REPORT ON THE RESULTS OF THE JOINT JOI/USSAC AND GSA PENROSE CONFERENCE

THE EFFECTS OF TRIPLE JUNCTION INTERACTIONS AT CONVERGENT PLATE MARGINS

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INTRODUCTION

The typical view of the subduction of oceanic lithosphere is as a two-dimensional process dominated by the underflow of oceanic lithosphere, the refrigeration of the forearc, and the concentration of calc-alkaline magmas along a linear chain situated 70-150 km above the downgoing plate. As first noted by De Long et al. (1979), however, a corollary of plate tectonics is that all trenches must ultimately interact with a spreading center. This interaction need not affect an entire plate margin, but where such interactions occur the changes in plate motion should trigger distinctive geologic "events." For example, triple junction migration along a convergent margin may generate "slab windows" that produce significant thermal anomalies. The characteristics of such "events" in the upper crust, however, are not well understood. Analogies with modern systems imply that the consequences of three-plate interactions should produce distinctive structural, metamorphic, and igneous effects, yet there is no present consensus on what those effects are.

The analysis of three-plate interactions was one of the first clear descriptions of relative motion effects in plate interactions (e.g., MacKenzie and Morgan, 1969). Indeed, the quantitative description of the history of the Mendocino triple junction and its relationship to the San Andreas fault stands is now recognized as a classic example of using plate tectonics to understand a long-standing geologic problem (e.g., MacKenzie and Parker, 1967; Atwater, 1970).

Despite the success of the Mendocino triple junction study and the requirements for ancient triple junction interactions, there are few studies of the rock record that have ascribed a particular tectonic event to a triple junction interaction. This is undoubtedly a false impression of the geologic record. This impression is an artifact of the ignorance of the geologic community to the importance of triple junction processes and an inability to identify distinctive characteristics of those events in ancient rocks. In pre-late Mesozoic rocks, where sea floor records of plate motion are absent, most "events" at convergent margins are synonymous with orogenesis. Most are either ascribed as collisional events or contractional events driven by changes in plate motion. Some of these events are probably the direct consequence of triple junction interactions. Thus, two important challenges for the earth sciences are to recognize characteristic features of modern triple junction interactions, and to identify fingerprints for correct interpretation of ancient systems.

Because of these general problems, a conference was held in Eureka, CA, April 22-26, 1994. The goal of the conference was to gather together earth scientists from a variety of disciplines to determine if there are distinguishing features of different classes of triple junction interaction. This conference was held as a joint Geological Society of America Penrose Conference and JOI/USSAC workshop with some additional support from the National Science Foundation. Our primary goal was to bring together groups working on ancient systems and presently active systems to compare observations from these diverse data sources. That goal was achieved by the attendance of international participants from seven countries, as well as fifteen students from the US and abroad. The last day of the meeting included extensive discussion of the use of ocean drilling as a tool for future studies of triple junctions. This discussion continued into the next day with a smaller working group consisting of the authors of this report.

OVERVIEW OF THE MEETING

The meeting began with a field trip showing the onland effects of the Mendocino triple junction in the vicinity of Eureka, CA. The trip was led by G. Carver, D. Merritts, and K. Aalto and was devoted to the neotectonics of the Cape Mendocino region. The field trip demonstrated the structural complexities and the scale of the tectonic processes involved. Many spirited discussions at various outcrops set the stage for the meeting to follow. All the participants were impressed by the magnitude of the complex compressional deformation in the vicinity of the triple junction, and the problems in relating the observed effects to the details of the three-dimensional plate interaction at the triple junction.

The second and third days of the meeting were devoted to presentations of the basic observations from examples of both modern and ancient triple junction interactions. As a direct extension of the field trip, the meeting began with continued discussion of the Mendocino triple junction.

Mendocino Triple Junction: Kevin Furlong began this session by reviewing the general tectonic features and the geodynamics of the Mendocino triple junction system. Key points raised in his presentation included: 1) a description of the process by which a slabless window was generated along the triple junction; 2) supporting evidence for the asthenospheric window from tomographic images of region; 3) a characterization of the unique geometry in which the transform grows by conversion of a trench to a transform--this conversion produces an unusual configuration in which the net strike-slip offset on the San Andreas transform goes to zero at the triple junction, yet the oldest part of the Pacific plate lies directly south of the triple junction; 4) temporal EW shifts in the lithospheric boundary as asthenosphere accretes to Pacific and North American plates; and 5) the three-dimensional complexities that are closely linked to the evolving thermal structure and seemingly require complex movements of the upper crust relative to the lower-crust and upper mantle. Mian Liu then showed geodynamic models of this three-dimensional interaction. He also argued that volcanism associated with the slab window lagged behind the actual triple junction because of a time-lag in upwelling processes in the wake of the migrating triple junction. Perhaps 7-9 m.y. are required for complete thermal decay by conduction. Anne Trehu then summarized existing geophysical data from areas to the north and south of the Mendocino triple junction and presented preliminary results from the Mendocino seismic experiment that began in 1993. A surprising result was evidence for a bright reflection just north of the projected position of the triple junction. This observation, together with an interpretation of underplated oceanic crust in areas to the south of the triple junction, led to an interesting discussion of slab windows at the site of the triple junction.

A series of short presentations summarizing critical points or background for poster sessions followed with: Bruce Beaudoin expanding on interpretations of the Mendocino refraction data to the north of the triple junction; Sam Clark emphasizing the three-dimensional complexities of the structure recognized offshore from the triple junction; Bob McPherson questioning the problem of positioning the triple junction as a recognizable feature in earthquake records; Paul Bodin and Mark Murray describing results from recent geodetic work including coseismic uplift from the 1992 earthquake and horizontal motions in the triple junction region deduced from GPS measurements. The GPS data were particularly intriguing because preliminary data indicate large horizontal motions well inboard from the position of the inferred triple junction. This observation was underscored by a brief summary of geologic evidence from Bob McLaughlin showing a large area of complex distributed deformation that varied with time in the vicinity of the triple junction. Finally, Mike Underwood and Kevin Shelton summarized vitrinite reflectance, stable-isotope, and fluid-inclusion data from the triple junction area and emphasized the anomalous thermal signature of the King Range region. The last point led to a debate about the role of this terrane as a characteristic feature of the Mendocino triple junction itself. The other point of view is that it is an anomaly, rooted in the subducting plate north of the triple junction. This leaves an open question of exact implications for active tectonic processes in this region.

Woodlark System: The Woodlark Basin contains the best example of active ridge subduction entirely within oceanic plates. Brian Taylor began this discussion with a survey of the regional tectonics. Following this, and subsequent presentations by Julian Pearce, Mike Perfett, and Keith Crook, many conference participants were left with a feeling of awe at the system's complexities, which include some of the most important fingerprints of tectonic processes that accompany ridge subduction.

Taylor emphasized a number of key characteristics of the Woodlark system that make this system dramatically different from the more extensively studied example of ridge-subduction in Chile. First, the Woodlark system developed entirely within oceanic microplates that evolved toward the present day plate-tectonic configuration. The very young south-facing subduction zone in the New Britain - South Solomon trench system is now consuming the Woodlark spreading center. It began when the Ontong Java Plateau collided with the Solomon Island arc. Thus, the consumption of the Woodlark spreading center is occurring during subduction zone flip. This effect produces distinct ambiguities in the interpretation of the tectonic system and the magmatic arc rocks produced within the system. Second, the system is characterized by very high convergence rates (10.7 and 7.2 cm/yr.) on both sides of the subducting and rapidly spreading (7.2 cm/yr.) of Woodlark spreading center. A distinctive configuration of ridge-transform segments has led to little migration of the triple junction during its interaction with the trench. Thus, only a small segment of the forearc has been subjected to the long-term effects of the ridge-subduction. This segment of the forearc is also characterized by a gap in deep seismicity consistent with the longer term interaction of the trench with the spreading center. Surprisingly, however, the site of the triple junction does not show a heat flow anomaly in the forearc basin. Third, the triple junction area is associated with morphologic anomalies including the lack of a bathymetric trench, unusual undulations on the subducting oceanic plate near the triple junction, and very rapid uplift rates of the forearc in the vicinity of the triple junction.

Probably the most impressive features of the Woodlark system are the voluminous forearc volcanoes that form the islands of the New Georgia Group. These forearc volcanoes are developed at the site of the ridge subduction and occur nowhere else within the arc-trench system. B. Taylor gave an overview of these volcanic sequences, and subsequent presentations by Mike Perfett and Keith Crook filled in the details on this critical petrologic assemblage. These rocks are characterized by remarkable diversity of compositions and in the distribution of compositional variations. In general, however, the rocks are dominated by island arc basaltic compositions with minor alkaline assemblages and a series of "transitional" rocks that appear to be a mixture of compositions from MORB to IAB. Although many petrogenetic models (e.g., presentation by J. Pearce) predict that boninites should be abundant in this setting, they appear to be conspicuously absent. Finally, perhaps the most surprising observation noted by all of the speakers, but emphasized particularly by K. Crook, is that the island arc type magmas are not limited to the forearc volcanoes but extend onto the oceanic plate well in advance of the subduction front. A discussion of the petrogenesis of these volcanic rocks considered the consequences of a ridge subduction vs. a system in which the subduction polarity reversal played a key role. That is, during a subduction flip, magmas generated from slab remnants of the older subduction zone could generate magmas that interact with the MORB-like rocks in subducting spreading center to form the mixed compositions observed in the New Georgia group. A subsequent presentation by Sarah Sherman, however, showed a similar unusual geochemical signature for volcanic rocks on the oceanic plate well in advance of the Chilean ridge subduction where no subduction flip is occurring. Thus, other factors may well be present.

As part of the discussion of the Woodlark system, Julian Pearce presented petrogenetic models attempting to fingerprint the geochemistry of rocks associated with various classes of triple junction interactions. This presentation emphasized that different classes of triple junction would undoubtedly produce different kinds of petrogenetic signatures. Three general types were considered based on the thermal structure of the footwall versus hanging wall of the system: type 1 = ridge subduction (hot footwall, cold hanging wall); type 2 = spreading in the overriding plate (hot hanging wall, cold footwall) with the best example represented by a backarc spreading center interacting with a trench; and type 3 = initiation of subduction along a spreading center (hot hanging wall, hot footwall). Using modern examples and predictions based on the thermal states of each of these systems Pearce concluded that adakites and bajaites should be diagnostic of type 1 interactions, high Ca boninites diagnostic of type 2, and low Ca-boninites typical of type 3 interactions. These interpretations led to spirited discussions which were continued in later small group discussions. The principal debate centered on the role of slab melting versus slab dehydration and associated melting of the mantle wedge.

Rivera Triple Junction: The session ended with short presentations by Jacques Bourgois and Laura Serpa showing the apparent onland affects of the Rivera-Cocos-North American triple junction in western Mexico. This example of complex microplate interaction involves four and possibly five plates within a small area (Bandy and Pardo, 1994). The convergent margin is presently interacting with a poorly defined plate boundary between the Cocos and Rivera plates. This region probably represents a FTT type triple junction (e.g., Serpa et al., 1992 and Bandy and Pardo, 1994). The effects of the triple junction interaction on the convergent margin are complicated. Bourgois described rifting of the submarine portion of the forearc with the extension direction sub-perpendicular to the strike of the convergent margin. However, Serpa presented evidence that much of the forearc along the Pacific coast is unextended, yet major extension has occurred inboard from the axis of the magmatic arc to a major forearc volcano. These discrepancies may be related to propagating rift systems within the forearc. The process driving the rifting may be caused by interactions between the subducting Rivera and Cocos slabs which show major velocity variations but a poorly defined plate boundary.

Chile Triple Junction: The Chile Triple Junction (CTJ) is the second unambiguous site of ridge subduction. This system contrasts with the Woodlark system in that the subducting segments are sub-parallel to the trench and at a high angle to the convergence vectors. An abundance of marine data (Cande and Leslie, 1986) allows the plate margin kinematics to be calculated through time. The Nazca and Antarctic plates separate along the Chile Rise at a full rate of 50 mm per year. The Nazca Plate subducts at about 70 mm per year. Finally, the Antarctic Plate subducts at about 20 mm per year. The Chile rise has several ridge segments separated by transforms. The first ridge collision occurred in Southern Patagonia (54° S) at about 18 Ma. The locus of ridge subduction has migrated northwards through time, with major segments being subducted at 14-10 Ma, 6 Ma, 3 Ma and 100 Ka-to-present. The triple junction is currently in RTT configuration with the locus of ridge subduction at the Taitao Peninsula (46°S). A series of speakers addressed manifestations of ridge subduction from the Pacific Ocean, through the trench and the Chilean forearc into the backarc regions in Chile and Argentina.

Amanda Lothian presented an analysis of GLORIA data from the CTJ, backed by an extensive poster presentation of the processed GLORIA images. These studies show no evidence of modifications of the tectonic processes at ridge segments as they approach the trench. This view is supported by analyses of the magnetic data which were presented by S. Lewis. The forearc shows major variations including a decrease in the width of the forearc toward the triple junction. Other physiographic features apparently are the product of uplift in the vicinity of the triple junction. For example, to the north of the triple junction are large submarine canyons emerging from the shelf, whereas to the south of the triple junction there was dendritic mass wasting on the trench slope.

Steve Lewis gave a summary of the results of ODP Leg 141, which sampled forearc material in the CTJ region, and made measurements of bore hole temperatures. Bore hole temperatures recorded widespread variations and support other data indicating the major role of hydrothermal circulation; for example, large temperature spikes at site 859 probably are due to transient fluid flow. Nonetheless, the data suggest an average geothermal gradient of ~100 °C/km for the triple junction region. The next two speakers, Nathan Bangs and Jan Behrmann, presented studies of the CTJ forearc based on seismic reflection data coupled to drilling data. One anomaly highlighted by both speakers is the lateral contrast in sediment ages in the Chile forearc. Little more than 100 km north of the CTJ, seismic interpretations indicate that accreted sediments as old as Cretaceous lies near the trench in the forearc. Conversely, drilling on Leg 141 close to the CTJ never penetrated sediments older than Pliocene. Tectonic erosion may be an important process at this site of ridge subduction.

The next three speakers covered related studies of forearc sediments recovered from ODP Site 863, situated in the forearc overlying a subducted ridge segment. K. Marsaglia showed that the clast types of Site 863 sands and sandstones are typical of the circum-Pacific belt, but the cements are unique. Site 863 sands and sandstones are extensively cemented by smectite-rich clay, zeolites and carbonate, probably in response to hydrothermal circulation. D. Prior showed textural evidence that the carbonate cements clearly postdate the clay-zeolite cements and are associated with dilatent fractures and extensional faulting. The clay-zeolite cement may relate to the thermal effects of subducting young, hot crust on the forearc hydrogeology whereas the carbonate cements may represent a direct tap into the subducted mid-ocean ridge hydrothermal system. The thermal history of the forearc is, in part, recorded by paleomagnetic data presented by R. Musgrave.

Changes in paleomagnetic signature with depth are related to diagenetic growth and destruction of sulfides and reflects high geothermal gradients during the evolution of this forearc.

Sarah Sherman presented geochemical data from dredge samples from four ridge segments along the Chile Rise. Some samples fell out of the MORB field on standard discrimination diagrams. Within one ridge segment, still several hundred kilometers from the trench, there are two isotopically and geographically distinct suites- one with island arc affinities and one with hotspot affinities. These data suggest that ridge magmatic processes and resultant geochemistry may be affected as a trench system is approached. The timing of magma contamination and the process for the contamination remains uncertain.

Ruth Murdie presented the results of the only microearthquake monitoring program at a site of ridge subduction. Three months of recording by 9 three-component stations at the CTJ yielded a linear trending band of hypocenters coincident with a subducted transform and a cluster at the predicted position of a subducted ridge. The latter set of events has focal mechanisms which are not compressional and are not trench parallel, which is unusual for a forearc setting. These earthquakes are interpreted as the direct influence of ridge extension on the overlying forearc. Eric Nelson took the tectonic analysis of the forearc a little further with a finite element indenter model for ridge collision at the CTJ. These models support the hypothesis that large scale strike-slip faulting and the development of microplates or terranes may be initiated by the ridge collision process.

Randy Forsyth summarized the anomalous forearc magmatism on the Taitao Peninsula as well as the site of active ridge subduction, the 3 Ma ridge subduction and the 6 Ma ridge subduction. The volcanic suite of the Taitao ophiolite is unusual in that is contains large volumes of pyroclastic material, both subaerial and submarine. Geochemically the suite is bimodal containing basalts and rhyolitic rocks of 3-5 Ma cut by 1.5 Ma rhyodacitic plutons. John Diemer presented sedimentological aspects in more detail; dike sequences grade up into pillow lavas, then proximal debris flows, storm sands and ultimately turbidites. Together with the magmatic data presented by Forsythe, these data suggest that the Taitao Ophiolite represents an anomalous forearc basin complex. This ophiolite resulted from the tectonic and thermal imprint of a subducting ridge rather than a pristine slice of ocean floor. This view was echoed by a presentation by J. Bourgois.

The next three speakers dealt with ridge-related processes in the arc and backarc regions of Chile and Argentina. S. Flint described the Tertiary sedimentary sequences to the east of Chile. In this region, base level changes control basin development and, at least locally, correspond to foreland thrust tectonic episodes. There is no obvious link between sedimentary sequences and the migrating triple-junction position. Victor Ramos clearly demonstrated, however, that there were temporal changes in the foreland fold-thrust belt that correspond to the timing of Late Tertiary ridge collisions. There is a clear change in tectonic style and sedimentary products across an east-west line. To the north, where there have been no ridge collisions there is only a thin Molasse succession and the tectonic style is extensional. To the south, a thick Miocene Molasse is intimately involved in a foreland thrust belt. The belt and the molasse young from south (18 Ma) to north (10 Ma) and can be correlated with the migration of the CTJ.

Some of the most significant studies related to the CTJ are geochemical investigations of arc and backarc volcanic rocks. These geochemical data were summarized by Suzanne Kay. A present-day arc gap corresponds with the zone of recent ridge subduction. Mapping and dating are not extensive enough to define equivalent gaps in the rock record. In the backarc, some late Tertiary plateau basalts correspond in position to predicted positions of slab windows related to subducted ridge segments for the age of the lavas. These lavas are likely to be associated with the development of slab windows. New geochemical data from backarc basalts were presented on an accompanying poster by Matt Gorring. Eocene basalts may relate to an earlier ridge collision and/or slab window. Kay particularly emphasized the significance of the Cerro Pampa adakites. The geochemistry of this 12 Ma stock in Argentina is consistent with 3-5% slab melting. Also, it is thought that this represents melting of a hot, subducted oceanic slab immediately prior to the slab window related back-arc basalts.

Peter Styles presented the results of a land based gravity survey across the region inboard of the CTJ. A large Bouguer low corresponds exactly, in both position and size, to the slab window predicted to develop from the ridge subducted at 6 Ma with magmatism shutting off at 60 km of burial. A Bouguer high corresponds to the predicted position of the ridge segment that subducted at 6 Ma. Spectral analysis is consistent with the hypothesis that these anomalies are generated by features at slab depths and suggest that subducted ridge systems are generating gravity anomalies. However, there are problems in this hypothesis. Modeling on the basis of mantle compositions alone suggests that the observed low should be a high. One explanation for this observation is that the upwelling asthenosphere in the slab window is anomalously hot. Perhaps subducting ridge systems allow us to trace thermal anomalies related to subduction zones that would normally go unnoticed.

Ancient triple junctions: The bulk of the third day was devoted to two ancient convergent margins, Japan and Alaska, where the effects of triple junction migrations are relatively well documented. A few additional examples were discussed briefly. These sessions began with an overview of the Japanese system by Mike Underwood. He summarized the thermal maturity data and structural observations from the Shimanto accretionary prism as well as evidence for near-trench magmatism in the outer zone during the middle Miocene. These data, together with inferred plate reconstructions for the Cenozoic, seemingly provide compelling evidence for a Miocene subduction of the Shikoku basin ridge. However, Jacques Charvet inferred that all of the Miocene events attributed to the ridge subduction were the result of an arc-polarity reversal followed by arc-trench collision. This hypothesis was highly controversial and led to extensive debate. Nonetheless, the discussion was important because it forced the group to focus on the difficulty of recognizing the effects of a triple junction interaction in the ancient record. Alternative hypotheses can always be presented until we have a better understanding of tectonic processes at triple junctions.

Discussions were extended to the older, late Mesozoic-early Cenozoic history of the Japanese margin. Here Japanese scientists have accumulated a large data base to document a prolonged interaction between the east-Asia convergent margin and the Kula-Pacific ridge. S. Osozawa summarized a large data base of fossil ages and radiometric ages and showed how these data could be used to construct "Δt/t" diagrams for the Japanese margin. This approach produced impressive evidence of multiple periods of subduction of zero-age oceanic crust based on differences between fossil ages in accreted packets of sediment and ages of volcanics incorporated into the prism. O. Kinoshita then followed up on this discussion with a compilation of radiometric age data from plutons of the east Asian arc and cooling ages Ryoke belt. This compilation showed a younging trend in apparent ages from ~100 Ma in the southwest to ~50 Ma in the northeast. This presentation was followed by what was one of the most thought provoking talks of the session. Mike Brown used Kinoshita's age data, together with observations of the metamorphic history, to argue that the Ryoke belt -- half of the world's classic paired metamorphic belt -- was not an arc terrane. Rather, he infers that the rocks represent forearc assemblage that was subjected to extensive heating and magmatic activity related to late Mesozoic subduction of the Kula (Izanagi?)-Pacific spreading center. In this hypothesis, the present paired metamorphic belt is the result of strike-slip duplication of the forearc assemblages. This discussion was then followed by four short presentations: K. Kiminami discussed the importance of greenstones incorporated in an accretionary prism as both dikes and volcanics, and he emphasized these as indicators of ancient ridge-trench interactions; J. Maeda described an early Cretaceous metamorphic assemblage on Hokkaido that contained unusual ophiolitic assemblages that were interpreted as products of ridge-trench interactions; G. Kimura showed that basalt blocks are due to in situ magmatism and changes in melange fabric are consistent with a shift to Kula plate subduction; and N. Tshuchiya who described a system in northern Japan where slab melting was an important process.

The last session on ancient triple junctions dealt with the southern Alaska forearc where a suite of forearc plutons has long been recognized. Marshak and Karig (1977) recognized as a likely candidate for a magmatic system related to early Cenozoic interaction with the Kula-Farallon spreading center. Terry Pavlis began the session with an overview of the regional tectonic setting of the system. Dwight Bradley summarized the age data demonstrating a distinct temporal migration of the forearc plutonic belt related to this event. A complex structural history is also recognized and closely tied to injection of a lithologically diverse suite of dikes that are also a manifestation of the ridge interaction. Dave Rowley then presented new models of Pacific plate motion and Kula-Farallon ridge interaction. He concluded that unusual ridge geometries were required to accommodate the apparently rapid migration implied by the plutonic age data. This hypothesis led to some discussion, however, because other plate reconstructions (e.g., Engebretson et al., 1985; Lonsdale, 1988) seemingly do not require this unusual interaction. Jinny Sisson and Terry Pavlis then described what is undoubtedly the most unusual feature of the Tertiary event; a low-P/high-T metamorphic belt developed within a portion of the forearc system. This metamorphic belt, the Chugach metamorphic complex, reaches upper amphibolite facies at pressures of <400 MPa. The metamorphism is associated with voluminous granitoids. These magmas have isotopic signatures suggestive of a composite source include a MORB component + anatectic melts of accretionary prism sedimentary rocks. This belt has a complex structural history with an early history of orogen-parallel motions along a low-angle ductile shear zone followed by dramatic telescoping during peak metamorphism. These events were interpreted as the products of a plate reorganization and associated backtracking of the triple junction. These presentations were followed by a series of short presentations related to posters or different topics. Sarah Roeske continued the discussion of the Tertiary Alaskan margin with a summary of the importance of forearc strike-slip systems associated with the interaction. Peter Heussler and Rich Goldfarb noted the close association between the ridge-trench interaction, deep crustal dewatering and gold mineralization within the forearc assemblages. Dan Barnett finished the Alaskan discussion by a brief description of an Early Cretaceous forearc plutonic belt that may represent a different process than ridge subduction--melting along a young subduction zone. Continuing on the theme of mineralization, Randy Koski expanded on the importance of mineralization in the California Borderlands and in the offshore environment. The session ended with Nan Lindsley-Griffin and Keith Crook proposing a Paleozoic ridge-trench interaction as a mechanism for metamorphic assemblages in the eastern Klamath Mountains and eastern Australia respectively.

Closing Presentations: The fourth day of the meeting began with a "grab bag" session with several diverse topics. Vince Cronin summarized the cycloid model of plate motion. He surmised that a direct implication of his model was that most triple junctions possess inherent instabilities related to constantly changing plate motions. This conclusion was first recognized by Dewey in the mid 1970's but commonly overlooked today. Two presentations then considered the ultimate ancient triple junction interaction, the Archean. Tim Kusky qualitatively argued that the greater heat flow in the Archean would have led to greater ridge lengths and increased triple junction interactions. He emphasized that many of the characteristic features of granite greenstone belts were lithologically reminiscent of forearc assemblages. However, these belts often show high-T metamorphism and are invaded by granitoids which are not features common in forearcs. The only

Phanerozoic settings that produced comparable systems are where ridge-trench interactions have occurred. Dallas Abbott quantified some of these statements by estimating the increased likelihood of a ridge-trench encounter during the higher heat flow of the Archean. The models suggested that during the Archean 60-70 triple junction interactions would occur globally making features like the Woodlark basin a typical paleogeographic feature of the Archean. In addition, she noted that the higher-T conditions would also lead to an average age of subducted oceanic lithosphere that was much younger than today, and shallower-level melting would by typical of Archean subduction zones. Both of these characteristics would enhance the "forearc" characteristics of the magmatic activity and the petrogenesis would be markedly different to produce the characteristic low-K tonalite/trondhjemite series typical of the Archean. This indicates that low-K series (e.g., adakites) should not be used as unique indicators of Precambrian ridge subduction.

Formal presentations were concluded with more coverage of modern examples including the change from ridge collision to passive margin sedimentation in the Antarctic Peninsula and the RFT triple junction in western Canada. Peter Barker described the rather unusual triple junction interaction on the Antarctic Peninsular where passage of the triple junction leads to conversion of a convergent margin to a passive margin. Thus, this system represents an ultimate end-member to the range of possible plate configurations that accompany ridge-subduction events. In this presentation he showed how changes in uplift are seen as sedimentary unconformities, an increase in hydrothermal activity, and cessation of arc volcanism at 20 Ma. Malcolm Hole then described backarc igneous complexes of the Antarctic Peninsula. In this region there is evidence for alkaline volcanics which do not have any geochemical evidence for subduction influence. There was a 5 m.y. gap between the predicted opening of the slab window and the generation of magmatism. The final presentation by Kristen Rohr covered the complex microplate interactions at the Pacific-Explorer-North American triple junction near the Queen Charlotte Islands. This presentation underscored the complex interactions that accompany most ridge subduction events as well as the development of unusual volcanic assemblages developed on the down-going plate in advance of the triple junction. Particularly striking was the clear development of a complex breakup of the oceanic plate. The result is a series of microplates and a resultant dispersal of the triple junction effects onto a broad portion of the convergent margin. This presentation as well as earlier presentations on the Rivera plate and Woodlark region underscored the complex microplate interactions that accompany most ridge-subduction events as well as the development of unusual volcanic assemblages in various positions above the down-going plate in advance of the triple junction.

Results of Detailed Discussions: The group then split into a series of smaller discussion groups to consider five topics. The first session on Tuesday morning addressed three topics:

Ophiolite development, Thermal manifestations, and Basin development. An afternoon session took up the topics of Petrogenetic signatures and Structural signatures.

This session led to stimulating discussions of what may be critical to identify ancient triple junction interactions. These systems seem to show a distinct geochemical signature of MORB's contaminated by sedimentary components. In addition, there are structural and lithologic assemblages typical of forearc regions clearly associated with the ophiolite and a stratigraphic cover sequence indicating volcanism in proximity to an existing convergent margin. All of these relationships may be critical in recognizing ancient examples of ridge subduction.

The thermal manifestations group discussion was led by Kevin Furlong, Dave Prior, and Mian Liu. This group was the largest of the three morning sessions and its diversity was reflected in the discussion. Initial discussion centered how fluid advection imposes transient effects on heat flow measurements in modern systems as well as long-lived alteration of the thermal structure. In many ancient systems, there appears to be a clear association between hydrothermal activity and slab-window development. For example, in Alaska, there is extensive hydrothermal quartz veining and local gold mineralization is linked to early-Tertiary ridge-subduction. Also, thermal maturity anomalies and mineralization occur near the present position of the Mendocino triple junction. The data base, however, is relatively small for offshore systems. Nonetheless, observations of depressed heat flow in the Woodlark forearc seemingly contradict data from other sites such as Chile, where heat flow is high. The observation in the Woodlark basin therefore suggests tremendous hydrothermal systems given the voluminous forearc magmatism. Comprehensive measurements and modeling of present-day geothermal regimes represent salient priorities for future studies.

A group discussion of basin development was led by Victor Ramos and Kathleen Marsaglia. The group was relatively small (<10) and met to address basin formation in conjunction with triple junctions. Sparse participation in this discussion section parallels the emphasis placed in the literature on the tectonic evolution and associated magmatism of triple junctions as opposed to associated basin development and sedimentological effects. Discussion focused on how triple junctions can be linked to basin formation, modification, and inversion on the overriding plate. The main controlling factors are: (1) the type of triple junction (e.g., TTT, TRT, TFT, and FFT); (2) triple junction geometry (e.g., angle of plate margin intersection); (3) the stability of the triple junction; (4) the presence of pre-existing structures on the overriding plate; (5) the nature of the crust in the overriding plate (continental versus oceanic); and (6) plate kinematics after collision. Major unanswered questions include the preservation potential for triple junctions in the sedimentary record and the uniqueness of these signatures.

The thermal manifestations discussion then addressed the broader problem of tectonic processes at the scale of the entire triple junction system. Several questions were discussed including: 1) What are the controlling parameters in the thermal system? 2) Can we simulate the thermal systems using numerical models? 3) Can we test these models with empirical data from modern systems, ancient systems, or both? 4) What is a slab window? and 5) How does the mantle respond to different types of triple junction interactions? It appears that many of these questions cannot be readily answered until there are more quantitative data on the time-temperature history of both ancient and modern systems. That is, data bases from thermally sensitive geochronometers (e.g., fission tracks and K-Ar systems) as well as geothermometers (vitrinite reflectance and metamorphic petrology) are needed to establish a broader data base.

As this discussion continued, several members of the group emphasized that different classes of triple junctions needed to be treated separately in terms of their thermal manifestations. Thermal response will depend critically on geometry (e.g., triple junctions which generate a slab window versus those that do not) and migration rate (fast versus slow). Moreover, there are major differences between subduction systems that involve destruction of a ridge-system in the footwall compared to a triple junction that carries a spreading center in the hanging-wall of the subduction zone. The latter example is a special case of a back-arc spreading center that interacts with a trench. These general distinctions are summarized in Figure 1, together with inferences on the variations in thermal state of each system.

Finally, in a wrap-up discussion, the thermal manifestations group considered the possibility that these systems probably behave very differently at different crustal levels. The evidence for intense hydrothermal systems in many ancient and young examples of ridge-subduction systems strongly suggest that focused advective heat transport by fluids, magmas, or both may be dominant in the shallow portions of these systems. At deeper portions of the systems, however, mantle convection associated with diffuse asthenospheric upwelling may play a dominant role. A key point is that simple models of conduction within deeper portions of such systems are inadequate. This is because they fail to consider advective heat transfer caused by asthenospheric upwelling, generation of basaltic melt, and the potential underplating of basaltic magma within the forearc.

The petrogenetic discussions mostly focused on igneous signatures which may be caused by triple junction interactions. These may include: (1) a gap in volcanic stratigraphy and/or location of volcanoes; (2) a change from arc-like volcanism to MORB/OIB volcanism as the slab window is opened; (3) para-autochthonous N-MORB or contaminated N-MORB in the forearc; (4) volcanics with slab melt components such as high Sr, Zr, and La/Yb and isotope signatures indicative of MORB; and (5) alkaline magmatism in the back arc. None of these criteria will uniquely identify a triple junction interaction. However, when recognized they should lead to a serious consideration of the possibility of a triple-junction interaction.

The Structural Associations discussions were led by Jan Behrmann and Gaku Kimura. The discussion initially centered on variations in near-field deformation patterns among different classes of triple junctions. Kimura reminded the group that the process of ridge subduction may be a major overlooked mechanism in the construction of continental crust. After extensive discussion the group generally agreed that the most distinctive structural characteristic of a triple junction interaction was an event that migrated in time. Also, they are associated with one, or more, of the following characteristics: (1) abrupt changes in the kinematics of deformation at regional scales; (2) migration of magmatic provinces and their thermal manifestations; (3) dynamic forearc sedimentation that records rapid lateral migration of sedimentary sources and basins as well as vertical responses to thermal perturbations; and (4) juxtaposition of rocks with a progressive decrease in the age gap between sediments and basalt reflecting approach of zero age lithosphere. Clearly these characteristics can be produced by other structural processes, and extreme caution should be used in simple application of these generalizations. Nonetheless, the recognition of several of these characteristics should be a strong indicator of a triple junction process.

Closing Sessions: Recognition of Ancient Systems and Future trends: The final half-day session by the entire group addressed the recognition of ancient triple junction interactions, future trends, and the potential role of ocean drilling in triple junction research. A smaller group continued these discussions into the afternoon and evening, the results of which are discussed below in a separate section.

The first session on recognition of ancient systems was led by Tim Byrne and Tim Kusky. This discussion began with a reminder that the conference was considering a whole range of triple junction types. Thus, to make any conclusions, we needed to focus on the controlling processes of specific systems; processes that probably vary with tectonic boundary conditions. Moreover, as illustrated in Figure 1, there are fundamentally three types of triple junction systems: 1) ridge-subduction types; 2) hanging-wall spreading center types; and 3) trench-trench-trench systems. The first type contains several variants that are recognized in modern systems, and undoubtedly occurred during ancient interactions (Figure 1). These variants include systems where one arm of the systems is a transform (Figure 1)--FFT, Mendocino type interactions and RFT, Rivera-type interactions--and the very special case typified by the Antarctic Peninsula where ridge-subduction is followed by conversion of the trench to a passive margin. The conference was devoted primarily to these variants on ridge-subduction process and triple junctions of the second and third type (Figure 1) had been largely omitted from our discussions. The interaction of three trenches, however, is simply a three-dimensional manifestation of arc collision, and the geologic record of this type of event is fundamentally a collision. The case of hanging-wall spreading center interaction (Figure 1) could conceivably produce many of the same effects as ridge-subduction events. Nonetheless, apart from the potential petrologic signatures described by Julian Pearce, recognition of this type of system will remain problematic until more information is available from these types of systems.

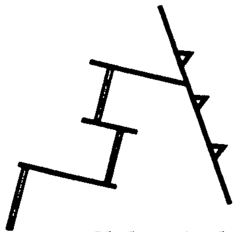
For the specific cases of various modes of ridge-subduction (Figure 1), there are two major classes of "upper plate variables" that must be considered in addition to the variations in geometry. These include: (1) composition of the trench hanging-wall -- that is, oceanic basement or continental basement, (2) the size of the accretionary prism, and (3) the kinematic variations that occur during the triple junction interaction. In addition, there is potential for periods of multiple interactions. For example, the variations the would occur during "normal" subduction of ridge-segments versus interactions with transform segments.

The various permutations of these "upper plate variables" lead to a bewildering array of possibilities, yet several common themes are recognized. Considering the previous day's discussion, it was suggested that the key phrase in all cases was diachroneity of processes, with dramatic migration a typical effect. However, it must be emphasized that diachroneity of events is not exclusively restricted to effects of triple junction interactions, nor do all triple junction effects migrate rapidly. Nonetheless, evidence for a rapidly migrating system seemingly is the most clear manifestation of a triple junction system, and the products of these effects should be most diagnostic. The discussion centered on summaries of each of the modern and ancient triple junction systems that were described in detail at the conference. Ultimately, this discussion lead to a general conclusion that there are seven types of indicators of diachronous events along convergent margins. This general conclusion is summarized below (Table 1).

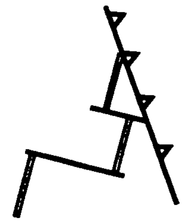
The general meeting ended with a session on future trends and studies needed to test hypotheses, particularly studies that will employ ocean drilling near triple junctions. Steve Lewis and Mike Underwood led this discussion. Mike Underwood summarized the present thematic program at ODP and projected realistic expectations for review of drilling proposals up to the beginning of the 21st century. He stressed that ODP drilling can not take place unless high-quality proposals are submitted. A series of short presentations and discussions followed which included both descriptions of projects which were underway or beginning. There were also some "pitches" for possible future studies that may be critical to resolving issues raised at the conference.

Dave Scholl offered a proposal that the Lau Basin region might represent a future showcase locality for the study of triple junction processes. This site was emphasized, in part, because the conference had not paid close attention to this type of system. He noted that there are several potential targets in the Lau basin that should be considered for ocean drilling. These may include drilling within the basin and across the triple junction to provide critical constraints on the timing of the development of the "backarc" spreading center and record the effects of the time-transgressive ridge-migration. Other studies could be done in the vicinity of the subducting Louisville aseismic ridge to document the responses of an active arc-trench system to ridge collision. This type of study may serve as a partial analog to the structural effects of spreading ridge-subduction.

GENERAL CASE: RIDGE SUBDUCTION

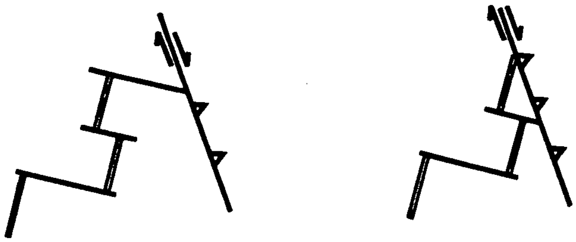


No Slab WindowPredicted
Exception: Microplate development may produce local slab window (e.g. Western Mexico)

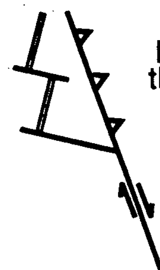


Slab Window
Predicted in all cases
Examples: southern Chile and Woodlark Basin

SPECIAL CASE OF RIDGE SUBDUCTION: TRANSCURRENT ARM DEVELOPED ON TRENCH HANGING-WALL



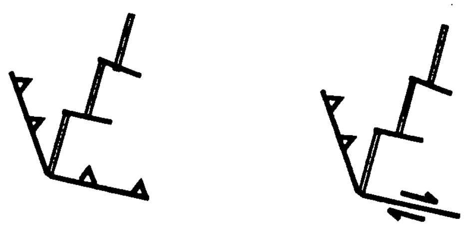
Special case 1: Rivera/Queen Charlottes type interaction with transform segment (left) vs. ridge segment (right) interaction. Slab window is generated in all cases along ridge segments, but for transform segments there is potential for a reverse window—asthenosphericplowing



Note: there are three equivalent sinistral cases

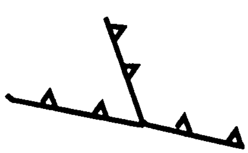
Special case 2: Mendocino type interaction with slab window generated along trailing transform

TRIPLE JUNCTIONS WITH HANGING-WALL SPREADING CENTER



No slab window in either case, but forearc rifting should be associated with extensive volcanism (e.g. boninites), ophiolite development, or both
Examples: Yap trench and Lau Basin

THREE-TRENCH SYSTEM (OBLIQUE ARC COLLISION)



General case of arc collision, no slab window produced but double island-arc slabs produce migrating magmatic fronts and migrating deformational events. Examples: Taiwan and Japan

Figure 1

Table 1: Diachronous Features in the Rock Record as Potential Indicators of a Triple Junction Interaction

Characteristic	*manifestations*	*pitfalls and alternative mechanisms*
Kinematics:	temporal and spatial variations in structural history; presumably manifest as multiple deformational events, changes generally rapid	Changes in plate motion or large-scale block rotations during collisional events could produce similar effects. Associated strike-slip systems can dismember the system and obscure the record
Magmatism:	Forearc magmatism that migrates through time, forearc granitoids common with hybrid sources magmatic arc: variable effects --arc shut-down in some systems, potential increase in magmatic activity in other cases; backarc slab-melt magma types may be diagnostic	difficulty in recognition of migration, potential to misinterpret an ancient forearc system as a magmatic arc assemblage, questions of petrogenetic processes unique to these systems.
Fluid circulation:	high-T fluid interactions in a forearc assemblage; e.g. regional scale hydrothermal overprint of paleothermal structure in the accretionary prism; is gold mineralization typical??	potential for misinterpreting any warm fluid as related to ridge-subduction derived heat when deep circulation could produce similar effect. Gold mineralization occurs in other settings, thus may not be diagnostic

Metamorphism:	high-T/low-P metamorphism in the forearc closely associated with plutonism; local development of contact aureoles near granitoids; potential thermal perturbations by advective heat-transfer by hydrothermal fluid circulation	possibly a unique manifestation of ridge. subduction. potential pitfall: easily misinterpreted as a magmatic arc system
Basin evolution:	rapid shifting of depocenters and uplift within the forearc, potential for basin destruction by develop-ment of forearc strike-slip systems	seamount collision, aseismic ridge collision, or plate motion changes could produce similar effects
Accretionary Prism Development or Destruction	Punctuated periods of tectonic erosion during ridge-interactions, systematic younging of accreted sediments culminating in zero age pelagic sediments associated with near-trench MORB'S accreted at the trench	Other potential causes for tectonic erosion at trenches, most ancient systems may have a record that is to incomplete to document near-trench MORB and accretion of zero-age pelagics
Ophiolite Development	accretion of forearc ophiolites with unusual chemistry, evidence of rapid uplift and emergence, association with near-trench granitoids, and trench-fill cover sequence recording rapid emergence	possibly a unique characteristic. Potential for only sporadic ophiolite development, difficulty in distinguishing stratigraphic association from back-arc basin assemblages

This discussion was followed by several descriptions of active studies that address specific problems of triple junction systems. These include: (1) Steve Lewis's description of 1994-95 field plans for the southern Andes that included an on-shore/offshore wide-angle seismic experiment to study of the Juan-Fernandez aseismic ridge collision as a comparison to the Chile Ridge subduction, (2) Sue Kay's description of GPS studies by M. Bevis and R. Smalley to look at active deformation of the Andean Cordillera in the vicinity of the triple junction, (3) Kristin Rohr's description of ongoing and planned studies by the Canadians that will look at the triple junction interactions associated with the Explorer plate, and (4) Tim Henstock's summary of planned studies along the Mendocino triple junction. Several geologists also summarized ongoing work and several viewpoints were shared including: (1) an emphasis that timing is a critical factor in virtually all triple junctions discussed, and clear geochonological information may hold the key to analyzing many ancient systems, (2) a discussion of how subduction of a hot spot might be difficult to distinguish from ridge subduction, and (3) a discussion of the three-dimensional complexity emphasizing the need for a multidisciplinary approach to solve problems of space-time evolution.

TRIPLE JUNCTION INTERACTIONS ALONG CONVERGENT PLATE BOUNDARIES -- AN ASSESSMENT FOR THE OCEAN DRILLING PROGRAM

Following the meeting of the larger group, the authors of this report met to develop general recommendations for ocean drilling projects that could be used to address major questions raised at the conference. To consider this problem we outlined the five major features that the group considered to be characteristic manifestations of triple junctions interactions. From each group we considered where the ideal site(s) were to test critical hypotheses.

I. STRUCTURAL ANALYSIS--TEMPORAL AND SPATIAL VARIATIONS OF KINEMATIC DATA

An important objective of all convergent margin drilling should be the documentation of the kinematics resulting from plate convergence. Shipboard structural geologists should be routinely assigned to each convergent margin leg. Furthermore, they should always document the geometry, distribution and kinematics of all structures observed in cores retrieved from these margins. In addition, for legs where triple junction migrations have been documented or are suspected, the temporal and spatial variations of the kinematics should also be systematically recorded. Specifically, we recommend that plans for any future "triple junction" legs include sites both "in front of" and "behind" the migrating triple junction. This is necessary to take advantage of the space-time equivalence provided by a migrating triple junction. Previous convergent margin drilling programs have been designed to document the evolution of the margin by drilling several sites perpendicular to the active trench. Although this may also be of some benefit for triple-junction margins, a more rewarding drilling program would have several sites located parallel to the migration vector of the triple junction in order to document the structural and kinematic affects of the triple junction.

Additionally, every effort should be made to determine the real orientation (i.e., remove the rotations induced by drilling) of any identified kinematic indicators. Although a relative change in kinematics (e.g., a change from thrusting to strike-slip faulting) would be important to document, the real orientation of the kinematic axes would allow both a more rigorous kinematic analysis and a comparison of the triple-junction kinematics to plate slip vectors. At shallow drilling levels the real orientation of the structural features can be made with the multishot tool whereas at deeper levels paleomagnetic data can be used. These techniques have proven successful on a number of ODP legs with Leg 131 (Nankai Trough) alone yielding over 1000 oriented kinematic axes. With these proven techniques available, we think it is appropriate and timely to apply ODP technologies to the problems of a triple junction interaction along convergent margins. To this end, we provide the following outline of scientific goals and site selection criteria as well as a list of possible drilling sites.

Goals to be achieved by drilling

Because of the importance of kinematic changes that accompany triple junction interactions, future drilling legs should emphasize collection of oriented drill core. These studies should attempt to achieve three major goals:

Quantify the relation between core-scale kinematic indicators and plate convergence vectors. This goal was also one of the main objectives of ODP Leg 131 and the success achieved on this leg justifies including it here. Moreover, correlating plate convergent vectors and ODP-derived kinematic data at other margins is necessary if we are to understand the kinematics resulting from migrating triple junctions and strain partitioning as discussed below.

Establish temporal and spatial variations of kinematics associated with triple junctions. One of the main reasons triple junction margins appear to be so complex is because they migrate in space and evolve through time. We propose that ODP take advantage of this space - time evolution by designing a drilling program where individual sites provide different "snapshots" of the triple junction evolution. The most logical approach would be to have a series of drilling sites that track the motion vector of the triple junction. These along-strike sites might also be complimented with sites along more normal transects perpendicular to the convergent plate boundary.

In areas of oblique convergence document any partitioning of the deformation into trench-parallel and trench-perpendicular components. Oblique convergence along subducting plate boundaries appears to the rule rather than the exception and this should also be true in areas where triple junctions are migrating. Detailed kinematic studies along these margins will therefore add to our understanding of oblique convergence and strain partitioning along these margins as well as to the consequences of triple junction interactions.

Site Selection Criteria

Sites for detailed kinematic studies should be chosen based on the following criteria:

(1) Regional-scale plate kinematics and local plate boundaries should be well known and well defined with available data (e.g., seismicity and/or seismic reflection data).

(2) There should be a high probably of recovering sedimentary sections. Sediments appear to be more sensitive to changes in the state of stress and therefore kinematics. A sedimentary section will therefore provide a greater opportunity for obtaining detailed kinematic data.

(3) High-resolution paleomagnetic and magnetostratigraphy data should also be considered as an integral part of any possible drilling site because these data have the potential to provide both time and space constraints on individual structures. Important kinematic analyses, however, can also be completed without these data.

(4) Finally, individual sites should be part of a strike-parallel transect as discussed above.

Possible Sites and Justification

We recognize four sites that have excellent potential for yielding new insights and important constraints for triple junction interactions along convergent plate boundaries:

1) Izu-Honshu Collision Zone (TTT)

This triple junction provides one of the best documented tectonic settings of any triple junction system in the world. In addition there is an extensive set of supporting marine data that includes: seismic reflection and refraction data; gravity and magnetic data; detailed bathymetry and side-scan sonar surveys of almost the entire triple junction region and direct, deep-sea observations of the trench regions "in front of" and "behind" the triple junction. ODP has also drilled parts of all three colliding trenches providing an important background of drilling data. Finally, the Izu-Honshu triple junction is also present onland providing an opportunity for comparative studies.

2) Mendocino (TFF)

Along with the Izu collision zone the Mendocino triple junction is probably one of the best documented triple junctions anywhere. Extensive supporting marine and onland data are also available for this region. ODP legs have also been completed to the north and south of the triple junction which could provide reference sites for a detailed study of this classic triple junction.

3) Chile Margin (RTT)

This margin also has a well-documented tectonic setting and substantial supporting marine data (e.g., seismic reflection and refraction data, gravity and magnetic data and detailed bathymetry and side-scan sonar surveys). Although, overall, the margin is less well understood than either Izu or Mendocino triple junctions. The Chile triple junction has the advantage, however, of having been previously drilled by ODP (Leg 141, see above discussion), and also represents a different tectonic setting with active ridge subduction. Like Izu and Mendocino, opportunities for onland comparative studies are also possible.

4) Mexico, Panama, and Queen Charlottes (FTT)

These margins represent less well known cases than the first three. They represent potential comparison sites, however, in that these systems both represent transform-trench-trench (FTT) triple junctions where slab window development is minimal or absent. Thus, these sites could represent important comparisons to other sites because they are not complicated by the massive thermal effects of ridge subduction or crustal thickening processes. They are also advantageous because:

a) They have a well documented tectonic setting.

b) There is an extensive catalog of supporting marine data (e.g., seismic reflection and refraction, gravity and magnetic data); detailed bathymetry and side-scan sonar surveys.

c) ODP legs have been completed to the north and south which could provide reference sites for a detailed study of either of these classic triple junctions.

MAGMATISM

Goals

Forearc magmatic activity is one of the most diagnostic manifestations of ridge-trench encounters and the migration of these magmatic systems is a key record of the interaction. Many of the critical problems raised during the meeting can be addressed by other kinds of marine geology such as dredge haul work or submersible work. Nonetheless, drilling could be readily employed to solve some critical problems.

Scientific drilling activity aimed at solving problems of petrogenesis and magmatic associations of triple junction interactions should consider one or more of three major goals:

Establishment of the spatial and temporal variability of magmatic products in the sedimentary record is a critical manifestation of any triple junction interaction that generates a slab window. Observations from Woodlark and Chile indicate, however, that modifications of the magmatic system are not limited to forearc volcanism. For instance, it appears that the ridge subduction also influences both MORB magmatism on the down-going plate as it approaches the trench and magmas within the arc itself. All of these interactions are poorly understood and any study that would help resolve the process responsible for these modifications would be a major step toward understanding these systems. Types of studies could range from spatial sampling with several shallow bore holes to establish a space-time sequence of a magmatic system to single site occurrences to address local variations such as temporal variations in geochemistry within a forearc volcanic suite

The geochemical mass balance of magmatic systems associated with triple junction systems is poorly understood. Studies should aim toward a better understanding of this mass balance for the entire arc-trench system with particular reference to how this mass balance may differ from normal subduction systems.

A major discussion that developed in the meeting was the role of slab windows, if any, in the production of various geologic effects. Some even doubted the existence of slab windows and the processes that would generate them; they ask if ridges really continue to spread uniformly after they are subducted? This problem could be unequivocally resolved in an attempt to drill through the inner slope into a subducting spreading center. The steering committee unanimously agreed that this goal represented a potential high-profile study that would excite significant interest in the scientific community as well as the public.

Site Selection Criteria

Selection criteria for studies of this type include the following:

Ridge subduction is generally required. Other systems such as Lau basin with a hanging-wall spreading center also represents potential targets, but the drilling strategy for such systems would be different.

Near-trench volcanic rocks that were generated in proximity to a triple junction must be exposed on the seafloor or at burial depths that are sufficiently shallow to be reached by drilling.

Ridge system should be segmented with well-defined petrologic variations among adjacent ridge segments.

Subaerial geology must be well documented, including ages and compositions of arc volcanoes. Information from geochemical tracers such as ^{10}Be would be useful.

Seismic stratigraphy of the forearc should be well defined.

Clear bathymetric link between volcanic sources and sedimentary depocenters should be established through swath mapping.

Site selection should be tied to strike-normal transects, including oceanic reference sites. Variants might include along-strike sampling to evaluate temporal variations associated with migration.

Possible Sites for Future Drilling

We recognize only two sites where these goals can be achieved: (a) the Woodlark basin system, and (b) the Chile triple junction. Each of these sites has specific attractions.

The Woodlark basin system represents the system with far and away the most voluminous magmatic activity in association with a triple junction system. This includes the huge forearc volcanic edifices in proximity to the triple junction. In addition, there are volcanic centers in the trench as well as on the down-going plate well outboard of the trench (e.g., Taylor and Exon, 1987; Crook and Taylor, 1994). This region offers many potential drilling sites to look at evolution of individual volcanic centers within the forearc, although there are potential logistical difficulties with a lack of a sedimentary veneer. New drilling developments with the introduction of HRB (hard-rock guide base) technology should overcome this problem, however, and the Woodlark system may ultimately offer some of the best sites to test petrogenetic hypotheses. A critical problem in this area may be a lack of sufficient data, at present, for adequate site selection. Thus, additional geophysical surveys may be needed before this area is mature for this type of study.

The Chile triple junction lacks the voluminous forearc volcanic rocks of the Woodlark system, but is more "mature" in terms of existing data that would allow careful site selection. Moreover, this area also offers additional targets relevant to petrogenesis in the form of ophiolitic rocks that have been accreted as a result of triple junction processes (see below). Thus, this area may represent the best near-term target for studies aimed at petrogenetic processes related to ridge subduction. For example, the Chile margin could be drilled now to accomplish the goal of drilling through the hanging-wall of the megathrust into the underlying subducted ridge.

A third area that might be an important comparison to sites of "true" ridge subduction would be the Lau Basin region. In this area a back-arc spreading center extends into the forearc (Figure 1) due to the three-dimensional complexities of the region. In this type of setting, there should be an entire suite of forearc igneous rocks generated at the "RTT triple junction." Yet, the geometry of this system with a hanging-wall spreading center implies a very different petrogenetic system. Indeed, the distinction between this type of system and "normal" ridge subduction was one of the key hypotheses presented at the meeting by Julian Pearce. Thus, a drilling leg to the Lau Basin would serve as a key test of Pearce's hypotheses. In addition, one would expect the hanging wall spreading center to generate ophiolitic rocks. These rocks would probably share many gross structural similarities to forearc ophiolites developed at sites of ridge subduction, but because they would have a very different petrogenesis they should be distinguishable. Thus, a careful study comparing these forearc igneous rocks and forearc igneous rocks such as the Chilean ophiolites or Woodlark igneous rocks would provide a simple test to determine if these two types of systems have distinctive geochemical signatures.

TRANSIENT FLUID CIRCULATION & CUMULATIVE THERMAL EFFECTS

Introduction

Fluid circulation plays several vital roles in the thermal and geochemical evolution of all types of plate boundaries. Regardless of the background regime of steady-state heat conduction within a particular region, heat can be transferred by episodic fluid advection or lateral fluid flow. These transient events are manifested as local geothermal and/or geochemical anomalies. Moreover, fluid-rock interactions exert considerable influence over the chemical mass balance of continental margins. In subduction zones, the geochemical influence of fluid circulation ranges from hydrothermal alteration of oceanic lithosphere, perhaps starting well outboard of the subduction front, all the way inboard to zones of arc-magma generation (Langseth and Moore, 1990). The physical growth or erosion of an accretionary prism is also strongly affected by fluids. Fluid pressure is probably the most important variable which controls the shear strength of rocks within fault zones. For instance, increasing fluid pressure to near-lithostatic values tends to trigger fault dislocation. Thus, understanding the dynamics of fluid-migration systems is important for assessments of seismic risk along active faults (e.g., Shipley et al., 1994).

In recognition of the necessity for additional research on this general theme, special attention has been directed recently toward the role of fluids and fluid budgets in accretionary prisms (e.g., Moore, 1989; Kastner et al., 1991; Moore et al., 1991; Le Pichon et al., 1991, 1993; Moore and Vrolijk, 1992). Drilling results from the Peru Trench (Leg 112), Nankai Trough (Leg 131), the Cascadia subduction zone (Leg 146), and the northern Barbados Ridge (Legs 110 and 156) have added a wealth of new empirical information pertaining to physical properties and pore-fluid chemistry. Important sources of fluid include porosity reduction during sedimentary and tectonic consolidation, diagenetic and metamorphic dehydration, and the breakdown of hydrous minerals. Significant diagenetic reactions include carbonate recrystallization and precipitation, bacterial and thermal degradation of organic matter, formation and dissociation of gas hydrates, dehydration and transformation of clay minerals and opal-A, and alteration of volcanic ash and basalt (Kastner et al., 1991). In addition, a variety of numerical models have been constructed to simulate patterns of fluid flow and their controlling variables (e.g., Shi and Wang, 1988; Fisher and Hounslow, 1990; Screaton et al., 1990; Wuthrich et al., 1990; Henry and Wang, 1991; Bekins and Dreiss, 1992). As a result of these studies, some of the most important first-order trends in the physical and chemical behavior of fluids have been described. These variations can be related to primary variables such as gross sediment texture and protolith composition (e.g., mud-dominated margins versus sand-dominated systems).

Depending on the permeability structure of a subduction zone, fluid migration may be focused or diffuse. Focused flow is common through: (1) shear zones (imbricate thrust faults or the basal decollement of an accretionary prism); (2) networks of extensional faults in the juvenile oceanic basement; and (3) lithofacies-controlled conduits (e.g., channel sands in an otherwise muddy trench wedge). Diffuse flow patterns are more likely with depositional systems that are dominated by sheets of sandy turbidites, but this situation is unusual. Instead, most subduction zones are highly anisotropic in properties that affect the generation and movement of fluids. Heat and fluid advection by way of mud diapirism is also possible within or near the accretionary prism. This phenomenon occurs in response to the development of excess pore pressure and a coincident density inversion (Brown, 1990). Three-dimensional flow systems become quite complicated when all of these local variables are superimposed over regional-scale first-order generalities.

Within the existing technological constraints of the Ocean Drilling Program, thermal processes and physical movement of fluids can be investigated on two time scales: short-term transient events and cumulative long-term products of diagenesis. Transients can be studied directly or indirectly through down hole temperature measurements, conventional extraction of pore fluids from cores, in situ fluid sampling, and deployment of pressure-temperature sensors in sealed bore holes (CORK systems). The long-term products of diagenetic gradients can be documented through conventional petrological, mineralogical, and geochemical analyses of the cores. These studies can also determine the lithologic controls on fluid budgets (e.g., effects of grain size and grain strength on compaction gradients, devitrification of volcanic glass, conversion of opal-A to opal-CT, and smectite-to-illite clay diagenesis). In the future, however, drilling strategies must be broadened to account for the inherent three- dimensional complexities of heat flow and fluid flow. In addition, more emphasis needs to be placed on a feedback between numerical models and collection of observations to constrain the models. Early models should be used to help design sampling programs and in situ monitoring experiments. The accuracy of advanced generations of the numerical models, in turn, will improve each time there is refined input of data from empirical sources.

Ridge-trench triple junctions represent special cases. In these situations, there may severe perturbations of heat flow, fluid flow, and sediment diagenesis. First, subduction of very young oceanic lithosphere, or collision between an active ridge segment and a subduction front, will raise the background of conductive heat flow by a large amount. This elevation of the average geothermal gradient represents a situation that can be exploited by ODP. It allows an examination of the effects of moderate to advanced stages of sediment diagenesis at relatively shallow depths (i.e., within the existing sampling capabilities of the JOIDES Resolution). Superimposed on this thermal background will be local anomalies associated with near-trench insertion of MORB-type magmas, anomalous forearc magmatism derived from partial melting of accreted sedimentary rocks, and active cells of hydrothermal circulation. These processes, in theory, could affect all three of the plates within a triple-junction system. Thus, with gradual migration of a triple junction, there should be clear time-space patterns of magmatic-hydrothermal overprints. Given the importance of triple-junction migration in the long- term evolution of continental margins and island arcs, we believe that a special triple-junction subset should be established within the broader thematic framework of fluids in accretionary prisms, as defined in the generic sense by previous ODP planning processes such as COSOD II and recent versions of the SGPP White Paper. Only one environment of this type has been drilled to date (Leg 141, Chile triple junction), and fluid-flow was never identified as one of the primary thematic objectives of that leg. To pursue this goal more effectively, future drilling strategies must take into account the special design considerations imposed by the dynamic nature of three-dimensional flow systems.

Goals to be achieved by drilling

With existing ODP technology, we believe that it is possible to make considerable headway toward achievement of the following goals:

1) Documentation of three-dimensional patterns of fluid circulation and sediment diagenesis, using direct measurements and both physical and chemical tracers. Appropriate methods could include: generation of 3-D seismic grids to help identify potential zones of abnormal fluid pressure, based on anomalies in acoustic impedance; conventional shipboard extraction and analyses of dissolved constituents in pore waters (e.g., chlorinity gradients); analysis of extracted hydrocarbons; use of in situ fluid samplers; installation of borehole seals with arrays of pressure-temperature sensors (CORK's); packer experiments; utilization of LWD systems (log while drilling) to help document in situ physical properties; mineralogical, geochemical, and isotopic analysis of diagenetic phases, including authigenic clay minerals, vein minerals, and cements; radiometric dating of authigenic phases; and analysis of organic-matter maturation, using techniques such as vitrinite reflectance and palynomorph coloration.

2) Documentation of the effects of triple-junction migration on fluid circulation. This objective would require application of the techniques listed above within an appropriate time-space domain that includes all three plates within a triple-junction system.

3) Documentation of spatial variations of heat flow and short-term temperature transients. This aspect should include conventional, but comprehensive, measurements of near-surface heat flow, together with in situ borehole measurements and CORK experiments.

4) Comparison of hydrologic and geothermal character among different domains of a triple-junction system. To be meaningful, this comparison should including several oceanic reference sections. These include the frontal portion of a forearc in advance of a migrating triple junction, the locus of ridge- trench collision, and regions in the wake of the migrating triple junction, be they parts of an accretionary prism or an incipient transform boundary.

5) Iterative numerical modeling of steady-state fluid flow, steady-state conductive heat transfer, and anticipated transient effects. Beyond simulations of background patterns, additional modeling of transients might include examples of near-trench magmatic intrusion, one-pass or multiple-pass hydrothermal convection, one-pass or multiple-pass fluid migration along discrete planar conduits (e.g., shear zones), and mud diapirism.

Criteria for site selection

Because of the hydrologic and geothermal complexities of triple- junction systems, it is unrealistic to expect definitive results from a single drilling leg. Consequently, the ODP planning process should strive to identify and commit to one or two targets as long-term experimental sites, with an expectation of several return visits. In addition, any future drilling efforts should take full advantage of existing ODP data sets and forthcoming (scheduled) drilling legs. Criteria for selection of appropriate localities, as well as individual sites within those localities, should include the following:

1) Lithofacies patterns and stratigraphic successions within outer-slope, trench, forearc, and transform borderland environments must be well understood. This information is required to help predict how 3-D facies architecture will affect the first-order permeability structure.

2) The first iterations of numerical models (both heat flow and fluid flow) should be completed prior to drilling. These simple models may be inaccurate, but they will help direct the design of hydrologic experiments and identify positions for optimal drilling/coring transects.

3) Major deformation features within the forearc (mud diapirs, imbricate thrusts, basal decollement, prism backstop, etc.) should be well imaged with high-quality multi-channel seismic data. Ideally, these data would include 3-D seismic surveys to define zones of anomalous fluid pressure, particularly within likely fluid conduits such as the prism decollement. Definition of the triple junction, itself, should include comprehensive mapping of active faults and analysis of seismicity patterns.

4) Comprehensive surveys of near-surface heat flow and fluid venting should be completed prior to drilling. Ideally, these data would include observations of vent sites from manned submersibles, ROV's, and/or camera tows.

5) Prospective drilling sites should be organized into both strike-parallel and strike-normal transects. Targets should include all three lithospheric plates in the triple junction system, and high-priority targets should be placed close to forearc volcanic edifices (if present) and/or subducting ridge segments. Reference sites outboard of the subduction front are essential, and every effort should be made to accommodate multiple thematic objectives at each site (e.g., deformation patterns, anomalous magmatism, basin evolution).

Possible Sites for Future Drilling

Although the themes of fluid-flow and thermal evolution could be addressed at virtually any triple junction (Woodlark Basin, Panama, Antarctic Peninsula, Rivera), we believe that only two sites are suited to take appropriate advantage of previous and forthcoming (scheduled) ODP drilling legs. The most attractive choice in this regard would involve boundaries of the Gorda/Juan de Fuca/Explorer Plate (Mendocino triple junction to the south; Queen Charlotte triple junction to the north). Future hydrothermal experiments and numerical models of this system would be able to incorporate the results of physical-properties measurements, down-hole measurements, and CORK deployments completed during Leg 146 (Cascadia; Vancouver and Oregon transects), Leg 139 (Sedimented Ridges I; Middle Valley), Leg 169 (Sedimented Ridges II; Escanaba Trough), and Leg 168 (eastern Juan de Fuca transect). Regional seismicity patterns are well defined (e.g., Stoddard, 1987; Oppenheimer et al., 1993). Modeling of heat flow and fluid flow for specific parts of the system is relatively advanced (e.g., Shi et al., 1988, 1989; Davis et al., 1990; Hyndman et al., 1993; Denlinger and Holmes, 1994; Wheat and Mottl, 1994). In addition, new information on lithostratigraphy, sedimentary facies patterns, and physical properties (mostly Pliocene-Pleistocene strata) will be extracted from the northernmost transect of Leg 167 (California margin). That transect will include three sites east of the Gorda Ridge and two sites south of the Mendocino Fracture Zone. Finally, the Mendocino triple junction has served as the type example for numerical modeling of the effects of slab-window development in the wake of triple-junction migration (Furlong, 1984; Liu and Furlong, 1992). ODP could provide a unique data set to help test these models.

A second choice for ODP would be a return to the Chile triple junction. In terms of thermo-hydrologic dynamics, our overall knowledge of this system is much less mature. A modest number of near-surface heat-flow transects have been completed (Cande et al., 1987), and subsequent results from Leg 141 did provide intriguing evidence of transient fluid flow (based on spikes in down-hole temperature profiles) and diagenetic fronts within the toe of the accretionary prism. The main advantage of this example would be its potential for combining several thematic objectives, particularly studies of ophiolite emplacement, magmatic processes and structural associations, as described elsewhere in this section.

IV POLYACHRONOUS BASIN EVOLUTION AND NEAR TRENCH SEDIMENTATION

General Summary of Stratigraphic/Sedimentological Issues

The main genre of triple junction discussed at conference involved subduction along one or more of three plate boundaries. The migration of subduction-related triple junctions affects sediment distribution across plate boundaries through uplift and subsidence along plate margins and the sequential migration of sedimentary sources, including volcanic/magmatic provinces, and large depocenters. Plate margin tectonics may also be reflected by intraplate deformation and subsidence, particularly in the backarc region.

The type of triple junction, resultant changes in plate configuration, and the direction of triple junction migration all contribute to the localization of uplifted highlands and adjacent basins or depocenters. Usually regions inboard (on the hanging- wall plate) of plate triple junctions are uplifted due to either thermal or compressional uplift. For example, uplift can be associated with a shift from subduction to strike-slip along a margin, or a change in the age (buoyancy) from one plate to another across a trench ridge-trench or trench-fault-trench triple junction. The uplifted/deformed zones in the forearc region include trench fill, accretionary prism and forearc basin sediments, and can be associated with anomalous near-trench magmatism in the case of ridge subduction. This uplift may be preceded or followed by subsidence; the localization of resultant basins may be a function of the presence of older structural grains on which the triple-junction is superposed. These inherited structures may be reactivated during compressional and extensional phases.

Due to progressive uplift, the sedimentological signatures of triple junction interaction along a plate margin are most likely restricted to regional unconformities across deformed forearc sequences. These should be time-transgressive in the direction of triple junction migration. The forearc region can undergo significant erosion due to uplift of the accretionary prism. Erosion of these uplifted regions supplies sediment shed into adjacent trenches or out onto submerged plates in the form of submarine fan complexes. Marine clastic sequences associated with triple junctions differ compositionally from "normal" forearc sedimentary sequences in that they contain a significant recycled component from the accretionary prism (e.g., Marsaglia and Ingersoll, 1992; Marsaglia et al., 1992; in press). Ridge subduction may also result in magmatic gaps along the arc axis; these time-transgressive gaps may be recorded in associated sedimentary sequences as minima in percent volcaniclastic detritus.

Possible Sites for Future Drilling

Future drilling targets that will shed light on triple junction evolution include site transects across plate boundaries recently affected by triple junction migration. The sedimentologic/stratigraphic aspects of each region are emphasized in this discussion.

Mendocino FFT (North American, Pacific and Juan de Fuca plates): In the case of the Mendocino FFT triple junction, there is uplift near the present-day triple junction, and foreland basin- style deformation precedes the triple junction to the north (Clarke, 1992; Merritts and Bull, 1989; Nilsen and Clarke, 1989). The passage of the triple junction is partly documented in the erosional remnants of fragmented sedimentary basins to the south of the present triple junction on the North American plate (Nilsen and Clarke, 1989; Graham et al., 1984). In general, triple junction migration along the length of California is/was associated with migratory uplift and erosional stripping of forearc deposits, followed by local subsidence (Bachman et al., 1984; Glazner and Loomis, 1984; Loomis and Ingle, 1994; Nilsen and Clarke, 1989; Unruh et al., 1995).

In response to triple junction uplift and global sea level fall in the early Pliocene, a large submarine fan system, the Delgada Fan, developed to the south of the triple junction on the Pacific plate (Normark and Gutmacher, 1985). The sedimentary pile that constitutes this fan provides a marine record of triple junction migration. Portions of this fan were cored during previous DSDP legs (Sites 32, 34, and 173). At Sites 32 and 34, a pronounced increase in terrigenous input at the boundary between the upper Miocene and lower Pliocene (McManus et al., 1970) has been linked to global sealevel fall coupled with onshore tectonic uplift of the Coast Ranges south of the Mendocino triple junction (Drake et al., 1989). According to Drake et al. (1989), low core recovery and distal site locations preclude answering some fundamental questions regarding the timing of breaks in sedimentation with onshore tectonic events. Perhaps the proposed ODP leg in this region (site surveys recently completed) will provide a more detailed picture of the sedimentary response to triple junction migration.

Chile (TRT) (Nazca, Antarctic, and South American plates): Migration of the Chile triple junction along the South American plate margin has affected both magmatism and sedimentation on the overriding plate. Most recently, at the latitude of the Taitao Peninsula, ridge subduction has been linked to initial subsidence/rifting and sedimentation associated with anomalously near-trench volcanism, and followed by partial uplift/inversion and erosion after passage of the triple junction (Forsythe and Nelson, 1985). In the backarc, syn-collision rifting or extension is followed by backarc compression resulting in backarc subsidence. Ramos and Kay (1992) outline the deformational history of the Austral Patagonian Andes, and suggest that the effects of short ridge segment subduction are most pronounced in the forearc region, whereas the effects of long ridge segment subduction might be concentrated in the backarc region.

One of the goals of ODP Leg 141 was to elucidate the effects of ridge subduction on the accretionary prism near the Chile triple junction. A transect of sites was first drilled north of the triple junction, in part, to establish a baseline to clarify the effects of subducting young oceanic crust, just prior to ridge collision and subduction. Only one site was drilled into the accretionary prism south of the triple junction. Spectacular, near vertical bedding at this site suggests that ridge subduction radically affects the structure of the accretionary prism. Geophysical data strongly support the case for tectonic erosion along this margin associated with ridge subduction (Cande and Leslie, 1986). A second, as yet undrilled, leg was proposed to examine the plate margin to the south in the wake of the modern triple junction. In this region, large sedimentary depocenters (discussed by Lothian) may provide more detailed information regarding the tectonic evolution of the margin during and after triple junction migration.

Japan (TTT) Eurasian, Philippine Sea, and Pacific plates: The Japan trench-trench-trench triple junction is the only modern triple junction of this type. It has not been the focus of previous DSDP or ODP legs. However, DSDP/ODP sites within the Nankai Trough to the southwest of the triple junction have recovered sediments derived from the onshore uplifts (Izu Peninsula/Central Honshu uplifts and volcanic centers) related to this triple junction (Marsaglia et al., 1992). Drilling of offshore sedimentary depocenters adjacent to this triple junction would provide insight into the evolution of this type of triple junction.

Other Possible Drilling Objectives: Although not a triple junction, one modern "double" plate junction is somewhat unique and deserves further attention. At the junction between the Antarctic and Scotian plates off the Antarctic Peninsula, ridge and fault segments have intersected an active margin. This plate boundary has migrated resulting in progressive shut down of subduction and "passification" of this margin. Although this is not a triple but a "double" junction, the active to passive transition would make an excellent drilling target. This is a mechanism by which active to passive margin transitions may have occurred in the past along Baja California and the Beringinian margin of Alaska.

One other aspect discussed at the conference was the a comparison of active spreading ridge subduction with aseismic ridge subduction. What are the different/similar effects of aseismic versus seismic ridge subduction across a magmatic arc? Dave Scholl discussed an example of aseismic ridge (Louisville Ridge) subduction along the Tonga Arc and associated effects in the Lau backarc basin. This setting would make an excellent drilling target.

OPHIOLITE EMPLACEMENT

Goals

Scientific ocean drilling designed to investigate the structural, chemical and petrological processes of the role of triple junction interactions and ophiolite formation and emplacement must address two fundamental objectives:

1) Drilling must seek to determine the relationship between ophiolites as they are observed on land, oceanic crust, and triple junction migration. Because triple junctions are defined and recognized on the basis of plate interactions, their position and character evolve rapidly with time.

Hence, drilling must seek to provide tight time constraints on the various events in ophiolite evolution. The events that need to identified include the initial formation of the oceanic crust, its arrival at a trench, its incorporation into the overriding plate, and any chemical or thermal events that accompany those kinematic events.

2) Drilling must seek to identify the specific mechanisms of ophiolite emplacement, including such factors as the geometry of faults, folds, and other structures related to the ophiolite, the rheology of the material involved in the deformations related to ophiolite emplacement and the kinematics, at all spatial scales, of the ophiolite emplacement process.

Site Selection Criteria

Criteria for the selection of suitable specific drilling targets for the study of triple junctions and their role in ophiolite formation include:

1) Well-constrained plate-scale kinematics, with well-studies magnetic anomaly patterns or other similar large-scale indicators of plate motion histories and triple junction geometries.

2) Well-developed sedimentary sections over or adjacent to potential ophiolite bodies, whose fossil record and structural histories can provide the continuous, sequential timing constraints necessary for defining the history of the ophiolite emplacement process.

3) High-quality marine geological and geophysical site survey data that provide both the ability to select the most scientifically advantageous sites for drilling and the regional structural and stratigraphic context within which to interpret the drilling results.

Possible Future Drilling Sites

Application of these criteria to the existing set of observations around the world suggest that there are two triple junction regions where the case is strong that there are ophiolite bodies in the process of emplacement into their respective overriding plates: the Taitao Ridge at the Chile Margin triple junction, and the Zenisu Ridge at the Boso and Mt. Fuji triple junctions. The Chile margin region has already been the subject of ODP drilling during Leg 141 in 1991-92, while the Zenisu Ridge has recently been the subject of an exhaustive marine geological/geophysical research program.

Other potential candidates for scientific drilling include the Woodlark basin region, the western Solomon Sea region, and perhaps the New Caledonia margin. Discussions of the Chile Margin and Zenisu Ridge triple junction regions follow:

<u>The Taitao Ridge:</u> The Taitao Ridge is a prominent bathymetric high that extends seaward from the South American continental margin approximately 25 km south of the present location of

the Chile margin triple junction. Because of the close proximity of the Taitao Ridge to the Taitao ophiolite and marine geophysical data that suggests that the ridge is of oceanic affinity, the Taitao Ridge was hypothesized to be of oceanic origin. It was speculated that it formed in the process of accretion to the Chile Trench forearc and represents an ophiolite assemblage emplaced in the Chile Trench forearc. ODP drilling during Leg 141 at Site 862 confirmed that the Taitao Ridge is underlain by mafic igneous material. However, the apparent youthful age of the Taitao Ridge, less than approximately 2 Ma, and the recovery of rhyolitic material from the ridge, indicate that its origin and tectonic evolution are more complex than originally hypothesized.

The suite of igneous rocks recovered from the Taitao Ridge is composed of intercalated submarine basalt, rhyolite and dacite flows with rare sediment interbeds, but poor recovery makes it very difficult to establish an unequivocal magmatic stratigraphy, (Behrmann et al., 1992). The Taitao Ridge basalts are sub-alkalic to tholeiitic, with phenocrysts of olivine, clinopyroxene and plagioclase. In the dacite specimens primary magmatic hornblende and plagioclase phenocrysts are present in a fine-grained groundmass mainly composed of plagioclase. Alteration is very minor or absent.

The petrogenesis of ocean ridge rhyodacites has been interpreted to be the result of differentiation in magma chambers behind propagating rifts (Langmuir et al., 1986; Perfit and Fornari, 1983). Rare earth element (REE) patterns from the Taitao Ridge basalts are diagnostic of normal or transitional type Mid-ocean ridge basalts (MORB). However, patterns from the rhyolite specimens show strong light REE enrichment, a distinct negative Eu anomaly, and heavy REE depletion. These observations preclude a simple genetic relation to N- or T-type MOR magmas by differentiation (Forsythe et al., 1994). Instead, contamination by a source of continental affinity is likely, perhaps by intermittent stoping of sedimentary rocks of continental provenance (turbiditic graywackes, for example) into a mid-ocean ridge magma chamber.

The depositional contact between sediments and the underlying glassy rim of a basaltic lava flow was recovered at Site 862, allowing paleontological age dating to provide constraints on the age of the Taitao Ridge. The uppermost Pliocene age of the basal sediment and its close facies relation to a local volcanic source (Strand et al., 1994; Forsythe et al., 1994) constrain a slightly older age for the volcanic rocks, also uppermost Pliocene. $^{40}Ar/^{39}Ar$ isotopic dating on hornblende separates from two rhyolite samples yielded ages of 1.54 + 0.08 Ma and 2.05 + 0.4 Ma. These ages are broadly comparable to the age of the Taitao ophiolite on land (Forsythe and Prior, 1992). This correlation lends support to the hypothesis that the Taitao Ridge is its submarine continuation (Cande and Leslie, 1986; Cande et al. 1987), or that the two structures have a similar origin.

The Taitao Ridge: An ophiolite to be?: The young age of the Taitao Ridge and its close spatial association with the Taitao fracture zone suggests that its origin is related to the fracture zone and/or one of its ridge-transform intersections. The thin but stratigraphically continuous sediment cover indicates that it was formed as a bathymetric high. Although major uplift of at least 1000 m has occurred since the formation of the ridge and sedimentation of at least part of its cover. The recovered basalt-sediment contact and the lack of chemical alteration, or even devitrification in the basaltic volcanics suggests that the Taitao Ridge was not subject to extensive hydrothermal fluid circulation. The example of the Taitao Ridge suggests that forearc ophiolites may not be dismembered and undergo intense hydrothermal alteration unless they are subducted beneath the forearc, reheated and hydrated. This may especially be true for ophiolite accretion from young subducting oceanic crust. The lack of major structural disruption of the Taitao Ophiolite on land (Keading et al., 1990) indicates that structural coherence may be retained during forearc accretion.

Zenisu Ridge: The Zenisu Ridge is a elongate bathymetric ridge located at the eastern end of the Nankai Trough, along the flank of the Izu-Bonin Ridge (Lallemant et al., 1989). The Zenisu Ridge strikes roughly parallel to the trend of the axis of the Nankai Trough for several tens of kilometers to the southwest from the Izu-Bonin Ridge, and lies 60-80 km seaward of the toe of the Nankai Trough accretionary wedge. The Zenisu Ridge is situated near both the trench-trench-trench Boso triple junction and the trench-fault-fault Fuji triple junction Ogawa et al., 1989).

A multidisciplinary investigation of the Zenisu Ridge was conducted by the R/V/ Jean Charcot, and included Seabeam swath bathymetric, seismic reflection, and submersible observations of Zenisu Ridge. Based on this extensive set of observations, it is clear that Zenisu Ridge represents a thrust-fault bounded sliver of oceanic crust, detached to some degree from the surrounding subducting plate, and hence a candidate to be incorporated into the Nankai Trough accretionary wedge as an ophiolite (Chamot-Rooke and Le Pichon, 1989).

Zenisu Ridge stands roughly 1200-1500 m above the flat floor of Nankai Trough (Ishihara, 1989). Seismic reflection profiles across the ridge image a sedimentary unit overlying the acoustic basement. Movement on seaward-vergent thrust faults that bound the seaward flank of Zenisu Ridge has produced about 1 to 1.5 km of vertical uplift of the ridge (Lallemant et al., 1989). Gravity modeling of Zenisu Ridge (Ishihara, 1989) indicates that the ridge is comprised of material of 2.87 g/cm^3 density, a value well within the range observed for normal oceanic crust. Marine magnetic anomalies over Zenisu Ridge indicate that the basement of the ridge formed together with the Shikoku Basin basement to the south (Lallemant et al., 1989).

Zenisu Ridge occupies the position of the flexural outer topographic bulge of oceanic basement seaward of the Nankai Trough axis, reflecting the elastic bending of oceanic lithosphere (Watts and Talwani, 1974). However Chamot-Rooke and Le Pichon (1989) present a mechanical model that incorporates both elastic bending stresses and horizontal compressive stresses related to the collision of the Izu-Bonin Ridge that provides a basis for understanding the formation of the thrust faults that underlie Zenisu Ridge.

Because Zenisu Ridge has its origin as a topographic high composed of oceanic crust largely through thrust faulting and other compressive deformation processes, it stands in contrast to the Taitao Ridge, which appears to have been formed largely by volcanic processes. Yet, both features lie immediately seaward of the toe of the overriding plate at their respective subduction zones, and both may well be destined to be incorporated into their respective accretionary wedges rather than being subducted. Because of the ophiolite exposures on land, the Taitao Ridge may be a more mature example of ophiolite formation than the Zenisu Ridge, but the seismic reflection profiles across the Zenisu Ridge clearly image the thrust faults that detach the ridge from the subducting oceanic crust of the Shikoku Basin. Together, these two modern examples of ophiolite formation may provide important insights in the diversity of processes of ophiolite formation and emplacement that typifies the geological record on land.

RECOMMENDATIONS

The authors of this report believe that we can speak for the entire conference group in concluding that the studies of triple junction systems are in their infancy and the study of triple junction systems represents a frontier area in tectonics research. Until now, the problems of triple junction interactions have largely been ignored in the community. This is a result of our we previous struggles just to understand the two-dimensional interactions of "normal" plate boundary processes. Extending these complexities to the three-dimensional effects of triple junction interactions has heretofore been rather intimidating. The level of knowledge on two-dimensional interactions has now matured sufficiently that geoscientists have now begun to make real progress on the complex three-dimensional interactions at triple junction. The caveat to this statement, however, is this problem is filled with ambiguities because of the bewildering array of interactions that can exist during triple junction interactions at convergent plate margins. Our goal should be to remove at least some of these ambiguities by developing better models and collecting basic data that can be used to constrain the tectonic processes that occur within the various systems.

Ocean drilling can make a major contribution to these problems through a variety of process oriented studies that we outline above. There should be a major effort to encourage submission of proposal on these and other topics relevant to triple junction processes. The maturity of our basic knowledge from modern triple junctions is highly variable among the different examples. Thus, in some systems new site surveys or even basic geophysical data need to be collected before the areas could be seriously considered for ocean drilling. The best example of such a site with major potential is the Woodlark basin area. This region has some of the most remarkable magmatic associations of any of the systems, yet the data base may not yet be sufficiently mature to accurately site the ideal drilling targets. The Chile triple junction is a site which should be seriously considered for a second leg to the Chile triple junction as a follow up to 141. This site offers the potential to study the ophiolitic associations at these systems, structural associations, fluid-flow problems and changes in sediment dispersal. More importantly, however, this area offers the potential for a "high profile" drilling leg if a hole could penetrate through the trench slope materials to the subducted spreading ridge.

Sites that are not areas of actual ridge subduction should also be seriously considered as drilling targets. These areas are critical because they serve as a guide to processes that are not driven by the massive thermal effects and magmatic activity of systems where slab windows are developed. For example, meeting participants had a general feeling that major structural changes should be recognizable in the abrupt kinematic changes that accompany any triple junction interactions. In ridge subduction systems where slab windows are developed, however, these direct consequences of kinematic changes could be masked by other effects; for example, magmatic processes, hydrothermal systems, etc. Thus, another priority should be placed on obtaining structural information from oriented core at sites such as the Rivera, Panama, Mendocino, or Queen Charlottes triple junctions. Such studies would need to be carefully formulated but they will ultimately be critical to understanding triple junction processes.

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