

An example of a kinking microfabric in Upper Pleistocene glaciolacustrine deposits from Llavorsí (Central Southern Pyrenees, Spain)

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Abstract

Glacially deformed glaciolacustrine rhythmites exposed at Llavorsí in the Central Southern Pyrenees show a well-developed macroscopic crenulation lineation. Microscopic studies (thin sections and SEM) reveal a crenulation cleavage associated with very small-scale symmetrical folding and a banded extinction pattern. Combination of the thin section and SEM observations allows the reconstruction of a herringbone-like arrangement of finegrained particles or kinking microfabric. The occurrence of this microfabric can be used as a criterion for shearing, also in the absence of macroscopic observations.

Introduction

Micromorphological studies of tills and related deposits carried out during the last ten years have proved to be useful to identify and characterize both the original sedimentary environment and the subsequent history of the deposits (e.g. Van der Meer 1987, 1994; Van der Meer et al. 1994). In these studies a variety of features at the microscopic level, like small-scale textural inhomogeneities, deformation structures or diagenetic changes, has been described and interpreted. The aim of these studies is to distinguish criteria that can be used to determine the genesis of the sediments. Such criteria can then be applied in the study of macroscopically homogeneous tills or in tills that are only known from boreholes (e.g. Van der Meer & Laban 1990).

The presence of discrete shear zones in unconsolidated sediments is a quite common feature, not only in subglacial tills and other glacial deposits (Derbyshire et al. 1985; Brodzikowski & Van Loon 1983; Bordonau 1992; Menzies & Maltman 1992; Van der Meer 1994), but also in naturally and experimentally deformed wet sediments (Maltman 1977, 1987, 1988; Tchalenko 1968; Foster & De 1971; Jim 1990).

Since a number of years we study the microstructures in glaciolacustrine deposits (Van der Meer et al. 1992), mainly rhythmites, starting on material from the Southern Pyrenees (Bordonau 1992). In this paper, we present and discuss an example of glaciolacustrine deposits showing a kinking microfabric, which is interpreted to be due to lateral compression.

Methods

Undisturbed samples of unconsolidated glaciolacustrine deposits were obtained by taking loose blocks (up to 10 cm in size) directly from the outcrop. The samples were air-dried, transported to Amsterdam and impregnated with synolite using monostyrene as a thinner, cobaltoctate as accelerator and cyclonox as catalyser (for details see Murphy 1986; Van der Meer 1994). After impregnation and cutting, the samples were mounted on glass and ground to a thickness of about 20 μm . The thin sections were studied at low magnification (2–10 \times) under a 'Wild Makroskop' petrographic microscope. In our description the terminology of Brewer (1976) is used. In this terminology the arrangement of oriented domains, as expressed by e.g.

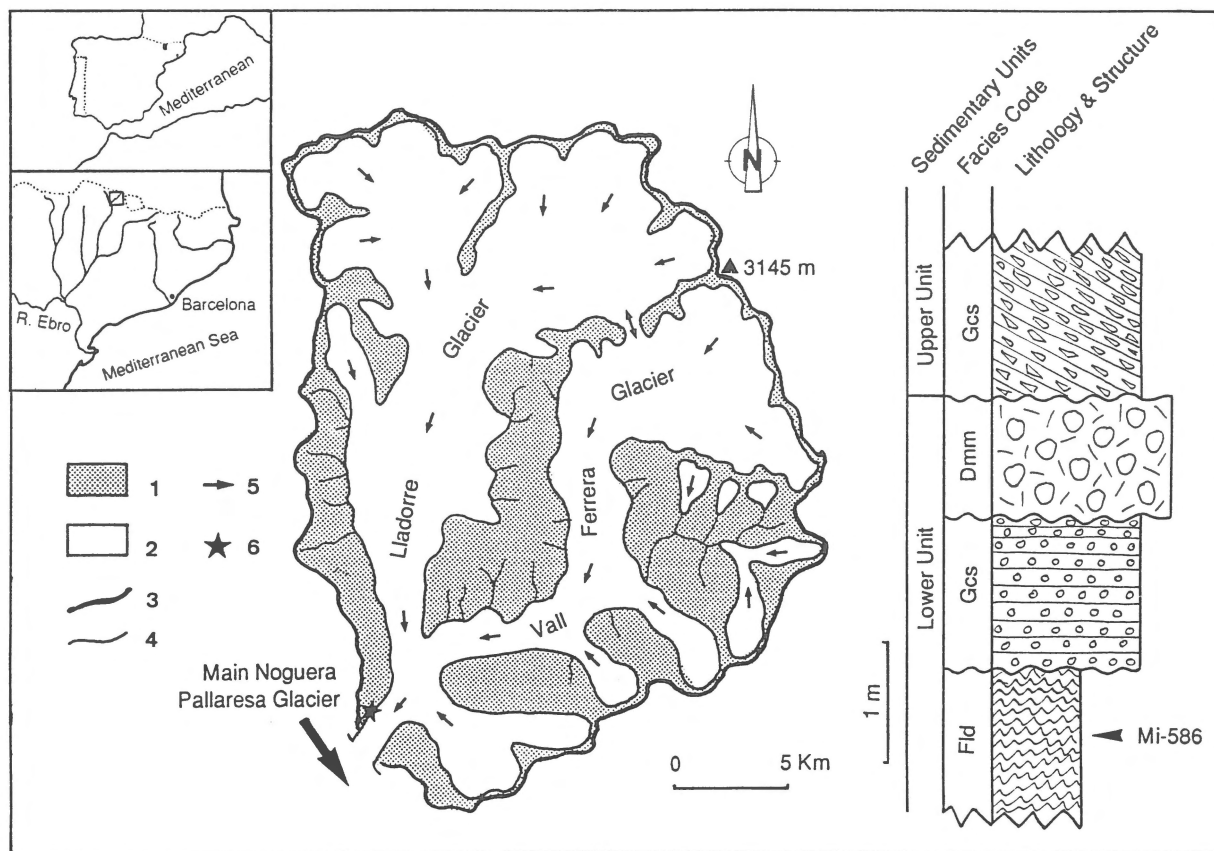


Fig. 1. Location map showing the reconstruction of the Lladorre and Vall Ferrera glaciers during the last glacial maximum in the Pyrenees (after Brú 1985). Legend: 1 Bedrock; 2 Glacier; 3 Ridge, crest; 4 River, torrent; 5 Ice flow; 6 Location of the 'Llavorsí outcrop'. Stratigraphic profile of the contact zone between the lower and the upper units in the 'Llavorsí outcrop' showing the position of the studied samples (Mi.586; the other samples are also from this 'Fld' layer). Facies code: Fld. Fines, laminated and deformed; Gcs. Gravels, clast-supported and stratified; Dmm. Diamiction, matrix-supported and massive.

birefringence, is known as the 'plasmic fabric'. The consequence of this and other terms is that different disciplines describe similar features of different scales in different terms. This paper will use Brewer's terms, with the understanding that, since it is a paper on the micromorphology of sediments, the terms pertaining to that discipline have preference.

In addition to the microscopic investigation, grain size analyses of the samples were carried out in Barcelona through a laser particle-size analyser (Coulter LS-100), while SEM images (42–1500 ×) were obtained by means of an ISI-SS40 electron microscope at the Rijks Geologische Dienst in Haarlem, the Netherlands.

Regional setting

During the last glacial maximum the Lladorre glacier joined up with the Noguera Pallaresa glacier, which had a length of about 50 km (Brú et al. 1985). The so-called 'Llavorsí outcrop' (Brú 1985) can be found in the surroundings of the Llavorsí village, on the right-hand bank of the Lladorre river and about 1 km upstream from its junction with the Noguera Pallaresa river in the Central Southern Pyrenees (Fig. 1). It constitutes a glacially deformed, ice-marginal (juxtaglacial) complex abutting against a small bedrock concavity between 820 and 900 metres altitude. According to Brú (1985), the sedimentary sequence of this complex contains two units (Fig. 1):

The lower unit has a visible thickness ranging between 2 and 4 m and consists, from bottom to top, of:

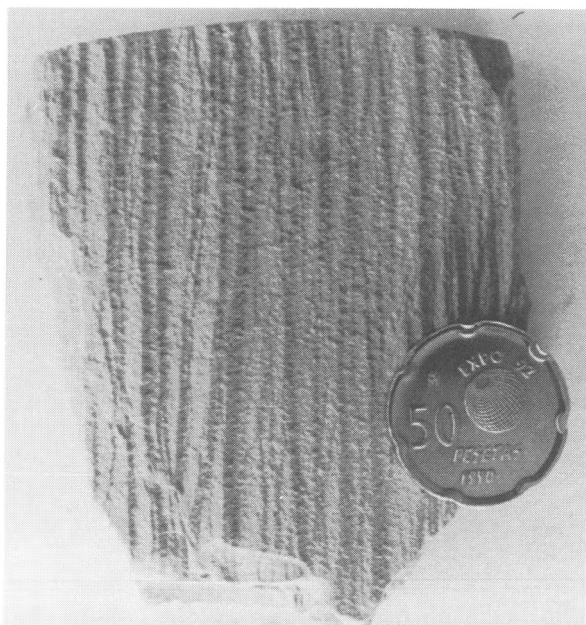


Fig. 2. Photograph of a sample of the glaciolacustrine deposits from the 'Llavorsí outcrop' showing a well-developed crenulation lineation, which affects the bedding planes, seen from above. Coin measures 2 cm.

- highly compacted fine sands and silts showing rhythmic parallel lamination. These glaciolacustrine deposits display a generalized macroscopic crenulation lineation as a result of horizontal compression. The samples (e.g. Mi.586) studied were collected from the lowermost part of the sequence;
- rounded gravels of glaciofluvial origin showing a poorly developed stratification and imbrication;
- a highly compacted, matrix-supported diamicton with a silty-clayey matrix and scattered glacial gravels and boulders. This diamicton is interpreted as a supraglacial flowtill (Brú 1985).

According to Brú (1985) the lower unit corresponds to the sedimentary filling of a small ice-marginal (juxtaglacial) lake dammed by the Lladorre glacier when it joined up with the Noguera Pallaresa glacier during the last glacial maximum, ca. 45 000–50 000 BP (Bordonau 1992).

The upper unit is constituted by angular gravels and corresponds to slope deposits of mainly periglacial origin. This upper unit crops out extensively and forms the main part of the Llavorsí complex. According to Brú (1985), the upper unit was deposited when the Lladorre glacier became disconnected from the main Noguera Pallaresa glacier. This happened during the

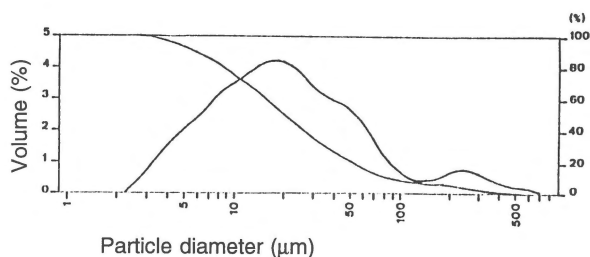


Fig. 3. Grain size distribution of a bulk sample from the glaciolacustrine deposits of the 'Llavorsí outcrop' showing a clear bimodal distribution, with a dominant mode at about 20 μm (silt) and a secondary mode at about 230 μm (fine sand). Also shown is a cumulative curve, the scale for which is at the right.

so-called 'Post-maximum stabilization phase' (Brú et al. 1985; Bordonau 1992; Bordonau et al. 1992), which in some localities has been dated between 18 000–21 000 BP (Bordonau et al. 1993).

Sample description

The samples are of an even, light yellowish-brown colour, and show a vague lamination. The most characteristic feature is the presence of a well-developed crenulation lineation visible on the bedding planes as a wavy pattern, uniformly spaced between 1 and 3 mm (Fig. 2). The crenulation has been interpreted by Brú (1985) as the result of horizontal glacial compression. It is related to a very well-developed kinking plasmic fabric (Bordonau 1992) as will be described in detail below.

The grain size of a bulk sample of the glaciolacustrine deposits shows a clear bimodal distribution with a dominant mode at about 20 μm (silt) and a secondary mode at about 230 μm (fine sand; Fig. 3).

Micromorphological description and SEM analyses

The microscopic analysis of thin section Mi.586 reveals banding, which corresponds to variations in grain size (Fig. 4). The most common fine bands correspond to silts and the few coarse bands to coarse silts and fine sands. Where present, the grading is normal. However, a large part of the sample does not show any banding and thus there is an even distribution of the particles. This is not uncommon in glaciolacustrine rhythmites where beds are often thicker than the size

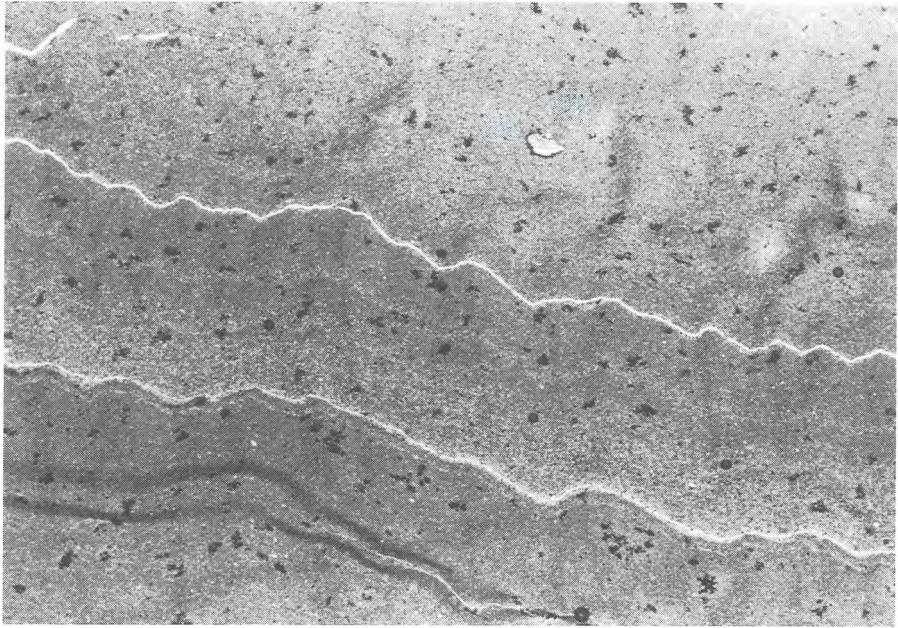


Fig. 4A. Detail of thin section Mi.586 in plane polarized light showing vague, normally graded banding and abundant Fe-mottling. Parallel, inclined dark bands running from base centre to the left are a processing artefact. Width of view 18.0 mm. For sample location see Fig. 1.

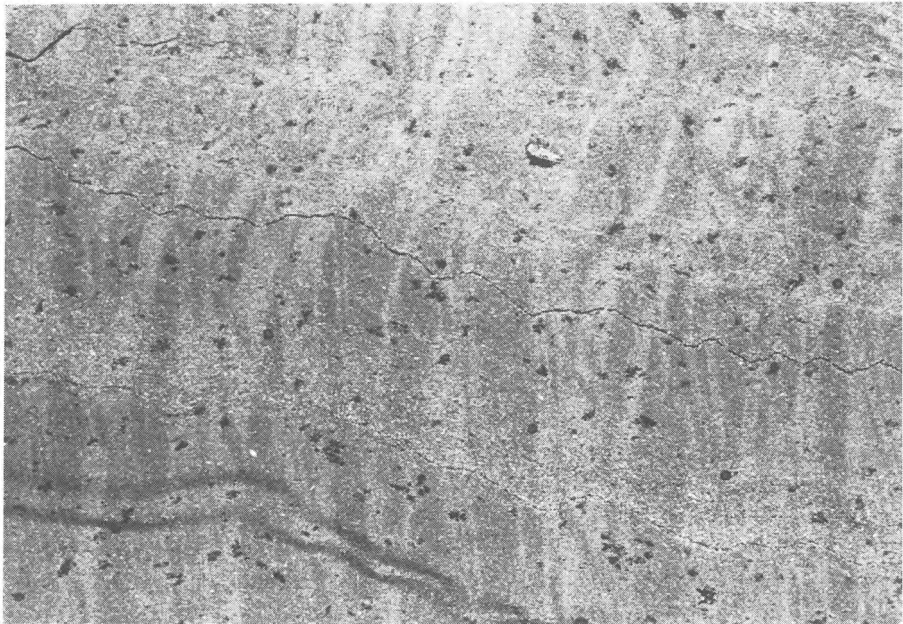


Fig. 4B. As Fig. 4A, crossed nicols. Alternating birefringent bands caused by kinking array of fine particles. In the upper half the bands are offset by shears. Width of view 18.0 mm.

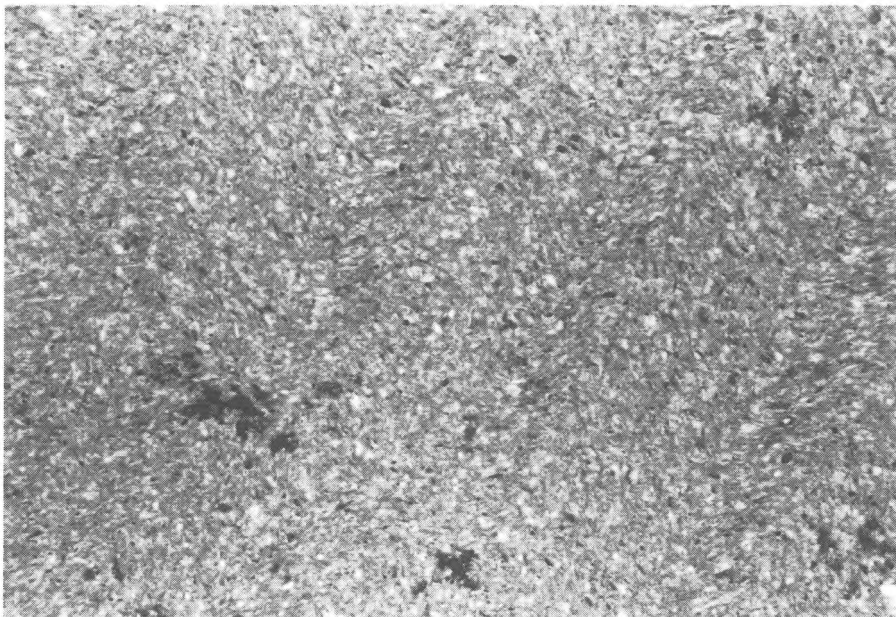


Fig. 5A. Explanation on the next page.

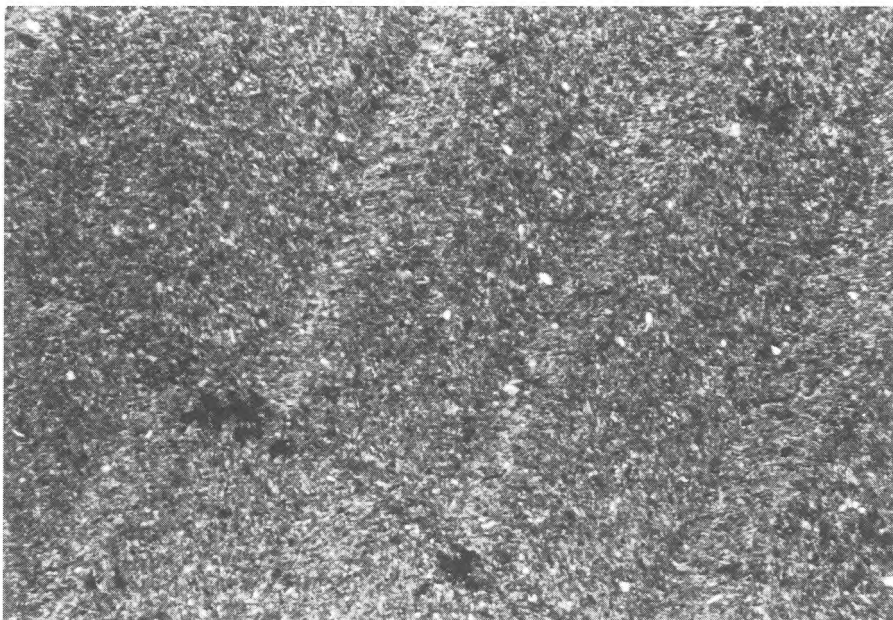


Fig. 5B. Explanation on the next page.

of this sample. The few sand grains that can be seen individually are mainly quartz and appear to be fairly angular.

Some elongated rounded pores, with a diameter ranging between 200 and 600 μm (Fig. 4), occur throughout the sample without any regularity in distribution. Furthermore, some textural boundaries are

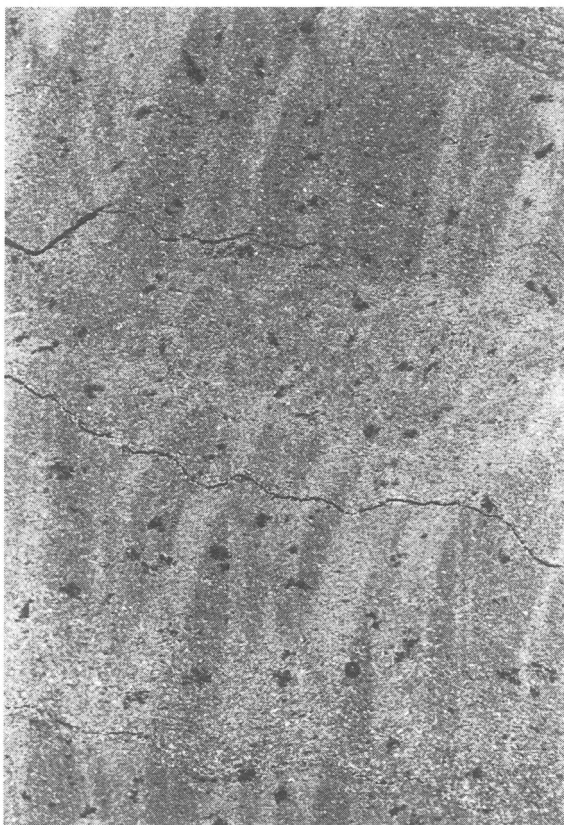


Fig. 5. A detail of thin section Mi.586 shows in plane polarized light (A, previous page) an undulating pattern of silt particles, while with crossed nicols (B, previous page) the same part of the sample shows a well-developed kinking fabric; width of view 3.5 mm. Fig. 5C (above) shows some of the discrete shears (unistrial plasmic fabric) that cut and offset the kinking fabric; height of view 11.2 mm, crossed nicols.

accentuated by long and about $50\ \mu\text{m}$ -wide cracks (Figs 4A, B).

Many irregularly shaped Fe-mottles, having a diameter between 200 and $300\ \mu\text{m}$ and displaying diffuse boundaries, are found in the thin section (Figs 4, 5). The diffuse boundaries point to an *in-situ* development. The pores, cracks and mottles usually are the result of postdepositional processes. There is no indication that these processes have influenced the original structure.

Birefringence occurs in different plasmic fabrics (i.e. kinking and unistrial), which are models of the plasma, based on the optical properties of the particles as well as on the optical properties caused by the orientation of particles relative to each other (Brewer 1976). The whole thin section displays a very well-developed kinking fabric (Fig. 5) as already cited by

Bordonau (1992). This kinking fabric is characterized by parallel, alternating bands showing more or less high birefringence or extinction. These bands are more or less vertical in Fig. 5 and perpendicular to the bedding planes. Most bands are several hundred micrometres wide, though some are as wide as $700\ \mu\text{m}$. Many bands show some subdivision or splaying. The kinking plasmic fabric is shown by a herringbone arrangement of particles due to a crenulation cleavage related to the crenulation lineation observed macroscopically on the bedding planes of the samples.

The kinking plasmic fabric is dissected by a pattern of bundles of narrow anastomosing thin lines known as a unistrial plasmic fabric, which is caused by shearing. These shear zones are more or less perpendicular to the kinking structure (Fig. 5C). The spacing between the shear zones is irregular, from several hundred micrometres to 2 mm. Sometimes the kinking fabric shows a minor offset along a shear plane.

A separate sample was selected for SEM studies. Pictures of increasing enlargements were made in three directions: perpendicular to bedding, parallel to bedding and vertical onto bedding. All pictures demonstrate the crenulated nature of the bedding with wavelengths up to 1.5 mm (Fig. 6). Although in Fig. 6 the small-scale folds (crenulation) look slightly asymmetrical the thin sections demonstrate that they are actually best described as symmetrical. Shear planes are visible as slightly inclined linear structures, though only in the pictures taken parallel to bedding.

With increasing magnification the pictures also demonstrate that the particles consist mainly of flakes; equidimensional particles are essentially lacking. The flakes are oriented parallel to each other and tightly packed, clearly following the folds.

The lack of pores is quite evident; at small enlargements a few rounded pores are visible. Very small packing voids only become visible at greater enlargements.

Discussion and conclusions

The macroscopic observations of Brú (1985) clearly demonstrate that the rhythmites at the 'Llavorsí outcrop' have been compressed by glacier activity. Such action of a glacier on its own lateral deposits is widely known, examples having been described by e.g. Stone & Koteff (1979), Van der Meer et al. (1992) and Bordonau (1992, 1993). However, there are few examples of such clearly expressed and preserved crenulation

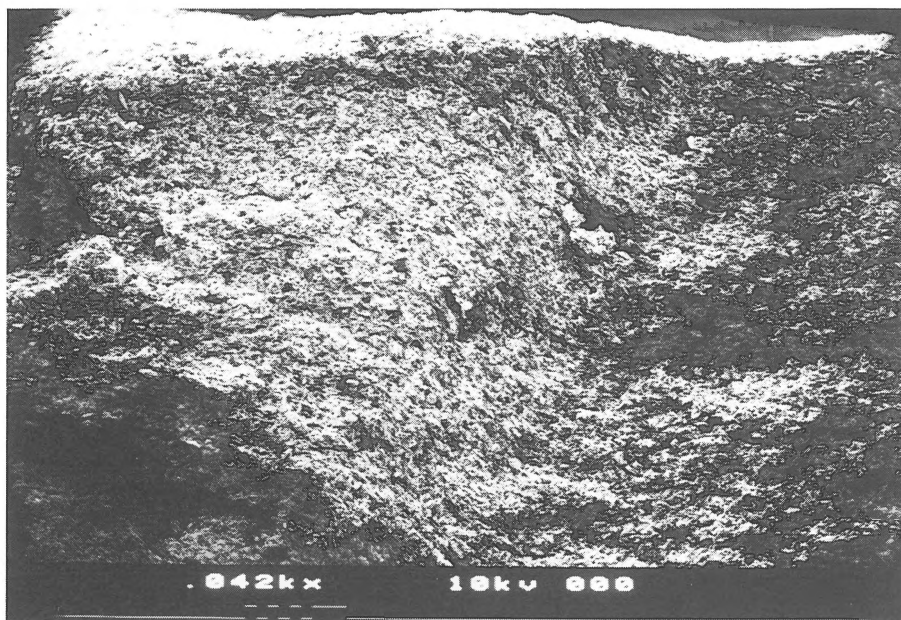


Fig. 6. SEM picture taken perpendicular to the bedding of a sample from the glaciolacustrine deposits of the 'Llavorsí outcrop'. The undulating pattern of the silt flakes is clearly visible. Scale bare at base (upper long stroke to the right of short strokes) is 100 μm long.

as present at the 'Llavorsí outcrop'. Another example, though only seen in cross-section, has been described by Kluiving et al. (1991).

Thin section and SEM studies of samples of the 'Llavorsí outcrop' demonstrate that glacial compression has resulted in symmetrical folding on the rhythmites on a microscale. The thin section study further demonstrates that the folding is associated with a typical banded extinction pattern. Such a pattern can only be explained by a consistent orientation of the particles in one band perpendicular to those in the adjoining bands. The orientation of the particles in a number of extinction bands results in the herringbone pattern, which is known as the kinking microfabric (Fig. 7).

Up to now this kinking pattern has been observed in thin sections of glacial sediments from a few other places, first in Switzerland (Van der Meer 1982), later also in the Netherlands (Van der Meer 1987) and in Canada (Menziés 1990; Menziés & Maltman 1992). In all these localities its occurrence coincided with strong glacial activity in the sense of demonstrable shearing. In the meantime it has also been found in soils (Fitzpatrick 1984), while it has already been produced artificially by subjecting clays to shear (Morgenstern & Tchalenko 1967; Tchalenko 1968; Foster & De 1971;

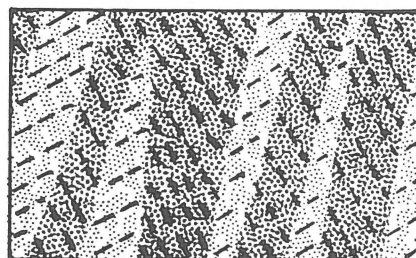


Fig. 7. Sketch (width ca. 5 mm) of the arrangement of fine-grained particles (broken lines) and its relation to extinction bands (alternating light and dark bands). The resulting pattern of oriented domains is a kinking microfabric.

Maltman 1977) and been explained by shearing of foliated rock (Dewey 1969).

The peculiarity of the 'Llavorsí outcrop' is that its kinking plasmic fabric has a macroscopic expression as a crenulation lineation, clearly visible on the bedding planes, while its silty composition allows simple demonstration of the orientation of the particles by SEM observations.

In conclusion, a kinking microfabric, or kinking plasmic fabric can be used as a criterion for shearing in a compressional regime. This should be regarded as

a first step in the microscopic recognition of deformational mechanisms in unconsolidated sediments. This criterion can be applied to sediments in situations where no or hardly any macroscopic observations can be made, such as in boreholes, both on land and at sea.

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