

Introduction: Neogene tectonics and climate-tectonic interactions in the southern Alaskan orogen themed issue

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OVERVIEW

Interest in Alaskan tectonic studies has varied through time as different events have focused attention toward and away from this North American frontier. In 1964 the great Alaskan earthquake focused attention on Alaska, and was a major factor in the establishment of the concept of subduction in the early days of plate tectonics (e.g., Cox, 1973). In the 1980s, the northern Cordillera, including Alaska, was the subject of extensive study using the terrane analysis approach, which spawned a series of new tectonic syntheses (e.g., Coney et al., 1980). These studies primarily focused on the Mesozoic accretionary history of the orogen, and in Alaska culminated in the extensive research by the U.S. Geological Survey along the Alaska pipeline corridor in the Trans-Alaska Crustal Transect (TACT) project. The TACT program together with other studies in Alaska revised thinking on the tectonic history of large parts of Alaska, including recognition of the role of Cretaceous extension in large regions, the complexity of the southern Alaskan margin including extensive mafic underplating within the accretionary complex and beneath the extensional terranes, the crustal architecture of Alaskan strike-slip systems, and the complex interactions between northern Alaska and the greater Arctic Ocean basin region. The TACT efforts culminated in three special volumes of the American Geophysical Union (AGU) *Journal of Geophysical Research* as well as numerous topical papers. Much of this work together with other work at the time was summarized in a series of papers in the Alaska and Canada Decade of North American Geology (DNAG) volumes published by the Geological Society

of America (GSA). Topical studies continued in Alaska through the 1990s and into the early part of the first decade of the twenty-first century, but in smaller research groups primarily working on specific, focused studies. The results of those studies are scattered through the geosciences literature, but three volumes summarized specific tectonic issues: (1) GSA Special Paper 371 (Sisson et al., 2003) focused on Eocene tectonic events along the southern margin that have been broadly linked to ridge subduction events; (2) GSA Special Paper 431 (Ridgway et al., 2007; see especially Trop and Ridgway, 2007, therein) comprised a broad collection of papers on Alaska in the first synthesis volume since the DNAG volumes of the 1990s; and (3) AGU Geophysical Monograph 179 (Freymueller et al., 2008), on the active tectonics of Alaska, was launched following an AGU Chapman Conference in 2006.

Larger multidisciplinary research projects were focused in Alaska at about the time of the 2002 Denali earthquake, which occurred while a large, collaborative research group was being assembled with a goal of understanding the general problems of the Neogene tectonics of Alaska associated with the collision of the Yakutat terrane. The St. Elias Erosion/tectonics Project (STEEP; <http://www.ig.utexas.edu/steep/>) arose in large part because of increasing evidence that erosion-tectonic interactions within mountain belts were poorly understood, and southern Alaska is in an ideal setting for examining the role of glacial erosional processes in this type of interaction. Specifically, Hallet et al. (1996) had assembled a large data set that suggested that temperate glaciers are the most erosive systems on the planet, with the ability to easily keep pace with any tectonic uplift rate known at that time.

Although subsequent studies (e.g., Koppes and Hallet, 2002) indicated that the original highest estimates of glacial erosion rates were overestimated, even these revised estimates indicated that fast moving, temperate ice was capable of removing rock at rates of centimeters per year. This rate may not seem surprising, considering the great glacial landforms that dominate the landscape of Northern Hemisphere mountains affected by Pleistocene glaciation. Nonetheless, most of the world's moderate- to high-latitude mountain systems are either no longer active or are marginally active tectonically, and erosion rates are orders of magnitude lower. Thus, the southern Alaskan orogen represents a premier site for studies of the interactions between tectonic processes and glacial erosion.

STEEP efforts, funded by the National Science Foundation (NSF) Continental Dynamics Program, together with other ongoing studies of Alaskan tectonics by the U.S. Geological Survey and other academic researchers, have focused attention back on Alaskan tectonics. The next decade promises to see even more profound changes in our level of knowledge of this last frontier for geologic studies in the United States. The NSF EarthScope and the GeoPRISMS programs both have Alaskan tectonics as a focus of their studies, and there was a recent Integrated Ocean Drilling Program expedition to the Gulf of Alaska (Expedition 341 Scientists, 2013). The new data from these programs will undoubtedly yield new insights into the tectonics and crustal structure of this region. Research reported in this *Geosphere* themed issue was launched by members of the STEEP research group with the intent of showcasing some of the unusual data sets that were being assembled in that project and exploiting the ability of an online journal

like *Geosphere* to display these data sets. At the same time, this group was aware of, and collaborating with, a number of other researchers involved in southern Alaskan tectonics, and our hope was that others outside the STEEP group would contribute to the volume. That goal has been met, and there are several contributions from researchers outside the immediate STEEP research group.

THEMED ISSUE CONTENTS

Several of the papers in this volume are a direct consequence of STEEP efforts with work centered on the St. Elias orogen and the most direct effects of the collision of the Yakutat microplate with North America. Two papers (Chapman et al., 2012; Pavlis et al., 2012) are companion articles on different aspects of the geology of the coastal fold and thrust belt of the St. Elias orogen, where sedimentary cover from the Yakutat microplate is stripped from basement within the actively deforming convergent and transpressional boundaries of the microplate. Bruhn et al. (2012) considered a broader synthesis of the regional tectonics of the orogen, emphasizing active structures recognized by indirect observations from geomorphic features, glacial geology, and glacial flow characteristics. At an even larger scale, Bauer et al. (2014) analyze the entire orogen from passive seismic imaging. In contrast, McCalpin et al. (2011) and Headley et al. (2013) are more focused studies of active deformation and glacial erosion, respectively, affecting the surface and upper crust.

The contributions from the STEEP research group are complemented well by three other submissions to this volume. The Benowitz et al. (2011) paper on the exhumational history along the Denali fault and the Trop et al. (2012) study of the Wrangell Mountains volcanic and sedimentary basins contribute important new regional information on the general consequences of the flat-slab subduction of the Yakutat microplate beneath southern Alaska. Mankhemthong et al. (2013) provide new data on the history and geometry of the Cook Inlet Basin, immediately west of the St. Elias orogen, that give information on the western fringe of the orogenic system. Thus, these studies, together with the STEEP studies in the volume, provide an important new regional data set for synthesis of this important orogenic system. We expand on some of the primary results of these studies in the following.

Chapman et al. (2012) emphasize the complex geology in the heart of the orogenic syntaxis, where the mountain front and structures make a 90° bend to the west within a few kilometers.

This study builds on the pioneering work of Plafker (1987), who first recognized the importance of the Samovar Hills for regional tectonics with the recognition of the main anticline, i.e., the conspicuous angular unconformity beneath synorogenic deposits and evidence of significant preorogenic deformation below the angular unconformity that includes the only known onland exposures of Eocene mafic volcanic rocks beneath Yakutat terrane cover. Chapman et al. (2012) describe the structural details and kinematics of the structures within the Samovar Hills, and show important details of the early deformation that occurred along the transpressional margin, prior to the arrival of the Yakutat terrane at the subduction-transform corner; they expand that work to a regional structural interpretation, including a synthesis of the structural history of this important plate corner collision in some of the most remote and rugged terrain in the world.

Pavlis et al. (2012) build on the work of Chapman et al. (2012) with a systematic treatment of the structural geology to the west, including the area surrounding Icy Bay and a transect along the Duktoth River in the core of the fold and thrust belt. Pavlis et al. evaluate the deformational history through a thorough description of the local geology in both the Icy Bay and Duktoth River transects, emphasizing the complexity and uncertainties in the eastern transect. They use the onland geology together with STEEP offshore seismic profiles (Worthington et al., 2010, 2012) to present a pair of balanced cross sections to evaluate the shortening history in these two transects of the fold and thrust belt; they also use map-scale structure to show that the deformation is four-dimensional with a three-dimensional (3D) structural history that evolved in time. In the core of the fold and thrust belt, this complexity is shown primarily as out-of-sequence thrusting oblique to earlier formed structures, but in the east the authors show a different structural evolution, indicating changing kinematic axes with time. Pavlis et al. structure in the Duktoth transect as the development of a young, out-of-sequence thrust forming in response to rapid erosion of the orogenic wedge during the past ~1 m.y., whereas the complexities in the Icy Bay transect are attributed to interactions in the tectonic corner (syntaxis), where the transpressional Fairweather system transfers into the fully convergent fold and thrust belt. Pavlis et al. present new balanced cross sections for both transects that account for ~150–200 km of convergence within the fold and thrust belt, and discuss the significance of the discrepancy between this apparent shortening and shortening indicated by the subducted part of the Yakutat microplate. They evaluate

the relative roles of erosional recycling, lateral extrusion, and sediment subduction, and conclude that sediment subduction is an important process and may account for unusual upper mantle structures observed to the north and west of the region, an important hypothesis in light of EarthScope studies planned for this region in the near future. Pavlis et al. also present 3D visualizations of their interpretation of the structures as well as an analysis of the structures that could produce the uplift leading to exhumation patterns seen in earlier thermochronology studies of Berger et al. (2008). Their conclusion, an actively growing antiformal stack driven by underplating, represents an alternative view to an inferred backthrust system and an important alternative hypothesis that could be tested with additional study. Pavlis et al. also present a preliminary deformation-through-time map for the orogen based on the 2012 best estimates for chronology and shortening along various structures. This hypothesis for the deformational history should be testable as new data become available for the region.

The third paper in this series of contributions on the geology of the St. Elias orogen, that of Bruhn et al. (2012), uses a novel approach to examine the bedrock geology in this heavily glaciated orogen. The authors use remote sensing data of exposed bedrock and glacier surfaces that integrate several years of observation for ice flow. The data record surface ice flux that is used as a guide to recognizing major faults, particularly active structures that are present beneath the ice and deform the glacier bed. Paramount in this study is the analysis of the structural details within the St. Elias corner (syntaxis) and the long linear valley of the Bagley Ice Field, where most of the active structures are buried by ice. Their analysis of glacial flow in the upper Seward Glacier leads to their suggestion of a releasing bend along the strike-slip system that they use to explain the unusual, very young, low-temperature cooling ages recognized in this area by Enkelmann et al. (2009). Bruhn et al. (2012) also use glacial flow and ice surface morphology to evaluate active structure across the Bagley Ice Field valley, and conclude that the valley is underlain by a long-lived, dextral-oblique structure that remains active. Their use of glacial valley morphologies and comparison of the geology across the Bagley Ice Field valley leads to a provocative interpretation of ~50 km of dextral slip along with several kilometers of south-side-up displacement across the buried structure. They also present a 3D visualization of the structure in this area that is complementary to the models in Pavlis et al. (2012), with additional interpretations of the geometry of the backstop from

their inference of the Bagley Ice Field valley structures. This novel use of ice flow and ice surface morphology presents new techniques for analyzing active structure in glaciated orogens, and may change interpretations of other orogens where ice covers active structures.

The study by McCalpin et al. (2011) considers the active tectonics of the western part of the St. Elias orogen through an analysis of surface ruptures. This area, between the Bering Glacier and Copper River, has long been a puzzle in the local geology because it is characterized by swarms of surface ruptures. The origin of these surface ruptures has been controversial because, although Carver and McCalpin (1996) described many of these ruptures as flexural slip scarps related to active folding, they are spatially associated with ridge tops, they seem too numerous for active faults unless deformation rates are very high, and at least some of the ruptures had been clearly associated with gravity collapse sacking (Bruhn et al., 2004; Li et al., 2010). McCalpin et al. (2011) carefully document a series of these surface ruptures, including trenching studies of several of the scarps as well as geomorphic analyses of local scarp arrays, and conclude that the system is a mix of gravity driven spreading structures and tectonic scarps with gravity structures including sacking and bedding-plane toppling scarps. An east-northeast-trending oblique-normal fault system was recognized within the area as an active fault system with slip clarified by both geomorphology and slickenlines on a trenched fault surface. Thus, the McCalpin et al. (2011) study illustrates the importance of unraveling details of individual scarps in this kind of setting to clarify true tectonic scarps versus features generated by gravitational collapse of steep mountains slopes.

The study of Headley et al. (2013) presents a new approach in combining glaciology data with detrital thermochronology to investigate the erosion processes acting beneath the largest glacial systems of the St. Elias orogen: the Bagley Ice Field–Bering Glacier and the Seward–Malaspina Glacier that covers large parts of the eastern syntaxis of the St. Elias orogen. Earlier studies of the detrital cooling ages of the glacial outwash material revealed exceptionally rapid exhumation rates beneath the Seward Glacier. Much lower rates occur beneath the Bagley Ice Field valley and in areas covered by smaller glaciers located within the fold and thrust belt and north of the Bagley Ice Field (Enkelmann et al., 2009). Headley et al. use the cooling age data as tracers to record the erosional efficiency of the various glacial systems. The available glaciological data are reviewed and a longitudinal profile of the Bagley–Bering glacier bed geometry, including main structures and over-

deepening of the valley, is presented. The subglacial hydrological potential is examined, and processes of surging as well as freeze-on at the glacier bed are discussed with respect to the carrying capacity of subglacial rivers to effectively evacuate sediment out of the orogenic system. The ice flux of the Seward–Malaspina Glacier is discussed with respect to its ability to erode the bed. Ice flux is orders of magnitude higher in the Seward throat, yet the most aggressive erosion occurs underneath the slow Seward Glacier ice. This result highlights the importance of focusing strain in the orogenic corner that causes rock fracturing and facilitates erosion.

Bauer et al. (2014) utilize P and S receiver function data computed from broadband stations of the Alaska network extended by stations installed for STEEP. Their results provide the highest resolution images of the crust and upper mantle ever produced for southern Alaska. They present evidence that the megathrust at the top of the subducting lithosphere of the Pacific plate extends eastward without a resolvable break into the Yakutat block at least as far as Icy Bay. The slab dip is found to increase slightly from west to east. Bauer et al. develop a 3D kinematic model for the geometry of the combined Pacific and Yakutat lithosphere. This model provides a framework for two important conclusions they make about crust and upper mantle for southern Alaska. First, their imaging results in combination with active source results from STEEP show that the subduction system transitions from a normal subduction mode to the west to a situation at Mount Saint Elias that is more analogous to the western and eastern syntaxes of the Himalaya. Second, their model shows that the Wrangell Volcanic Field is consistent with a standard model of subduction, albeit above thickened oceanic plateau crust. Active volcanoes can be projected updip along flow lines in their model to locations west of Mount Saint Elias in the Yakutat block. They find that the depth to the top of the slab under the Wrangell Mountains is 80 km, which is near the shallowest slab depths for arc volcanoes observed globally. Bauer et al. argue that this geometry is consistent with sediments of the Yakutat block being largely stripped in an active fold and thrust belt west of Mount Saint Elias, with the implication that the Wrangell volcanics are a product of partial melting of the lower crust of the Yakutat block; this hypothesis is testable through focused studies of this volcanic system.

Contributions that are not from the STEEP research group provide a valuable extension of the tectonic and surface deformation processes at the immediate Yakutat collision zone and document the far-field effect of the Yakutat subduction in southern Alaska throughout Cenozoic

time. Benowitz et al. (2011) investigate the pattern and rates of rock exhumation in the eastern Alaska Range located >400 km north of the St. Elias orogen. They employ a wide range of thermochronometric methods, including $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of biotite and K-feldspar, apatite fission track, and U-Th/He dating. The biotite cooling ages reveal that exhumation commenced in this area ca. 22 Ma, documenting the beginning of flat-slab subduction of an increasingly thicker Yakutat microplate; this is an interesting conclusion in light of STEEP studies in the Saint Elias Mountains, where the only evidence of similar age events is indirect, from older exhumation ages in the core of the St. Elias orogen (Enkelmann et al., 2008). The spatial distribution of cooling ages in the Alaska Range reveals variations in the amount of Neogene exhumation across and along the strike of the Denali fault that vary from >11 km to <3 km. The low-temperature cooling ages range from 4 to 1 Ma and suggest an increase in exhumation rates during the Pliocene–Pleistocene. Possible reasons for this increased exhumation are discussed, and include a tectonic forcing and a climate driven signal due to the beginning of glacial erosion.

Mankhemthong et al. (2013) seek to locate and determine the geometry of the Border Ranges fault system, a major feature of the Alaska–Aleutian forearc region, using gravity, aeromagnetic, and other geophysical data in the Cook Inlet Basin region. They present 2.5D cross sections showing 6–10-km-thick sedimentary cover over the Peninsular terrane, the lithospheric mantle of which is serpentinized at depths of 14–34 km. Border Range ultramafic and mafic assemblages characterize the eastern Cook Inlet Basin region and are interpreted as the source material for the serpentinization. The Border Ranges fault system is presented as the structural boundary between the overthrust Border Ranges ultramafic and mafic assemblages and the underthrust Chugach terrane to the east. The fault system dips 50° – 70° toward the west-northwest and extends to at least 15 km. The observed gravity low over the Chugach terrane may suggest underplated sediment at the base of the accretionary complex (15–40 km) and may be associated with Yakutat microplate subduction.

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