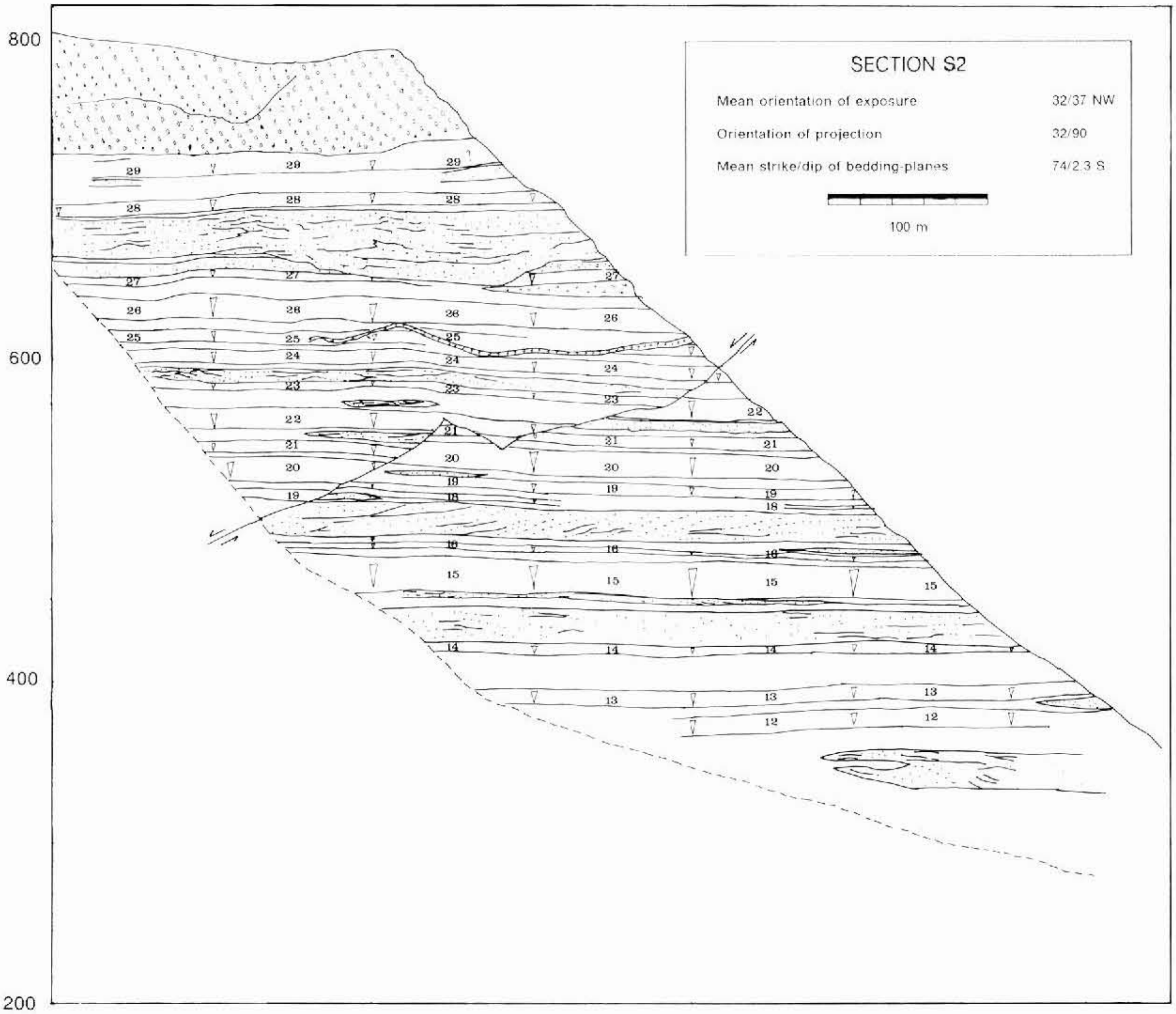

Fig. 3. An example showing one of the vertical sections. Coarsening-upward delta front sequences have been numbered according to their stratigraphic occurrence. Fluvial sand-bodies are marked with dots and Tertiary sills are marked with crosses. The jagged appearance of one of the sills and the fault plane is due to topographic relief of the exposure. The top of the exposure is capped by hyaloclastites (see text for more explanation).

a scale of 1:10 000 to 1:40 000. The 7 strips were mounted on 3 template sets (see Dueholm, 1990, 1992 for a description of the procedure).

After the initial orientation procedure, which is relatively time-consuming, the individual template sets could be set up for mapping within 5 minutes. In this project a total of *c.* 5 weeks were spent using the photogrammetric equipment. During this time the author became familiar with the procedure and was able to perform all steps of the process including the initial orientation of the photographs. It is suggested that after a learning period a geologist should be able to mount and orientate a template set (up to 18 60 × 60 mm photographs) in a couple of days. The time spent analysing and plotting should be roughly equal. However, in this project the multi-model photogrammetric method was used for several purposes and 4–5 days were spent on each template set.

The set of photographs covers almost all of the good exposures within the area. On this basis 18 vertical sections of the exposures were prepared (see Fig. 2 for location). These usually cover a height interval of *c.* 400 m and range in lateral extent from 400 m up to 2 km. One of the sections is shown in Fig. 3.

Due to the picture scale, sedimentary units had to be at least 2 m thick on the photographs from 1987 and 1 m thick on those from 1988 to be accurately located and mapped. These demands were met by the delta front

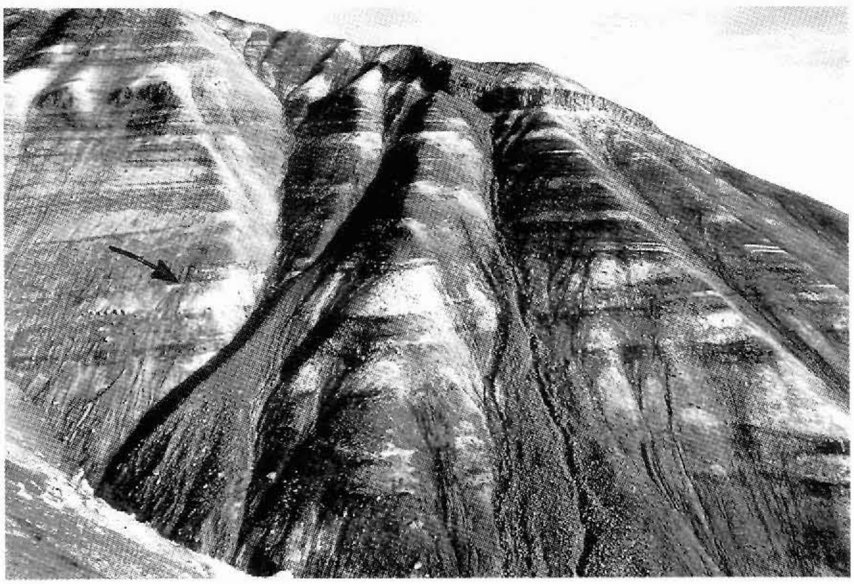

Fig. 4. A transverse section through a distributary channel sand-body is seen in the centre of the picture (marked with arrow). Although relatively poorly exposed, the lenticular appearance of this up to 14 m thick sand-body can readily be recognised.

sequences, the fluvial sand-bodies and the intervals with delta plain sediments. The transgressive sand layers are too thin to be distinguished and were therefore included in the overlying delta front sequence.

The first step in the analysis was to locate and trace out all delta front sequences (indicated on Fig. 3 with triangles and numbers). When this task was completed, the fluvial sand-bodies were mapped (dotted signature on Fig. 3). These show in vertical section a very variable horizontal extent but are almost never amalgamated. Individual sand-bodies are normally surrounded by darker coloured sediments and therefore easy to map (Fig. 4). It was only in a few instances possible to recognise and trace internal bounding surfaces within the sand-bodies. After having delineated the sand-bodies no separate tracing of the delta plain intervals was needed as only three types of sedimentary units were recognized. The delta plain intervals are shown as white areas on Fig. 3.

After the completion of all sections, these were plotted at a scale of 1:2000. The sections were then interpreted and redrafted by hand (Fig. 3).

Sand-body mapping

The vertical sections drawn by the multi-model photogrammetry in conjunction with 5 km of sedimentological logs drawn by H. H. Midtgaard, the GGU coal project (Shekhar *et al.*, 1982) and the author were used for correlation. After establishing a complete stratigraphy of the delta cycles, the sand-bodies within each cycle were correlated from section to section. This correlation was based on the stratigraphic occurrence and sand-body thickness, the latter measured photogrammetrically. Major sand-bodies (> 15 m thick) are rare and thus relatively easy to correlate. There are often several smaller sand-bodies within each delta cycle, and thus the correlation of these was more ambiguous.

A horizontal projection of the Paatuut area was then plotted at a scale of 1:35 000 in order to map the extent of individual sand-bodies. A separate map was produced for each sand-body of interest. The stratigraphic interval in question was traced across all exposures within the area. In this analysis the orientated templates had to be reset numerous times in the stereoplotter. When the sand-body was found it was marked by a thick solid line. If only delta plain sediments could be observed, this was indicated by a thin broken line (Fig. 5). As no observations could be made in poorly exposed areas or areas in front of or behind exposures these areas have no signature. The result of the mapping was thus a horizontal projection of the good exposures within a particular stratigraphic level.

The interpretation of the sand-body geometry relied mostly on these maps but some additional data such as palaeocurrent measurements were included as well. In many cases the mapped sand-body was only intercepted at a few points and the interpretation thus poorly constrained. However, in some instances, many margins of a sand-body were mapped in several adjacent outcrops. In these cases the morphology of the sand-body could be interpreted unambiguously (Fig. 5). The geometry of the best documented examples served as a guide to the interpretation of sand-bodies with fewer data points.

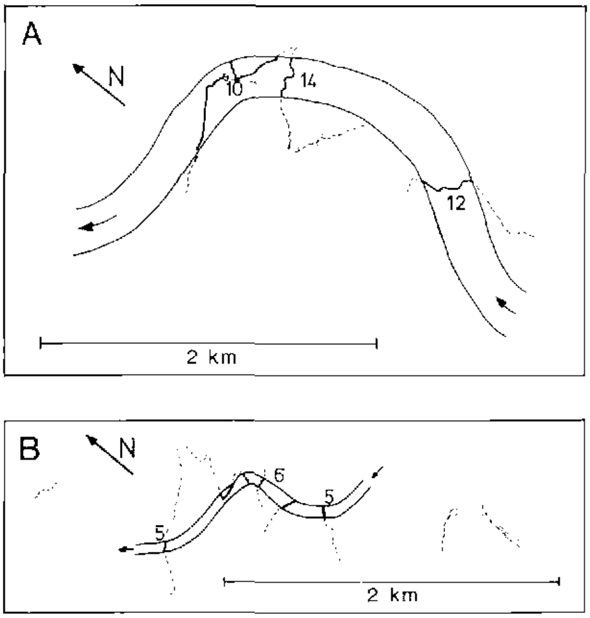

Fig. 5. Two examples of the shape of distributary channel sand-bodies interpreted on the basis of photogrammetric mapping. Stippled lines mark the contour of the outcrop, heavy lines marks the exposed sand-body. The thin arrow in A illustrates a measured palaeocurrent direction, flow was towards the north-west. In both cases the interpretation of horizontal shape is well confined by observed sand-body margins. Maximum thickness of the sand-bodies in the various outcrops are shown in metres. A shows the plan form geometry of the sand-body illustrated in Fig. 4.

Sand-body geometry and fluvial style

A fluvial facies analysis of the sand-bodies was carried out mainly on the basis of the vertical sections and the horizontal maps. As a result of this analysis, the *c.* 100 investigated sand-bodies can be divided into two important types based on horizontal extent, internal composition (architectural elements) and the relations to other facies associations (Olsen, 1991a).

Channel mouth complexes are 3–10 m thick and have a large lateral extent with a width/thickness ratio of 50 or more. They are associated with the progradation of an underlying delta front sequence. Internal bounding surfaces observed during the photogrammetry indicate that these sand-bodies were generated by lateral amalgamation of many small channel fills.

The rest of the sand-bodies (80 %) can be interpreted as *distributary channel fills*. They vary in thickness from 3 m up to as much as 30 m. They reflect the migration and infilling of rather narrow distributary channels that existed on a flat, vegetated delta plain. The sand-bodies show an increasing degree of migration with increasing depth and thus the width/depth ratio increases from *c.* 6 for the smaller sand-bodies to *c.* 20 for the largest. Many small and medium sized distributary channel sand-bodies have very narrow cross-sections and show no signs of migration (epsilon cross-beds). Consequently, the geometry of these sand-bodies closely represents the channel morphology. On this basis the distributary channels can be interpreted as deep and narrow with a width/depth ratio around 6. They were only moderately sinuous with an average sinuosity of 1.2. The relationships with the surrounding sediments as well as faint epsilon cross-beds which extend right through some of the sand-bodies indicate that the thicknesses of the sand-bodies are comparable to the bankful depth of the palaeochannels. This interpretation of fluvial style can further be confirmed by information gained from architecture element analysis (Olsen, 1991a).

The sand-bodies at Paatuut are confined within fine-grained sediments and thus form potential reservoirs for hydrocarbons. The channel mouth complexes contain large reservoir volumes due to their lateral extent. Their quality might, however, be rather poor as the finer-grained intervals within them would create permeability barriers. The distributary channel sand-bodies have a clean medium and coarse-grained texture and thus comprise good quality, but very narrow reservoirs. The increase in width/thickness ratio with increasing thickness suggests that the best reservoirs would be thick distributary channel sand-bodies. The quantified data regarding the geometry of the distributary channel sand-bodies from the Atane Formation are usefull when modelling deltaic hydrocarbon fields such as those in the Jurassic Ness Formation on the Norwegian continental shelf.

Conclusions

The results presented in this paper provide the first attempt to apply the multi-model photogrammetric method to fluvial and deltaic sediments with their very rapid three-dimensional facies changes. The sedimentological investigations of the Paatuut area were aided by the photogrammetry in several ways.

Firstly, photogrammetry made it possible to construct accurate, detailed vertical sections of the very extensive exposures within the area. Comparable although less accurate sections might have been prepared from detailed topographic maps and field measurements. However, this would have demanded much more time (several field seasons) or seriously reduced the investigated area.

The mapping of the horizontal extent of the sand-bodies made it possible to describe the complete three-dimensional geometry of the sand-bodies. Comparable mapping would have been almost impossible in the field. During the photogrammetric analysis, the stereoscopic models had to be reset in the stereoplotter numerous times for each map produced. The capability of the system to perform this in a few minutes thus proved to be extremely valuable.

Being able to repeatedly overview the exposures was of great value when correlating the various sections. It was also important that interpretations of sand-body geometry could be tested against a three-dimensional image of the actual outcrop. The ability to view areas in three-dimensions and from different angles (in different models) is considered very important when investigating sedimentary rocks with rapid facies changes.

The method has a very high potential for architectural element analysis *sensu* Allen (1983) and Miall (1985). In addition to the tracing of elements the method can also to some extent be used to measure the orientation of cross-beds and bounding surfaces. However, in this project, the picture scale was too small compared to the size of the cross-beds. It is suggested that the picture scale should be larger than 1:5000 for architectural element analysis.

In conclusion, during this project the multi-model photogrammetric method was successfully applied to fluvial and deltaic sediments. With regard to the scientific results, economic considerations when doing research in remote areas, and danger of working in loose outcrops in steep terrains, the method presents a very desirable supplement to traditional sedimentological field work.

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