Ephemeral plate tectonics at the Queen Charlotte triple junction

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ABSTRACT

Three plate boundaries, the Queen Charlotte transform, the Cascadia subduction zone, and the Juan de Fuca Ridge, meet in a complex triple junction offshore Vancouver Island. Some interpretations of the plate tectonics of the region have included the Explorer ridge, the Dellwood Knolls, and the Tuzo Wilson volcanic field as part of the spreading system, requiring up to three triple junctions in the region. New SeaBeam bathymetry interpreted with existing regional data sets indicate that the Dellwood Knolls and Tuzo Wilson volcanic field are not independent plate boundaries, but the result of leaky transform tectonics between two overlapping transform faults. Seismicity shows that the Explorer plate is being deformed by Pacific–North American relative motion as a new transform plate boundary forms and cuts off the Explorer ridge. The system is evolving to a single triple junction at the northern terminus of the Juan de Fuca Ridge where it meets the Nootka deformation zone. Thus the Explorer microplate, which was spawned ~5 Ma, is an ephemeral adjustment to mechanical difficulties at the triple junction. This new model implies that the Explorer subduction zone is no longer active. Ephemeral oceanic microplates have also existed at Pacific–North American triple junctions off southern California and Baja California.

INTRODUCTION AND REGIONAL SETTING

In the northeast Pacific, the Cascadia subduction zone, Queen Charlotte transform fault, and Juan de Fuca Ridge meet in a poorly understood triple junction. Widely varying models have been published for this region (Srivastava et al., 1971; Barr and Chase, 1974; Chase, 1977; Keen and Hyndman, 1979; Farrar and Dixon, 1980; Lister, 1989; Allan et al., 1993). Riddihough et al. (1981) and Carbotte et al. (1989) posited that two triple junctions lie adjacent to the continental shelf but they did not explain the high rate of seismicity in the Explorer plate. In this paper we present new SeaBeam data for this region and reinterpret the sea-floor morphology to be the result of leaky transform tectonics, not sea-floor spreading. To locate the triple junction, we reexamine regional geological and geophysical data and formulate a tectonic model that can reconcile both the morphologic and the seismicity data.

A transform-trench-ridge triple junction has been offshore western Canada for probably as long as 40 m.y. (Riddihough, 1977); a lack of clear magnetic stripes in a band 50 km wide at the base of the continental slope limits accurate reconstructions. Earthquakes and morphology define the present Queen Charlotte fault to the southern tip of the Queen Charlotte Islands and the Cascadia subduction zone as far north as the Nootka fault. Between these features several elongate ridges and volcanic edifices interact with turbidite sedimentation from Queen Charlotte Sound. The Juan de Fuca Ridge lacks large earthquakes and is defined by its sea-floor magnetic stripes and classic spreading-center morphology. The Explorer ridge has left a clear magnetic signal only on the Pacific side, and although its southern segment has some classic ridge features, the northern segments are more complex (Botros and Johnson, 1988).

SPREADING CENTERS OR LEAKY TRANSFORM?

New SeaBeam data over the suggested triple junctions (Fig. 1) provide telling detail about their morphology. Because there are no magnetic stripes around the recent volcanic features, interpretations of their origin have relied heavily on morphology. Although some have interpreted the Tuzo Wilson volcanic field and Dellwood Knolls as spreading centers, we believe that an origin in a leaky transform setting is more consistent with the new data as well as with regional geological observations.

Transform tectonics of the southern Queen Charlotte fault are evident in the steep narrow continental slope, which broadens south of the Tuzo Wilson volcanic field. Ridges parallel to the fault divert turbidite channels to extend along the slope instead of perpendicular to it, implying that the rate of uplift has exceeded the rate of deposition. A small cone on top of a ridge is in line with the cones of the Tuzo Wilson volcanic field; new 3.5 kHz data show a hard bottom, suggesting that the cone consists of hard rock, not simply sediments. Its location is suggestive that it could be part of the Tuzo Wilson volcanic field, but on the continental side of the present Queen Charlotte fault.
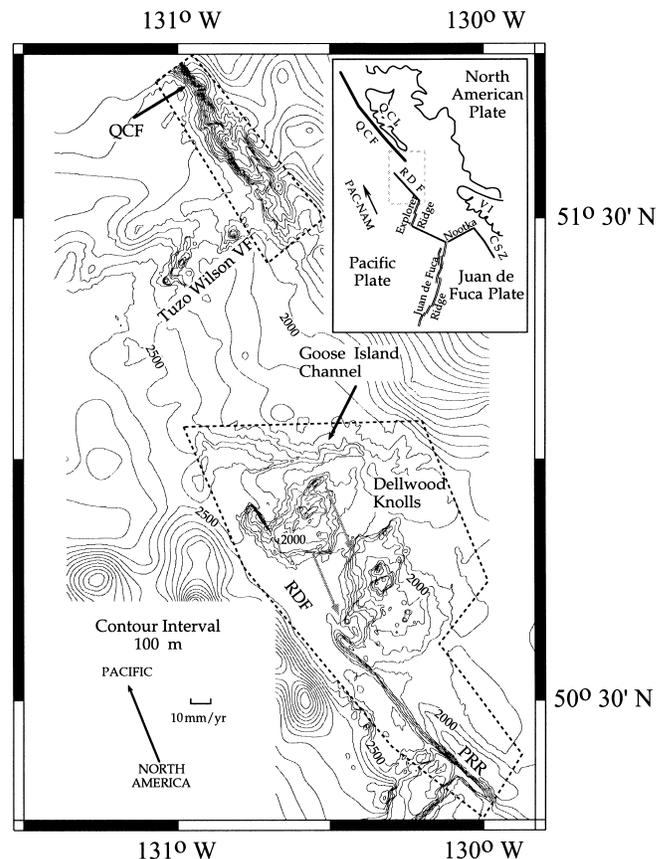

Figure 1. Map of bathymetry contoured at 100 m interval; dashed lines enclose areas of new SeaBeam data. SeaBeam survey swaths were spaced every 1700 m for ~100 m overlap in 2600 m water depth; spacing was progressively decreased on continental margin to 1000 m, allowing 100% coverage in most areas. Data over Tuzo Wilson volcanic field were collected previously (Hammond et al., 1984). Inset shows location of main map (box) in its regional tectonic setting. CSZ is Cascadia subduction zone, RDF is Revere-Dellwood fault, QCF is Queen Charlotte fault, PRR is Paul Revere Ridge, VI is Vancouver Island, and QCI is Queen Charlotte Islands.

The numerous small volcanic cones of the Tuzo Wilson volcanic field appear more akin to seamounts than to the long thin ridges of the Juan de Fuca, including the incipient rift valley, West Valley (Davis and Currie, 1993). Unsedimented basalts imaged in side-scan data (Carbotte et al., 1989) form a 10–20-km-wide apron around the Tuzo Wilson field, indicating that recent flows are not confined to a rift valley. Although small faults are evident in the side-scan sonar data, they cannot be distinguished in SeaBeam data; long normal faults perpendicular to the supposed spreading direction are absent. All of these features support a non-ridge genesis for the volcanism in the Tuzo Wilson field, as argued by Allan et al. (1993).

The new SeaBeam data show that the Dellwood Knolls also have a strikingly different morphology from that of spreading centers: they are wider than they are long. The outer perimeters are rounded like seamounts, but their inner faces are linear. These linear faces are undoubtedly tectonic in origin and are at angles of N35°E and N125°E to the previously proposed direction of spreading for the knolls. Faults imaged in side-scan data in the sedimentary trough between the northern ends of the knolls strike 65°–70° to the Revere-Dellwood fault. This wide variation in fault orientations argues against a spreading-center setting.

The shallow graben between the knolls is a key feature that led to their interpretation as a sea-floor spreading center (Keen and Hyndman, 1979; Riddihough et al., 1981). A more detailed examination of its structure in the new data, however, shows that it formed fairly recently and has minor tectonic displacements. It is 10 km long and 5 km wide with only 60 m relief. New 3.5 kHz acoustic data show that shallow reflectors in the graben are offset by only tens of metres. Seismic reflection data (Riddihough et al., 1981) image faults that have cut the sediments in a set of tilted blocks. However, ongoing extension and sedimentation, typical of spreading centers, creates half grabens with sedimentary layers thicker toward the active normal fault (e.g., Middle Valley, Davis and Villinger, 1992).

The Dellwood Knolls can be reconstructed into a single edifice along a slip vector with a 160° orientation to bring the two truncated sides against each other (Figs. 1 and 2). This vector is essentially the present-day orientation of Pacific–North American relative plate motion (DeMets et al., 1990). The necessary displacement of 12–15 km would represent 0.25–0.3 m.y. at the full plate-motion rate.

Single-channel profiles around the Dellwood Knolls image shallow basalt flows or sills intercalated with sediments in a halo ~20 km wide (Riddihough et al., 1981). Middle Valley, a sedimented rift, contains a considerable number of basalt flows and sills

in the sediments, but the basalt is confined to the rift and is not observed outside the major normal faults that define the valley (Rohr and Schmidt, 1994).

Structures on the Revere-Dellwood fault are transpressional. Slices of the Dellwood Knolls that have been translated northwest are several hundred metres higher than the knoll on the other side of the fault. The extra height is probably the result of compression across the fault. Analysis of a magnitude 6.8 earthquake and its aftershocks on the Revere-Dellwood fault in 1992 (Cassidy and Rogers, 1995) shows that three of five events have slip vectors in the Pacific–North American plate-motion direction. The main shock occurred along the Revere-Dellwood fault, which is 15° different from the Pacific–North American motion.

If the underlying lithosphere is moving in the Pacific–North American direction, brittle crust above it will follow this direction where possible, but in the presence of structural weaknesses the displacement may be partitioned to allow motion parallel to existing faults. The resulting motion on the Revere-Dellwood fault is transpression, whereas the resulting motion between the Dellwood Knolls is transtension.

The juxtaposition of a spreading ridge and the continental margin is expected to produce significant thermal and tectonic effects along the margin. Off eastern North America, the Grand Banks underwent passage of a spreading center (Keen et al., 1990) and were thinned by a factor of three within 30 km of the transform margin. A multichannel seismic reflection profile along the margin 15 km east of the axis of the Tuzo Wilson volcanic field images a remarkably thick section of undeformed upper Miocene to Pliocene postextensional sediments (Rohr and Detrick, 1992). Shaking from nearby earthquakes may have dislodged sediment slumps (H. Josenhans, 1994, personal commun.), but none of the profiles that cross the margin near the supposed spreading centers show significant deformation.

It is unlikely that the volcanic effusions called the Dellwood Knolls are the surficial expression of the creation of new oceanic crust; rather, it appears that new igneous material is simply being added to older crust in a leaky transform setting (Fig. 2). This process is more chaotic than sea-floor spreading and would create the observed variety of fault azimuths as well as the widespread igneous activity in the past few million years.

Geochemical evidence from the Tuzo Wilson volcanic field has been used to argue that these volcanoes are the result of leaky-transform tectonics (Allan et al., 1993). The geochemistry of Tuzo Wilson basalts is distinct from that of both nearby spreading centers and hotspot seamounts and indicates that the percentage of melt in the mantle which generated the volcanoes is only 1%–3% compared with the 9%–11% typical of the Juan de Fuca and other spreading centers.

Crustal faulting has probably jumped northward on the Revere-Dellwood fault (Fig. 2), and the Queen Charlotte fault has retreated to the north so that the pull-apart activity previously responsible for the creation of the Dellwood Knolls is now at the Tuzo Wilson volcanic field, which yields radiometric ages of 0 Ma. The Dellwood Knolls are being dismembered by plate-motion displacements with relatively minor accompanying volcanism.
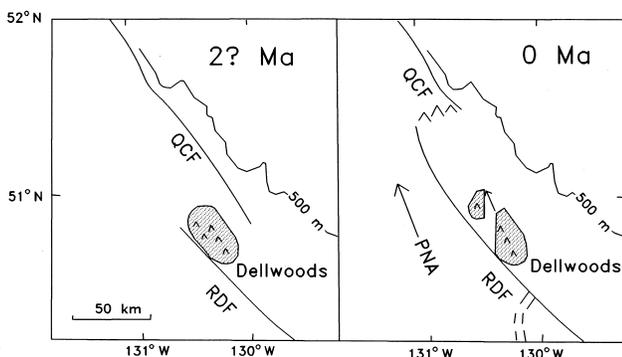

Figure 2. Cartoon of tectonic development. Dellwood Knolls formed as volcanic extrusions in leaky transform between Queen Charlotte fault (QCF) and Revere-Dellwood fault (RDF). More recently, RDF lengthened to northwest, and active part of QCF shortened. Location of fault overlap and leaky transform are now at Tuzo Wilson volcanic field resulting in dismemberment of Dellwood Knolls along vectors parallel to Pacific–North American plate motion (PNA). Ages are approximate.

PLATE KINEMATICS

An analysis of the relative plate motions in the region can provide insight into the present-day regime. Uncertainties over identification of magnetic anomalies (Wilson, 1993), timing of initiation of the Explorer plate as an entity separate from the Juan de Fuca plate (Riddihough, 1977; Hyndman et al., 1979; Wilson, 1993), and evidence for internal deformation all preclude a simple description of relative plate motions for the Explorer and adjacent plates. Re-

cent attempts to describe plate motions among the Pacific, Juan de Fuca, and Explorer plates (Davis and Currie, 1993) at a triple junction have been unsuccessful—there is significant lack of closure of the triple-junction vector triangle. The present relative motions (and associated Euler poles) for the Pacific, North American, and Juan de Fuca plates have been determined (DeMets et al., 1990; Wilson, 1993), but the relative motions between these plates and the Explorer plate are difficult to determine.

Combining plate motions from the NUVEL-1 model (DeMets et al., 1990) for Pacific–North American motions with Juan de Fuca motions from Wilson (1993) allows us to test plate motions in the vicinity of the Queen Charlotte triple junction. Although time intervals vary slightly for each of the rotation poles used and they were not jointly determined, all reasonably represent current plate motions (Table 1 and Fig. 3A). The triple-junction vector triangle among the Pacific, Juan de Fuca, and North American plates both closes and is stable. The slight misfit in the final vector triangle (Fig. 3A) is small (~4 mm/yr) and well within reasonable uncertainties for any of the plate motions.

Seismicity (Fig. 3) occurs in two main regions: the Nootka fault zone (predicted bearing 64°) and one that cuts the Explorer plate (predicted bearing 158°). The alignment of events and slip-vector directions are close to the relative motion between the Juan de Fuca and North American plates for the Nootka events, and the relative motion between North America and the Pacific plate for the intra-Explorer earthquakes (Wahlstrom et al., 1990) (Table 1). Although we cannot constrain the rate of motion along this feature, a new plate boundary must be forming. Distributed deformation as manifest by the widespread occurrence of small earthquakes (Wahlstrom and Rogers, 1992) is also occurring. The Nootka is reinterpreted as taking up North America–Juan de Fuca motion, not Explorer–North America motion.
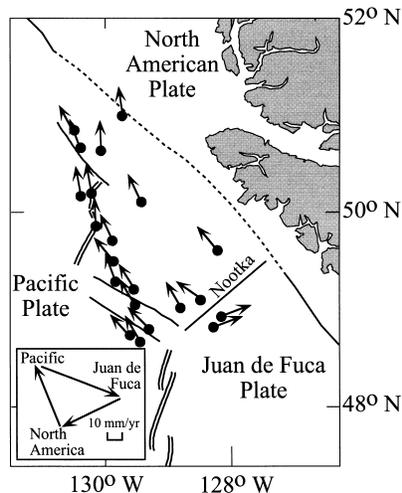
EPHEMERAL EXPLORER PLATE

In this region seismicity, sea-floor morphology, and magnetic anomalies yield different locations of the plate boundaries. Good

TABLE 1. PLATE MOTIONS AT 49°N, 129°W

Plate pair (Fixed/moving)	Azimuth (from N)	Velocity (mm/yr)
Pacific - North American*	158°	46.9
Juan de Fuca - North American	244°	45.7
Pacific - Juan de Fuca†	111°	58.6

*Rotation pole from DeMets et al. (1990).
†Rotation poles from Wilson (1993).

regional coverage of seismicity has existed over the past 45 yr; sea-floor morphology has taken tens of thousands of years to develop and resolution of magnetic anomalies is on the order of millions of years. In this rapidly evolving system we place more weight on the seismicity data to locate present-day plate boundaries.

We propose that the Explorer plate is an ephemeral plate behaving independently for only a short time period (4–1 Ma). Its rapid evolution is culminating in its elimination as a new transform plate boundary forms. Its eastern side is becoming coupled to North America, whereas the western side is becoming part of the Pacific plate. Large earthquakes within the Explorer plate are the present-day manifestation of the new plate boundary separating the Pacific and North American plates. Small events are indicative of distributed deformation that commonly accompanies initiation of strike-slip faults (Wilcox et al., 1973). The new Queen Charlotte triple junction lies at the intersection of this seismicity and the Juan de Fuca Ridge.

The Explorer ridge is clearly different from the rest of the Juan de Fuca Ridge (Botros and Johnson, 1988; Johnson and Holmes, 1989; Wilson, 1993). Since 5 Ma it has migrated west at a rapid pace by means of jumps, asymmetric spreading, and segment propagation, whereas the main body of the Juan de Fuca has remained relatively stable. The northern end of the Explorer ridge consists of three short segments; one is parallel to the Pacific–North American plate motion vector. Topographic relief of these northern segments varies by >1 km along and across strike, whereas the southern Explorer ridge, which has produced no teleseismically recorded events, does not exhibit such rough topography. The chemistry of basalt recently erupted from the Explorer ridge is distinct from the chemistry of basalts erupted from the Juan de Fuca Ridge, and there is no simple relation between chemistry and morphology as seen in many other ridge systems (Cousens et al., 1984; Michael et al., 1989).

This model implies that the Queen Charlotte fault is lengthening to the south, fragmenting the Explorer plate in its wake (Fig. 4). As a result, the Explorer ridge is being captured within the Pacific plate, probably soon to be extinguished. Batiza (1989) estimated that it may take 1 m.y. before an abandoned ridge is truly dormant. Young crust east of the Explorer ridge straddles the high seismicity zone. The magnetic anomalies are chaotic and markedly different from the stripes observed on the complementary Pacific plate; deformation associated with distributed deformation could disrupt the magnetic anomalies. Few structural data have been collected in this region; a refraction profile within the Explorer plate interpreted crust to be as thick as 11 km (Malacek and Clowes, 1978), whereas Juan de Fuca crust is typically 6–7 km thick.

The previously subducted parts of the Explorer plate will re-

Figure 3. Locations and slip vectors for teleseismically recorded earthquakes, after Wahlstrom et al. (1990). Mechanisms are strike slip parallel to Pacific–North American relative motion; locations are also aligned with this vector. Vector triangle shows relative motions of Juan de Fuca–Pacific–North American plates. Slip vectors for earthquakes that define Nootka fault are parallel to Juan de Fuca–North American relative motion.
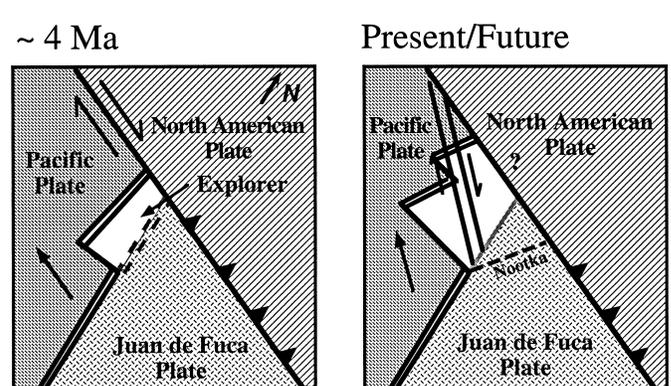
Figure 4. Tectonic model of birth (after Botros and Johnson, 1988) and death of ephemeral Explorer plate. Between 4 and 5 Ma, Explorer ridge formed and began to migrate westward. Pacific–North American plate boundary is extending southward into Explorer plate.

main in place beneath and coupled to North America, while the Explorer ridge and immediately adjacent oceanic lithosphere, once attached to the Pacific, will translate with the Pacific plate. The recent jump in spreading on the northernmost tip of the Juan de Fuca from Middle Valley to West Valley (Davis and Villinger, 1993) is probably also the result of ongoing readjustments to the new location of the triple junction.

Equivalent situations developed several times during the evolution of the southern (Rivera) triple junction of the San Andreas system (Fernandez and Hey, 1991; Nicholson et al., 1994; Stock and Lee, 1994). Similar small, ephemeral plates, such as the Monterey and Arguello plates, formed at the northern end of the Farallon plate. The small ridge-crest segments were captured by and are still preserved within the Pacific plate adjacent to North America. The evolutionary process observed in the Explorer plate, in which the transform boundary forms, implies that these small plate remnants adjacent to the San Andreas along coastal California abandoned their subducted parts at about 20 Ma when they joined the Pacific plate.

CONCLUSIONS

The Pacific–North American plate boundary extends from the Queen Charlotte Islands across the Tuzo Wilson volcanic field and the Dellwood Knolls, and is establishing itself within the Explorer microplate, terminating at the northernmost Juan de Fuca Ridge. The underlying mantle lithosphere is probably moving in a pure strike-slip mode and the brittle crust above it is accommodating this motion along previously existing weaknesses, all the time minimizing the difference between upper crustal and lithospheric motions. Overlapping crustal strike-slip faults, the Queen Charlotte and the Revere-Dellwood faults, produce the localized extension and associated volcanism of the Tuzo Wilson volcanic field and Dellwood Knolls seen in the SeaBeam data. The Explorer ridge is in the process of becoming extinct, and high seismicity in the Explorer plate indicates that it is being dismembered by the establishment of this new simpler plate boundary configuration.

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