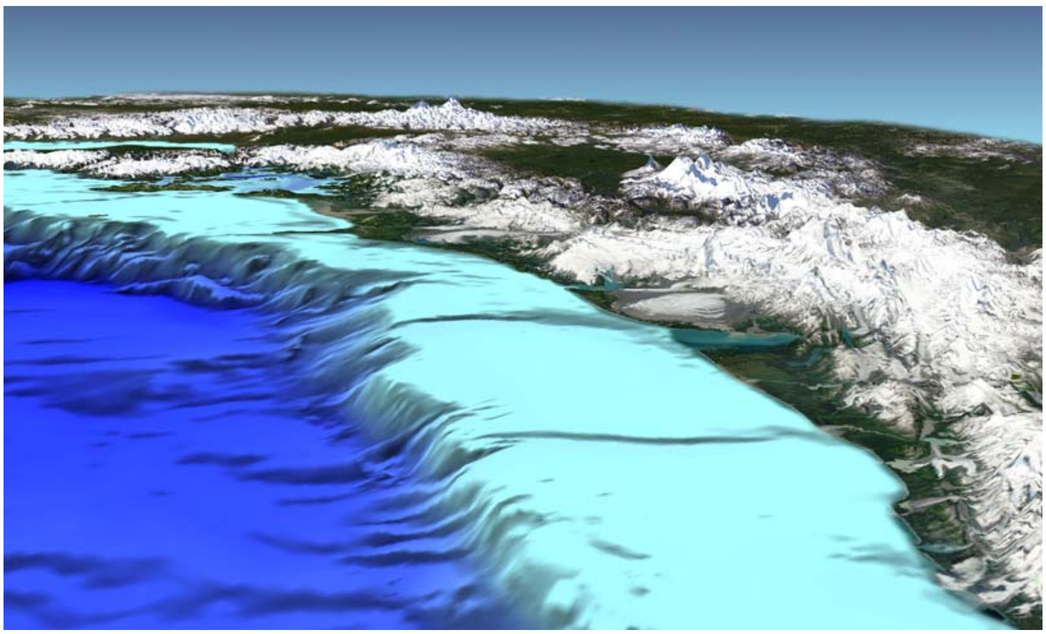
The Interplay of Collisional Tectonics and Late Cenozoic Glacial Climate in Alaska and the Northeastern Pacific Ocean



A Science Plan resulting from a workshop held at Austin Texas, May 5-6, 2003 jointly sponsored by the Continental Dynamics Program, Earth Sciences Division, National Science Foundation (CD/GEO/EAR) and the Joint Oceanographic Institutions/ U.S. Science Support Program (JOI/USSSP)

Website and downloadable pdf file available at:
http://web.clas.ufl.edu/users/jaeger/JOI_CD/index2.htm

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Preface

Collisional glaciated continental margins are premier locations on earth where tectonics, orogenic processes, glacial landscape modification, and continental margin sedimentation can be studied in unison, allowing for quantitative models to be developed linking this broad suite of processes. Theoretical considerations and field studies strongly suggest that erosion rates and rock uplift rates are often closely matched in diverse settings and probably reflect direct, but as yet poorly understood linkages between geodynamic and surficial processes. Climate and topography, in turn, directly affect precipitation rates and types, thus controlling glacial motion. As a result of dynamic glacial behavior, high rates of weathering lead to correspondingly elevated rates of sediment accumulation on adjacent continental margins. When coupled with the proximity of the mountains to the ocean, a high-resolution sedimentary record is created of the diverse terrestrial and marine processes active in these settings. Southeastern Alaska is one such setting where the deformational and depositional products of this interplay between tectonics and climate are recorded at exceptionally high temporal resolution.

Southern Alaska (Fig. 1) is an exceptional natural laboratory for studying a range of geologic problems, including linkages between orogenic processes and continental accretion, landscape modification by glacial processes, and continental margin sedimentation. Geologic processes operate at rapid rates along the southern Alaska margin, which allows scientists to concurrently collect data on tectonic deformation, uplift, erosion, and sedimentation and develop comprehensive geodynamic models that connect these diverse processes. The geological processes of southeastern Alaska are comparable to those observed in the Himalayan orogeny and include extremely high erosion rates, active faulting beneath mountains and alpine glaciers, and orogenesis coincident with extensive glacial cover. Important advantages of Alaska over the Himalaya include the proximity of the highest coastal mountain range on earth next to an energetic ocean with essentially no intervening basins to trap sediment, and present tectonic convergence rates that are substantially higher than the shortening across the Himalaya. Therefore, tectonic signals have the potential to be quickly recorded in offshore areas with little modification resulting from long transport in rivers or temporary storage in intervening sedimentary basins.

A Continental Dynamics/National Science Foundation (CD/NSF) and Joint Oceanographic Institutions/U.S. Science Support Program (JOI/USSSP) sponsored workshop was held on May 4-5, 2003 at the University of Texas at Austin in recognition of new opportunities for cross-discipline research in climate-land-ocean interactions on the scale of Southern Alaska. The purpose of the workshop was to gather a diverse group of earth scientists familiar with the region and with the relevant scientific topics to generate a hierarchy of fundamental research questions concerned with the climatic, oceanographic, and tectonic evolution of the Southern Alaska/Gulf of Alaska region during the Neogene (~25 Ma to the present). A community consensus was reached at the workshop on four broad topical research questions of global importance:

- What are the three-dimensional kinematics and dynamic processes of oblique microplate accretion/plateau subduction, and what are the implications for continental growth?
- What have been the critical Neogene climatic shifts in the high-latitude Pacific and what were the consequences for northern hemisphere climate, glaciation, and environmental change?
- At what temporal and spatial scales does orogenesis influence global and local climate and how do major glacial fluctuations shape orogenesis?

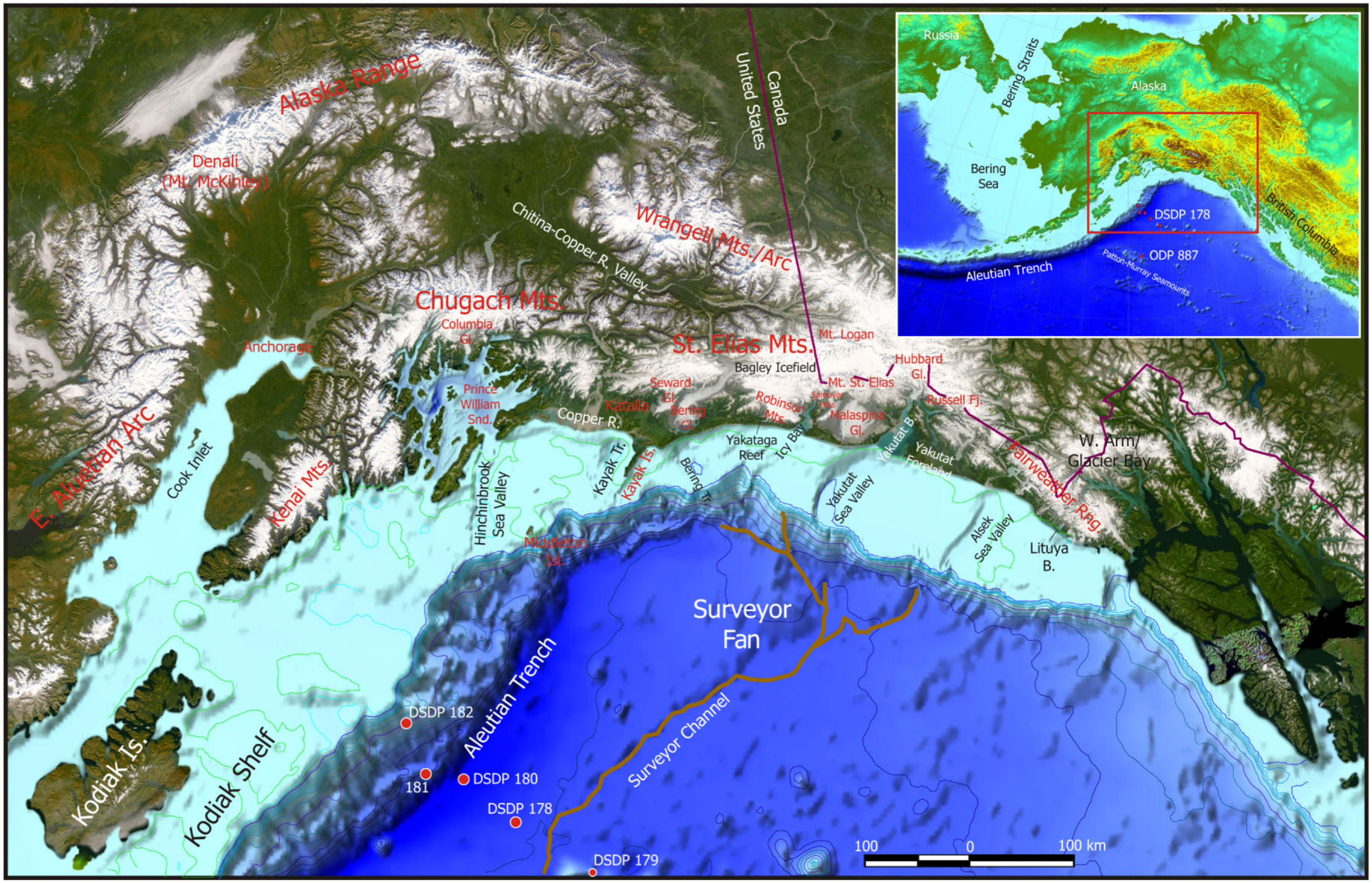


Figure 1. The Gulf of Alaska region: geography and location of previous DSDP and ODP drilling locations (see inset). Composite of MODIS images for southern Alaska courtesy of MODIS Rapid Response Project at NASA/GSFC. The figure is a composite of many separate images taken at different times. Note the inset map for overall location. Shaded bathymetry from ETOPO2 global elevation data set.

Executive Summary

South-central Alaska and the glaciated Chugach-St. Elias range (Fig. 1) is one of the premier locations on earth where tectonics, orogenic processes, glacial erosion, landscape modification, and continental margin sedimentation can be studied in unison, allowing for quantitative models to be developed linking this broad suite of processes (e.g. Jaeger et al., 2001). Southern Alaska is an exceptional natural laboratory for studying a range of geologic problems, including the links between orogenic processes and continental accretion, landscape modification by glacial processes, and continental margin sedimentation. Geologic processes operate at rapid rates along the southern Alaska margin, which allows scientists to concurrently collect data on tectonic deformation, uplift, erosion, and sedimentation and develop comprehensive geodynamic models that connect these diverse processes. The active processes in southeast Alaska are comparable to those studied in the Himalayan orogeny and include extremely high sediment yields, active faults beneath mountains and mountain glaciers, and orogeny coinciding with extensive glacial cover. An important advantage of Alaska over the Himalaya is proximity of the highest coastal mountain range on earth next to an energetic ocean with essentially no intervening basins to trap sediment. Tectonic signals are therefore quickly recorded in offshore basins with little signal modification resulting from long transport in rivers or temporary storage in intervening sedimentary basins.

Due to the variety of climatic and tectonic processes that interact through the orogenesis of a glacially dominated coastal mountain belt such as the St. Elias range, a wide scope of expertise and techniques must be brought to bear for making a fundamental leap forward in our understanding of such systems globally. To that end, a workshop, funded jointly by the National Science Foundation-Continental Dynamics program and the Joint Oceanographic Institutions, was held in Austin, Texas, May 5-6th, 2003, that brought together researchers interested in using the southeastern Alaska region (i.e., coastal mountains, continental margin, Gulf of Alaska abyssal plain) as an *in situ* natural laboratory to study tectonic-climatic interactions in a glacial environment. Fifty-seven scientists attended the workshop and represented the fields of tectonophysics and geodynamic modeling, terrestrial and marine observational geology, geomorphology and geophysics, GPS-based geodesy, glaciology, glacimarine geology, micropaleontology, palynology, paleomagnetics, paleoclimatology and paleoceanography. Because of the broad scientific scope of these issues, the most productive way to begin to address them is by fostering synergistic collaboration among the ocean drilling, glaciology, tectonophysics, and climate dynamics communities. By bringing together such a diverse group of earth scientists, it was possible for the first time to outline the science issues associated with gaps in our understanding of the linkages between late Cenozoic collisional tectonics and climate in Alaska and the northeastern Pacific Ocean. The two-day workshop consisted of a brief number of keynote presentations, thematic poster sessions, and a series of interdisciplinary breakout sessions to identify integrated terrestrial, marine, and modeling issues and priorities. The product of this workshop is a science plan that summarizes the state of knowledge of the relevant topics, provides a list of detailed scientific questions, and contains suggestions for implementation. The science plan can be downloaded from: http://web.clas.ufl.edu/users/jaeger/JOI_CD/index2.htm .

The workshop participants felt that the scientific goals for using the Gulf of Alaska as a natural laboratory for evaluating tectonic-climate interplay could be best summarized by four broad topical research questions of global importance:

1. What are the three-dimensional kinematic and dynamic processes of oblique microplate accretion/plateau subduction, and what are the implications for continental growth?
2. What have been the critical Neogene climatic shifts in the high-latitude Pacific and what were the consequences for Northern Hemisphere climate, glaciation, and environmental change?
3. At what temporal and spatial scales does orogenesis influence global climate and how do major glacial fluctuations shape orogenesis?
4. How can we use this natural laboratory with its active tectonics, abundant geologic hazards, aggressive glacial processes, and dramatic landscape for geoscience education and outreach?

Several key points were raised as to why southern Alaska is an excellent natural laboratory for gaining insights into these global questions. Tectonically, it can serve as a modern analog for processes that have constructed much of the continental crust. The margin encompasses a subduction to strike-slip transition that is observable onshore and offshore that allows imaging of crust-mantle interaction at such transitions. This plate boundary has generated the second largest historical earthquake (1964), the largest historical tsunami (1958), the largest area of coseismic uplift (1964), and the greatest documented coseismic uplift (14.2 m in 1899). Present tectonic convergence rates are 2-3 times as high as the Himalaya, and are comparable to the total convergence between India and Eurasia. Climatically, the area includes the oldest and thickest Northern Hemisphere Cenozoic glacial record and may provide insight into the initiation of the Cordilleran ice sheet. Studies in this orogen can illuminate the currently poorly constrained history of the Cordilleran ice sheet and its significance for global climate dynamics. The expanded Neogene marine and glacial sedimentary record within the north Pacific can enhance other high-latitude climate records. Comparison of Neogene vegetation from pollen records north and south of the orogenic belt can help reconstruct the tectonic history by determining when the associated rain shadow developed. The Gulf of Alaska is a prime site for assessing the history of Holocene (or longer) decadal-scale (e.g., Pacific Interdecadal Oscillation, PDO) climate change. Finally, there is an opportunity to constrain the Late Quaternary marginal marine environment to assess the feasibility of pre-historical human coastal migration routes.

The Chugach-St. Elias range is a mini-orogeny that allows for the study of tectonic and climatic processes and their interactions at a tractable scale. The landscape is sculpted primarily by glacial processes that produce the highest global glacial denudation rates (locally greater than 10^1 mm a^{-1}), and in turn provide record high sediment accumulation rates allowing for very high-resolution proxy sedimentary records. This margin is the type location for temperate glacimarine systems and their models, and a unique ~5 km thick sedimentary record of glacimarine deposition recording at least 6 Ma of tectonic and climatic interaction is present. Due to the relatively confined and closed source-to-sink depositional system, there may be little lag between sediment production and marine accumulation. Tectonically, observable deformation patterns in oblique convergent settings may reflect climatic influences. The tectonic setting, Neogene stratigraphy and sedimentary processes, glacial mass-balance, structural and metamorphic history are reasonably well characterized, which allow for development of integrated experiments and modeling in tectonic and climatic interaction.

A substantial portion of this science plan is devoted to summarizing the state of knowledge of important aspects of the integrated climate-tectonic system and important gaps in knowledge, which are a guide towards future research. In the marine, terrestrial, and modeling breakout sessions, a series of questions were posed that expand upon the global questions about tectonic interactions, climatic effects, interplay between the two, and education and outreach. As this science plan is intended to assist in proposal preparation and evaluation for future Gulf of Alaska studies, practitioners of the numerous techniques summarize the key measurements necessary for addressing the scientific questions. Opportunities for education and outreach including "teacher in the field" programs, interactions with National Parks, and Native American nations are discussed. This research initiative into tectonics and climate in southeast Alaska also has strong links to several programs beyond IODP and NSF funded core research including Earthscope, ICESat, Marine Aspects of Earth System History (MESH), Paleoenvironmental ARctic Sciences (PARCS), PAst Global changes (PAGES – IGBP), U.S. GLOBal ocean ECosystems dynamics (U.S. GLOBEC), Community Surface Dynamics Modeling System (CSDMS), RiOMar (River-dominated Ocean Margins), and the Mt. Logan Ice Coring Project.

Because of the far-reaching scope of the issues raised by participants, it was not possible to create a detailed implementation plan during the two days of the workshop. Instead, a general list of recommended tasks was generated. These recommendations have been grouped into three implementation phases that largely reflect logistical concerns and the need to first address the most glaring gaps in knowledge and data:

- **Phase 1:** Suggestions included maintaining a Gulf of Alaska research website and an Alaska GIS database for integration of emerging datasets. Due to the outreach potential of southeast Alaskan science, one recommendation of the workshop is for all future field and laboratory projects to have a strong outreach component from the beginning of the program with websites identified and accessible to K-12 education. Particular Phase 1 experiments should include the acquisition of both high-resolution and regional marine seismic reflection surveys to adequately understand the regional sedimentary budget, examine the offshore tectonic deformation, and plan for future IODP drilling. A comprehensive suite of very high-resolution paleoclimate, paleoceanographic and paleoecological studies on cores from the margin and from the interior will establish proper chronometers and a series of climate proxies leading to an understanding of the Quarternary climatic history that can be extended into the Neogene through ocean drilling and terrestrial outcrop sampling. A GPS array should be installed as soon as possible within any tectonic field program to ensure a sufficiently long period of observation to approach 2 mm a^{-1} precision. Existing monitoring surveys of glacial and fluvial mass fluxes should be maintained and expanded to ensure continuity of records in an aim to capture transients in mass flux. The expansion of modern automated meteorological arrays is important to construct sufficiently long climate time series that permit integration of records from high altitude ice core sites to sea level marine records. Establishment of a passive seismic monitoring array will be necessary to image crustal and upper mantle velocity structure and evaluate seismic hazards. A modeling program should be initiated to aid in sampling strategies, to investigate cooperation among systems and to develop numerical strategies for handling the non-linear interactions in the climate-tectonic and topographic systems.

- **Phase 2:** The collection of the initial data sets in Phase 1 will allow for the refinement of experiments that can investigate processes, stratigraphic, structural, and petrologic relationships to examine orogenic history, mass flux, and regional climate interactions through the system. A geochronological framework should be developed early in Phase 2 to identify trends in local kinematics using low- and high-temperature thermochronology, cosmogenic dating, detrital thermochronology, fluid inclusion and geological studies including paleobotanical and paleomagnetic analyses. To constrain the spatially varying tectonic geometry, an active seismic study of crustal architecture should be conducted onshore and offshore to collect 2-D and 3-D tomographic information. Aerogeophysical, marine geophysical, and remote sensing programs need to be initiated to determine the gravity field, ice thickness, and integrated topographic-bathymetric surface to serve as baseline data for repeat surveys that monitor temporal changes in these properties. Geometric information available from seismic studies together with mass flux data should be used to condition, test, and develop the numerical models focused on kinematics, denudation, sediment transport and storage.
- **Phase 3:** This phase would consist of repeat aerogeophysical, marine geophysical, and satellite-based remotely sensed surveys to examine landscape evolution. Repeat surveys of GPS arrays would provide additional information on local velocity fields. Offshore drilling through IODP from fjords to deep sea fan will examine the integrated tectonic-climate history of the margin. Drilling builds on all previous geophysical, geological, ecological, climatic, and modeling efforts to enhance an integrated picture of the cooperation between climate and tectonic uplift history.

While these recommendations are wide-ranging and ambitious, it is through the proposed targeting of the St. Elias natural laboratory with a broad range of techniques to study a series of dynamic, but interrelated, processes that will allow significant advancement in our understanding of continental dynamics, glacial-interglacial climate, and their interactions. The process has already begun as some of these recommended studies have been proposed and recommended for funding by NSF.

Rationale for Focusing on Southern Alaska and the Adjacent Gulf of Alaska

Neotectonic record of Late Cenozoic collision, uplift,
and glaciation along the Gulf of Alaska margin
Contributed by George Plafker

The Gulf of Alaska margin is amongst the most seismically and tectonically active regions in the world due to interactions between the combined Pacific plate and overlying Yakutat microplate with the North American plate. This collision has produced the second highest peak in North America (Mt. Logan) and the largest concentration of peaks higher than 4300 m in the North American continent. Within this region Mt. St. Elias rises more than 5500 m from the sea over a horizontal distance of less than 25 km, possibly the largest topographic escarpment on this planet (Fig. 1).

Basement of the Yakutat microplate possibly consists of Mesozoic continental crust in the eastern one-third and probable Eocene oceanic crust in the western two-thirds overlain by up to 10 km of Cenozoic sedimentary strata. Along its eastern margin, the Yakutat microplate moves northwest with the Pacific plate relative to interior Alaska at 40-50 mm a^{-1} along the Queen Charlotte-Fairweather transform fault system (Fig. 2). The Transition fault, which marks the southern boundary of the microplate and its contact with the Pacific plate, is characterized by sparse historic seismicity that suggests a low rate of relative plate motion. At the leading western and northwestern edge, oceanic Yakutat microplate basement is actively subducting beneath North America along the extension of the Aleutian megathrust onto the continental margin. As a consequence, off-scraping of the sedimentary cover has developed a wide thrust and fold belt in which the deformation front has migrated progressively southward and eastward some 50 to 100 km from the microplate boundary. North of this structurally complex trench-transform transition zone, transpression between continental crust of the Yakutat terrane (Fig. 2) and North America has resulted in extreme uplift of the spectacularly high and glacier-covered eastern Chugach and Saint Elias Mountains that together comprise the Saint Elias orogen of southern Alaska and southeastern Yukon.

The Yakutat microplate formed at about 30 Ma at which time the Queen Charlotte-Fairweather transform stepped inboard to its present position. Subsequently, the microplate moved northwestward and subduction of the leading edge of the microplate to a depth of ~100 km resulted in onset of arc volcanism in the Wrangell Mountains at ~25 Ma. Abrupt shoaling and upward coarsening of marine sediments record uplift of the Yakutat microplate beginning in Miocene time. Subsequent deposition of thick marine sequences containing abundant glacimarine units (Yakataga Formation) indicates that active glaciers reached tidewater intermittently during at least the last 5-6 Ma (Fig. 3). This anomalously long duration of glaciation in the northern Gulf of Alaska for the Northern Hemisphere presumably reflects the fortuitous combination of great elevation of the coastal mountains, a sub-Arctic climate, and heavy precipitation from prevailing southerly storms--an environment that persists to the present.

Both long- and short-term denudation and uplift rates in the Gulf of Alaska region are among the highest in the world. Sparse apatite fission-track data suggest Plio-Pleistocene denudation rates in the northern St. Elias Mountains that average 1.5-1.9 km Ma^{-1}, and total denudation to expose these samples at the surface of 4.5-8 km (O'Sullivan and others, 1997). Ongoing rapid uplift of the region is indicated by (1) folded, multiply tilted, and faulted Plio-Pleistocene

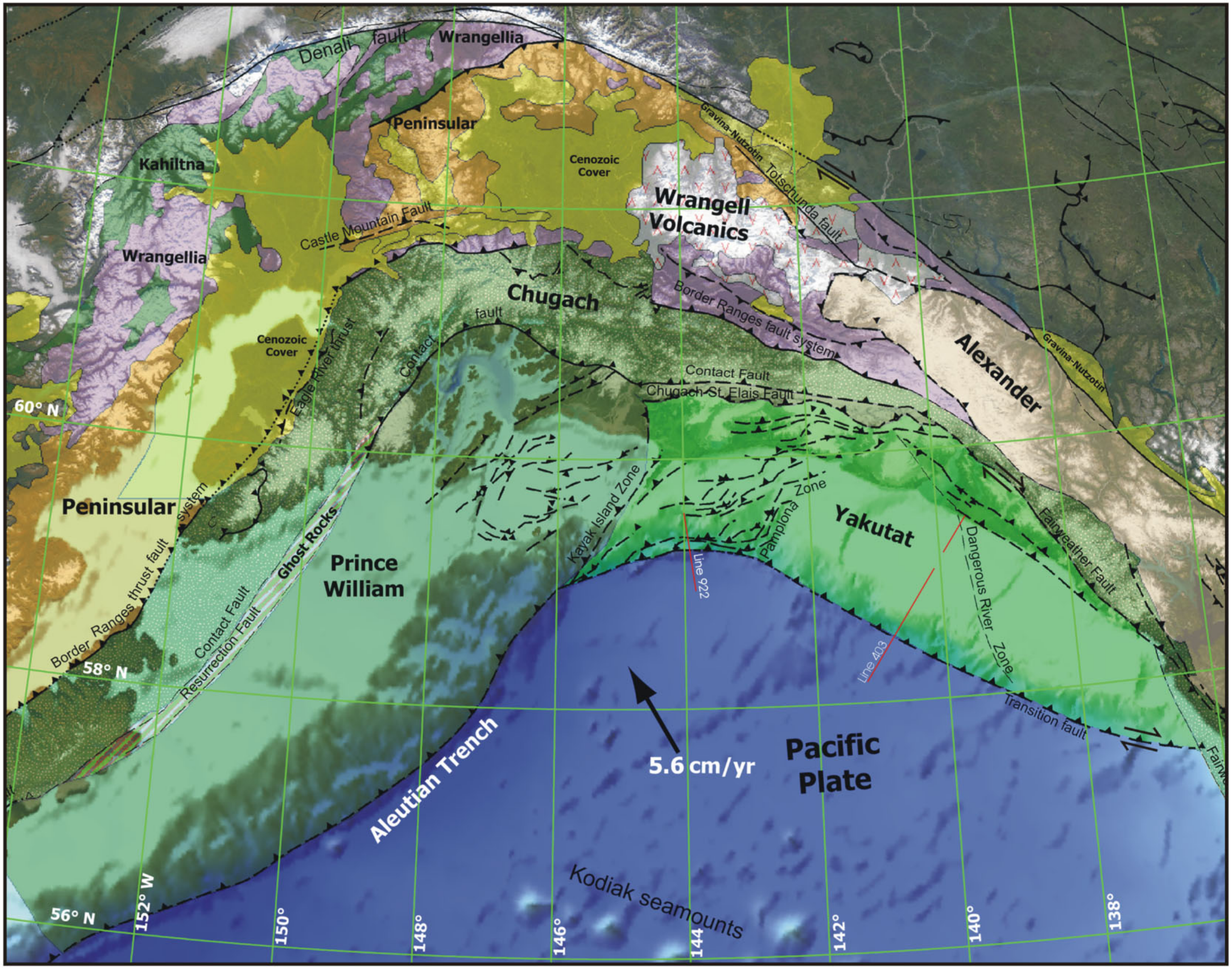


Figure 2. Tectonostratigraphic terranes and structural features of southern Alaska and adjacent Gulf of Alaska. Major faults mentioned in text are indicated. The locations of seismic reflection lines 403 and 922 in Figure 8 is shown. Modified from Plafker (1987) and Plafker et al. (1994).

marine strata at elevations to 1500 m; (2) extreme topographic relief in an alpine environment characterized by high erosion rates; (3) local late Holocene marine terraces having average uplift rates as high as 11 mm a^{-1}; (4) the world's largest measured coseismic uplift (14.4 m in the 1899 Yakutat earthquake); and (5) the most extensive area of coseismic uplift ever recorded (140,000+ km^2 in the 1964 Alaska earthquake).

Key Points about the Study Area

Based on discussions at the workshop, the following salient aspects or issues were raised as to why the Gulf of Alaska is a near-ideal natural laboratory for the study of tectonic and glacial climate processes and their interactions:

Tectonics

- Modern analog for processes that have constructed much of the continental crust
- Encompasses a subduction to strike-slip transition that is observable onshore and offshore
- Allows imaging of crust-mantle interaction at a subduction to strike-slip transition
- Plate boundary has generated the second largest historical earthquake in 1964 and largest historical tsunami
- Also generated the largest area of coseismic uplift (1964) and the greatest documented coseismic uplift (14.2 m in 1899)
- Present tectonic convergence rates are 2-3 times as high as the Himalaya and are comparable to the total convergence between India and Eurasia.

Climate and Glaciation

- Expanded marine and terrestrial record of Neogene climate within the North Pacific area that can enhance other high-latitude climate records
- The prime site for assessing the history of the Pacific Decadal Oscillation (PDO) due to its immediate location and ultra-high precipitation and sedimentation rates
- Potentially earliest record of Northern Hemisphere glaciation and may provide insight into the initiation of the Cordilleran Ice Sheet, and precursor of events in the Laurentide Ice Sheet
- Can illuminate the currently poorly constrained history of the Cordilleran ice sheet relative to its significance on global climate proxies
- Some of the most sensitive glaciers in the world to climate forcing with rapid response times, e.g., the 100 km advance in Glacier Bay during the Little Ice Age

Interaction

- Mini-orogeny that allows for the study of tectonic and climatic processes and their interactions at a tractable scale
- Landscape sculpted primarily by glacial processes
- Highest global glacial denudation rates (10^1 mm a^{-1}) provide extreme sediment accumulation rates, which allow for very high temporal resolution proxy sedimentary records
- A unique 4600-m thick sedimentary record of glacimarine deposition recording at least 6 Ma of tectonic and climatic interaction
- A 390-m thick sediment core at Fort Yukon containing pollen assemblages that may re-

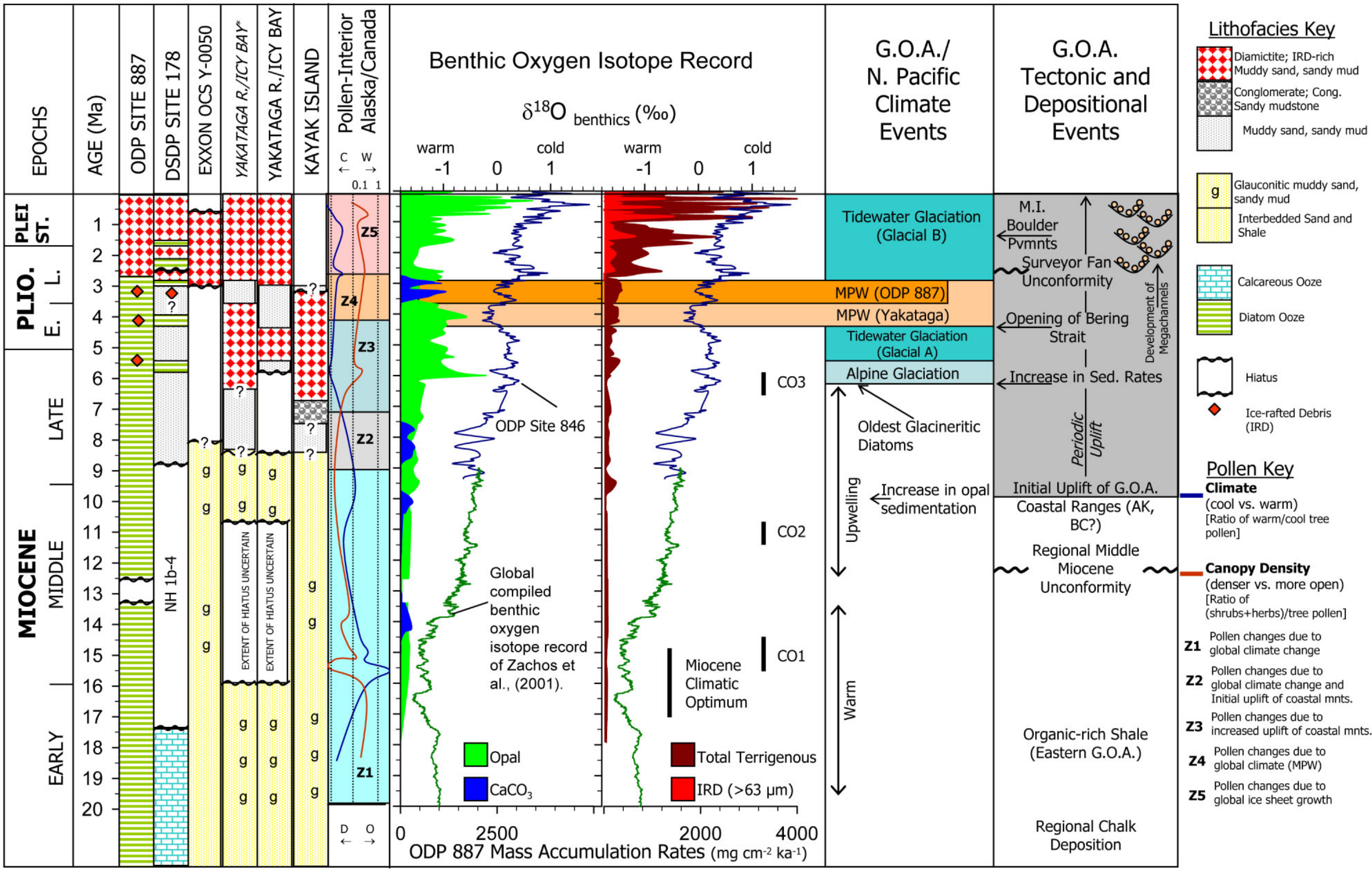


Figure 3. Stratigraphic, depositional, and climatic history of the Gulf of Alaska and adjacent regions as modified from Lagoe et al. (1993). Lithological data are from Lagoe et al. (1993), Rea and Snoeckx (1995), and Lagoe and Zellers (1996). Pollen data are from White et al. (1997). Tectonic events from Lagoe et al. (1993) and Stevenson and Embly (1987). Oxygen isotope data from Shakelton et al. (1995) for ODP Site 846 in the equatorial East Pacific Ocean and Zachos et al. (2001).

cord a continuous climate record in interior Alaska over the past 15 Ma

- Type location for temperate glacimarine systems and their models
- Due to the relatively confined and closed source-to-sink depositional system, there may be little time lag between sediment production (erosion) and deposition
- Observable deformation patterns in oblique convergent settings may reflect climatic influences
- Ability to constrain the marginal marine environment and to assess the feasibility of prehistorical human coastal migration routes
- Tectonic setting, Neogene stratigraphy and sedimentary processes, glacial mass-balance, structural and metamorphic history are reasonably well characterized, which allow for development of integrated experiments in tectonic and climatic interaction

State of Knowledge

This section of the report is intended to provide interested investigators with a basic background in the relevant processes of the study area and thorough inclusion of past studies that can be used as a starting point for further proposals, manuscripts, and reports. It was envisioned that this section also would be of significant interest to workshop attendees, which would allow them to learn more about fields outside their area of interest and expertise and would serve as a mechanism for initiating cross-discipline research. A brief state of knowledge is given for the climate setting, climate and orogenic history, tectonic setting, lithospheric dynamics, crustal evolution, linkages between uplift, erosion, climate, and topography, and rates, patterns and models of sediment dispersal and accumulation.

The Climatic Setting of the Gulf of Alaska

The Gulf of Alaska is influenced by a variety of modes of climate variability, with time scales ranging from interannual to interdecadal and beyond. Some of these modes include the Pacific Decadal Oscillation (PDO) (Gedalof et al., 2002), the Pacific-North American Pattern (PNA) (Wallace et al., 1981), El Nino/Southern Oscillation (ENSO) (Papineau, 2001), and the Arctic Oscillation (AO) (Thompson and Wallace, 1998). These modes of variability are potentially interrelated, and their impact on North Pacific climate is still an area of active research.

Modern North Pacific climate is largely controlled by the semi-permanent Aleutian Low pressure center situated over the Gulf of Alaska, which controls Gulf of Alaska atmospheric circulation. The Aleutian Low is closely associated with enhanced storm production over daily to seasonal periods, with the PNA, PDO and ENSO extra-tropical response over annual to decadal periods, and may be linked to millennial climate fluctuations (Wilson and Overland, 1987; Trenberth and Hurrell, 1994) (Fig. 4).

The Gulf of Alaska and surrounding coastal areas receive abundant precipitation, ranging from about 1000 mm a^{-1} in the central Gulf to as much as 7000 mm a^{-1} in some coastal areas. In contrast, a rain shadow exists in interior Alaska, on the leeward side of the Alaska Range, which receives as little as 350 mm a^{-1} (Fig. 5). Southeastern Alaska and British Columbia represent the northeastern terminus of the Pacific storm track, a wide zone of active cyclogenesis that originates in the western Pacific off the coast of Japan (Chang et al., 2002). Due to the presence of steep coastal topography, much of the precipitation that falls on coastal Alaska returns to the ocean as runoff, though the hydrologic cycle is complicated by freezing and melting (Royer, 1979). The Alaska Current and the Alaska Coastal Current are driven by this intense influx of fresh water (Royer, 1981a; Royer, 1981b) (Fig. 6) and are thought to advect warm water from the south along the Alaskan coast (Royer et al., 2001). The freshwater input into the coastal Gulf of Alaska has likely varied widely during the Neogene due to the combined effects of tectonic uplift of the coastal ranges and long-term climate variability. The impact of this freshwater variability is unknown, but potentially significant for regional oceanic heat transport, especially into the Arctic through the Bering Strait (Stabeno et al., 2001).

The entire North Pacific is less saline than the North Atlantic due to complex and still poorly understood processes. In contrast to the more saline North Atlantic, the presence of fresh water in the North Pacific has inhibited the development of deep water masses, with important consequences for oceanic heat transport (Weaver et al., 1999). This freshwater balance has surely varied throughout the Neogene, but the magnitude and effects of such variability are presently unknown. An emerging body of evidence (Ohkushi et al., 2003; Hendy and Kennett, 2000; Schmittner and Clement, 2002; van Geen et al., 1996) suggests that the deep circulation of the North Pacific may have been significantly different earlier in the Quaternary. An intriguing but untested hypothesis is that there was active deep-water formation in the North Pacific as suggested by active sediment accumulation in the Meiji sediment drift until the late Miocene/ Pliocene, when the uplift of the Chugach-St. Elias Mountains trapped much of the incoming moisture and rerouted it into the Gulf of Alaska, possibly shutting off production of North Pacific deep water (Rea et al., 1995). Another testable hypothesis is that while an equable maritime climate prevailed along the coast, a continental climate developed in interior Alaska as uplift of the Alaska Range formed a barrier to the Pacific air mass.

Superimposed on the long-period (millennial) Holocene climate shifts in the North Pacific are seasonal to decadal ocean-atmosphere oscillations (e.g., ENSO, PDO, PNA, and AO). These rapid climate oscillations affect air and sea-surface temperature, precipitation, atmospheric pressure, and circulation patterns in the North Pacific and downstream in North America (Leathers et al., 1991; Trenberth and Hurrell, 1994; Mantua et al., 1997). Annual tree-ring width records from the North American Pacific coast reveal that the PDO has been an important component of North Pacific climate for at least the past 400 years (Gedalof et al., 2002; Wiles et al., 1996; Wiles et al., 1998), with a shift at ~1850 A.D. from predominately decadal temperature oscillations to shorter-period, interannual oscillations more indicative of ENSO (D’Arrigo et al., 2001). This shift is coincident with the end of the LIA, suggesting a possible interplay between climate fluctuations of different periods.

Until recently, high-temporal-resolution pre-instrumental records of Gulf of Alaska climate were sparse. However, tree-ring studies (Wiles et al., 1998) and ice core glacichemical time series from the St. Elias Mountains in the Gulf of Alaska (Moore et al., 2003) provide seasonally-to-decadally resolved proxy records of atmospheric pressure, circulation patterns, temperature, moisture and particle source location, and natural and anthropogenic pollution (e.g. volcanic eruptions and anthropogenic lead), among others. A 103 m-long ice core was collected in 1980 from the Northwest Col (NW Col) region of Mt. Logan’s summit plateau (5340 m above sea level (asl)). In 2001-2002, a new 187 m-long summit ice core (PR Col core; 5343 m asl) was collected in concert with two longer ice cores at nearby King Col (4135 m asl) and Eclipse Dome (3100 m asl). The new St. Elias ice cores are ideally situated to record North Pacific seasonal-to-millennial period climate oscillations. Because of the Aleutian Low control on Gulf of Alaska atmospheric circulation intensity, the transport of sea-salt aerosol and particulate dust to the St. Elias ice core sites is climatically controlled. For example, the NW Col sea-salt aerosol record, represented by Na^+ concentration, is statistically correlated with the strength of the Sep-

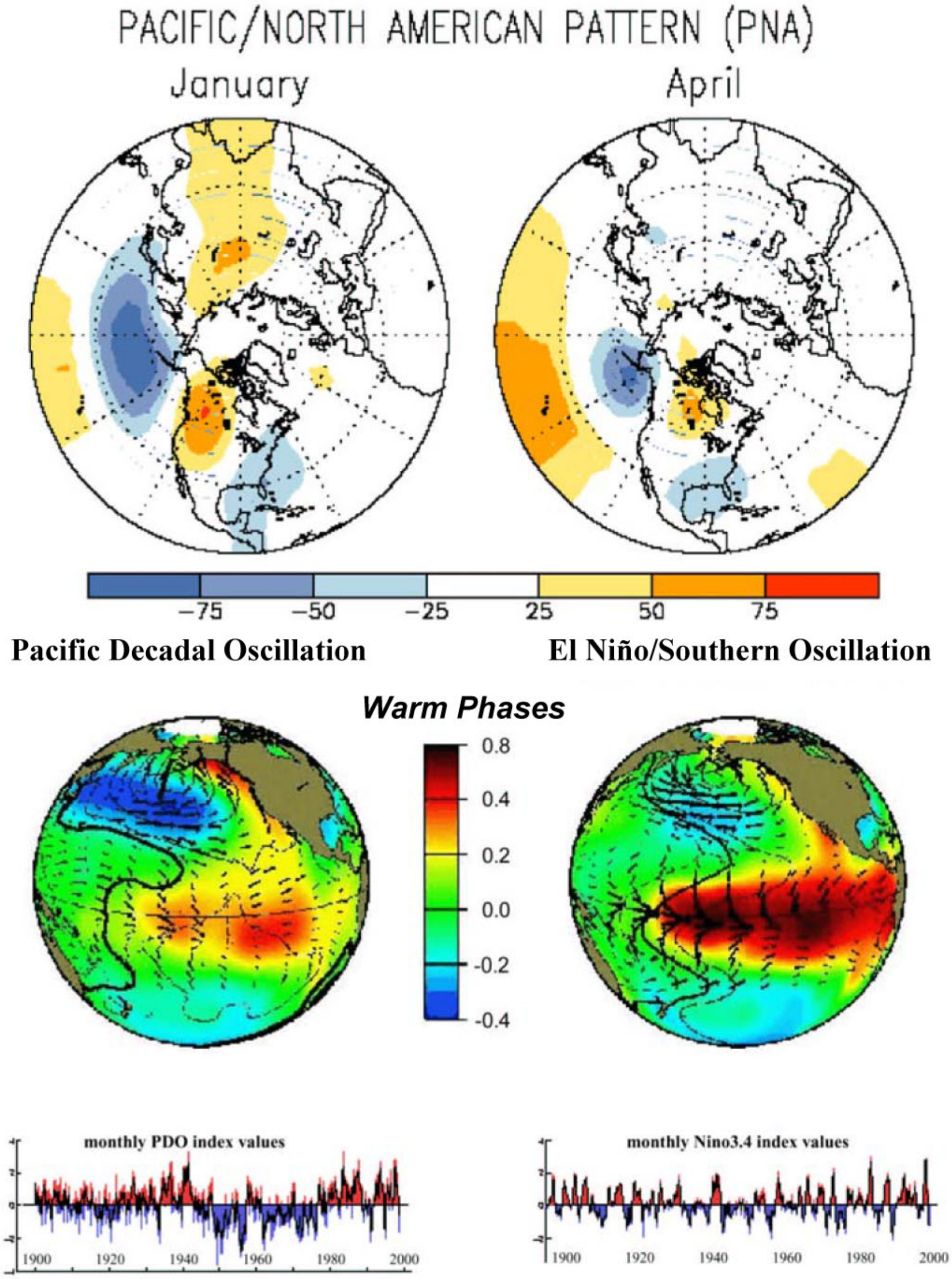


Figure 4. The Pacific North America (PNA) teleconnection pattern is the most prominent mode of wintertime low-frequency climate variability in the subarctic Pacific (Overland et al., 2002). The PNS acts to either enhance (positive state) or suppress (negative state) the climatological pressure differences between the Aleutian low and a ridge over the Canadian Rocky Mountains. The time series of the PNA pattern also indicates substantial interseasonal, interannual and interdecadal variability that are also seen in an inter-related pair of modes, the Pacific Decadal Oscillation (PDO) and the North Pacific Index (NPI). The PDO is based on the pattern of SST in the North Pacific while the NPI is passed on sea level pressure. The positive phase of the PDO is associated with warm ocean temperature along western North America. The North Pacific Index provides a measure of the intensity of the mean wintertime Aleutian Low pressure cell. El Niño-Southern Oscillation also contributes to interannual variability in the far north Pacific, but to a lesser degree than the PNA/PDO. Figures courtesy of: Nate Mantua (Joint Institute for the Study of the Oceans and Atmosphere, University of Washington) and Nick Bond, Jim Overland and Nancy Soreide (NOAA / Pacific Marine Environmental Laboratory).

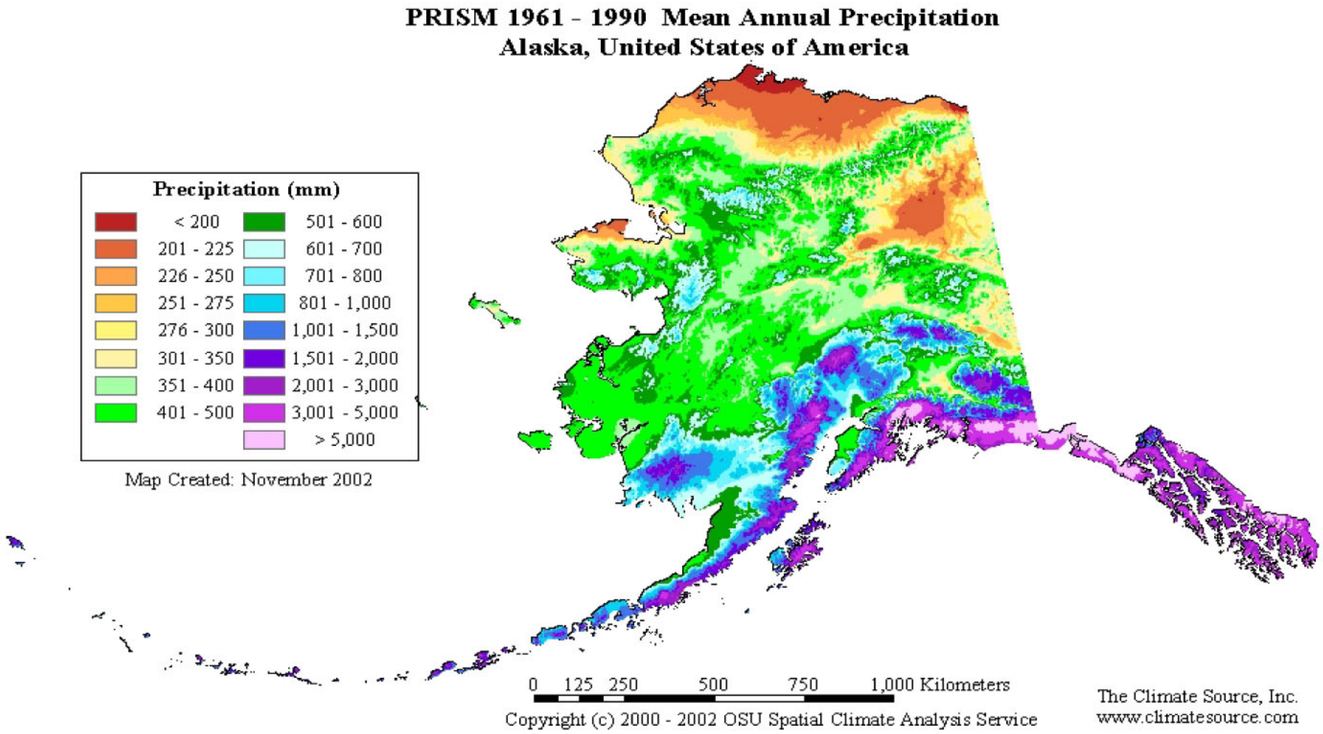


Figure 5. Modeled annual precipitation data for Alaska created using the PRISM climate mapping system (http://www.ocs.oregonstate.edu/prism: Daly et al., 1994). PRISM uses point data and a digital elevation model (DEM) to generate gridded estimates of precipitation and is well suited to regions with mountainous terrain such as Alaska, because it incorporates a conceptual framework that addresses the spatial scale and pattern of orographic precipitation. Note that modeled precipitation estimates are highest on the windward side of the Chugach/St. Elias Range, matching patterns shown in Figure 13.

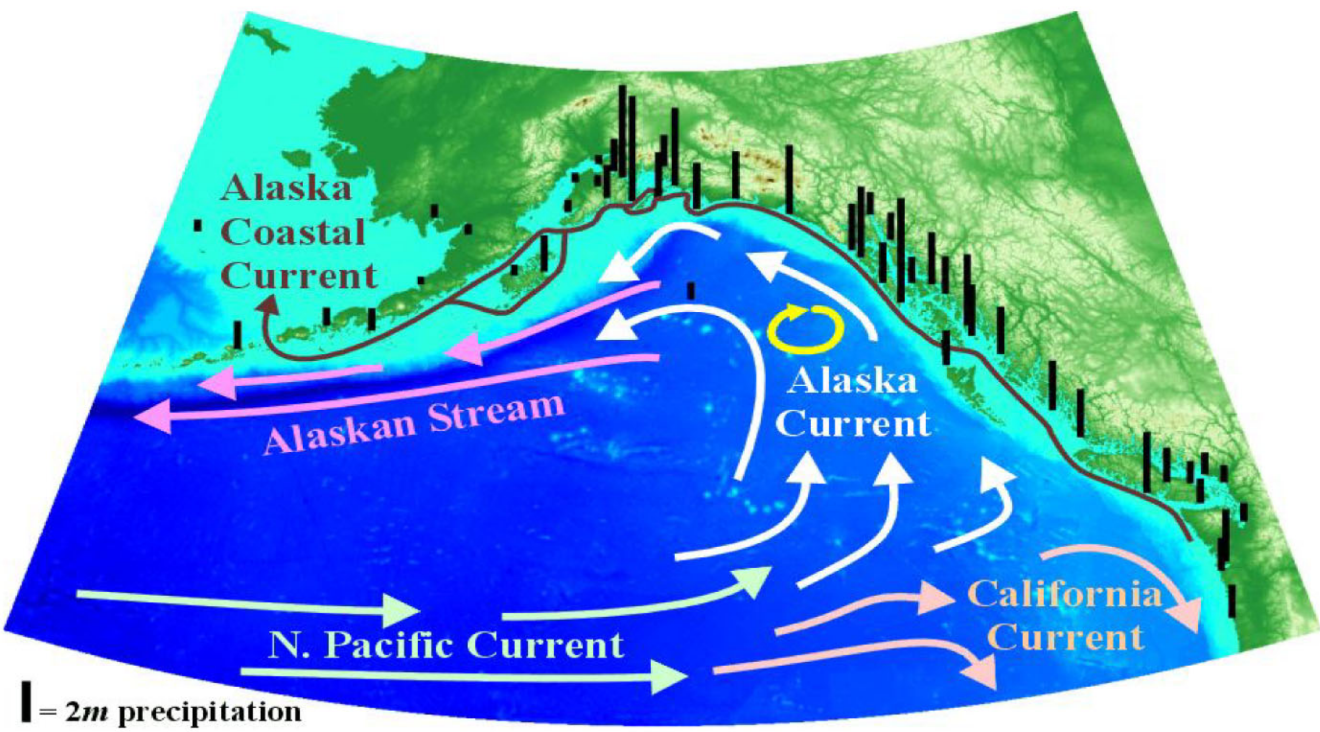


Figure 6. Regional circulation schematic for the Gulf of Alaska with mean annual precipitation rates indicated. The Alaska Coastal Current (ACC) is a persistent, wind- and buoyancy-forced current that circumscribes the inner GoA shelf from British Columbia to the Bering Sea (~2500 km). It serves as a migratory corridor and habitat for marine organisms and may advect climate signals (particularly freshwater) over vast distances. After Weingartner et al. (2002).

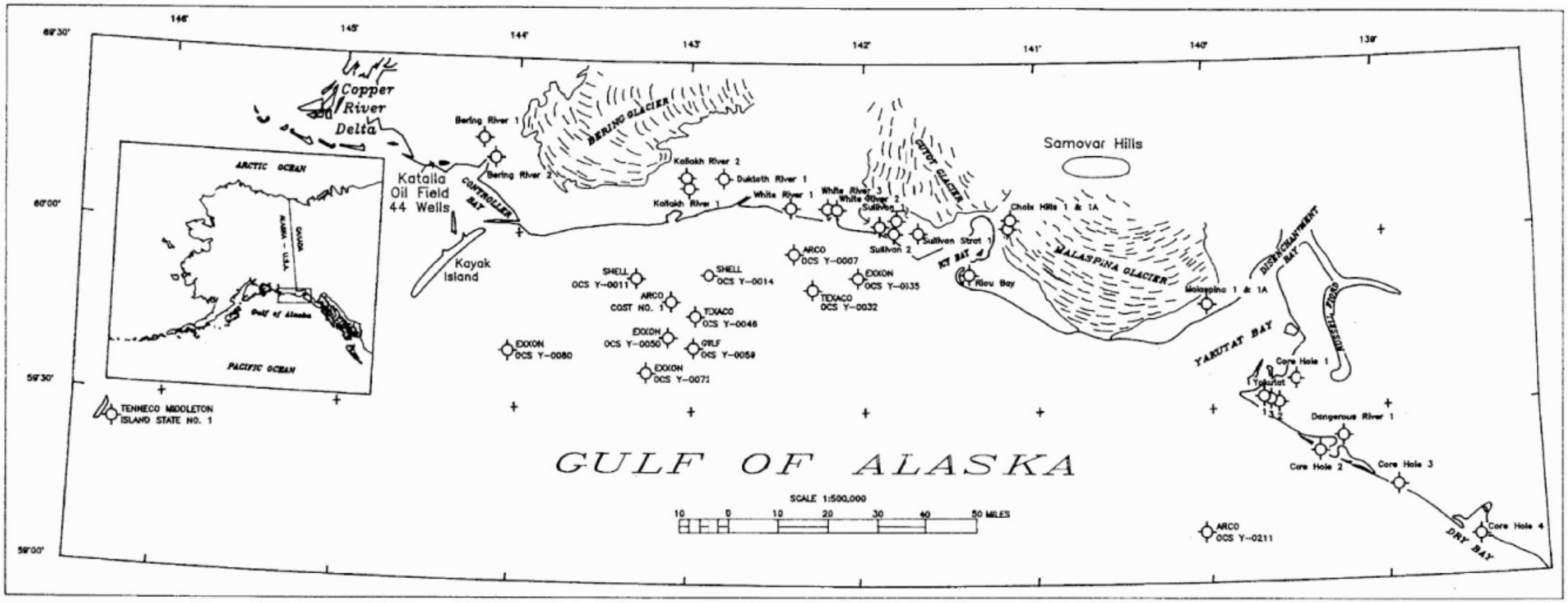
tember-October-November Aleutian Low and the June-July-August North Pacific High pressure center (Kang et al., in review (b)). Likewise, the NW Col Mg^{2+} dust record has a statistically significant correlation with the strength of the Arctic High, Aleutian Low and Tibetan High (Kang et al., in review (a)).

Neogene Climate and Orogenesis History

The geologic and climatic evolution of southern Alaska during progressive late Cenozoic (~10 Ma to Recent) uplift and glaciation of the Chugach-St. Elias range is recorded in sedimentary deposits from central Alaska to the distal Gulf of Alaska (Martin, 1993; Plafker, 1987). The Gulf of Alaska is a site of extremely rapid sedimentation due to the combination of vigorous tectonic uplift of the coastal mountains and tectonized weak bedrock and heavy precipitation that fuels intense glacial activity (Powell, 1984; Hunter et al. 1996). The long sedimentary record of the Gulf of Alaska makes this region a prime locale for studying the interplay of tectonic and climatic processes throughout the Tertiary. In particular, the sedimentary record of the Gulf of Alaska may record important information about North Pacific climate variability from decadal to millennial time scales.

The Neogene record of climate and tectonic processes within the study area (Fig. 1) has been studied through a combination of surface-outcrop sampling and subsurface coring (USGS 390-m pollen-rich core at Fort Yukon), scientific drilling (DSDP Leg 18, ODP Leg 145), and industry drilling (Lynch, 1992) (Figs. 1, 7). The focus of Leg 18 in 1971 in the Gulf of Alaska was to understand subduction zone processes and to develop a chronology of Neogene climate and tectonics as recorded in Surveyor Fan sediments (Kulm et al., 1973). The Leg consisted of five sites (178-182) drilled across the southwestern corner of the Surveyor Fan, the Aleutian Trench, and up the slope of the accretionary prism. Recovery was poor at these sites (<50%) due to problems associated with the rotary drilling used, and the maximum depth penetrated was ~800 m at site 178. In 1992, ODP Leg 145 occupied an additional site (887) in the far southwestern Gulf of Alaska on the Patton-Murray Seamount Group for the purpose of documenting Neogene high-resolution biostratigraphy, paleoceanography, and paleoclimatology of the sub-Arctic northeast Pacific (Rea et al., 1995). Recovery was excellent at this site (>90%) using piston coring, and the maximum depth penetrated was ~270 m. Lastly, the presence and extraction of petroleum at Katalla near the Copper River spurred a large number of industry-related drilling dating back to the early 20th century. Over 25 wells were drilled on the coastal plain between 1927 and 1962, with the majority completed between 1960 and 1962 with a maximum depth of 3.5 km. Offshore, six deep stratigraphic test wells (i.e., COST wells) were drilled on the Kodiak shelf to a maximum depth 3.2 km. Thirteen wells were drilled on the northern Gulf of Alaska shelf between 1969 and 1983 with a maximum penetration of 5.5 km. Gulf of Alaska climatic and tectonic events revealed by these industry wells are discussed in Zellers (1995). Outcrops of Neogene sediments have provided a long paleobotanical record (leaves and pollen) from the Kenai lowland (Wolfe et al., 1966) and the Nenana coalfield north of the Alaska Range (Leopold and Liu, 1994).

In the locus of convergence and uplift along the Gulf margin, up to 5 km of terrestrial, marine, and glacimarine clastics, collectively known as the Yakataga Formation on the margin and the upper (?) Surveyor Fan in the Gulf, have accumulated and represent one of the longest and most complete records of late Cenozoic sedimentation in the world. Coupled with distal records from the Patton-Murray Seamounts (ODP Site 887) and terrestrial deposits from interior Alaska (White et al., 1997), a basic chronology can be established of Miocene-to-modern paleo-



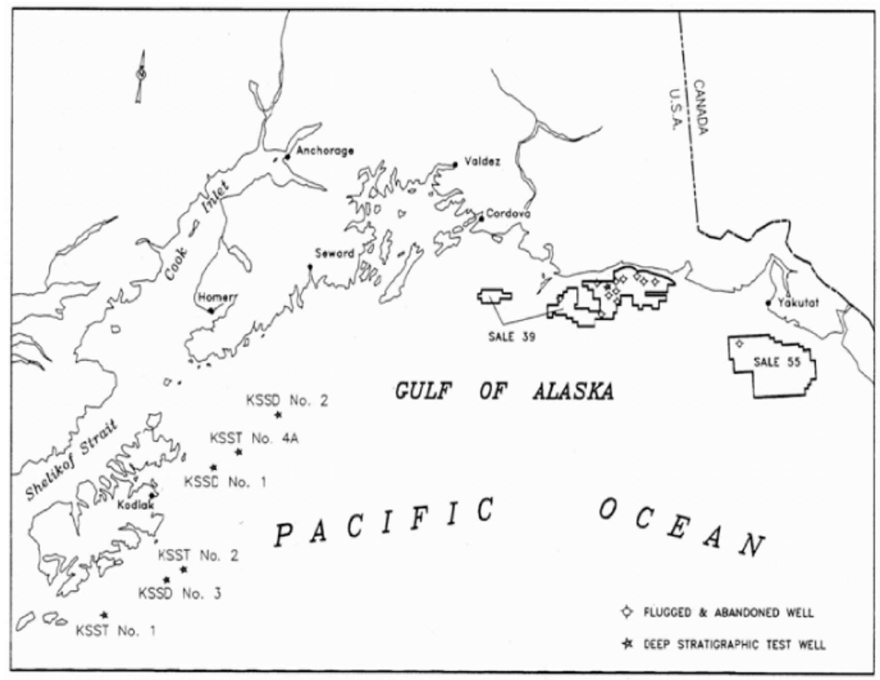


Figure 7. Locations of industry and COST wells in the Gulf of Alaska and adjacent coastal plains. Information on well locations, operators, total well depths, and date of completion can be found in Risley et al. (1992).

climate in the Gulf of Alaska and northeastern Pacific Ocean (Fig. 3) (Lagoe and Zellers, 1996). However, important gaps exist in the record of climate-tectonic interactions that can only be filled by recovery of high-resolution sedimentary records and seismic reflection data from the shelf and proximal Surveyor Fan and a renewed phase of geologic mapping and sampling in the Chugach-St. Elias Range.

The lithostratigraphy and biostratigraphy of the Yakataga Formation has been discussed in detail by Armentrout (1983), Eyles et al. (1991), Eyles and Lagoe, (1990), Lagoe et al. (1993), Lagoe and Zellers (1996), and Zellers (1995). The Yakataga Formation depositionally overlaps the continental margin of the northern Gulf of Alaska and spans from the coastal mountains to coeval strata in the adjacent Surveyor Fan. The evolution of this fan during progressive northwestward transport on the Pacific Plate has created a potentially detailed but largely unexplored stratigraphic record of long-distance sediment transport, shifting sediment sources, shifting depocenters, and climatic and tectonically controlled changes in sediment supply (Stevenson and Embley, 1987; Dobson et al., 1998). In contrast, much more is known about changes in sediment supply and regional climate from the continental shelf and onshore Yakataga sections due to greater accessibility from outcrops and industry drilling performed during the 1960s and 1970s.

The primary strata of the orogen have accumulated during the last 25 Ma at the inception of collision of the Yakutat microplate with the eastern end of the Aleutian trench, which has lead to >600 km of subduction of the microplate and the onset of Wrangell volcanism (Plafker, 1987). Early-to middle-Miocene-age strata currently found in the Gulf of Alaska region accumulated farther to the southeast, likely west of modern British Columbia. During this period, rates of terrigenous sediment input were low both on the margin and in the deep sea as indicated by the widespread presence of glauconitic sandstones (e.g., Poul Creek Formation) and deep-water chalks (Fig. 3; Lagoe et al., 1993; Rea and Snoeckx, 1995). Regional middle Miocene hiatuses were common, probably due to a lack of sediment accumulation (Lagoe et al., 1993; Lagoe and Zellers, 1996), suggesting that the regional border to the Gulf was low relief (Fitzgerald et al., 1995; Wahrhaftig et al., 1969). During the Miocene, changes in global climate left a strong signal in regional climate records, as indicated by periods of increased carbonate deposition at Site 887 and a dominance of dense vegetation cover of thermophilous plant taxa from interior Alaska (White et al., 1997).

The timing of the initial uplift of the mountains surrounding the Gulf and the initiation of glaciation has been a controversial topic, largely due to discrepancies in biostratigraphic correlation, and ages range anywhere from early Miocene (~20 Ma; Marincovich, 1990; Plafker, 1987) to late Miocene (~6 Ma; Lagoe et al., 1993). Paleovegetation results from interior Alaska (White et al., 1997; Leopold and Liu, 1994) and biostratigraphic and paleomagnetic results from ODP Leg 145 (Rea et al., 1995) have placed a tighter constraint on the timing of uplift (~10 Ma) although significant (~4 Ma) geographic variability in age of this orogenesis exists (Fig. 3). The onset of alpine glaciation is more difficult to discern from the sedimentary record and is likely time transgressive as a result of the initial uplift occurring towards the northwest. It is proposed that such glaciation only began when the regional mountains were high enough to trap precipitation from storm systems generated in the Gulf. Consequently, alpine glaciation was likely well underway by 5.5 Ma and may have started as early as ~7 Ma (Lagoe et al., 1993; Rea and Snoeckx, 1995; White et al. 1997; Froese et al., 2000). The age of inception of glaciation to tidewater, termed Glacial A by Lagoe et al. (1993), and the delivery of ice-rafted debris to the Gulf is still a debated topic, but is likely to have started at or before 4.3 Ma. The initial appearance of ice-rafted debris (IRD) in Gulf deep-sea records at Site 178 is ~2.4 to 4.3 Ma (Lagoe et al., 1993) and at Site 887 is debatable, and ranges from ~5.5 Ma (Krissek et al., 1995) to 4.3 Ma (Rea and Snoeckx, 1995).

By mid-Pliocene, a reduction in glacimarine influence and warming to cool temperate conditions is supported by both marine and terrestrial records, although again, the timing varies among locations in the Gulf of Alaska region. In benthic oxygen isotope records from the eastern equatorial Pacific (Shackleton et al., 1995), a distinct period of oceanic warming termed the "Mid-Pliocene Warm Interval (MPW)" occurred from ~4.5 to 2.8 Ma, with two distinct warmer sub-periods within this interval, centered on 4.0 and 3.2 Ma (Fig. 3). In interior Alaska, a warmer period from ~2.5-3.0 Ma is indicated by paleovegetation records (White et al., 1997). In the Yakataga Formation, the MPW lasts from 4.2 to 3.0-3.5 Ma (Lagoe and Zellers, 1996), which is the entire period indicated by the benthic oxygen isotope record, whereas at Site 887, the MPW lasts only during the second sub-period (3.6-2.8 Ma). Additionally, a strong reflector is seen in seismic reflection profiles of the Surveyor Fan that is believed to represent an unconformity in fan strata and is the basis for separating the Surveyor Fan into upper and lower turbidite sequences (Stevenson and Embley, 1987). Near Site 178, the depth of this reflector is at ~260 m, which corresponds to a period of close to 2.5-3.0 Ma (Lagoe et al., 1993). Stevenson and Embley (1987) propose that the lower, southward-thinning sequence represent sediment delivery from far north of the current location of Site 178, whereas the upper sequence represents sediment delivery from the Surveyor Channel. The timing of this reflector falls within the period of the MPW, and may reflect the brief period of reduced sediment input during the warmer conditions of this period.

The most distinctive temporal event recorded in the region is the onset of intense glaciation after ~3.0 Ma, termed Glacial B by Lagoe et al. (1993). By 2.6 Ma, a ten-fold increase in IRD accumulation occurred across the sub-arctic Pacific, indicating a dramatic cooling of the region (Prueher and Rea, 2001). In interior Alaska, boreal forests and tundra were well established by 2.3 Ma (White et al., 1997). In Gulf of Alaska coastal outcrops and industry wells from the southern Alaska shelf, this period is represented in Yakataga strata by thick successions of glacimarine diamictite. After ~2.6 Ma, IRD becomes more abundant than in older intervals at Site 178, and at Site 887significant amounts of IRD are delivered and terrigenous sedimentation rapidly increases.

Throughout the Pleistocene, noteworthy advances of ice occurred from the Chugach-St. Elias Mountains into the Gulf waters. These advances were to the shelf edge, as indicated by the presence of boulder pavements on Middleton Island near the shelf edge (Eyles, 1988), as well as the construction of large, glacially eroded u-shaped sea valleys that cut across the shelf (Carlson et al., 1982). The timing of these advances is better estimated at Site 887 due to its superior paleomagnetic stratigraphy record for this period, although von Huene et al. (1973) attempt to recreate the timing of IRD pulses at Site 178 but with limited success due to the poor recovery and chronologies for this period. There appear to be five distinct pulses of terrigenous sediment occurring at 1.5 Ma, 0.8 Ma, 0.5-0.6 Ma, 0.25 Ma, and the Last Glacial Maxima (LGM) (Rea and Snoeckx, 1995). Krissek et al. (1995) contend that Site 887 contains at least 10-12 IRD maxima between 0.0 and 0.5 Ma and 10-11 maxima between 0.5 Ma to 1.0 Ma, with an average "cyclicity" of 40 ka, fairly close to the 41 ka obliquity cycle, suggesting that the IRD record in the Gulf region appears to record major northern hemispheric climate variations.

Although the Holocene was previously thought to be climatologically stable, high-resolution (seasonal to decadal) global climate proxy records have recently revealed the propensity of

Holocene climate to shift dramatically over mere years to millennia. Because the time period covered by reliable instrumental records in Southern Alaska is relatively short (<100 years), high-resolution climate proxy records such as tree-ring widths, ice cores, and marine cores in high sedimentation sites are essential for gaining an understanding of the timing, intensity, forcing mechanisms and feedbacks of seasonal to millennial climate shifts during the Holocene. Temperature and precipitation trends from pollen data indicate an interval of warm temperatures and low precipitation (known as the Hypsithermal) occurred between about 10,000 and 7000 cal yr B.P. along coastal southern Alaska (Heusser et al., 1985; Peteet, 1986; Mann and Hamilton, 1995) also reflected in fjord infilling (Goldthwait, 1966). An early Holocene glacial advance (7500 to 6000 cal yr B.P.) has been reported for the Fairweather Range (Mann and Ugolini, 1985) and Hubbard Glacier region (Barclay et al., 2001), although a similar advance has not been documented elsewhere along coastal southern Alaska. There is also sketchy evidence for a glacial advance around 5000 cal yr BP in West Arm Glacier Bay (Goodwin, 1988). Pollen records indicate that a cooler and wetter climate established itself in Southeast Alaska after about 3300 cal yr B.P. (Heusser et al., 1985). Evidence for glacier advances at about this time come from several locations around coastal southern Alaska including Glacier Bay (Goldthwait, 1966; Goodwin, 1988; McKenzie and Goldthwait, 1971), LeConte Glacier (Viens, 2001), Juneau Icefield (Motyka and Beget, 1996), Lituya Bay (Mann and Ugolini, 1985), Rusell Fjord and Yakutat Bay (Barclay et al., 2001), and Southern Kenai Mountains (Wiles and Calkin, 1994).

Over the past ~2000 years, advances and retreats of coastal piedmont and land-terminating glaciers in the Gulf of Alaska are roughly correlated with millennial climatic oscillations such as the Little Ice Age (LIA) and Medieval Warm Period (MWP) (Calkin et al., 2001). Roughly synchronous intervals of expansion across the entire region occurred from 500 A.D.- 900 A.D. (Barclay et al., 2001; Goodwin, 1988; Porter, 1989; Post and Motyka, 1995; Wiles et al., 1999). The majority of Alaskan glaciers occupied retreated positions well landward of LIA terminal moraines during the MWP (Wiles et al., 1999). The MWP/LIA transition was perhaps the most abrupt and severe Holocene climatic shift in the Northern Hemisphere (O'Brien et al., 1995; Mayewski et al., 1997), marked by a depression of Alaskan equilibrium line altitudes of 150-200 m (Calkin et al., 2001), a 0.5-1 ºC drop in average Greenland surface temperatures (Dahl-Jensen et al., 1998), and a 2-4 ºC depression of average sea-surface temperatures in the Atlantic (Keigwin, 1996). In response to LIA cooling, most Alaskan glaciers expanded during three phases of advance from ~1200-1850 A.D., with the majority attaining their maximum Holocene volumes during the mid 19th century (Wiles et al., 1999; Calkin et al., 2001). The LIA is generally considered to have lasted until about 1900 A.D. but calving retreats of tidewater glaciers were initiated at a number of locations in southeast Alaska during the mid to late 18th century including Lituya Bay (Mann and Ugolini, 1985), Glacier Bay (Goodwin, 1988), Taku Glacier (Motyka and Beget, 1996), and LeConte Glacier (Post and Motyka, 1995). Exceptions to this chronology include Lituya Bay where the advance continued until about 1700 A.D. (Mann and Ugolini, 1985) and Yakutat Bay where the Hubbard Glacier expansion that began about 3000 cal yr B.P. continued uninterrupted until about 1300 A.D. (Barclay et al., 2001). In contrast, tidewater glaciers in Icy Bay and Prince William Sound did not begin retreating until the late 1800s A.D. (Porter, 1989; Wiles et al., 1994) and land-terminating glaciers in many locations either retreated very slowly or continued their expansion well into the late 1800s A.D. (Rothlisberger, 1986; Porter, 1989; Wiles et al., 1994).

As with the earlier Neoglacial expansion there are several noteworthy exceptions to the general LIA chronology outlined above. One of the most conspicuous is the retreat of Hubbard Glacier that began around 1300 A.D., which was completely asynchronous with LIA expansion elsewhere. Another exception is Columbia Glacier in Prince William Sound, which remained at its LIA maximum until about 1984 A.D. when it began a rapid calving retreat. These differences have been attributed to non-climatic calving instabilities and the tidewater calving glacier cycle as discussed by Field (1947), Mercer (1961) and Post (1975)) and further elaborated upon by Borwn et al. (1982), Mann (1986), Meier and Post (1987), Powell (1991) and Post and Motyka (1995).

The recent and rapid wastage of the majority of the region's glaciers and the acceleration of this trend during the late 20th century has now been well documented (Arendt et al., 2002; Echelmeyer et al., 1996; Meier et al., 2003; Motyka et al., 2003; Sapiano et al., 1998). Exceptions include Taku Glacier and Hubbard Glacier, which have advanced 7 km and 2.3 km since 1893 A.D. respectively (Motyka and Beget, 1996; Trabant et al., 2003), Lituya Bay glaciers (Goldthwait et al., 1963) and several in Prince William Sound (ref) and Glacier Bay (summarized in Powell 1984) The advance of these and several other tidewater glaciers in the region have been attributed to advancing phase of the tidewater glacier cycle noted above.

Regional Tectonic Setting

The St. Elias orogenic system is the belt of active mountain building related to the interactions between the Yakutat microplate and North America (Fig. 2). By this definition, the orogen encompasses at least four major mountain ranges (Fig. 1): the Fairweather Range, the St. Elias Range, the eastern Chugach Mountains, and the Wrangell Mountains, as well as deformed offshore regions in the Gulf of Alaska. In addition, it seems likely that the entire eastern Aleutian arc from the Alaska Range to the south is affected by the Yakutat microplate interaction (e.g. Lahr and Plafker, 1980; Eberhart-Philips et al., 2003).

The most significant topographic features of the orogen occur along the U.S.-Canadian border where the Pacific-North American plate boundary changes from the Queen Charlotte-Fairweather transform system to the convergent Alaska-Aleutian trench (Fig. 2). The Yakutat microplate has moved into this transform-subduction transition as more or less a part of the Pacific plate (e.g. Plafker et al., 1978, 1994). As a result, deformation and uplift are concentrated primarily near the leading edge of the Yakutat microplate and into the adjacent North American continental crust (e.g. Lahr and Plafker, 1980; Plafker, 1987; Plafker et al., 1994b, Bird, 1996). The present-day high topography is developed primarily in the northwestern St. Elias Mountains within an ~100 km long segment where the Yakutat microplate is more continental than elsewhere along its length (e.g. Plafker, 1987).

Recent studies (Ferris et al., 2003) suggest the collided block in this orogen includes both a microcontinental block and an oceanic plateau, indicating this region may contain critical clues to the role of oceanic plateau collisions in continental dynamics. The continental vs. oceanic portions of the Yakutat microplate are possibly separated by a regional high-angle structure that Plafker (1987) referred to as the Dangerous River zone (Fig. 2). The Dangerous River zone presently strikes ~N-S and is recognized primarily by stratigraphic differences across the boundary. To the east, Pre-Pliocene sedimentary cover is absent or thin above an angular unconformity/ nonconformity developed on variably metamorphosed Cretaceous assemblages of the Chugach terrane (Fig. 8). To the west, however, a thick Eocene to Miocene sedimentary cover was deposited on a composite basement that includes Chugach terrane on the east, in close proximity to the Dangerous River zone, and to the west, a mafic crust representing either an oceanic plateau or oceanic crust. Ferris et al's (2003) data imply that the oceanic part of the Yakutat terrane may represent an oceanic plateau and if true, has important implications for not only the tectonic evolution, but also the stratigraphic evolution. Most of the pre-orogenic strata now exposed in the core of the orogen represent marginal marine to shallow marine deposits (Plafker, 1987), which is consistent with deposition on relatively thick crust like an oceanic plateau. This hypothesis needs to be tested. Similarly, if the Yakutat terrane contains an oceanic plateau, an important problem is where that plateau originated. For example, Bruns (1983) suggested the Yakutat terrane may be a fragment of the Coast Ranges terrane of western Washington and Oregon; a hypothesis that needs re-evaluation in light of Ferris et al's (2003) findings.

In the eastern Aleutian arc, intermediate depth seismicity shows a well-defined Wadati-Benioff zone and associated active magmatic arc that extends from the Aleutians to the Alaska Range (Fig. 9). The Wadati-Benioff zone continues to the northeast from the last volcano of the chain to near Mt. McKinley (e.g. Jacobs et al., 1977) but then jumps to the southeast where a short magmatic arc segment and associated Wadati-Benioff zone form the Wrangell Mountains (Page et al., 1989). The volcanoes of this short arc segment in the Wrangell Mountains have produced some of the highest rates of magma influx observed in any magmatic arc (e.g. Nye, 1983). Plafker et al (1994) noted the close correspondence between the position of the eastern limit of the presently active Wrangell volcanic arc and the northward projection of the Dangerous River zone, and concluded that the Wrangell volcanic arc was fundamentally related to subduction of the western, oceanic half of the Yakutat microplate. This conclusion indirectly implies that the underlying process driving the microplate interactions in the St. Elias orogen is a small slab remnant, now represented by the Wrangell arc, dragging the Yakutat Microplate into the subduction-strike-slip transition. Recent passive seismic imaging of the down-going plate in the central Alaska Range, near Mt. McKinley, indicates, however, that the subducting oceanic crust is anomalously thick (Ferris et al., 2003). Based on its position, this thickened crust should be part of the Yakutat microplate suggesting that the oceanic part of the Yakutat microplate is either an oceanic plateau or that oceanic crust has been doubled by contraction. In either case, these data have important implications for the geodynamics of the orogen because the increased buoyancy of this thick subducting crust (Fig. 9) may account for the large-scale affects of the interaction of the Yakutat microplate.

Early tectonic studies emphasized the collisional character of the orogen (e.g. Plafker, 1983, 1987; Bruns, 1983, 1985) but more recent work emphasizes the transpressional character of the orogen (e.g. Plafker et al., 1994). Recent studies (Sauber et al, 1997, Fletcher and Freymueller, 1999, Doser and Loomis, 2000; Bruhn et al., 2004; Fletcher and Freymueller, 2003; Pavlis et al., 2004) indicate that the orogen is affected by slip-partitioned transpression (contractional strike-slip systems in which the deformation is partitioned between strike-slip and thrust faults). GPS observations (Fig. 10) reveal ~40 mm a^{-1} of total convergence between the Yakutat microplate south of Yakutat Bay and the northern side of the orogen (Freymueller et al., 2002; Fletcher, 2002; Fletcher and Freymueller, 2003).

Internally, the Yakutat microplate is virtually undeformed with active deformation occurring on all sides (Plafker, 1987; Plafker et al., 1994; Bruhn et al., 2003, Pavlis et al., in review):

1. To the east (Fig. 2), convergence is highly oblique and deformation is partitioned into nearly pure-strike-slip along the Fairweather fault and thrusting along the base of a low mountain range between the Fairweather fault and the Yakutat foreland (Bruhn et al., in review). Active deformation is clearly indicated by at least two great earth-

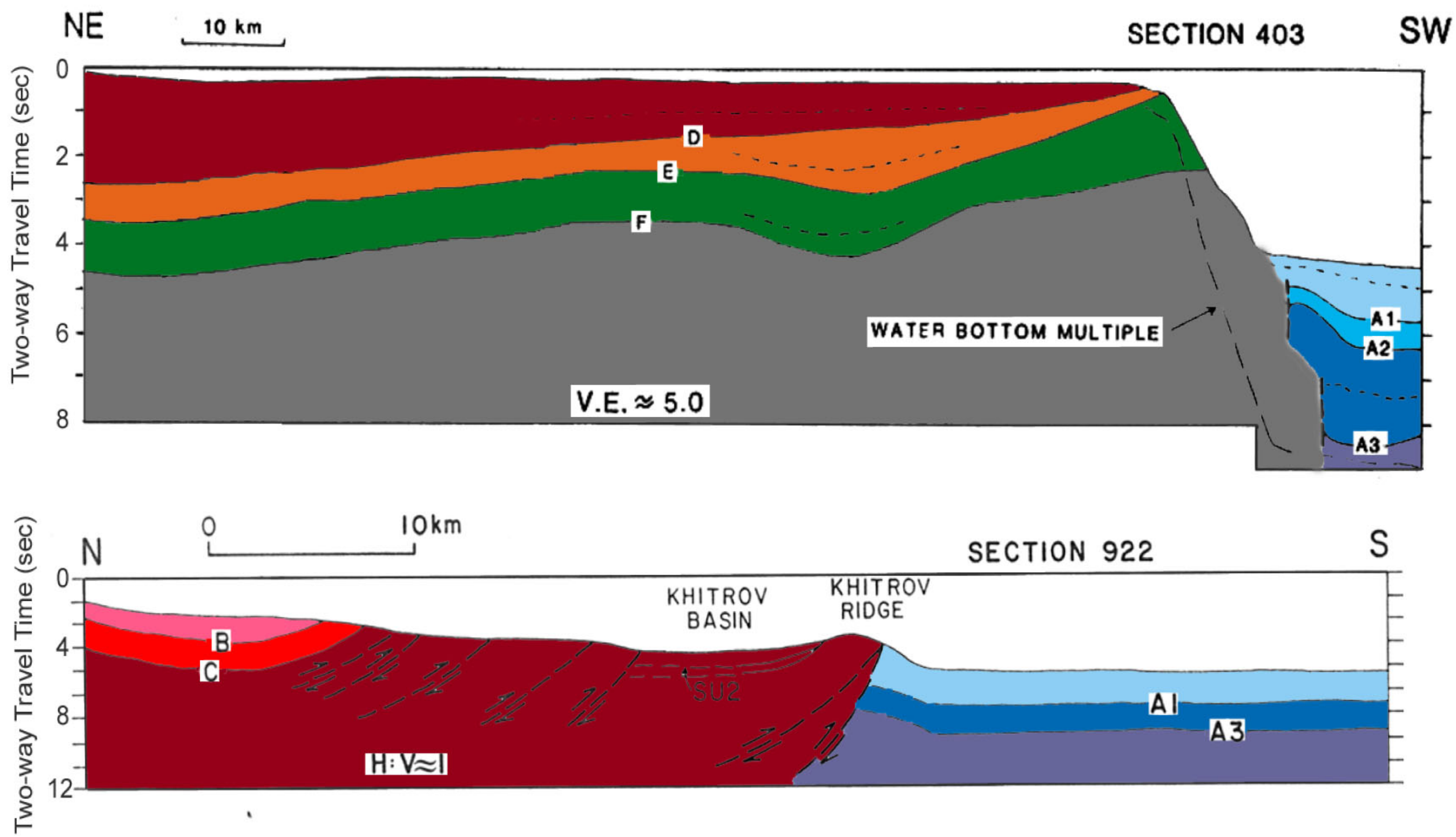


Figure 8. Structural cross sections of the eastern (top, 403) and western (bottom, 922) segments of the Yakutat terrane on either side of the Dangerous River zone, modified from Plafker (1987), Bruns (1983), and Bruns and Schwab (1983). See Figure 2 for location of sections. Horizons A-D represent the Yakataga Formation, E is a middle Oligocene Horizon (Poul Creek Formation), F is acoustic basement (basalt?). On the Surveyor Fan, Horizon A1 is earliest Pleistocene, A2 is earliest Pliocene, A3 is top of oceanic basalt. Note that shelf strata have a planar geometry and are not conformable with fan strata east of the Dangerous River Zone, with 6 seconds of offset between shelf and fan basement. Also note that the depth to basement on the shelf/slope varies from ~4 seconds east of the Dangerous River zone deepening to >14 seconds west of the zone (Risely et al., 1992).

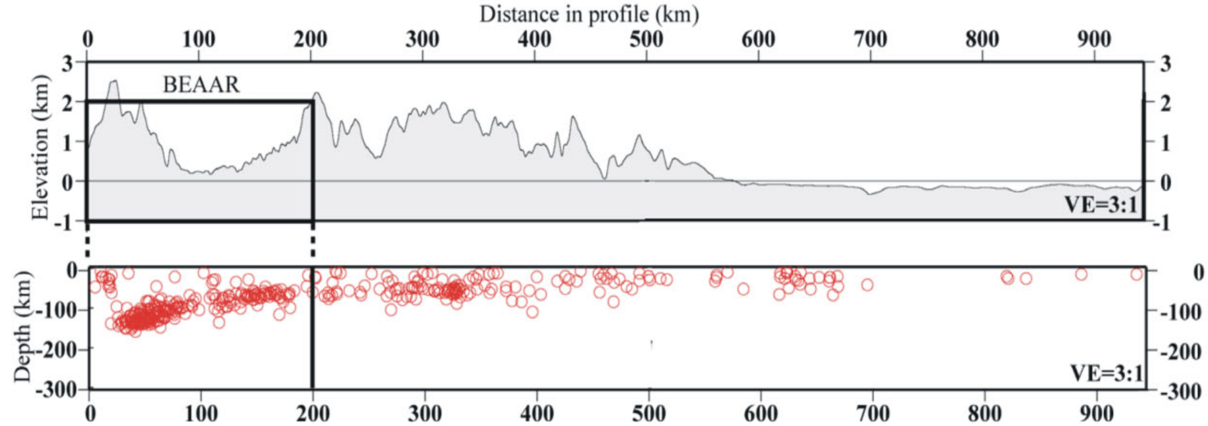


Figure 9. (Top) Topographic profile across southeast Alaska from the offshore Yakutat microplate to the northwestern limit of orogenic uplift. Approximate coverage for the BEAAR experiment (Ferris et al. 2003) is shown. **(Bottom)** Earthquakes along a 100-km swath centered on this profile from the NEIC catalog. Note the relatively flat subduction from ~200-600 km beneath southeast Alaska suggestive of a downgoing oceanic plateau. See Figure 10 for location of transect.

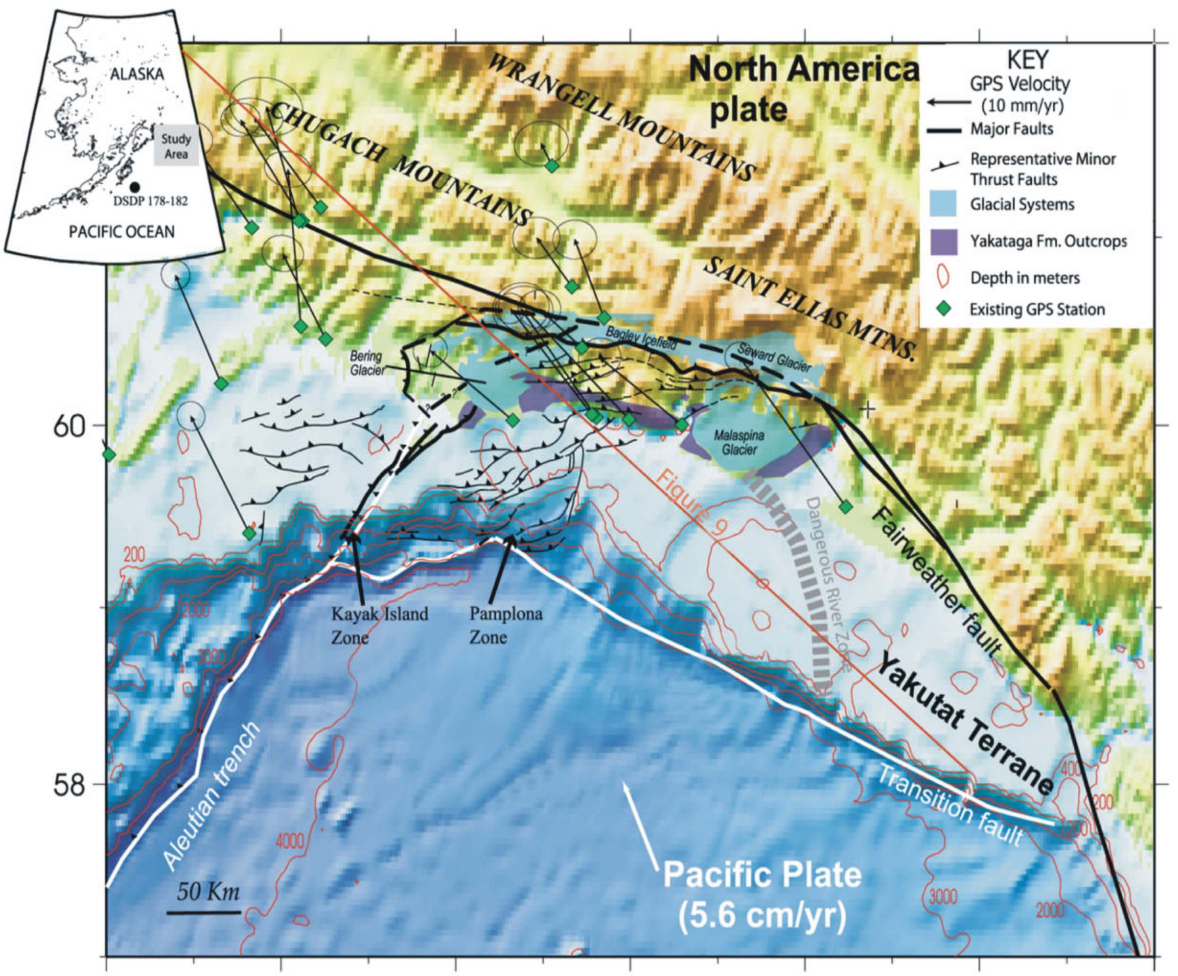


Figure 10. Location of existing GPS sites in southern Alaska and corresponding velocities relative to a stable North America. GPS observations reveal ~40 mm a-1 of total convergence between the Yakutat microplate south of Yakutat Bay and the northern side of the orogen.

quakes within the zone during the last ~100 yrs: a) the 1958 Lituya Bay earthquake that ruptured the Fairweather fault in virtually pure strike-slip mode (Doser and Loomis, 2000); and b) at least one of the great earthquakes in the 1899 earthquake sequence that ruptured blind thrust faults beneath the Yakutat foothills to produce the largest coseismic uplifts ever recorded (Tarr and Martin, 1912; Thatcher and Plafker, 1977, Bruhn et al., 2003).

2. Along strike to the west and north from Yakutat Bay, structures turn sharply to ~E-W trends and deformation becomes dispersed in a broad fold and thrust belt that connects westward to the Aleutian trench. GPS data (e.g. Sauber et al., 1997) and geologic data (e.g. Plafker, 1987) both indicate that little active deformation extends beyond a large glacial trough occupied by the upper Seward Glacier and Bagley Icefield. This observation together with structural details suggests that the slip partitioning along the Fairweather fault extends westward into the interior of the orogen with dextral slip along the Seward-Bagley trough and thrusting accommodated within the fold-thrust belt (Bruhn et al., 2003). The fold-thrust belt involves Mesozoic basement east of the Dangerous River zone, but to the west is a thin-skinned fold-thrust belt developed in Tertiary sedimentary cover of the Yakutat terrane. From Yakutat Bay to the Bering Glacier (Fig. 2) the fold-thrust structures are parallel to the suture, which is shown on regional maps as the Chugach-St. Elias fault (CSEF). To the west and south of the Bering Glacier, however, the structural style changes. Onshore between the Bering Glacier and the Copper River (Fig. 2) early fold-thrust structures as well as the suture (CSEF) are refolded about steeply plunging fold systems (Bruhn et al., 2003). These structures apparently continue offshore and connect into an actively deforming, ~NE striking contractional or transpressional faults of the Kayak Island zone (Fig. 2) that ultimately links up with the Alaskan-Aleutian subduction zone.

3. To the southeast is the most poorly understood structure of the entire orogen, the Transition fault. This structure parallels the base of the slope, directly or indirectly forming the oceanic-continental transition. The structure has been variably described as inactive (Bruns and Carlson, 1987), a dextral-oblique thrust fault (Lahr and Plafker, 1980, Plafker, 1987), and a thrust fault (Perez and Jacob, 1980; Bayer et al., 1978; Griscom and Sauer, 1990; Plafker et al., 1994). More recently, Fletcher and Freymueller (1999) argued on the basis of GPS data that as much as 20 mm a^{-1} of convergence must be occurring along the Transition fault or an unrecognized offshore structure to account for the more westward motion of the Yakutat Microplate relative to NA-Pac convergence.

Lithospheric Dynamics in Southern Alaska

The interaction of surficial and mechanical processes occurs at several different spatial scales. In the first instance, increased rates of erosion may be expected to reduce both relief and average topography (Whipple and Tucker, 1999), but the non-linearities that arise from coupling deformation and erosional processes produce a threshold beyond which increased rates of erosion result in an increase in average elevation and relief (e.g. Zeitler et al., 2001, Koons et al., in review). The threshold is influenced in part by thermal thinning related to exhumation and in part by crust-mantle coupling. The balance of these two controlling influences is poorly understood, but windows into the controlling parameters exist in regions where anomalous relief and anomalous strain distribution are associated with active surficial processes. The influence of geomorphic processes at the earth's surface on the mechanical behavior of a deforming orogen can assume at least two forms, both related to the integrated strength of the crust (Sonder and England, 1986). Firstly, crustal strength may be perturbed by the differential loading due to existing topographic features. Secondly, the process of exhumation can significantly influence the integrated strength of the crust. In a two layer continental crust with a brittle upper layer of thickness, h_{BD}, and a thermally activated ductile lower layer (Brace and Kohlstedt, 1980), the high-strength brittle member provides most of the resistance to shear with a vertically integrated strength that varies as the square of the crustal thickness, h_{BD}, (Koons et al., in review). The sensitivity of the integrated strength to the square of the crustal thickness magnifies the influence of any upper crust thermal perturbation that acts to reduce this thickness. In a region undergoing tectonic advection, h_{BD}, is strongly influenced by the material velocity field as described by the transient heatflow equation for a moving medium (Koons, 1987; Craw and others, 1994; Batt and Braun, 1997). In the lithosphere, the thermal and mechanical processes are coupled through a rheological dependence upon temperature and a thermal dependence upon local particle velocities (Fig. 11). This coupling produces a positive feedback between exhumation and strain concentration that can lead to a tectonic aneurysm manifested in local strain rate fields, topography, metamorphic, and structural patterns (Zeitler et al., 2001; Koons et al., in review).

The coupling of surficial and mechanical processes is drawn into focus in the St. Elias Range where the extreme relief is associated with a left-stepping restraining bend in the Fairweather Fault system (Fig. 2; Plafker et al., 1994b). Two possible paths can be postulated to explain the generation of the restraining bend and associated topographic relief: 1) an externally imposed step in the plate boundary geometry and topographic growth is in response to this step, or 2) the structure forms in response to thermal thinning due to concentrated exhumation in a manner similar to the tectonic aneurysm behavior of Nanga Parbat (Koons et al., in review) (Fig. 11).

As well as providing an excellent natural laboratory to examine specific issues in geodynamics, Southeast Alaska presents us with a greater intellectual opportunity. Currently, one serious challenge in geodynamic modeling lies in the reduction of time scales from that of plate realignments (10^6-10^5 years) to the much shorter periods reflecting climatic changes (~10^4 years) and even shorter interseismic scales (<10^4 years). In the absence of adequate observations of natural orogens, steady state behavior of nearly all controlling mechanical parameters including fluid pressure, brittle failure mechanisms, ductile flow systems, and climatic variation are assumed in most geodynamic models. The climatic, tectonic and sedimentary signals in Southeast Alaska are so large that many of the uncertainties that currently drive us to accept the steady state assumptions should be dwarfed by the signals. Thus we have the opportunity to unpack the response of an orogen to transients in these controlling processes. For instance, glacial unloading represents a significant transient perturbation to orogen dynamics. Isostatic rebound that followed the LGM continued to about 6,000 to 7,000 cal yr B.P. in southeast Alaska with total uplift ranging from 50 m near Lituya Bay (McKenzie and Goldthwait, 1971) to 230 m above current sea level in the Juneau area (Heusser, 1960, Miller, 1972; 1975). Post-LIA isostatic rebound resulting from the general rapid wastage of glaciers in the region and in Glacier Bay in particular is producing the highest rates of uplift in the world. Rates as high as 35 mm a^{-1} and 25 mm a^{-1} have been measured near Russell Fjord and in Glacier Bay respectively (Larsen et al., 2003a), while total uplift since 1780 A.D. ranges from 3.1 m in the Juneau area

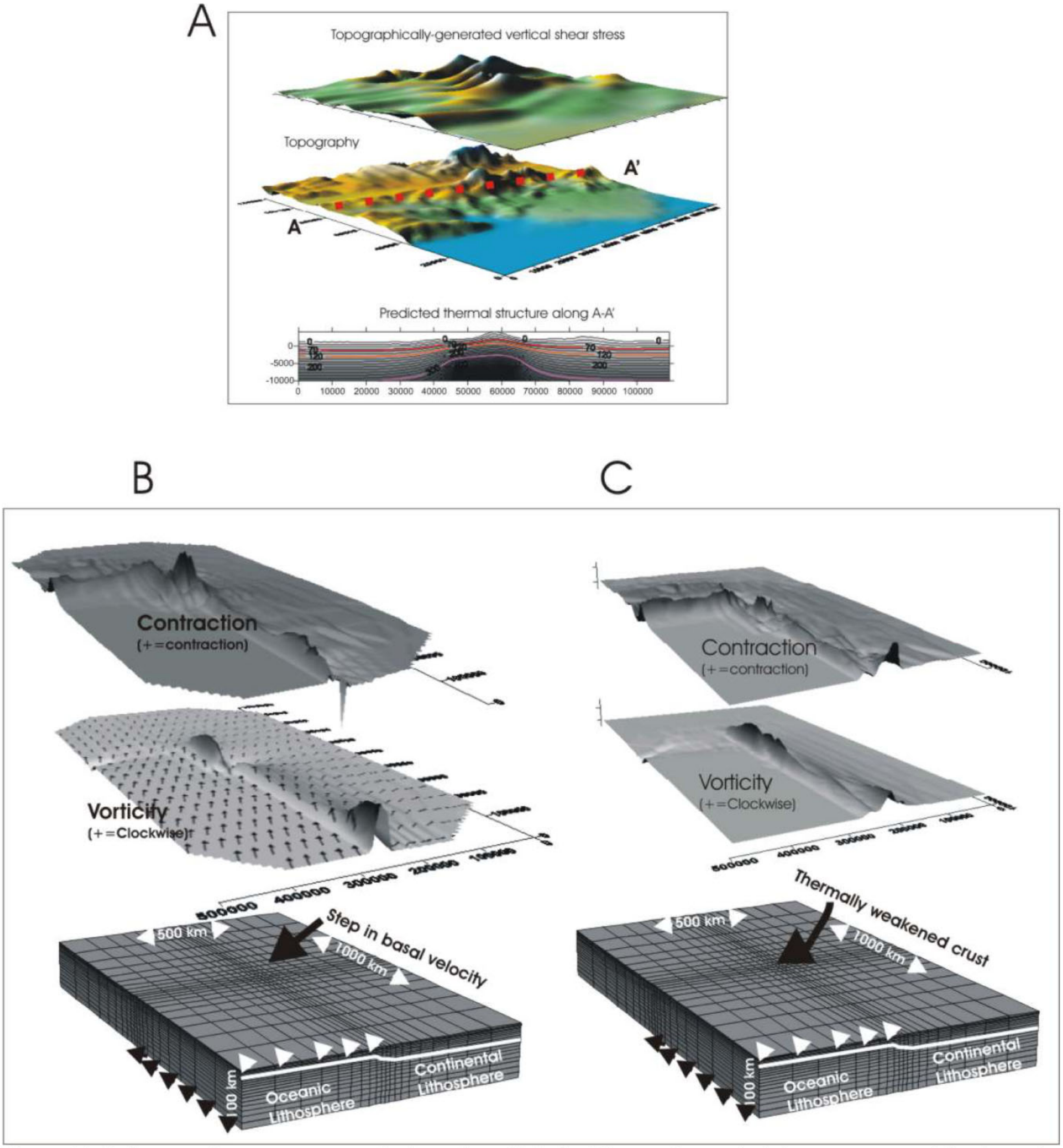


Figure 11. Influence of extreme topography in region of Mt. St. Elias on the vertical shear stresses and the thermal field. Vertical shear stresses (txz2 + tyz2)1/2 (z = vertical; x = north; y = east) generated by topography at 5km below sea level appear as maxima on either side of the Mt. St. Elias and Mt. Logan massifs. The thermal field is depicted in cross section and assumes a long-term averaged velocity field similar to that of Nanga Parbat (Zeitler et al., 2001). Isotherms relevant to low temperature geochronological systems are highlighted. **(Below)** Initial geodynamic model comparing the contraction $(= -0.5(\partial Vx/\partial x + \partial Vy/\partial y))$ and vorticity $(= 0.5(\partial Vx/\partial dy - \partial\ V \partial x))$ fields caused by oblique subduction with an externally imposed step in the basal boundary condition **(A., lower left)** or **(B., lower right)** internal rheological step arising from exhumation-related thermal thinning (Koons et al., 2002). With the exception of the restraining bend region, the far field velocities and rheological structure of the two models are identical with an oceanic block in the southwest impinging and subducting beneath the continental material to the north and east with a ratio of velocities of Vx:Vy of 5:1. The rheological structure and the implications for petrological evolution are discussed elsewhere (Koons et al., 2003b). After Meigs and Sauber (2000).

(Motyka, 2003) to 5.7 m near Glacier Bay (Larsen et al., 2003b). Consequently, the spatial and temporal accommodation of this perturbation will provide important information on short-term rheological behavior.

Timing and Rates of Crustal Evolution in Southern Alaska: Key Elements

Development of the modern Chugach/St. Elias orogen is related to the northwestward translation, collision, and subduction of the Yakutat terrane along the North American plate margin since ~25 Ma (Plafker, 1987). Motion of the Yakutat terrane is closely tied to northwestward motion of the Pacific plate with respect to North America. Pacific-North America plate motion is characterized by a N60°W azimuth between 30 and 8 Ma at the latitude of northern California, although the rate apparently increased from ~33 to ~52 mm a^{-1} after 12 Ma (Atwater and Stock, 1998). The rate and direction of Pacific plate motion relative to North America have been relatively steady since ~8 Ma (~ 52 mm a^{-1} and N37°W, respectively).

Low-temperature thermochronometry demonstrates that Pliocene and younger cooling ages are concentrated in the core of the range (O'Sullivan and Currie, 1996; O'Sullivan et al., 1997; Spotila and Buscher, 2002). Converting the ages to exhumation rates, peak rates of 1-3 mm a^{-1} mark a belt that parallels the modern coastline (assuming a 25-30° C km-1 geothermal gradient). Finally, Yakataga Formation strata exhibit growth stratal geometries on the limbs of folds developed in the collision zone between the Yakutat terrane and North America (Bruns and Carlson, 1987; Lagoe and Zellers, 1996; Suppe, 1990; Zellers, 1993).

A number of general interpretations can be formulated on the basis of these observations. Roughly 600 to 825 km of subduction of the Yakutat terrane beneath southern Alaska after ~25 Ma is indicated by plate velocity vectors and reconstructions (Plafker, 1987). This convergence is partitioned into ~NNW-SSE crustal shortening and ~NNW-WNW directed right-lateral translation. The inference that the coastal ranges did not contribute substantial material to the Gulf of Alaska until the Upper Miocene (Lagoe et al., 1993), suggests that the rate of material transfer from the incoming Yakutat terrane lower plate to the southern Alaska continental margin upper plate increased after 9.5 Ma. Flexural basin development related to thickening of the upper plate began 6 Ma and subsidence rates increased by nearly an order of magnitude after 3.25 Ma (Zellers, 1993). More than 5 kilometers of sediment sourced from both the Yakutat terrane and North American plates accumulated in the basin (Miller, 1953; Plafker, 1987; Plafker and Addicott, 1976).

Linkages between Uplift, Erosion, Climate, and Topography

Southern Alaska is a continent-scale region of ongoing crustal deformation where glaciers and glacial erosion have dictated patterns of denudation in the orogen over the last ~6 Ma (Meigs and Sauber, 2000). The orogen comprises three discrete topographic domains from south to north, respectively: (1) the Chugach/St. Elias Range; (2) the Wrangell Mountains; and (3) the eastern Alaska Range. The Chugach/St. Elias Range extends from the coast to the Chitina-Copper River valley and includes the two highest peaks in the area, Mt. St. Elias (5490 m) and Mt. Logan (6050 m). Altitude in the Chugach/St. Elias Range is bimodally distributed with nearly equal amounts of area at 300 and 1200 m, a distribution that reflects, in part, the surface elevations of the extensive ice fields and glaciers and unoccupied glacial valleys. Mean elevation (~1225 m) is low in comparison with the elevation of highest peaks. More than 90% of the land area lies in an altitudinal band between 300 and 2200 m above sea level; the surface area above 3200 m occupies less than 2% of the landscape. Mean elevation decays exponentially from ~2500 m to ~1100 m in less than 100 km west of Mts. Logan and St. Elias. Relief changes from east to west as well, from ≥2100 m to ≤600-800 m, respectively. To the north, a prominent series of stratovolcanoes (~4000 to 5000 m summits) dominates the topography of the northwest-trending Wrangell Mountains, and mean elevation (1670 m) is only slightly higher than the modal elevation (1500 m). The volcanoes appear to have developed on a landscape with an initial elevation of ~1800 to 2500 m regionally. The eastern Alaska Range is topographically subdued when compared with the Wrangell and Chugach/St. Elias domains to the south. Altitude is normally distributed about the mean elevation (1214 m). Peak elevations exceed 2600 m, yet these peaks occupy ≤1% of the surface area. As a distinct topographic entity, the eastern Alaska Range maintains about the same height (~1000 m) and relief (<600 m) across the study area.

Equilibrium line altitude (ELA) in the Chugach/St. Elias Range appears to be linked to mean topographic elevation (Meigs and Sauber, 2000). The ELA is characterized by a rise of 27m km^{-1} northward, from an elevation of <800 m near the coast to >2000 m west of Mt. Logan (Mayo, 1986). It is interesting to note that the surface elevation of this Range is only slightly higher than the west-striking, south-facing plane defined by the ELA regionally. Mean elevation corresponds to the ELA in the Chugach/St. Elias Range and more than 50% of the landscape lies at or above the ELA presently (Mayo, 1986). Because the area above 3000 m represents <2% of the surface area, the summits of Mts. Logan and St. Elias project like needles nearly 4000 m above the plane of the ELA. Between ~40 and 60% of valley walls would be ice covered given the extent of glaciers at the turn of the century. Eighty percent or more of the valley walls would have been covered at the last glacial maximum (Péwé, 1975; Porter, 1988, 1989b).

Net erosion of glaciated orogens is the sum of: (1) primary bedrock erosion by glaciers and (2) erosion in areas of the landscape that are ice-marginal and are deglaciated at glacial minima (Meigs and Sauber, 2000). Quantifying the extent to which the land surface moves relative to the ELA provides a qualitative sense of the temporal variation in percent surface area covered by glaciers. Even though the percent change is not specified explicitly by such approximations, the estimates suggest that the locus of primary bedrock erosion by glaciers should oscillate in synchrony with altitudinal shifts of this plane due to climatic fluctuation (Fig.12), if glacial erosion is a function of mass flux through the ELA (Andrews, 1972; Harbor, 1992). Moreover, the down-valley extent of glaciers on the windward and leeward flanks of the range during a given climatic state (i.e. full glacial), will vary as a function of orographically moderated differences in precipitation and temperature across the range (Figs. 12 and 13) (Østrem, 1972; Péwé, 1975; Porter, 1977; Østrem et al., 1981). Thus, the glacial, interglacial, and mean position of the ELA define an across-strike and altitudinal band where primary bedrock erosion by glaciers is focused, a band which, by definition, coincides with the maximum sliding velocity at a glacier's base (Fig. 12). On the windward, southern flank of the Chugach/St. Elias range specifically, the bandwidth is likely to be particularly wide because the ELA is at ~600 m and many of the glaciers are at or near sea level (Mann, 1986; Molnia, 1986; Porter, 1989).

Additionally, the ice-marginal portions of the landscape are sensitive to changes in ice height and distribution (Meigs and Sauber, 2000). Ice height and distribution controls erosional processes in ice free areas; processes such as deep-seated bedrock landsliding, fluvial incision of glacial valley bottoms, and remobilization of colluvial and fluvial deposits graded to the former glacier margins are key factors contributing to high sediment yields. A key implication for the long-term erosion of glacially-dominated orogens is that the relative importance of glacial

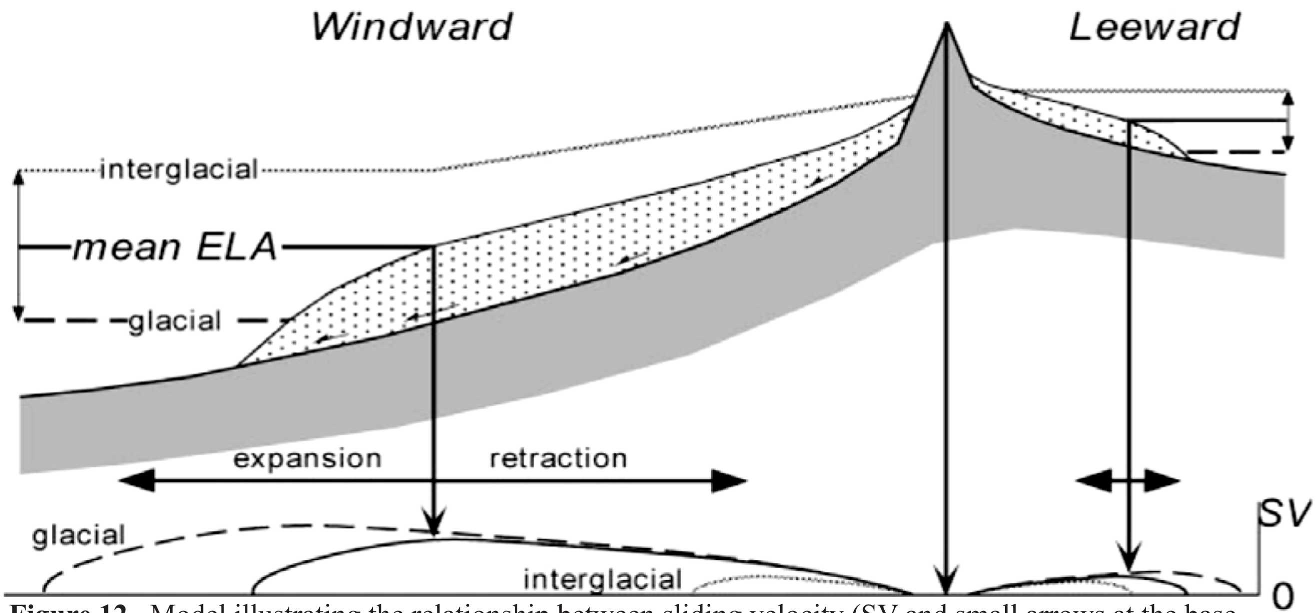


Figure 12. Model illustrating the relationship between sliding velocity (SV and small arrows at the base of the windward glacier) and the ELA across an orogenic belt (Meigs and Sauber, 2000). An orographically induced rise in the ELA from the windward to the leeward side of the range leads to a higher mean ELA (solid black line) (see Figure 11). Smaller amplitude fluctuations of the ELA between glacial (dashed line) and interglacial (gray line) is shown schematically (the leeward range is ~33% of the wind-ward range, consistent with that of the Chugach/St. Elias). Assuming that bedrock erosion rate scales with basal sliding velocity (Hallet, 1979; Humphrey and Raymond, 1994), the model suggests concentra-tion of erosion in a topographic band whose height is dictated by glacial/interglacial altitudinal limits to the ELA and whose width is a function of the concomitant glacial expansion/retraction in the landscape. The windward band width and height are likely to be greater than those of the leeward flank. Note that the range crest is defined by a topographic peak that corresponds spatially with a zone of low erosion rate by glaciers (arrow). After Meigs and Sauber (2000).

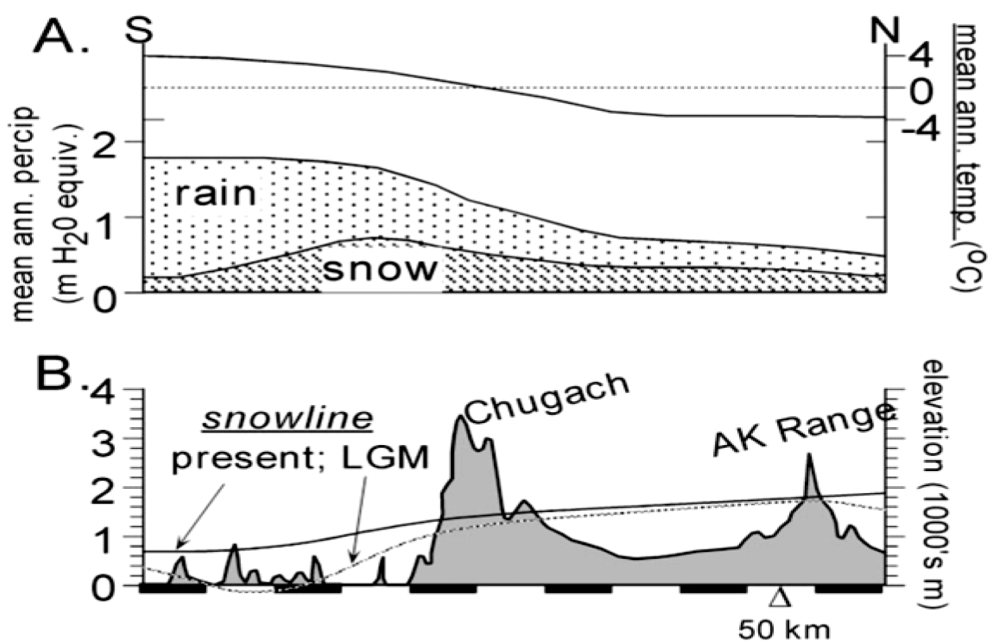


Figure 13. Plot of **(A)** mean annual precipitation and annual temperature and **(B)** topography, present snowline, and last glacial maximum (LGM) snowline. Note the strong orographic effect of the Chugach/St. Elias Range on precipitation. Where topography has relatively little effect on precipitation and temperature on the south, the present snowline lies between 600 and 800 m above sea level. Modified from Péwé (1975). After Meigs and Sauber (2000).

and other erosional processes in the net denudation per unit area of an orogen varies as a function of climate change operating on 10^2 to 10^5 year time scales.

Sediment yields, as a measure of denudation rate, from the coastal mountains of southern Alaska appear to be the highest in the world (Elverhoi et al., 1998, Hallet et al., 1996; Hunter et al., 1996; Powell and Molnia, 1989; Powell, 1991). Coastal mountains are being cut down by ice as fast as the crustal belt grows. The extreme erosion rates are due in part to high physical weathering rates of diverse rock types heavily affected by tectonic deformation (Powell, 1984). Rates of weathering of diverse rock types along the southern coast of Alaska seem to be the highest reported in the literature (Roche, 1994). Many processes actively move material down slope to the coast; they range from the frost-induced motion of individual rock fragments to large-scale mass movements (Meigs, 1998) that have spectacular proportions, particularly in recently deglaciated areas.

Active orogenic topography is dictated by the magnitude of tectonic flux of rock from below relative to the erosive flux by the geomorphic systems operating from above. Because geomorphic systems are forced by both climate and tectonics (Bull, 1991; Whipple and Tucker, 1999), two classes of potential feedbacks merit consideration. First, how does topography at the orogen scale compare with uplift and denudation rates (i.e. across the Chugach/St. Elias range)? If topographic change is modulated by competition between rates of uplift and erosion, it becomes important to place independent constraints on the rates and patterns of uplift and denudation. Coupling and feedback between uplift and erosion implies that they ought to correlate (Willett et al., 1993; Koons, 1994; Koons, 1995; Beaumont et al., 1996). Second, do specific characteristics in the form of landscape (i.e. mean elevation, slope, hypsometry, relief), reflect feedback between uplift, topography, and climate? Mean fluvial topography scaling with uplift rate is suggested by models that show close coupling between drainage network geometry and uplift rate (Tucker and Bras, 1998; Whipple et al., 1999; Whipple and Tucker, 1999). However, connections between glacial drainage network geometry and uplift rate have not been explored quantitatively.

Rates, Patterns and Models of Sediment Accumulation in the Gulf of Alaska

As noted previously, the northern Gulf of Alaska region contains the longest and most complete stratal record of late Cenozoic glacimarine sedimentation in the world. One of the outstanding questions regarding the formation of the five-km thick Yakataga Formation is what were the microplate morphology, tectonic, and isostatic processes that allowed for the development of such significant accommodation space. The voluminous supply of sediment to develop such thick strata, however, is not in question and reflects this temperate glacial setting where sediment fluxes are tremendous (Hunter et al., 1996, Powell and Molnia, 1989; Powell, 1991).

Prior to the onset of tectonic uplift ~10 Ma, the margin was dominated by low sedimentation rates (<0.01 m ka^{-1}) of glauconitic-phosphatic sandstones, siltstones, organic-rich shales, and lenticular limestones that likely formed on a nutrient-rich upwelling margin at bathyal depths and may be time-equivalent of the Monterey Formation and related Miocene rocks of the north Pacific margin (Martin, 1993). Following the onset of uplift, the continental margin marine clastics (interbedded sandstones, mudstones, and conglomerates) of the lower Yakataga and/or Redwood Formations were deposited in neritic (10-150 m water depth) to bathyal (>150 m) water depths (Martin, 1993; Plafker, 1987).

The interpretation of the initial depositional setting for the Yakataga Formation is controversial (Eyles et al., 1991; Eyles and Lagoe, 1990; Lagoe et al., 1989; Lagoe and Zellers, 1996;

Powell and Cooper, 2002), spanning from outer neritic (<150 m) to upper bathyal environment (150-500 m) as defined by Lagoe and Zellers (1996) based on the paleoenvironmental interpretations of Echols and Armentrout's work on modern Gulf of Alaska foraminifera. The dominant facies of the lower Yakataga are stacked graded beds of bioturbated medium-fine grained sandstones containing scattered bivalves and mollusks, which are interpreted to represent turbidites, although trough cross-bedded sands are also observed. Large clasts (<20 cm diameter) occur locally in the graded sandstones as well as in more concentrated clast-rich beds and may represent initial evidence of iceberg-rafted debris (Eyles et al., 1991). Another key facies of the lower Yakataga are mudstone- and sandstone-rich stratified diamictite beds composed of well-rounded clasts. These beds are inferred to be stacked debris flows. The interpreted combination of turbidites, debris flows, the presence of the benthic foraminifera *Epistominella pacifica*, normally thought of as an upper bathyal (150-500 m; Lagoe and Zellers; 1996) species, and the *Cruziana* ichnofacies lead Eyles et al. (1991 and 1992) to propose that the initial deposition of the Yakataga occurred along a high-relief (upper slope) basin margin fronted by a rather narrow shelf and sediment sourced from valley glaciers (Fig. 14).

Based on similar lithofacies, ichnofacies, and foraminiferal biofacies, the slightly younger Yakataga sediments are proposed to represent a transition to a shallower (outer shelf/upper slope) depth as the continental shelf prograded rapidly seaward as a result of frequent mass-flow processes generated during a period of much increased sediment input, possibly during the Glacial B period. Finally, during the Pleistocene, there was establishment of a broad shelf influenced by repeated glaciation, iceberg-rafting of coarse debris, changes in water depth and salinity, storms, earthquakes, and high (>10 m ka^{-1}) sedimentation rates (Eyles et al., 1992) (Fig. 14). Many of the sedimentary facies and ichnofacies such as turbidites (i.e., graded beds) and the *Cruziana* ichnofacies, used by Eyles et al. to estimate depositional water depths of upper bathyal (150-500 m; Lagoe and Zellers; 1996) for the early Yakataga recently have been shown to occur in modern neritic depths of 50-150 m on the Gulf of Alaska shelf (Jaeger and Nittrouer, in press), and some of the distinctive benthic foraminiferal fauna, such as *Epistominella pacifica*, used in the interpretation of upper bathyal depths are commonly observed on the modern shelf in 100-200 m deep basins. Consequently, initial Yakataga strata may have been deposited in shallower water depths than bathyl, especially considering that the precursor conformable strata to the Yakataga (i.e., Redwood Formation) were shallow-water marine clastics.

Recently, Powell and Cooper (2002) used seismic reflection data to refine this proposed model of depositional architecture of the Yakataga to include the development of distinct glacial system tracks that are defined and related to glacial advance and retreat signatures up through the modern late Holocene (Fig. 15). From these observations, Powell and Cooper (2002) developed glacial sequence characteristics of temperate glaciated continental margins (Table 1). Foremost of these conclusions is that accommodation space on the order of 10^2 m can be generated through a combination of isostasy, including glacial, water, and sediment loading, coupled with potential tectonic forcing.

While most coastlines around the world are experiencing retreat due to rising sea level, coastal plains in southern Alaska are undergoing rapid progradation, periodically and locally greater than 5 km ka^{-1}. Modern sediment accumulation rates in the fjords of southern Alaska are unsurpassed worldwide, exceeding several m a^{-1} and locally can exceed 80 m a^{-1} at glacier termini (Powell, 1991, Fig. 9E). Fjords act as sediment traps; they provide a unique method for analyzing Holocene sediment flux because for many tidewater glaciers in southern Alaska, there is minimal sequestration of sediment on land before they enter fjord waters. The Holo-

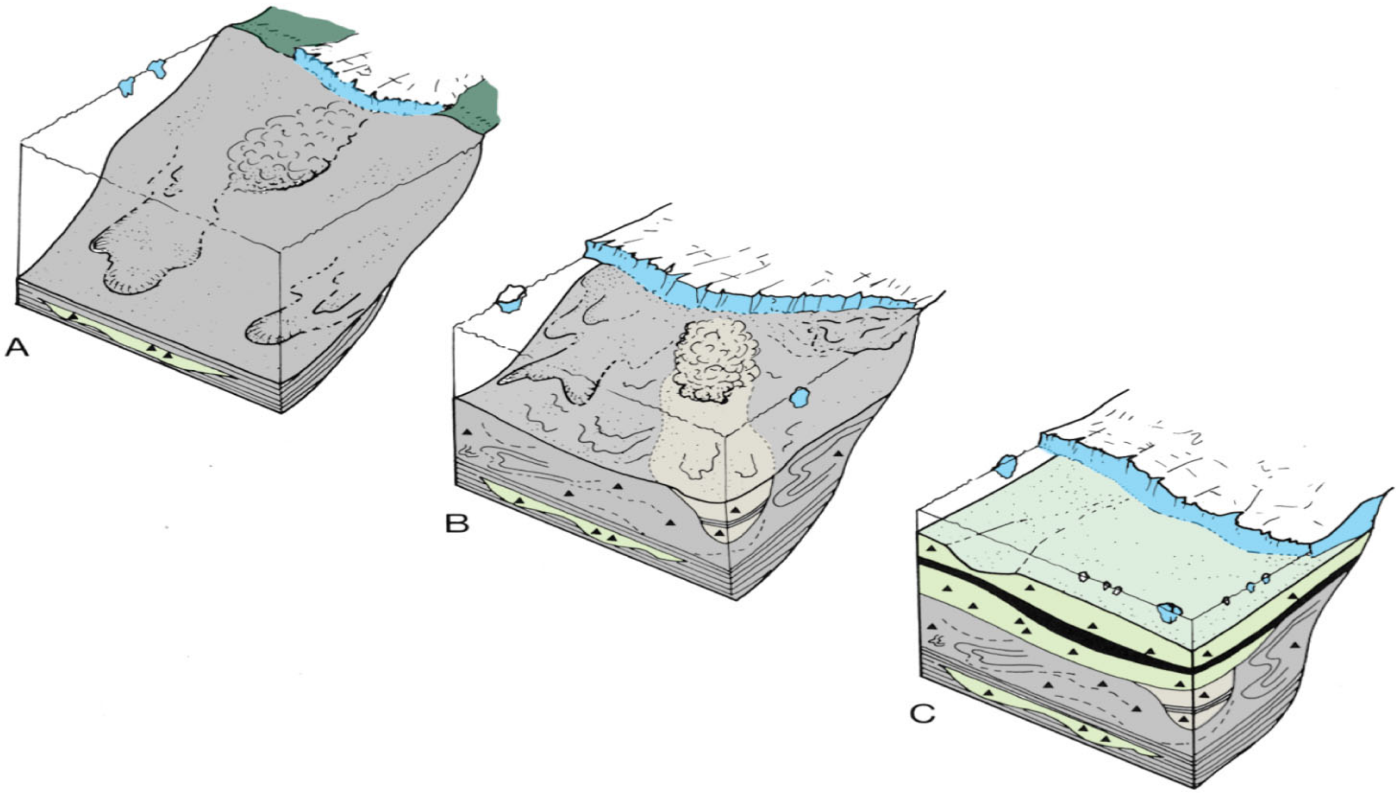


Figure 14. Conceptual model illustrating general environmental evolution of the northern Gulf of Alaska regressive margin during the Neogene (Eyles et al., 1991). (A) Initiation of glaciation (~6Ma) and initial deposition of ice-rafted facies within steep-basin margin dominated by debris-flow deposits and turbidites. (B) Rapid progradation of margin due to massive input of sediment from tidewater glaciers (~2.6 Ma?). Strata dominated by debris flow deposits and minor glacimarine facies. (C) Establishment of low-relief margin during Pleistocene. Strata formation dominated by paraglacial and ice-proximal glacimarine sedimentary facies. Modified from Eyles et al. (1991).

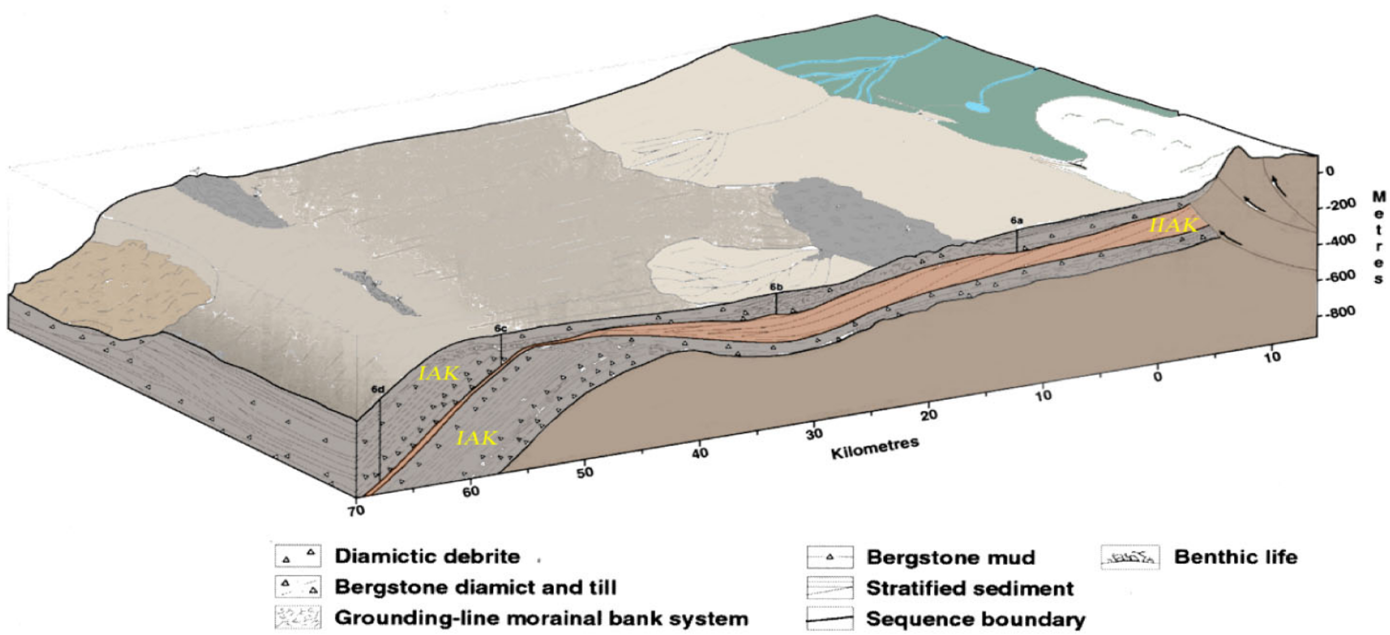


Figure 15. Conceptual model illustrating three sequences on a temperate glaciated shelf. A sequence representing a partial glacial advance (Type IIAK) occurs between two full-advance sequences (Type IAK). Each Type IAK sequence is composed of four glacial systems tracks related to glacial advance-and-retreat cycles, analogous but unrelated to eustatic sea-level cycles on lower latitude shelves. Type IIAK sequences are produced during minimal glacial advances or during normal marine conditions of a glacial minimum, equivalent to the modern Gulf of Alaska shelf. Scaling is approximated from the modern Gulf of Alaska shelf. Modified from Powell and Cooper (2002).

Seismic facies No.	Acoustic stratification	Internal configuration	Reflection		External form	Boundary condition	Position & distribution	Interpretation (lithofacies)
			Continuity	Amplitude				
1	Stratified	Oblique-tangential	High to discontinuous	Medium-high	Slope fan	Sharp to diffuse erosional top	Continental slope	Debris-flow diamicton (DFo)
2	Stratified	Sigmoid	Medium-high	High	Channel fill	Sharp truncating top, downlap on to sharp bottom	Within troughs	Interbedded glacimarine and flow deposits (IGFs)
3	Stratified	Complex sigmoid-oblique	Medium to discontinuous	Medium-high	Slope fan	Sharp to diffuse top, erosional and toplap; no bottom	Continental slope	Combination of IGFs and DFo
4	Stratified	Hummocky clinoform	Low to medium	Medium	Lens	Gradational top and bottom	Trough walls	Debris flow deposit (DFh)
5	Stratified	Dipping-parallel	Medium	Medium	Sheet	Sharp top and bottom	Continental slope	Sediment gravity flow deposit (SGFs)
6	Unstratified	Semi-transparent	Locally chaotic, occasional discontinuous reflections, point-source diffractions		Tabular to hummocky sheets	Sharp hummocky top, sharp to diffuse bottom	Mid-shelf to outer shelf	Ice-marginal diamicton (IMf)
			Locally discontinuous reflections, point-source diffractions		Basin fill	Sharp top, sharp hummocky bottom	Mid-shelf basins above SF	Ice-proximal diamicton (IPf)
7	Unstratified	Chaotic	Local discontinuous, hummocky reflections		Lens	Sharp top and diffuse bottom	Forms sea floor shoal on outer shelf	Winnowed lag deposit (Wlc)

Note: The capital letters in the abbreviations refer to the lithofacies; and the lower case letters refer to their seismic facies.

Table 1. Seismic facies characteristics and their interpretations as lithofacies. After Powell and Cooper (2002).

cene terrestrial record of glacial activity is well preserved in the Glacier Bay region, where current studies suggest that a complete record of Neoglacial glacial cycles may exist for the entire Holocene. These terrestrial records will provide key constraints on the interpretation of similar Neoglacial cycles that may be present in the extremely thick sedimentary sequences deposited on the continental shelf of southern Alaska. Here, as much as 350 m of sediment has accumulated during the Holocene. On land, substantial outwash plains and glacilacustrine deposits in the Copper and Alsek drainage basins may also contain a rich but unexplored Holocene history of terrestrial weathering and erosion essential to interpreting the marine record. Thick Copper River deltaic strata may be equally important to defining hydrologic signals. Because mountain ranges are close to the sea in southern Alaska, large foredeep basins are absent on land and terrestrial storage is minimized to brief periods of time in fjords. Consequently, there is a minimal time lag between onshore denudation and sediment production and preservation in offshore clastic sedimentary sequences.

In addition to tectonically influenced deposits, paleoenvironmental information may be contained in coastal Alaskan sediments. The two requirements for development of a laminated sediment sequence containing paleoenvironmental data are met in the fjords and bays of Southern Alaska (cf. Kemp, 1996). These are: 1) seasonal variations in sediment supply and biological activity and 2) environmental conditions that will preserve laminated sediment from bioturbation. In coastal Alaska, high sediment discharge from temperate glaciers coupled with tidal forcing produces an ultra high-resolution record where laminae representing daily deposition can be identified in marine sediment cores (Mackiewicz et al., 1984; Cowan and Powell, 1990; Cowan and Powell, 1991; Cowan et al., 1997; Jaeger and Nittrouer, 1999b).

Detailed Scientific Questions

During the workshop, attendees broke into three groups to raise detailed marine, terrestrial, and modeling questions that expand on the four broad topical research questions established on Day 1. The purpose was to come to a consensus on the most important components comprising the four topical questions. Groups also met with each other to discuss questions and considerations that had been raised within individual breakout sessions that crossed thematic or geographic boundaries. The purpose of these cross-discipline meetings was to generate further questions that addressed the interplay of processes over a range of temporal and spatial scales. The notes from these sessions are summarized below.

Climate

- What is the Neogene climate history of the high-latitude North Pacific and what role does climatic variability in the North Pacific play in Northern hemisphere climate and glaciation history? When did the continental climate develop in interior Alaska in contrast to the maritime climate that prevails on the coast?
- Did explosive volcanic events affect Neogene climate of the northeast Pacific margins? Specifically, what is the impact on vegetation cover, temperature, and precipitation? How long do volcanically induced climate perturbations last?
- What is the glacial history of the Alaskan continental margin? What processes were responsible for the onset of Cordilleran glaciation of the region? When did it begin in southern Alaska and what is its history west of the continental divide? What role has it

played in Northern Hemisphere climate and its contribution to global proxy records of glacial and climatic changes (sea level, $\delta^{18}O$, etc.)?

- What were the characteristics of climate in the Gulf of Alaska and the northern North Pacific prior to Cordilleran glaciation?
- When did the Bering Straits first open up and how did that affect regional climate and circulation?
- Can we document Miocene/Pliocene and Quaternary glacial and marine events in the Gulf of Alaska? How do these correlate to terrestrial records?
- How have the oceanic circulation patterns in the Gulf of Alaska changed throughout the Neogene? When did the Alaskan gyre develop and how has it evolved? What regional oceanic currents existed during the LGM and other glacial maxima?
- How have the dynamics of the Pacific storm track changed during the Quaternary, and what are the implications for the hydrologic cycle in western North America?
- To what degree has fresh water flux to the Gulf of Alaska varied during the Neogene? How did Cordilleran glaciation influence runoff? How did uplift of the southern Alaskan Orogen influence fresh water input? What role does runoff/freshwater discharge play in the N. Pacific climate system?
- Does surface water in the marine realm reflect a $\delta^{18}O$ signal of local glacial growth and decay?
- How has the deep circulation of the northern North Pacific varied during the Quaternary? Is there evidence for formation of North Pacific deep water? Did influx of fresh water from the uplifted Chugach/St. Elias Mountains influence circulation of the north Pacific?
- How have Alaskan glaciers contributed to global ice budget and sea level over the last 6 Ma?
- How have interdecadal modes of variability affected the climate of the Gulf of Alaska region during the Holocene? What is the stationarity of PDO/ENSO scale climate variabilities and when did they start in the Gulf of Alaska?
- What climatic factors are the Alaskan ice fields sensitive to? Do Alaskan glaciers respond to Milancovich orbital forcing? Pacific-rim volcanism? Gulf of Alaska uplift and moisture trapping? Was glaciation sustained or pulsed?
- What is the response of Alaskan glaciers to PDO/ENSO forcing? Do Alaskan glacial advances and retreats correspond to Holocene climate oscillations?
- Are the occurrence of PDO and conceivably ENSO modulation of PDO definable in glacial outwash deposits?
- What is the evidence for rapid glacial-interglacial and interstadial climate change in the Gulf of Alaska? How did the Younger Dryas and DO events affect the climate around the Gulf of Alaska?
- Is the early Holocene climate variability on decadal to century scales similar to or different than late Holocene variability?
- Can the marine/fjord record discern PDO/LIA Holocene glacier fluctuations on decadal/century scales?
- Are there regional climatic responses to glacial activity?

Tectonic

- What are the tectonic driving mechanisms of the Chugach-St. Elias orogen and have they evolved? Is the St. Elias orogen generated by subduction of an oceanic plateau or collision with microcontinental sliver? What are the far-field effects that are coupled with the tectonic driving forces generating the Yakutat collision?
- Where, when, and at what rate does strain accumulate (on 10^0 to 10^7 yr scales)?
- Are there differential rates of exhumation and denudation within the orogen?
- What were the major tectonic events, kinematics and thermal history? What are the timing of the deformation phases?
- What are the dynamics of the mantle and how do they interact with the tectonics? What is the magmatic input from the mantle?
- What are the structures that accommodate the relative motions in 3-D?
- What are the tectonic processes, 3-D effects, and driving forces behind the possible subduction to strike-slip transition?
- How much and what incoming material is transferred to the upper plate? How does the transfer occur?
- To what extent does mass redistribution affect strain localization?
- What is the nature of the Transition Fault? Is it in fact a fault?
- Does the proximity of subduction zone to continental shelf impact glacial isostasy?
- What has happened to the subducting slab and how does this effect current tectonic/ erosional deposition processes?
- What drives Wrangell volcanism? What is the history of volcanism in the Wrangells, how is its chronology/volume/composition related to tectonics, of Yakutat terrane especially? Is increased volcanic activity synchronous with rapid tectonism?
- When and where did initial uplift begin ±1 Ma? When and where did strong uplift occur that led to alpine glaciation?
- What is the mechanical evolution of the plate boundary over the past 10 Ma? Can it be resolved and modeled at a precision of $<10^5$a during the past 2 Ma?
- What is the mechanical response to glacial perturbations, glacial incision, and sediment loading?
- What is the evolution of the thermo-metamorphic field during orogen formation?
- What geodynamic characteristics are unique to glacier-dominated systems?
- What is the degree of crust mantle coupling and how do geomorphic processes influence this?
- What crust and mantle deformation occur at velocity corners during accretion? What are the driving forces?
- What is the pressure-temperature history of the rocks within the orogen? What is/was the relationship between topography and thermal structure of the upper crust?
- How does deformation evolve in space and time? How much shortening occurs in the upper plate and what are rates of shortening? Have shortening rates changed with time? Is strain partitioned between strike- and dip-slip faults?
- Can a volcanic signal be identified in the palynological and/or isotopic climate proxies?
- How can margin strata be used to constrain timing of uplift of various lithologic units within Yakutat/North America collision zone?

- What do cooling ages from multiple thermochronometers indicate about particle trajectories and P/T conditions in the orogen?
- Can topographic evolution be inverted from low-T thermochronometers?
- What unroofing history is indicated by detrital cooling ages? Do thermochronometric cooling ages vary as a function of climate change over the Pliocene?
- What grade metamorphic rocks are exposed at the surface and from what depths are these rocks exhumed? How does metamorphic grade change spatially within the orogen?
- What is the present geothermal gradient? What unroofing history is indicated by sediment petrology?
- What other mechanisms could initiate mass-flow or gravity-flow processes?

Interplay of Climate and Tectonics

- How have the atmospheric, marine, and surficial processes co-evolved with the formation of the Chugach-St. Elias Mountains?
- How and when did orogeny block passage of the Pacific air mass to interior Alaska?
- Can tectonic uplift be inferred from proxy data reflecting the formation of a rain shadow cast by the Alaska Range?
- What temporal and spatial variations of climate are required to get a coupled tectonic and climatic system? What are the feedbacks within this coupled tectonic and climatic system? What are the temporal and spatial scales of cooperation among climatic and tectonic processes and at what scale can they be resolved?
- What is the spatial and temporal history of glaciation and glacial erosion in southeast Alaska in the context of active orogenesis?
- Where and when is glacial erosion occurring and what is the interaction between uplift and erosion? What are the relative contributions of hillslope and glacial denudation?
- What is the evolution of topography throughout the St. Elias orogen through the Neogene?
- What is the tectonically-driven mass flux into and out of the orogen? Is there any long term crustal thickening and/or accretion? How are tectonic and erosional fluxes grossly balanced through the interrelationships among glacial processes, landscape evolution, crustal deformation, and geodynamics? What are the pathways and mechanisms of sediment transfer from land to sea?
- What are the timing, distribution, and rate of exhumation?
- In a glacial environment, what are solute fluxes and what are their effect on carbon dioxide and carbon cycling?
- How deep do geodynamic effects extend relative to the spatial/temporal distribution of glaciers?
- Do strain localizations determine glacier locations or do glacier locations determine strain localizations?
- At what temporal and spatial scales does southern Alaskan orogenesis influence regional and hemispheric climate? How do major global climate fluctuations influence southern Alaskan orogenesis?
- How has uplift influenced the Aleutian low-pressure atmospheric system and local precipitation patterns?

- What is the timing of major changes in depositional facies observed in the Yakataga formation and Surveyor Fan? How have sediment sources changed with time?
- What are the sediment budgets of the continental margin basins and Surveyor fan during the Neogene? How do glacial-interglacial cycles affect them? At what time-scale do sediment accumulation rates balance long-term denudation rates? How much sediment shed from the orogen is lost due to subduction or transport out of the Gulf of the Alaska?
- What processes and geodynamic conditions create accommodation space on the Yakutat margin?
- How do temperate glacier-ocean interactions form margin-scale strata?
- How and why does the mineralogy and petrology of iceberg-rafted sediments change from Miocene to latest Pleistocene and Holocene?
- What is the role of the Bering Strait in controlling the fresh-water budget and water temperatures in the Gulf of Alaska?
- What change occurred in the volume of freshwater runoff to the Gulf of the Alaska due to southern Alaskan orogenesis? Was there a thermohaline circulation response in the north Pacific?
- What is the timing of activity in Meiji tongue relative to Alaskan uplift? Is freshwater trapping in the Gulf of the Alaska a control of North Pacific deep-water sources and formation?
- Do mega channels similar to those seen in upper Yakataga Fm occur in offshore sediment packages? How did these form? What are controls on their formation?

Education and Outreach

- What learning module or modules can we create to summarize what we know and what we want to know? (These will be online materials submitted to DLESE.)
- What groups should be targeted in outreach efforts? Elementary? Middle School? High School? College? General public?
- What products should be generated for outreach? Pamphlets, multimedia products (such as Mountains to Monsoons), exercises?
- Can we create data sets and activities to lead ~7-12 grade students through study of the change in coast region related to changing climate—either short term glacial or ice age scale?
- Can we develop detailed teaching modules describing Gulf of the Alaska glacimarine deposition to be paired with extensive Antarctic examples?
- Can we use Gulf of Alaska as a resource education about fisheries?
- Can we develop opportunities for students (High School) and teachers to be involved in site survey operations?
- Can we provide teachers with materials that can introduce students to Alaska's geologic history?

Key Measurements and Techniques

During the breakout session, group members also were asked to consider scientific methods, key geographic areas for study, and relevant timeframes that could be used to answer the detailed questions that had been raised. This input was then grouped by the Steering Committee after the meeting into the following categories. With contributions by: Jeff Freymueller, Sean Gulick, John Jaeger, Peter Koons, Karl Kreutz, Dan Lawson, Andrew Meigs, Roman Motyka, Eric Osterberg, Gary Pavlis, Terry Pavlis, Ross Powell, and Peter Zeitler.

Tectonics

Previous Seismic Imaging

From the 1950s to early 1980s the Gulf of Alaska region was the site of extensive oil exploration and the USGS Oil and Gas Division, which later became the Minerals Management Service, acquired a significant grid of offshore seismic data during the 1970s to evaluate lease sales related to this exploration effort. At the same time, industry acquired thousands of kilometers of offshore seismic data in the Gulf of Alaska, although unlike the USGS data, these data were acquired exclusively on the shelf to uppermost slope (Fig. 16). A summary of the exploration activity and regional interpretations of the data acquired from these studies can be found in Bruns and Schwab (1983), Plafker (1987), and Risely et al. (1992).

Although the available seismic data have provided critical information on the tectonics of the orogen, these data cannot answer many critical questions that remain within the orogen. The principal limitation of these data include:

1. Limited geographic coverage: Although the public domain data (Fig. 16) extend into deep-water and onto the abyssal plain, the geographic coverage into the deep water segments of the orogen is extremely limited. Large parts of the deep-sea fan complex have not been imaged at all by multichannel seismic reflection profiles, particularly the mid-fan portions of the complex. There is an extensive proprietary seismic database in the shallow water parts of the shelf, particularly between the Kayak Island zone and the Alsek Canyon, but none of these data extend past the upper slope. Moreover, although it is clear that some of these proprietary data are still available (e.g. the University of New Orleans has several of these lines), much of this data set has probably become essentially unrecoverable due to mergers within the oil industry. That is, these data are sufficiently old that most have been archived to remote sites where they are difficult to recover and some data has undoubtedly been corrupted. Thus, although it appears from Figure 16 that there is a large data set on the shelf, in reality only a small fraction of those data are likely to be recoverable to the scientific community.
2. Poor data quality and penetration: Both the public domain data and industry data from the Gulf of Alaska are all relatively low quality seismic data compared to what most modern surveys can produce. This is largely the result of the vintage of the data—late 1960s to late 1970s—when data acquisition systems and seismic sources were primitive compared to modern systems. Thus, the available data all suffer from serious problems with water bottom multiples, poor penetration (typically <4 seconds), and short spreads with relatively low fold (24).

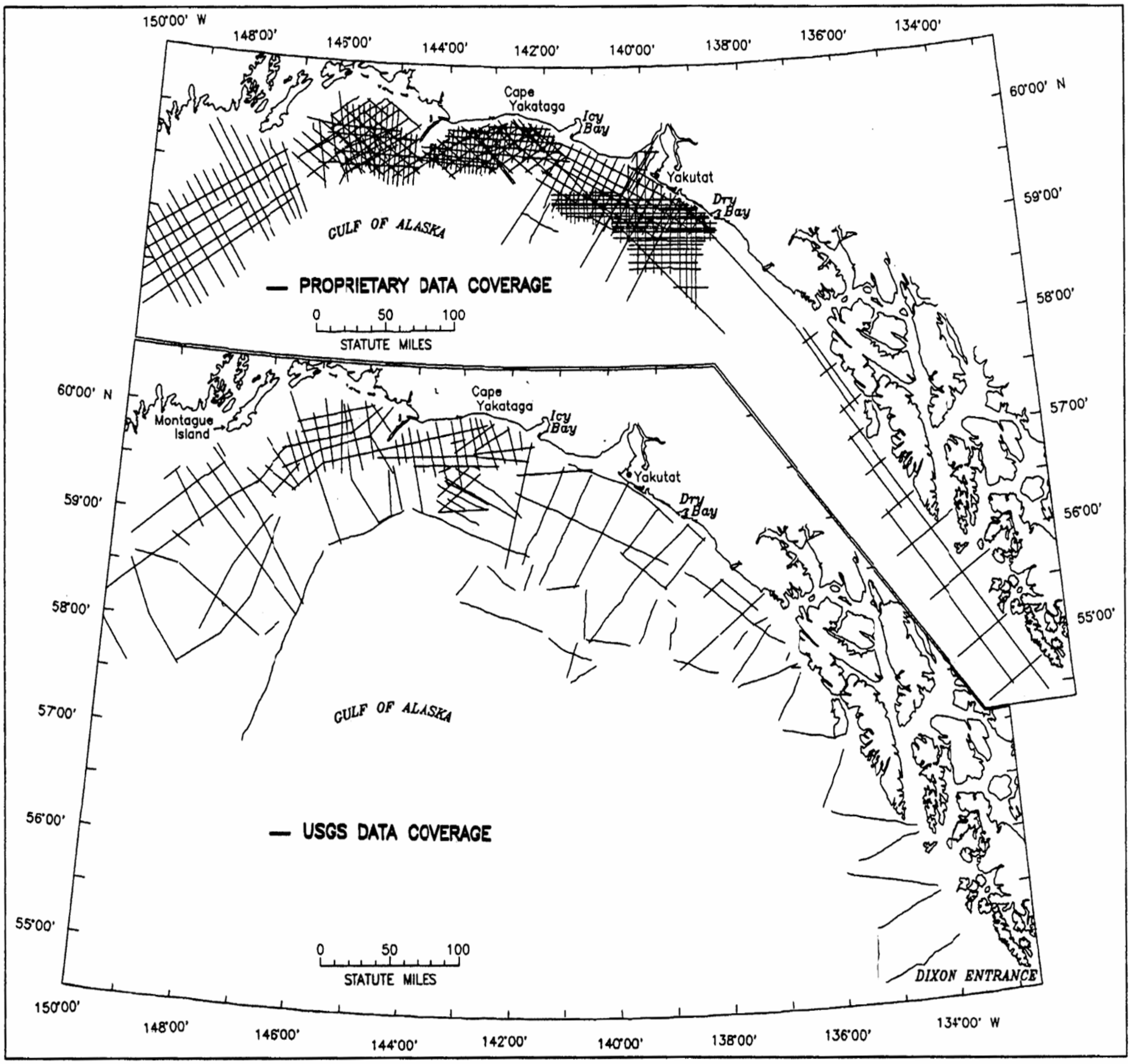


Figure 16. Coverage map of proprietary and USGS multichannel seismic reflection tracklines. See Risely et al. (1992) for listing of industry donors of data. After Risely et al. (1992).

3. Limited coverage in key areas: Finally, although there is broad geographic coverage of the area, there are few seismic lines that actually cross structures or sedimentary dispersal systems that are critical to developing a better understanding of the orogen. For example, terrestrial studies (Bruhn et al., 2004 and Pavlis et al., 2004) suggest that the Kayak Island zone may be one of the most significant structures accommodating the plate motion, yet only two seismic lines cross the structure (Fig. 16). Similarly, the large submarine Surveyor fan complex developed at the base of the continental slope, which is critical to understanding sedimentation during glacial-interglacial cycles as well as tectonic questions, is virtually unknown aside from a few USGS lines that cross the proximal portion of the fan.

Chronology/Long Term Exhumation Rates

Petrological and thermochronological techniques when integrated with structural and geophysical measurements can provide important timing and rate constraints on mass fluxes into and out of the orogen. Although by their very nature such measurements afford imperfect spatial and temporal resolution, their advantage is that they can provide, robust, long-term, and synoptic estimates of fluxes against which estimates made by short-term or direct observation can be compared and understood. These techniques can help elucidate the geodynamics of southern Alaska in three main areas. As might be expected, work in these areas will overlap and reinforce one another.

Geologic context and baseline constraints. The use of the Ar-Ar and U-Pb methods to determine the age and histories of faults, magmatic events, floras, and high-grade terranes is well established and routine. Any geodynamical models of a region require a tectonic framework that includes the ages of rock and structural units and the timing and rates of processes such as faulting, rock uplift, and extensional collapse. In addition, petrological estimates of P-T conditions, together with judicious use of a suite of thermochronometers, constitute another key constraint on particle paths through an orogen. Moreover, such data can be used to calculate the overall amount of sediment likely to have been shed off the orogen, clearly a first-order observation that needs to be reconciled with geophysical data collected offshore.

Longer-term exhumation history via thermochronology. U-Th/He dating on apatite and zircon, Ar-Ar dating of K-feldspar, and Ar-Ar dating of micas can be used to look at patterns and rates of exhumation-induced cooling in rocks of even relatively low metamorphic grade, as these techniques address the temperature range 70 ˚C though 350 ˚C. Again, these are all well-established techniques. The greatest challenge in applying them to southern Alaska will be obtaining sufficient sample density of sufficient quality.

There is a developing consensus in the thermochronology community that in an area such as southern Alaska, the 3D problem must be addressed, particularly for the lower-temperature systems whose closure isotherms occur at depths that are significantly affected by the topography. While this effect of topography is a complex problem that incorporates coupled evolution of both the landscape as well as the subsurface temperature field, a well-designed sampling program holds out hope of addressing issues such as the evolution of topographic relief and possible feedbacks between crustal deformation and erosion. What is required for each dating scheme is a sampling density that does not alias the thermochronological signal; for higher-temperature (thus deeper) systems, geological features such as active shear zones are most significant, whereas for systems such as U-Th/He dating of apatite, the critical sampling frequency is determined by the nature of vertical age gradients and the characteristic wavelengths of topography that couple with the ~70 ˚C isotherm.

It is important to keep in mind that thermochronometers only give information about thermal history, and attempts to estimate mass fluxes from such data are perilous in the absence of significant geological constraints and constraints on the thermal field. This area is one in which petrological work can be very useful, by providing at least an approximate portrait of the region's thermal evolution. Fluid-inclusion measurements on veins are a particularly valuable in providing P-T estimates, which if reasonably well dated, can provide at least one snapshot of the shallow geotherm.

Detrital thermochronology. Even a detailed bedrock sampling program using many dating methods cannot completely constrain the evolution of an orogen because one is generally limited to sampling the topographic surface, and much of the long-term record has been stripped away. A great advantage of the Chugach/St. Elias system is that this material has not been lost, but simply relocated. If it becomes possible to obtain well-dated sedimentary cores through a drilling program, it would be possible to carry out thermochronological studies on detrital minerals and paleomagnetic measurements on rock to learn something about provenance and bedrock evolution at earlier time periods. Of particular note, P. Reiners at Yale University has had success in determining, on single zircons, both U-Pb ages and U-Th/He ages (closure temperature about 200 ˚C). Because the source region for Gulf of Alaska sediments is reasonably well constrained, if one knows something about the bedrock currently exposed within the orogen, it would be possible to use the U-Pb ages on detrital zircons to locate the grains' origins, and the U-Th/He ages to learn something about exhumation rates and timing at various stages in the exposure of the orogen.

Pre-collisional Crustal Architecture and Exhumation of Metamorphic Terranes on North America

Much of the older bedrock framework of the interior of the St. Elias orogen is known in only reconnaissance style with geologic mapping at scales of 1:250k or smaller. Thus, as studies of the orogen evolve, there will be a growing need to improve on our understanding of this bedrock framework. For example, any study of orogenic exhumation (see above) ultimately depends on a knowledge of the source terranes contributing to the sedimentary record, and at present parts of this source region are not well understood.

Foremost among these problems that will ultimately be important are structural-metamorphic relationships within the Chugach metamorphic complex. The Chugach metamorphic complex is a high-T, low-P metamorphic belt that formed in the southern Alaskan forearc at least 30m.y. before the St. Elias orogen developed (e.g. Plafker et al., 1994). The unusual high-T metamorphism of the forearc in this region is widely recognized as a consequence of ridge-trench interactions along the Paleogene northern Cordilleran convergent margin (e.g. Sisson et al., 1989, 2003a; Pavlis and Sisson, 2003), and is critical to studies of the St, Elias orogen because these rocks form the North American "backstop" against which the Yakutat terrane was accreted. That is, from the Copper River, through the St. Elias Mountains, southward to Icy Strait rocks of the "Chugach terrane" (Figure 2) are upper greenschist to upper amphibolite facies schist and gneiss that were rapidly heated in the Eocene and quenched by subduction refrigeration in the late Eocene (~48Ma) (e.g. Sisson et al., 1989; 2003b) and it is these rocks that form much of the core of the orogenic highland. This assemblage provides an important baseline for constraining the exhumation in the core of the orogen. Specifically, in the eastern Chugach Mountains, this assemblage is a remarkably uniform low-P metamorphic assemblage with peak pressures less than 400MPa and peak temperatures as high as 650°C (e.g. Sisson et al., 1989). In line with orogenic topography, higher-P assemblages are exposed within the orogen east of Yakutat (Sisson et al., 2003b) and in the Mt. Logan area (V. Sisson, K. Stuwe and T. Pavlis, unpublished data), but details remain poorly resolved. Changes in structural style are also recognized with level of exhumation, and the origin of these variations is not well understood due to large unknown areas. Similarly, garnet amphibolites and gabbroic rocks recognized in the Mt. St. Elias region (K. Stuwe, written communication to T. Pavlis and T. Pavlis, unpublished field observations) may record deep exhumation of this metamorphic complex to the level of gabbroic magmatic underplates beneath the metamorphic complex. Recovering information from these remote sites will be logistically challenging, but may ultimately prove critical to full reconstruction of the orogen.

Modern Displacement Field

Recent work onshore (Bruhn et al., 2004; Pavlis et al., 2004) and offshore (Picornell, 2001; Picornell et al., 2001) on the structure of the orogen indicate that the deformation within the orogen is dispersed through a broad region and there is no single "plate boundary" structure accommodating the bulk of the deformation. This stands in contrast to the region south of Yakutat Bay, where the Queen Charlotte/Fairweather Fault accommodates the great majority of relative plate motion (Fletcher and Freymueller, 2003). If this orogen is to serve as a natural laboratory for understanding tectonic-climate linkages, it will be necessary to clarify exactly how this deformation has evolved in time. From these data we can begin to understand the underlying tectonic processes. Thus, these results underscore the need for new studies that identify not only where the active structures are today, but also how these structures have evolved in time.

One of the most basic data sets needed in the orogen is a further clarification of the modern day movements occurring in the orogen, which can now be routinely accomplished through GPS-based geodetic studies (Fig. 10). Sparse regional data exists within parts of the orogen (e.g. Sauber et al., 1997; Sauber et al., 2000; Fletcher and Freymueller, 2000; Fletcher and Freymueller, 2003), but the present data is too sparse to clearly define the movement field in critical parts of the orogen. The Earthscope Plate Boundary Observatory (PBO) will install only three continuous GPS sites in this region, so it will provide little new data relevant to tectonic studies. New, more densely spaced campaign or continuous GPS networks are needed within the orogen.

Based on geologic observations, available GPS data, and seismicity data the highest priorities for new GPS observation include: 1) the western 1/3 of the orogen and adjacent regions to the west, as available GPS data (Sauber et al., 1997; Freymueller et al., 2000; Zweck et al., 2002) indicate a major change in trend of GPS displacements between Prince William Sound and the central part of the orogen, indicating a critical tectonic transition; 2) local detailed studies across the Bering, Seward, and Hubbard Glacier valleys where they cross the mountain front; sites where geology and seismicity both appear to show active deformation that is poorly understood; 3) the "corner" northeast of Yakutat Bay where the orogen makes a transition from dominantly strike-slip to dominantly convergent; and 4) additional data from the Yakutat area where GPS based displacements (Fletcher and Freymueller, 2000) make predictions that contradict the offshore geology (see above). Also, there is a need in this area east of Yakutat to determine the normal component along the Fairweather fault to help constrain how much material is transferring to the orogen.

Recent advances in airborne altimetry systems (e.g. Haugerud et al., 2003) suggest that these systems may also prove useful in this region of very high tectonic rates. These systems offer the potential opportunity of repeat, high-resolution measurements that could afford a spectacular 4-D perspective on the active tectonic displacement field in this region.

Latest Quaternary-Holocene Displacement Field

Tectonic geomorphology and other active-tectonic techniques (c.f., Burbank and Anderson, 2000; Keller and Pinter, 2002) are proven techniques for unraveling the paleoseismic and Quaternary displacement histories on active faults. The St. Elias Orogen, however, affords some unique opportunities at the same time as unique problems in using these techniques to unravel the most recent tectonic history.

Probably the most important unique opportunity offered by this region is the rich offshore record of active deformation synchronous with rapid sedimentation, which affords the opportunity to use growth strata (e.g. Suppe et al., 1992) to uniquely characterize folding mechanism and displacement rates of young structures (e.g. Picornell, 2001). Using these data it is theoretically possible to have a complete picture of the movement history of offshore faults and fault-related folds, provided there is sufficient high-quality seismic reflection data to constrain fold geometry and drilling of growth-strata to constrain the depositional age of the growth strata. Submersible studies (both manned and unmanned) of surface deformation at the outcrop scale can prove very important for collection of detailed samples where drilling is not feasible. Particular structures that might be target for study by submersibles include the Kayak Island zone, the Pamplona zone, and the Transition fault.

Onshore these types of studies are not possible due to erosional exhumation. Classical tectonic geomorphology and paleoseismology studies thus will be critical to unraveling the young displacement history. These types of studies, however, are handicapped by one critical problem: the orogen was largely buried in glacial ice during the last glacial maximum, and glaciation planed off most of the low-elevation surfaces in the orogenic foreland. Thus, glaciation virtually “wiped the slate clean” in terms of the onshore Quaternary record throughout the area where the orogen appears to contain most of the active deformational structures. As a result, the techniques that can address the pre-Holocene structural evolution in these regions with the most likely success are classic geologic studies that employ an integration of structural geology, stratigraphy, and low-temperature geochronology.

Conversely, the “clean slate” affect may ultimately turn out to be an advantage in unraveling the Holocene displacement history. Specifically, in the area between the Copper River and the Bering Glacier, where Bruhn et al. (2004) and Pavlis et al. (2004) infer significant active deformation, there are spectacular surface manifestations of ongoing movements. These manifestations are surface ruptures of a glacially planed surface in both uplands and lowlands between the Chugach-St. Elias fault (suture) and the coast. Plafker (pers. comm.) has interpreted most of these surface ruptures as sackung, which are surface ruptures produced by gravitational failure of steep slopes during large accelerations from great earthquakes. This conclusion is clearly consistent with the known seismicity record in that this region was strongly affected by 1964 Great Alaskan earthquake (e.g. Plafker, 1969). Nonetheless, many of these features do not closely mirror topography, and it has been suggested (McCalpin, 1996) that many of these surface ruptures are flexural slip scarps on actively deforming folds. If even partially true, this hypothesis suggests that these features could be used to unravel a detailed picture of deformation rates by folding, which theoretically could be combined with offshore information to further clarify a true 4-D picture of the young deformation.

Obtaining this type of movement picture, however, will require a combination of on-the-ground studies of the surface ruptures, modeling of surface slope stability, and regional remote sensing to clarify the distribution of the surface rupturing. Now the latter could be relatively easily accomplished through airborne laser altimetry studies. Moreover, the ability for modern technology to post-process these data to extract a terrain model below vegetation (e.g. Haugerud et al., 2003) affords a unique opportunity to address this problem in this region where the surface ruptures continue beneath a brush-forest canopy that is virtually unreachable on foot. Also, a detailed paleoseismological record of great earthquakes may exist in turbidites contained in offshore strata.

Neogene Displacement History

To fully understand the evolution of the orogen throughout the Neogene will require new data on the basic structural and stratigraphic evolution of the orogen. Unraveling the 3-D structural geometry can ultimately resolve the longer-term kinematics of the collision and test tectonic models like that proposed by Bruhn et al. (2004) and Pavlis et al. (2004). These types of studies, however, cannot be done strictly as a structural problem because the orogen contains a rich stratigraphic record of syn-orogenic sedimentation in the Yakataga Formation. Indeed, the onshore record, like offshore, contains known examples of growth-strata development on fault-related fold structures as well as angular discordances within syn-orogenic strata in the Samovar Hills (e.g. Bruhn et al., 2004). The recent studies by Ferris et al. (2003) also present an important rationale for new stratigraphic studies of the pre-orogenic strata of the Yakutat Terrane. Undoubtedly there are many other cases that have not yet been recognized. Thus, we suggest that new detailed mapping in conjunction with stratigraphic studies are badly needed to evaluate the long-term evolution of the orogen.

Studies of the long-term evolution of the Yakutat orogen can be aided by new, emerging technology. Detailed geologic studies of this region have been handicapped in the past by access problems including both the difficulty of reaching remote field sites in this, the modern world's large wilderness, and difficulty in accessing rock exposures once you reach a remote site because of extremely steep terrain or dense vegetation. The use of laser altimetry together with high-resolution imaging offers a unique opportunity for geologic studies in this region. Specifically, large cliff exposures could be easily mapped for structural and stratigraphic study using imagery draped on a high-resolution DEM produced by laser altimetry. Indeed, with the resolution of laser altimetry this type of study could, in theory, provide not only a detailed map, but also orientation information using 3-D positions of layers or other surface elements in the rock—i.e. essentially multiple 3-point problem analyses. Thus, a full characterization of 3-D structural geometry and reasonable characterization of 3D stratigraphic architecture could be analyzed in this region by exploiting the large topographic relief.

Crustal Architecture

Key measurements and techniques for examining the crustal architecture involved in the Yakutat microplate collision and the crustal structure that generates and supports the Chugach-St. Elias Mountains include: active and passive seismic imaging and modeling, field geology, seafloor mapping, magneto-tellurics (MT), aerogeophysics, downhole seismometers/strain meters, petrological observations, and fluid regime characterization. These methods include active and passive studies that are important for examining both the current crustal architecture at the surface, near-surface, and crustal-scale depths as well as gaining insight into the deformation history of the margin. Surficial and near-surface studies of active deformation offshore including high-resolution reflection seismology studies, seafloor bathymetry/sidescan sonar, and submersible/ROV surveys of the shelf are necessary to determine the current and recent deformation within the Yakutat microplate. Onshore, geological field mapping is needed for accurately mapping active faulting and basic geologic relationships observable at the surface, while aerogeophysical surveys using ice penetrating radar and LIDAR have great potential for mapping the current morphology, active deformation, and most importantly sub-glacial fault systems. Deformation history of the Chugach-Robinson-St. Elias Mountains may also be gleaned in the examination of the surface petrology in key locations.

At the crustal scale, active seismic reflection imaging via multichannel seismic (MCS) surveys of the shelf and fan is vital to detail the history and patterns of deformation, the nature of the Transition fault, and the changes in crustal architecture across the Pacific to Yakutat plate boundary, the Yakutat to North American plate boundary, and the Pacific to North American plate boundary. In order to examine the architectural changes throughout the collision zone, reflection and refraction studies along onshore-offshore profiles will be required and have great potential at answering several key questions as to the deep architecture of the Yakutat collision. A combined land/marine geophysical and drilling program can be conducted near the Kayak Island zone to document conditions coming into and out of the transition from strike-slip to subduction motion. Aerogeophysical surveys over the orogen provide a highly efficient method for mapping the gravity and magnetic signature of the on-going mountain building and crustal accretion. While MT may be difficult given the logistical considerations of working in the Robinson or Chugach-St. Elias mountains, the data would be highly useful for aiding in the characterization of the mountain-building deformation.

Passive studies within the Gulf of Alaska should include a detailed multi-year deployment of seismometers for recording earthquakes to accurately determine the patterns and magnitude of local seismicity along the plate boundaries and related faulting and to construct 3-D crustal and upper mantle velocity models. IODP drilling in the Gulf of Alaska can provide additional long term monitoring of this dynamic margin to determine the seismic hazards the Yakutat collision represents to southeast Alaska and northwestern Canada. The fluid pressure regime offshore can be observed directly through the deployment of CORK/ACORK borehole technology and detailed seismicity and *in situ* strain data can be collected through the installation of downhole seismometer(s) and strainmeter(s).

Rheology

The characterization of elastic material properties, the surface strain rate pattern, and the metamorphic environment within the corner can lead to a thorough evaluation of the rheological behavior of the subduction zone. The petrological evolution of the balance of buoyancy versus viscosity forces that determines whether crustal material will be dragged down into regions of ultra high metamorphism, should in part be visible through this comprehensive data set. Recent seismic imaging of a thick Low Velocity Zone at depths of 50-150 km associated with earthquake generation (Ferris et al., 2003) provides strong evidence for devolatilisation and high pore pressures within this block. The rheological implications of these observations are significant and provide rather tight constraints for mechanical calculations on slab-crust coupling. These observations should help constrain the role of mineral kinetics in shifting this force balance through, for instance, devolatilization of crustal or upper mantle rocks during the formation of eclogite assemblages (Abers, 2000; Hacker et al., 2003).

Mantle Architecture and Kinematics

The driving force for deformation in southeastern Alaska is well understood to be related to the general processes of plate tectonics. The wide-ranging framework is known, but because this area is so remote and logistics are so difficult, there remain a number of unanswered first-order questions about the role of the mantle in the tectonic framework:

1. What is the actual geometry of the subduction system in this corner? It is unquestionably a three-dimensional geometry, but the details are ambiguous.
2. How does the subduction process impact the deformation? It is not certain if the mantle contributes to uplift or dampens it.
3. How are the Wrangell volcanics related to the subduction process? Is there a continuous slab dipping beneath the Wrangells and connected to the Yakutat microplate? Does subduction of an oceanic plateau affect these magmatic processes?
4. How is internal deformation of the Yakutat block related to variations in mantle properties below or near it? Is the mantle driving the system or simply a passive element in being driven by remote forces?

The best tool for addressing these questions is modern, passive array seismology. No other technique can provide 3D images at the scale (laterally and vertically) and resolution required to answer questions on the coupling of surface and mantle processes. Numerous examples in the past decade have demonstrated the capabilities of this technology. The best results have been obtained by multifaceted analysis tools applied to the same basic data. This includes relatively standard P and S wave tomography, shear-wave splitting, and receiver function inversions. The technology is expanding rapidly, however, to newer forms of 3D converted wave imaging that promise to provide higher resolution images of the lower crust and upper mantle though the base of the transition zone. With the deployment of USArray as part of Earthscope, imaging technologies and our ability to make geologic sense of the results is nearly certain to improve dramatically. However, t will be at least a decade before the USArray will be deployed in Alaska. The USArray will eventually provide a comprehensive framework for the structure of all of Alaska at a resolution scale comparable to that it will achieve in the lower 48 states. Between that time and now numerous experiments can and should be considered for more focused deployments on specific tectonic targets in the region.

Climate

Present Climate

Recent climate research in the North Pacific Ocean has documented the importance of the Aleutian Low Pressure System in the regional and northern hemispheric climate. Detailed studies of the present Gulf of Alaska climate have been impaired in the past by access problems including the difficulty of maintaining enough meteorological stations, either automated or manned, to capture the diverse microclimates of the region. Several key measurements that can be instituted to better describe the modern Gulf climate include:

- Automatic Weather Stations positioned to monitor both synoptic-scale weather and locally influenced weather. These would ideally include sensors for: temperature, atmospheric pressure, humidity, wind speed and direction, snow accumulation rate (when placed on glaciers) and incoming short-wave radiation.
- Mass balance poles on glaciers that can be monitored annually to determine accumulation vs. melting rate
- Remote sensing: using airborne laser altimetry for glacier mass balance studies or synthetic aperture radar from satellites to determine snow wetness (melting).

As expected, the regional climate has a very strong influence on the physical oceanography in the Gulf (Weingartner et al., 2002). To better understand the proxy records of climate contained in coastal marine strata, the coupling between climate forcing and the physical oceanography is needed. Global climate datasets, such as the NCEP/NCAR reanalysis, have been downscaled using mesoscale meteorological models (such as the PSU/NCAR MM5 model) to force regional and Gulf of Alaska ocean models (Hermann et al., 2002), and the results agree favorably with ship-based, remotely sensed, and drifter studies of upper-water column circulation and temperature/salinity.

Late Pleistocene-Holocene

The climate of Alaska and the northeastern Pacific Ocean appears to respond to Holocene climate change, such as the transition from a warm, early Holocene (i.e., Hypsithermal period) to the colder late Holocene Neoglacial period, which includes the Little Ice Age. This Holocene climate change record has been established through a combination of climate proxy measures made from ice core records from Mt. Logan, tree-ring studies from around the Gulf, and paleoceanic and paleolake and glacial records. To better reconstruct North Pacific Holocene climate variability, the multi-proxy approach needs to be advanced in order to adequately capture the lateral and vertical spatial variability associated with such a broad area covering >6 km of elevation. To further address some of the outstanding climate questions raised in the workshop, the following key measurements were suggested.

Ice cores from the St. Elias Range best capture changes in upper-tropospheric climate change in the region (Moore et al., 2003). Measurements on ice cores from this area include:

- Ice density
- Visual ice stratigraphy (melt lenses)

- Ice accumulation rates once annual dating is done
- Glaciochemical analyses (for climate proxies AND dating): major ions (using ion chromatography), trace elements (using ICP-MS or similar), oxygen isotope ratios
- Beta activity levels (to find 1950s-60s bomb horizons for dating)

Ice cores have been sampled and analyzed for major ions (Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, SO_4^{2-}, MSA), trace elements (Al, Fe, Zn, Pb, Cd, Cu, Co, Ti, Ba, Cr, Sr, V, U, Cs, Mn, As, Se, REE suite), volcanic tephra, and oxygen isotope ratios ($\delta^{18}O$, δD). Using analytical techniques developed by Meeker and Mayewski (2002), the major ion, trace element and isotopic time series will be calibrated with overlapping instrumental records to produce environmental proxy records stretching well beyond the instrumental record. Preliminary analyses of $\delta^{18}O$ data suggests that the PR Col glacichemical record extends through the Holocene and possibly into the last deglaciation, with the King Col and Eclipse Dome cores covering the late Holocene (D. Fisher, personal communication). With a vertical sample resolution of 1-2 cm, annual sample resolution (≥6 samples/year) is expected from 0-2000 y.b.p., with multi-annual to centennial resolution for the remainder of the Holocene (Yalcin and Wake, 2001; Wake et al., 2002).

Because climate oscillations are associated with intensification and weakening of atmospheric pressure centers (e.g., Aleutian Low, North Pacific High), St. Elias glacichemical time series can be used as proxy records to reconstruct the history of rapid climate oscillations in the North Pacific and Northern Hemisphere prior to the instrumental record. In addition, trace metal and REE data can be used to distinguish marine, continental, volcanic and anthropogenic chemical constituents, identify tephra source composition (e.g. mafic vs. felsic), determine the environmental conditions at source regions (e.g. wet vs. dry), and elucidate transport processes (Hinkley, 1993, 1994; Hong et al., 1996; Van de Velde et al., 1998; Kreutz and Sholkovitz, 2000). Precipitation oxygen isotope ratios can provide air temperature proxies and moisture source information, and may be a proxy for tropospheric stratification at the PR Col summit site (Holdsworth et al., 1991). In addition, comparison of the St. Elias ice-core records to similarly resolved records from Greenland (GISP II) and Antarctica (Siple Dome) may reveal global-scale variability in the timing and intensity of centennial (e.g., Little Ice Age) to millennial climate shifts, which may provide further evidence of their forcing mechanisms (cf. Meeker and Mayewski, 2002).

To better investigate such rapid Holocene ocean-atmosphere oscillations and forcing mechanisms (e.g., solar output, ocean and atmospheric circulation), proxy climate records from lower altitudes are needed that can be compared to upper-tropospheric St. Elias ice cores. Examples include tree-ring studies and cores from high-resolution Gulf of Alaska marine settings and paleolimnological studies from the windward and leeward sides of the Chugach St. Elias range. Tree-ring studies covering the past several hundred years have provided proxy measures of precipitation and temperature that compare well to instrumental records and ice-core records. Additional tree-ring studies from Glacier Bay and other coastal gulf localities are underway and may provide temporal coverage of the entire Holocene. Mapping and dating glacial moraines, which have proven invaluable in describing terrestrial glacial dynamics throughout the Holocene (Barclay et al., 2001) should continue. Lacustrine paleoecologic and sediment geochemical records (stable carbon and nitrogen isotopes, elemental carbon and nitrogen concentrations) have proven useful in establishing millennial-scale climate change of the Gulf region (Anderson et al., 2001; Finney et al., 2002; Gregory-Eaves et al., 2003; Heusser et al., 1985; Kaufman et al., 2003), although the number of such studies is small due to difficulty in accessing many of the lakes in the region, which are remote. Also, Neoglacial ice advances have covered many of the lakes over the past 3 ka, limiting their respective length of record. Evaluation of the proxy records of climate contained in Gulf of Alaska marine sediments is in its infancy. Key measurements of marine strata sampled through piston coring and ocean drilling should include standard sedimentological (texture, sedimentary structures, provenance), geochemical (opal, bulk organic matter, compound specific stable isotopes, organic biomarkers, etc.) integrated with multi-proxy paleoecology data sets (e.g., foraminifera, diatom, radiolarian, palynology, ichnology). Time-series palynological data require sites with relatively high organic content, such as offshore basins or organic-rich fjords. Paleotemperature and paleosalinity proxies (e.g., $\delta^{18}O$ of planktonic organisms, Mg/Ca, alkenones) are key to addressing climate-induced changes in precipitation, runoff, and glacial melting. Chronologies can be established through ^{14}C-dating, paleosecular variations in sediments, and tephrachronology, all of which will be necessary to allow for correlations among cores and with terrestrial records.

The stratal architecture of fjords and the continental shelf also can be used to explore climate-induced changes in glacial dynamics, sediment production, transport, and accumulation. Although the U.S. Geological Survey explored the geometry of the fjord and shelf strata in the 1970s, a new generation of geophysical studies (e.g., swath bathymetry, high-resolution seismic reflection profiles) is needed to better resolve the stratal architecture on spatial scales comparable to coring. Major climate-induced changes in the stratal record can be evaluated using a combination of numerical glacial and sediment facies modeling forced by regional and global climate models to create stratal models that can be compared to conceptual glacimarine sequence stratigraphic models developed for tectonically active temperate glacial systems in forearc fjord basins (Powell, 1981) and on the continental shelf/slope (Powell and Cooper, 2002).

Neogene to Quaternary

To understand fully Neogene to Quarternary climate/tectonic interaction in the south-central to interior Alaska it will be important to study both offshore and onshore sequences. The climate record in the Gulf of Alaska over the past 10 Ma can be determined for the large part through detailed examination of the offshore sediment record and strata of equivalent age that crops out onshore in southern Alaska. The size of this mini-orogen makes the offshore record a tractable problem that can be solved through imaging of the shelf and deep-sea fan with crustal scale MCS techniques, drilling the shelf and fan deposits, and modeling the suite of glacial, climatic, and sedimentary processes. Key moments in the history of the region are: 1) the onset of topographic relief and valley glaciation, 2) the timeframe over which this sparse alpine style glaciation coalesced into the beginnings of the Cordilleran Ice Sheet; and 3) Cordilleran ice sheet on the shelf in LGM or through several cycles. The prominent changes in physical properties from marine hemipelagic-pelagic sediments to glacial diamicitites should generate prominent reflections in seismic data, which are seen in DSDP Site 178. Mapping these reflections that are sampled by IODP drilling is vital to understand the magnitude and extent these climatic events and their sedimentary products. Examination of the IODP drillcores using paleoecological, paleoceanographic, paleoclimatologic techniques and comparing these marine proxies with information of the industry wells on the shelf and the onshore stratigraphy is equally vital for understanding the forcings of these significant changes in climate history. Lastly, it will be important to understand the linkages among the climatic forcing, glacial erosion, and sediment dispersal and deposition of the resulting eroded material through detailed modeling to understand how the glacial, climatic, and sedimentary processes combined throughout the Neogene to generate the phenomenal sedimentary record within the Gulf of Alaska.

Specific continental margin areas that could be targeted for focused studies of Neogene climate change include the Glacier Bay/Cross Sound and the Bering Trough margins (coastal plain to fan) (Fig. 1). Both of these regions may be focal points of Cordilleran Ice sheet dynamics, as indicated by exceptionally thick (>1 km) Neogene (?)-age deposits that have accumulated on the slope and rise seaward of these features (Stevenson and Embley, 1987, Dobson et al, 1998). They are likely to have been areas fed by convergent ice flow feeding major outlet glaciers or perhaps fast-flowing ice streams. DSDP Site 178 reveals that distal Surveyor Fan sites will also contain a high-resolution record of Neogene climate. Additional areas to examine include outcrops in the Cook Inlet region, where regional Pliocene glaciation may have originated, a drilling site between 145°-148° W and 49° -51° N, and a depth transect of drilling sites in the Emperor Seamounts building on ODP Leg 145. Consideration should be given to modifications of logging techniques that are needed to deal with unique mineralogies, such as rock flour. These can be modeled along the prior successful Cape Roberts Project and newly established ANDRILL (Antarctic Geological Drilling Program) in Antarctica.

The onshore climate research can best be established by comparing paleobotanical data from the windward and leeward sides of the Alaska Range. Neogene deposits mapped by Wahrhaftig et al. (1969) and Wolfe et al. (1966) have provided a rich paleobotanical record and some radiometric dates. At Cook Inlet and north of the Alaska Range at Nenana all these deposits are pollen rich, and further dating may be possible using ash horizons. A palynological transect in Neogene deposits from near Homer (~60^{o}N) on the coast to Nenana (~65^{o}N) in the interior records development of a rain shadow across the Alaska Range. Studying the long USGS core at Fort Yukon would allow us to extend this transect even farther north (~67^{o}N), as far back in time as mid Miocene (15 Ma).

Interplay

<u>Interplay of Climate and Tectonics-Material Fluxes</u>

The Gulf of Alaska is an ideal natural laboratory for the study of tectonic and glacial and climatic processes because it is a mini-orogeny that allows for the study of the interplay of these processes and their interactions at a tractable scale. One of the benefits of a reduced spatial scale and a relatively confined and closed source-to-sink depositional system is there is little lag in sediment production (erosion) and deposition, which allows for better constraints on material fluxes through the margin as a consequence of orogenesis under a glacial climate. As mentioned during the workshop, one of the most important measurements for developing robust geodynamic models is quantifying the flux into and out of the orogen, including volumes and timing, since the beginning of uplift. Key measurements for examining these material fluxes include:

- Quantification and partitioning of denudation processes (e.g., glacial abrasion and plucking, landslides, fluvial incision, etc.)
- Spatial correlation of active tectonic structures and erosion
- Terrestrial sediment storativity, sediment transport, and dispersal rates

- Marine sediment storativity, sediment transport, and dispersal rates. The continental shelf has a series of catchment basins that trap for a while and which may the fill and spill over time.
- Identification of marine depocenters in space and time, including documenting sediment accumulation rates and volumes of glacimarine sediment
- Determine the timing of changes in sediment accumulation rates and facies at major time intervals: the initiation of significant uplift; the initiation of significant glaciation; glacial/interglacial cycles.
- Palynological determination of vegetation and Neogene climate differences on the windward versus leeward sides of the Alaska Range, for pre-orogen compared to post-orogen times.
- Fundamentally, three key techniques/approaches were suggested for making these physical measurements:
- high-resolution and multi-channel seismic reflection studies to identify major sediment distribution pathways and depocenters
- drilling of major shelf, slope, basin depocenters once geophysical surveys are completed
- modeling of climate/glacial/sediment dynamics

New geophysical data are needed that can resolve the geometry of units in offshore strata at vertical scales of 100s of meters. One area of high priority is the Bering Trough area to slope/rise using high- and intermediate-resolution seismic surveys to map all sediment packages for flux measurements over a glacial cycle. Also, it may be possible to use the Little Ice Age as a well constrained mini-glacial to address climate/tectonic erosion mechanisms associated with the Bering Glacier. Also, an MCS transect across the Yakutat block is needed that images the entire sediment package and oceanic crust-mantle. Seismic reflection acquisition may include either a series of long 2-D profiles or a swath of 3-D data. Well-dated, long sediment cores that penetrate ~1 km with high recovery are absolutely critical to providing age control on prominent seismic reflections, thereby determining the sediment flux into marine basins, from fjords to the Surveyor Fan.

Results from drilling should give indications of whether the Holocene interglacial is similar or not to previous interglacials. To tie the marine and terrestrial records, it will be crucial to correlate marine chronology methods with onshore dating and to establish robust provenance techniques to identify sources and sinks of sediment. Sediment provenance can be used as a proxy for the magnitude of uplift in source terranes. Sediment fluxes through time can be addressed via integrated terrigenous source fingerprinting (onshore) and analysis of sinks. Some of the suggested provenance tools include: magnetic susceptibility; clay mineralogy as a proxy for terrain vs. hot/icehouse weathering; detrital zircons-shrimp; vitrinite reflectance; heavy mineral suites; geochemical analysis of sediments, such as long-lived radioisotopes (U-Th-K) and REE; and new sediment provenance techniques for rock-flour dominant systems. Finally, an integrated modeling approach was suggested to bring together the diverse flux measurements. Global circulation models and regional climate models can force glacial models. Glacial models in turn can be integrated with sediment dynamic models to examine margin strata formation over glacial and tectonic time scales, and these mass fluxes can be used within geodynamic models to evaluate the lithospheric response to the transfer of mass through time.

Landscape and Seafloor Evolution

In order to determine the true evolution of the landscape and seafloor through the orogen's history, accurate topographic and bathymetric measurements are needed. The best currently available topography the covers the whole study are 30 m digital elevation models (DEMs) available from the USGS, but digitized from old topographic maps and of low accuracy. The high-accuracy 90 m SRTM DEM only covers the area south of 60 °N latitude and therefore for the Gulf of Alaska only cover the coastal areas. Improved topographic information from satellite or airborne measurements would be useful to tying into higher resolution field studies. The best currently available bathymetry covering the entire Gulf region is the ETOPO2 dataset (Smith and Sandwell, 1997), which has only a 2 km grid spacing, and is available through NOAA's National Geophysical Data Center (NGDC). There are individual coastal regions and fjords that have better coverage and higher resolution but these have not been compiled into a usable bathymetric dataset. Higher resolution bathymetric and sidescan datasets are necessary for adequately determining the subsurface seafloor of today. Submersible field operations to examine key structural features on the seafloor also will require higher accuracy bathymetric data as well as sidescan surveys.

Glacial Isostacy and Tectonics

As discussed in the background sections above, the sedimentary record of the southern Alaskan margin is a result of interactions amongst several intrinsic and extrinsic forcing variables. These include: sedimentary systems (glacial advances and retreats, types of glacial systems and their termini, types of paraglacial systems, rates and styles of sediment delivery to the sea, continental marine morphology, marine dispersal and redepositional processes), glacial and sediment isostatic loading, local and regional tectonic movements, eustasy and climate. In addition, differences in rates, magnitudes and relative timing of changes in each of these variables need to be resolved in order to establish the main drivers and responders to intrinsically or extrinsically forced changes. These factors are the main controls of not only sediment accommodation space on the margin, but also mean that if we can obtain the appropriate proxy data for constraining each of the factors, then we have a strong database on which to test leads, lags and consequences in the system. Modeling can carry us the next step to help constrain feedbacks within the system and provide hypothesis and predictions to test.

Key measurements for constraining these variables for sedimentary systems include those discussed for crustal architecture. However, also critical are determining proxies for water depth (e.g., sedimentary facies analysis, paleoecology) within the sedimentary successions in order to help resolve causes of relative sea-level change. Variables that result in crustal motion (isostacy and tectonics) need to be constrained using a variety of data (e.g. modern and paleoseismology, GPS, LIDAR). Eustasy can only be resolved in differences evident after constraining the other variables of local crustal motion and water depth changes. For Holocene time, local crustal motion studies as well as global sea-level records can be used for this purpose. For the older record sequence stratigraphic approaches can use with the proviso that the other variables are constrained, but again global proxy records will need to be used. Climatic forcing may be constrained by as many paleoclimatic proxies from the marine, land and lake sedimentary records as possible.

Modeling

Because of time limitations, workshop participants interested in modeling issues focused on establishing appropriate time and spatial boundary conditions and addressed scaling issues rather than detailed discussion on integration of models. These recommendations were presented to the marine and terrestrial groups for discussion and a consensus was reached on the following temporal and spatial scales of interest:

Scaling: Temporal

- Tectonic-Climatic scale ~ 10^7 a
- Paleomagnetic scale ~10^6 a
- Neogene pollen studies~ 10^6 a – 10^5 a
- Thermal scale (for x_t = 1 km) ~10^5a
- Orbital Climate Forcing ~10^5a -10^4 a
- Elastic strain accumulation ~10^3 a
- Viscoelastic recovery ~10^3 –10 a
- Rapid Climate Change (e.g., LIA) ~10^2 a
- Geodetic measurements ~10 a
- North Pacific Climate Patterns (e.g., PDO, ENSO) ~10^1a –10^0 a
- Co-seismic release~ 10^{-7}a

It was also discussed that tectonic/climate interactions may converge at <100 ka time-scales, and erosion and deposition should balance on a short time scale, ~10^5a –10^6 a, although it was agreed that models should strive to resolve the interaction at higher temporal resolution/shorter time scale, ~10-50 ka. Over these converging time scales, it was discussed that temporal precision could be <5 ka with marine techniques, although temporal precision using thermochronometers would be much longer, >10^5 a. Temporal resolution of climate forcing will depend upon the time scale of interest and the climate proxy used, ranging from monthly for last 100 years (meteorological), annual for past several hundred (tree rings, ice cores, varved sediments), 10^2 a for LGM, and 10^3 a for the Quaternary.

Scaling: Spatial

- Spatial scale from Global Circulation Models to weather stations
- Regional model must match scale of kinematic constraints and extend to beyond Denali fault in north, east of Logan in east and > 1 lithospheric thickness to the west of the Transition Fault. (1000 km x 1000 km)
- Vertical axis should extend into aesthenosphere to test role of mantle strain
- Spatial resolution must be capable of carrying the physics of incision and deposition at 1- 2 km scale
- Vertical resolution must match thermal, metamorphic and structural observations: ~ 1 km
- Metamorphic geobarometry resolution equivalence +/- 3 km
- Metamorphic geothermometry resolution equivalence ~ 2 km

- Low temperature geochronology resolution equivalence ~ 0.5 km
- Surface processes: Glacial erosion observation and modeling scale of ~ glacier thickness (~100 m). Scaling relationships are unclear as of now.
- Glaciaological models need to be basin-scale rather than ice-sheet-scale as most GCM-driven models are at present.

Orogen Evolution: Surface process modeling

Additional time was spent developing a conceptual framework for a holistic surficial processes model for the region, which should include the following:

- For the tectonic model: measurements of thermal properties, strain rates, velocities, rheologies, anisotropy
- Climate system pertinent to glacial mass balance: Precipitation, Temperature with appropriate orographic forcing and with proper attention to long term variation in mean (regional) climate
- Comparing climate models for times before and after uplift of the St. Elias and Alaska Ranges
- Glacial dynamics and extent (internal deformation and sliding)
- Description of glacial erosion and transport rates as a function of time (hence climate) and space
- Attention to differences in erosion and sediment evacuation among glaciers of different sizes and types (tidal vs. alpine; cold vs. temperate), including response times to climate (order of 100 years).
- Terrestrial sediment delivery system (if not directly delivered to the ocean): Fluvial transport system/ hillslopes above glaciers.
- Marine sediment delivery systems: hypopycnal and hyperpycnal flows, iceberg rafting, shelf dispersal processes and patterns, deposition patterns on fan
- Storage systems. Fluvial basins, continental shelf, deltas, fans; Erosion of and deposition in fjords and on continental shelf

Opportunities for Education and Outreach

Existing Programs

The Gulf of Alaska is both an ideal laboratory for understanding the interplay of tectonics and and climate and a natural classroom for demonstrating the variety of dynamic processes to scientists and the public. Wrangell-St. Elias National Park and the Gulf of Alaska Ecosystem Monitoring and Research Program (GEM) and their partners provide opportunities for outreach and education.

Wrangell-St. Elias National Park and Preserve located within the Chugach-St. Elias study area has exceptional opportunities to reach a wide sector of the local and general public. Wrangell-St. Elias National Park and Preserve is part of a 9,838,650 hectare World Heritage Site; among the largest protected areas on earth..The park has a visitor center in Copper Center, Alaska that receives approximately 18,000 visitors annually. The exhibits and the park movie feature the unique geology and physical resources of the park. The Park has one Education Specialist and two Park Interpreters dedicated to outreach to local schools. These three individuals and other park resource professionals spend time in classrooms and provide local teachers with information and classroom resources. Alaska Park Science is a new semi-annual journal that was developed to connect the public with their national parks and the natural and cultural resources found the unique resources in Alaska's national Parks. Alaska Park Science's website can be found at: http://inside.nps.gov/regions/level2.cfm?lev2=105&rgn=AKR&page=home

Wrangell-St. Elias National Park and Preserve has several partnerships with local organizations that are largely dedicated to Science education and cooperative resource management projects. The Wrangell Mountain Center is primarily a summer college field program, but it also houses researchers and hosts lectures for the community of McCarthy. Wrangell Institute for Science Environment (WISE) is a young organization that has focused on all aspects of science education for local students (both elementary and high school level). WISE has organized field trips for local students and a science lecture series that have been extremely successful. Prince William Sound Community College offers a wide variety of courses and has partnered with the park to present several geology and physical science lectures. The Copper River Watershed Project was formed to protect the Copper River watershed and the salmon resources dependant upon the river. Park staff serve on either the board of directors or on the community council for all of theses organizations.

An additional example of public outreach in the region is through the Gulf of Alaska Ecosystem Monitoring and Research (GEM) program funded by the Exxon Valdez Oil Spill Trustee Council [http://www.evostc.state.ak.us/]. Since its inception, the Exxon Valdez Oil Spill Trustee Council has been committed to public participation and local community involvement in all aspects of the restoration program. As the Gulf of Alaska Ecosystem Monitoring and Research (GEM) program is established over the next decade, the Trustee Council hopes to expand community involvement, use of local and traditional knowledge, public participation, education, and outreach. These will be major components of the Trustee Council's long-term effort to restore and better understand the northern Gulf ecosystem. Examples of community outreach supported trough GEM include: 1) planning and developing the program, 2) guiding the goal and topics of research projects, 3) collecting data and participating in long-term monitoring efforts, 4) providing traditional ecological knowledge, 5) interpreting results in a local context, 6) educating other community members about ongoing research.

New Opportunities

Recommendations to optimize the use of this laboratory for educational outreach are essentially two-fold. First, distribute this information, through a variety of means, to students, educators, scientists, government and industry representatives, and the general public. Second, create opportunities for educators and students to play an active role in the investigations planned for this region.

Disseminating Information: The results of the ongoing investigations outlined in the science plan will be published in scientific journals and will be distributed to students, educators, and the general public through a variety of means including the Internet.

Central website: It is recommended that a central website be created and maintained that highlights all scientific activities identified in the science plan. These would include, but are not limited to, the following:

- Gulf of Alaska State of Knowledge Section – geared toward the public
- Descriptions of ongoing research projects, including links to principal investigator's sites, preliminary results, etc.
- Descriptions of completed research projects outlined in the science plan
- Education – pages for Educators and Students with links to activities and opportunities described below
- Links to IODP, Earthscope, MARGINS and other related programs
- Links to the Alaskan and Canadian National parks
- Video footage of field work
- Educational case study: Hubbard glacier advance and closure provides an ideal field site for students to study the balance between glaciers and political issues of the salmon fishery.

Printed materials: Individual investigators should create printed outreach materials, such as pamphlets, posters, and fact sheets describing their research efforts. These materials should be distributed to schools, libraries, museums, land managers, and research centers where the general public has access.

Opportunities for Students and Educators: Opportunities exist for both active participation in research and for designing activities and grade-appropriate curriculum materials.

Active participation: It is recommended that each team of investigators identify opportunities for active participation by students (K-16) and educators in their research programs. As the nature of the research varies from onshore and offshore fieldwork, to computational modeling, the potential activities for students and educators will also vary. Active participation includes the following:

- Providing berth space for students and teachers on site survey cruises or IODP cruises in the Gulf of Alaska (see below)
- Including students and or educators on onshore field parties
- Monitoring instrumentation for analysis of data such as real-time links between field parties and school computers
- Online, interactive curriculum based opportunities for students to participate in research projects

Curriculum materials: Following the national science standards, science educators should utilize the results of research in the Gulf of Alaska to design grade appropriate activities and curriculum materials. These activities should reflect the interdisciplinary nature of the research efforts in the area. For instance, the ongoing threat to fishing communities near the town of Yakutat by the potential surge of the Hubbard Glacier could form the basis of educational units that could include science, mathematics, social studies, and language arts.

Additional curriculum materials may include:

- CD-ROMs, similar to the those produced by the ODP (e.g. ODP from Gateways to Glaciation)
- Activities designed around simulations produced by researchers modeling tectonic and climatic interactions in the area
- Shipboard activities for students and teachers who participate in seagoing research
- Cross curriculum investigations of environmental problems such as oil spills
- Rock and mineral kits with associated displays and activities, distributed to classrooms, that represent the record of the evolution of the Gulf of Alaska

In summary, education and outreach should be considered an important part of Gulf of Alaska Tectonics and Climate Interactions Program. Researchers in this program will work with science educators, museum and park educators, classroom teachers and students to take advantage of the opportunities presented by research in the Gulf of Alaska.

Implementation Recommendations

Because of the far-reaching scope of the issues raised by participants, it was not possible to create a detailed implementation plan during the two days of the workshop. Instead, a general list of recommended tasks was generated. These recommendations have been grouped into three implementation phases that largely reflect logistical concerns and the need to first address the most glaring gaps in knowledge and data:

PHASE I

- Marine seismic experiments, both high-resolution and regional MCS, need to occur early in order to adequately understand the regional sedimentary budget, examine the offshore tectonic deformation, and plan for an IODP drilling expedition.
- A comprehensive suite of very high-resolution paleoclimate and paleoceanographic studies on jumbo piston cores will establish a series of climate proxies and climatic history to be later extended into the Neogene through ocean drilling.
- GPS array should be installed as soon as possible within any tectonic field program to ensure a sufficiently long period of observation to approach 2 mm a^{-1} precision.
- Existing monitoring surveys of glacial and fluvial monitoring studies should be maintained and expanded to ensure continuity of records in an aim to capture transients in mass flux.
- Expansion of climate monitoring array to construct sufficiently long time series to permit integration of records from high altitude ice core sites to sea level for correlation with mass flux surveys. The linkages with related programs should be cemented.
- Vital to gain access to or copies of existing industry and USGS data; USGS has agreed to make available existing Gulf of Alaska geophysical datasets.
- Establishment of a passive seismic monitoring array to image crustal and upper mantle velocity structure and evaluate seismic hazards.
- A modeling program should be initiated to aid in sampling strategies, to investigate cooperation among systems and to develop numerical strategies for handling the non-linear interactions in the climate-tectonic system.

- Due to the outreach potential of southeast Alaskan science, one recommendation of the workshop is for all future field and laboratory projects to have a strong outreach component from the beginning of the program with websites identified and accessible to K-12 education.
- Maintain a Gulf of Alaska website portraying the ongoing research activities in southeast Alaska for use by geoscientists and the public.
- Establish a GIS database for integration of the emerging datasets which is accessible through the Gulf of Alaska website, and establish housing and long-term storage of data (includes interacting with community databases). The comprehensive database could be built from existing databases at Universities of Florida, Texas, and New Orleans.

PHASE II

- Investigation of stratigraphic, structural, and petrologic relationships onshore and offshore to examine orogenic history, mass flux, and climate interactions through the system.
- A geochronological framework that integrates measurements from the diverse methods available should be developed early in the investigation to identify trends in local kinematics. These methods include: Low and high temperature thermochronology, cosmogenic dating, detrital thermochronology, fluid inclusion, paleobotanical, and geological studies.
- Conduct an active seismic study of crustal architecture onshore and offshore. These studies need to collect 2-D and 3-D tomographic information in order to constrain the spatially varying tectonic geometry.
- Initiate an aerogeophysical, marine geophysical, and remote sensing program to determine the gravity field, ice thickness, and integrated topographic-bathymetric surface to serve as baseline data for repeats surveys to monitor temporal changes.
- Geometric information available from seismic studies together with mass flux data should be used to condition, test, and develop the numerical models focused on kinematics, denudation, sediment transport and storage.

PHASE III

- Repeat surveys of GPS array to provide initial information on local velocity field. Aerogeophysical, marine geophysical, and satellite repeat surveys to examine landscape evolution.
- Offshore drilling from fjords to deep sea fan to examine integrated tectonic-climate history of the margin. Drilling builds on all previous geophysical, geological, climatic, and modeling efforts to enhance an integrated picture of the cooperation between climate and tectonic processes.

Links to Other Programs

The scientific topics raised in this report are ambitious in scale and cut across many scientific disciplines. In some cases, preexisting scientific programs are thematically or logistically linked with issues raised in this report and may provide avenues for exploring the questions discussed in this report. Some of the more relevant programs include:

Earthscope (http://www.earthscope.org/) is comprised of three facility-based components that are applicable to the scientific topics of the report: PBO, USArray, and InSAR. The goal of the USArray facility will be to routinely image the crust and mantle beneath the U.S. and adjacent regions in Mexico and Canada, using an array of portable seismic instruments, thereby providing subsurface imaging of the plate boundary zone, obtaining high-quality constraints on the deformation processes; mechanical (fault zone), thermal (topography), mantle (anisotropy), and density (tomography and gravity). Because it is anticipated that the deployment of the USArray's transportable (Bigfoot) components in Alaska is over a decade away, it is recommended by workshop attendees to propose to use the USArray's flexible array in the Gulf of Alaska earlier and within Gulf of Alaska study area.

The objective of the Plate Boundary Observatory (PBO) facility is to supply primarily geodetic data to characterize the 3D deformation (velocity) field of the western U.S., Alaska, and Baja California. It will thus define plate boundary dynamics and crustal rheology, define distribution and timing of the active tectonic processes and their relation to geology, and aid in understanding the physics of the earthquake process, and of volcanic processes. Three sites are proposed for the Gulf of Alaska region: Yakatat, Cape Yakataga, and Kayak Island. Because of the large geographic region of interest described in this report and because of the multiple plate/ terrane boundaries, the PBO should be augmented by some continuous multi-year sites as well as overall Alaska campaign sites.

The Synthetic aperture radar interferometry (InSAR) project operated by NASA will be used as a satellite tool to provide spatially continuous maps of the displacement field over the 100 km-swath width imaged by the satellite radar in those areas investigated with USArray and PBO. The use of InSAR in much of this area may be difficult because of the abundant snow and ice cover and steep topography, but where InSAR produces coherent data it can provide unparalleled spatial resolution on the displacement field. InSAR applications in areas of steep topography require particularly accurate high-resolution DEMs.

ICESat (Ice, Cloud, and land Elevation Satellite) (http://icesat.gsfc.nasa.gov/) is the Earth Observing System mission for measuring ice sheet mass balance, cloud and aerosol heights, as well as land topography and vegetation characteristics through time. The ICESat mission, part of NASA's Earth Observing System (EOS), was launched in January 2003. The Geoscience Laser Altimeter System (GLAS) is the sole instrument on satellite. The National Snow and Ice Data Center (NSIDC) will archive and distribute 16 products, including Levels 1A, 1B, and 2 laser altimetry and atmospheric lidar data. Preliminary versions of all ICESat/GLAS products are available as of 31 October 2003. In southern Alaska, ICESat will measure ice and land elevations, roughness, and slope along profiles. Five data sets of 8-day repeat track observations crossed the Bering and Malaspina Glaciers during 2003. For unsaturated, cloud free observations, the ICESat data can be used in Alaska to estimate glacier roughness and slope. A formal research announcement is expected from NASA to allow for analyses of these data sets.

Community Surface Dynamics Modeling System (CSDMS)
(http://instaar.colorado.edu/deltaforce/workshop/csdms.html)

A group of earth system modelers have recently launched an international effort to develop a suite of modular numerical earth system sediment models able to simulate the evolution of landscapes and sedimentary basins, on time scales ranging from individual events to many millions of years. Like the established Community Climate Model or the Princeton Ocean Model, the sediment models would be based on algorithms that mathematically describe the processes and conditions relevant to sediment transport and deposition, and would incorporate all the important input and boundary conditions that define a sedimentary system. The effort, to be coordinated and funded by government agencies and industry, would see sedimentary modelers determine the optimum algorithms, input parameters, feedback loops, and observations at the relevant scales necessary, to better predict sedimentary processes and ultimately to better provide an understanding of the earth system. Integration of a glacilogical module based on observations stemming from questions raised at this workshop would satisfy a greatly needed component.

Gulf of Alaska/Northeast Pacific GLOBEC Program
(http://globec.oce.orst.edu/groups/nep/index.html)
The Global Ocean Ecosystem Dynamics (GLOBEC) program addresses the physical and biological interactions linking ecosystem alterations to climate change. The goals of the GLOBEC program in the Gulf of Alaska are: 1) to understand the effects of climate variability and climate change on the distribution, abundance and production of marine organisms and 2) to incorporate this understanding in diagnostic and prognostic models. The Gulf of Alaska shelf supports a diverse ecosystem that includes several commercially important fisheries such as crab, shrimp, pollock, salmon, whose abundance varies on decadal time scales in conjunction with northern North Pacific Ocean temperatures. These correlations suggest that the Gulf of Alaska ecosystem is sensitive to climate variations on time scales ranging from the interannual to the interdecadal; however, the specific mechanisms linking climate to ecosystem alterations are unknown. Elucidation of these mechanisms is a goal of the Gulf of Alaska GLOBEC program and requires an understanding of the seasonal cycle of the principle physical, chemical and biological variables. To date such a description is largely lacking for the Gulf of Alaska shelf.

Marine Aspects of Earth System History (MESH)/ Earth System History (ESH)
(http://mesh.whoi.edu)

The geologic record of the last 10,000 years of Earth history is an important archive of data on natural climate variability at annual-to-millennial timescales under boundary conditions similar to those prevalent today. The goal of this area of research is to define the full range of natural environmental and climatic variability and to evaluate the extent to which changes in climate are forced by external means (i.e., variations in solar constant, tides or volcanic eruptions) or internal interactions among components of the climate system (i.e., variations in thermohaline circulation, tropical air-sea interactions, ice-ocean-biosphere feedbacks).

MESH projects should address the collection and analysis of high-resolution time series to advance the global study of patterns, processes, and causes of annual-to-millennial scale climatic and environmental variability beyond the instrumental record. Specific areas of primary interest are: 1) collection of new Holocene paleoclimate records from key terrestrial and marine archives, 2) examination of marine-terrestrial-atmosphere-cryosphere connections and North American climate response, and 3) synthesize and integrate data and model efforts expanding our understanding of forcing mechanisms relevant to Holocene climate variability.

Research and implementation plans that address these Holocene science priorities are available on the ESH web page at http://www.nsf.gov/geo/egch/gc_esh.html. Additional information can be obtained at http://mesh.whoi.edu.

Mount Logan Ice-Coring Program, 2000-2002

In the spring of 2001, an international team of scientists led by Canada's National Glaciology Program instituted a program of drilling a core of ice through the >200-m thick icefield that caps the summit of Mount Logan. The new Mount Logan ice-coring program is a joint effort between several institutions from Canada, the USA, Japan and Denmark. The goal of the ongoing program is to develop long (>10 ka), detailed multivariate record of past climatic and atmospheric conditions for the southwestern Yukon-southeastern Alaska region.

The present research program will update the Mount Logan ice-core record to the present day and extend it back in time over that entire Holocene interglacial epoch and possibly into the last ice age (> 12,000 years ago). It is expected that the new Mount Logan ice core will provide geoscientific information on the pivotal role of the Pacific Ocean in atmospheric teleconnections and climate dynamics, thereby complementing existing knowledge on the climatic role of the North Atlantic region. Field measurements and modeling of parameters such as air temperature and vapor fluxes will help characterize the atmospheric structure for the complex ocean-air-land system presented by the Saint Elias Mountains/North Pacific Ocean region. These data will assist in the calibration and validation of General Circulation Model (GCM)-based climate reconstructions and projections being performed by other Canadian agencies (e.g., Meteorological Service of Canada).

Juneau Icefield Research Program

The Juneau Icefield Research Program provides undergraduate and graduate students the opportunity to participate in field-based, interdisciplinary research to understand the environment and resource potentials of arctic and mountain regions. For over 58 years students have spent eight-weeks on the icefield each summer conducting research projects focused on the geology, geomorphology, geophysics, mineral exploration, physical geography and GIS, glaciology, arctic ecology, meteorology, climatology, glaciohydrology, environmental science, remote sensing of the region. In addition to field research, participants can take courses are in Earth Systems Field Science, emphasizing geological, glacial, periglacial, geophysical and glacio-atmospheric systems. More information can be found http://www.mines.uidaho.edu/glacier/ and http://www.uas.alaska.edu/envs/research/jirp.html.

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