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Introduction: An overview of ridge-trench interactions in modern and ancient settings

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ABSTRACT

Virtually all subduction zones eventually interact with a spreading ridge, and this interaction leads to a great diversity of tectonic processes in the vicinity of the triple junction. In the present-day Pacific basin, there are seven examples of active or recently extinct spreading ridges and transforms interacting with trenches. In contrast, there are only a few well-documented cases of spreading ridge interactions in the ancient geologic record, which indicates this process is grossly underrepresented in tectonic syntheses of plate margins. Analogies with modern systems can identify some distinctive processes associated with triple junction interactions, yet an incomplete understanding of those processes, and their effects, remains. Additional insights can be gained from well-documented examples of ancient ridge subduction because exhumation has revealed deeper levels of the tectonic system and such systems provide a temporal record of complex structural, metamorphic, igneous, and sedimentary events. This volume focuses on ridge-trench interactions in the Paleogene forearc record of the northern Cordillera (north of the 49th parallel). Insights from this system and modern analogs suggest that there is no single unique signature of ridge subduction events, but a combination of processes (e.g., igneous associations, changes in kinematics, motion of forearc slivers, thermal events, etc.) can be diagnostic, especially when they are time-transgressive along a plate margin. Understanding these processes in both modern and ancient systems is critical to our understanding of the creation and evolution of continental crust and provides a new framework for evaluating the evolution of the onshore and offshore tectonic history of the northern North American Cordillera.

Keywords: Neogene, Pacific plate, Cordillera, triple junction interaction, ridge subduction, Antarctica, Chile, Japan, Spain, accretionary prism, forearc magmatism.

INTRODUCTION

The typical view of subduction of oceanic lithosphere is a two-dimensional process dominated by underflow of oceanic lithosphere, refrigeration of the forearc, and development of an associated linear chain of calc-alkaline volcanoes situated 70–150 km above the downgoing plate. As first noted by DeLong and Fox (1977), all trenches must ultimately interact with a spreading center, yet there are very few ridge subduction events described in the geologic record. It is doubtful that this is an accurate reflection of the tectonic history of Earth.

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A triple junction that develops when a spreading center interacts with a convergent margin is a combination of two or more of the following types of boundaries: an active spreading ridge, a transform fault, or a trench. In this volume, we do not consider subduction of aseismic ridges, though some consider this as ridge subduction. Specifically, we consider the following triple junction interactions: ridge-trench-trench (e.g., Chile triple junction), ridge-trench-transform (e.g., Rivera triple junction), and trench-transform-transform (e.g., Mendocino triple junction). Ridge subduction can be either a ridge-trench-trench or a ridge-trench-transform fault triple junction as both involve subduction of an active spreading ridge (Fig. 1). As a margin evolves, it can interact with different boundaries, which makes interpretation of geologic events difficult. For example, a triple junction can switch from ridge-trench-trench to ridge-trench-transform, as we speculate occurred in southern Alaska (Sisson et al., this volume, Chapter 13), or from trench-ridge-transform to trench-transform-transform as has occurred along the California margin at ca. 26 Ma.

A difficulty faced by the geoscience community in assessing the role of triple junction interactions is the diversity of possible geometries, all of them characterized by four-dimensional processes. Not only are there dozens of possible plate configurations (e.g., Cronin, 1992; Farrar and Dixon, 1993), but the actual geologic consequences are strongly influenced by plate geometry and velocity. For example, ridge-trench interaction may generate a “slab window” (Dickinson and Snyder, 1979), an asthenosphere-filled gap beneath the continental margin. A slab window can produce significant forearc thermal anomalies and geochemically unusual magmatic events that migrate with the triple junction. A simple scenario of a slab window migrating steadily in one direction may become geometrically and geologically complicated as subduction of ridge segments alternates with subduction of transform faults (Thorkelson, 1996) and plate motions change (this volume, Chapters 1 and 8).

Figure 1. Lambert projection of circum-Pacific basin showing locations of modern ridge subduction events and the region in the northern Cordillera affected by Cretaceous-Tertiary subduction of the Kula-Farallon ridge. Double thin lines indicate spreading ridges, thin lines indicate strike-slip boundaries, and thick lines with teeth are for subduction zones. Map created using projections available at http://www.aquarius.geomar.de/omc/omc_intro.html.

Two of us (VBS and TLP) convened a Penrose conference in 1994 on the general problem of triple junction interactions at convergent margins. Two conference summaries (Sisson et al., 1994; Pavlis et al., 1995) arose from that meeting. One result of that conference was a general acceptance that the Paleocene and Eocene geologic record of the northern Cordillera of North America preserves an example of the geologic consequences of ridge-trench interaction and subsequent ridge subduction (Fig. 2). Although there are several modern examples that provide excellent analogs for ancient systems, the northern Cordillera provides an important perspective on the long-term temporal evolution of a ridge subduction event, its regional manifestations, and something no modern system can provide, exposure of mid-crustal rocks that reflect some of the deep processes that accompany the event.

This volume presents results of a number of studies of the processes and consequences of Paleogene ridge-trench interaction beneath the northern Cordilleran margin. The main emphasis of this volume is on the effects of the ridge-trench interaction in the accretionary prism and forearc regions, but a number of the papers also look at consequences of terrane translation. Ridge subduction took place during a time of oblique convergence and large-scale northward translation of blocks along much of the margin. The combination of the relative motions of both the triple junction migration and the inboard terranes make the reconstruction of the paleogeography particularly challenging.

In this introductory paper, we first summarize existing information on modern triple junction interactions, and then summarize available data on ancient triple junction interactions. This summary sets up the framework for understanding triple junction interactions in general and the specific implications of these processes to the evolution of the northern Cordillera. We end with a brief summary of the results reported in this volume.

Triple Junction Processes: Insights from Modern Analogs

There is only modest consensus on what the effects of triple junction interactions are when integrated over time in the geologic record. However, modern examples of triple junction interactions in the circum-Pacific region (Fig. 1) do provide insight into processes that may be indicators of triple junction interactions along convergent margins. A summary of key indicator features appears in Table 1.

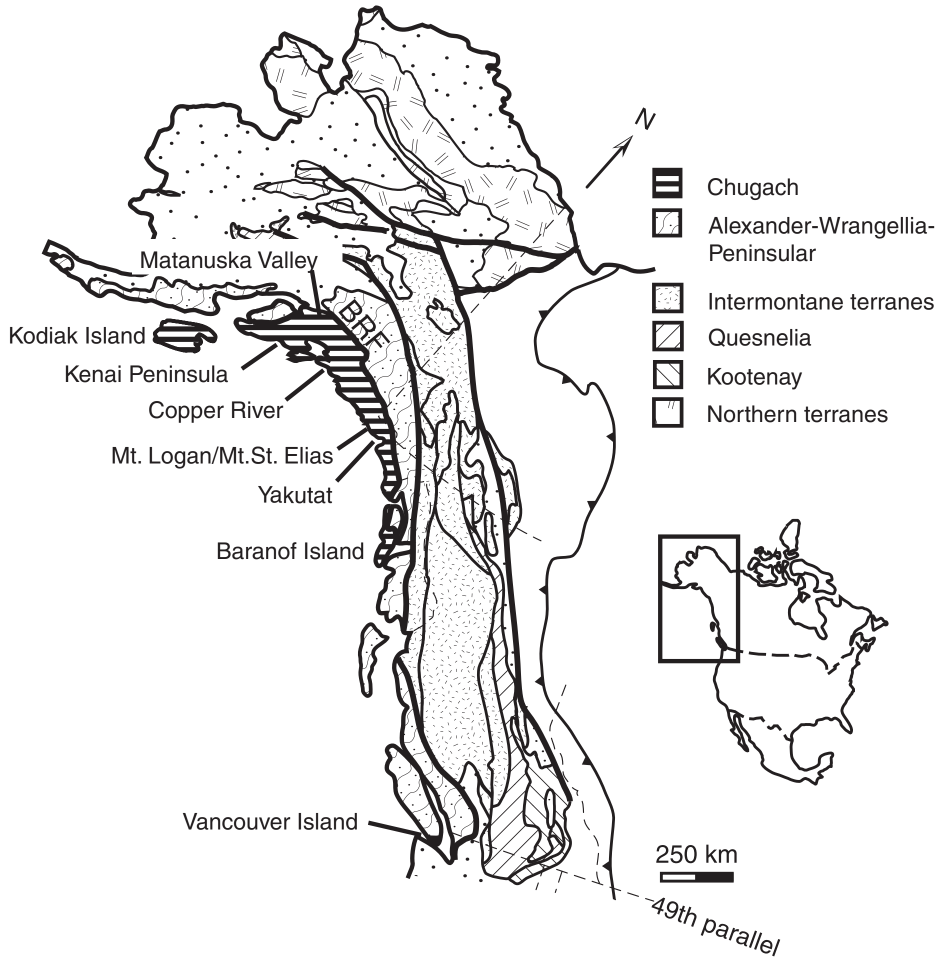

Figure 2. Tectonostratigraphic terrane map of the northern Cordillera showing geographic locations discussed in this volume. Most of the ridge subduction processes discussed in this volume occur in the Chugach terrane even though the effects are observed far from the Eocene Cordilleran margin. For simplicity, we have grouped together many of the terranes in the Intermontane belt as well as the Ruby Mountains, Seward Peninsula, and Brooks Range in northern Alaska. The stippled and unpatterned regions represent sedimentary sequences that were deposited since terrane amalgamation. BRF—Border Ranges fault system. Adapted from McClelland (2001, personal commun.).

Modern Triple Junctions of Western North and Central America: Mendocino, Rivera, British Columbia, and Panama Examples

The present-day triple junction interactions along western North and Central America involve ridge-trench-trench (e.g., British Columbia triple junction), ridge-trench-transform (Rivera triple junction) and trench-transform-transform (Mendocino and Panama triple junctions). Along this margin, the configuration of the various components has changed through time. This has led to considerable debate about the geological consequences of their interactions and whether or not a slab window forms in these complicated tectonic settings.

Mendocino

The Mendocino triple junction and its companions along the western margin of North America originated in the Oligocene (Atwater and Stock, 1998). These modern triple junctions began to evolve when the easternmost promontory of the Farallon-Pacific spreading ridge first encountered the subduction zone of western North America, and the Farallon plate was broken into several smaller microplates (McKenzie and Morgan, 1969; Atwater, 1970; Atwater and Stock, 1998). This interaction set up an unusual plate configuration in which the relative motion of two of the plates, North America and Pacific, was within a few degrees of parallel to the plate margin. The unusual plate configuration resulted in the formation of the San Andreas transform system between the two triple junctions (McKenzie and Morgan, 1969). Migration of the triple junctions, particularly the Mendocino triple junction, produced a lengthening of the San Andreas transform with time, and produced numerous broader effects throughout the southwestern edge of North America (Atwater, 1970; and numerous more recent studies).

Recent studies have focused particular attention on the Mendocino triple junction where two very different scenarios are called upon to explain observations in the vicinity of the triple junction: (1) a “stalled plate” scenario in which either microplates are still present as underplated slabs, or that subducted slab stretched to fill the gap (ten Brink et al., 1999; van Wijk et al., 2001); or (2) a “slab window” scenario, in which an asthenosphere-filled gap opened inboard of the triple

TABLE 1. FEATURES USED TO EVALUATE CONVERGENT MARGIN TRIPLE JUNCTION INTERACTIONS

Geologic process	Characteristics	Examples in coastal regions of the Northern Cordillera
Kinematics	Temporal and spatial variations in structural history; rapid shifts in kinematics in one region.	Change in regional kinematics (Chapters 1 and 8) Strike-slip faults (Chapters 6, 7, and 8) Emplacement of plutons (Chapters 12 and 14) Brittle deformation (Chapter 5)
Magmatism	Forearc magmatism that migrates through time; magma source from mantle and/or crust. Magmatic arc ceases or increases in activity; arc may develop alkaline signature. Backarc magmatism with alkalic and ocean-island signatures; slab-melt magmas in arc and back arc.	Sanak-Baranof forearc magmatic belt (Chapters 12 and 13) Magmatism in southern Vancouver Island (Chapter 14)
Fluid circulation	High temperature fluid interactions in forearc and accretionary prism; hydrothermal activity with stratiform sulfide deposits; gold mineralization.	Regional gold deposits (Chapter 5) High temperature fluids (Chapters 7, 9, and 10) Volcanogenic massive sulfide deposits (Crowe et al., 1992)
Metamorphism	Low-pressure/high-temperature metamorphism of forearc; possibly regional-scale contact metamorphism; Buchan series metamorphism.	High-temperature metamorphism (Chapters 9, 10, 11, and 14)
Basin evolution	Rapid shifting of depocenters and uplift within the forearc; destruction of basins by forearc strike-slip systems.	Transpressional evolution of forearc basins (Chapter 4)
Accretionary prism	Punctuated periods of tectonic erosion during ridge interactions, systematic younging of accreted sediment culminating in zero age pelagic sediments associated with near-trench MORBs accreted near the trench.	Uplift of accretionary margin (Chapters 2, 3, and 14)
Suprasubduction zone ophiolite	Accretion of forearc ophiolites with unusual chemistry.	Resurrection Peninsula ophiolite (Chapter 1)

Note: Both temporal and spatial variations with progressive younging along a margin can be used as a guide for evaluating the likelihood of triple junction interactions.

junction as the Cascadia subducted slab was carried northward with the triple junction (Dickinson and Snyder, 1979; Zandt and Furlong, 1982; Atwater and Stock, 1998). Both scenarios are consistent with higher heat flow (Lachenbruch and Sass, 1980; Underwood et al., 1999) and northward progression of volcanism (Dickinson and Snyder, 1979; Fox et al., 1985; Dickinson, 1997). The transient thermal effects have also been linked to ephemeral crustal thickening through viscous coupling between the Gorda plate and North America (Furlong and Govers, 1999). The northward migration of the triple junction is also attributed to variations in forearc sedimentation and deformation, particularly northward tilting and reduced deposition in the forearc basin (McCrory, 2000; Gulick et al., 2002). In the Gorda plate, immediately north of the present-day triple junction, there has been counterclockwise rotation of preexisting structures, uplift in the Eel River Basin, channel incision, shift in sediment source, and decrease in sediment preservation (Gulick and Meltzer, 2002; Burger et al., 2002).

The Mendocino triple junction is widely used as an instructional example of the effects of triple junction interactions. Unfortunately, from the broader perspective of ridge subduction processes, the Mendocino triple junction is not an ideal type example as its stability is highly dependent on maintenance of a specific geometry through time. As more data have accumulated, the broader effects of this unusual geometry have become increasingly clear (e.g., see Bohannon and Parson's [1995] reappraisal of Atwater's [1970] hypothesis).

Rivera

To the south, the Neogene breakup of the East Pacific rise also generated the Rivera triple junction. This ridge-transform-trench triple junction geometry resulted in complex microplate interactions that produced multiple triple junctions, many of which were unstable (e.g., Bandy and Pardo, 1994; Nicholson et al., 1994; Bourgois and Michaud, 2002). As a consequence, broad areas of deformation surround these triple junctions, both on the continental and oceanic plates (Bandy and Pardo, 1994; Nicholson et al., 1994; Atwater and Stock, 1998). The genesis of this deformation is difficult to assess within a broader context, however, because two ridge jumps occurred during the history of the Rivera triple junction (Atwater and Stock, 1998). For example, Dickinson and Snyder (1979) proposed that the Rivera triple junction caused rifting and formation of the California Borderlands. However, Fletcher et al. (2000) found that extension in Baja California postdates southward passage of the triple junction and Miller (2002) attributed Miocene extension and mafic underplating in the California Borderlands to a ridge-transform jump during southward migration. Several papers in this volume also examine the association of microplate formation with triple junction interactions (see Chapters 6, 7, and 8).

British Columbia

Prior to development of the Mendocino and Rivera triple junctions, the northern end of the Pacific-Farallon spreading ridge intersected the North American trench along the coastline of British Columbia and southeast Alaska. The triple junction first formed after the death of the Kula plate at ca. 43 Ma (Lonsdale, 1988) and migrated southward from southeast Alaska to its present position north of Vancouver Island (Riddihough, 1982). Currently, the plate margin north of the triple junction is dominated by the dextral Queen Charlotte transform fault. South of the triple junction, the Juan de Fuca plate is subducting eastward beneath British Columbia and Washington. In detail, the plate geometry in the region near the triple junction is complex, involving intraplate deformation and microplate formation (Riddihough, 1984; Rohr and Furlong, 1995). High heat flow (up to 100 mW/m^2) in northern British Columbia and the Yukon Territory near the present triple junction suggests that the ridge has been intersecting the trench in approximately the same location for several m.y. (Lewis and Hyndman, 1998; Hyndman and Lewis, 1999). Neogene volcanic rocks on northern Vancouver Island (Armstrong et al., 1985) and the Queen Charlotte Islands (Hamilton and Dostal, 2001) have been interpreted as products of “descending plate edge” and slab window environments, respectively. Throughout British Columbia and the Yukon, Miocene to Recent volcanic rocks range from small monogenetic centers to large polygenetic successions with alkaline to tholeiitic compositions and intraplate trace element signatures (Bevier et al., 1979; Hart and Villeneuve, 1999; Edwards and Russell, 2000). The boundaries of this intraplate volcanic field correspond closely with the margins of the proposed slab window.

According to Thorkelson and Taylor (1989), the combined effects of northward subduction of the Pacific plate and eastward subduction of the Farallon (Juan de Fuca) plate yielded a large, long-lived slab window beneath much of British Columbia, Yukon Territory, and southeast Alaska. In their model, the window is bounded to the northwest by a subducted slab of the Pacific plate and to the south by the Juan de Fuca slab. Using seismic tomography, Frederiksen et al. (1998) imaged the subducted eastern edge of the Pacific plate near the Yukon-Alaska border and identified anomalously hot mantle to the east and south, which they attributed to upwelling of asthenosphere through the slab window.

Panama

Another North American triple junction, the Cocos-Nazca-Caribbean triple junction in Panama is a poorly understood but potentially significant modern analog for ancient triple junction interactions. Johnston and Thorkelson (1997) made the case that although this triple junction is now a trench-trench-transform triple junction, a slab window is probably present beneath Panama due to relatively recent subduction of a ridge-segment. This section of the Middle American arc has ocean-island-like geochemical and isotopic characteristics, interpreted as a result of contamination of the mantle wedge by enriched sub-slab asthenosphere, and by localized “adakitic” volcanic assemblages interpreted as slab melts (Drummond et al., 1995; Johnston and Thorkelson, 1997). The absence of sublithospheric seismicity beneath the region is also consistent with a slab window between the Cocos and Nazca plates.

Modern Southern Pacific Triple Junctions: Woodlark, Chilean, and Antarctic Examples

All three triple junctions in the southern Pacific involve ridge subduction. The Chilean triple junction and the Woodlark Basin (Fig. 1) represent triple junction configurations that are probably the best modern examples illustrating the range of processes associated with ridge subduction. These systems display active subduction of ridge segments with different plate configurations: The ridge enters the trench at a high angle in the Woodlark system, whereas the ridge segments of the Chilean margin are nearly parallel to the trench. This variation is important for studies reported in this volume, as both configurations probably occurred during the Paleogene ridge-trench interactions in the northern Cordillera (e.g., Sisson and Pavlis, 1993).

Woodlark Basin

The Woodlark ridge-trench interaction developed entirely within oceanic microplates where the New Britain–South Solomon trench system is now consuming the Woodlark spreading system (Fig. 1). Ridge-trench interaction began when the Ontong Java Plateau collided with the Solomon Island arc (Taylor and Exon, 1987), causing the subduction zone to flip and initiating consumption of the Woodlark spreading center. The system is characterized by very high convergence rates (10.7 cm per year) as well as high spreading rates (7.2 cm per year) for the subducting ridge. The plate geometry is the closest modern analog for ridge-trench interactions in which oceanic plates on both sides of a ridge meet a trench at a moderate angle and are subducted. Different angles of incidence of the ridge with the trench would produce different triple junction migration rates along the trench. The sense of offset of transforms along the ridge would further control the rate of migration along the trench, possibly even causing a temporary reversal of migration direction.

In the Woodlark triple junction, only a small segment of the forearc is subjected to the effects of ridge subduction because of the configuration of the ridge-transform segments and the resultant back tracking of migration of the triple junction (Taylor and Exon, 1987). Some of the key signatures of this interaction are (1) a gap in deep seismicity in the vicinity of the triple junction, (2) the lack of a bathymetrically distinct trench, (3) rapid rates of uplift of the forearc near the site of the triple junction that produce local emergence and exhumation of the forearc and arc, and perhaps most significant, (4) voluminous forearc magmatism, including formation of large forearc volcanoes and volcanoes outboard of the triple junction on the ocean floor (Johnson et al., 1987; Perfit et al., 1987; Staudigel et al., 1987; Taylor and Exon, 1987; Crook and Taylor, 1994). The Paleogene of the northern Cordillera has similar forearc uplift and magmatism, which are well documented (this volume, Chapters 1, 3, 13, and 14).

Chilean Triple Junction

The Chilean triple junction, where the Nazca-Antarctic ridge is being consumed in the Andean subduction zone, provides a second example that may be similar to the Paleogene of the northern Cordillera (Forsythe and Nelson, 1985; Cande and Leslie, 1986; Tebbens et al., 1997; Lagabrielle et al., 2000). In this system, subducting ridge segments are subparallel to the trench. The Nazca plate subducts at about 70 mm per year compared to only 20 mm per year for the Antarctic plate, and the resultant plate geometry produces rapid triple junction migration during subduction of ridge segments and minor migration during transform subduction. Interestingly, the spreading rate for the ridge apparently slows down when the ridge segments collide and increases when transforms are being subducted (Tebbens et al., 1997). The earliest documented ridge collision occurred in southern Patagonia (54°S) at ca. 18 Ma (Forsythe and Nelson, 1985). The locus of ridge subduction then migrated northward through time, with major segments subducted at 14–10 Ma, 6 Ma, 3 Ma, and 100 ka to present (Forsythe and Nelson, 1985; Cande and Leslie, 1986; Bourgois et al., 2000).

Behrmann et al. (1994) summarized the results of ODP Leg 141 drilling and noted heat flow anomalies in the forearc, changes in forearc sedimentation, and hydrothermal alteration and mineral deposition, all consistent with subduction of a ridge. Other recent studies have identified many other features attributable to ridge subduction. The most prominent of these are magmatic effects, including the development of geochemically unusual mid-ocean ridge basalts on ridge-segments near the triple junction (Klein and Karsten, 1995; Karsten et al., 1996; Sherman et al., 1997; Sturm et al., 1999), anomalous forearc magmatism and a gap in the volcanic arc (Forsythe et al., 1986), the local occurrence of adakitic volcanic rocks interpreted as slab melts (Kay et al., 1993), and the presence of high-Mg backarc plateau basalts with ocean-island affinity (Gorring et al., 1997; Gorring and Kay, 2001; D'Orazio et al., 2000, 2001). In addition, the Taitao ridge and Bahai Barrientos ophiolite were obducted in the forearc during ridge subduction periods (Kaeding et al., 1990; Nelson et al., 1993; Lemoigne et al., 1996; Moores, 1998; Guivel et al., 1999; Bourgois et al., 2000; Shervais, 2001). At the same time, a forearc sliver developed north of the triple junction due to oblique subduction, and a small rift basin developed at the southern edge of the forearc sliver (Nelson et al., 1993; Flint et al., 1994; Behrmann and Kopf, 2001; Bourgois et al., 2000). Similar effects are seen in the Paleogene of the northern Cordillera (Chapters 1, 4, 5, 6, 7, and 8, this volume).

The region near the subducted ridge in Chile also has a complicated upper mantle structure which suggests significant orogen-perpendicular mantle flow (Murdie and Russo, 1999). The long history of convergence between the Chile rise and South America and the absence of significant microplate development implies that the ridge-transform system subducted beneath the continent and progressively formed a slab window (Forsythe and Nelson, 1985; Kay et al., 1993; Daniel et al., 2001). Unlike the Woodlark example, there has not been uplift in the forearc or backarc (Thomson et al., 2001).

At the Chilean triple junction, three large plates have interacted for an extended period of time, in contrast to the complex, short-lived microplate interactions at Woodlark. A configuration similar to the Chilean triple junction probably characterized part of the Paleogene north Pacific interactions discussed in this volume (e.g., Sisson and Pavlis, 1993), and thus, is particularly important as a modern analog. In particular, the Chilean system has a forearc ophiolite as well as forearc volcanism, both of which are observed in the north Pacific geologic record (Chapters 1, 12, 13, and 14). In addition, both the Chilean and Woodlark triple junction have anomalously high thermal gradients in the forearc during ridge subduction, a process that is represented in the northern Cordillera by extensive Paleogene hydrothermal activity in southern Alaska (Chapters 5, 9, and 10) as well as areas of high-grade metamorphism and plutonism (Chapters 1 and 8–14).

Antarctic Peninsula

The Aluk-Antarctic spreading center subducted beneath the Antarctic Peninsula in Miocene and Pliocene time (Barker et al., 1984; Larter and Barker, 1991; Henriet et al., 1992; Maldonado et al., 1994; Birkenmajer, 1994). Timing of ridge and transform fault subduction is constrained by collisional unconformities between deformed and undeformed horizontal strata, seen in seismic profiles of the shelf sediments (Larter and Barker, 1991; Bart, 1993). As the ridge moved northward along the Peninsula, there was increased uplift and erosion of the continental shelf (Bart, 1993). In addition, eruption of a small volume of alkalic basalt, geochemically indistinguishable from ocean island and continental alkali basalts, occurred in Recent time (Hole and Larter, 1993; Hole et al., 1994; Hole and Saunders, 1996). Farther south along the Antarctic Peninsula, near Alexander Island, there was high-Mg magmatism in the forearc that migrated northward (McCarron and Millar, 1997). Also in this region, the accretionary prism was uplifted and high mountains formed (Storey et al., 1996). This region is complicated by subduction of fracture zones that break up the margin into fragments with different structural and sedimentologic histories (Johnson and Swain, 1995; Johnson, 1997). Some speculate that there were two previous ridge subduction events in the Mid-to-Late Jurassic and Late Cretaceous (Scarrow et al., 1998; McCarron and Larter, 1998). Although important in the general context of ridge subduction processes, the plate configuration of this system is distinct from the Paleogene northern Cordillera. A few processes, such as uplift of the accretionary prism, are seen in the northern Cordillera (this volume, Chapter 1).

Synopsis of Recent Triple Junction Interactions

Significant signatures of triple junction interactions observed in recent convergent margins include: a gap in arc magmatism; anomalous locations and compositions of arc magmatism; forearc magmatism ranging from felsic (including peraluminous) to mafic (largely of MORB affinity); arc and backarc volcanics with characteristics ranging from slab melts to ocean island basalts; lateral migration of sedimentary sources and basins; ophiolite emplacement, high geothermal gradients extending from forearc to backarc; abrupt changes in plate kinematics that migrate with time; formation and juxtaposition of microplates both offshore as well as in forearc slivers driven by oblique subduction; and diachroneity of these geologic events (Table 1). Not all these features occur at all sites of triple junction interactions and subsequent ridge subduction. The different geometry and relative rates of plate interactions lead to a range of possible signatures. Although some of these geologic signatures are not unique to ridge subduction, several taken together can help identify regions where ridge subduction and/or triple junction interactions have occurred in the past.

INSIGHTS FROM ANCIENT SYSTEMS

Although modern triple junction interactions provide important constraints on variations in the driving processes and short-term effects of triple junction interaction, ancient examples provide additional insights to the process because (1) they provide a temporal record of the long-term evolution of processes such as magmatism, kinematic changes, and thermal perturbations, and (2) later exhumation can provide important views of mid-crustal processes. In addition to the northern Cordilleran system described in this volume, other areas have been suggested as sites of past triple junction interactions and serve as important guidelines for features characteristic of triple junction interactions. Here we present examples from the Precambrian to Cenozoic.

Precambrian Examples: Slave, Arunta Inlier, and Hemlo

A long-standing controversy has been the origin of Archean granite-greenstone terranes, and Kusky and Polat (1999) proposed that these terranes represent Archean ridge subduction episodes. Typically, granite-greenstone terranes are similar to large accretionary complexes with terrigenous sediment intruded by a tonalite-trondhjemite-granitoid (TTG) suite. The TTG suite was likely generated by melting of hot young subducted slabs. These rocks are commonly associated with a sanukitoid suite formed from the mantle wedge. Two aspects of Archean plate tectonics are particularly relevant. First, many more ridges probably occurred in the oceanic crust, thus increasing the chance of ridge-trench interaction. Secondly, oceanic slabs were hotter and thus more buoyant, so that both normal subduction and ridge-trench triple junction interactions produced potentially different effects compared to the Phanerozoic (Abbott and Menke, 1990).

The presence of a TTG suite may be an indicator of ridge subduction as it is also common in southern Alaska (see Chapters 1, 12, 13, and 14), but this association has not been extensively explored. The abundance of this igneous association in the Archean and Abbott and Menke's (1990) analysis of the probability of ridge subduction events in the Archean together suggest that forearc metamorphism and felsic magmatism related to ridge subduction may have an important, but generally overlooked, role in continental growth.

Kusky (1990) proposed that ridge subduction occurred during Late Archean evolution of the Slave province of northern Canada and ascribed low-pressure metamorphism in association with anatectic migmatites as a consequence of ridge subduction. However, others have interpreted these *P-T* conditions as reflecting crustal thinning and rifting (Thompson, 1989). Another possible example of Precambrian ridge subduction is in the northern Arunta Inlier of central Australia, which contains two separate episodes of low-pressure/high-temperature metamorphism related to granitoid emplacement (Collins and Williams, 1995; Myers et al., 1996). A third possible example is the late Archean Hemlo-Schreiber and White River–Dayohessarah greenstone belts of the Superior province, Canada (Polat et al., 1998).

Paleozoic Example: Spain

Castro et al. (1996, 1999) proposed that the Aracena metamorphic belt in the Paleozoic Hercynian region of Spain is related to ridge subduction. They also describe a linear belt of low-pressure/high-temperature metamorphism with steep lateral thermal gradients associated with norites that are geochemically similar to boninites. There is also a belt of low-pressure/high-temperature amphibolites with an inverted metamorphic gradient. Recently, Castro et al. (1999) documented a west to east linear progression of Rb-Sr ages from 343 to 328 Ma. This temporal evolution is suggestive of migration of a triple junction. Also, the magma geochemistry and high-temperature conditions suggest a ridge subduction event. There is not an associated ophiolite, although the belt of amphibolites has a mid-ocean ridge affinity. Thus, these amphibolites may be a high-temperature equivalent of suprasubduction ophiolites in other regions.

Superimposed Mesozoic and Cenozoic Example: Japan

There have been several episodes of triple junction interactions with Japan (see Brown, 1998a), from a relatively well-documented Miocene event to two more speculative Cretaceous and Tertiary events (Uyeda and Miyashiro, 1974; Taira et al., 1988; Osozawa et al., 1990; Osozawa, 1992; Tokunaga, 1992; Kiminami et al., 1993; Underwood et al., 1993a; Sakaguchi, 1996).

The Miocene subduction of the Kyushu ridge between the Pacific and Philippine Sea plates (ca. 15 Ma) resulted in anomalous near-trench magmatism, cessation of backarc spreading in the Shikoku Basin, opening of the Sea of Japan, rotation of crustal blocks, and relatively high geothermal gradients in the forearc (Underwood et al., 1993b). Another signature of this ridge subduction event is that the forearc accretionary complex records accretion of sediments with a successively narrower age range until sediments and associated basalts are indistinguishable in age, implying subduction of successively younger lithosphere as the triple junction approached (Osozawa et al., 1990). The magmatism in the forearc was mostly felsic with minor mafic bodies (Hibbard and Karig, 1990). The high geothermal gradients resulted in anthracite coals with paleotemperatures of 180 to 315 °C and up to 500 °C adjacent to intrusives (Tokunaga, 1992; DiTullio et al., 1993; Hibbard et al., 1993; Laughland and Underwood, 1993; Underwood et al., 1993b). Sakaguchi (1999a, 1999b) also recognized high-temperature fluids in association with these high paleogeothermal gradients. Another feature is a set of normal faults that parallel the trend of the subducting ridge in the Shimanto accretionary sequence (Osozawa, 1992).

Evidence for a Cretaceous ridge-trench encounter in Japan is seen in the migration of igneous activity along the Shimanto accretionary complex in southwest Japan (Kinoshita and Ito, 1986; Kiminami et al., 1993). This event has been correlated with eastward migration of the Kula-Pacific ridge as it was subducted underneath Eurasia. Coeval “in situ basalts” in the accretionary prism have a large compositional range from alkalic and high-alumina to tholeiitic (Osozawa and Yoshida, 1997). Sakaguchi (1996) noted high geothermal gradients in the accretionary prism coincide with this magmatic activity, which is consistent with the ridge subduction model. Osozawa (1993) also identified a series of normal faults associated with this event.

To the northwest of the Shimanto belt is the Ryoke belt, a long linear belt with a high-temperature/moderate-pressure metamorphic history. This metamorphic belt is historically significant as it was the type example of the high-temperature half of Miyashiro’s (1959) paired metamorphic belts. For years, this belt was virtually synonymous with an ancient arc terrane. Work by Brown (1998b), however, questioned that association, and it now appears this classic “arc terrane” is actually the product of ridge-trench interactions. The metamorphic assemblages record clockwise pressure-temperature paths that parallel the temperature axis for both heating and cooling (also known as hairpin pressure-temperature paths; Brown, 1998b; Ikeda, 1998). The metamorphic isograds are independent of the location of voluminous granitoids. Based on K-Ar biotite ages of granitoids, Kinoshita and Ito (1988, 1990) and Kinoshita (1995, 1999) found a west to east decrease in cooling ages from 96 to 63 Ma. They postulated that these cooling ages were associated with subduction of the Farallon-Izanagi ridge. Geochronologic data on monazite show, however, that the cooling trend is not the same as the emplacement history (Suzuki and Adachi, 1998). Recently, Kinoshita (2002) reevaluated all geochronologic data on granitoids and adakitic intrusives in this area and determined that ridge subduction produced a V-shaped slab window oriented at an angle to the Japanese margin, based on the geometry of the trends in the geochronologic data both along and across the entire belt.

A problem in the ridge subduction interpretation of this belt is the occurrence of the adjacent high-pressure/low-temperature blueschist belt that was the basis of Miyashiro’s (1959) original interpretation of the belt. Brown (1998b) suggested that strike-slip offset has juxtaposed these two coeval belts to form the present paired belts, a suggestion consistent with well-known evidence for strike-slip rejuvenation of the Median tectonic line, the major structure separating the Ryoke and Sambagawa belts. Alternatively, new thermal models suggest that it is possible to develop the low-pressure metamorphism simultaneously with blueschist facies metamorphism during ridge subduction (Iwamori, 2000).

In northeast Japan, the Abukuma belt is an andalusite-sillimanite terrane, which was originally correlated with the Ryoke belt (Miyashiro, 1959). Subsequent work has shown that this correlation is incorrect as there was an initial low-pressure metamorphism followed by high-pressure metamorphism and subsequent isothermal decompression; all of these events occurred 10 m.y. before peak metamorphism in the Ryoke belt (Hiroi et al., 1998). Brown (1998a) speculated that the initial low-pressure metamorphism may relate to the subduction of the Farallon-Izanagi ridge and that subsequent plate reorganization caused the high-pressure event. The terrain was then displaced northward along arc-parallel strike-slip faults.

Many of the features seen in the Japanese ridge subduction events are also recorded in the Cenozoic northern Cordillera. These include low-pressure/high-temperature metamorphism, normal faults, and age progression in forearc magmatism that includes both felsic and mafic magmas.

Mesozoic Example: North American Cordillera South of the 49th Parallel

Pavlis (1997) speculated that ridge subduction occurred during the Jurassic beneath the Klamath Mountains of northern

California. This region has voluminous granitoid plutons, calc-alkaline volcanic rocks, and low-pressure/high-temperature metamorphism superimposed on forearc assemblages. Most previous workers have interpreted these relationships in the context of a magmatic arc constructed on previously accreted forearc assemblages (e.g., Wright and Fahan, 1988; Saleeby et al., 1992), and associated ophiolites generally have been interpreted as backarc basin systems (e.g., Harper and Wright, 1984). Alternatively, ophiolites like the Josephine ophiolite (Harper and Wright, 1984) and Coast Ranges ophiolite (e.g., Saleeby et al., 1992) may represent forearc ophiolites accreted during ridge subduction. The calc-alkaline volcanic associations and oblique spreading axes documented for these ophiolites have direct analogs in the modern Chilean triple junction. Thus, these ophiolite complexes do not require a backarc origin, and a forearc origin is possible. The best candidate for an entirely forearc event, however, is the Middle Jurassic history of the Marble Mountain and Hayfork terranes. In this area, most of the pre-Jurassic rocks were accreted as forearc accretionary complexes that were subsequently invaded by Jurassic intrusive complexes (e.g., Saleeby et al., 1992). In the Marble Mountains terrane, for example, low-pressure amphibolite-facies metamorphism is superimposed on older mélange (Donato, 1989). Also, a complex history of high-*T* metamorphism, deformation, and intrusion affects the Hayfork terrane, much of which is composed of forearc accretionary complexes (Wright and Wyld, 1994). These now exist only as thin thrust sheets atop younger forearc accretionary assemblages, and in most cases the present exposures are too small to comprise an entire oceanic arc assemblage. Comparison between this belt and parts of the Paleogene forearc of southern Alaska are striking, and it is conceivable that much, or all, of the mid-Mesozoic high-*T* metamorphism in the Klamath province is the product of a ridge subduction event.

The Kula-Farallon spreading center may also have had effects on the southern Cordillera that predate the events described in the volume. From ca. 83 to 65 Ma, the Kula-Farallon spreading ridge is likely to have intersected the continent somewhere along the Mexico-Alaska coastline (Atwater, 1970). Engebretson et al. (1985) suggested that the triple junction in Late Cretaceous time was located alongside Mexico or California and traveled northward toward British Columbia by the Eocene. Thorkelson and Taylor (1989) and Thorkelson (1995) used this model to propose the existence of a long-lived northerly migrating slab window beneath the western United States, and suggested that the Laramide magmatic gap of Late Cretaceous through Paleocene age was generated by the absence of subducted slab beneath much of the western United States. Babcock et al. (1992), Breitsprecher et al. (2003), and Haeussler et al. (2003) suggested that a slab window was positioned alongside Oregon, Washington, and Vancouver Island in Paleocene to Eocene time. However, the location of the Kula–Farallon–North America spreading ridge remains controversial and strong arguments for a more northerly (Alaskan) triple junction, particularly in the early Cenozoic, are presented in some articles of this volume and are highlighted below.

Cenozoic Example: North American Cordillera North of the 49th Parallel

Overview

The first geologic mapping in the Gulf of Alaska investigated reports of copper mineralization in the McCarthy region near the Copper River (Alaskan Military Expedition, 1898; Scharder and Spencer, 1901; Fig. 3). The expedition geologists recognized an association of greenstone and low-grade metamorphic rocks even though they had a difficult time traversing the glaciated terrane on foot and by boat. Sixty years later, Brabb and Miller (1962) were the first geologists to traverse this glaciated region from the coast to the interior. Later, Hudson and Plafker (1982) systematically described the metamorphic rocks of the Chugach metamorphic complex and hypothesized several different scenarios to account for their presence in a paleoaccretionary margin. On a larger scale, Marshak and Karig (1977) recognized the occurrence of anomalous near-trench felsic plutons in the southern Alaskan complex, and proposed the then revolutionary idea that ridge subduction could be an appropriate explanation for the high heat flow and related magmatism. Inspired by the Marshak and Karig (1977) article and their own studies of anomalous processes in the Kodiak accretionary complex, faculty and students at University of California, Santa Cruz, began to interpret the Paleogene history of the southern accretionary complex in the context of a ridge subduction event (Byrne, 1979; Hill et al., 1981; Moore et al., 1983). These early works set the stage for recent geologic studies that investigate whether or not Cenozoic ridge subduction is a plausible tectonic scenario for southern Alaska. In the 1980s, the U.S. Geological Survey Trans-Alaska Crustal Transect program also began to investigate various portions of southern Alaska related to ridge subduction. For example, James et al. (1989) investigated thermal models related to subduction of young oceanic crust. Many other studies were published from these studies (see references in various chapters).

Highlights of This Volume

Almost all the chapters in this volume examine the latest Cretaceous and Cenozoic evolution of the margin of the northern Cordillera, focusing on regions where ridge subduction processes may have occurred between Kodiak and Vancouver Islands (Fig. 2). These chapters are organized approximately by location from west to east along the margin as well as by topic ranging from sedimentology, structural evolution, fluid history, metamorphism, and magmatism. A summary of some of the central themes of the papers follows.

Dwight Bradley, Tim Kusky, Peter Haeussler, Dave Rowley, Rich Goldfarb, and Steve Nelson present an overview paper with regional data as well as new data that pertain to the Paleogene events of the northern Cordillera with particular

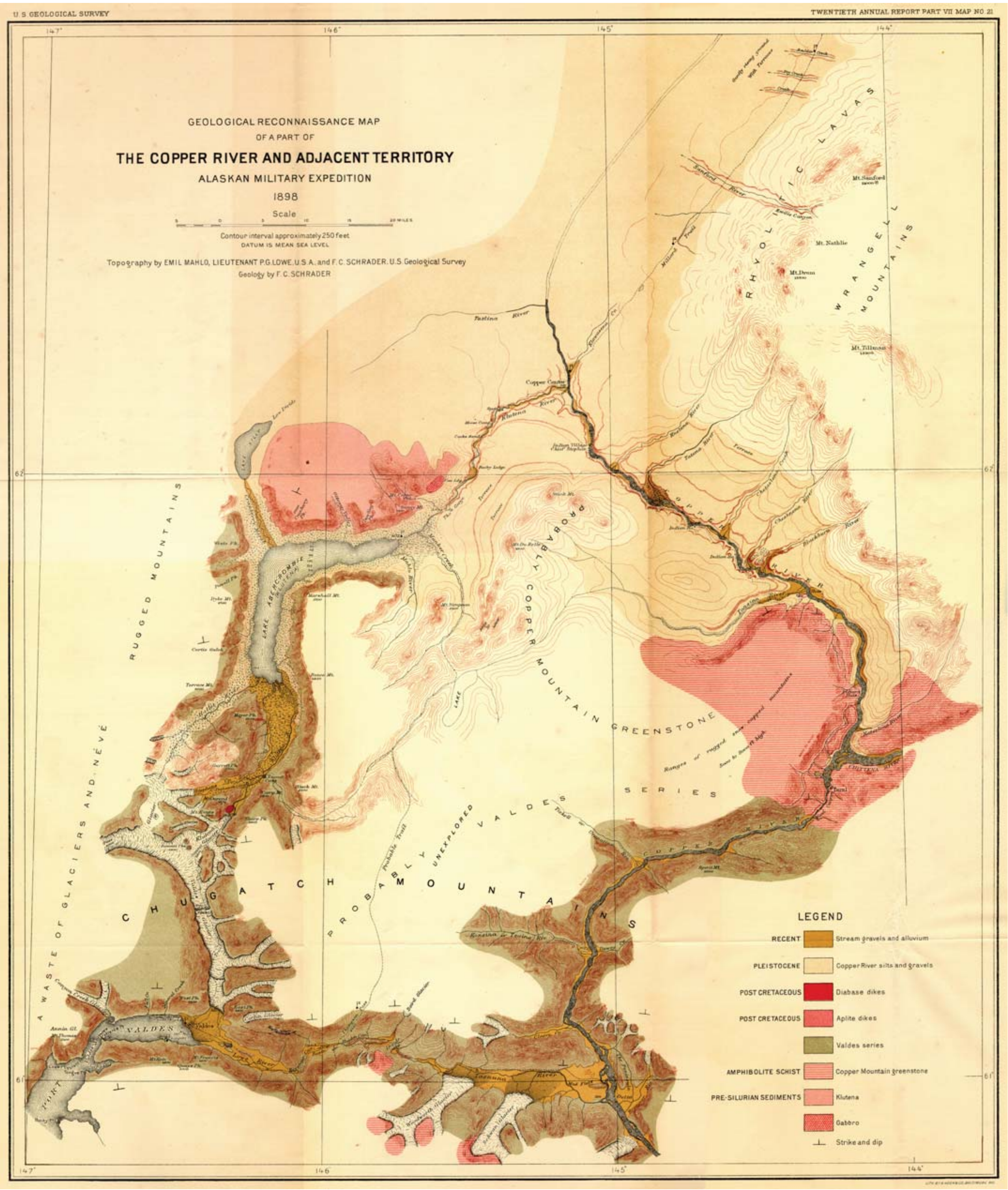

Figure 3. First geologic map of the Prince William Sound region, Alaska (Alaskan Military Expedition, 1898). Some of the geologic units are not correctly identified in terms of stratigraphic age, but all units are important components related to Eocene ridge subduction.

emphasis on Alaska (this volume, Chapter 1). For readers unfamiliar with this region, this paper is an ideal introduction to the general features associated with ridge-trench interactions. This is particularly important because the Eocene was a period of many complex interactions in the North American Cordillera, many of which are probably only indirectly related to a ridge subduction event—e.g., the close of the Laramide orogeny, the transition to Eocene extensional terranes of the southern Canadian Cordillera, exhumation in the Coast Mountains of western Canada and southeast Alaska, Eocene magmatism in the Coast Mountains synchronous with coast-parallel strike-slip faulting (Hollister and Andronicos, 1997; Stowell and McLelland, 2000), and the accretion of an oceanic plateau/seamount assemblage in what is now the Cascadia subduction zone. Thus, this overview paper sets the stage for what events are likely to be key processes associated with ridge subduction and triple junction interactions. The authors also evaluate alternative models and emphasize that the ridge subduction hypothesis is the only available hypothesis that satisfactorily explains all of the available data. They also address specific issues for the early Cenozoic northern Cordilleran region, including (1) implications for north Pacific plate reconstruction, including the provocative hypothesis of a fourth north Pacific plate (Resurrection plate); (2) uncertainties from poorly constrained reconstructions of the northern Cordilleran—problems of margin-parallel strike slip, early Cenozoic formation of the Alaskan orocline, and reference frames that moved in time; and (3) the broader effects of ridge subduction ranging from magmatism, deformation, and uplift within the forearc to possible far-field effects.

James Sample and Mary Reid reexamine the tectonic implications of the phenomenal thickness of the clastic member of the Chugach accretionary prism, known as the Kodiak Formation on Kodiak Island (this volume, Chapter 2). New faunal data and calculations of the size of the turbidite complex indicate it was deposited as an immense turbidite fan in a very short time period and thus records very large-scale erosional processes in an adjacent mountain belt. Nd isotope signatures and petrography of the sandstones lead them to conclude that the turbidites originated from the Coast Plutonic Complex of southeast Alaska and British Columbia and were deposited in a near-trench and within-trench environment, not far from the source as first postulated by Hollister (1979). The short time between deposition and accretion leads them to interpret the current location of the Kodiak Formation as due to margin-parallel tectonic transport of the accretionary complex.

Bill Clendenen, Don Fisher, and Tim Byrne discuss thermochronology of the Kodiak Islands (this volume, Chapter 3). Their data show the interplay between exhumation and changing thermal gradients associated with ridge subduction. Early Cretaceous low-temperature cooling ages from rocks on either side of the Border Ranges fault, the backstop to the accretionary prism, suggest that no significant slip occurred along this fault since that time and that there was no additional heating related to ridge subduction. The authors note a temporal correlation between subduction accretion with uplift in the adjacent Cook Inlet forearc (Trop et al., this volume, Chapter 4). Within the accretionary prism, zircon fission track cooling ages correlate with location of a regional antiform, whereas apatite data show a post-40 Ma cooling history. Thus, cooling from the ridge subduction event on the Kodiak Islands is regionally dispersed or did not produce significant thermal manifestations because the rocks had already been uplifted to relatively shallow levels. This is a similar to the present-day subduction of the Chile Ridge (Thomson et al., 2001).

Jeff Trop, Ken Ridgway, and Terry Spell report detailed sedimentological and stratigraphic studies of the early Cenozoic deposits exposed in the Matanuska Valley and southern Talkeetna Mountains (this volume, Chapter 4). Their study documents paleogeography accompanying early Cenozoic ridge-trench interactions in a large forearc basin complex. They identify sources from the arc to the north and the accretionary complex to the south within a Paleogene coarsening-upward megasequence. The authors give two alternative interpretations of this sequence that depend on the magnitude of strike-slip displacement on the Border Ranges fault. In a minimum slip scenario, the depositional sequence would record basinward progradation and syndepositional deformation and uplift, whereas in a maximum slip scenario there would be basin wide uplift forming a major unconformity. Interestingly, the authors note that either or both uplift events recorded in the basin (latest Cretaceous and middle Eocene) could be tied to regional effects of ridge subduction, and both uplift events have corresponding cooling histories recorded in the accretionary prism to the southwest (Clendenen et al., this volume, Chapter 3).

Peter Haeussler, Dwight Bradley, and Rich Goldfarb present details on the brittle deformation during and after the ridge subduction episode (this volume, Chapter 5). This deformation is commonly associated with hydrothermal activity that deposited gold-quartz veins and dikes. There is a diffuse network of faults that host small lode gold deposits in central southern Alaska, quite distinct from the significant dextral faults with large gold deposits in southeastern Alaska. The geometry of the faults is similar to brittle faults near the Chile triple junction, fault orientations determined from earthquake focal mechanisms associated with ridge subduction in the Woodlark basin, and extensional faults in the Shimanto accretionary prism. The authors speculate that both extensional and strike-slip deformation may be a common occurrence above slab windows.

Sarah Roeske, Larry Snee, and Terry Pavlis investigated the Border Ranges fault zone east of the Copper River in southern Alaska using a combination of detailed field mapping and structural analysis with Ar/Ar geochronology (this volume, Chapter 6). This fault system originated as a subduction zone megathrust between Wrangellia and the Chugach terrane. Subsequently, it was reactivated as a dextral fault zone with some oblique slip in the Late Cretaceous, prior to or synchronous with accretion of the coarse clastic unit of the Chugach accretionary complex, the Valdez Group, and continued through the Early Eocene. The long-lived (>20 Ma) history of oblique convergence occurred before and after the ridge subduction event and constrains plate geometries during this time. The zone of dextral slip may extend to Glacier Bay and Baranof Island in southeast Alaska, a distance of ~700 km. A 170 Ma diorite provides a possible piercing point for the Border Ranges fault system, indicating a minimum of 700 km of displacement, and possibly much more, since the Late Cretaceous.

In a pair of companion papers, Terry Pavlis, Kevin Marty, and Jinny Sisson (this volume, Chapter 7) and Terry Pavlis and Jinny Sisson (this volume, Chapter 8) describe the structural evolution in the vicinity of the western termination of the Chugach metamorphic complex. In these papers, the authors use field observations, detailed mapping, finite strain analyses, metamorphic petrology, and fluid inclusion data to develop a perspective on this down-plunge view of the western termination of the Chugach metamorphic complex. A transect to the west of the Chugach metamorphic complex crosses a significant dextral shear zone near Stuart Creek that developed during the ridge subduction event. Observed constrictional finite strains suggest that the bulk flow was constrictional—lengthening shear or lengthening-narrowing shear. The constrictional strain probably reflects vertical shortening associated with ridge subduction occurring at the same time as dextral shear produced subhorizontal shortening and orogen-parallel elongation.

In Chapter 8, this structural theme is carried into the high-grade core of the Chugach metamorphic complex, where there is a lithologically homogeneous section from greenschist facies phyllite to upper amphibolite facies gneiss. Within this sequence is a petrologic transition from schist to gneiss coincident with a regional, low-angle structural boundary that separates rocks displaying grossly different tectonic responses. Above this contact, the latest deformation is a system of dextral shear zones separated by relatively undeformed domains. As these shear zones are traced downward, however, they disappear into homogeneously deformed gneissic rocks below the schist-gneiss transition. Pavlis and Sisson propose that this boundary represents a decoupling horizon developed during dextral shearing that occurred at the same time (ca. 54 Ma) as the Kula-Farallon ridge was subducted along the margin. They hypothesize that the gneiss transition is an important rheological boundary between gneisses characterized by ~Newtonian viscous flow and overlying schists with a power-law, shear-thinning rheology, a conclusion that is also consistent with experimental and theoretical studies of rock deformation. If this rheological stratification is typical of schist-gneiss transitions, this conclusion has implications well beyond regions associated with ridge subduction.

Jill Weinberger and Jinny Sisson discuss higher-than-normal geothermal gradients resulting in greenschist facies metamorphism and a significant volume of quartz veins associated with Cenozoic subduction of the Kula-Farallon ridge (this volume, Chapter 9). Some of these veins record significant pressure drops of up to 140 MPa resulting from a change from lithostatic to hydrostatic conditions. In addition, one vein system was emplaced close to the brittle/ductile transition: Its appearance changes from ductile to brecciated. At some point after the ridge subduction event, these veins trapped late stage hydrocarbons that may indicate long-distance, post-metamorphic, fluid flow through this region.

John Bowman, Jinny Sisson, John Valley, and Terry Pavlis present an oxygen stable isotope study for a transect through the low-pressure/high-temperature Chugach metamorphic complex (this volume, Chapter 10). There is a systematic decrease in $\delta^{18}O$ values of quartz from both rock matrix and associated veins that is interpreted to result from a geometrically complex fluid flow system with at least two major periods of fluid infiltration. This infiltration occurred prior to the peak metamorphism with fluids that had exchanged with magmatic intrusions. Thus, magmatic heating associated with ridge subduction is most likely responsible for this episode of high-temperature/low-pressure Buchan metamorphism.

Cathy Zumsteg, Glenn Himmelberg, Sue Karl, and Peter Haeussler discuss low-pressure/high-temperature metamorphism on Baranof Island, the southern end of the Sanak-Baranof plutonic belt (this volume, Chapter 11). This region experienced four periods of metamorphism; only two, M1 and M4, are discussed in this paper. The first metamorphism, M1, was a Mesozoic moderate pressure amphibolite facies event. The final event, M4 at ca. 50 Ma, began at moderate pressure in sillimanite facies and then the region was exhumed as evidenced by the presence of andalusite. They suggest that the extensive (~25 km wide) biotite zone may be associated with a slab window formed during ridge subduction. They point out that the metamorphic history of this region is different from the Chugach metamorphic complex to the northwest. Instead, this region has a similar metamorphic history to the Hidaka belt of northwestern Japan, which records rapid changes in metamorphic pressure during a ridge subduction event (Hiroi et al., 1998).

Tim Kusky, Dwight Bradley, Thomas Donley, Dave Rowley, and Peter Haeussler used plutons of the Sanak-Baranof belt as time and strain markers during the ridge subduction event (this volume, Chapter 12). The early structures in the accretionary prism are typical of convergence followed by margin-parallel strike-slip faulting. An orthorhombic set of late faults may be the conduit for magma emplacement and may have also facilitated exhumation. A younger plutonic suite (ca. 35 Ma) that intruded after the ridge subduction event records a significant component of dextral transpression.

Jinny Sisson, Anne Poole, Holly Cooper Burner, Nancy Harris, Terry Pavlis, Peter Copeland, Ray Donelick, and Bill McClelland investigated geochemistry and geochronology of felsic plutons and associated rocks between the Copper River and Johns Hopkins Inlet in Glacier Bay National Park and Preserve (this volume, Chapter 13). The data indicate that this predominantly tonalite-trondhjemite-granitoid suite with minor mafic intrusives was derived from melted accretionary wedge and underplated mafic material during subduction of the Kula-

Farallon ridge. The amount of mafic material incorporated into these felsic magmas appears to increase toward the east. Previous geochronologic studies imply a linear age progression younging from west to east. In detail, this pattern is not linear as there are identical ages in the western Chugach metamorphic complex and Nunatak Fjord, 130 km to the east. The authors propose that this apparent age jump is related to either subduction of a transform fault and formation of a microplate sliver or a period of northward migration of the ridge.

Wes Groome, Derek Thorkelson, Richard Friedman, Jim Mortensen, Nick Massey, Daniel Marshal, and Paul Layer studied the Leech River complex, a fault bounded sliver on southern Vancouver Island (this volume, Chapter 14). New geochronologic data identify the age of deposition (103–88 Ma) of the metasediments as well as two felsic intrusive events at 88 Ma and 51 Ma. Both intrusive events occurred at depths of approximately 10 km. There are also undated metagabbros and greenschist facies volcanics, both with MORB geochemical signatures. Rapid cooling and exhumation in the Eocene was followed by deposition of Oligocene sediments. This assemblage is more than 1000 km to the south of coeval metamorphic and plutonic suites of the Sanak-Baranof belt and supports the concept of large-magnitude strike-slip displacement of the Alaskan segment northward (Sample and Reid, Chapter 2; Roeske et al., Chapter 6, this volume); however, it may also indicate rapid margin-parallel ridge migration (Pavlis and Sisson, Chapter 8, this volume) or the presence of a missing microplate (Bradley et al., Chapter 1, this volume).

SUMMARY

Figure 4 is a schematic diagram of our vision of the ridge subduction processes that affected the Paleogene northern Cordillera margin. The diagram shows two oceanic plates that are growing along a mid-ocean spreading ridge and are concurrently subducting beneath an overriding plate (shown partially transparent and cut away for clarity). As the spreading ridge enters the trench, it "unzips" and widens into a slab window (geometric principles and assumptions provided in Thorkelson, 1996). The ridge-trench-trench triple junction is migrating to the left, but jumps either left or right as transform faults are subducted. Mantle that was previously beneath the slab upwells through the slab window toward the base of the overriding plate. Mantle metasomatism from the downgoing slabs is absent in the slab window region, and arc volcanism is interrupted and replaced by magmatism of differing character, extending from forearc to backarc. Forearc magmatism occurs where the subducting ridge has opened into a narrow window, and MORB magmas rise into the forearc, triggering crustal anatexis, a process aptly named the "blowtorch effect" by DeLong et al. (1979). This effect also

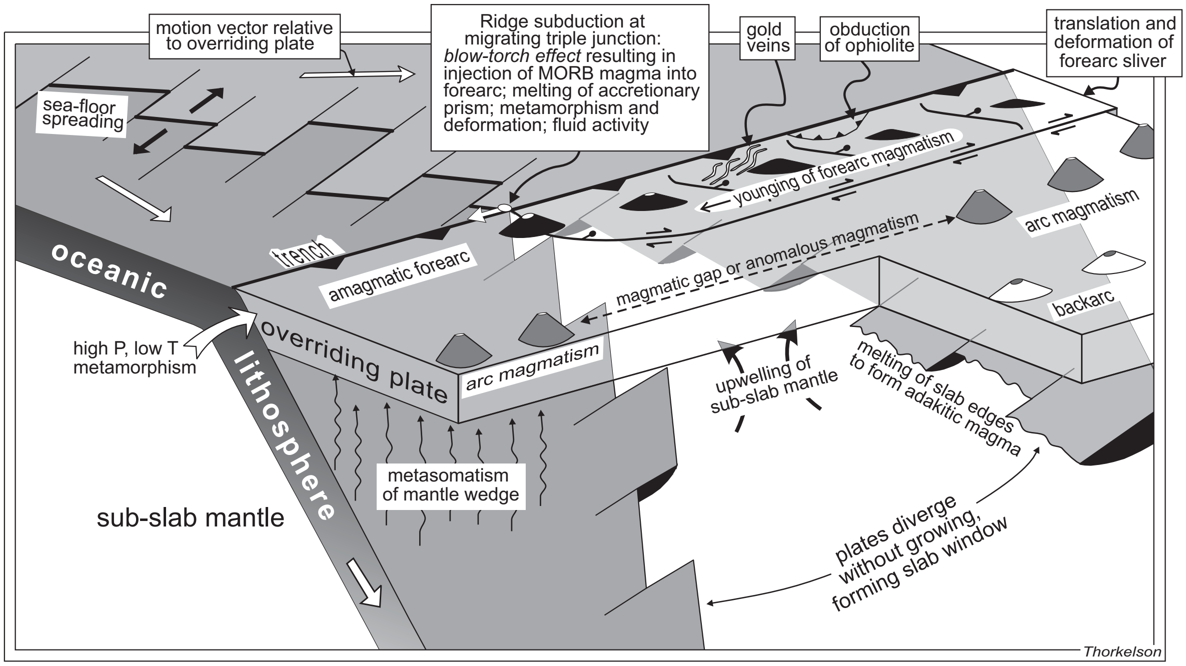

Figure 4. Schematic block diagram of ridge subduction illustrating various processes that affected the northern Cordillera. The Kula-Farallon ridge is shown subducting beneath North America without the overlying mantle wedge to show the "unzipping" of the ridge as it subducts, creating a slab window. In this reconstruction, the ridge is moving to the left. This creates temporal changes in the magmatic activity, kinematics, and geothermal gradients, as well as involves creation of a microplate or forearc sliver and obduction of an ophiolite. These processes are described more fully in the text. Modified from Thorkelson (1996).

generates thermal metamorphism and hydrothermal activity, supplanting the high-P/low-T metamorphism typical of most forearcs. If this process is localized for extended times due to slow triple junction migration velocity or repeated interactions, the entire forearc could be rapidly heated to high temperature to form high-T, low-P assemblages like those observed in the Chugach metamorphic complex (Chapter 10, this volume) or in the Cretaceous Ryoke belt of Japan (see above). Inboard, partial fusion of the slab edges results in adakitic magmas, and low-percentage melts of the upwelling sub-slab asthenosphere generate alkalic magmas. Deformation and exhumation in the forearc are variably affected by subduction of ridge segments and transform faults. All of these effects are time-transgressive and controlled by the migration of the triple junction, resulting in a general younging of triple junction–slab window features to the left (or south, in present-day coordinates). Basal drag from lateral movement of the triple junction is imparted to the overriding plate, and a trench-parallel strike-slip fault forms. The resultant forearc sliver is partially coupled to one of the descending plates and moves dextrally relative to the rest of the overriding plate.

We hope that this volume will stimulate researchers to re-examine the established tectonic models and consider the potential role that triple junction processes have played in various convergent margins. If the classic “arc terrane” of Japan can be reinterpreted as a forearc metamorphic belt generated by ridge subduction (Brown, 1998a, 1998b), then many other “arc terranes” may need re-evaluation. The papers here, and citations within, should serve as a template for evaluating other systems.

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