

Escape tectonics and the extrusion of Alaska: Past, present, and future

T. F. Redfield Geological Survey of Norway, Leiv Eirikssens vei 39, 7491 Lade, Trondheim, Norway

David W. Scholl Department of Geophysics, Stanford University, Stanford, California 94035, USA, and U.S. Geological Survey, Menlo Park, California 94025, USA

P. G. Fitzgerald Department of Earth Sciences, Syracuse University, Syracuse, New York 13244, USA

Myrl E. Beck, Jr. Department of Geology, Western Washington University, Bellingham, Washington 98225, USA

ABSTRACT

The North Pacific Rim is a tectonically active plate boundary zone, parts of which may be characterized as a laterally moving orogenic stream. Crustal blocks are transported along large-magnitude strike-slip faults in western Canada and central Alaska toward the Aleutian–Bering Sea subduction zones. Throughout much of the Cenozoic, at and west of its Alaskan nexus, the North Pacific Rim orogenic Stream (NPRS) has undergone tectonic escape. During transport, relatively rigid blocks acquired paleomagnetic rotations and fault-juxtaposed boundaries while flowing differentially through the system, from their original point of accretion and entrainment toward the free face defined by the Aleutian–Bering Sea subduction zones. Built upon classical terrane tectonics, the NPRS model provides a new framework with which to view the mobilistic nature of the western North American plate boundary zone.

Keywords: Alaska, Anatolia, orocline, extrusion, escape, Denali Tintina, fault, Bering Sea.

INTRODUCTION

For more than half a century, the geotectonic evolution of Alaska has been viewed from the context of its arcuate internal structure. Under the Alaskan Orocline paradigm of Carey (1955), counterclockwise (CCW) vertical-axis paleomagnetic rotations have been interpreted as small block rotations related in some way to tectonic reshaping of Alaska (e.g., Coe et al., 1989). However, simple bending of Alaskan crust conflicts with the lack of extensional and compressional structures outside and inside the curvature of the arc (Schultz and Aydin, 1990). Although consistent with orocline models, the southern Alaskan CCW rotations require another explanation (e.g., Glen, 2004).

Alaska has long been known as a tectonic collage. Packer and Stone (1972, 1974) suggested southern Alaska had moved north and rotated clockwise (CW) to achieve its present position. Packer et al. (1975) defined three distinct regions, bounded by the Tintina–Rocky Mountain Trench and Denali fault systems, and made up of multiple blocks of continental lithosphere brought together in a progressive series of accretionary events. Later, Jones et al. (1977) identified Wrangellia as exotic to Alaska. Consolidating the terrane paradigm, Beck (1980), Stone (1980), and Coney et al. (1980) suggested that the assembly of much of western North American crust was driven by Pacific–North America (PAC–NAM) relative convergence.

However, the conventional terrane model incompletely describes the mobility of the present-day margin. Western British Columbia and southern Alaska constitute a diffuse plate boundary zone characterized by non-rigid deformation, mountain building, and block rotations (e.g., Stein and Freymueller, 2002). Here, we suggest that the “Bering Block” of Mackey et al., (1997) and Fujita et al. (2002) is part of this mobilized zone (Fig. 1). We extend the zone eastward to include the 500- to 1000-km-wide belt of diffusively deformed crustal material south of the Brooks Range and outboard of stable parts of the Canadian Cordillera. We suggest that non-rigid behavior characterizes much of this region, and that it has been tectonically active throughout much of the Cenozoic

as a laterally moving crustal raft or orogenic float (e.g., Oldow et al., 1990; Mazzotti and Hyndman, 2002).

We refer to this mobilization of crustal blocks as the North Pacific Rim orogenic stream (NPRS). We postulate that, since the Eocene, NPRS crust has ascended the British Columbia margin, entered the apex of the Alaska orocline, encountered a buttress or backstop preventing further northward displacement, and escaped southwestward toward the Aleutian and Bering Sea subduction zones (Beck, 1986; Scholl and Stevenson, 1991; Dumitru et al., 1995; Mackey et al., 1997; Fujita et al., 2002).

ANATOLIA: AN INSTRUCTIVE ANALOGY

Anatolia, whose crust is extruded toward the Hellenic subduction zone in response to the northward impingement of the Arabian block (Nyst and Thatcher, 2004), provides a tectonic analog. The escaping Anatolian crustal panel (Fig. 1A) is a structurally complex and internally deforming region, comparable to southern Alaska. The Eurasian Plate to the north acts as a rigid backstop: the dextral North Anatolian fault system accommodates westward escape. The north-dipping Hellenic subduction zone to the west and southwest makes room for extruded crust. Global positioning system (GPS) data have resolved complicated relative motions between individual Anatolian crustal domains (McClusky et al., 2000; Nyst and Thatcher, 2004).

The Anatolian model provides a useful kinematic and dynamic framework with which to analyze the tectonics of southern and southeast Alaska. Structures in Canada, Alaska, and the Bering Sea region have direct counterparts in Anatolia (Figs. 1A, 1B, 1C). The role of the Arabian indenter is played by PAC–NAM dextral oblique to strike-slip coupling, which drives the NPRS northward along the eastern Pacific Rim.

KINEMATICS AND STRUCTURE IN CENTRAL ALASKA

Fitch (1972) proposed that oblique subduction could drive continental-scale transform faulting. Plate kinematic models for at least the past 50 m.y. predict dominantly transpressional convergence between Cascadia and southeast Alaska (Tarduno et al., 2003). Subduction zone–driven oblique shear along the western North American margin clearly drove inboard transform faulting (Beck, 1980, 1986; Gabrielse et al., 2006). Piercing points along the Kaltag–Tintina–Rocky Mountain Trench and Denali Fault System (DFS) require significant net northward translation toward the interior of eastern Alaska since 55 Ma (Lanphere, 1978). Approximately 430 km of dextral displacement occurred across the Tintina fault system in the Eocene (Gabrielse et al., 2006; Fig. 1D). Along the eastern segment of the DFS, the geologic record since the earliest Tertiary requires ~370 km of dextral offset (Eisbacher, 1976, Fig. 1D). The sum of these numbers (~800 km) multiplied by the width of the orogen (between ~700 km in British Columbia and ~1200 km in Alaska south of the Kobuk fault) provides a sense of the length and width of the NPRS conveyor.

The 2002 large-magnitude dextral rupture of the DFS (Haeussler et al., 2004) demonstrated that relative PAC–NAM plate convergence continues to drive crust along the interior strike-slip faults of western Canada and southeast Alaska. Geologic, seismologic, and paleomagnetic evidence for northward translation predicts that a significant space problem should develop in central Alaska. In the apices of the

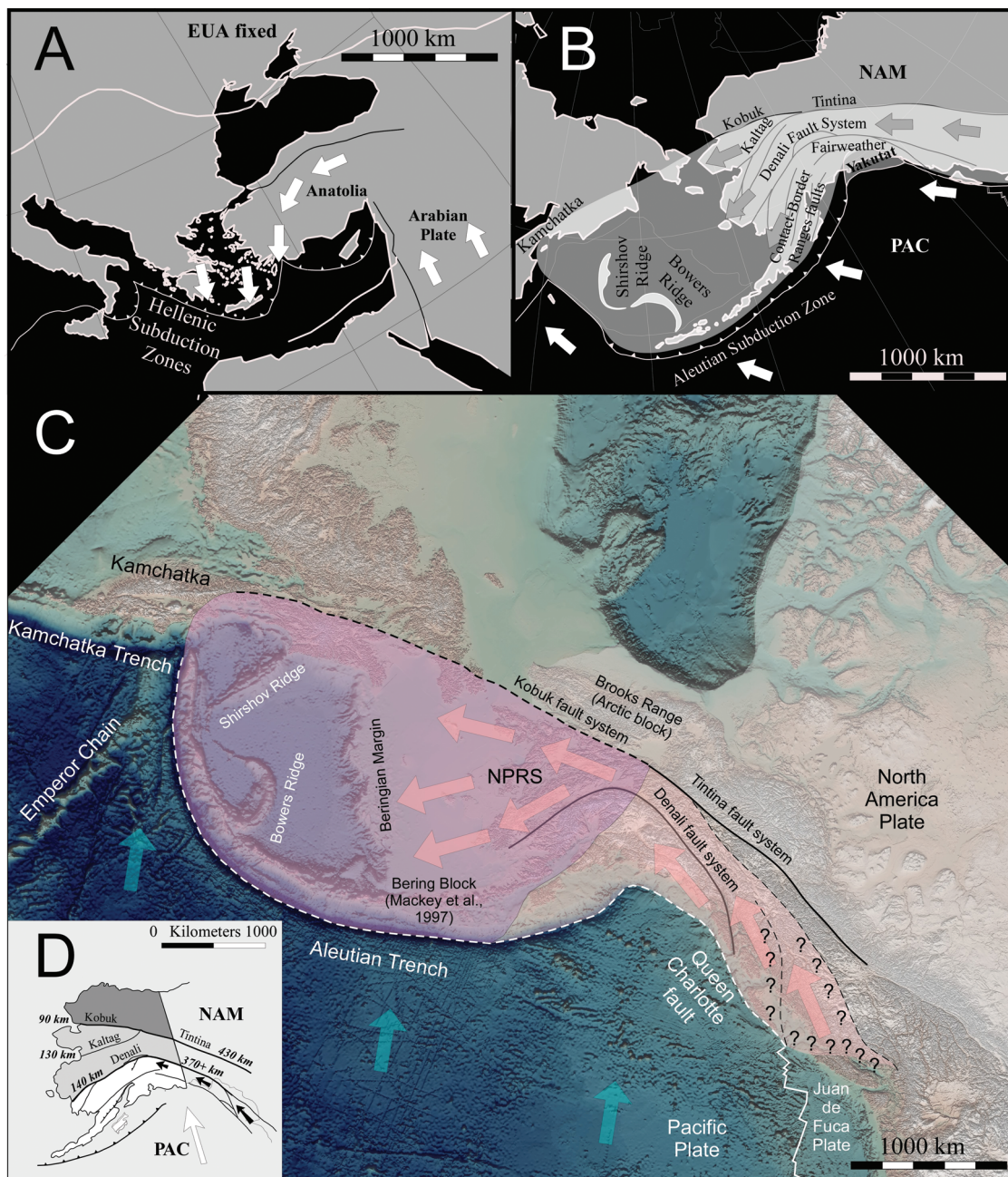


Figure 1. Inset maps (polar stereographic projections) comparing documented Anatolian extrusion (A) with hypothesized escape of western Alaska (B). C: Polar stereographic map showing principal physiography of North Pacific Rim region. Arrows schematically show motion of North Pacific Rim orogenic stream (NPRS) and Pacific Plate relative to fixed North America. Heavy white lines and light plum-colored color delineate the approximate boundaries of the stream. Dark plum colored overlay delineates the Bering Block as originally defined (Mackey et al., 1997). NPRS comprises all the crustal terranes of the Canadian Pacific, Alaska, and the Bering Sea that are undergoing lateral transport northward toward Alaska and west of the curving nexus of central Alaska's "orocline," south-westward toward the Aleutian subduction zone. D: Offset map illustrating the space problem in central Alaska associated with varying offsets across the great curved fault systems of Alaska.

great curved faults of the Alaskan orocline, the increasingly orthogonal resolution of PAC-NAM relative convergence significantly reduces the tangential component driving right-lateral slip (Redfield and Fitzgerald, 1993; Glen, 2004). Experiencing much greater tangential components, the northern end of the British Columbia sector of the orogen should impinge upon crustal blocks already transported into the orocline. Lacking a mechanism for tectonic escape, telescoping of crust and consequent uplift, mountain building, erosion, and laterally extensive deep exhumation in central Alaska would appear inevitable.

However, crustal thickening under the central Alaska Range (Veenstra et al., 2006) is minimal, probably related to the growth of these mountains since the late Miocene (Fitzgerald et al., 1995; Ridgway et al., 2002; 2007), and likely coincident with the subduction of a buoyant Yakutat slab (Eberhart-Phillips et al., 2006). Exhumation of vast quantities of deep-seated high-pressure rocks in interior Alaska has not occurred. While

Alaskan seismicity is dominated by Benioff zone events, interior Alaskan earthquake solutions support translation along strike-slip faults and escape of crust to the southwest. Between the curved faults, thrust faults accommodate some of the relative motions of individual tracks of crustal terranes. The disparity of offset between east and west ends of the curved fault systems (Lanphere, 1978; Miller et al., 2002) also presents a space-motion problem that cannot be resolved by conventional models of terrane transport. However, velocity changes across strike-slip fault systems may cause apparent fault reversals, perhaps partly accounting for the disparity of offsets observed between the eastern and western sectors of the curving Alaska-British Columbia fault systems. Similar to Anatolia and the larger extrusion system of Southeast Asia, the solution to lateral distribution of crustal movement along and across fault boundaries without tectonic stacking may be found in the kinematics of tectonic escape (Tapponnier et al., 1982; Burke and Sengor, 1986).

THE NORTHWEST PACIFIC RIM OROGENIC STREAM TODAY

A growing GPS database shows that Alaska and northern British Columbia/Yukon together form a diffusely deforming composite microplate bounded by more rigid crustal terranes and lithospheric plates (Mazzotti and Hyndman, 2002; Mazzotti 2006). Thus, we expand the Bering Block to encompass a larger part of the northern Pacific Rim, including much of the orogenic region of Bird (2003) and recognized by Hyndman et al. (2005) as weak backarc lithosphere readily mobilized by plate boundary forces. The NPRS does not behave as a coherent block, but rather as a tectonic conveyor belt rolling toward the Aleutian subduction zone along curving slip-line paths roughly parallel to the regional strike-slip faults.

We include within the NPRS all the defined terranes of Alaska south of the Kobuk and west of the Tintina–Rocky Mountain Trench faults to the Alaska Trench and southeast to at least where the DFS splays from the Queen Charlotte fault north of Queen Charlotte Island. The southern boundary is the continuous Alaska–Aleutian subduction zone. The western border of the NPRS is the seismically active, diffusely deforming coastal region of northeastern Russia (Mackey et al., 1997). The NPRS embraces all of central and northern coastal Kamchatka (see Bourgeois et al., 2006; Pedoja et al., 2006), itself an orogenic region perhaps undergoing eastward extrusion (Riegel et al., 1993). The southeasternmost beginning of the NPRS is a diffuse transition zone between relatively normal northward oblique, Cascadia (Juan de Fuca–North America) subduction characterized by onshore CW rotating blocks (Wells and Simpson, 2001) and highly oblique PAC–NAM transpression accompanied by active faulting.

GEOTECTONIC EXTRUSION OF THE NORTH PACIFIC RIM

From a stable Canadian Cordillera (landward of the Tintina fault system) reference frame, northward translation of crustal slivers of North America along the British Columbia margin drives terrane fragments into the apex of the Alaskan restraining bend. Crust then escapes westward toward the Aleutian subduction zone.

We envision the Brooks Range and its bolstering Arctic Basin to the north as a buttress firmly in place by at least the early Eocene. We attribute CCW block rotations in southwest Alaska to the transport of crustal blocks around an existing nexus within an orogenic stream (Glen, 2004). We postulate that many of the crustal blocks of western Alaska underwent varying degrees of CCW rotation throughout the Tertiary, but those in west-central Alaska were most strongly rotated by a late Miocene tightening of the arc of the Denali and Contact-Border Ranges fault systems caused by the plunge of the Yakutat block into the eastern end of the Aleutian subduction zone (Eberhart-Phillips et al., 2006).

Prior to the Yakutat collision, the bend may have been straighter and transport through the nexus correspondingly less impeded. However, sufficient constriction existed to form in echelon, strike-slip couples in central and western Alaska, allowing material to fan out to the southwest, accentuating the arc, and eventually causing the DFS to dominate transport. Before formation of the Alaska–Aleutian subduction zones, the northwest-striking Beringian margin formed the Pacific's highly oblique, underthrust plate boundary, and the western limit of NPRS. There, an unconformity (e.g., Worrall, 1991) documents the middle Eocene shift of the PAC–NAM (or Kula) plate boundary from the Beringian margin to the Aleutian–Bering Sea subduction zones.

The Beringian margin is marked by near-right-angle terminations where strike-slip faults meet and offset the margin. As extrusion proceeded during the Cenozoic, offset at the distal end of each fault became less favorable from a “least-work” point of view. Because it became energetically preferable for active extrusion to transfer to another portion of the system, large offsets are neither observed nor expected at the outboard end of the NPRS.

As the NPRS continued to flow, the older Beringian margin subduction zone was pushed seaward over obliquely underthrusting oceanic crust. Subduction eventually shifted south and offshore, perhaps first to the Bowers and Shirshov Ridges, and by ~50 Ma to the new Aleutian subduction zone (Fig. 1; Scholl and Stevenson, 1991; Jicha et al., 2006).

CONCLUSIONS

Building upon escape tectonic models, we have defined the laterally moving crust of the British Columbia margin, Alaska, and the Bering Sea as the North Pacific Rim orogenic stream (NPRS). The stream is a composite of crustal terranes undergoing northwestward transport parallel to the British Columbia margin, CCW motion through the Alaskan nexus, and, farther west, escape toward the north Pacific subduction zones of the Aleutian–Bering Sea region. Offsets across the inboard Tintina and Denali fault systems indicate northward transport and southwestward extrusion took place since the earliest Eocene. We speculate extrusion may also have occurred during Cretaceous time.

Our model implies that the present-day terrane framework of Pacific Rim North America is as much a product of differential flow lines within the NPRS as of individual accretionary events at the margin. This marriage between terrane accretion, entrainment, strike-slip transport, and escape permits the wide variation in magnitude of small block rotation observed throughout southern and central Alaska, and indeed, everywhere along the Pacific boundary north of southern Mexico. Relatively rigid crustal blocks acquired their paleomagnetically determined rotations and fault boundaries while moving through the system. Active since at least the earliest Eocene, the NPRS has accommodated a minimum of 800 km of total offset with respect to stable North America. Offset and extrusion may have been accelerated by the collisional impact of the Yakutat block toward the end of the Miocene (Mackey et al. 1997). The NPRS continues to extrude its leading edge toward the Aleutian subduction zone (Cross and Freymueller, 2006; Mazzotti, 2006). Behaving in a similar tectonic and kinematic manner to Anatolia and Southeast Asia, the NPRS illustrates the fundamentally mobile nature of a typical obliquely convergent, plate boundary zone.

ACKNOWLEDGMENTS

The authors are grateful to many people for engaging discussions concerning the ideas explored in this paper. In particular, we acknowledge Andy Stevenson, Peter Haeusseler, Marti Miller, Ken Ridgway, Stephane Mazzotti, Roy Hyndman, and Roland von Huene. Reviews by Ken Ridgway, John Glen, and an anonymous third reviewer greatly improved the manuscript.

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Manuscript received 1 March 2007

Revised manuscript received 21 June 2007

Manuscript accepted 29 June 2007

Printed in USA