TEM MICROFABRIC OF ALASKA'S BOOTLEGGER COVE FORMATION

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ABSTRACT

Transmission electron microscopy (TEM) reveals microfabric signatures indicative of environmental processes active during the developmental history of the Alaska's Bootlegger Cove Formation (BCF). Three sedimentological factors largely controlling the geotechnical properties, (1) mineralogy, (2) grain size, and the (3) microfabric can be resolved by TEM. Selected samples of the BCF clay reveal an arrangement of predominantly clay-sized particles (chlorite and illite dominated) indicative of a remolded and iceloaded glaciomarine sediment. Relatively undisturbed microfabric was laboratory prepared for TEM analyses using techniques first described by Bennett (1976) and Baerwald et al. (1991) and include fluid substitution, critical point drying, epoxy impregnation, and ultra-thin sectioning. Mosaics of consecutive micrographs were constructed to provide a field of view of >4000 sq µm, yet show submicron-sized particle-to-particle associations resulting from depositional and post-depositional processes, as revealed by the microfabric.

The matrix is comprised of mechanically pulverized crystalline material (rock flour), probably dominated by chlorite. Remolded fabric signatures include chains of stepped FF domains wrapped around subrounded clasts ranging in size from 2 to 16 µm resulting in the low void ratio and high density packing of the grains. The overall arrangement of grains appears poorly sorted and random, although localized packets of 1 µm domains suggest zones of microshearing. Other remolded features observed in ultrathin sections include compressed, bent and swirled domains similar to previously documented remolded features (Bennett, 1976; Bohlke and Bennett, 1980; Burkett et al., 1987). High magnification of the matrix reveals rolled basal plates of crystals preferentially aligned reminiscent of a direction of shear. The microfabric observed in TEM is consistent with a low void ratio (~.8) and low porosity (~44%) sediment. Olsen's (1989) geotechnical investigations of the sensitive strata of the Bootlegger Formation show little variability within the formation. Water contents range between 25% and 35%, and liquid and plastic limits are about 30% and 15%, respectively.

INTRODUCTION

On March 27, 1964, the Prince William Sound Earthquake produced a series of landslides in Anchorage, Alaska. The largest lateral movement of soil masses occurred along the coastline of the Turnagain Heights area. The Anchorage lowland area is built on alluvial sand and gravel underlain by flat-lying strata of the Bootlegger Cove Formation (BCF) deposited in a glacioestuarine environment and subsequently elevated (Miller and Dobrovolny, 1959; Schmoll and Dobrovolny, 1972). The BCF consists of a sequence of silty clays and clayey silts with interbedded silt, fine silty sand, and fine to medium sand; and with scattered pebbles and cobbles in widely varying concentrations (Updike et al., 1988). Two theories were proposed to explain the nature of the failure mechanism resulting in the landslides: (1) that underlying sands liquefied resulting from the induced shock (Shannon and Wilson, 1964; Seed and Wilson, 1967), and (2) that the clay facies within the formation behaved as quick clays with high sensitivities resulting in loss of strength (Kerr and Drew, 1965; Updike et al., 1988; and Olsen, 1989). The latter theory is supported by microfabric analysis.

We used Transmission Electron Microscopy (TEM) to examine the microfabric of the BCF clay collected from 13-cm-thick subsample at a depth of about 16.5 m in borehole B-5, Lynn Ary Park, about 70 m south of the head scarp of the Turnagain Heights landslide (Updike et al., 1988) Because TEM provides such stellar resolution, visual inspection of particle-to-particle configurations on a submicron-size scale is achievable. The use of TEM for clay microfabric analysis provides an excellent tool for correlating structure to fine-grained sediment formation processes. TEM observations allow determination of grain size; arrangement, sorting, and orientation of particles; and of pore characteristics that contribute to the microfabric.

In conjunction with geotechnical analyses of slope failure (Pusch, 1967), the evidence discussed here from microfabric analyses supports the geologic inference that the sediment was of glacial origin, perhaps including a fluvial component. This poorly sorted sediment type may also have resulted from subaqueous slides or debris flows. The TEM analysis of the microfabric suggests that remolding of the sediment was contemporaneous with deposition. Although poorly sorted, the samples examined using TEM are relatively fine grained, consisting dominantly of clay and small silt-size particles.

SEDIMENT PROPERTIES

Microfabric of a sediment is defined as the expression of the three-dimensional spatial arrangement, orientation, and particle-to-particle relationship of the predominantly clay-size particles and domains (Bennett, 1976). The microfabric and the physicochemical interactions (the forces bonding the particles) together determine the clay microstructure that largely controls the physical and mechanical (geotechnical) properties of a sediment. Thus, microfabric is a fundamental property of a sediment that is a fine-scale expression of processes that control bulk properties. In turn, the particle-to-particle interactions can be related to larger scale sediment behavior. Inspection of the ultrathin sections that show submicron-sized features comprising the microfabric and correlation to measured physical and geotechnical properties provide a better understanding of sediment behavior (past and present). For example, Bennett et al. (1989) noted that grain size alone is insufficient to explain porosity and permeability variations from laboratory and field measurements of fine-grained terrigenous and öolitic carbonate sediments. Thus, the microfabric of the sediment must be considered. The geotechnical properties considered in our microfabric study include shear strength, water content, porosity, wet bulk density, void ratio, and consolidation characteristics reported in Burkett (1992).

The microfabric is a product of diagenesis that encompasses all changes that occur from processes relating to the post-depositional conversion of sediment to rock (Scholle, 1978). Diagenesis significantly affects the mineral solids as well as the porometry of a sediment (Bennett et al., 1989). Consolidation of a sediment occurs via compression by an applied external load. A volume decrease results from the expulsion of the pore fluid and the rearrangement of the mineral solids (Lambe, 1951; McCarthy, 1982). Little is known about the actual microscale mechanisms of the dewatering process, the fluid flow from sediments, and subsequent evolution of sediment physical properties (Bennett et al., 1991).

Microfabric Nomenclature and Descriptions

Microfabric nomenclature follows the examples outlined by Bennett (1976) for relatively high void-ratio sediment. The smallest TEM-resolvable unit of the matrix consists of clay particles (Fig.1). These often form well-defined domains. More commonly in natural systems, the matrix is made of small domains of multiplate FF (face-to-face) mineral layers (planes perpendicular to the "c" crystallographic axis) that are often stair-stepped. Domains can be linked in various configurations such as EE (edge-to-edge) chains, EF (edge-to-face) chains, or in combination. Another common matrix constituent is amorphous, poorly crystalline, or microcrystalline material, the identity of which is a function of the available resolution. Other possible solid components include (1) biogenic fragments, (2) grains of a single mineral species that are typically coarse clay size and larger, (3) randomly oriented aggregates composed of one or more minerals, (4) mixed layer silicates, and (5) minor constituents such as trace organics.

The arrangement of particles, domains, grains, and aggregates creates voids that are either fluid or gas filled. In the micrographs seen in Figs. 2-5, the mineral solids are distinguished by the dark gray-to-black color. The resin-filled pore spaces are light gray. White holes are artifacts that occur when grains are plucked during ultrathin sectioning. The boundary between solids and voids is not always readily identifiable (sharp) because of irregular edges of

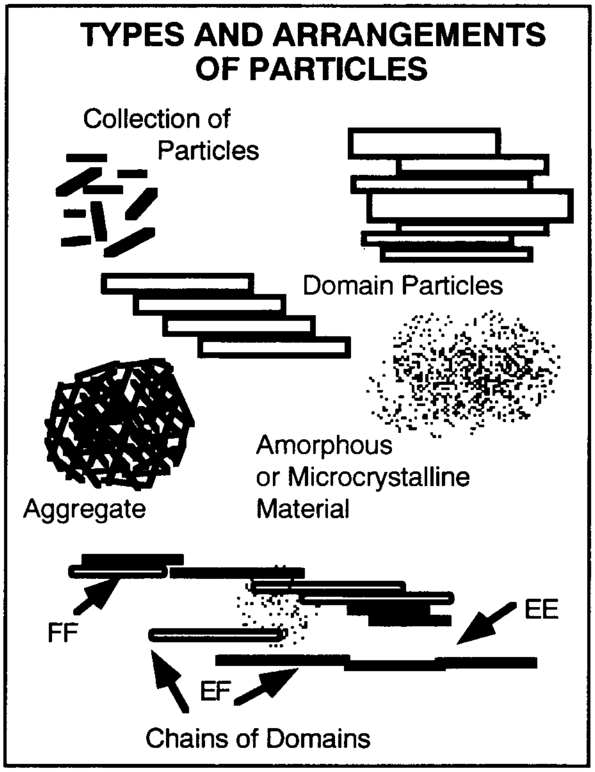

Fig.1. Description of microfabric terms (after Burkett, 1992).

grains, variable grain orientation, and the occurrence of amorphous material.

Physicochemical, biological, and mechanical processes are three dimensional. While ultrathin sections do have a depth component, the plane view of a mosaic typically shows an area to depth ratio of 30,000:1 (i.e., > 3,000 μm² area × 0.1 μm (1000 Å) depth.) Construction of photomosaics (composed of adjacent micrographs showing a total area in excess of 2,000 μm²) provides the ability to examine the effects of diagenetic processes on marine sediments. Higher magnifications provide detailed information on particle interactions and mineralogy.

Imaging by TEM requires array of sample preparation techniques. The procedures were employed first by Bennett (1976) and Bennett et al. (1977), modified by Burkett (1987 and 1992), and described in detail to include organic material in Baerwald et al. (1991). In summary, the techniques used following subsampling include pore fluid exchange, critical-point drying, low-viscosity resin (Spurrs) impregnation, microtoming of ultra-thin sections, and carbon coating.

Mineralogy

Previous analyses of the clay facies of the BCF showed a striking similarity to a Norwegian clay, referred to as the Oslo quick clay (Drew, 1966). The bulk clay mineralogy of the BCF clay consists of 20% quartz, 25% feldspar, 28% chlorite, 25% illite, and 2% calcite. The fine clay fraction (<2 μm) consists of 8% quartz, 17% feldspar, 38% chlorite, and 36% illite with 1% calcite.

Physical Properties

Size analysis of the BCF at Anchorage consists of: (1) 39% fine clay (<2 μm), (2) 17% coarse clay (2 to <5 μm), and (3) the remaining 44% silt (5 to 74 μm) (Drew, 1966). The water content from 15 samples averaged at 34.2% . Sensitivity ranged from 3 to 40 but averaged 14.7. Plastic limits varied little with an average of 22.8. Another previous analysis (Miller and Dobrovolny, 1959) determined the Atterberg limits to be 39 for the liquid limit, 22 for the plastic limit, and 17 for the plastic index. The moisture content was calculated at 35% with a relatively weak shear strength at 1,150 lbs/ft² (~55 kPa). The porosity was computed to 40%. Other detailed analyses can be found in Mitchell et al. (1973).

RESULTS AND DISCUSSION

The photomosaic (Fig.2) reveals approximately 4,500 μm² of sediment microfabric. The most conspicuous feature of the Bootlegger Cove microfabric is the poorly sorted nature of the grain assemblage with particle sizes ranging from microcrystalline to silt-size. The floury, dense, amorphous appearance of the matrix of this remolded sediment is indicative of a glaciomarine origin. The largest holes could have initially contained quartz which does not cut during ultrathin sectioning. In spite of the holes, the integrity of the surrounding microfabric is maintained due to the resilience of the Spurrs resin. Also scattered within the floury matrix are (1) clay-size electron opaque angular grains, (2) dispersed ≥ 4 μm grains with the largest silt-size grain approaching 16 μm, and (3) fine clay-sized chains of domains. The grains vary in shape from angular to subrounded with aspect ratios approaching one. The grains appear randomly oriented within the fabric.

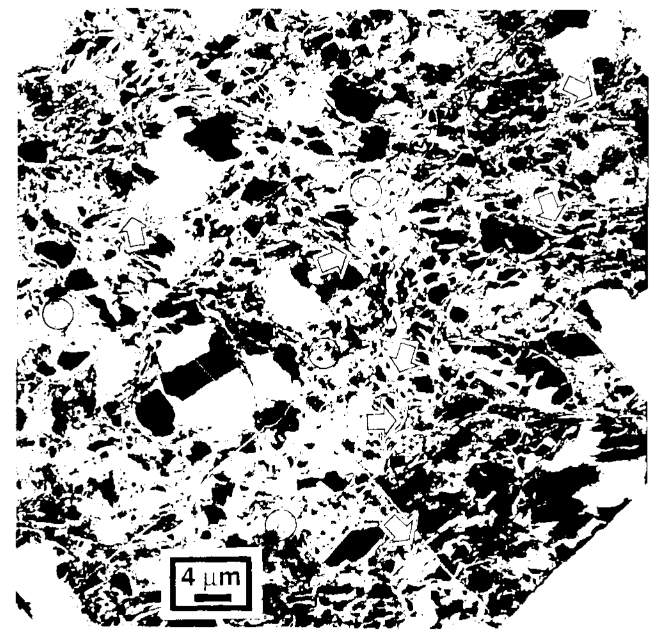

Fig.2. Photomosaic of BCF clay showing the poor sorting of the grain sizes. The matrix is comprised of microcrystalline glacial flour (circles) and dispersed packets of small domains (arrows). Dispersed within the matrix are silt-sized (>4 μm) grains. The white holes represent silt-sized grains plucked during ultrathin sectioning.

A more detailed view (Fig.3) reveals that ~1 μm and smaller domains form the EE chains and small packets of FF domains.

These domains appear to delineate areas of amorphous material. The dotted lines in Fig.3B more clearly display the juxtaposed position of small domains indicative of microshear features. Similar features were observed by Bennett (1976), Bohlke and Bennett (1980), and Burkett (1987) for other

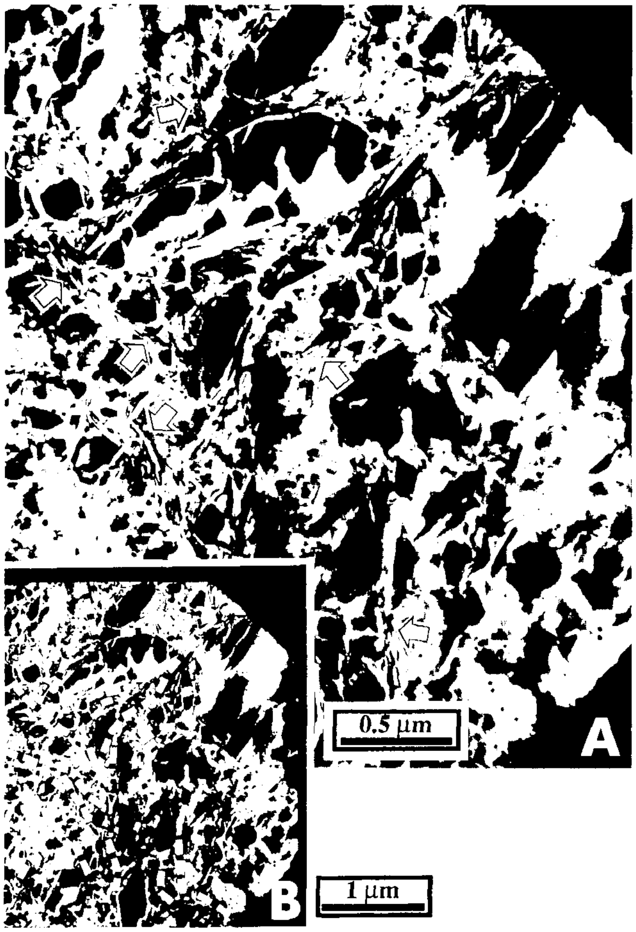

Fig.3. High-magnification view of BCF sediment. (A), Closeup of chains of small domains (arrows) forming zones of microshearing and (B), Outlines of the microshears. The black spots in some of the micrographs are heavy metal contaminate co-sputtered with graphite during carbon coating.

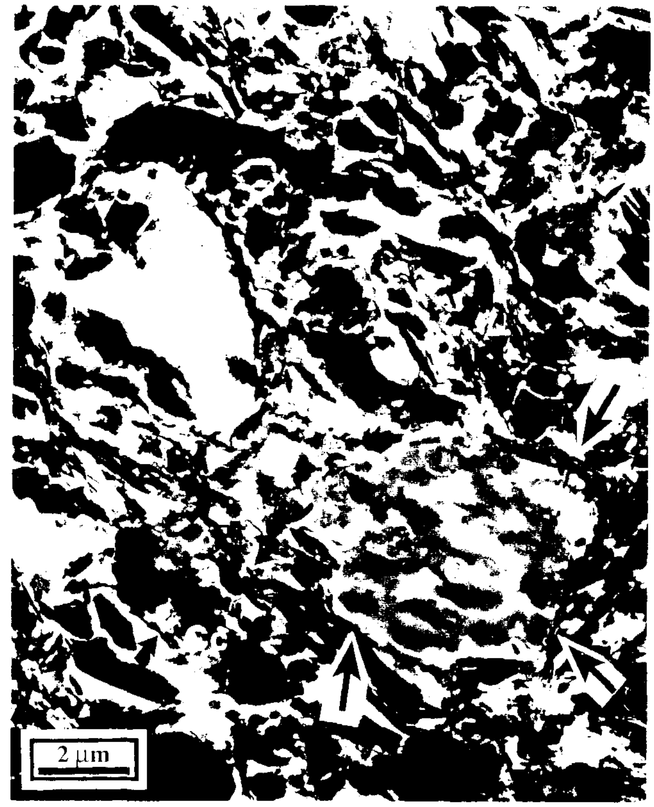

Fig.4. High-magnification view of BCF sediment. Domains (arrows) are wrapped around a shlorite grain (C). Pulverized or degraded microcrystalline chlorite (Cc) and fine clay-size domains (small arrows) comprise the matrix.

sediments. Fig.4 also depicts the chains of small domains (arrows) of illite surrounding and conforming to the shape of the silt-sized clasts. The clast (labeled C) is composed of chlorite, and the larger white hole probably is an illite remnant mostly removed during ultrathin sectioning. The floury matrix material is chlorite probably pulverized during glacial processes. Fig.4 shows the varying electron density of the amorphous or microcrystalline matrix. The extremely fine grain size of the matrix results in a microfabric that is relatively dense, which is indicative of dewatering and suggests the possibility of loading by glacier ice following deposition. The geology does not support this latter concept (Miller and Dobrovolny, 1959; Karlstom, 1964) although the model of Schmoll and Yehle (1986), in which the glacier front is fluctuating in Bootlegger Cove water over a poorly known amount of time and space, could allow for such an interpretation. Also scattered within the floury matrix are submicron-sized illite domains. This association suggests that the matrix is penecontemporaneously deposited with the other constituents, and not a later infilling material that subsequently reduced the porosity, resulting in lower permeability (the measure of the fluid flow under a differential pressure gradient). Permeability is largely controlled by the linkage of adjacent pores or voids and the nature of the pore fluid pathways.

Upon closeup examination the relationship between the clay-sized domains and silt-sized grains appears to be typical of fine-grained remolded materials (Bohlke and Bennett, 1980). Examples of remolding (Fig.5) features include chains of small domains wrapped around grains and bent, swirled, and/or locally preferred orientation domains (Burkett, 1987). Figs.5A and 5B demonstrate domains wrapped around subrounded clasts of illite that probably formed during transport. Figs.5C and 5D show bent domains similar to remolded features described by Bohlke and Bennett (1980). Fig.5E shows domains compressed into fractured-appearing clast. Fig.5F depicts another

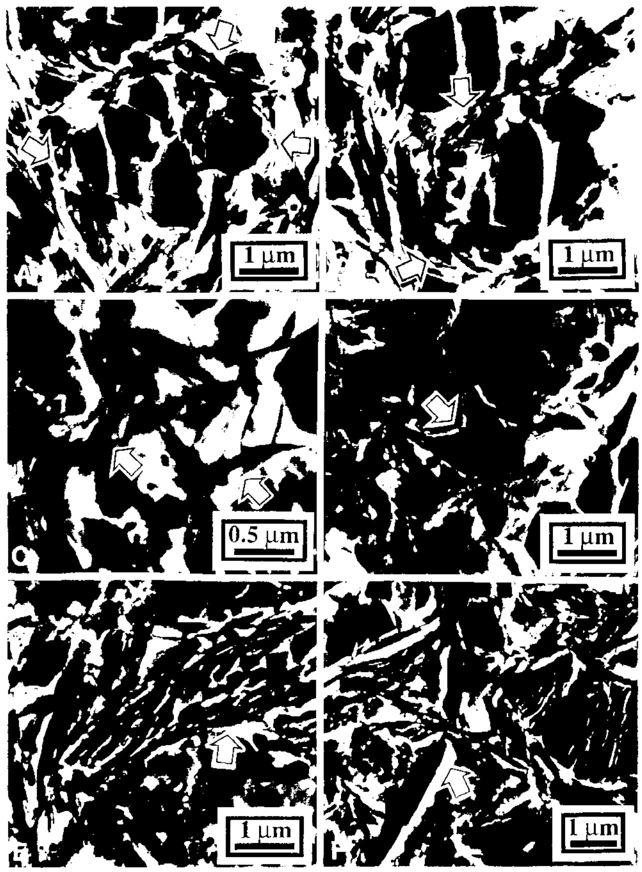

Fig.5. High-magnification view of remolding features. (A) and (B), Alignment of domains surrounding grains; (C) and (D), Bent and swirled domains; (E), Domains compressed against a fractured clast; (F), Squeezed and bent domains.

remolded feature showing chains of domains squeezed by larger domains.

Remolding and transport of poorly sorted grains are features consistent with glacial materials. This study reveals various microfabric features of clay-size domains and larger clasts within packets of matrix material indicative of glacial processes. The matrix represents materials pulverized during transport. No clear evidence is seen of alteration, neoformation, chemical weathering, or other subtle diagenetic mineralization. Mechanical weathering and remolding are the dominant processes driving microfabric development.

CONCLUSIONS

Microfabric observations can be used to verify the BCF as glaciomarine and further substantiate the sedimentation processes involved. In our analysis, the following characteristics were observed: (1) Poorly sorting grain size indicates mass transport. (2) Subrounded shape of silt size clasts indicates mechanical transport. If the larger clast, as revealed by the holes, are indeed quartz or another remnant grain, the subrounded shape could have been inherited from previous events. (3) Pulverized matrix indicates mechanical weathering. (4) Domains sheathing larger clasts indicate remolding. (5) Locally oriented, swirled, and bent domains also indicate remolding. (6) Angular, small to medium clay-sized clasts indicate short transport distances. (7) The absence of well-developed linear chains of domains that either were never formed or were broken indicate transport. (8) The occurrence of oriented, stepped FF chains of domains possibly results from microshearing during remolding similar to processes observed by others in different sediment types (Pusch, 1967; Burkett et al., 1990).

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