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FJORD CIRCULATION AND SEDIMENTATION, SOUTHEAST ALASKA

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ABSTRACT

Large scale transport of sediments in turbid suspension is observed in Alaskan fjords. Seasonal thermohaline stratification of high latitude fjord waters may support concentrations of suspended sediment greater than 10 g/l, the maximum value measured in a fjord. Sediment transport in turbid layers may also be important, although not as obvious, in lower latitude estuarine systems.

INTRODUCTION

High latitude fjords commonly develope pronounced seasonal density stratification. During the summer, solar heating and fresh water inflow produce one or more pycnoclines within the water column. Routinely the density contrasts between layers are as great as 10-15 g/l. The result is an exaggerated version of standard estuarine circulation in which warm fresh water overlies cold saline waters. The abruptness of the density gradients suggests that mixing between various water layers is inhibited, and it is believed that this may provide a mechanism for the large scale transport of fine grained sediments.

Rates of sedimentation in southern Alaskan fjords have never been measured directly, but both bathymetric and sedimentologic evidence suggests that they are very high (1, 2). Contemporary deglaciation and a maritime climate result in the introduction of large volumes of detritus of all sizes. Where sills do not restrict bottom currents, turbidites are often found; beyond this zone there is rapid deposition of poorly sorted muds, often extending beyond the fjords.

The evidence suggests that the periglacial muds associated with the fjord systems are transported as turbid suspensions. Since turbulence at the surface induces rapid mixing and flocculation, and sills prevent long distance bottom current transport, large quantities of sediments must be transported as turbid suspensions on density interfaces within the water column.

FJORD SEDIMENTS

The sedimentary regime within fjord systems is usually relatively simple. Sediment is introduced on a large scale only at the heads of the fjords, where glacial debris enters as turbid fluvial suspensions, the familiar "glacial flour". The precipitous walls of the fjords reduce lateral contributions of fresh water and sediment to a minimum. Where there are tidal glaciers, some material (often very coarse) enters fjords rafted by the ice, but the bulk of the sediment is carried in meltwater streams. The turbulence of these streams is so great that coarse sands and even gravel can be carried in suspension.

Morainal Deposits

Most recently deglaciated fjords are punctuated by one or more distinct sills, which are covered with coarse, very poorly sorted debris. Where the local history of deglaciation is known the position of these sills usually corresponds to times of temporary readvance or stillstand. In some cases the sills may be bedrock features mantled with winnowed coarse debris, rather than true moraines. Relief above the basins is commonly in the tens of meters, and may be over 100 m. These sills divide the fjords into a series of distinct flat-floored basins and serve to pond considerable thicknesses of unconsolidated stratified sediment (3).

Turbidite Sands

Turbidity current deposition of graded sands has been noted in many of the older fjord systems (4). Individual turbidite sands have been traced for many kilometers along the axes of Norwegian fjords. Graded sands have also been observed in the recently deglaciated fjords of southeastern Alaska, but they are found only above the first well-defined sill (G. D. Sharma, personal communication). Apparently turbid bottom flows are not competent to cross the ubiquitous sills.

Periglacial Muds

The characteristic sediment of Alaskan fjords is an undistinguished mixture of silt and clay, which has been termed periglacial mud (2). This sediment is poorly sorted and is often polymodal, with peaks in both the silt and clay range. Fine sand is sometimes present, but coarse detritus that might suggest ice-rafting is extremely rare. Organic carbon in the sediment is low, ranging from 0.01 to 0.3% by weight (5), although carbonized woody fragments are sometimes encountered. Carbonate content is low other than in areas with a limestone hinterland. Clay fractions are largely chlorite and trioctahedral micas; quartz and kaolinite are rarely encountered (5,6). It is believed that this periglacial mud is largely transported in turbid suspension (7).

FJORD CIRCULATION

The geometry and climate of fjords dictate a relatively simple circulation pattern (8,9,10). In high latitude fjords, cooling and reduction in run-off results in uniform, unstratified water masses during the winter. During the remainder of the year, large volumes of fresh water are introduced from melting and precipitation, producing a strong stratification of water masses.

Although the fresh water is often very turbid, it spreads and flows out above the denser marine waters. Both haloclines and thermoclines serve to separate the distinct water masses. In Muir Inlet, a fjord tributary to Glacier Bay, winter profiles show almost completely uniform thermohaline characteristics within the water column. Summer profiles show a very pronounced surface halocline, from 14°/₀₀ at the surface to 25°/₀₀ at 2 m depth, and a deeper thermocline at about 40 m. The density contrasts between layers are great; typically in the summer σ_t values at the surface in the fjords will be as low as 10 while they are the oceanic average of 25 at depth.

Summer circulation in the fiords is a simplified version of standard positive estuarine circulation (11). Normal marine waters responding mainly to the tides are found beneath a variable lens of mixed water at the surface. This surficial layer tends to be inhomogenous and can often be as much as 50 m thick. Net movement of the surface mixed layer is out the fjord; the deep marine waters move predominantly into the fjord. Downfjord, wind and wave mixing destroy the distinct character of the surface layer and conditions approach those of normal sea water (12).

DISCUSSION

High latitude fjord systems can be regarded as models for the study of turbid suspension as a sedimentary agency. During the run-off season there is a plentiful supply of suspended sediments entering the fjords from meltwater streams. Quantities in suspension as great as 10 g/l have been measured in the tidal portion of Taku River and over 1.5 g/l in the surface waters of Taku Inlet (13). The density gradients within the fjord water column are quite adequate to carry the observed sediment load without disrupting the simple thermohaline estuarine circulation pattern. The rapid accumulation of muds beyond fjord sills proves that some agency transports detritus of at least the silt size range considerable distances in the fjord system. Suspension transport is the most likely mechanism, but the competence of this agency is usually believed to be limited to the finest, almost colloidal, sizes of sediment.

Turbid suspension as an agency of sediment transport in marine environments has been assumed to be minimal for a variety of reasons. The fine clay mineral particles common in suspension are assumed to flocculate and settle out immediately upon encountering the electrolytic effect of sea water. However, as Postma (14) has observed, the floccules that are formed are of extremely low density, and settling velocities calculated from their size and their mineral densities are quite unreal in nature; their actual settling velocities would be extremely slow and floccules would continue to maintain the density of the turbid layer long after they might be assumed to have settled out. If even a very gentle initial slope of the turbid layer downfjord can be assumed, internal turbulence would also tend to maintain particles in suspension, even particles as coarse as fine sand (15). Further, considerable amounts of suspended sediment have less influence on water density than might be expected; the addition of one gram of sediment with a density of 2.6 to a liter of water only increases its density by about 6×10^{-4} g/ml. Consideration of these factors suggests that very large quantities of sediment can readily be transported in suspension, especially in such stratified waters as most fjords.

Turbid surface waters are commonly observed in many estuarine systems; fjords merely display this phenomena dramatically because of the high concentrations of glacial flour present. Turbid waters as discrete layers have also been observed at depths as great as 50 m in some Alaskan fjords (2). It appears that such layers travelling on density surfaces within the water column may be a major mechanism of fine sediment transport. Turbid waters may well be the dominant type at the base of the mixed surface water layer. A proposed model for fjord circulation is shown in Figure 1.

CONCLUSIONS

Transport of large quantities of suspended sediment for considerable distances is observed in fjord systems. These turbid waters are supported by the pronounced density stratification observed during the run-off season in fjords. This phenomenon may be quite influential although not as obvious in lower latitude estuarine systems.

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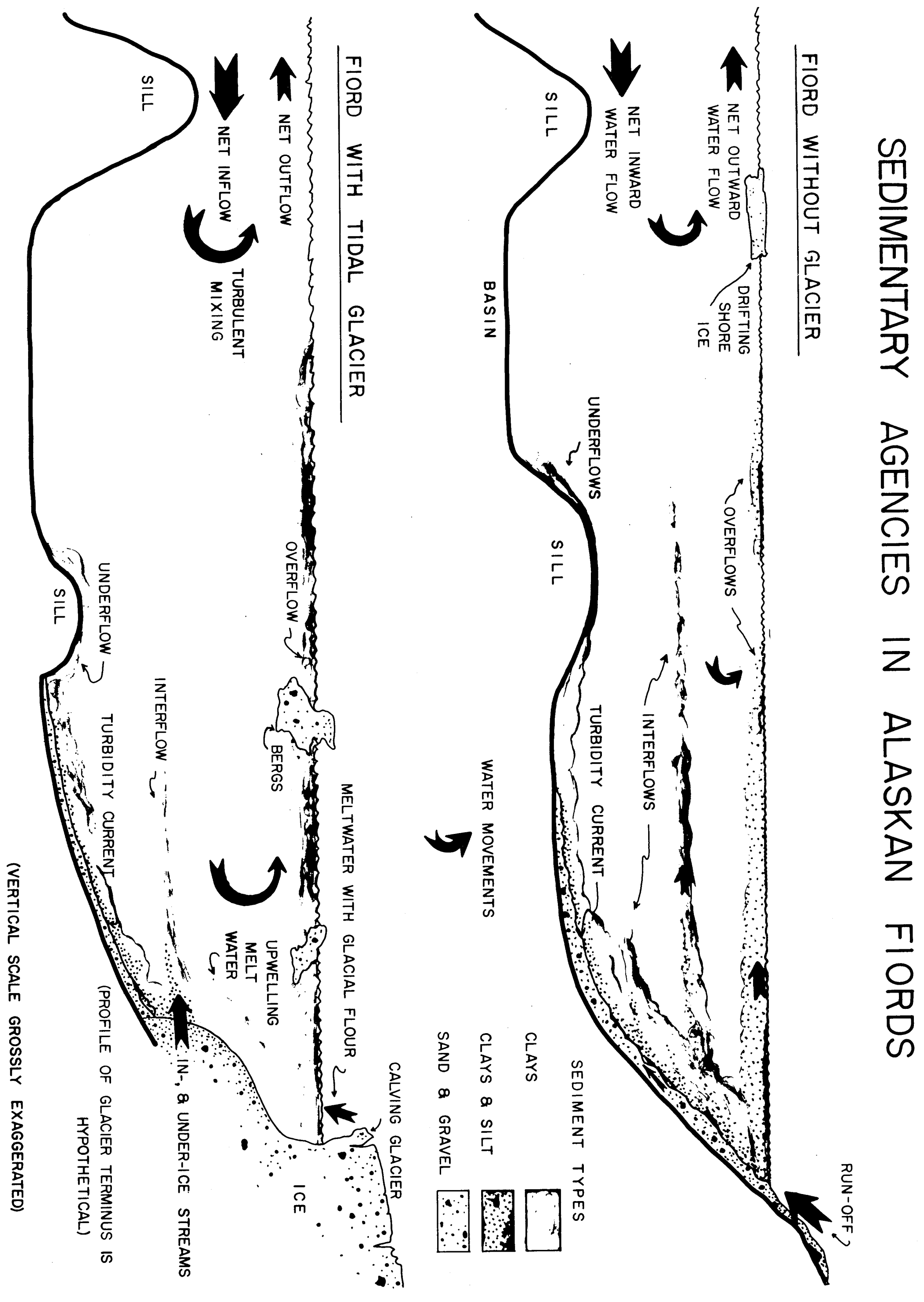

Figure 1. Proposed model of summer water and sediment circulation in fjords.