Volcanism and Subduction
The Kamchatka Region

John Eichelberger, Evgenii Gordeev,
Minoru Kasahara, Pavel Izbekov,
and Jonathan Lees
Editors

AGU

Geophysical Monograph Series

Including
IUGG Volumes
Maurice Ewing Volumes
Mineral Physics Volumes

Geophysical Monograph Series

Volcanism and Subduction: The Kamchatka Region

John Eichelberger
Evgenii Gordeev
Pavel Izbekov
Minoru Kasahara
Jonathan Lees
Editors

CONTENTS

B. Topical Studies

Section III: Volcanism

A. Overview

B. Topical Studies

PREFACE

Long before introduction of the subduction paradigm, it was recognized that there was a "Pacific Ring of Fire" characterized by explosive eruptions, devastating earthquakes, and far-reaching tsunamis. This belt of closely coupled tectonism and volcanism girdles a hemispheric ocean. We chose a segment of this ring as the subject of this volume, a choice that deserves some explanation. An astronaut arriving here, had Earth's oceans gone the way of Mars' oceans, would certainly be drawn to this deep kinked furrow in the planet's skin, but there are more reasons than topography.

One reason is the high level of activity. Five of Earth's ten largest earthquakes of the 20th century occurred in this segment, and over a span of only 12 years. Volcanism is likewise robust. Exceptional volcanic events include the great Katmai/Novarupta eruption of 1912, by far the largest on Earth in the last hundred years; the Bezymianny and Shiveluch collapse/Plinian events of 1956 and 1964, respectively; and the Great Tolbachik Fissure Eruption of 1975 with a vent span of 30 km. At this writing, 5 volcanoes of the Kurile-Kamchatka system and 3 of Aleutian-Alaska are in continuous to frequent intermittent low-level eruption. Tsunamis of the past century have obliterated whole villages, Severo-Kurilsk in 1952 and Valdez, Alaska in 1964. Here is a place where Earth's interior dynamics are illuminated dramatically and sometimes tragically by earthquakes, deformation, and melting.

Obviously the activity does not end at the geographic limits of this volume. Vigorous subduction continues uninterrupted south of the Kuriles into Japan. At the other end, volcanism but not seismicity diminishes in southeastern Alaska where the plate boundary becomes the Queen Charlotte transform fault of western Canada. The chosen segment does, however, coincide with relative lack of visibility within the global geoscience community. This is somewhat ironic, because the Aleutian arc is a place where important aspects of the subduction paradigm were first introduced.

One impediment to science in this region is the harsh environment. The weather is often cold and stormy, and supply points are few and far. In most cases, a helicopter or ship or both are required. The high cost of transportation and support are exacerbated by the need for budgeting weather days. Scientists stuck in bad weather and unaccustomed to this fact of northern life have been known to contact their embassies for help in improving flying conditions. Field seasons are generally limited to mid June to mid September, and maintaining

operation of geophysical instruments through the long winter is difficult. A team or expedition approach to field work is often needed, though happily this has benefits in encouraging cross-discipline collaboration and cross-culture understanding.

The new driving force toward scientific understanding of this part of the world is the concern shared by all governments about natural hazards. Significant local populations are at risk to earthquakes and eruptions, and the entire northern Pacific basin is at risk to tsunamis generated here. For volcanology, the risk for jet aircraft encountering ash clouds from explosive eruptions has motivated rapid growth of volcano observatories in Alaska, Kamchatka, and in Sakhalin for the Kuriles. Some 25,000 passengers and equally impressive amounts of cargo are carried by roughly 200 large aircraft per day along the Kurile-Kamchatka-Aleutian volcanic line en route between eastern Asia and North America. Approximately one hundred volcanoes in this subduction segment are capable of erupting ash clouds to flight levels.

Before the growth in volcano monitoring, for which a triggering event was the near-disastrous encounter of a wide-body passenger jet with an ash cloud from Redoubt volcano over southcentral Alaska in 1989, only the Soviet Union maintained volcano observatories in the region. Alaska Volcano Observatory (AVO) now employs dense seismic networks on 30 volcanoes, as well as continuously recording, telemetered GPS networks on four of them. The Kamchatka Volcanic Eruption Response Team (KVERT) monitors 10 Kamchatka and northern Kurile volcanoes seismically in real time. Both in Kamchatka and Alaska, a great deal of work has gone into developing stand-alone telemetered geophysical stations that can withstand the rigors of the environment for long periods without expensive helicopter visits.

An important parallel development was the use of satellite-based remote sensing observations to detect and warn of volcano unrest and eruption. Nowhere in the world is satellite data used so intensively for volcano hazard mitigation as at the observatories of Alaska, Kamchatka, and Sakhalin. Rapidly advancing technology has changed not just the resolution of satellite systems but also the kinds of data that can be acquired, including volcano deformation, eruption cloud composition, and estimation of effusion rate. Although seismic data from dense proximal networks remains the preferred means of detecting activity precursory to eruptions, satellite remote sensing makes possible monitoring of volcanoes for which ground installations are prohibitively expensive and provides essential confirmation of explosive ash production where ground stations are present.

Another societal imperative motivating geoscience investigations of active processes is the need for economical, clean,

reliable energy for isolated communities. Important use of geothermal energy has been a reality in Kamchatka and the Kurile Islands for some time, and is under serious consideration in Alaska. With concern about oil spills in rich fisheries and rising oil prices, geothermal will likely grow so that northern coastal communities can remain viable.

In order to view the geophysics of this region as a whole and to encourage development of international and interdisciplinary investigations, workers from Hokkaido, Kamchatka and Alaska formed the Japan-Kamchatka-Alaska Subduction Processes Consortium (JKASP). Five biennial meetings, each attracting 100 to 200 scientists and students, have taken place to date: 1998 in Petropavlovsk-Kamchatsky, 2000 in Sapporo, 2002 in Fairbanks, 2004 in Petropavlovsk-Kamchatsky, and 2006 in Sapporo. The present volume is an outgrowth of the birth of this geoscience community.

The contents of the volume span a broad range of disciplines within the general theme of subduction processes. Students will rapidly appreciate that this classic subduction zone lacks the classic simplicity of textbook cartoons, wonder at the relationship of present-day topography to tectonic history, and find that the crowning volcano at Earth's sharpest subduction corner is not andesite but basalt. For scientists of more southern experience, we hope that the book will serve as a stimulating and useful introduction to the research and the researchers of the far north Pacific. For those who have worked here, we hope that the papers herein will point the way to new connections, collaborations, and directions. Most of all, we hope that through these and other efforts the window of opportunity for collaboration that has opened among Japan, Russia, and the US will remain open; that the Kurile-Kamchatka-Aleutian-Alaska subduction system will be a shared natural geodynamic laboratory of our countries, and indeed of the world.

John Eichelberger
Evgenii Gordeev
Pavel Izbekov
Minoru Kasahara
Jonathan Lees

Introduction: Subduction's Sharpest Arrow

John C. Eichelberger[1]

Alaska Volcano Observatory, Geophysical Institute, University of Alaska Fairbanks,
Fairbanks, Alaska, USA

In the center of the 6000-km reach of Kurile-Kamchatka-Aleutian-Alaska subduction is arguably Earth's most remarkable subduction cusp. The Kamchatka-Aleutian junction is a sharp arrowhead mounted on the shaft of the Emperor Seamount Chain. This collection of papers provides context, definition, and suggestions for the origin of the junction, but a comprehensive understanding remains elusive, in part because of the newness of international collaborations. Necessary cross-border syntheses have been impeded by the adversarial international relations that characterized the 20th century. For much of this period, Kamchatka and the Kurile Islands were part of the Soviet Union, a mostly closed country. The entire region was swept by World War II, abundant remnants of which are wrecked ships and planes, unexploded ordnance, and Rommel stakes.

Of the three countries with a direct interest in this region, Russia has the longest presence. Russia established settlements in Kamchatka beginning in the early 18th century, then colonized the Aleutians, Kodiak, and southeast Alaska following A. Chirikov's and V. Bering's discovery voyage from Petropavlovsk-Kamchatsky in 1741. Hokkaido was the last territory area added permanently to Japan, during the latter half of the 19th century. Similarly, the United States purchased the Aleutians and Alaska from Russia in 1867 in the interest of territorial expansion, whaling, and harvesting of fur.

The strategic importance of the region to the US and Russia increased dramatically with World War II, when Japan began launching military operations from the northern Kuriles and occupied the American Near Islands (so named because they are close to Kamchatka) of the Aleutians. At the same time, Alaska and Kamchatka airfields were needed to ferry materiel in support of the Soviet Union's war effort against Nazi Germany. An immediate American response to these events

was to build a road through Canada to Fairbanks, providing what is still Alaska's only land link to the rest of the United States. In contrast to Alaska, Kamchatka is geographically continuous with Russia but still lacks a land transportation connection. During the war, American soldiers wrote of the Aleutian Islands as a sort of cold, damp hell, while American school teachers more often described them as a flower garden with an advanced native culture. In any case, they were a remote and exotic place to those Americans who even knew they existed. This is still the largely true, and few Americans are aware of the hardships the Aleuts endured during the war, nor of the rich legacy of Russian culture that persists in Alaska among Native people.

Hardly better for science than World War II was the Cold War. The situation changed from the US and Soviet Union allied against Japan to the US and Japan allied against the Soviet Union. Kamchatka and Alaska became armed camps, with the US testing its largest nuclear weapons on Kamchatka's doorstep in the western Aleutians and with Kamchatka off-limits even to most Russians. The Soviet Union did, however, maintain a robust geoscience effort in Kamchatka. Likewise, the United States, in part in support of defense activities, conducted extensive geological and geophysical work in the Aleutians.

The end of the Cold War brought an end to most travel prohibitions. A lingering border dispute over the southern Kuriles is now being addressed in a positive way by Russia and Japan in terms of access for hazard monitoring and science. But easing of tensions did not make travel easy, only possible. Issues of expense, language, culture, and cumbersome visa procedures remain. Air routes are inconvenient and expensive.

For Russians, the Kurile-Kamchatka-Aleutian-Alaska region is a fabled part of their history, and Kamchatka is the one place in their vast country where spectacular volcanism and the greatest earthquakes can be studied firsthand. It is perhaps not surprising, then, that only recently did the state of knowledge of Aleutian/Alaska volcanoes reach the level of knowledge about Kamchatka volcanoes. The record of eruption from historical

---

[1]Currently at Volcano Hazards Program, USGS, Reston, VA.

documents and careful tephrochronology in Kamchatka, some of which is presented here in the overview paper on volcanism by V. Ponomereva and coauthors, still surpasses that of Aleutia/Alaska. The Kurile Islands, posing transportation and telemetry difficulties in their central portion and lingering international tension in the south, remain the least known.

The positioning of the Emperor seamount chain as the shaft at the Kamchatka-Aleutian arrowhead may or may not be a coincidence, but what seems not a coincidence is the prodigious rate of magma production inboard of this junction, represented by the largely mafic Kliuchevskaya group and its more silicic northern neighbor, Shiveluch. In this volume, M. Portyangin and coauthors suggest an answer in large-scale slab melting, as the Pacific slab, torn open under the western Aleutians, dives into hot mantle under Kamchatka. In tectonic overview papers, G. Avdieko and coauthors and D. Scholl wrestle with the meaning of the cusp from vantage points from the west and east of it, respectively. A. Lander and M. Shapiro focus on constraining the onset of the modern volcanic and subduction regime of Kamchatka with seismic data. Intriguing related problems are the welding of arc fragments to Kamchatka as the eastern capes, the origin and behavior of neighboring microplates, and the apparent double arcs of Kamchatka, one young and robust and the other old and dying.

On either side of the arrow's point are two almost matching arc pairs: continental Kamchatka Peninsula with oceanic Kurile Islands, and continental Alaska Peninsula with oceanic Aleutian Islands. We use the term "arc" for the volcanic expression of subduction in deference to history and to economy of letters, but the volcanoes more properly comprise "supra-subduction zone volcanism". Much of the segment of interest is not an island arc because, except for the Aleutians, the arrangement is not arcuate and, except for the Aleutians and Kuriles, the volcanoes are not islands. The arcuate shape seems irrelevant and to call continent-sited volcanoes "islands" is even worse. Continental margin subduction faithfully follows the shape of the unsubductable continental margin, as is clear along Kamchatka and Alaska. Kurile subduction is a straight line pinned to continental margins at both ends, Hokkaido and Kamchatka. D. Scholl suggests that the Aleutians, a true arc and perhaps an inspiration for the term, "budded" off continental margin subduction of the Alaska Peninsula and progressed westward, turning to the right as it went until it was parallel to Pacific Plate motion and became a transform fault. We should perhaps view the western end as "free", unconstrained by a continental margin because it is perpendicular to it, and hence able to migrate in either direction. Confusingly, arguments can be made for migration in either direction: southward because older "supra-subduction zone volcanism" extends north of the current junction and northward if the east coast capes of the Kamchatka Peninsula represent prior positions of the junction. Indeed, the current

plate boundary, the "corner" representing the northern limit of the subducting Pacific plate, is not where the Aleutian arc/trench pair meets Kamchatka but north of this at a back-arc shear zone. Bering Island seems destined to become another cape on the east coast of Kamchatka.

Scholl argues that the Aleutians, and Avdeiko and coauthors and Lander and Shapiro argue that the eastern volcanic front of Kamchatka, record a large forward jump in volcanism due to jamming of subduction by arc fragments. For the Aleutians, this resulted in capture by North America of the Bering microplate. But now the western Aleutians are being fritted and torn from the North American/Bering plate. For Kamchatka, the postulated jump caused the death of Sredinny Range volcanoes and rise of the prolific and caldera-rich volcanism of the eastern Kamchatka Peninsula. It would seem then that the only steady state subduction regimes are the Kuriles and the Alaska Peninsula, though the latter has a relative dearth of older volcanic rocks on its Mesozoic basement, giving the impression of a very recent start to volcanic growth. These interpretations remain speculative. For example, Scholl observes that the age of Bering microplate crust is poorly known and Ponomareva and coauthors show that the Sredinny Range can be viewed as back-arc volcanism arising from the modern subduction configuration.

The volume is divided into three themes: tectonics, earthquakes, and volcanism. Each section begins with one or more overview papers that not only provide background and context, but also new ideas. They are followed by topical studies focusing on specific features or processes. Of course, the ultimate goal should be a holistic view that encompasses all these manifestations of subduction. It is clear that we are far from that. But although the discussions of tectonics are highly speculative, they pose hypotheses that are clearly testable with more data on age and origin of terranes and on current rates of deformation. Perhaps the greatest progress is evident in seismology, with an understanding of earthquake distribution in time and space based on slab age, convergence rate, stress distribution, and formation of asperities. The diversity of volcanic expression of subduction, in contrast to all other tectonic domains, seems most resistive to solution, though increasingly under attack by new sophisticated geochemical techniques and synthesis with geophysical results. An accompanying DVD provides a view of eruptions in Kamchatka and of the style of field work conducted there not previously available outside Russia.

If there is one place where tectonic, seismic, and volcanic interpretations seem to be converging, it is the arrow itself. The subduction of the torn Pacific plate corner, the seismically inferred rounding of its leading edge, and geochemical inference of a large slab component in resultant eruption products are internally consistent. It is towards such a synthesis of geological, geophysical, and geochemical techniques at the micro and macro scales that this volume strives.

Viewing the Tectonic Evolution of The Kamchatka-Aleutian (KAT) Connection With an Alaska Crustal Extrusion Perspective

David W. Scholl

Department of Geophysics, Standford University, Standford, California, USA, and
College of Natural Science and Mathematics, University of Alaska, Fairbanks, Alaska, USA

The Kamchatka and Aleutian (KAT) arc-trench systems meet orthogonally at Cape Kamchatka Peninsula. The KAT connection is the intersection of the NE-striking Kamchatka subduction zone and the NW-striking, transform setting of the western, Komandorsky sector of the Aleutian Ridge. Deciphering the origin and evolution of the KAT connection is challenging because of the paucity of constraining information about the age and latitude of formation of major crustal blocks of the deep water Bering Sea Basin.

It is proposed that in the late early Eocene (~50 Ma) the combined tectonic machinery of subduction zone obstruction and continental margin extrusion created the tectonic and rock architecture of the Aleutian-Bering Sea region. Accretion of the Olyutorsky arc to the north Kamchatka-Koryak subduction zone forced the offshore formation of the Aleutian subduction zone (SZ), added a sector of Pacific crust—Aleutia—to the North America plate, and established the KAT connection. Subsequently, but also in the middle Eocene, extrusion of Alaska crust southwestward across the Beringian margin connecting Alaska and NE Russia buckled Aleutia and forced the offshore formation of the Shirshov and Bowers SZs. Extrusion was driven by northward oblique underthrusting beneath British Columbia and SE Alaska.

In the early Tertiary the Aleutian and Kamchatka SZs, linked at the KAT connection, thus consumed northwest moving crust of the Pacific Basin and within the Bering Sea the Beringian, Shirshov, and Bowers SZs accommodated SW extruding Alaska and captured Aleutia crust. Since the early Miocene extrusion space has been provided by the Aleutian SZ. Arc-arc collisions at the KAT connection have been guided by the right-lateral Bering-Kresta shear zone, which lies at the Bering Sea base of the Komandorsky section and terminates at Cape Kamchatka Peninsula. In the past the tectonic connection with Kamchatka may have been farther to the north.

1. INTRODUCTION

The northwestern corner of the Pacific basin, as widely recognized, is an unusual right-angle confluence of two lengthy arc-trench systems, those of the Kamchatka and

Aleutian subduction zones. Their tectonic contact is, for the convenience of this paper, dubbed the KAT connection (Fig. 1A). The KAT connection is widely believed to be an intermittent collision zone between the arc massifs of the two subduction zones. Collision began in the late Neogene or earlier in the Tertiary as terranes or blocks of arc crust of the far western or Komandorsky sector of the Aleutian Ridge entered the Kamchatka subduction zone (SZ) from the east. The eastward projecting promontory of the Cape Kamchatka Peninsula physiographically marks the collision zone (Fig. 1B; Watson and Fujita, 1985; Zinkevich et al., 1985; Zoneshain et al., 1990; Baranov et al., 1991; Geist and Scholl, 1994; Seliverstov, 1998; Gaedicke et al., 2000; Freitag et al., 2001; McLeish et al. 2002). In the past, the collision zone may have been farther to the north.

Collision at the KAT connection is the kinematic consequence of the circumstance that the Cape Kamchatka Peninsula is the intersection of the NE-striking Kamchatka SZ and the right-lateral transform plate boundary striking NW along the Komandorsky sector of the Aleutian Ridge (Fig 1B). The transform boundary along the far western Aleutian Ridge is a complex, distributed shear zone that embraces the width of the arc massif from trench floor to the backarc (Cormier, 1975; Geist and Scholl, 1994; Gaedicke et al., 2000, Freitag, 2001; Kozhurin, this volume).

So how did the KAT connection come to be? This paper explores an hypothesis that Pacific rim tectonism created, in the Aleutian-Bering Sea region, the geometry of the offshore subduction zones of the Aleutian-Shirshov-Bowers system that led to arc-arc collision at the KAT connection (Fig. 1A). The scenario outlined in this paper is based on the published ideas and data of many colleagues as cited. The tectonic sketch advance is speculative because constraining information is lacking to test assumptions that must be made about the ages and origins of key crustal blocks and terranes that construct the Aleutian-Bering Sea region. Compounding matters, the paucity of regional paleomagnetic data east of Kamchatka means that assumptions have also to be made about the paleogeographic origins of the crustal blocks of the Bering Sea Basin and the Cenozoic style(s) of north Pacific rim tectonism that brought the key pieces of the KAT junction together. A spotty but improving GPS data set for the Aleutian Ridge, however, apparently reveals the fundamental nature of westward block transport toward collision with Kamchatka (Oldow et al. 1999; Avé' Lallemant and Oldow, 2000); Gordeev et al., 2001; Steblov et al., 2003, Cross and Freymueller, 2007). Nonetheless, the troubling circumstances of insufficient regional information to constrain models apply equally to all evolutionary schemes that have been suggested for the origin of the Aleutian-Bering Sea region and thus the KAT connection.

Three tectonic models for the early Tertiary genesis of the Aleutian SZ have been posited. The most accepted of these is the clogging or occlusion model describing the tectonic jamming of the north Kamchatka-Koryak SZ then occupying the northwestern-most or Cape Navarin corner of the Pacific Basin (Fig 1A). Southwest of the corner, subduction was obstructed by docking or accretion of the northward migrating Olyutorsky arc complex (Fig. 2A; Zonenshain et al., 1990, Garver et al., 2000). Suturing of the exotic arc complex to the north Kamchatka-Koryak margin forced formation of a new offshore subduction zone—the Aleutian SZ. The driving force was continuing slab pulls beneath Alaska and Kamchatka, west and east, respectively, of the obstructed north Kamchatka-Koryak SZ.

The colliding arc complex is also referred to as the Achaivayam-Valagin or Olyutor-Valaginskii arc complex (see discussion in Park et al., 2002; Sukhov et al., 2004; Chekhovich et al., 2006, Chekhovich and Sukhov, 2006). This Late Cretaceous–early Tertiary arc complex is commonly viewed as having formed well south of it present location either proximal to the NW margin of the Pacific Basin or far offshore. The arc complex would thus be exotic to the Aleutian-Bering Sea Region. This arc complex is usually shown as including the Shirshov and Bowers Ridges of the Bering Sea Basin (Fig. 1A).

In various forms, models for the formation of the Aleutian-Bering Sea region as a consequence of terrane(s) accretion and subduction zone occlusion have been explored and thought through by many authors, for example Ben- Avraham and Cooper (1981), Cooper et al. (1987), Zonenshain et al. (1990), Stavsky et al. (1988; 1990), Seliverstov (1998), Worrall (1991), Scholl et al., (1992), Zinkevich and Tsukanov, (1992), Baranov et al. (1991), Park et al. (2002), Sukhov et al. (2004) and Garver et al. (2000, 2004).

A contrasting model ascribes the origin of the Aleutian-Bering Sea region to the plate-boundary-driven deformation of the north Pacific margin (Scholl et al., 1989). Formation in place of the offshore Aleutian-Shirshov-Bowers subduction zone systems is linked to the SW extrusion of the Beringian margin that trends southeastward from the Koryak margin at Cape Navarin, NE Russia, to the western tip of the Alaska Peninsula (Fig. 1A). Before the formation of the offshore subduction zone system, probably in the late early Eocene about 50 Ma (Jicha et al., 2006), the Beringian margin is inferred to have been the northernmost sector of the dominantly transform boundary separating the North America plate and that of either the Kula or Pacific plate (Moore, 1972; Scholl et al., 1975, 1986; Cooper et al., 1987a; Haeussler et al., 2003; Nokelberg et al., 2005). Figure 2 suggests that the Beringian margin was highly obliquely underthrust by Pacific Basin crust.
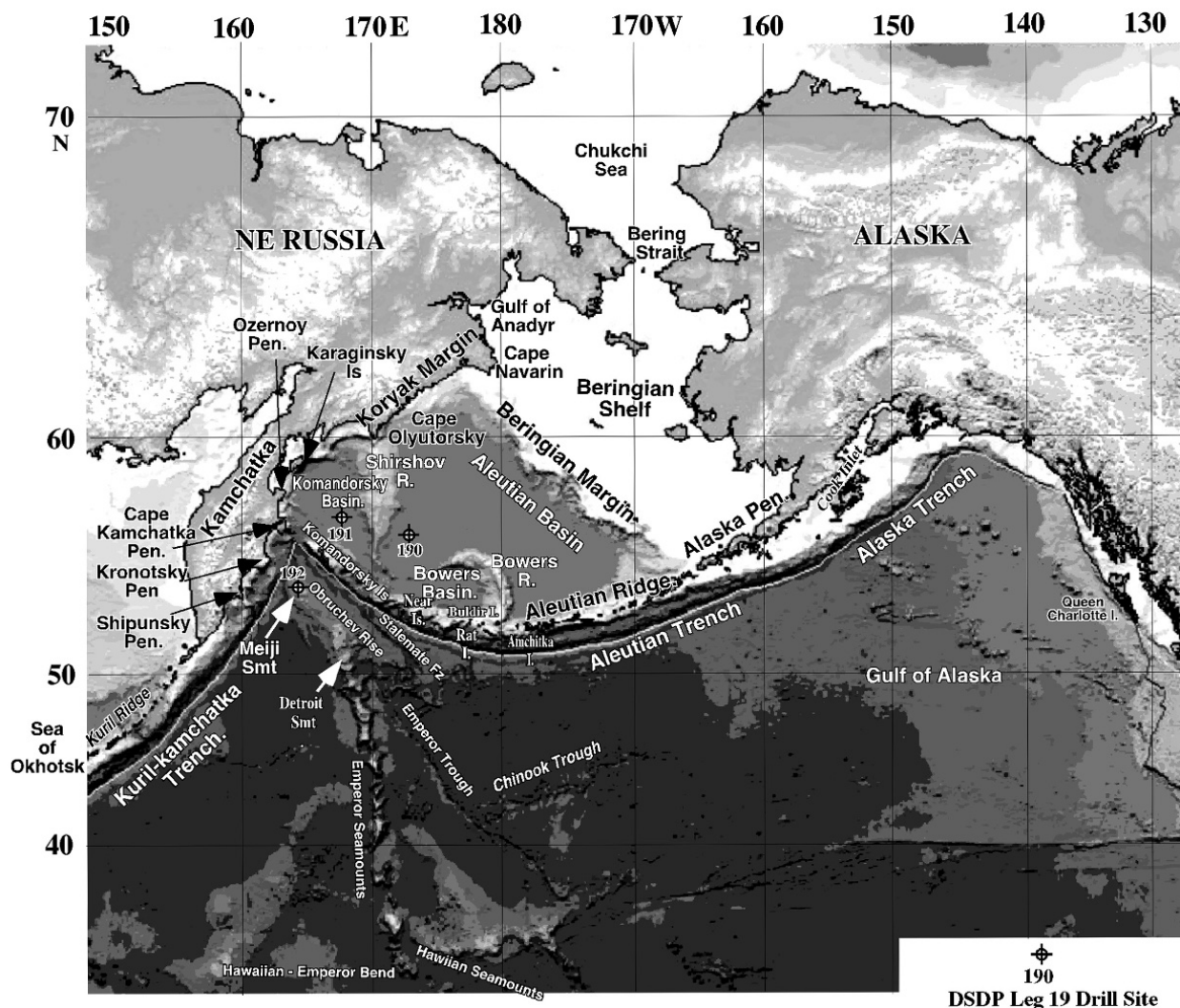
Figure 1A. Physiographic and bathymetric index maps of northeastern Russia, Alaska, and the north Pacific-Aleutian-Bering Sea region. Mercator-projection map derived from This Dynamic Planet (http://www.minerals.si.edu/tdpmap/index.htm). Major tectonic elements are identified on companion Figure 1B.

Seaward displacement and deformation of the Beringian margin is conjectured to have been effected by the extrusion of western Alaska toward the Bering Sea region. Tectonic push-out or extrusion of Beringian crust toward and along the Beringian margin is hypothesized to have buckled the oceanic crust then residing in the area of the modern Bering Sea Basin leading to establishment of the Shirshov, Bowers, and Aleutian SZs (Fig. 2B). The extrusion or escape model for the genesis of the Aleutian-Bering Sea region has been outlined by Scholl and Stevenson (1989,1991), Scholl et al. (1992, 1994), Scholl, (1999), and Lizarralde et al. (2002) and most completely by Redfield et al. (in press). Southwestward extrusion of western Alaska and Bering Sea crust is on-going today as the Bering block identified with regional seismic

and geologic data assembled and interpreted by Mackey et al. (1997) and Fujita et al. (2002). Enhanced movement of the Bering block southward toward the Aleutian SZ and westward toward the Kamchatka-Koryak margin is presently driven by the late Neogene collision of the Yakutat block with the eastern end of the Alaska SZ (Fig. 1B; see also Mazzotti and Hyndman, 2002; Eberhart-Phillips et al. 2006).

A third model merges or couples the tectonic machinery of the first two scenarios as forcing the formation of the Aleutian-Bering Sea region and its three offshore SZs (see Fig. 10; Scholl et al., 1992; Cooper et al., 1992; Scholl 1994). The occlusion-extrusion or coupled model is explored in this paper as the working hypothesis principally because it is evident that the Late Cretaceous-early Tertiary Olyutorsky
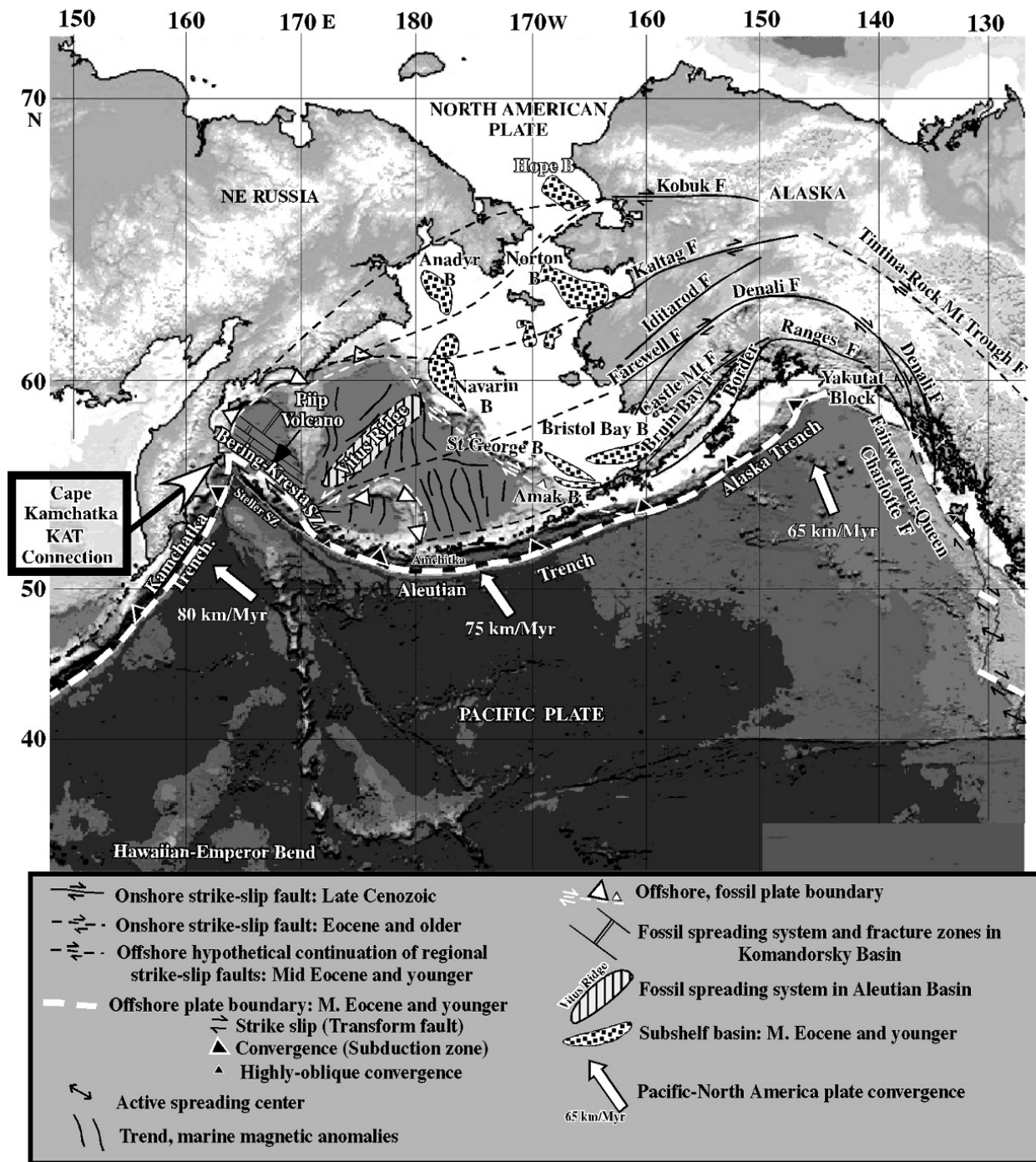
Figure 1B. Major tectonic elements of the north Pacific rim and offshore Aleutian-Bering Sea region and north Pacific Basin. Active and inactive strike-slip faults (F) and shear zones (SZ), and major Beringian shelf basins (B).

arc complex was accreted to the Kamchatka margin of the western Bering Sea at the same time as, or just before, the arc volcanic construction of the Aleutian Ridge began to form in the middle Eocene (Levoshova et al., 1997, 2000; Zonenshain et al., 1990; Seliverstov, 1998; Garver et al., 2000; Garver et al., 2004, Jicha et al., 2006, Chekhovich and Sukhov, 2006). Paleomagnetic data also document that the Aleutian Ridge, which is not known to include pre-Tertiary rock, is not an

exotic terrane but formed effectively in place (Harbert, 1987) as a western addition to the much older continental crust of the Alaska Peninsula (Burk, 1965). Similarly, the Aleutian SZ is viewed as a westward continuation of the Alaska SZ (Scholl et al., 1975; 1986; 1987). Farther west, the newly formed Aleutian SZ was presumably connected by a NW-trending, right-lateral shear zone or transform system to the older Kamchatka SZ (Lonsdale, 1988). In this way the KAT connection was first established that ultimately led to the collisions of blocks of the far western sectors of the Aleutian arc massif with the landward slope of the Kamchatka Trench (Fig. 2).
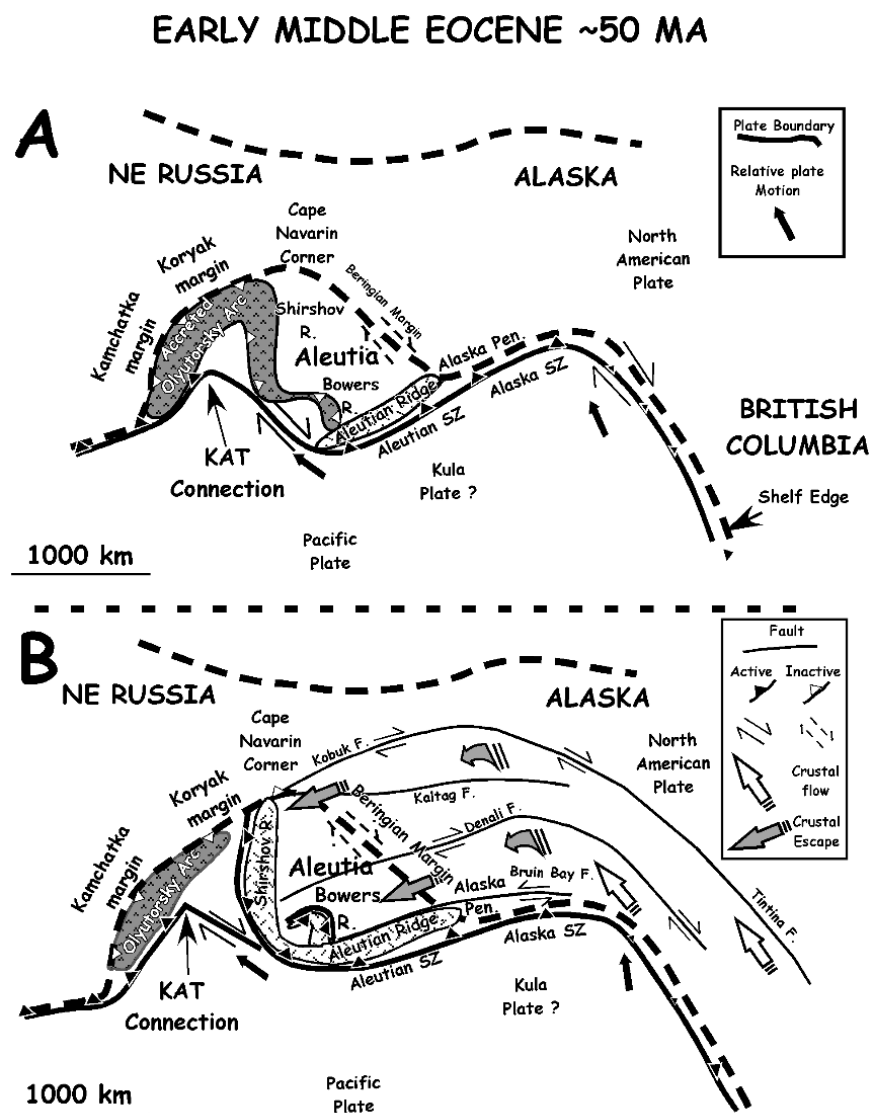
Figure 2. Two general models, (A) subduction zone (SZ) occlusion of the Kamchatka-Koryak margin, and (B) plate boundary extrusion of the Beringian margin, have been proposed for the origin of the offshore Aleutian SZ, accretion of a sector of Pacific lithosphere (Aleutia) to the North America plate, and consequent formation of the Aleutian-Bering Sea region. (A) Accretion of a Pacific-basin born, and thus exotic to the Bering Sea, Olyutorsky-Shirshov-Bowers arc complex to the Kamchatka-Koryak margin occludes (jams) the SZs of the Pacific's northwestern rim and forces offshore formation of the Aleutian SZ. (B) Plate-boundary driven lateral crustal streaming and extrusion of the Pacific's northeastern rim forces the in-place formation of the offshore Aleutian-Shirshov-Bowers SZ system.

   This paper presents a model that merges both plate-boundary modifying forces to create the Aleutian Bering Sea region and the Kamchatka-Aleutian or KAT tectonic connection.

In the coupled model, the Bowers and Shirshov Ridges would have formed in-situ as a consequence of extrusion of western Alaska and Bering shelf crust toward the Beringian plate margin. Woven into the working hypothesis are the recent findings in the north Pacific concerning the age, origin, and tectonic implications of the prominent change in trend or bend in the Hawaiian-Emperor seamount chain (Figs. 1A and B; Tarduno et al., 2003, Paré's and Moore, 2005; Sharp and Clague, 2006; Steinberger and Gaina, 2007). The beginning age of the sweeping bend, which required about 8 Myr to complete, is ~50 Ma (Sharp and Clague, 2006). This age matches the final docking time of the Late Cretaceous-early Tertiary massif of the Olyutorsky arc complex (Garver et al., 2000; Garver et al., 2004; Chekhovich and Sukhov, 2006) and the best estimate of the origin of the Aleutian SZ (Jicha et al., 2006).

The coupled model considers that the Bering block of Mackey et al. (1997) and Fujita et al., 2002) is the westernmost part of a laterally moving crustal track that extends northwestward from NW British Columbia in a broad counterclockwise curving arc through central Alaska to the KAT connection (Fig. 2). The northward and westward moving track of British Columbia, Alaska, and Bering crust is collectively referred to (see discussion below) as the North Pacific Rim orogenic stream or NPRS (Redfield et al. in press). The plate boundary forces and suprasubduction zone setting described by Mazzotti et al (in press) that have long mobilized a Pacific rim orogenic float (Oldow et al., 1990) are those involved in laterally moving the NPRS. The expanse of Bird's (1996) computer simulations of north Pacific rim tectonism is effectively that of the NPRS.

2. MAJOR CRUSTAL BLOCK

2.1 The Bering Block

2.1.1 Observations. Seismic and geological observations of Mackey et al. (1997) and Fujita et al. (2002) define the Bering block as the largest tectonostratigraphic element of the KAT connection. The Bering block includes much of western Alaska and the whole of the Aleutian Ridge including the KAT connection (Fig. 3). The Bering block rotates clockwise and deforms the Koryak and northern Kamchatka margins of the Bering Sea.

The Okhotsk microplate exists west of the Bering block and, as documented by Bourgeois et al. (2006) and Pedoja et al. (2006), the westward extrusion of the Okhotsk lithospheric slab (Riegel et al., 1993) toward the Kuril-Kamchatka SZ is importantly involved in the KAT collisional processes. Extrusion of the Okhotsk microplate forces Kamchatka to overrun the Komandorsky Basin that forms the western side of the deep water Bering Sea Basin (Figs. 1A and 3).
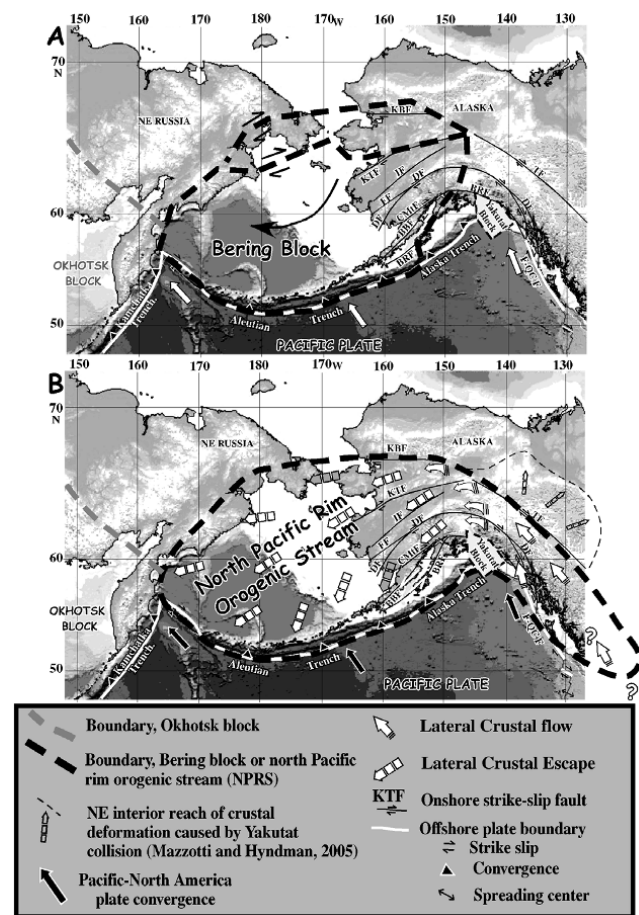
Figure 3. Upper diagram (A) sketches outline of the Bering Block of Mackey et al. (1997) and Fujita et al. (2002). Lower diagram (B) sketches outline of the CCW flowing north Pacific orogenic stream the leading front of which is the Bering Block (Redfield et al., in press). Abbreviations of strike-slip faults match full names shown on Figure 1B.

2.1.2 Interpretations. Kinematically, the Bering block can be viewed as the westward or leading edge of the NPRS as described by Redfield et al. (in press) and that embraces the regional tectonic concepts of the orogenic float of Oldow et al. (1990), Mazzotti and Hyndman (2002), and Mazzotti et al. (in press) (Fig. 3). The Bering block can be tectonically added, as the leading edge, to the laterally moving crust included within the great family of strike-slip faults that strike northwestward along the British Columbia margin and coastal region (e.g., Tintina, Denali, Fairweather, Queen Charlotte, etc fault systems) and curve through the so-called Alaska oroclinal bend to fan out southwestward toward the Bering Sea (e.g., the Kobuk, Kaltag, Iditarod-Nixon Fork, Denali, Farwell, Castle Mountain, Bruin Bay and Border Ranges, etc fault systems; Fig. 3B; Redfield et al., in press). This view is based on the

observation that the major shear systems of the NPRS are or have been active in the late Cenozoic (Mackey et al. 1977; Page et al., 1991; Fujita et al., 2002); Haeussler et al., 2004). In western Alaska the southwestward expanding pattern of strike-slip faults implies the faults are slip lines bordering differentially extruding gores of Alaskan and Bering shelf crust. The pattern is similar to that of the differentially extruding and rotating crustal slices of SE Asia (Tapponnier et al., 1982, 1986) and Anatolia (Nyst and Thatcher, 2004).

2.1.3 Issues. The notion that the northward and westward moving North Pacific Rim orogenic stream existed in the early Tertiary is based on the absence of significant interior Alaska mountain building yet the recording of hundreds of kilometers of offsets across, and localized deformation along, the curving pattern of regional strike-slip faults that tectonically connect western Alaska and British Columbia (Redfield et al., in press). The concept of a currently extruding western crustal track is based on the seismically defined Bering block, deformation along its western or NE Russian edge, and a limited but growing inventory of epicentral and fault mechanism data stretching eastward back into central Alaska (Page et al., 1991, 1995; Eberhart-Phillipps, 2006). To test this idea an extensive network of GPS stations is needed in western Alaska and on the Bering shelf. Extrusion or tectonic escape can be identified if crustal blocks are detected moving westward and southwestward toward the Aleutian SZ at a rate exceeding a component of motion in these directions generated by convergence between the North America and Pacific plates. The complex movement of blocks of crust documented by Nyst and Thatcher (2004) for the extruding Anatolian microplate implies that similar patterns of crustal shearing, extension, and both large and small scale rotations will be true for the hypothesized NPRS (Mackey et al. 1997; Fujita et al. (2002).

2.2 Komandorsky Basin

2.2.1 Observations. The broad expanse of the Komandorsky Basin, the far western part of deep water Bering Sea Basin, lies north of the KAT connection (Fig. 1B). The Bering-Kresta shear zone trending along the southern edge of the basin most likely separates its oceanic crustal framework from that of the arc massif of the Komandorsky sector of the Aleutian Ridge (Seliverstov, 1984; Baranov et al, 1991; Geist and Scholl, 1994). To the east, the arc crustal mass of Shirshov Ridge separates the oceanic basement of the Komandorsky Basin from that of the Aleutian and Bowers Basins (Figs. 1A and 1B).

Muzurov et al. (1989), Baranov et al. (1991) and Valyasho et al. (1993), established that the Komandorsky basin was formed by a style of rear or backarc spreading in a direction parallel to the axis of the arc. Baranov et al. (1991) note that opening of the Komandorsky Basin in a NW-SE direction took place parallel to the active Pacific-North America (PAC/ NAM) transform boundary of the Bering-Kresta shear zone. Opening was thus parallel to relative plate motion (Plate 1 and Fig. 4). The opening of the Miocene Komandorsky Basin is similar to the opening of the backarc Andaman Sea subparallel to the relative motion between the India-Australia plate and that of the Sumatra sector of the Eurasian plate (Subarya et al., 2006). Although concentrated at the Bering-Kresta shear zone, transform shearing is distributed southward across the width of the Komandorsky sector of the Aleutian Ridge to the Stellar shear zone in the Aleutian Trench (Fig. 1B and Plate 1, see also Fig. 7; Cormier, 1975; Seliverstov, 1984; Baranov, 1991; Geist and Scholl, 1994; Gaedicke et al., 2000; Freitag et al., 2001; Kozhurin, this volume**).**

Magnetic anomalies constrain the emplacement of rear-arc crust between about 20 and 10 Ma and document that the speed of opening increased southward toward the Bering-Kresta shear zone (Fig. 4; Valyasho et al., 1993). The young age is consistent with the relatively thin sedimentary sequence (1–2 km) filling the basin, the late Cenozoic age of its basal sediment at DSDP Site 191, and ~9 Ma age (K-Ar) of the underlying basement (Creager, Scholl, et al., 1973; Baranov et al., 1991; Cooper 1987a, b). The thickest (3+ km) sedimentary sequences occur in trench-shaped depressions at the base of the basin's northern Kamchatka margin (Baranov et al., 1991). The basin's high heat flow (typically > 100 mW/m^2 and as high as 230 mW/m^2) is also consistent with its young crust (Fig. 1B, Plate 1, and Fig. 7); Cormier, 1975; Cooper et al., 1987b, Baranov et al., 1991). In the northwestern Pacific, emplacement of crust in the Komandorsky basin took place after the earlier Tertiary opening of the Kuril Basin of the Sea of Okhotsk and, farther south, the Sea of Japan (Baranov, et al., 2002).

2.2.2 Interpretations. The Aleutian SZ is at least older than the oldest known arc igneous rock at ~46 Ma (Jicha et al., 2006), and the crust of the Komandorsky Basin was emplaced 25–35 Myr later (between ~20–10 Ma; Valyasho et al., 1993). The direction of spreading was parallel to the Bering-Kresta shear zone (Figs. 1A and Plate 1). So it seems evident that the direction of spreading was controlled by the pre-existing strike of the Aleutian Ridge's transform or Komandorsky sector and that its NW trend may not have significantly changed since at least the early Miocene.

Yogodzinski et al. (1993) recognized that the Komandorsky Basin resides in a transform-boundary setting similar to that
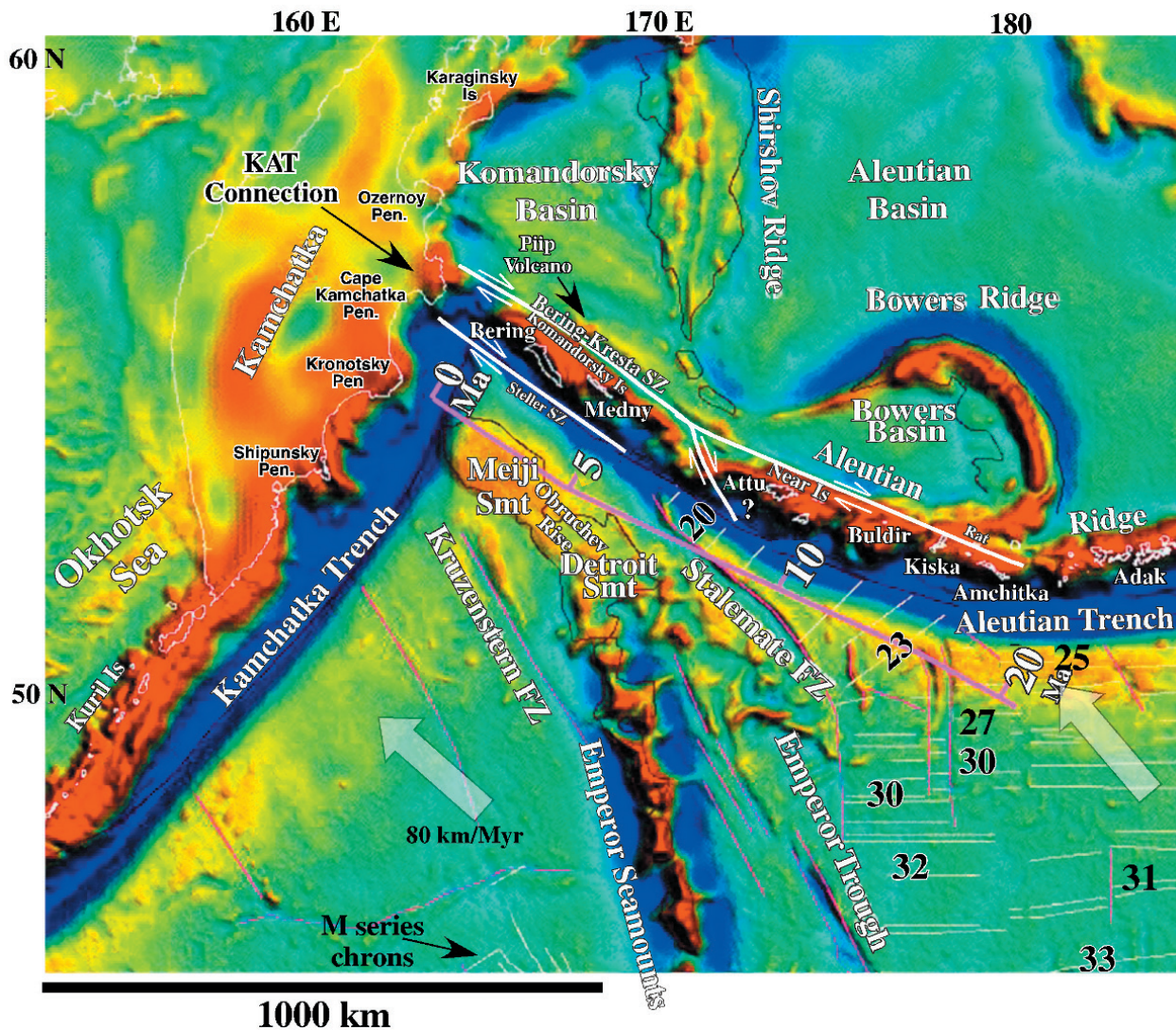
Plate 1. Index map of gravity (lows are in blue tones and highs in orange and red) and magnetic anomalies (white lines) adapted from Norton (in press) for the northwestern most or Meiji corner of the Pacific Basin. Mid Cretaceous oceanic crust, which lacks a pattern of magnetic anomalies, underlies the Meiji corner. Older early Mesozoic or M-series anomalies are recorded to the south on the western side of the ridge of the Emperor Seamounts. East of the ridge are Late Cretaceous and early Tertiary magnetic anomalies (Chrons 33 to 20 in black numbers). Fracture zones are traced with thin red lines. See also Miller et al. (2006).

Pink line with 0, 5, 10, and 20 Myr ticks (white numbers) tracks the WNW movement of the Pacific plate toward the Kamchatka subduction zone during the past 20 Myr. The high bathymetric relief lying east of the Emperor Seamounts and including Stalemate Fracture Zone, Emperor Trough, and an unnamed cluster of seamounts between them, began to obliquely enter the western sectors of the Aleutian subduction zone ~20 Myr ago. Tectonism of the Aleutian Ridge was a likely consequence (Vallier et al., 1992, 1996), causing or contributing importantly to the fragmentation of the arc massif and rapid transport of block toward the Kamchatka Trench and the tear in the Pacific plate underlying the Near and Komandorsky Islands sector of the ridge (Yogodzinski et al., 2001). Potentially, entrance of high relief into the western sector of the subduction zone also stimulated rear-arc spreading in the Komandorsky Basin from ~20 to ~10 Ma (Baranov et al., 1991; Valyashko et al., 1993).

of the Andaman Sea. They also conjecture that Miocene spreading involved the westward transport of blocks of arc crust along the Bering-Kresta shear zone. Their collision with Kamchatka significantly changed arc-volcanic processes operating along the far western Aleutian Ridge.

Formation of the mostly early Miocene crust in the Komandorsky basin requires that either room was tectonically opened for its emplacement or that older, pre-existing crust was assimilated or buried in place, an hypothesis considered by Scholl and Creager (1973) and Cormier (1975). But the mapping of fossil spreading centers and companion magnetic anomalies and fractures zones document that crustal replacement was by backarc spreading (Baranov et al. 1991). Evidence is unknown to the author that Komandorsky spreading was accompanied by displacement of Kamchatka to the NW (by a minimum of several hundred kilometers), or Shirshov Ridge to the east over the older crust of the Aleutian Basin, or the subduction of this crust beneath the basin's Beringian margin (Scholl et al., 1986; Cooper et al., 1987a, b; 1992). Hence older crust existing in the area of the Komandorsky Basin—a part of the Aleutia terrane of Marlow and Cooper (1983)—was evidently removed to the west in the early and middle Miocene by basin-edge subduction below northern Kamchatka (see Fig. 10).

Hochstaedter et al., 1991 cites the eruption and geochemical characteristics of the Vyvenka igneous bodies (15–6 Ma.) in northern Kamchatka as recording the westward subduction of Komandorsky crust beneath Kamchatka. The existence of a sediment-filled trench at the base of the eastern Kamchatka margin is arguable evidence for west-directed subduction of the pre-existing crust occupying the basin prior to the early Miocene (Baranov et al., 1991; Avdeiko et al., this volume).

Tectonic circumstances that reinitiated subduction beneath the northern margin of Kamchatka and the emplacement of early Neogene crust in the Komandorsky Basin are unknown. But the southern crust of the Komandorsky Basin resides above a probable regional tear in the subducting Pacific plate that passes deeply beneath the basin (Creager and Boyd, 1991). The tear, the southern edge of which lies parallel to and below the Bering-Kresta shear zone (Fig. 1B), begins near Buldir Island (176 deg E; Fig. 1A and Plate 1), the westernmost subaerial volcanic edifice of the Aleutian Ridge, and extends northwestward ~1000 km to dive westward below Kamchatka (Yogodzinski et al., 1994, 1995, 2001; Peyton et al., 2001; Levin et al., 2002; Park et al., 2002, Kelemen et al., 2003; Levin et al., 2005).

It is tempting to link crustal emplacement in the Komandorsky Basin to early Miocene tearing of the Pacific slab highly obliquely underthrusting the western and far western sectors of the Aleutian Ridge. Tearing may have ini-
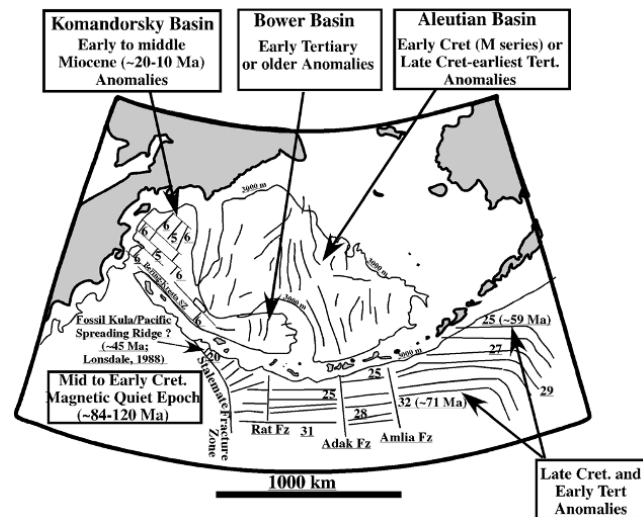
Figure 4. Drawing of magnetic anomaly patterns, showing Chron numbers, for north Pacific and Bering Sea Basin region. Aleutian Basin pattern from Cooper et al. (1992); Komandorsky Basin pattern and age estimates from Valyasho et al. (1993)—see also Baranov et al., (1991); north Pacific pattern from various sources (see Figure 4 and Atwater, 1989; Atwater and Severinghaus, 1989; and Norton, in press).

tiated asthenospheric upwelling in the Komandorsky Basin, a general concept explored by Cormier (1975). Although back-arc basins are characterized by high heat flow (Hyndman et al. 2005), ascent of the asthenosphere is consistent with the basin's exceptionally high heat flow that increases toward the southern end of the basin where the massive and submerged Piip volcano erupts in a graben just north of the Bering-Kresta shear zone (Fig. 1B and Plate 1; Cormier, 1975; Cooper et al. 1987b; Baranov et al., 1991). As noticed by Yogodzinski et al. (1993, 2001), the slab tear posit is supported by the Neogene and younger eruption of calc-alkaline magma and high magnesium andesite ("adakite") along the western sectors of the Aleutian Ridge and including at Piip volcano.

An alternative model is to recognize that slab tearing may have been a consequence of the re-initiation of subduction westward beneath northern Kamchatka. Subduction start-up would have led to rifting of the Shirshov forearc, the end of subduction beneath it, and the beginning of asthenospheric ascent or upwelling to nourish within-basin spreading behind the east or trailing edge of the westward subducting sector of Aleutia (Yogodzinski et al., 1993). Upwelling beneath the basin could have promoted the tearing away of the Pacific slab then residing deep beneath it, but connected across the Komandorsky sector's transform fault system to the Pacific Basin south of the Aleutian Ridge. Tearing and falling away of the Pacific lithosphere north of the ridge was evidently

focused below the Being-Kresta shear zone. Melting of the heated edge of the Pacific plate would have favored the ascent of adakitic magma along the western sectors of the Aleutian Ridge and including at Piip volcano (Fig. 1B and Plate 1; Yogodzinski et al., 1994, 1995).

2.2.3 Issues. Capture of the basement of the Aleutian Basin on the east side of Shirshov Ridge—Aleutia—was apparently in the late early Eocene (~50 Ma) and thus most likely involved accretion of a sector of Pacific or Kula plate because the only other candidate plate, the Resurrection plate (Haeussler et al., 2003; Farris et al., 2006), had by 50 Ma disappeared beneath Alaska and the Pacific margin of British Columbia (Fig; 2, also see Fig. 10A). Prior to its replacement between ~20 and ~10 Ma, the westward expanse of Aleutia would have included the existing area of the Komandorsky Basin (See Figs. 10A and B).

Allowing that in some form the Aleutia replacement scenario and accompanying slab tearing is correct, it is not obvious why westward subduction beneath northern Kamchatka to accommodate basinal crust generated by spreading did not happen until at least 25 Myr after the formation of the Aleutian-Bering Sea region. Possibly, the removal mechanism was driven by the heating and eclogite densification of the fossil slab of Aleutia dipping westward beneath northern Kamchatka. Vallier et al. (1987, 1994, 1996) also speculate that early Miocene entrance of high bathymetric relief into the western sectors of the early Miocene Aleutian SZ may have led to significant tectonism of the Aleutian Ridge west of about Amchitka Island (Plate 1) and the consequent rapid movement of crustal blocks toward the Kamchatka subduction zone. These concepts are explored further below.

2.3 Far Northwest Pacific and Coastal Kamchatka.

2.3.1 Observations. Oceanic crust of the Pacific plate forms the south side of the KAT connection. The age of this crust is not accurately known because it was created at a north Pacific spreading center during the Cretaceous Long Normal Polarity Chron (~83–119 Ma) and thus lacks a reversal fabric of magnetic anomalies, (Plate 1 and Fig. 4; Mammerickx and Sharman, 1988, Lonsdale, 1988; Sukhov et al., 2004; Sager, 2005; Norton, in press; Miller and Kennett, 2006). However, paleomagnetic and age dating studies establish that the oceanic crust south of the Aleutian Trench and flanking the northern base of Detroit Seamount formed at ~81 Ma at a paleolatitude of ~36 degs N (Fig. 1A; Tarduno and Cottrell, 1997; Cottrell and Tarduno, 2003; Tarduno et al., 2005). The volcanic edifice of Detroit Seamount rises above the northern end of the NNW-trending ridge of the Emperor Seamounts. Detroit was eruptively emplaced at

about 76 Ma, at a paleolatitude near 34 deg N (Duncan and Keller, 2004, Tarduno et al., 2005), and proximal to a spreading center most like trending NW-SE parallel to Obruchev Rise (Keller et al., 2004; Norton, in press). The rise is the deeply sediment-buried ridge that connects Detroit and Meiji Seamounts (Fig. 1A; Scholl et al., 1977; Scholl et al., 2003; Kerr et al., 2005). Meiji, bathymetrically and by continuity, is presumably the northernmost of the Emperor Seamounts, was probably emplaced toward 80 Ma, a paleontologically based age assessment because rock alteration of recovered basalt core has significantly reset the K-Ar clock (Creager, Scholl, et al., 1973; Duncan and Keller, 2004). The Meiji edifice is poised to orthogonally enter the Kamchatka SZ at the Kronotsky Peninsula (~55 deg N; Figs. 1A, 1B and Plate 1).

A significant tectonic and physiographic companion to the KAT connection is Obruchev Rise, which is carried on the Pacific plate and trends parallel to the Komandorsky transform sector and enters the Kamchatka Trench at Cape Kronotsky (Plate 1). Both the Komandorsky sector of the Aleutian Ridge and the Obruchev sector of the Emperor Seamounts thus terminate at paired, effectively non-migrating collision zones. Orthogonal collisions at these capes have probably been ongoing since at least the mid Tertiary. Based on GPS data, the Komandorsky sector of the Aleutian Ridge enters the Kamchatka SZ at close to the speed of the rise (~80 km/Myr; Avé Lallemant and Oldow, 2000; Gordeev et al., 2001; Steblov, et al., 2003). Effectively, the Komandorsky sector is, like the Obruchev Rise, part of the Pacific plate.

2.3.2 Interpretations. When the formation of the Aleutian SZ created the KAT connection (Fig. 2), the Late Cretaceous ocean crust and cresting Obruchev Rise and Emperor Seamounts resided at least 2500 km to the SE. Detroit Seamount, for example, was positioned in the general vicinity of 35 deg N and perhaps as far east as 150 deg W (Engebretson et al., 1984; Tarduno et al., 2003; Norton, 1995; in press). Thus much of the length of the Pacific plate along which the original transform connection between the Aleutian and Kamchatka SZs was established has been subducted (Plate 1).

Most authors agree that the Cape Kamchatka Peninsula records late Cenozoic collision of the Aleutian Ridge's Komandorsky sector with eastern Kamchatka (Watson and Fujita, 1985; Zinkevich et al., 1985; Zoneshain et al., 1990; Baranov et al., 1991; Geist and Scholl, 1994; Seliverstov, 1998; Gaedicke et al., 2000; Freitag et al., 2001; McElflesh et al., 2002). Views differ about what tectonic and structural processes formed the other two eastern peninsulas, Kronotsky and Shipunsky, south of the Cape Kamchatka Peninsula (Fig. 1A and Plate 1). The accretion of sectors of

Pacific-basin born arc massifs is commonly suggested (see for example Seliverstov, 1998; Alexeiev et al., 2006, Avdeiko et al., this volume). Alternatively, from Shipunsky to at least the Cape Kamchatka Peninsula, Park et al. (2002) envision a northward migrating collisional scheme sequentially adding sectors of the Aleutian Ridge to eastern Kamchatka.

However, as noted by Park et al. (2002), the existing base of data does not clearly define when the eastern capes formed, how they were created, or if their formations are tectonically kindred. It is equally plausible to suppose that the prominent capes of eastern Kamchatka record the orthogonal subduction of bathymetric relief, Kruzenstern Fracture Zone at Shipunsky (Plate 1; Bürgmann et. al, 2005), Obruchev Rise at Kronotsky, and the Komandorsky sector of the Aleutian Ridge at Cape Kamchatka Peninsula (Fig. 1A and Plate 1). Crustal elevation to form the capes could be effected by collisional underthrusting and consequent upper plate shortening or underplating. The underthrusting oceanic or arc relief need not be coastally exposed.

It is not known how much of the length of the Obruchev Rise has entered the Kamchatka SZ to potentially build the elevated structure of the Kronotsky Peninsula, but the deformed slab dipping beneath it suggest a period of at least several million years (Gorbatov et al., 1997). The rise's thick sediment cover provided by the deposition of the Meiji drift body implies a subducted length of at least 1000 km (Scholl and Rea, 2002; Scholl et al., 2003). At the present convergent speed of ~80 km/Myr, the Pacific crust immediately south of the KAT connection approached the Aleutian Trench in the vicinity of Near Pass approximately 10 Myr ago (Fig. 1B and Plate 1; Norton, in press; Miller et al., 2006), or about the time when spreading ceased in the Komandorsky Basin (Baranov et al., 1991; Valyasho et al., 1993). The Obruchev Rise has thus probably been underthrusting and building the Kronotsky Peninsula since the middle Miocene if not before.

2.3.3 Issues. That collisional processes are the cause for the seaward-projecting peninsulas of eastern Kamchatka might be tested with submarine sampling. Where bathymetric ridges underun a convergent margin sedimentary and igneous material from the summit area of the ridge can be detached and accreted to the landward trench slope. Accretion of ridge material has been described from the collision zone of the Nazca Ridge and the Peru Trench (Kulm et al., 1974) and where the Louisville Ridge—the south Pacific's tectonic "twin" of the Hawaiian-Emperor seamount chain—collides with the Tonga Ridge (Ballance et al., 1989). Potentially, oceanic material accreted from the underthrusting Obruchev Rise can be recovered from the landward trench slope east of Kronotsky Peninsula (Plate

1; Gorbatov et al., 1997; Bürgmann et al., 2005). If oceanic debris exists on Kamchatka's landward trench slope, then invaluable information about the history of underthrusting, much as described by Ballance et al., (1989) for the Tonga Ridge, can be obtained.

2.4 Aleutian and Bowers Basins

2.4.1 Observations. The Aleutian and Bowers Basins occupy the eastern side of the deep water Bering Sea Basin (Fig. 1A). The larger Aleutian Basin is flanked to the northwest and northeast, respectively, by the NE-striking Koryak and the NW-striking Beringian continental margins. Arc massifs border the other sides of the basin: Shirshov Ridge to the west and Bowers and Aleutian Ridges to the south. Prominent N-S striking magnetic anomalies are recorded in both the Aleutian and Bowers Basins, and the velocity structure of their basement rock is typical of oceanic crust (Fig. 4; Shor, 1964, Cooper et al., 1987a, b, 1992; Stone, 1988). The age of the magnetic anomalies that stripe the Aleutian Basin has been tentatively identified as Chrons M1 through M 13, younging to the east, of early Cretaceous age (Cooper et al., 1976a, b, 1977). The age of the magnetic pattern in Bowers Basin is poorly constrained. Both basins are characterized by heat flow averaging near 60 mW/m2, which is higher than that expected of Cretaceous crust but not atypical of suprasubduction zone or backarc settings (Hyndman et al., 2005).

The sedimentary sequence underlying the abyssal floor of the Aleutian Basin is typically 2–3 km thick, but the section is as thick as 10–12 km in fossil trenches at the base of the Beringian margin, along the length of the Koryak margin, and below the outward curving, northern side of Bowers Ridge (Fig. 5; Cooper et al., 1987b, 1992). Shirshov Ridge is not flanked by a sediment-filled trench along either its Kamchatka or Alaska-facing sides (Figs. 4 and 5: Rabinowitz and Cooper, 1977; Baranov et al., 1991).

The Beringian continental margin bordering the Aleutian Basin along its Alaska side is underlain by a subsided and erosionally decapitated fold belt—the Beringian fold belt (Fig. 6)—of broadly deformed shallow marine and non-marine beds of late Jurassic, Late Cretaceous, and early Tertiary age. These units are collectively referred to by Worrall (1991) as the Carapace Sequence. Units of the Beringian fold belt accumulated in a forearc setting. No deep water or accretionary complex facies have been recovered along the Beringian margin by dredging or drilling (see summarizing map and descriptions of Grantz et al., 2002). The Mesozoic rocks are unconformably overlain by little-deformed Eocene and younger generally marine shelf facies beds that accumulated to thicknesses as much as 10–12 km
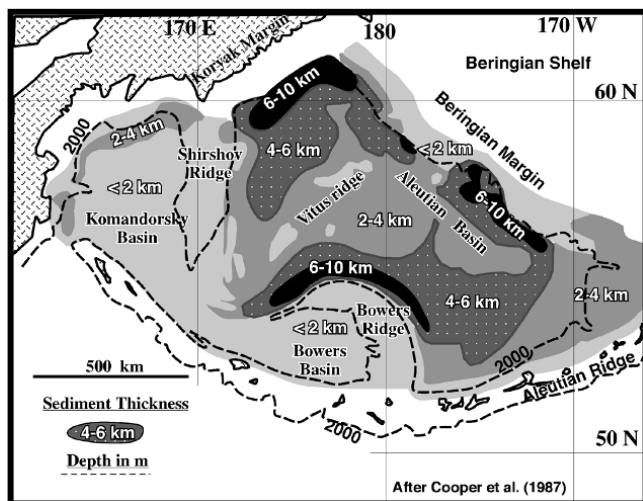
Figure 5. Isopach map of sediment thickness in Bering Sea Basin. Thick (6–10 km) trench-filling sequences, presumably identifying abandoned subduction zones of early Tertiary age, rest at the base of sectors of the Beringian margin, the Koryak margin, and north of Bowers Ridge.

in margin-paralleling basins (e.g., Navarin and St. George; Fig. 6) (Marlow et al. 1987; Worrall, 1991; Grantz et al., 2002). The prominent unconformity is referred to as the "top of Cretaceous" unconformity by Marlow et al. (1987) and the "Red Event" surface by Worrall (1991) (Fig. 6).

The NW margin of the Aleutian Basin, the southern Koryak margin of NE Russia, exposes at and southwest of Cape Navarin shallow marine and non-marine units of middle and late Cenozoic age unconformably overlying deformed early Tertiary and older Cretaceous and Jurassic sequences (Marlow et al. 1987; Worrall, 1991; Grantz et al., 2002). The Mesozoic sequences are recognized as accretionary complexes generally similar to those exposed along the northern margin of the Gulf of Alaska (Plafker et al., 1994). Southwest along the Koryak margin, the Late Cretaceous Olyutosky arc massif that many authors project offshore to include Shirshov Ridge is thrust over the early and middle Eocene margin and basinal flysch sequences (Garver et al., 2004, Chekhovich et al, 2006; Chekhovich and Sukhov, 2006).

The Alaska border of the Aleutian Basin is thus constructed of a framework of broadly deformed miogeoclinal rocks of a Jurassic, Cretaceous, and early Tertiary forearc setting topped unconformably by little deformed basinal sequences of submerged Eocene and younger shelf and upper slope beds (Fig. 6). In contrast, the complementary Koryak margin of NE Russia is an assembly of deformed accretionary eugeosynclinal sequences of Jurassic, Cretaceous, and earliest Tertiary age and accreted arc complexes unconform-

ably overlain by younger, less deformed and subaerially exposed miogeosynclinal deposits (Stavsky et al., 1988, 1990; Zonenshain et al., 1990; see regional maps of Worrall, 1981 and Grantz et al., 2002).

A sediment-filled trench section overlying the oceanic crust of the Aleutian Basin is conspicuous beneath the base
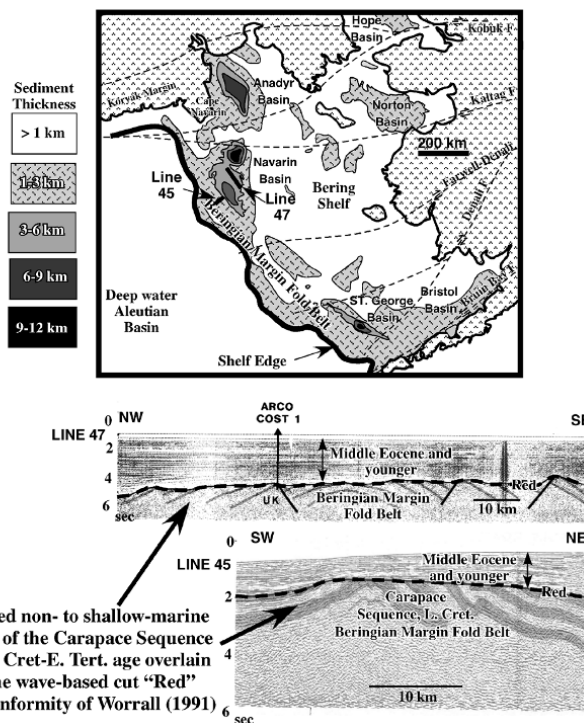
Figure 6. Seismic sections imaging the wave-eroded and depositionally buried antiformal and fault structures of the Beringian margin fold belt of Late Cretaceous and early Tertiary beds. The "Red" unconformity of Worrall (1991) formed until the late middle Eocene (~45-42 Ma). The Beringian margin fold belt is the basement for large, margin paralleling shelf basins largely filled with shelfal deposits of late Eocene and younger age. The history of these basins (e.g., Anadyr, Navarin, St. George) extends back into the Cretaceous when the Beringian margin was largely a transform plate boundary between the North America and Kula or Izanagi plates of the north Pacific Basin (see Norton, in press). Index map and seismic sections are adapted from Worrall (1991). Offshore continuations of onshore, western Alaska strike-slip faults are hypothetical and guided seaward by major shelf structures, volcanic centers, and offsets in the NW-SE trend of the Beringian margin. It is posited that Anadyr and Navarin basins were originally aligned but relative Cenozoic motion across the right-lateral Kobuk and Kaltag fault systems and extrusion of the north Pacific rim orogenic stream (NPRS) offset the basins by more than 200 km (see Figures 1B and 3). Extrusion also juxtaposed the Mesozoic accretionary complexes of the Koryak margin and the similar age but shallow marine and continental deposits of the Beringian Carapace sequence.

of the Koryak margin and also along sectors of the modern Beringian margin (Fig 5; Cooper et al. 1987a, b; Marlow et al., 1987; Worrall, 1981; Klemperer et al., 2002; Grantz et al., 2002). The oldest sampled sedimentary sequence that drapes the margins of the Aleutian and Bowers Basin and extends over the basin floor is Oligocene. Over the basin the oldest sediment recovered by DSDP drilling (at Site 190, Fig. 1A) is middle Miocene (Creager, Scholl et al., 1973; Scholl et al., 1987; Marlow et al., 1987). Drilling at Site 190 was targeted to reach basement but failed to do so. Thus no direct information exists about the age of the oceanic crust of the Aleutian Basin or the much smaller Bowers Basin inside the arc of Bowers Ridge (Fig. 1A). In contrast, the largely early Miocene age of the igneous crust flooring the Komandorsky Basin is known (Muzurov et al., 1989, Baranov et al., 1991).

2.4.2 Interpretations. It has long been supposed that the basement of the Aleutian Basin is a sector of Pacific oceanic crust (Shor, 1964; Ewing et al.1965) generated at a north Pacific spreading center but captured by the North America plate with the formation of the Aleutian-Bering Sea region. (Scholl et al., 1975; Cooper et al., 1976a, b; 1977). This exotic terrane was given the name "Aleutia" by Marlow and Cooper (1983). The principal reason for the capture concept is the prominent basement magnetic anomalies and their N-S, arc-normal trend (Figs. 2 and 4), characteristics not typical of a basin formed by backarc spreading (Stone, 1988).

The time of entrapment of the oceanic crust of Aleutian is constrained by the middle Eocene age (~46 Ma) of the Aleutian Ridge (Jicha et al., 2006). If the trapped crust is indeed early Cretaceous in age, it could be a sector of the Izanagi plate that was incorporated into the Kula plate at its apparent formation at ~83 Ma (Engebretson et al., 1984, 1985; Cooper et al., 1976a, b; Scholl et al., 1986; Norton, in press). If the anomaly pattern is younger than about 83 Ma and older than early to middle Eocene, then the captured sector is not of the Izanagi plate. In the Late Cretaceous and early Tertiary an eastward-migrating spreading ridge separated the Kula plate to the west from the Resurrection plate subducting eastward beneath British Columbia (Fig. 2; Haeussler et al., 2003). Potentially, the N-S pattern of Aleutia's magnetic fabric may be a sector of Kula plate generated west of the eastward migrating Kula-Resurrection spreading ridge (Haeussler et al., 2003; also see Fig. 10A).

Probably during or soon after crustal capture, rifting in the backarc east of Shirshov Ridge formed the now sediment-buried and seamount-populated NE-trending Vitus ridge, a short-lived spreading ridge trending roughly parallel to those that in the early Miocene opened the adjacent Komandorsky

Basin (Cooper et al., 1992; Fig. 1B, also see Figs. 10A and B). A phase of post-capture backarc spreading may also have formed Bowers Basin behind a northeastward migrating Bowers Ridge. Three views have been stated about this possibility, (1) basin formation as part of the early Miocene opening of the Komandorsky Basin (Yogodzinski et al., 1993), (2) basin formation tied to regional scale deformation of western Alaska and the Aleutian Bering Sea region (Cooper et al. 1992), and (3) basin formation linked to extrusion-driven formation of the Bowers and Shirshov SZs (Scholl and Stevenson, 1989; Scholl et al., 1992).

2.4.3 Issues. Knowing the age and latitude of formation of the crust of the Aleutian Basin—Aleutia—is central to reconstructing the configuration of plates and the pattern of crustal ages occupying the high north Pacific when the Aleutian-Bering Sea region formed in the middle Eocene. Although it seems likely the Aleutian Basin is floored by lower Cretaceous crust, this inference has not been confirmed by drilling nor has a wealth of newly collected magnetic data been integrated into the age analysis (Bering Sea EEZ-SCAN Staff, 1991). The age of the probably younger Vitus ridge is also not directly known, nor is that of Bowers Basin (Fig. 1. The age of oceanic crust underlying the Aleutian and the Bowers Basins remains equally uncertain.

Placing N-S magnetically patterned crust of early Cretaceous age in the Bering Sea region at the time of the middle Eocene entrapment of Aleutia, remains problematic for several reasons: (1) confirmation is lacking of their M13–M1 age assignment, (2) the discovery of the Resurrection plate implies that the N-S pattern could have been generated in the Late Cretaceous and early Tertiary west of the eastward migrating Kula/Resurrection spreading center (Haeussler et al. 2003), and (3) the unresolved problem of whether a significant change in motion of the Pacific plate is signaled by the prominent, middle Eocene bend in the Hawaiian-Emperor Seamount chain (Tarduno et al., 2003; Steinberger et al., 2004; Koppers and Staudigel, 2005; Andrews et al. 2006; Sharp and Claque, 2006; Stock, 2006; Steinberger and Gaina, 2007).

Until age and formative latitude data are in hand, for example as are now available for the Detroit sector of the NW Pacific Basin (Tarduno and Cottrell, 1997; Tarduno et al., 2003), the reasons for, and setting of, the Eocene formation of the Aleutian-Bering Sea region and its KAT connection will remain unresolved.

2.5 Shirshov and Bowers Ridges

2.5.1 Observations. Based on geophysical data and dredge sampling, Shirshov and Bowers Ridges, which,

respectively, flank the western edge and part of the southern edge of the Aleutian Basin (Fig. 1A), are recognized as the massifs of volcanic arcs. The northern end of Shirshov Ridge is connected to NE Russia at Cape Olyutorsky (Fig. 1A). Rock assemblages of the accreted Late Cretaceous-early Tertiary Olyutorsky arc are exposed at the cape and also extend farther to the north along the Koryak margin (Levoshova et al., 1997, 2000, Seliverstov, 1998; Garver et al., 2000); Garver et al., 2004; Chekhovich et al., 2006; Chekhovich and Sukhov, 2006). Shortening structures suggestive of a collisional contact between the cape and the ridge are not mapped at Cape Olyutorsky, for example as they are farther to the south at the KAT connection ((Shapiro et al., 1984; Tsukanov and Zinkevich, 1987; Geist and Scholl, 1994).

Basement rock of Shirshov Ridge is extensionally faulted normal to its longitudinal, N-S length, as documented by prominent ridge-paralleling half-grabens (Baranov et al. 1991) mapped prominently by gravity anomalies (Plate 1). Basement highs at depths of 1000–2000 m cresting the northern and central sectors of the ridge are truncated by wave-based erosional platforms (Scholl et al., 1975; Baranov et al., 1991). Neither side of the N-S-trending ridge is flanked by sediment-filled trench structures revealed by satellite gravity (Plate 1) and seismic-reflection-based sediment thickness maps (Fig. 5; Scholl et al., 1975; Rabinowitz and Cooper, 1977; Cooper et al., 1987b; Baranov et al., 1991).

Mafic ocean crust and chert deposits of Late Cretaceous and Triassic age have been reported from dredge samples recovered from the ridge (Bogdanov et al., 1983; Savotsin et al., 1996; Gladenkov, 1990). Dating of Cretaceous beds is based on the radiolaria taxa included within the chert, an assemblage that is also found in similar chert deposits exposed in the nearby Koryak mountains, which are fjord-scarred (Fig. 1A). Hence, ice-rafting of Koryak-derived Mesozoic material to the surface of the offshore Shirshov Ridge is a troubling concern.

Arc volcanic material collected from the southern end of Shirshov Ridge includes feldspar of late Oligocene age (K-Ar date of 27.8 Ma +/- 1.1) that has to be view as minimal (Scholl et al., 1975; Cooper, 1987a, b). The sampled sector of the ridge trends NW-SE, thus striking parallel to the major fracture zones of the Komandorsky Basin and the Aleutian Ridge (Figs. 1B and 4) and very different from the ridge's prominent N-S alignment and strike of it graben system (Plate 1: Baranov et al., 1991). As a consequence it possible that the dated late Oligocene arc material from the southern extremity of Shirshov Ridge is actually a fragment of the Aleutian Ridge rifted away during the Miocene formation of the Komandorsky Basin or, earlier, the Bowers Basins (Scholl

et al., 1989; Cooper et al., 1992 and Yogodzinski et al., 1993). Arc material dredged farther to the north by Russian colleagues has not been radiometrically dated (Baranov, written communication, 2006) but N-MORB amphibolite recovered from the ridge is reported at ~47 Ma (Sukhov et al., 1987). Well preserved diatom and silicoflagellates assemblages have been recovered from overlying stratified deposits of Miocene and Oligocene age (Gladenkov, 1990).

Bowers Ridge appears to be structurally connected to the southern end of Shirshov Ridge (Rabinowitz, 1974). Late Cenozoic deposits of the Aleutian Basin that bury the connection are deformed above it. Submerged sectors of the summit of Bowers Ridge as deep as 1000 m are, similar to Shirshov Ridge, wave-truncated platforms of former islands. The summit platform of the eastern end of Bowers Ridge abuts and merges with the wave-flattened summit platform of the Aleutian Ridge (Fig. 1A).

The northern side of Bowers Ridge is flanked by a prominent trench structure filled with a sequence of Aleutian Basin sediment as thick as 10 km (Fig. 5). The infilling Bowers Ridge trench sequence exhibits only slight post-depositional deformation, suggestive of minor late Cenozoic shortening between Alaska and the ridge (Marlow et al., 1990). Older, underlying sedimentary material at the base of the ridge's northern slope are more deformed, but not greatly so, and a frontal accretionary prism wider than 10–15 km is not evident (Cooper et al., 1987a, b).

Basement of calk-alkaline arc breccia was recovered in 1970 by the Scripps Institution of Oceanography from the north side of Bowers Ridge (http://walrus.wr.usgs.gov/info-bank/m/m170bs/html/m-1-70-bs.meta.html; Creager, Scholl et al., 1973). The breccia was too altered to date by K-Ar methodology (Scholl et al., 1975). Drilling on the southern slope of Bowers Ridge (DSDP Leg 19) did not reach basement or sediment older than late Miocene (Creager, Scholl et al., 1973). Decades earlier, G. Dallas Hanna (1929) described diatom-bearing sediment of late Miocene age recovered by dredging the submerged flank of Bowers Ridge. This study was probably the first attempt to decipher the geologic history of the Bering Sea Basin.

2.5.2 Interpretations. Geophysical and sample data document that the Shirshov and Bowers Ridges were, like the Aleutian Ridge, largely constructed by arc volcanism. It is also evident that both Shirshov and Bowers Ridges were formerly emergent arc massifs that sometime in the mid Cenozoic subsided below wave-base erosion to depths of >1500 m. On Shirshov Ridge, Oligocene sediment recovered at depths of 1400–1500 m contain neritic and sublittoral diatoms, documenting subsidence, and possibly recording that arc-extinction occurred after the late Oligocene (Gladenkov,

1990). The present Aleutian Ridge, although still volcanically active, exhibits a similar history of wave-base truncation and subsidence of its crestal summit platform to depth of several hundred meters and as deep as ~1500 m along the flanks of the ridge (Scholl et al., 1987).

Deformation studies by Marlow et al. (1990) of the sedimentary sequence filling the Bowers Ridge trench and seismicity and GPS data from the Aleutian Ridge (Oldow et al., 1999; Avé' Lallemant and Oldow, 2000: Cross and Freymueller, 2007) imply that Bowers Ridge is tectonically disconnected from the clockwise rotation and westward transport of blocks of Aleutian arc crust moving along the Pacific-North America plate boundary toward the Kamchatka subduction zone (Geist et al., 1988: Geist and Scholl, 1992). Evidently, an active right-lateral shear zone separates the Aleutian and Bowers Ridges (Ryan and Scholl, 1989, 1993). Also, only modest late Cenozoic basement deformation or possibly magmatism has occurred in the subsurface structural septum connecting the western end of Bowers Ridge and the southern end of the physiographic relief of Shirshov Ridge (Rabinowitz, 1974). Apparent vertical deformation in late Cenozoic sediment overlying the septum is not understood.

Evidence of collisional impact between the Aleutian and Bowers Ridges has not been recognized, and both appear to be arc massifs of similar age, possibly built upon thrust-thickened oceanic crust (Savotsin et al., 1986). Thus Bowers is viewed as having formed effectively in place as a northward projecting, westward curving growth added constructionally to the larger Aleutian Ridge.

Shirshov Ridge is physiographically the submarine extension of the promontory of the Olyutosky Peninsula (Fig. 1A), which is underlain by a framework of Late Cretaceous arc rocks accreted to the margin most likely in early and middle Eocene time (Stavsky et. al, 1988; 1990; Levashova et al., 2000, Garver et al. 2000; Garver et al., 2004; Chekhovich and Sukhov, 2006; Chekhovich et al., 2006). The submerged extension is in itself not confirming evidence that the ridge is the seaward continuation of the Late Cretaceous arc massif that forms the peninsula. For example, the Cenozoic Aleutian Ridge is not the seaward extension of the continental framework of the Permo-Triassic, Jurassic, and Cretaceous rocks that underlie the Alaska Peninsula (Burk, 1965, Nokleberg et al., 1994). So it can be entertained that Shirshov Ridge was similarly constructed in the Tertiary seaward of an existing framework of Cretaceous and older rocks of the Koryak-Kamchatka margin.

Unlike Bowers Ridge, Shirshov Ridge is not flanked by a preserved structural trough of a sediment-filled trench (Fig. 5). Most likely, as surmised by Baranov et al., (1991), a trench and eastward-dipping subduction zone formerly lay at the base of the ridge's western or Kamchatka-facing side. Destruction of the structural trench was likely a consequence of ridge extension and fracturing during the creation of the early and middle Miocene crust of the Komandorsky Basin. Older, probably Cretaceous, Pacific oceanic crust of Aleutia and western fragments of the Shirshov Ridge were presumably swept into a north Kamchatka-south Koryak SZ bordering the western side of the Basin (Baranov et al., 1991; Hochstaedter et al., 1994; Park et al., 2002)

The relations noted above are drawn upon to conjecture that Bowers and Shirshov arc systems are not exotic to the Bering Sea Basin region but rather formed there in the early Tertiary in response to plate-boundary-driven tectonism of the far north Pacific rim and offshore areas. Although subduction continues beneath much of the length of the Aleutian Ridge, subduction beneath Bowers and Shirshov ridges waned and ended in the Oligocene or early Neogene. This inference is based on the 1000–2000 m depth of ridge crest subsidence (Dietrick et al., 1977), the Oligocene age of recovered shallow water taxa from the crest of Shirshov Ridge (Gladenkov, 1990), the radiometric age (minimum) of late Oligocene of arc fragmental material recovered from the southern end of Shirshov Ridge (Cooper et al. 1987a), and the early Miocene inception of spreading in Komandorsky Basin (Muzurov et al., 1989; Baranov et al., 1991).

2.5.3 Issues. As discussed earlier, lacking definitive age and paleolatitude controls, the formative place and age of initial arc activity for Shirshov and Bowers Ridges cannot be established. If the ridges are mostly Mesozoic igneous accumulations overlain by Cenozoic deposits, then these arc massifs could have formed in the north Pacific Basin well south of the Bering Sea Basin and thus would be exotic to it. If the igneous basement of these ridges is Cretaceous in age and exhibit OIB geochemical characteristics, then their formation as part of the NW extension of the north Pacific's Hawaii-Emperor seamount chain can also be hypothesized (Steinberger and Gaina, 2007).

If they formed in the Eocene, then they did so within the setting of the Bering Sea Basin because outboard of them construction of Aleutian Ridge appears to have gotten underway in the middle Eocene or a little earlier (Jicha et al., 2006). Reconstructing the tectonic setting and deciphering the cause for the formation of the Aleutian Bering Sea region and its subsequent evolution thus requires at the least accurate information about when Bowers and Shirshov began to formed and when arc volcanism ceased along them.

2.6 The Aleutian Ridge and the KAT Connection

2.6.1 Observations. The critical tectonic element of the KAT connection is the westward extension of the Aleutian

sector of the PAC/NAM boundary to the Kamchatka SZ, which is either the eastern edge of the Okhotsk microplate (block) or a tectonically simpler southward striking continuation of the PAC/NAM plate boundary (Fig. 3; Riegel et al., 1993; Bourgeois et al., 2006; Pedoja et al., 2006). In its curving path across the north rim of the Pacific Basin, the ~2200-km-long Aleutian Ridge extends to within ~100 km of Kamchatka (Figs. 7 and 8). The width of the ridge ranges from ~250 to 75 km, narrowing west of about 180 deg. longitude and markedly so west of Near Pass (172 E) across the Komandorsky sector of the Aleutian Ridge (Fig. 8).

In relief, the ridge rises ~7 km above the generally smooth, flat, and thickly (1–2 km) sedimented floor of the Aleutian Trench to the south and 3–4 km above the abyssal plain of the Bering Sea Basin to the north. The lateral continuity of the ridge's arc massif is disrupted in the forearc by large NNE-SSW-trending submarine canyons, and along the crest of the ridge by tectonically controlled between-island passes and ridge-axis elongated summit basins (Figs. 7 and 8).

The Aleutian Ridge is an arc construct of Cenozoic age flanked to the south, and presumably to the north, by older oceanic crust. Although not known to include pre-Eocene crust, the ridge buds westward from the tip of the Alaska Peninsula underlain by continental basement of late Paleozoic and Mesozoic age (Fig. 1A: Burk, 1965; Nokleberg et al., 1994; Vallier et al., 1994). Beneath its structural summit the arc massif is 30–35 km thick, an
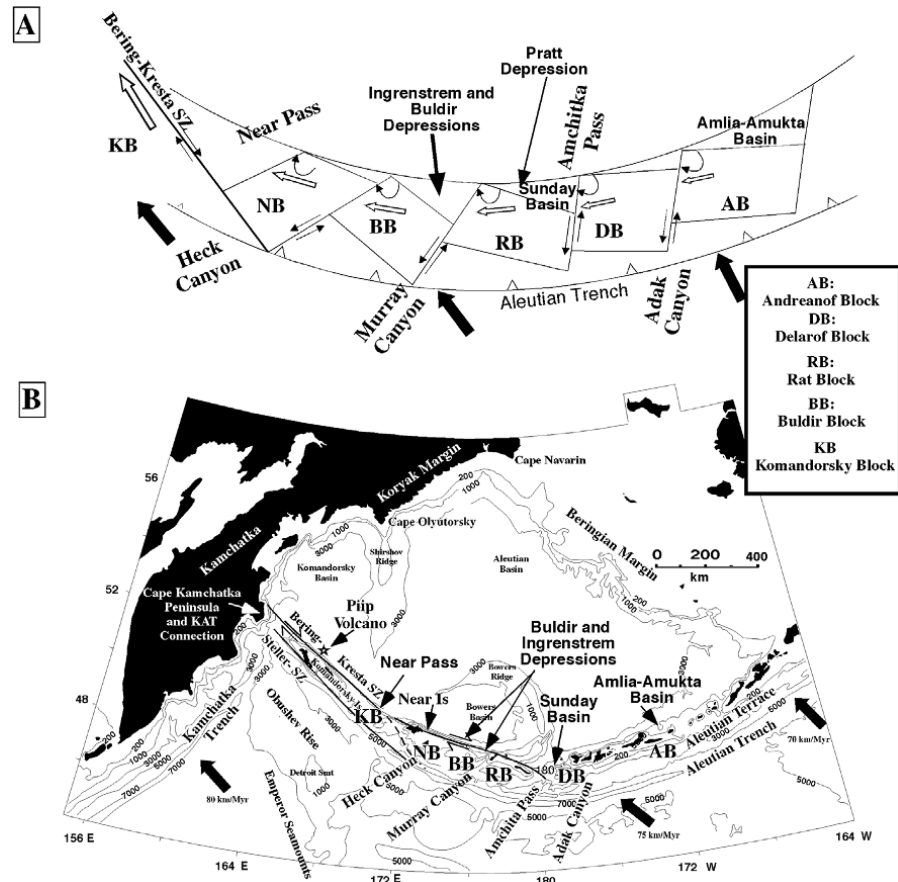

Figure 7. Geographic and tectonic setting maps for Aleutian Ridge. Top panel (A) is diagrammatic model of clockwise rotation and westward translation of blocks of the arc massif moving toward the Kamchatka subduction zone. Rotating blocks leave trail-edge basins along their northern sides (e. g. Amlia-Amukta Basin, Sunday Basin, Buldir Depression) and large, left-lateral tear canyons along their eastern flanks (e. g., Adak, Murray, and Heck Canyons). The far western or Komandorsky block is effectively moving to the NW with the Pacific plate. Bottom panel (B) shows that via the right-lateral Bering-Kresta shear zone, which runs along the base of the Bering Sea side of the Komandorsky block, westward moving blocks of the Aleutian massif are guided toward collision with Kamchatka at the Kamchatka-Aleutian or KAT tectonic connection, which is presently located at the Cape Kamchatka Peninsula.
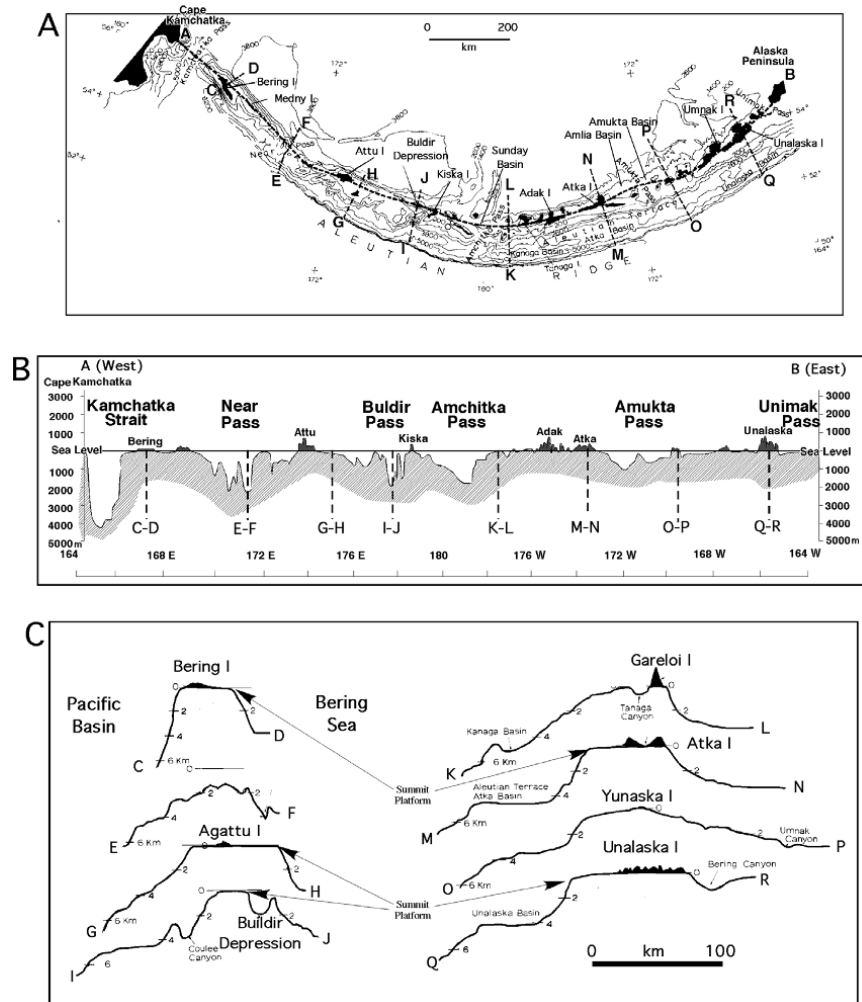
Figure 8. (A) Index map showing locations of longitudinal (W-E along-ridge) and transverse (S-N across ridge) bathymetric profiles of the Aleutian Ridge. Longitudinal profile (B) shows, in the westward direction of increasing obliquity of convergence, increasing deepening of between-island passes separating the major CW and westward translating blocks of the arc massif (see Figure 7). Transverse profiles (C) display the westward narrowing of the width of the arc massif, in particular west of Amchitka Pass (profile I-J). Both physiographic measurements are consistent with the GPS-documented determination that westward blocks of the arc massif move with increasing speed toward the Kamchatka subduction zone.

unusual thickness for an intra-oceanic arc (Fig. 9; Shor, 1964; Grow, 1973; Fliedner and Klemperer, 1999; Holbrook et al., 1999, Lizarralde, et al., 2002; Shillington, et al., 2004; Takahashi et al., 2007; Calvert et al., in press). Arc crust thins seaward beneath the submerged forearc and landward below the backarc slope descending toward the Bering Sea Basin (Fig. 9).

The oldest radiometrically-documented age for arc volcanic material is middle and late Eocene (Vallier et al., 1994; Jicha et al., 2006). Late to middle Eocene fossiliferous sequences are widely exposed in the Aleutian and Komandorsky Islands (Scholl et al., 1987; Vallier et al.,

1994). The report of early Eocene or late Paleocene beds from the Komandorsky Islands (Shmidt, 1978; Rostovtseva and Shapiro, 1998) is based on a poorly identified planktonic foraminifera fauna (K. McDougall, written communication, 2006). The linked paleomagnetic stratigraphy is permissive of the older Tertiary ages (Minyuk and Gladenkov, 2007). However, the basalt and andesite flows underlying the basal sedimentary units have middle and late Eocene K-Ar ages (45–37 Ma; Tsvetkov, 1991). If these dates are correct, and the "flows" are not sills or lie beneath a thrust, basement cannot be overlain by the fossiliferous beds of older early Eocene or late Paleocene age.
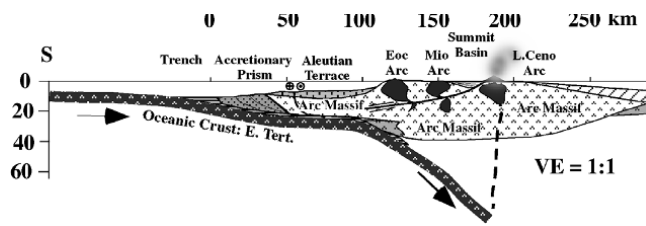
Figure 9. Idealized cross-section through the Aleutian Ridge showing major structural and tectonic units. Frontal accretionary prism is late Cenozoic in age and consists principally of turbiditic sediment transported westward along the trench axis from Alaskan drainages. The basins of the deep-water Aleutian Terrace and the ridge's summit area are late Cenozoic in age. Since at least the late Eocene the axis of arc volcanism has shifted progressively northward toward the Bering Sea Basin or backarc. Information is from various source but in particular from Shor (1964), Grow, 1973, Scholl et al. (1987), Ryan and Scholl, (1989, 1993), Vallier et al. (1994), Fliedner and Klemperer (1999), Holbrook at al. (1999), and Lizarralde et al., 2002.

The ^{39}Ar-^{40}Ar determination of Jicha et al (2006) dates the Aleutian Ridge's oldest securely known volcanogenic material at ~46 Ma, or middle Eocene. The sample was dredged immediately west of Kiska Island from the submerged eastern wall of Murray Canyon (Fig. 7). This age closely matches the oldest K-Ar dated lava reported by Tsvetkov (1991) from the Komandorsky Islands farther to the west. Initiation of the Aleutian SZ that produced these middle Eocene magmatic rocks must necessarily have been earlier. Because the start-out phase of arc growth is a voluminous outpouring across a broad front (see discussion in Jicha et al., 2006), it can be surmised that middle Eocene basement rock recovered from the crestal region of the Aleutian Ridge is not going to be significantly younger than the massif deeply buried beneath the ridge's forearc and backarc slopes, or the missing seaward sector, probably on the order of 60 km, of the arc massif removed by subduction erosion (von Huene and Scholl, 1991; Jicha et al., 2006; Scholl and von Huene, 2007). Thus the initiation of the new offshore Aleutian SZ is earlier than 46 Ma but most likely, unless the paleontologically-based Komandorsky early Eocene or late Paleocene ages are confirmed, not before ~50 Ma, in the late early Eocene.

Structurally, except for its far western or Komandorsky sector, from south to north the ridge in cross section is constructed of a frontal prism of accreted trench material of late Miocene and younger age bordering a submerged forearc of arc crust of Eocene age. The submerged forearc basement is overlain by dredge-recovered samples of Oligocene and younger slope-conforming sediment and, beneath the deep water (3500–4500 m) Aleutian Terrace, basin-filling sequences of late Miocene and younger beds (Figs. 8 and 9;

Scholl et al., 1987). At the summit of the ridge, island exposures of the middle Eocene igneous massif are intruded by late Eocene, Neogene, and younger bodies and unconformably overlain by lava and sediment. The greater width of the summit of the ridge is truncated by a wave-beveled surface, the summit platform, cut across Miocene and older rocks (Fig. 8). During the past ~5 Myr, the arcuate alignment of dormant and active centers of the Aleutian volcanic arc has been constructed generally along the northern edge of summit platform. North of the ridge crest the sediment-covered surface of the Eocene basement descends toward the abyssal floor of the Bering Sea (Fig. 9; Scholl et al., 1987).

The Komandorsky section, above which Bering and Medny Islands rise, is narrower (~75 km), presumably lacks a frontal prism of accreted debris, and lacks active or dormant summit volcanoes (Fig. 7). However, just beyond the northern or Bering Sea base of the sector, Piip Volcano has built nearly to sea level from a graben-like depression. The depression borders to the north the principal trace of the Bering-Kresta shear zone that separates crust of the Komandorsky Basin from that of the Aleutian Ridge (Fig. 1B, Plate 1, and Fig. 7; Baranov et., 1991; Yogodzinski et al., 1993, 1994, 1995, 2001; Geist and Scholl, 1994). Piip appears to be a "bleeding" transform construct.

Tectonically, the Aleutian arc massif is arranged along the far northern sector of the PAC/NAM boundary (Fig. 1B). With respect to the trend or strike of the ridge, from east to west plate convergence is NW and orthogonal near the Alaska Peninsula and increasingly oblique westward (to the left or west of NW). West of the Near Islands, relative motion is highly oblique to virtually strike slip along the Komandorsky sector (Vallier et al., 1994; Fig. 7). Based on regional studies of bathymetric, seismic, paleomagnetic, and geologic data, the width of the ridge involved in ridge-parallel or longitudinal shearing broadens to the west, in particular west of Amchitka Pass and then more so west of Near Pass where the right-lateral Bering-Kresta shear zone passes along the northern base of the Komandorsky sector (Figs. 1B and 7; Cormier, 1975; Geist et al., 1988; Ryan and Scholl, 1989; Geist and Scholl, 1994).

GPS and seismic motion studies appear to document that the major plate boundary is now the Bering-Kresta shear zone (Avé' Lallemant and Oldow, 2000; Gordeev et al., 2001; Steblov, et al., 2003). However, differential right-lateral shearing occurs across the width of the Komandorsky sector defining the Komandorsky shear zone of Freitag et al. (2001). The impact of the collisional process at the KAT connection is exhibited by a horizontal gradient of vertical tectonism at Cape Kamchatka Peninsula that increases southward away from the Bering Kresta shear zone and toward that of the western most reach of the Aleutian Trench and the Steller SZ