# Abstract

## Temperate Glacimarine Sequence Stratigraphy

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Temperate glaciated continental shelves are an extreme end-member of glacimarine environments, typically occurring in the mid-latitude range of glaciation, and as such their glaciers rely on mountain-system glaciers and a very dynamic climate to maintain their presence at sea level. Alternatively, temperate glacimarine systems occur at the extreme limit of large ice sheets as they expand into lower latitudes, or they may occur at high latitudes during major climatic transitions, such as into and out of icehouse and hot(green)house periods. These forcing mechanisms dictate a condition of many important allogenic factors that drive the resulting stratigraphic architectures and succession motifs in a glaciated basis.

Under these temperate glacial conditions, debris fluxes and inferred erosion rates are very high providing a significant source of sediment for growth of a continental margin and deposition of thick stratigraphic sequences. In addition, these settings provide for positive feedbacks for the whole continental margin system in that the high erosion rates may well enhance isostatic uplift of the mountains, and the glaciers may enhance local relief by increasing erosion at lower elevations as shown by over-deepened fjords and a higher debris flux with increasing drainage basin size. The tectonic regime of either compressional-transpressional or extensional-transtensional can also provide significant space in which to accommodate the large volumes of sediment produced rapidly from high sediment fluxes and high accumulation rates.

Sediment can accumulate to hundreds of meters in thickness over very short time periods of tens (locally) to hundreds-to-thousands of years. Although the shelf is eroded or by-passed during glacial advance with most sediment originating in fjords and foreland areas to then be redeposited on the slope, older sequences may still be preserved on the shelf. But the shelf preserves most of its sediment during the subsequent retreat.

Compared with non-glacial successions, sea level on glaciated continental shelves is not necessarily the only control on baselevel; the sole of the glacier is as well. The glacier has the ability to erode major regional unconformities well below sea level, and the glacier bed is also a primary source of large volumes of sediment introduced below sea level. Even with a significant water depth on the shelf provided by tectonic forces, during one advance into the sea, a glacier can supply sediment to fill that space, and even aggrade to above sea level if a glacier terminus stabilizes for some time, without necessarily any change in eustasy. Thus facies changes may occur simply by a glacial advance and retreat that is independent of other variables. This is especially relevant for glaciated shelves that are deep below sea level as is the case currently for Antarctica and may have been common in the past during warmer glaciations. However, perhaps the most problematic successions are those nearshore in shallower water and within "normal" baselevel changes, because there, eustatic changes will be superimposed on glacial baselevel changes with a complex interaction among the various allogenic drivers.

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The timing of glacial fluctuations relative to eustatic changes are perhaps more critical in temperate glacial systems than for others because local glaciers may commonly fluctuate independently of major global events. Furthermore, ice streams within major ice sheets may behave independently of eustatic changes, especially with surging glaciers or ice streams (e.g., Hudson Bay ice stream producing Heinrich layer debris). Rapid sediment accumulation at temperate grounding-lines is also known to enhance their stability and reduce water depth without a change in relative sea-level or the location of the glacier terminus. Thus, glacial advances are partly controlled by sediment accumulation and may occur independently of major eustatic change.

Consequently, sediment produced at glacial grounding-lines (the local baselevel) accumulates as aggradational, progradational or retrogradational packages that may be only secondarily dependent on relative sea-level changes for controlling accommodation. Furthermore, within particular systems tracts, changes in baselevel are also a function of gravitationally compensated sea level distribution and glacial isostasy in addition to the more common isostatic forces (water and sediment loading), tectonism, and local water-depth controls of local erosion and sediment accumulation rates.

Based on this background, establishing a stratigraphic framework on which to interpret temperate glaciated continental margins is more complex than for lower latitude margins. There is a complex interaction of glacial advance and retreat, eustatic changes, glacial and sediment isostatic loading, rates and styles of sediment delivery to the sea, marine dispersal and redepositional processes, local tectonic movements, continental shelf morphology, and type of glacial terminus in controlling sediment accommodation on temperate glaciated shelves. The complexity created by differences in rates, magnitudes and relative timing of changes in each of these factors is enhanced when trying to interpret a stratigraphic record in which paleo-water depth indicators are commonly few. Furthermore, changes in facies driven by glacial proximity versus relative sea-level changes are often debatable. Cycles of glacial advance and retreat may often act as a more important control on sedimentation and genesis of particular systems tracts than other forces such as relative sea-level.

These characteristics make temperate glaciated margins not only different from non-glaciated shelves, but also different to polar and subpolar (polythermal) glaciated shelves. Glacial regimes other than temperate may not have thick interglacial wedges on the shelf. These characteristics are also important considerations relative to the original sequence stratigraphic concepts. Facies changes, such as large-scale fining and coarsening trends, may occur simply by a glacial advance and retreat and if so, are independent of other allogenic variables.

This brief overview demonstrates that temperate, glaciated continental shelves are by their nature complex sedimentary basins in that they not only have typical low-latitude siliciclastic processes acting to produce a sedimentary record and depositional architecture, but they also have the consequences of glacial action superimposed. For these settings glacial systems tracts (GST) are, therefore, defined and related to glacial advance and retreat signatures, which can then be evaluated relative to changes in other external forces. Defined systems tracts are: glacial maximum (GMaST), retreat (GRST), minimum (GMiST) and advance (GAST) that are separated by glacial bounding surfaces (GBS), which are respectively, a grounding-line retreat surface (GRS), a maximum (glacial) retreat surface (MRS) and a glacial advance surface (GAS). Each glacial advance and retreat sequence is bounded by a regionally significant unconformity, a glacial erosion surface (GES), or its equivalent conformity. Sections also may include the equivalent of low-latitude sequence boundaries, but they need not coincide with a GBS, even a GES. Often a GES may be produced at a time when relative sea-level is high due to glacial isostatic loading during glacial advance plus a significant gravitational attraction on the local ocean mass by a large expanding ice mass.

Within-trend motifs vary across a shelf but include facies dominated by the movement of grounding lines. Facies motifs may have subglacial till above a GES and is the main facies of the GMaST; however, tills may often absent. Although diamictic debrites occur associated with grounding-line deposystems, the GRST succession is dominated by sorted deposits of gravel, rubble and poorly sorted sands due to the dominance of glacial meltwater. These deposits commonly have the geometry of banks or wedges/fans. They form the break at the outer continental shelf and also form a retrogradational stacking of bank systems on the shelf. Banks are capped by glacimarine rhythmites including thin debrites, turbidites, cyclopsams and cyclopels and perhaps iceberg-rafted varvites in fan to sheet-like geometries. Above these are draped sheets of bergstone muds that grade to paraglacial muds. The GMiST occurs with glacial retreat onto land or into fjords. The GMiST is represented in nearshore areas by progradational deposits of paralic systems dominated by deltaic and siliciclastic shelf systems, and in offshore areas by condensed sections. The GAST is represented by the inverse of the GRST facies succession, but is also the most likely interval to be eroded during readvance.

This sequence stratigraphic model may be used to compare direct glacial records of ice volume changes through time with more distal proxy records such as global eustasy curves and oxygen isotopes. After all, on high latitude margins it is the glacial signal that is strongest and may be compared with the more distal proxy records of global ice volume changes. Eustatic history is probably more easily established from non-glaciated shelves. However, if, after establishing a glacial sequence stratigraphy, it is possible to also establish temporal changes in local water depth and their forcings, then it would be possible to infer both glacial fluctuations and relative sea-level change, and that could be ultimately the definitive case. Another important aspect is to recognize is that glacial regime changes through periods of glaciation and so there is a need for different sequence stratigraphic models transitioning into and out of “normal” siliciclastic models and colder-regime glacial models.