Mid-Pleistocene climate transition drives net mass loss from rapidly uplifting St. Elias Mountains, Alaska


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Erosion, sediment production and routing on a tectonically active continental margin reflect both tectonic and climatic processes: partitioning the relative importance of these processes remains controversial. Gulf of Alaska contains a preserved sedimentary record of Yakutat Terrane collision with North America. Because tectonic convergence in the coastal St. Elias orogen has been roughly constant for 6 Myr, variations in its eroded sediments preserved in the offshore Surveyor Fan constrain a budget of tectonic material influx, erosion, and sediment output. Seismically imaged sediment volumes calibrated with chronologies derived from Integrated Ocean Drilling Program boreholes shows that erosion accelerated in response to Northern Hemisphere glacial intensification (~2.7 Ma) and that the 900-km-long Surveyor Channel incision appears to correlate with this event. However, tectonic influx exceeded integrated sediment efflux over the interval 2.8-1.2 Ma. Volumetric erosion accelerated following the onset of quasi-periodic (~100-kyr) glacial cycles in the mid-Pleistocene climate transition (1.2-0.7 Ma). Since then erosion and transport of material out of the orogen has outpaced tectonic influx by 50-80%. Such a rapid net mass loss explains apparent increases in exhumation rates inferred onshore from exposure dates and mapped out-of-sequence fault patterns. The 1.2 Myr mass budget imbalance must relax back toward equilibrium in balance with tectonic influx over the time scale of orogenic wedge recession (Myrs). The St. Elias Range provides a key example of how active orogenic systems respond to transient mass fluxes, and the possible influence of climate driven erosive processes that diverge from equilibrium on the million-year scale.

Introduction

Orogenesis reflects the balance of crustal material entering a mountain belt to undergo shortening and uplift versus material leaving the orogen through exhumation, erosion and sediment transport. Perturbations in the influx/efflux from the orogen are expected to result in predictable changes in deformation within the orogen as it attempts to reestablish equilibrium. The long-term sink for sediment transported out of mountain belts is often in the deep sea, particularly in large submarine fans where sediments accumulate at anomalously high rates (>10 cm/kyr) compared to deep-sea pelagic sedimentation. Even

Significance

In coastal Alaska and the St. Elias orogen, over the past 1.2 million years mass flux leaving the mountains due to glacial erosion exceeds the plate tectonic input. This finding underscores the power of climate in driving erosion rates, potential feedback mechanisms linking climate, erosion, and tectonics, and the complex nature of climate-tectonic coupling in transient mountain belts toward longer-term dynamic equilibration of landscapes with ever-changing environments.

Reserved for Publication Footnotes
Fig. 1. A) Gulf of Alaska study area with Last Glacial Maximum glacial extent (light blue), limit of exhuming St. Elias orogen (dashed green), glacial flow paths (blue arrows; dashed where presumed secondary contribution), and glacially fed deep-sea Surveyor Channel system (black dashed). Yakutat Terrane shaded in tan with deformation front of the Yakutat-North American plate boundary as eastern thrust fault and boundary with Pacific Plate as southern strike-slip faults. Brown vectors mark mass influx to orogen from Yakutat Terrane and portion of eroded sediments on Pacific Plate that are subducted/accreted at the Aleutian Trench. Seismic traverse in (B) is shown in green and IODP Exp. 341 drillsites in yellow. B) Multichannel seismic transect through Site U1417 where base of seismic Sequence III (correlated to the MPT) is in green and base of seismic Sequence II (correlated to the PPT) is in light blue. Note the Surveyor Channel, a conduit for sediment transport from the shelf to the deep sea, which appears to become active near the PPT, thus dominating sediment depositional processes for all of Sequences II and III (since ~2.6 Ma). Seismic subsequence subdivision also shown for Sequence I (pre-PPT). Depth of recovery at Site U1417 (thick green line) near 6.4 sec TWTT.

Fig. 2. Representative topography through the IODP Expedition 341 drill sites (see Fig. 1 for location), and the principle lithologies at each site along with chronologies and accumulation rates in cm/kyr. Depths are in meters of core composite depth below the seafloor (CCSF-B) that approximates the drilled interval. B/M= Brunhes/Matuyama. G/M= Gauss/Matuyama. Vertical exaggeration ~18x.
higher sedimentation rates (>100 cm/kyr) proximal to glacially eroded regions suggests that wet-based glaciers are extremely efficient agents of erosion. Observations and modeling have argued that erosion rates can influence tectonic processes, but the timescales of adjustment, and the role of landscape disequilibrium, remain unclear. For example, exceptionally high local sedimentation rates (100-1000 cm/kyr) recorded on the century scale have been suggested to reflect an unsustainable, short-term erosion perturbation due to the Little Ice Age.

Time-varying sediment accumulation rates at individual sites have been interpreted to reflect an allogenic control on sediment production, especially related to a fundamental climate-induced change in terrestrial sediment production in the Pleistocene. An alternate explanation is that autogenic sediment dispersal processes and/or subsequent erosion of accumulated strata can result in an apparent decrease in sediment accumulation rates with increasing age (the so-called "Sadler Effect", first described by Moore and Heath, 1977), especially as the averaging time increases and in environments where accommodation limits accumulation (e.g., floodplains, continental shelves). Testing between the allogenic and autogenic viewpoints requires spatially continuous sedimentation data to address potential sampling bias.

Southeastern Alaska represents a key location to constrain such sampling biases and to examine the interactions among climate, erosion, and orogenesis. Tectonic forcing creating the St. Elias Mountains is a product of low-angle subduction of the Yakutat Terrane (Fig. 1A); convergence has been essentially constant since a reorganization of neighboring Pacific Plate motion (~6 Ma) but sustained high rates since the MPT (~1.2 Ma). Glacial influence is thought to have increased with intensification of Northern Hemisphere glaciations at the Plio-Pleistocene transition (PPT) and perhaps further increased with the transition to 100 kyr cycles at the middle Pleistocene transition (MPT). Sediments eroded from the orogen that are deposited on the continental shelf either lie within the orogen if within the Pamplona Zone fold and thrust belt, or may re-enter the orogen with the subducting Yakutat Terrane (Fig. 1A). Sediments that bypass the shelf to be deposited on the deep-sea Surveyor Fan or within the adjacent Aleutian Trench are permanently removed from the orogen as these sediments will travel with the Pacific Plate westward to be eventually accreted or subducted along the Aleutian system (Fig. 1A). In 2013, Integrated Ocean Drilling Program (IODP) Expedition 341 drilled a transect of sites (U1417-U1421; Figs. 1, 2) across the Surveyor Fan in the Gulf of Alaska and Bering-Malaspina slope and shelf offshore of the St. Elias Mountains to examine the sedimentary record of unroofing during a cooling global climate with increasing intensity of glaciations.

**Results and Discussion**

The Surveyor Fan covers >300,000 sq. km, the western 2/3 of which is sourced from the St. Elias Mtns. Distal fan Site U1417 reveals that the fan has been active since at least Miocene time; preglacial fan sediments, referred to as Sequence I, were recovered by drilling and are imaged and mapped by seismic reflection data (Figs. 1B, 2). The first occurrence of gravel-sized debris (>2 mm grain size) is now well dated and documents the onset of ice rafted deposition just prior to the Gauss-Matuyama paleomagnetic reversal (~300 m below the sea floor (2.581 Ma) (Fig. S3, S4). This onset of ice rafting is consistent with recent cosmogenic-nuclide dating of the earliest apparent Cordilleran Ice Sheet (2.64 Ma and 2.86 Ma) and is inferred to reflect the regional response to intensification of Northern Hemisphere glaciation (NHG). This depth/age within the cored
interval lies a few meters above the base of geophysically mapped Sequence II which is assigned an age of 2.8 Ma (Fig. 1B, 3A, S1, see methods) and is comprised primarily of overbank deposits from the Surveyor Channel. The Surveyor Channel system has not avulsed since its initiation11 and appears to have formed at about the same time as the first occurrence of tidewater glaciation and the associated change in sedimentary system based on the mapping of the Sequence II/III boundary from Channel to Site U1417 (Fig. 1B).

Overlying Sequence II, Sequence III (also comprised of overbank strata from the Surveyor and related channels, but with different seismic reflection character) (Fig. 1B, 3B, S2) thickens significantly towards the orogen11. At distal Site U1417 the Sequence III/II boundary lies just below the 1.2 Ma onset of the middle Pleistocene transition (MPT)20,26 whereas at the proximal fan Site U1418 the reflector lies to the upper Jaramillo paleomagnetic reversal (0.99 Ma) within the MPT (Fig. 2, S3, S4). Sequence II/III boundary is conservatively assigned an age ∼1.2 Ma. At Site U1417, the post-upper Jaramillo average sedimentation rate is 129 m/Ma; at Site U1418, it is 813 m/Ma, a six-fold increase towards the orogen (Fig. 2). Sediment thicknesses and approximated sedimentation rates from seismic reflection isopachs support these rates as representative of large-scale spatial patterns and not local anomalies (Fig. 3B, S2, Table S1).

These results demonstrate elevated glaciogenic sediment accumulation in the Gulf of Alaska in the middle-Late Pleistocene that may be even more pronounced on the continental shelf/slope. On the slope, Sites U1419 (drilled to 177 m) and U1421 (drilled to 702 m), and at shelf Site U1420 (drilled to 1020 m), sediments were all of normal paleomagnetic polarity and the Brunhes-Matuyama paleomagnetic reversal was not encountered, indicating depositional ages >0.78 Ma (Fig. 2). Biostratigraphic data from U1421 show these sediments to be < 0.3 Ma. Benthic foraminiferal δ13C analyses at U1419 indicate the sediments recovered at that site to be <0.06 Ma (Fig. S5). Thus, sustained Late Pleistocene sedimentation rates on the slope average 200-300 cm/kyr, and on the shelf averages >100 cm/kyr (Fig. 2), consistent with shoreward thickening of seismic units mapped throughout the region. These remarkably high-long term accumulation rates determined for the first time with an independent age-calibrated offshore depositional record, are similar to rates within the last century in Alaskan waters13,20, suggesting that the recent rates are not local aberrations but are sustained features of the St. Elias - Gulf of Alaska erosion-deposition system.

Mapping the seismic reflector at the base of Sequence II (~2.8 Ma, early in the PPT) and the reflector between Sequences II and III (~1.2 Ma, early in the MPT) throughout the Surveyor Fan provides a minimum estimate for the total sediment yield over these time intervals. This use of a sediment volume to examine the integrated sediment efflux from the St. Elias Mountain range allows us to avoid complications associated with potential local bias15 since we have integrated all of the unsubducted sediments in the system and are not dependent on sedimentation rates at discrete locations to examine flux through time. The sediment volumes here are minimum estimates due to the possibility that some sediment is lost to the system, but we have estimated the volume of subducted sediments at the Aleutian Trench based on MOREVEL2010 trench-normal Pacific Plate velocity of 48 mm/yr (Fig. 1A) and the cross-sectional area of sediments of Sequence III and II currently subducting/accreting. The sediment volumes in the portion of the Surveyor Fan sourced from the Bering-Bugley and the Seward-Malaspina-Hubbard-Alseck drainages via the Surveyor Channel, are ~29800 ± 6700 km3 for Sequence II and ~66700 ± 13900 km3 for Sequence III with additional Aleutian Trench subducting/accretion volumes estimated at ~9800 ± 400 for Sequence II and ~41900 ± 13000 for Sequence III (Fig. 3, S1, and S2 and Table S1, see methods).

In support of a glaciogenic influence on fan volume, preglacial sedimentation rates at Site U1417 (averaged over 0.4 Ma intervals to avoid shorter-term transient effects25) Fig. 4) of ~30-70 m/kyr between 5.2-2.8 Ma rose to peak values of 120 + 20 m/kyr between 2.4-2.0 Ma following the expansion of northern-hemisphere glaciation near the Plio-Pleistocene boundary. Although glaciation continued, at Site U1417 sedimentation rates relaxed back to ~60 m/kyr from 1.6-1.2 Ma, implying an apparent reduction of regional glacial erosion. This inference assumes that Site U1417 is representative of sediment dispersal to the fan by the Surveyor Channel, which is supported by comparison with Early-mid Pleistocene sedimentation rates modeled from regional seismic isopachs (Fig. 3A, S1, S2). Sedimentation rates at Sites U1417 increase starting at 1.2 Ma to peak at ~140 m/kyr by 0.8 Ma, coincident with the onset of 100-kyr glacial cycles (Fig. 4). Such a resurgence of rapid sedimentation with the MPT ice expansion is expected, however sustained high sediment yields through the Late Pleistocene is not predicted based on an isostacy-only uplift response3,4.

Observed sedimentation rates from the Expedition 341 sites (Fig. 2) and from sedimentation rates modeled from seismic isopachs (Fig. 3B) in the distal Surveyor Fan over ~1.2 Myr are comparable to those of the Bengal Fan, where a similar increase in sedimentation is observed in the middle to Late Pleistocene6,8. Sites proximal to the Yakutat margin record some of the highest sedimentation rates ever recorded in the deep-sea; for example on the Bering-Malaspina slope, rates recorded for the last few glacial cycles are a factor of two larger than the glacially fed sedimentary deposit filling the south-central Chile Trench, previously the highest reported sedimentation rates observed over these timescales14.

To place the MPT increase in Gulf of Alaska sediment yield into an orogenic framework, we calculate the tectonic influx of material into the St. Elias Range (Table S2, see methods) using the length of the deformation front of the Pamplona Zone16, the GPS-determined Yakutat-Southeast Alaska block convergence rate (37 mm/yr)17 (Fig. 1A), and the thickness of sediments above the Yakutat decollement based on seismic data6,8. We estimate that ~36800 ± 8800 km3 and ~31800 ± 7500 km3 of glaciomarine sediments entered the ocean from 2.8-1.2 Ma and 1.2-0 Ma, respectively (Table S2). Using our mapped Sequence II and III sediment volumes including the estimating subducted/accreted volumes and correcting for porosity (see methods), we determine a total erosional efflux of ~20500 ± 4000 km3 for 2.8-1.2 Ma and ~56,400 ± 13600 km3 for 1.2-0 Ma (Table S2). The early Pleistocene influx exceeded efflux by ~16300 ± 10100 km3 i.e., at a greater than 95% confidence level there was a net positive mass flux in the orogen. In contrast, since the onset of the MPT efflux has exceeded influx by ~24600 ± 15,600 km3 (a ~50% net negative mass balance at a greater than 90% confidence level) (Table S2, see methods) producing the marked change in sediment volumes in the Surveyor Fan (Fig. 3, S1, and S2).

Implications

If the St. Elias orogen behaves as a critical-taper wedge, then given enough time the sustained net efflux after the MPT should result in structural responses. However, predicted dynamic equilibrium timescales in models that seek a steady-state solution3,19 are > 3 Myr. The glaciated critical wedge model3,15 predicts that if sufficient glacial erosion occurs to result in net efflux then the active orogen would narrow and seek to maintain critical taper through internal deformation (e.g., out-of-sequence thrusting). Sandbox modeling further suggests that focused erosion within one portion of a critical wedge can result in a sequence of fault duplexes that focus rock uplift17, where these structures may be...
an expression of internal deformation due to erosion-reduced taper. Onshore data including low-temperature thermochronol-
ogy and structural mapping within the fold and thrust belt have been interpreted to display accelerated exhumation since the
mid-Pleistocene and structural response to focused erosion.
Merging these onshore observations and our offshore determined
switch to net efflux for the last 1.2 Ma, we suggest that the MPT
has caused a perturbation in the tectonic erosion balance of the
St. Elias orogen and that transient structural readjustment is
observable on timescales much shorter than those required to
reach steady state.

These results suggest that the longer and more intense 100
kyr glacial cycles since the MPT (relative to the shorter ~40 kyr
period pre-MPT glacial cycles) increased the integrated ice cover
and erosion within the region of high relief originally created
by tectonics. Our drilling-derived, calibrated history of sediment
accumulation preserved within the proximal and distal Surveyor
Fan documents a pattern of exceptionally high accumulation rates
since the MPT, ranging from 130 cm/kyr (shelf) to 81 cm/kyr
(proximal fan) to 13 cm/kyr (distal fan) (Fig. 2); even higher
rates are observed on the proximal slope (Fig. 2, S5). We find that
high modern rates of glaciomarine sedimentation, which have been
previously attributed to a short-term transient response to Little
Ice Age forcing (e.g., 27, 28), are unlikely in even more rapid pulses associated with glacial cycles
since the onset of the MPT. At these timescales isostatic re-
sponses can be considered instantaneous due to the low viscosity
mantle within this active orogen setting. We assume that the topo-
graphically controlled drainage basin area did not greatly increase
across the MPT, suggesting several testable controls that could be
the key to this post-MPT effect: 1) increased volume of ice driving an increased instantaneous erosion rate, 2) increased duration
of glaciations driving an increased integrated eroded volume, 3)
larger area of glaciated topography, driving an increase in net
erosional efflux, and/or 4) an accelerated mechanism to remove
sediment previously stored within the orogen. The St. Elias orogen
since the MPT likely represents an end-member example of rapid climate-driven erosion combined with efficient removal of
sediment entirely out of the orogen by glacial advances reaching
the shelf edge; this resulted in an orogen-scale mass imbalance
that persists for at least 1 Myr. Thus an active, glaciated, coastal
mountain belt may contrast with settings such as the Himalaya
where climate has been reported to have lesser influences on
orogenic development. The continued existence of relief de-
spite the 1.2 Ma of net efflux likely reflects internal deformation
maintaining critical taper. Our results underscore the importance
of a high-fidelity time-series approach and regionally mapped
sediment volumes with dense seismic coverage to understand the
dynamic interplay of tectonics and erosion.

Methods
Calculation of mass accumulation rates based on the composite depth scales (known as Core Composite depth below Sea Floor, CCSF-A) correct for ex-
pansion of the sediment column artifact during of the coring process. This
corrected composite depth scale (CCSF-B) comprises the composite depth scales to the same total thickness of the drilled interval. Minimum and max-
imum shipboard age models are based on all available paleomagnetic and
bioturbatigraphic age datums (Figs. S3 and S4). The age models at Sites U1417,
U1418, and U1419 were constructed in the composite depth scales, and are
scales to the same total thickness of the drilled interval

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in the efflux-influx between Sequence III and Sequence II (Table S2, S4, File 2).

Additional uncertainty analyses were performed using 104 (v fan volume) and 105 (efflux-influx) Monte Carlo simulations of Gaussian white noise supplied with the standard deviation of all influx-efflux values. Mean values of a posteriori are recorded of summation sequences. The data are stored in the simulation event. The parameter data sources are noted as the supplementary Python code text files (File S2-2). Matematik-formatted MAT-files Sequence II and IWT isopacts are provided as supplementary files for use with Python code (File S3-4). The Monte Carlo model was adapted for sensitivity testing, where the value of each parameter was varied from 50-150% of the mean value, leaving all the other values set to their mean value and then the net change in flux value was calculated. Based on the sensitivity tests, for influx-efflux, Seq III results are most affected by fan porosity whereas for Seq II, results are.

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