

Transpression between two warm mafic plates: The Queen Charlotte Fault revisited

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Abstract. The Queen Charlotte Fault is a transpressive transform plate boundary between the Pacific and North American plates offshore western Canada. Previous models for the accommodation of transpression include internal deformation of both plates adjacent to the plate boundary or oblique subduction of the oceanic plate; the latter has been the preferred model. Both plates are warm and mafic and have similar mechanical structures. New multichannel seismic reflection data show a near-vertical Queen Charlotte Fault down to the first water bottom multiple, significant subsidence east of the Queen Charlotte Fault, a large melange where the fault is in a compressive left step, and faulting which involves oceanic basement. Gravity modeling of profiles indicates that Moho varies fairly smoothly across the plate boundary. Isostatic anomalies indicate that the Pacific plate is flexed downward adjacent to the Queen Charlotte Fault. Upward flexure of North America along with crust thickened relative to crust in the adjacent basin creates topography known as the Queen Charlotte Islands. Combined with other regional studies, these observations suggest that the plate boundary is a vertical strike-slip fault and that transpression is taken up within each plate.

1. Introduction

Ideas on accommodation of transpression have been heavily influenced by studies of oblique subduction zones [e.g., *McCaffrey*, 1996; *Burbridge and Braun*, 1998]. How a transform plate boundary with a near-vertical dip changes into a shallow dipping subduction zone is not obvious. At the onset of and during transpression the relative mechanical properties of the plates and geometry of the plate boundary are critical to understanding subsequent deformation. In the case studied here, the initial conditions are that of a well-established transform fault separating plates with similar mechanical structures: thin, warm, and mafic.

The Queen Charlotte Fault (QCF) separates a young Pacific plate from an anomalously mafic and recently thinned section of the North American plate in western Canada (Figure 1). Reconstructions of global plate motions indicate a small but significant component of compression during the Pliocene (5 Ma) [*Engelbreton*, 1985; *Norton*, 1995; *Stock and Molnar*, 1988], which may have begun at 8 Ma [*Atwater and Stock*, 1998]. A more southerly section of the Pacific-North America plate boundary, the central San Andreas Fault, is thought to absorb 14–72 km of estimated transpression solely by intraplate deformation [*Crouch et al.*, 1984; *Wallace*, 1990]. In California, studying geologic effects of relative plate motions is complicated by migration of triple junctions which produces significant variations in mechanical properties with time [e.g.,

Atwater, 1989; *Furlong*, 1993]. In comparison, the QCF has had a relatively simple plate history for the last 20 Myr or more [*Rohr and Currie*, 1997] and provides a good location to study the poorly understood geologic effects of transpression in both oceanic and continental plates.

Two main models have been presented for plate interactions on the QCF: one in which transform faulting alternates with subduction thrusting [*Hyndman and Ellis*, 1981] and one in which transform motion is accommodated on the QCF and compression by deformation of the oceanic plate and the Queen Charlotte Islands [*Mackie et al.*, 1989]. The latter was considered an unlikely solution because they believed that hundreds of kilometers of compression had to be accommodated (Figure 1) [*Yorath and Hyndman*, 1983; *Mackie et al.*, 1989]. Their tectonic reconstructions of the Queen Charlotte region and the Explorer plate placed the commencement of transpression just north of Vancouver Island. The lack of compressive structures in Queen Charlotte Sound and abundant compressive structures in Hecate Strait [*Rohr and Dietrich*, 1992] indicate that significant ongoing transpression begins north of the Tuzo Wilson Seamounts. Since then, *Hyndman and Hamilton* [1993] used the poles of *Stock and Molnar* [1988] and *Engelbreton* [1985] for a simple calculation that 80 km of compression had occurred across the QCF, although the tectonic model of a subducted slab [*Hyndman and Ellis*, 1981; *Hyndman et al.*, 1982; *Yorath and Hyndman*, 1983] was not revised. *Prims et al.* [1997] placed the relative plate motions' vector on a map to show that the average net predicted overlap of the plates is only tens of kilometers; the value gradually increases from zero at the Tuzo Wilson Seamounts to a maximum of 80 km over a lateral distance of 350 km. Large amounts of compression might well need a subduction zone to be accommodated; tens of kilometers may not [*Crouch et al.*, 1984].

Other studies in the last 10 years such as microseismicity,

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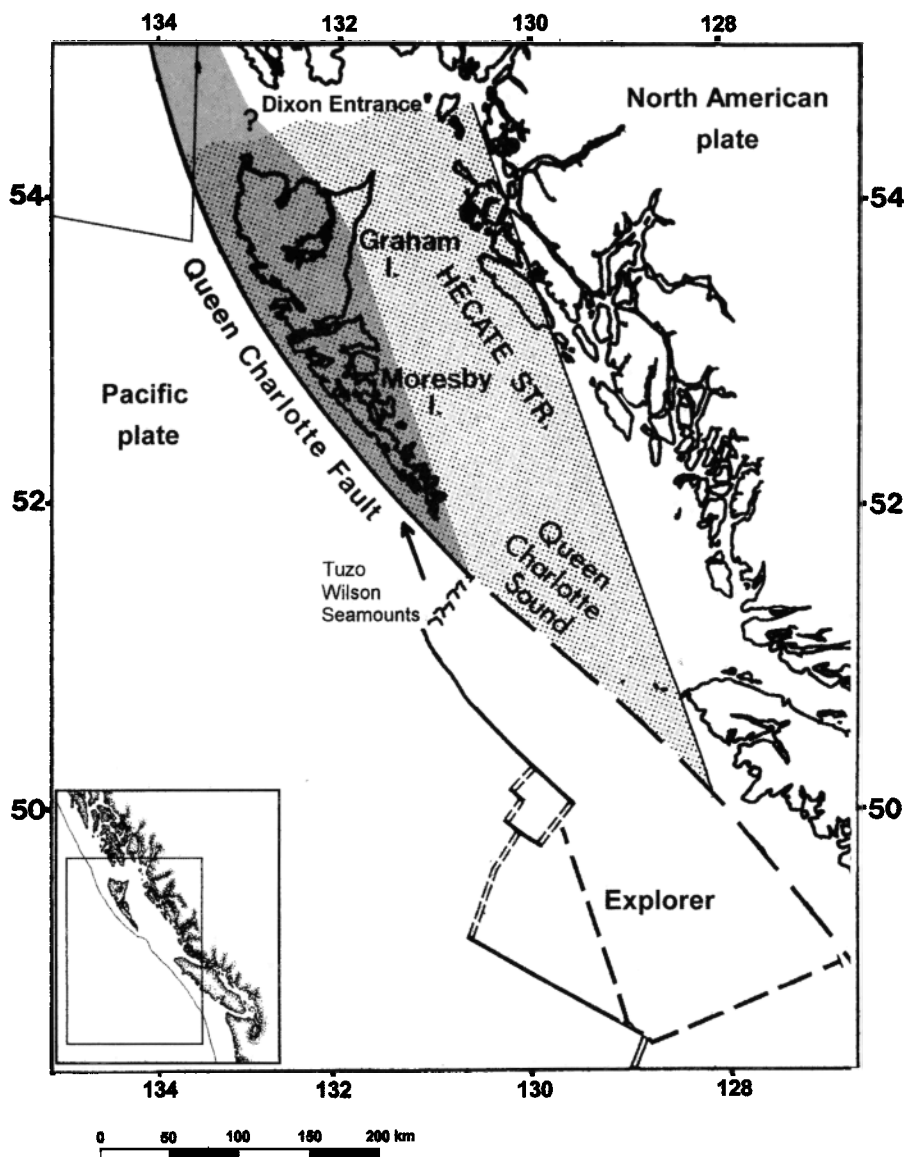


Figure 1. The Queen Charlotte region, western Canada. Stippled area indicates the amount of compression that was thought to have occurred in the last 5 Myr [after Mackie *et al.*, 1989] and darker stippling shows the amount of overlap if transpression starts at the Tuzo Wilson Seamounts at 5 Ma. If relative plate motions began to change at 8 Ma [Atwater and Stock, 1998], then the eastern boundary of the predicted overlap simply projects linearly across Dixon Entrance and Alaska. Whenever transpression began, net predicted transpression reaches a maximum at Graham Island; the instantaneous angle of transpression decreases to the north as the Queen Charlotte Fault (QCF) trends more northerly. Inset shows location of figure in regional context. Graham and Moresby Islands are the principal islands of the Queen Charlotte group. These islands, a region of thicker crust, lie east of the QCF in the region of predicted plate overlap. Their eastern shore is subparallel to the azimuth of relative plate motion as shown by arrow. The relative plate motion vector was calculated from NUVEL-1 [DeMets *et al.*, 1990]. Box in northwest corner shows approximate area of Figure 2.

refraction, and heat flow data, geologic mapping and paleomagnetic study of the Queen Charlotte Islands, modeling of gravity anomalies and flexure of the Pacific plate, and reconstructions of sea level during the last glacial retreat suggest that a rethinking of lithospheric interactions along the QCF is in order. The regional implications of this work are combined with new multichannel seismic reflection data and gravity models across the northern QCF to infer that compression is most likely accommodated by deformation within both plates and that the QCF continues to accommodate most of the strike-slip motion.

2. Overview of Regional Tectonics

2.1. Queen Charlotte Fault

Between the Tuzo Wilson Seamounts and the Alaska border the QCF is clearly imaged by GLORIA side-scan data as a distinct line in the seafloor [Bruns *et al.*, 1992]; the QCF between 54° and 55°N is shown in Figure 2. In the northern region, where the multichannel data were collected, two linear segments can be observed; the northern segment strikes 338°, and the southern segment strikes 328°. The difference in angle

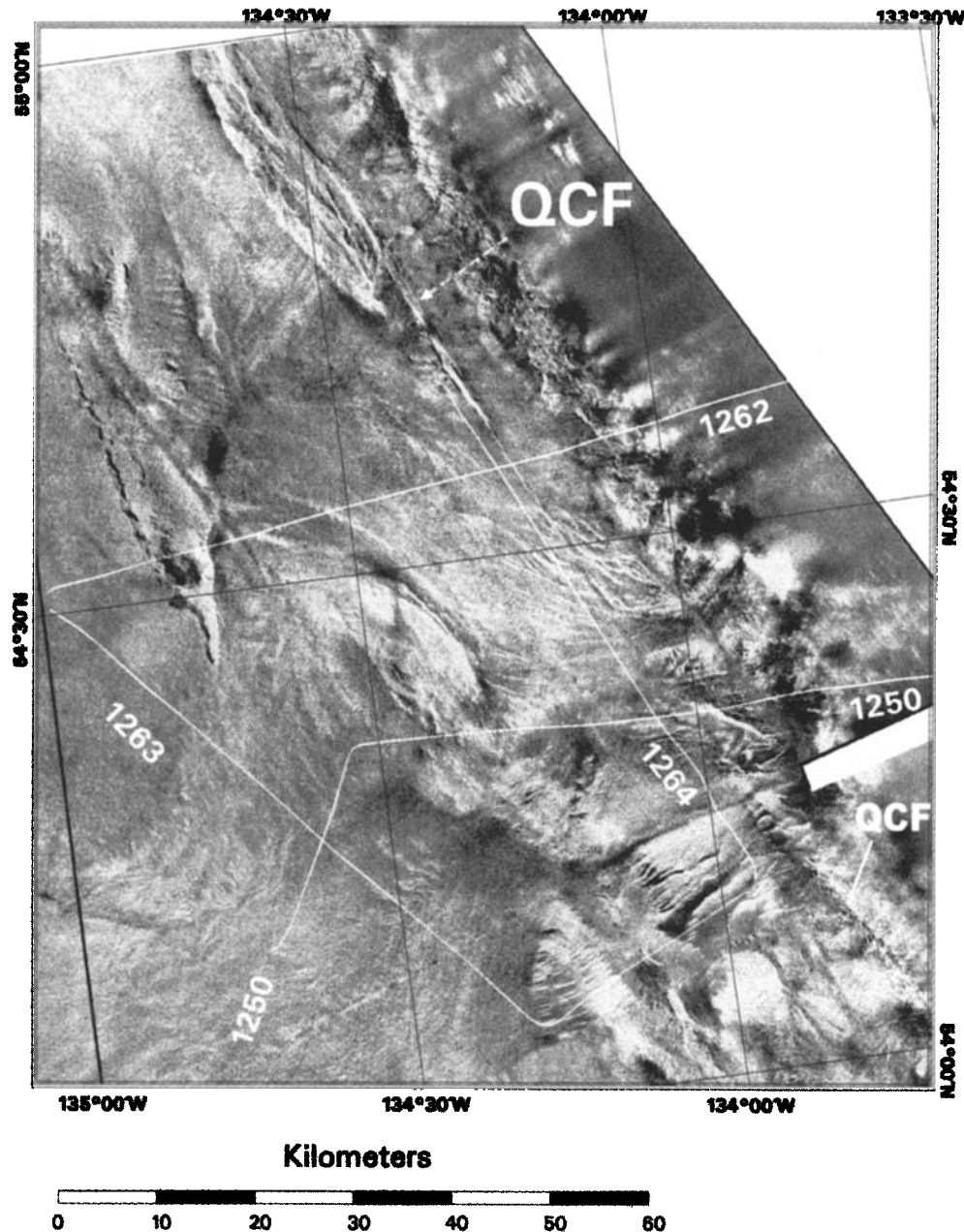


Figure 2. GLORIA data [Bruns *et al.*, 1992]. The QCF is evident as a linear feature on the seafloor. The northern segment trends 337° and the southern 328° . The NUVEL-1 vector trends about 345° here. They meet in a compressive left step imaged by line 1250. Fine white lines show location of seismic data.

and left step between them creates a compressive bend. Striations consistent with compressive structures formed by north-west directed shear are observed in the bend. In other locations, canyons and striations appear to be offset right laterally by a few kilometers.

2.2. Plate Morphology

This oceanic-continental transform fault is characterized by an abrupt transition between the two plates (Figure 3). The continental shelf under Hecate Strait is fairly flat with two main incised channels. West of the Queen Charlotte Islands the shelf is <10 km wide, and the continental slope consists of a terrace, roughly 30 km wide and 1500–2000 m deep bound by two scarps. The outer scarp of the terrace steps down to water depths of 2500–3000 m, the Queen Charlotte Trough. Along

strike the terrace changes from a single block defined by one main scarp into several blocks defined by scarps which appear to splay off the QCF [Scheidhauer, 1997]; this change in morphology may be related to decreased obliquity of transpression to the north (A. M. Trehu and M. Scheidhauer, manuscript in preparation, 2000). The trough, of probable flexural origin [Hyndman *et al.*, 1982; Prims *et al.*, 1997], is several hundred meters deeper than the abyssal plain and begins 90 km north of the inception of the QCF at the Tuzo Wilson Seamounts. North of the Alaska border the terrace is less distinct [Bruns and Carlson, 1987], and there is little obvious contemporary deformation in the North American plate [e.g., Gehrels *et al.*, 1987]. South of the Tuzo Wilson Seamounts the oceanic plate is very young and broadly deformed [Rohr and Furlong, 1995],

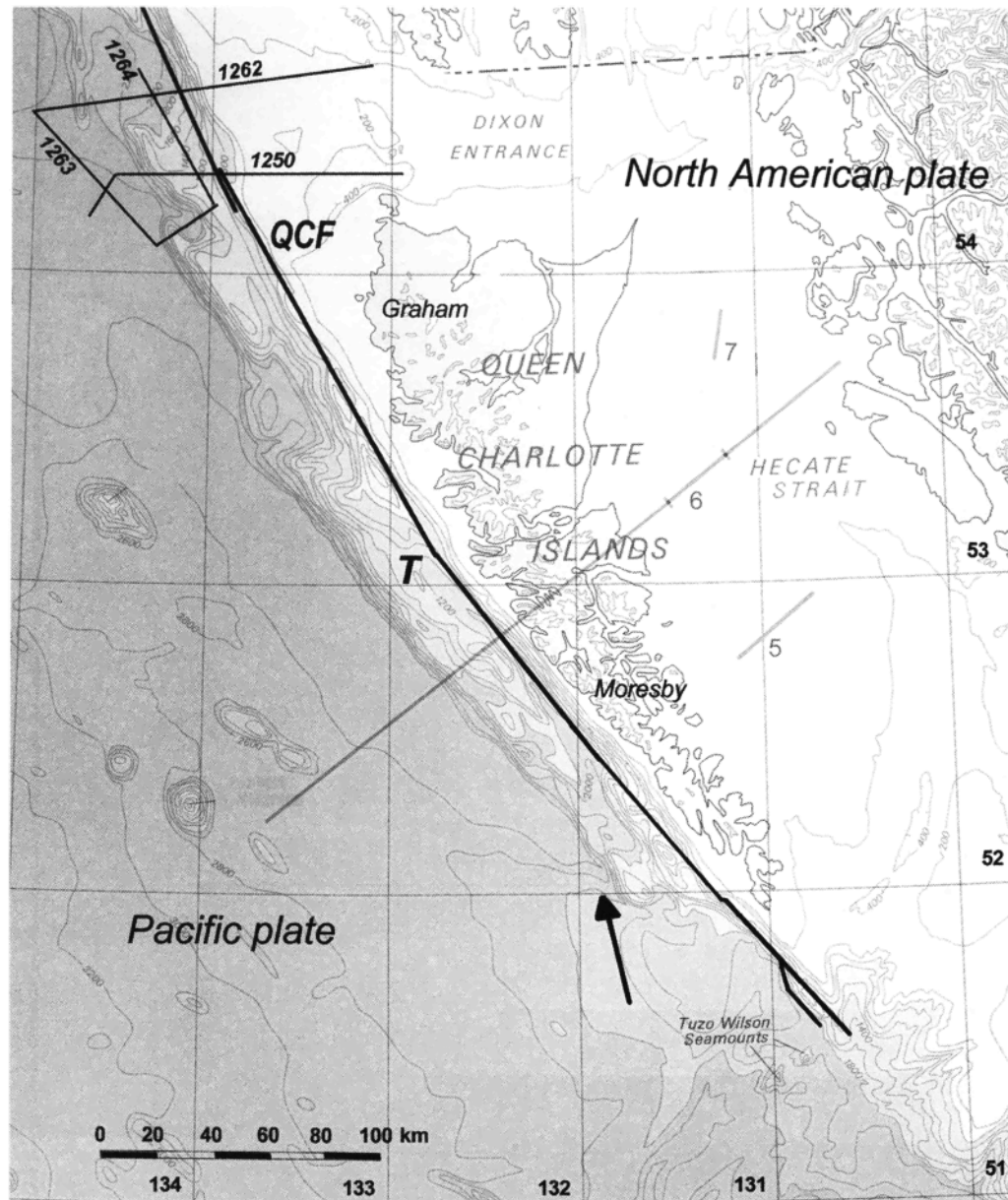


Figure 3. Regional morphology with location of new multichannel seismic reflection data: lines 1250, 1262, 1263, and 1264. T is the Queen Charlotte terrace. Arrow shows direction of relative plate motion calculated from NUVEL-1 [DeMets *et al.*, 1990]. Location of QCF was picked from GLORIA data (Figure 2). Light shaded line is location of cross section shown in Figure 4. Short line segments show locations of multichannel seismic reflection lines 5, 6, and 7 displayed in Figure 6.

and south of the Queen Charlotte Islands the North American plate is simply subsiding in response to Miocene extension [Rohr and Dietrich, 1992].

The age of the Pacific plate increases from 7 Ma at the southern end of the Queen Charlotte Islands to 15 Ma off northern Dixon Entrance. Magnetic anomalies of the Pacific plate strike approximately north-south and fade out under the outer scarp of the terrace [Atwater, 1989].

2.3. Plate History

The tectonics of western Canada are dominated by the boundary between the Pacific and North American plates (Figure 1). Relative motion between the two plates has been dominantly strike slip for at least 20 Myr, if not 45 Myr [Rohr and

Currie, 1997] with a component of transpression in the last 5 Myr. Prior to 45 Ma the plate boundary was a subduction zone, but its configuration and history are poorly known. A single fault, the Queen Charlotte Fault, is thought to take up most of the past transcurrent motion; distributed deformation may have occurred during Miocene extension [Rohr and Dietrich, 1992]. Pliocene inversion of Miocene basins indicates that compression was distributed across the continental margin over a width of at least 150 km [Rohr and Dietrich, 1992].

The amount of predicted compression changes along strike because of the angle of relative motion and changes in strike direction of the QCF. The difference between the strike of the Queen Charlotte Fault off Moresby Island (320° , Figure 1) and the direction of relative motion of plates is $\sim 26^\circ$ in the south

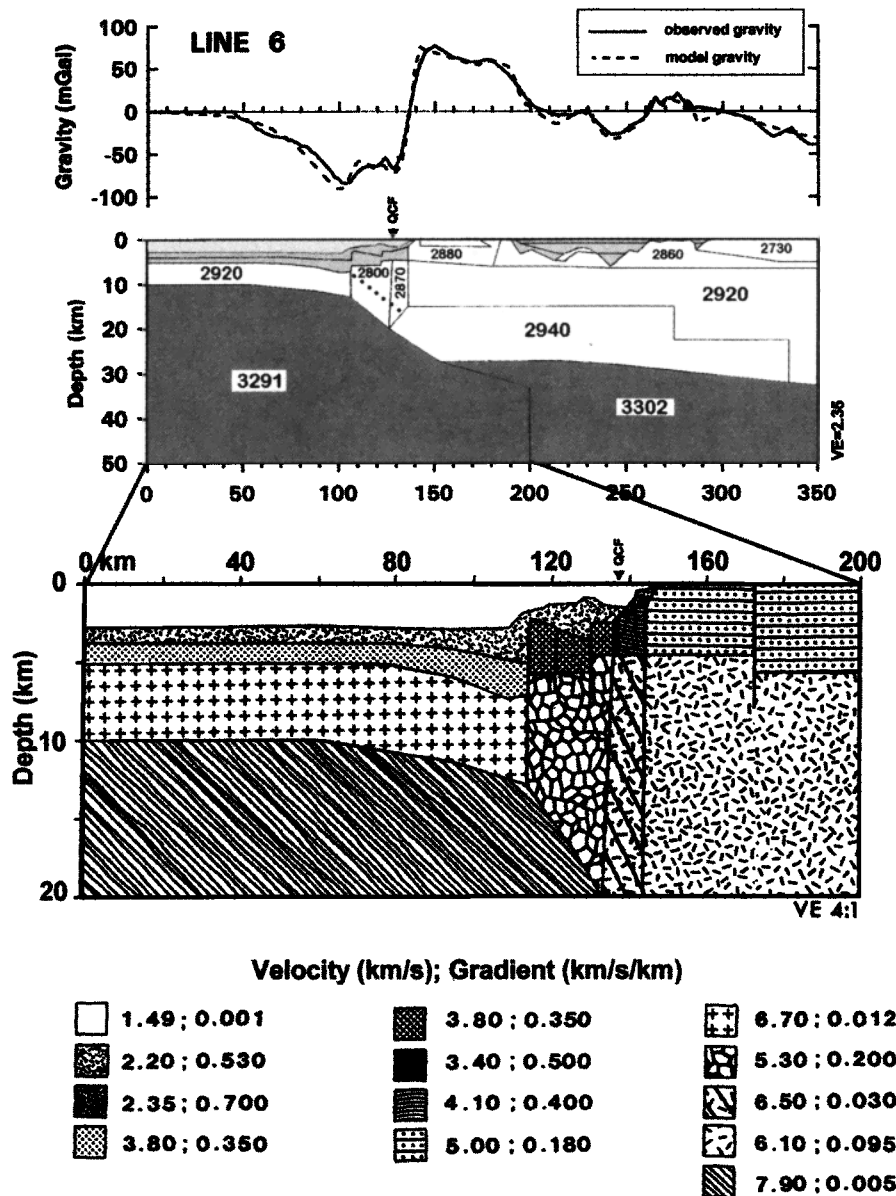


Figure 4. (bottom) Refraction results of *Dehler and Clowes* [1988]; note thickening of material with velocities greater than 5.3 km/s in terrace. (top) Gravity interpretation of this refraction line combined with line 6 [after *Spence and Long*, 1995]. Location of profile is shown in Figure 3. The white layer corresponds to crust with velocities greater than 5.3 km/s (crystalline basement); light shading corresponds to water, medium shading corresponds to velocities 2.2–4.7 km/s (sediments and upper oceanic crust); and darker shading corresponds to velocities of 7.9–8.1 km/s (mantle). Numbers are density values modeled (kg/m^3). Triangle marks location of QCF. Dotted line is drawn from the top of layer 3 in oceanic crust across the terrace to show how much of the terrace would be occupied by a simple undeformed slab. The volume above the dashed line must then be deformed oceanic crust and sediments.

and decreases northward to 7° off Dixon Entrance. Average velocities are north-northwest 4.7–4.8 cm/yr west of Graham Island and Dixon Entrance. The amount of predicted overlap of the Pacific and North American plates (Figure 1) was calculated assuming no internal deformation of either plate and using the NUVEL-1 vector [DeMets *et al.*, 1990] over 5 Myr. Predicted overlap across the QCF increases from zero at the Tuzo Wilson Seamounts to a maximum of 80 km at northernmost Graham Island and then rapidly decreases again. *Atwater and Stock* [1998] have recently suggested that the Pacific North America relative plate motions changed gradually from trans-

current to transpressive beginning at 8 Ma. This would increase the amount of overlap predicted in Dixon Entrance to 100 km but does not affect the rest of the map shown.

2.4. Structure

A multichannel survey in 1977 imaged folded sediments in the terrace and inverted basins of northern Dixon Entrance [Snively *et al.*, 1981]. The terrace's deeper structure was studied in two refraction transects at about 52°N [Horn *et al.*, 1984] and 53°N [Dehler and Clowes, 1988] (Figure 4, bottom); interpretations featured crust in the terrace which is lower in seis-

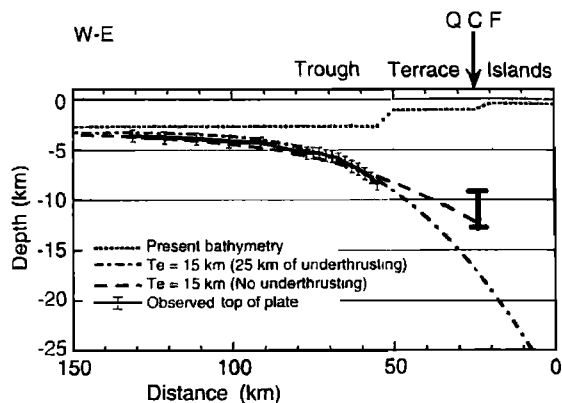


Figure 5. Flexural modeling by *Prims et al.* [1997] shows that the weight of the terrace alone is sufficient to match observed flexure assuming a density of 2000 kg/m^3 . Under the QCF, heavy bar represents top of putative plate in gravity models (see Figure 15). Thrusting of a slab under North America predicts a greater amount of downwarp than is allowed by gravity models. Downwarp is taken from a reflection profile west of Graham Island [Rohr et al., 1992].

mic velocities than crust on either side. Velocities graded from 5.3 to $>7 \text{ km/s}$ above Moho and crust thickened from 7 to 18–20 km toward the continent. Most of the rays which defined Moho under the terrace also traversed the Queen Charlotte Islands, where crustal structure was not constrained. Several gravity models based on these refraction studies as well as refraction interpretations in the Queen Charlotte Basin interpreted that Moho dips eastward under the terrace and then flattens under the islands (Figure 4, top) [Horn et al., 1984; Mackie et al., 1989; Sweeney and Seemann, 1991; Spence and Asudeh, 1993; Spence and Long, 1995].

High velocities (6.5–7.3 km/s) in the lower continental crust [Spence and Asudeh, 1993] indicate that its composition is dominantly mafic. This is consistent with the surface geology of the Queen Charlotte Islands, which includes 7–10 km of Karmutsen basalt flows and shows that they are part of the Wrangellia terrane [P. D. Lewis, et al., 1991], which was accreted in the Cretaceous [Gabrielse and Yorath, 1991].

2.5. Flexure and Vertical Motions

Bathymetry and isostasy indicate that the Pacific plate is being flexed [Harris and Chapman, 1994]. In three dimensions the wavelength and amplitude of flexure vary with the strength of the plate as it increases with age. A flexural trough is not evident in the southernmost 90 km of the fault, indicating that until this point the load of the terrace or the compressive stresses are insufficient to flex the plate. Calculations of flexure (Figure 5) [Prims et al., 1997] found that a model of underthrusting predicted too much downwarp of the Pacific plate. Instead, a clean break at the QCF matched downwarp observed in a reflection profile and a depth of 12 km to the top of a putative undeformed oceanic plate at the QCF.

In the Miocene, extensional faults and subsidence were active in Queen Charlotte Sound and Hecate Strait forming the Queen Charlotte Basin [Rohr and Dietrich, 1992; Hyndman and Hamilton, 1993; Lowe and Dehler, 1995; Dehler et al., 1997; Rohr and Currie, 1997]. The basin consists of a network of half grabens and grabens across a 200-km-wide region. Plate motions have been fairly constant between 40 and 5–8 Ma; a

previously postulated time of transtension is no longer thought to have occurred [Norton, 1995; Atwater and Stock, 1998]. The mode and cause of extension remain enigmatic, but coincident acceleration of uplift of the Coast Mountains led Rohr and Currie [1997] to propose that extension was accommodated on a large low-angle detachment.

Transpression has inverted subbasins inboard of the Queen Charlotte Islands (Figure 6) [Rohr and Dietrich, 1992] but not in Queen Charlotte Sound. Compression deformed some upper Miocene sediments (e.g., shot points (SP) 600–800, Figure 6a) and was followed by broad folding and tilting up to the west which included Pliocene postrift sediments. Strike-slip faults and flower structures cut the folds. Glacial scouring and fast tidal currents have planed off the upthrust sediments (Figures 6b and 6c); only the northernmost basins (e.g., Figure 6c) are seismically active [Bird, 1997].

No quantitative work has been done to assess the uplift history of the Queen Charlotte Islands, yet their topography and geology indicate uplift which increases southward along strike. Mountains on the western Queen Charlotte Islands exceed elevations of 1000 m. In Moresby Island, upper crustal Paleogene batholiths are exposed [Anderson and Reichenbach, 1991], but on Graham Island, Neogene rocks formed at sea level are just above current sea level. Yorath and Hyndman [1983] suggested that the Queen Charlotte Islands were flexed above sea level in the last 6 Myr by underthrusting; they did not consider along-strike variations in flexure.

Quaternary history includes periodic glacial loading over the last 2 Myr accompanied by rapid sea level changes caused by eustatic variations as well as significant regional flexural effects. A glacier in Dixon Entrance came within 12 km of the QCF only 11,000 years ago; as it retreated, sea level rose by 100 m in only 1000 years [Barrie and Conway, 1996]. This rapid rise has been documented as a regional phenomenon [Barrie et al., 1991; Josenhans et al., 1995] and suggests a viscoelastic time constant of a few 100 years or less (T. James, personal communication, 1998), which is significantly smaller than time constants used for most of North America. The rapid regional sea level changes may only be possible given the warm state of the continental lithosphere and if the QCF is a free edge (T. James, personal communication, 1998).

2.6. Seismicity

The Queen Charlotte Fault is seismically active (Figure 7); Canada's largest recorded earthquake, a magnitude 8.1, occurred on it in 1949. For that event, Bostwick [1984] found a rupture length of ~490 km (300 km north and 190 km south of the epicenter) with an average coseismic displacement of 4–7.5 m. The azimuth of the vertical fault plane corresponds with the strike of the Queen Charlotte Fault, implying that no convergence was taken up by this event. A short ocean bottom seismometer (OBS) survey defined a near-vertical zone of seismicity to depths of 20 km under the QCF cutting down to Moho [Hyndman and Ellis, 1981]. A study of regional seismicity between 1982 and 1996 [Bird, 1997] also found that events clustered around the QCF lie in a near-vertical band. This study only had arrivals recorded from the eastern side of the QCF for each event, but events located on the QCF along the middle outer edge of the array did not significantly change location solutions when different depths were used to locate a given event. This implies that the earthquakes are distributed vertically. This study could not, however, determine the maximum depth of faulting.

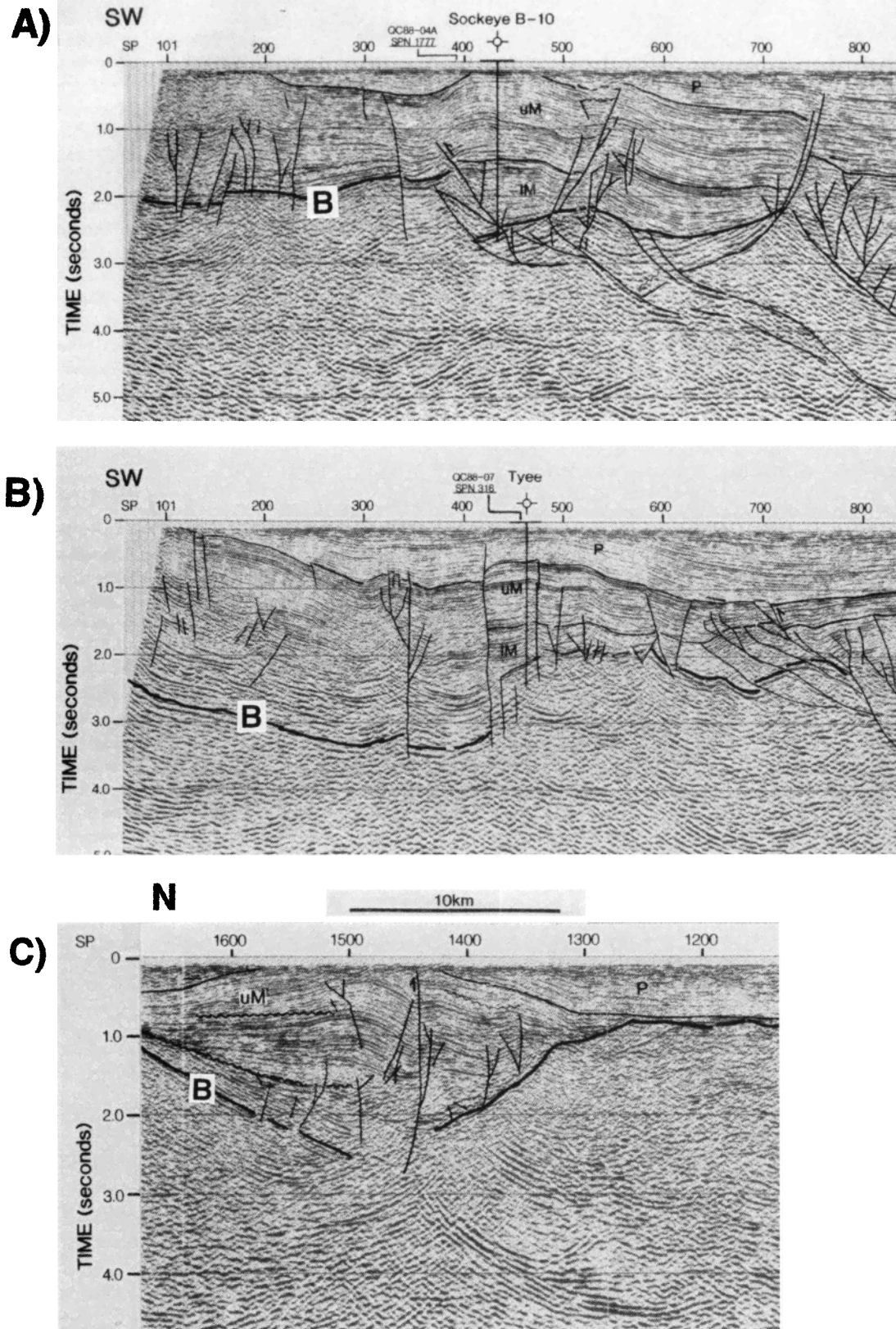


Figure 6. Inversion of basins formed in the Miocene; see Figure 3 for location [after Rohr and Dietrich, 1992]. P, Pliocene sediments; uM, upper Miocene; and lM, lower Miocene sediments as determined from well ties. B indicates probable basement rocks. (a) Line 5 showing basement faults below folding in sedimentary section. (b) Line 6 imaging vertical faults, folding of Miocene and Pliocene sediments as well as tilting of basement, and Miocene/Pliocene section up to the west. Note strike-slip fault underneath shotpoint location 420. (c) Line 7 showing folding of sedimentary section and strike-slip fault which is active today (shot point (SP) 1445). A magnitude 5.3 strike-slip earthquake occurred ~20 km below this basin in 1990.

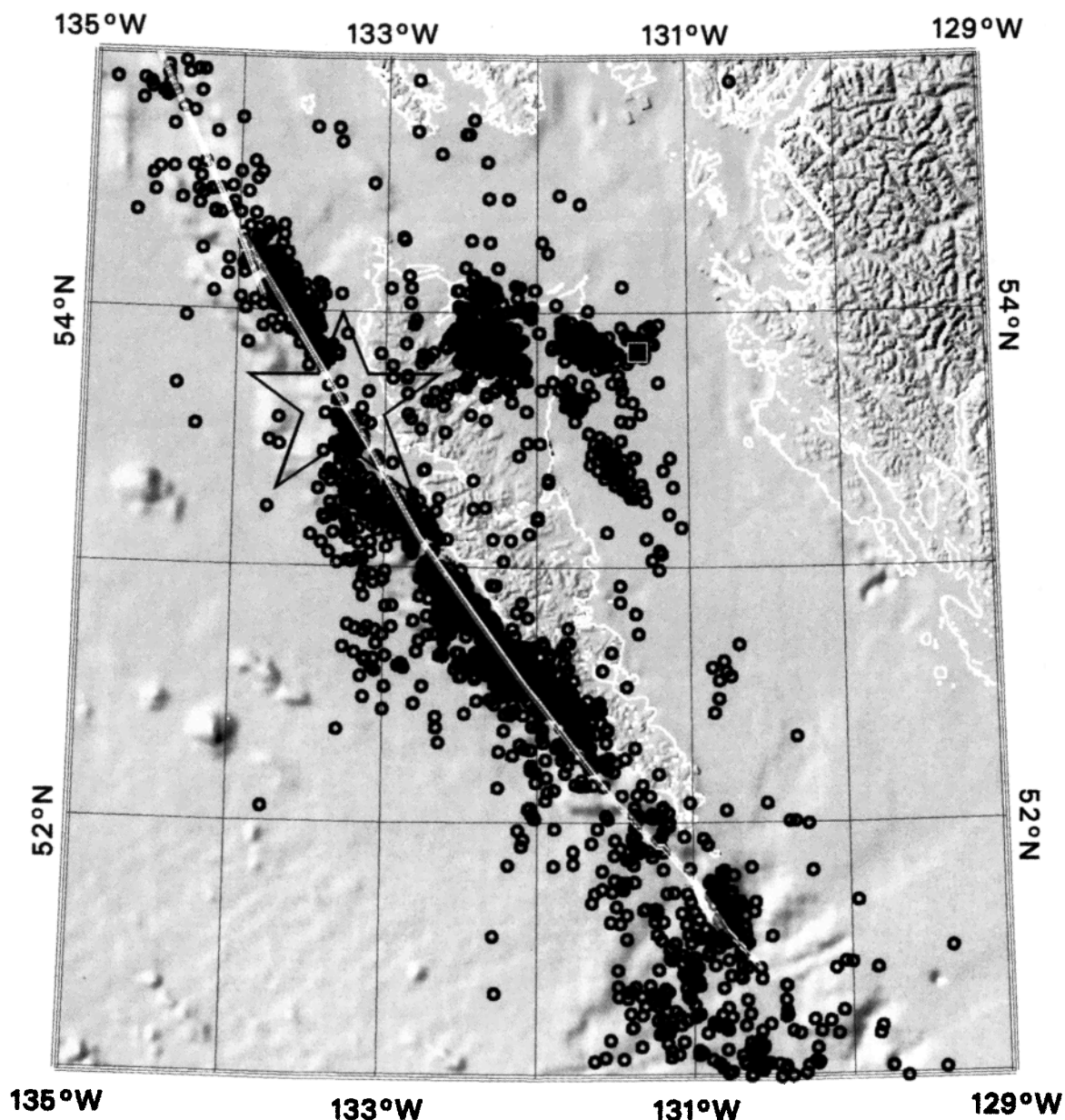


Figure 7. Microseismicity from Bird [1997] plotted on bathymetry; magnitude 8.1 event is shown as large open star. Seismicity occurs along the QCF; east of the QCF microseismicity is concentrated under northern Graham Island and Hecate Strait. White square denotes location of $M = 5.3$ event in 1990. Nine stations used to locate the events were on the Queen Charlotte Islands (QCI); three were across Hecate Strait on the mainland.

Focal mechanism solutions of groups of microearthquakes, and individual events [Bérubé *et al.*, 1989; Bird, 1997] show that pure strike-slip as well as oblique, thrust, and extensional events occur near the QCF, beneath the terrace and northern Graham Island. The axis of maximum compression strikes north to north-northeast. Events in Figure 7 were located assuming a depth of 20 km. Events located north of the station array are slightly east of the QCF probably because the assumed depth is too deep. Nevertheless, the spread of activity over the physiographic terrace and the variety of mechanisms suggest that the terrace is seismically active. Treated as a group, 90% of the events under Graham Island occur at depths <16 km, and 90% of the events under Hecate Strait occur at depths <20 km.

3. New Seismic Reflection Data

3.1. Acquisition and Processing

Data collected in 1994 as part of the Accrete program [Andronikos *et al.*, 1999] cross the QCF in two places; tie lines image mildly deformed Pacific plate and the terrace (Figures 2 and 3) [Scheidhauer *et al.*, 1999]. The source, an array of 20 air guns, had a total volume of 138 L (8400 cubic inches). The streamer had 224 channels with a group spacing of 12.5 m for a total length of 2800 m. The data were recorded with a sampling rate of 4 ms for 16.5 s. An anti-aliasing high-cut filter of 125 Hz was applied in the field prior to digitization. Using Global Positioning System (GPS) navigation, the shotpoint data were sorted into common midpoint (CMP) format with a

bin size of 12.5 m resulting in CMPs with an average fold of 60. Processing followed the basic steps of editing shot points, band-pass filtering, analyzing velocities, and stacking [Schei-dhauer, 1997]. The data were migrated using a finite difference technique.

3.2. Line 1262

Line 1262 (Figure 8) crosses the QCF at latitude 54.5°N off Dixon Entrance. The Pacific plate is ~15 Myr old here, and the western edge of the terrace is a ridge which runs north-south, parallel to the magnetic anomalies (Figure 2). Sedimentary unit B thins to the west and onlaps unit A, implying that the oceanic plate was already flexed before deposition of unit B. We have no independent estimate of age of sediments, but it seems likely that, similar to the Cascadia basin, the bulk of the sediments are Pleistocene.

The outer ridge of the terrace is so deformed that only short segments of coherent reflections are visible (CMP 10200–10700); the standard processing used was unable to resolve its internal structure. The terrace is ~45 km wide; two turbidite channels which carry sediments from Alaska and the Coast Mountains have been focused here into one channel by the outer ridges of the terrace. Broadly folded sediments underlie the seafloor; the intensity of folding increases toward the outer ridge and with depth. An incoherent unit, F, abuts the QCF; its incoherence and association with a major fault suggest that it is a melange. Farther to the west, sedimentary layers are folded, and their contact with the melange is not defined. Whether these layers have been caught up in the melange or if they onlap an older melange cannot be distinguished here.

The data show striking differences in structure and stratigraphy across the QCF; marked tilting on the North American plate does not occur on the Pacific (Figures 8–10). On the North American side the top 1.0 s of sedimentary layers dip down toward the fault and are underlain by a nearly flat event at 4.5 s (Figure 9). West of the fault, reflections are subparallel to the seafloor and are higher in amplitude than to the east. The configuration of reflections at the present seafloor suggests that tilting the North American plate relative to the Pacific creates a depression which would be filled by the next sedimentary deposit. Dips exceed those typically observed on continental slopes. The dip of the seafloor is 5°, and dips of reflections below that are as much as 12° and 20° assuming an interval velocity of 2.0 km/s. In contrast, sediments immediately seaward of the shelf break on passive margins typically dip 3° to 5° on today's Atlantic continental slope and up to 7.5° on Miocene prograding clinoforms off New Jersey [Fulthorpe and Austin, 1998].

On the North American plate the sedimentary record shows two different processes at work: tectonic subsidence and flexure from glacioisostatic forces. The latter entails rapid changes which are superimposed on the former, a longer-term, presumably steadier process. Dips which exceed even those observed during massive sediment buildup suggest that subsidence is ongoing. Subsidence could be caused by local thinning of North America or simple flexure. Counterclockwise rotation between two active right-lateral strike-slip faults can create extension in one section and compression in another. Dixon Entrance is broken by a series of northwesterly trending en echelon faults [Rohr and Dietrich, 1992]; shear distributed from the QCF onto one of these faults could easily induce rotation adjacent to the QCF.

The angular relations above unconformity U3 (Figure 10)

show that subsidence was faster than the rate of deposition since layers onlap the substrate. Above U2, layers downlap; the sedimentary units are building outward indicating a faster rate of deposition. Such variations in sedimentary rate are expected to occur during glacial cycles and may have occurred during the last major glacial cycle (0.125 Ma). This would imply that the Pacific plate was <6 km to the southwest during deposition of the layers on the North America plate. Plate flexure, sea level, and sedimentation rate changes are regional in effect, and one would expect them to be coherent over distance scales of 5 km. Yet those effects are not evident on the Pacific plate.

3.3. Line 1263

Line 1263 (Figure 11) shows mild, apparently inactive deformation of the Pacific plate west of the terrace. This line was shot at a low angle to the strike of the terrace and crosses the outer terrace fault imaged by line 1262 where it has plunged below the seafloor (CMP 2300–2500). In this area, which has undergone less deformation, the internal structure is more evident; a small anticline is curved up south of a fault. Dip moveout processing shows that it dips at an angle of at least 52° and that it cuts basement. Compression has tilted both sediments and basement as opposed to just thickening the sediments, indicating that basement is involved in the deformation. An angular unconformity is associated with the crest of this anticline. On either side of this structure, reflectors dip smoothly toward the terrace. Steep faults between CMPs 4300 and 4500 are also currently inactive.

3.4. Line 1250

Line 1250 (Figure 12) was collected across the terrace 30 km south of line 1262. The trough section shows layers similar to those seen in line 1262; although the lower layers are thicker, they still show unit B onlapping unit A. In the terrace a set of fault-bend folds is cut by nearly vertical faults. The geometry of these sediments suggests that a compressive fault has cut up through the sediments possibly on a set of ramps and flats [e.g., Shaw and Suppe, 1994], reaching the surface at the westernmost edge of the terrace. Subsequent tilting of the ramps suggests that later faulting was deeper, perhaps because the brittle layer thickened over time. Much of the recent sedimentation was deposited during formation of the folds since layering onlaps the fold crest (CMPs 3500–3650). The near-vertical faults could be the result of later strike-slip deformation.

On this line the plate boundary is visible, not as a distinct fault, but as an incoherent, apparently uplifted unit (CMPs 4900–5100). The lack of coherent reflection energy and weak returns from this region suggest that the sediments have been deformed enough to destroy original bedding, i.e., constitute a melange. This profile crossed a restraining bend in the QCF which is ~3 km wide and 30 km long. Northwest trending high-amplitude reflections in the GLORIA data lie between overlapping traces of the fault (Figure 2); they are most likely uplifted melange.

3.5. Line 1264

On line 1264 (Figure 13) the melange can be traced from line 1250 to line 1262, but it is not as extensive in the shallow section of line 1262 as in line 1250. The melange could have formed locally on the QCF or at the restraining bend and been dragged north 30 km. This would imply an age of 0.64 Ma for the top of melange in line 1262 using an along-strike velocity of 47 km/Myr. Folding of the sediments at the northernmost end

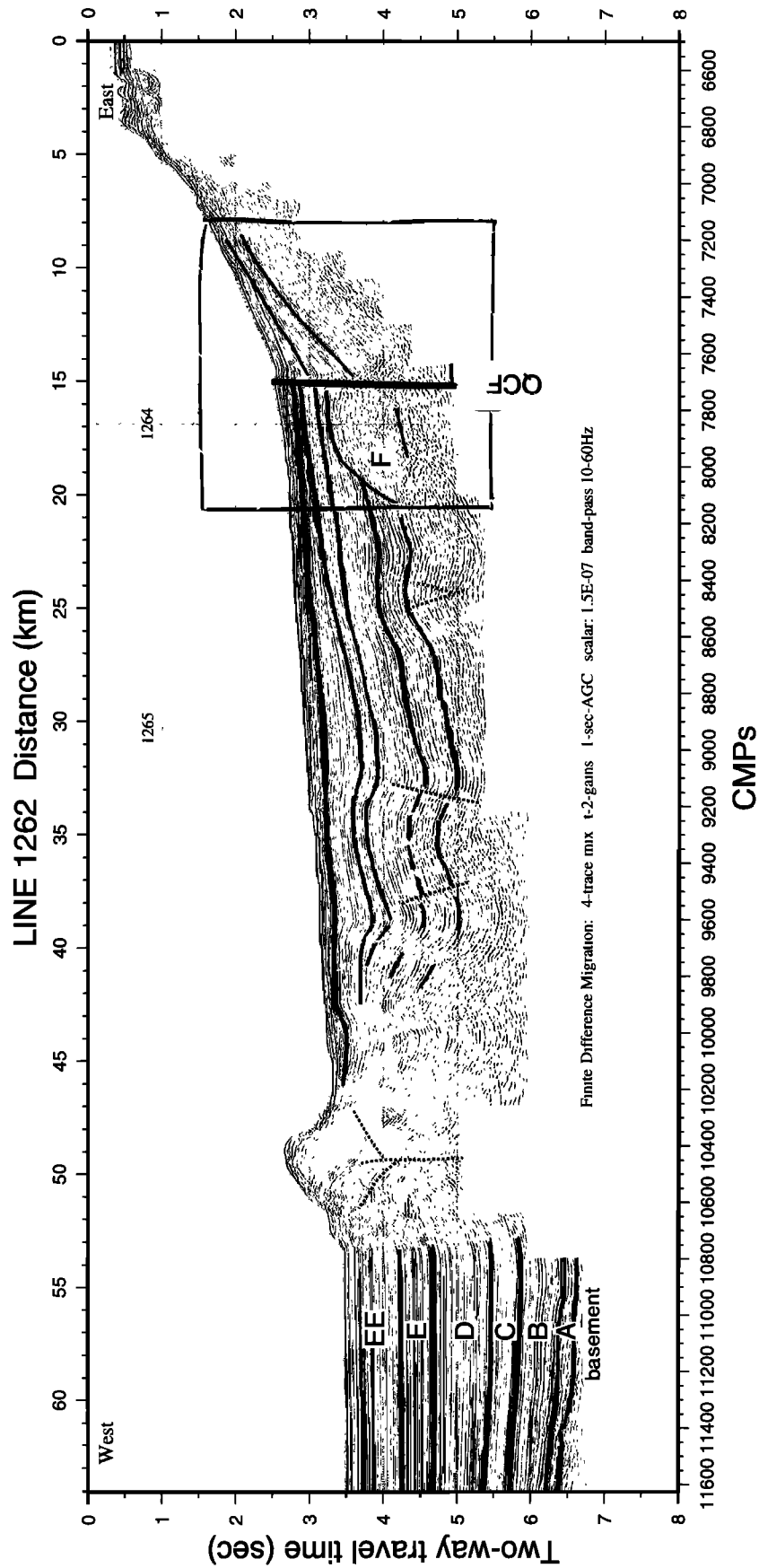


Figure 8. Line 1262, migrated and scaled with a 1000-ms automatic gain control (AGC) filter. This reflection profile crossed the QCF where the fault is a simple trace on the seafloor (see Figure 2). The terrace here is 45 km wide; a small ridge (approximate CMP 10500) separates undeformed abyssal plain sediments from folded sediments of the terrace. Box shows area displayed in Figure 9. Fine lines denote crossing with another seismic line.

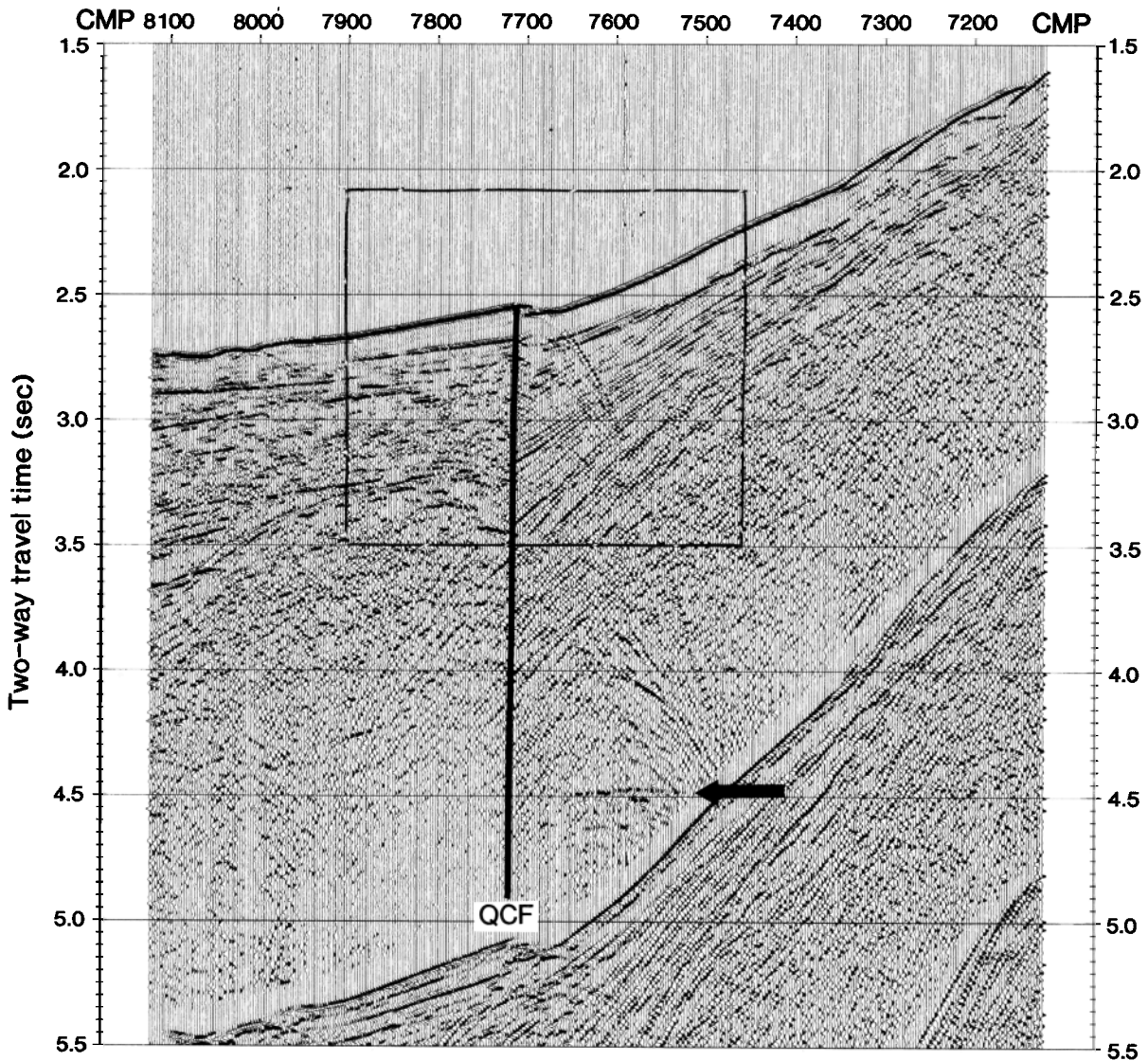


Figure 9. Detail of line 1262; sedimentary sections are quite different either side of the QCF. Note the deep reflector on North American plate at 4.5 s which does not continue across to Pacific plate. Section is displayed unmigrated so deeper events are not obscured by migration noise from the multiple. Data were scaled with a 200-ms AGC filter. Box shows area displayed in Figure 10.

of the line (CMPs 4800–5200) corresponds with westerly trending short lineations in the GLORIA data (Figure 2) and may be the counterpart to possible extension on line 1262.

4. Gravity Data

4.1. Data and Analysis

The free-air gravity signature around the Queen Charlotte Fault (Figure 14) is characterized by a large negative anomaly over the terrace and a large positive anomaly on the continental shelf. Gravity data were collected coincident with the seismic data and were modeled using GMSYS™. Since the profile is approximately perpendicular to the strike of the anomalies, a two-dimensional interpretation was assumed to be valid. Edge effects from the outer boundaries of the model were avoided by extending the model 30,000 km to the west and east. Water density was taken to be 1024 kg/m³. In the sediments (units A–H), density values were based on interval ve-

locities (Table 1) [Scheidhauer, 1997] using Gardener's rule [Telford *et al.*, 1994]. Thickness of the oceanic crust was assumed to be 7 km. Calculations included mantle to depths of 40 km, although only the upper 25 km are shown in Figure 15.

Gravity models were constructed for two different geometries of the plate boundary: transform and subduction (Figure 15). In the transform model, density values and structure are similar to those of Spence and Long [1995], which are based on a refraction study of the terrace [Dehler and Clowes, 1988] and a refraction study of the Queen Charlotte margin [Spence and Asudeh, 1993]. The subduction model used density values similar to those of Horn *et al.* [1984], which were based on their refraction study of the terrace and assumed values for density and thickness in North America. Without coincident refraction data, either set of values could be valid.

In both models, the negative gravity anomaly is largely created by the decreasing thickness of crust and concomitant increase in water thickness seen on any continental shelf. The

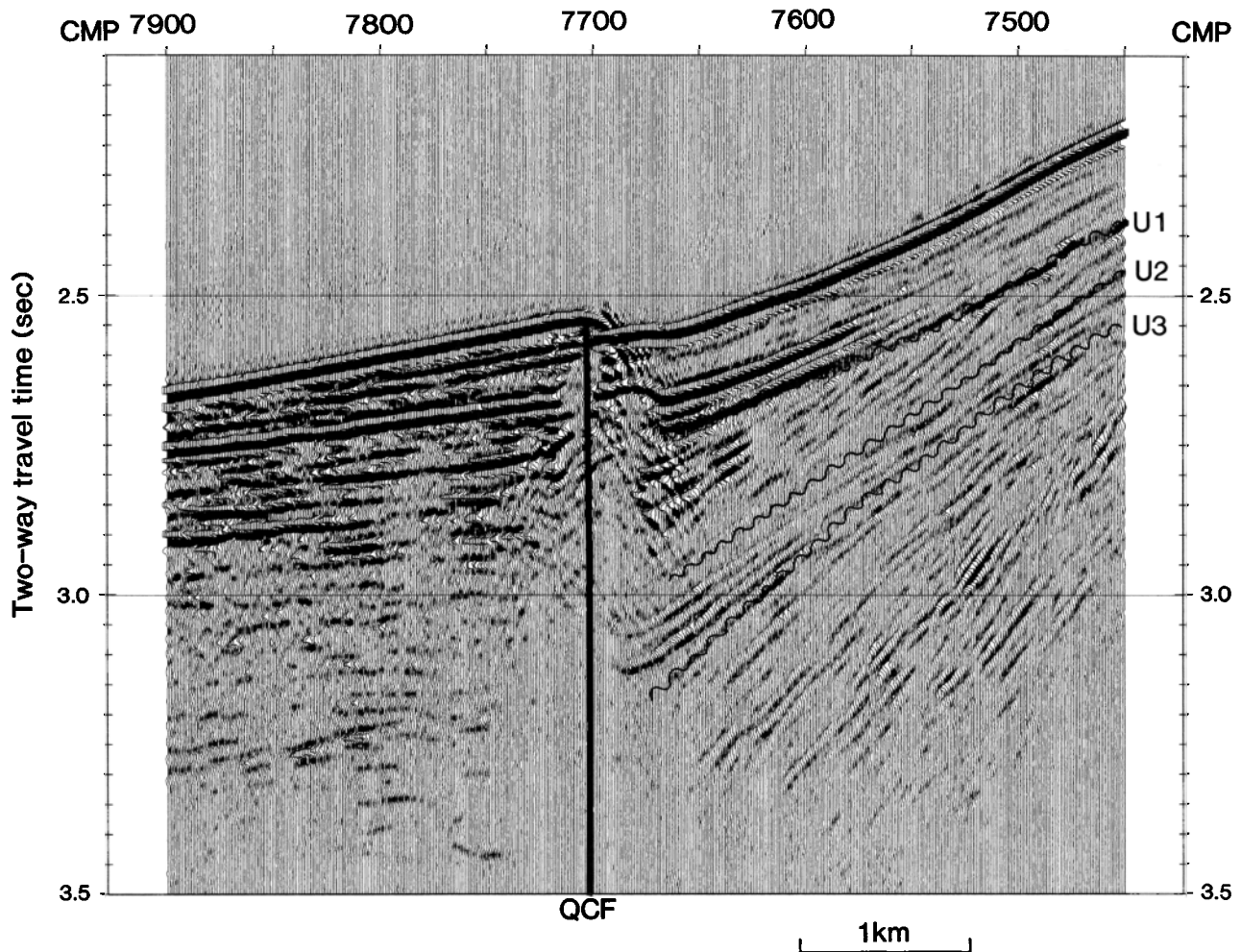


Figure 10. Detail of line 1262 migrated, no amplitude scaling. Sediments on the Pacific plate are subhorizontal, whereas sediments on the North American plate dip up to 20° and contain several unconformities. Wavy lines indicate unconformities.

short wavelength of the anomaly here is created by the abrupt transition from continental to oceanic crust. In the transform plate model the negative anomaly is augmented by decreased density of crust in the terrace. A model which has lower densities of (2720–2880 kg/m³) in the top 6 km of North America as modeled for the Queen Charlotte Islands [Spence and Long, 1995] requires thinning of up to 6 km in the North American crust within 40 km of the QCF in order to match the data.

In the subducted slab model the amplitude of the anomaly is largely created by low-density material above an intact oceanic slab. Assuming a uniform dip of the slab across the entire model resulted in a density of 2200 kg/m³ above the slab, which was considered to be unrealistically low [Scheidt, 1997]. In the geometry shown, density above the slab is 2550 kg/m³ west of the QCF and 2600 and 2750 kg/m³ east of the QCF. The gravity data were matched by merging the end of the slab smoothly with continental Moho.

A model with a sharp end to a slab 30 km east of the QCF created a 35-mGal positive discrepancy in predicted versus observed gravity values on the continental side. In all other respects the model was identical to that of Figure 15b. Lateral density changes in the crust could be invoked to compensate exactly for Moho topography.

4.2. Interpretation

Without independent data to constrain crustal densities or thicknesses the gravity data across Dixon Entrance cannot discriminate between the two plate boundary models. In both cases the QCF constitutes a boundary in density with higher densities to the east. Another common feature of both models is that crystalline crust under Dixon Entrance is similar in thickness (24 km) to crust in the rest of the basin [Spence and Asudeh, 1993; Lowe and Dehler, 1995] and thinner than crust under the islands.

Dip of the Moho under the terrace is only 7°–8°, considerably less than the 19°–20° dip interpreted for the terrace west of Moresby Island [Horn et al., 1984; Dehler and Clowes, 1988]. Oceanic crust profiled by line 1262 is about 3 km deeper than crust profiled by Dehler and Clowes and continental Moho is shallower by 3–4 km, resulting in less vertical topography to be accommodated by a broader terrace.

All previous models computed across the QCF and those presented here show smooth transitions in crustal thicknesses. Short-wavelength variations of Moho depth of the order of a kilometer or two are permissible in the models; a model with shallower Moho on the North American side can fit the data. Moho has been interpreted to be offset across other transform

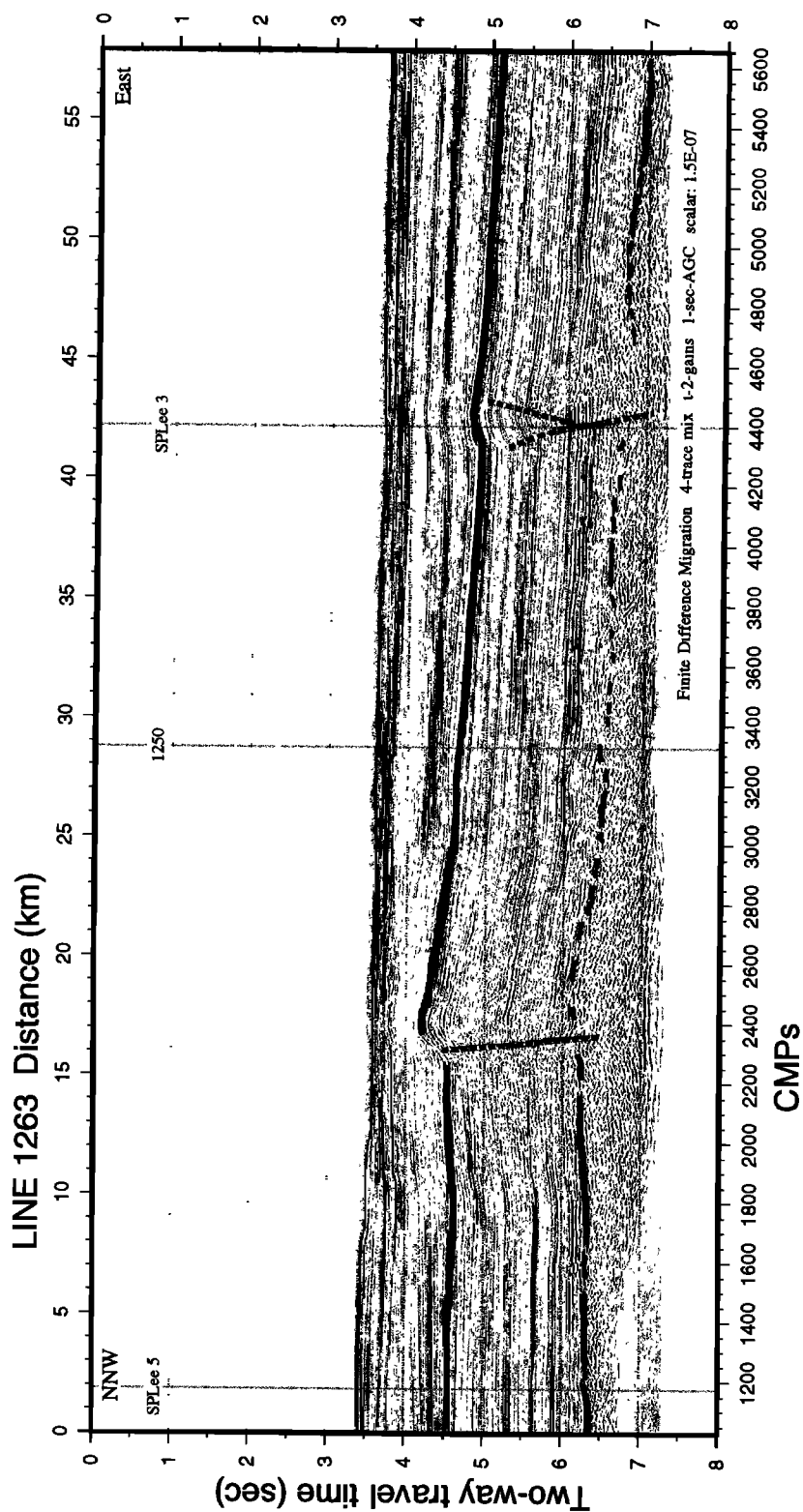


Figure 11. Line 1263, migrated and scaled with a 1000-ms AGC filter. The fault at CMP 2300 is along strike the outer terrace ridge of line 1262. A narrow fault zone is obvious; it offsets and tilts basement by a small amount. Fine lines denote crossing with another seismic line; seismic lines SPLee5 and SPLee3 are as presented by Scheidhauer *et al.* [1999].

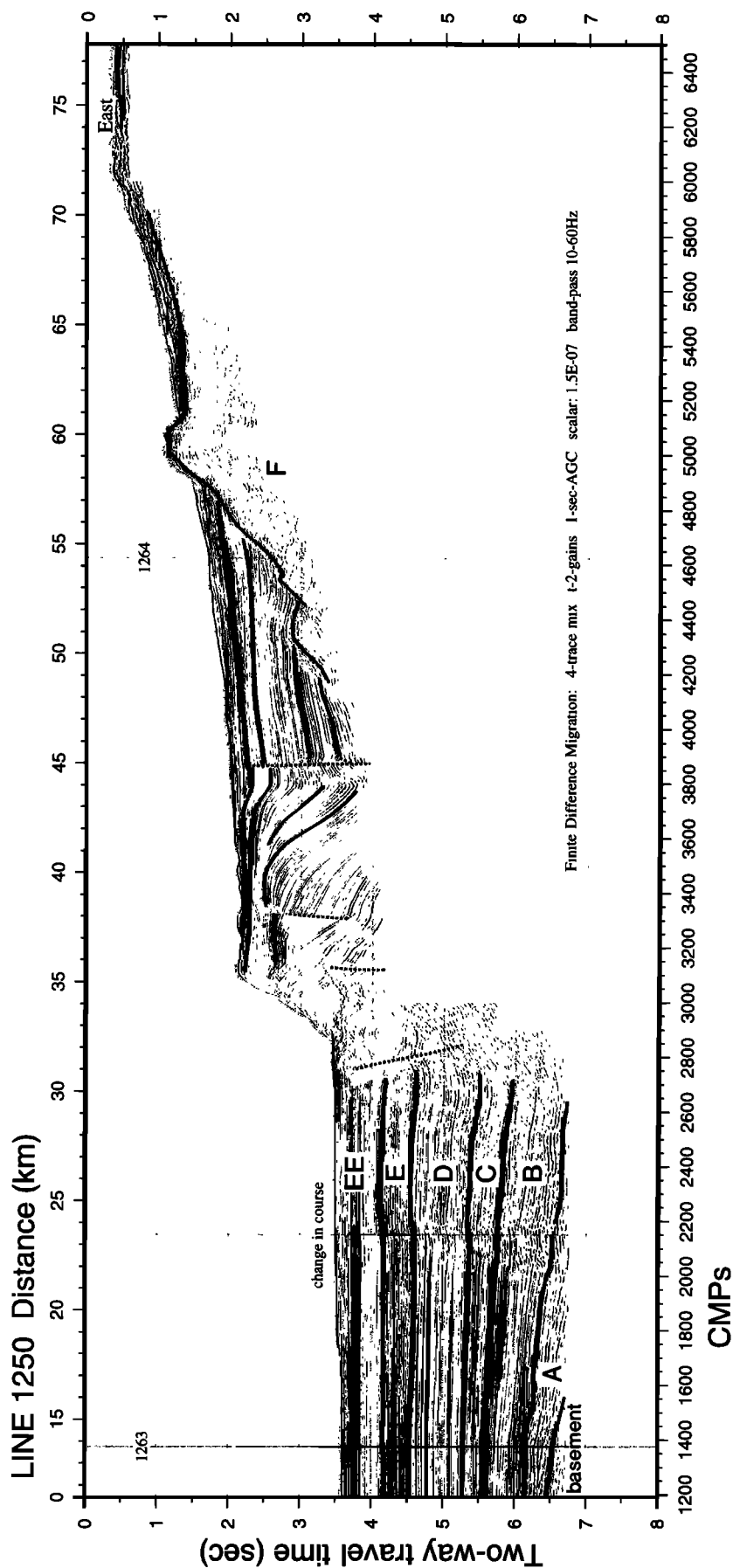


Figure 12. Line 1250, migrated and scaled with a 1000-ms AGC filter. A steep deformed zone defines the outer edge of the terrace. At this location the QCF steps to the west and changes strike, creating compression between the two strands of the fault (see Figure 2). A large melange (F) underlies the compressed sediments of the terrace and outcrops in a ridge at the seafloor.

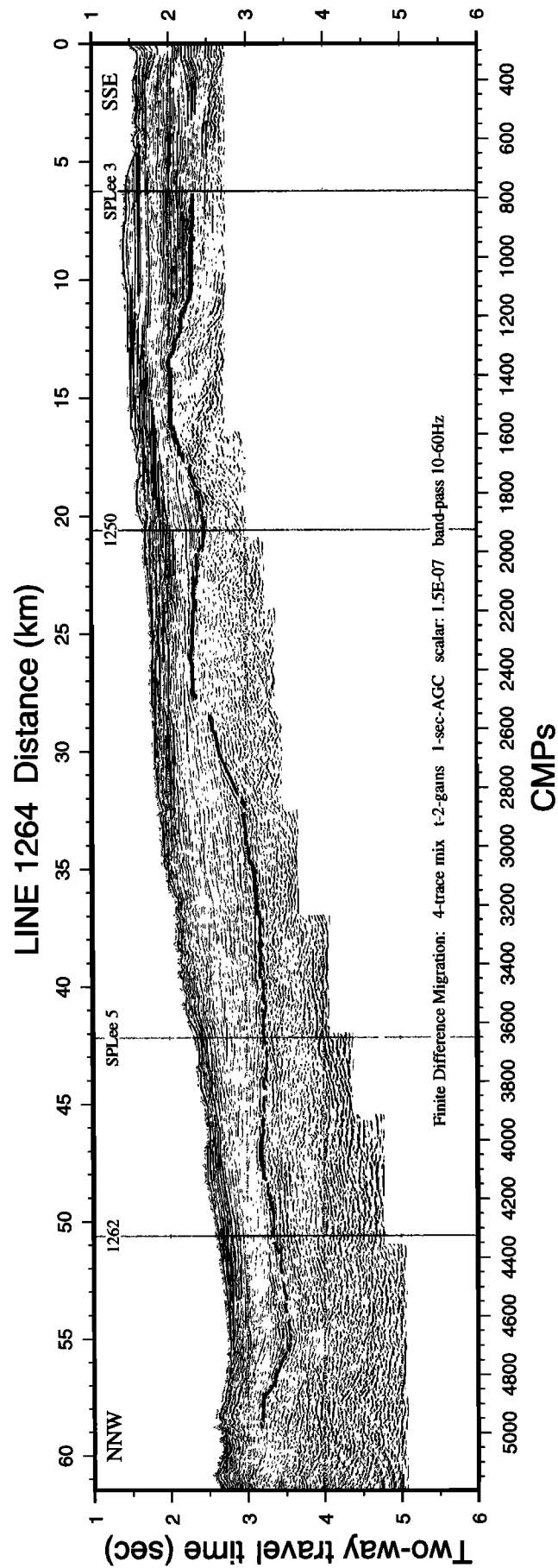


Figure 13. Line 1264, migrated and scaled with a 1000-ms AGC filter. A melange can be traced from the region of compression in line 1250 up to line 1262. Note folded sediments at the seafloor on northernmost section of line. Fine lines denote crossing with another seismic line; seismic lines SPLee5 and SPLee3 are as presented by *Scheidhauer et al.* [1999].

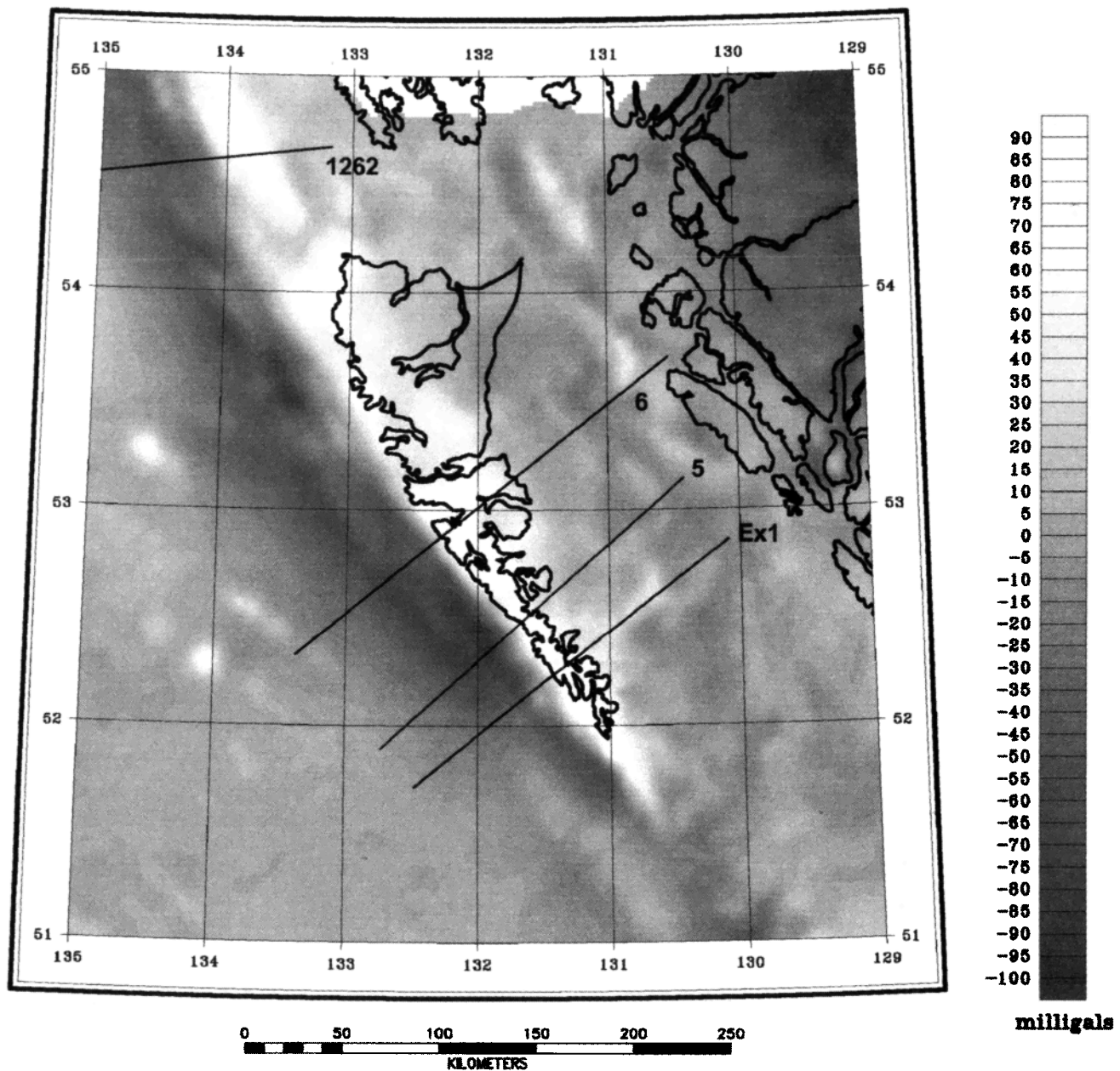


Figure 14. Free-air gravity anomaly data. A strong negative-positive anomaly pair coincides with the QCF; otherwise, the anomaly field is relatively smooth. In the basin most anomalies can be explained by known sediment thicknesses [Lowe and Dehler, 1995]. Seismic profiles modeled in other studies and here are marked: line EX1 [Horn *et al.*, 1984]; lines 5 and 6 (Figure 4) [Spence and Long, 1995] and line 1262.

plate boundaries, namely, the northern San Andreas Fault [Henstock *et al.*, 1997] and the Alpine Fault [Stern and McBride, 1998]. Kilometers of relief on the Moho caused by a subducted slab would create a significant increase in the gravity field, unless its anomaly is exactly offset by lateral density changes in the continental crust. That kind of coincidence along 400 km of plate boundary seems implausible. Therefore it seems most likely that if an oceanic slab exists east of the QCF, it cannot create more than a few kilometers of topography on the Moho.

4.3. Isostasy

Immediately adjacent to the QCF, both plates are out of local isostatic equilibrium. Isostasy was calculated to a depth of 40 km at 20-km intervals along both models for lines 1262, EX1

[Horn *et al.*, 1984], 5, and 6 [Spence and Long, 1995] (Figure 16). Isostatic anomalies were calculated relative to a reference column which was 90 km east of the QCF for models 6, 1262s (the subduction model of 1262), and EX1. Calculations for models 5 and 1262t (the analogous transform model of line 1262) used the same reference value as model 6. The location of the reference column is an arbitrary choice based on the length of the modeled profiles. Both plates are probably flexed to some small degree over distances of several hundred kilometers either side of the plate boundary [e.g., Harris and Chapman, 1994].

A consistent pattern between the models computed by three different studies allows some generalizations to be made. The

Table 1. Densities Used for Sediments in Gravity Models

Unit	Interval Velocity, m/s	Density, kg/m ³
AB	4700	2500
CD	3300	2300
E	2100	2100
F	4880	2550
G	3960	2450
H	2300	2150
III		2700

From Scheidhauer [1997]

magnitude of the peak to trough values on these profiles is similar: 3.4%, 2.2%, 3.6%, 2.9%, and 5.1% from south to north. The positive deviation on North America indicates more mass, and the negative deviation over the Pacific plate indicates less mass than the reference column. The isostatic anomaly over the Pacific plate becomes wider from south to north,

as one would expect for constant force along strike flexing an oceanic plate which is aging and increasing in strength along strike. Thickness of the brittle region grows from ~13 to 20 km (see below) over the length of the QCF. EX1 was shot across the southernmost portion of the terrace and coincides with an area with no bathymetric trough. Its profile has <20 km width of negative values, all of which are directly under the terrace. The isostatic anomalies under the Queen Charlotte Islands are of similar widths, implying that the North American plate does not significantly change mechanical properties along strike, assuming a constant force along strike. This rules out the possibility that the Queen Charlotte Islands are created purely by flexural forces. If they were, they would have the same width along strike instead of widening to the north. The isostatic profile of the transform model 1262t is interesting in that it seems to imply that most of Dixon Entrance is out of isostatic equilibrium. The isostatic profile of the subduction model 1262s, however, is similar to that of profile EX1, which is the basis for its density values.

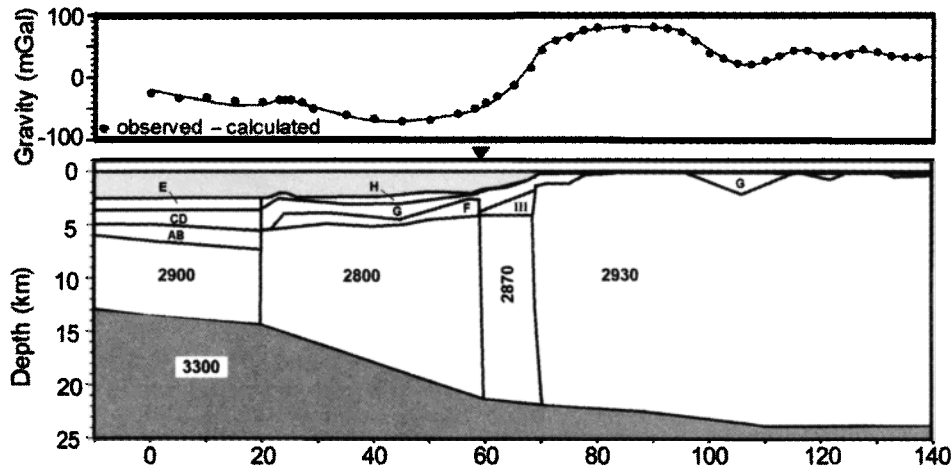
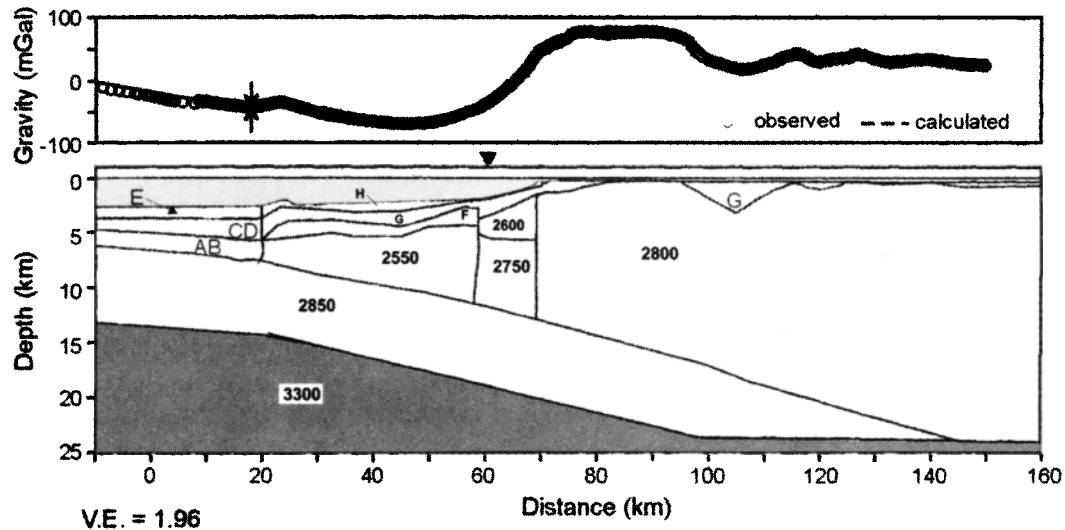
A. 1262t**B. 1262s**

Figure 15. Gravity models for line 1262. (a) Transform plate boundary using densities similar to those of Spence and Long [1995] (Figure 4). (b) Subducted slab. Densities in the terrace are based on refraction data and assumed for the continent [Horn et al., 1984]. Densities for units A–H are listed in Table 1.

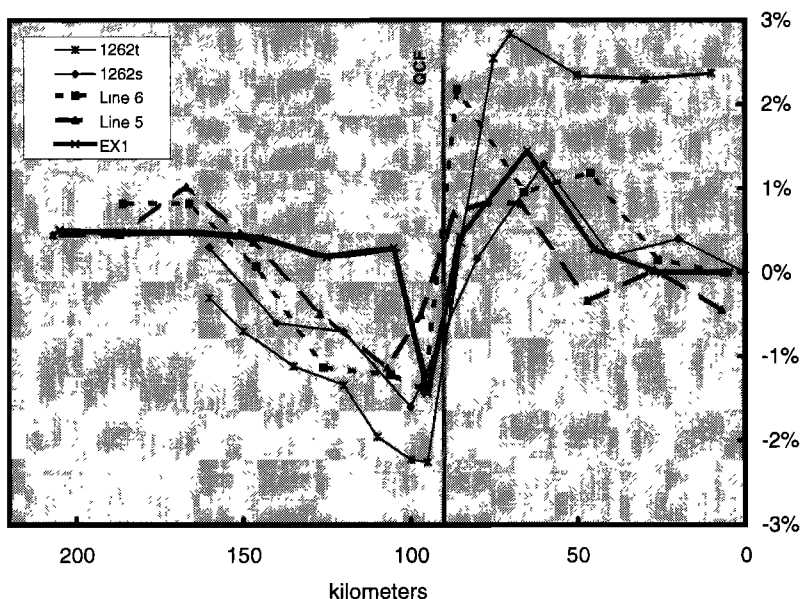


Figure 16. Isostatic anomalies were calculated relative to a column 90 km east of the QCF based on gravity models of lines EX1 [Horn *et al.*, 1984], 5, 6 [Spence and Long, 1995], and 1262. Model 1262s refers to a subduction geometry for the plate boundary and model 1262t refers to a transform geometry, as in Figure 15. The negative values west of the QCF indicate a mass deficit in the Pacific plate, and the positive values east of the QCF indicate a mass excess.

5. Model of Accommodation of Transpression

A better understanding of regional deformation as well as a number of data sets acquired in the last few years suggest that the QCF is a vertical throughgoing plate boundary which separates two elastically independent plates (Figure 17). Placing the initiation of transpression just north of the Tuzo Wilson Seamounts results in <80 km of predicted net plate overlap between 52°N and 54°N in the last 5–8 Myr. Each of the plates absorbs transpression independently; brittle compressive and strike-slip deformation are observed in both plates. The three-dimensional interactions of the plate boundary and the relative motion vector results in North America absorbing more compression than the Pacific plate. By implication the ductile portions of each plate thicken and/or are deflected downward into the asthenosphere to accommodate transpression.

5.1. Vertical Fault

Seismicity recorded by OBSs indicates that the QCF is a vertical fault which cuts down to Moho at 21 km [Hyndman and Ellis, 1981; Horn *et al.*, 1984]. A magnitude 8.1 earthquake on the QCF was a pure strike-slip event; no compression was accommodated during the event. Studies of microseismicity also show high levels of activity on the QCF in a vertical zone [Bird, 1997]. The combination of the flexural study of the Pacific plate [Prims *et al.*, 1997] and regional rapid sea level changes during glaciation [Barrie *et al.*, 1991] further indicate that the two plates are elastically independent. In other words, the QCF is a clean break between the plates, and there is no underthrusting of the Pacific plate under the North American plate.

The QCF has a long history of strike-slip motion; the fact that much of it is still parallel to the direction of relative plate motion between 40 and 8 Ma (320°) off Moresby Island [Rohr and Currie, 1997] implies a continuous history of the fault, as

well as resistance to changing the plate boundary. When the plate directions began to change to transpression, the QCF continued to accommodate strike-slip motion (43–46.6 km/Myr). Since the plates on either side of the fault are warm and thin, compression (6–20 km/Myr) was more easily accommodated within each plate rather than forcing the oceanic plate into the continental plate in a subduction zone geometry.

5.2. Mechanical Structure and Deformation

From the Tuzo Wilson Seamounts to Alaska the two plates are similar in mechanical properties, and they are both deforming internally. Both plates are mafic so there is no strength discontinuity at the mantle; the depth to the brittle-ductile transition is a key feature in mafic plates. Microseismicity [Bird, 1997] shows that the brittle-ductile transition (the depth above which 90% of the events occur [Sibson, 1982]) begins between 16 and 20 km depth under Graham Island and northern Hecate Strait. For the rest of the region we use thermal models and heat flow data to assess the depth to the brittle-ductile transition. Whether that transition begins at 650°C or 750°C in mafic plates is not strictly known, but the high heat flow in both plates means that the vertical separation between the 650°C and 750°C isotherms is only ~3 km. We will arbitrarily use the number 700°C since the relative differences between the two plates is more important than pegging the transition to the nearest kilometer.

Heat flow values average 70 mW/m² in the Queen Charlotte Islands and northern Hecate Strait, indicating a depth of 22 km to the 700°C isotherm [T. J. Lewis *et al.*, 1991]. Values of 87–112 mW/m² which have been measured in Hecate Strait [T. J. Lewis *et al.*, 1991] indicate a depth to the 700°C isotherm of 17–21 km again assuming a linear gradient. In North America, depths to the brittle-ductile transition predicted from heat flow data are in broad agreement with the 16–20 km depths inferred from microseismicity.

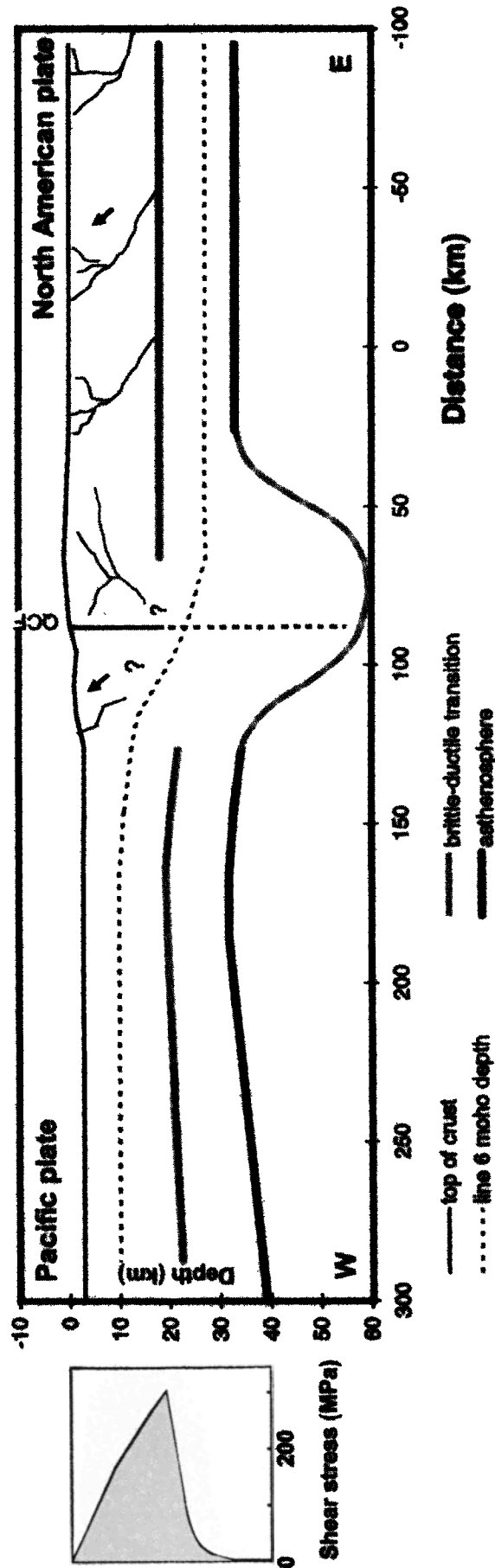


Figure 17. Schematic cross section of new model of lithospheric interaction between the Pacific and North American plates midway across Queen Charlotte Islands. No vertical exaggeration. The QCF accommodates strike-slip motion, while the compressive component of motion and some strike-slip motion are accommodated within each plate. Crustal thicknesses are consistent with those on line 6; as discussed in text, variations occur along strike. The Pacific plate is older to the west and is shown thickening slightly with age (on the left). Note that for oceanic crust (10 Ma shown in this cross section) the brittle-ductile transition (700°C) occurs at a similar depth to the current brittle-ductile transition in northern Graham Island and Hecate Strait. The depth to the asthenosphere is considered to be the depth of the 1300°C isotherm and was taken from *Chen and Morgan* [1990] for the oceanic plate and extrapolated from the thermal data for the continental plate assuming a linear thermal gradient. Shear stress versus depth for a 10 Ma oceanic plate is shown on the extreme left [after *Chen*, 1988]. The shear stress profile of North America would be similar to this since it is dominantly mafic in composition and has a similar thermal structure. Brittle deformation is observed in each plate. In the Pacific plate the terrace is created by compressive deformation of the oceanic plate. In North America, Miocene extension faults are inverted (fine lines denote flower structures), and crustal thickening creates the Queen Charlotte Islands. Strike-slip faults cut compressive structures in both plates. Ductile thickening of the lower plate is inferred to occur. Note that the Queen Charlotte Islands are deforming compressively in a direction perpendicular to the page.

A thermal model of young oceanic plates [Chen and Morgan, 1990] shows that the depth of the 700°C isotherm changes from 13 to 20 km depth in the Pacific plate as it ages along the QCF. The youngest oceanic plate is warmer than North America, but simple thermal models indicate that the mechanical structure of both plates is broadly similar. There is no reason to suppose that one plate would deform exclusively leaving the other untouched.

When transpression began, the Queen Charlotte basin would have been warmer than it is now and the brittle-ductile transition would have been closer to that of the youngest oceanic plate along the QCF. As deformation proceeded, the thermal field would be disturbed; bulk strain heating might be important in highly deformed regions. Motion on the fault might be an additional important source of heat tens of kilometers from the fault itself [Chen, 1988]. Nevertheless, the generalization that the two plates have similar mechanical behavior is supported by current observations.

Transform plate boundaries have been imaged as near vertical zones of lowered velocities in reflection and refraction experiments as summarized by Stern and McBride [1998] and Detrick et al. [1993]. Fault gouge and enhanced pore pressures are thought to occupy regions 5–10 km wide and up to 10–20 km deep. Experiments show that once formed such a region tends to carry most of the ongoing strike-slip deformation [e.g., Wilcox et al., 1973]. Some deformation can be distributed within the plates especially in relatively weak plates, as here, and/or when the relative plate motions change. Nevertheless, a magnitude 8.1 strike-slip event is more likely to occur on the main fault strand than at some random location within either plate.

5.2.1. Deformation adjacent to the QCF. Structures on the QCF vary from subsidence in North America (line 1262) to folding on the Pacific plate just 10 km to the north (line 1264). Rapid subsidence east of the QCF on line 1262 may indicate that extension is occurring. Thinner crust under the subsiding portion of line 1262 is one of several models which can fit the gravity data. Although apparently contradictory to the regional stress regime, extension could occur with counterclockwise rotation of a segment of North America between two right-lateral faults. Rotation simultaneously creates regions of local extension and compression. The east-west oriented folds crossed by line 1264 are in the right location to be the compressional counterpart to the apparent extension; folds farther west in the terrace are oriented northwesterly. Shearing must be distributed into the North American plate and is not carried solely by the QCF; any one of the northwesterly Miocene extensional faults in Dixon Entrance could be active, although little seismicity has been detected on them in the last 50 years.

An alternate explanation for the subsidence observed east of the QCF on line 1262 is that it is caused by flexure and does not entail plate thinning. The apex of the uplift in North America is 20 km east of the QCF on the continental shelf which would create a westward dip on the plate under the slope. However, the magnitude of the dip seems too large for this process and such dips have not been observed on the available seismic reflection profiles.

5.2.2. Brittle deformation: Pacific plate. The Pacific plate is being deformed and duplexed in the terrace. Reflection profiles across the terrace image folded and compressed sediments which are presumably riding a substrate of compressed basement; line 1263 shows that the outer terrace fault cuts upper basement. This study and several others [Horn et al.,

1984; Dehler and Clowes, 1988; Spence and Long, 1995] interpreted crustal velocity and density material (>5.3 km/s and 2800 kg/m³) 3–4 km below the terrace seafloor for total thicknesses of 5.5–15 km. These values are interpreted as arising from highly deformed crystalline material. Volumetrically there is room for ~30 km of 5.5-km-thick gabbroic oceanic crust to be incorporated into the terrace along line 1262, 20 km on lines 5 and 6, and 9 km on EX1. A simple two-component system of 25% sediments (2500 kg/m³) and 75% oceanic crust (2900 kg/m³) can produce the modeled density of 2800 kg/m³. Oceanic crust or mantle altered to serpentinite (2550 – 2600 kg/m³) could also be a constituent of the terrace. If 75% of the volume of the deepest layer in the terrace is oceanic crust, then 6–20 km of compression could be accommodated by duplexing. Because the mechanical properties of the oceanic plate vary along strike, the amount of compression absorbed within the plate may not be linearly correlated with the amount of predicted overlap.

5.2.3. Brittle deformation: North America. The rest of the compression must be accommodated within the continental plate. The amount varies gradually along strike from 0 to 60 km. Early interpretations concluded that little deformation of North America occurred in the Pliocene [Horn et al., 1984], but images of folding and uplift of the basins under Hecate Strait give direct evidence of widespread Pliocene deformation (Figure 6), and microseismicity provides ample evidence of recent deformation in Graham Island. Evidence discussed below suggests that the compression is oriented north-south and is pervasive within the islands. The islands, then, are the result of crustal thickening and uplift during transpression. Possible mechanisms responsible for the deformation are also discussed.

Complex and multistage compressive deformation affects many of the Miocene basins inboard of the Queen Charlotte Islands but not Queen Charlotte Sound [Rohr and Dietrich, 1992] (Figure 6). In most cases, the sense of motion on normal faults has been inverted to create uplift. The intensity of deformation increases toward the islands. There are several kilometers of vertical relief between basement rocks exposed on Moresby Island and basement rocks imaged under western Hecate Strait, a distance of only 20 km, indicating that a major structure is probably responsible for this relief.

Two-dimensional line length calculations can estimate the amount of compression absorbed in the basin but must be used with caution because the structures vary significantly in all three dimensions, coverage of the region is sparse, and the lines are not oriented optimally with respect to each structure. In addition, there were difficulties in correlating reflections across strike-slip faults and basement highs; strike-slip motion renders the two-dimensional assumption invalid. Nevertheless, line length compression was computed for the Miocene/Pliocene reflector as a rough indication of the amount of compression. Two kilometers of shortening were accommodated along 63 km of line 5 (3%), 7–9 km of shortening along 118 km of line 4 (6–7%), and 9 km of shortening along 70 km of line 7 (13%). These estimates do not include compression, which is evident immediately prior to deposition of the reflector or compression taken up in basement structures which the reflector does not overlie. Line 5 is roughly perpendicular to the QCF, and lines 4 and 7 are subparallel to the QCF. Higher percentages of shortening are evident in the direction of maximum compressive stress (north-south) predicted in a north-west shear stress regime.

The amount of recent deformation in the islands is hard to

estimate because few Neogene rocks are exposed on Moresby Island and exposure of rocks on Graham Island is only 3% [Hickson, 1991]. Steep Tertiary block faults are common, but sense and age of motion on the faults are difficult to quantify [e.g., Thompson *et al.*, 1991; P. D. Lewis *et al.*, 1991]. Vigorous microearthquake activity in northern Graham Island indicates that present-day deformation is occurring.

The shape of the islands suggests that they were formed by the northward push of transpression and consequent brittle and/or ductile thickening of the crust over the last 5–8 Myr. Their western edge is determined by the QCF, and the eastern edge is subparallel to the current relative plate motion vector. Their northern edge runs east-west which is the predicted strike direction of compressive structures in a northwestern directed shear stress regime. The shape of the islands is also coincident with the net predicted overlap. If simple underthrusting was occurring, the region of uplift should continue north into Dixon Entrance instead of terminating in an east-west edge which is seismically active. Shallow sediments just north of Graham Island are not compressively deformed [Rohr and Dietrich, 1992]. The coincidence of seismic activity and the coastline indicates that the deformation creating the seismic activity has been active for some time and has uplifted the Miocene basalts and sediments which comprise Graham Island.

If the Queen Charlotte Islands were an intact fault-bound block [Rohr and Dietrich, 1992] which has been squeezed upward and northward between the QCF and a fault which splays off the QCF, then pervasive earthquake activity under the islands' eastern and northern shores should be occurring. The splay could be blind but approach the surface near the eastern shore of the islands creating the structural relief between the islands and the basin. The Louscoune Inlet and Sandspit Faults are subparallel to the eastern shore of the islands, but mapping has not identified evidence for recent motion on these faults [P. D. Lewis *et al.*, 1991]. If 50 years of earthquake recording is representative of long-term deformation, then the idea of an intact block is not viable because little microearthquake activity occurs on the east coast of the islands [Berube *et al.*, 1989; Bird, 1997].

North American crust adjacent to the QCF may have been quite thin and been pervasively and progressively thickened during the Pliocene on compressive or flower structures which are blind. Compressional flower structures can consist of many faults which flatten toward the surface but do not necessarily break the surface. Such structures have the potential to create regional tilting and crustal thickening with few visible surface faults. Microseismicity suggests that current deformation occurs on pervasive faults from 3 to 20 km depth; mechanisms can be oblique, extensional, thrust, or strike-slip, but pressure axes are generally consistent with the north-northeast compression direction which occurs in a north-northwest shear [Bird, 1997]. No surface faults on Graham Island which might be caused by microearthquakes have been reported [Hickson, 1991], but the exposure of the surficial geology above the seismogenic region is only 3%. In Hecate Strait the largest strike-slip event ($M = 5.3$) is associated with a strike-slip fault which cuts folded Miocene sediments (Figure 6c).

Evidence that North American crust adjacent to the QCF may have been quite thin can be found in a reflection/refraction profile that runs just south of Moresby Island and the Tuzo Wilson Seamounts, line 3. The sedimentary basins show no compressive deformation [Rohr and Dietrich, 1992], and crystalline crust thins seaward from 23 km under Queen

Charlotte Sound to 7 km over a distance of 75 km [Spence and Long, 1995]. If such crust were present along the QCF at the onset of transpression, it would easily deform and could have absorbed significant compression to reach the islands' current thickness of 27 km.

Compressional deformation active over periods of time has a tendency to expand laterally [e.g., Masek and Duncan, 1998]; new faults and folds carry deformation out from the region of maximum uplift. The apparent greater uplift of the southern islands suggests that deformation of North America began in Moresby Island and progressed northward creating Graham Island. This mechanism explains vigorous seismic activity in northern Graham Island and Hecate Strait and relative quiescence elsewhere.

Paleomagnetic data indicate that mid-Tertiary dikes in the Queen Charlotte Islands have been tilted down to the north 9° – 16° (and allow tens of kilometers or even 100 km of northward motion of the islands since the dikes formed (13–54 Ma). As noted by Prims *et al.* [1997], the direction of tilt coincides with the current plates' relative motion. More recent work (E. Irving, personal communication, 1999) reveals that locations just north of the seismogenic zone in Graham Island are not tilted. This substantiates our idea that the seismogenic zone is a deformation front advancing northward. Irving *et al.* [1992] interpreted the tilting to occur on pervasive east-west Miocene extensional faults; in one location, such faults have been mapped but not dated [Lewis, 1991]. Nor has the tilting been independently dated. The amount of tilting is sufficiently uniform that it must occur on numerous faults; otherwise, very deep rocks would be exposed along strike. This uniformity is at odds with the variety of focal mechanisms and fault planes interpreted by Bird [1997] but could be explained if, over the long term, reverse or one-sided flower structures dominated deformation.

Compression may also be accommodated within the Coast Mountains which border the basin on the east. Inboard of Queen Charlotte Sound and northern Vancouver Island, single-crystal fission track data detected an acceleration of uplift rates in the Coast Mountains after 5 Ma [O'Sullivan and Parrish, 1995]. No compressive deformation is observed in Queen Charlotte Sound, but GPS data indicate that northern Vancouver Island is moving at a rate of about 3 mm/yr to the northwest [Dragert and Hyndman, 1995; Henton *et al.*, 1998], implying that a small amount of Pacific-North American relative plate motion is distributed across the margin here. Uplift of the mountains in response to compression is easily understood if the mountains are a weak and warm zone as discussed by Rohr and Currie [1997]. This style of deformation might be occurring inboard of Hecate Strait; single-crystal fission track measurements could easily test this idea.

5.2.4. Ductile deformation. Intraplate compression is probably accommodated by flow and thickening within the ductile portions of the plates. The biggest difference between the two plates mechanically is that the ductile region consists purely of mantle material in the Pacific plate but includes some crust in North America. Thickening of the crustal ductile portion under the islands could result in some uplift, whereas thickening of the denser mantle ductile portion will tend to cause subsidence.

In Figure 17 we have schematically drawn the deformation of the ductile portions of the plates as occurring mostly in North America based on the inference that most of the brittle deformation occurs within North America. We have no direct

measurements to indicate that such thickening is occurring or how that deformation is arranged at depth; seismic measurements of plate thickness could test the idea. If an asymmetry arises such that one plate is deeper than another, it might initiate a subduction-type geometry.

5.3. Plate Flexure

5.3.1. Pacific plate. Flexure of the Pacific plate does not begin until 90 km north of the inception of the QCF. Modeling by *Prims et al.* [1997] showed that the load of the terrace is more than sufficient to cause the degree of flexure observed further north in the Pacific plate (Figure 5). Densities used to load the terrace above assumed basement were lower than those found in gravity models; increasing them above 2000 kg/m³ increased the predicted downward flexure to unrealistic values. Using a density of 2800 kg/m³ in the terrace to create a load of similar mass indicates that a smaller volume of the terrace (~70%) is loading the plate. This in turn implies that the plate is broken west of the QCF, probably by the fault system which defines the outer edge of the terrace.

5.3.2. North American plate. The relatively consistent pattern of isostatic anomalies associated with the Queen Charlotte Islands on the North American plate shows that the plate is flexed upward along the QCF and, assuming that the forces along the fault are relatively uniform, that the plate has relatively constant mechanical properties along the QCF. The profiles crossed the fault where predicted amounts of convergence vary from ~20 to 50 km and where basement is above and below sea level. Some short-wavelength variations exist and may be related to the short-wavelength heterogeneities in plate thickness predicted by *Dehler et al.* [1997] and/or variations in the thermal field.

The lack of any unconformity in the upper sediments west of the QCF on line 1262 (Figure 10) argues that the Pacific plate did not experience the same flexural response to glacioeustatic loading that North America did. If the two sedimentary sections overly the same subducting slab which intrudes North America, then glacial loading of North America affects the slab dip and consequently the dip of all sediments deposited on it. This is readily seen east of the QCF. If there is no slab and North America is completely decoupled from Pacific by a vertical fault, then the Pacific plate would experience no flexure during glacial cycles. Glacial tilting in continental crust where the depth to the brittle-ductile transition is 30 km deep is typically 1 m/km [*Thorson*, 1989]. In thinner plates and if the QCF is free edge, then the amount of flexure may be significantly greater than this value. Loading of this margin by a glacier affords an interesting test of the mechanical nature of a transform plate boundary.

The possible positive flexure in Dixon Entrance indicated by the isostatic anomalies of profile 1262t is reinforced by the observation that crust of similar thickness in Hecate Strait has subsided and carries up to 1 km of postrift sediments. In Dixon Entrance, no such subsidence or postrift sequence is visible [*Rohr and Dietrich*, 1992]. Lateral heat loss during stretching may have cooled it enough that there was little postrift subsidence, or it could be actively held up by the compressive forces developed by the northern push of the Queen Charlotte Islands into the more competent Alexander terrane of the Alaska panhandle. Folding in the northern ends of the subbasins of Dixon Entrance corroborate the notion of significant north-south directed compression within North America [*Rohr and Dietrich*, 1992].

6. Discussion

The hypothesis favored in this paper is that the QCF is a vertical plate boundary and that transpression has been accommodated by significant deformation within both the oceanic and the continental plates. In this model the Queen Charlotte Islands are the direct result of pervasive transpressive deformation. Previous models have favored a geometry in which the oceanic plate is being subducted, the plate boundary switches between thrust and strike-slip geometries [*Hyndman and Ellis*, 1981; *Yorath and Hyndman*, 1983], and the islands are a coherent block. A model in which both plates were deformed has been presented by *Horn et al.* [1984] but was dismissed because evidence of deformation within North America was lacking at the time.

6.1. Comparison to Previous Models

A plate geometry similar to that found in zones of oblique subduction is at first glance a possible solution to the geometry of oblique transcurrent motion. In Sumatra, strike-slip motion is accommodated by a strike-slip fault in the upper plate 300 km east of the trench [*Fitch*, 1972]. The OBS survey of *Hyndman and Ellis* [1981], although short, did locate several earthquakes underneath the surface expression of the QCF and near Moho at depths of 18–21 km. Most event locations were within the OBS array and are probably reliable; a velocity model similar to that of a coincident refraction survey [*Horn et al.*, 1984] was used. No event mechanisms could be computed, but the overwhelming probability is that earthquakes under the QCF are the result of strike-slip motion on the QCF. If this is accepted as the most likely explanation, then a Sumatra-type model is not possible here. Flexure models and refraction data further argue against the existence of an undeformed subducting slab.

Previous models tended to assume that all deformation occurred close to the QCF. *Mackie et al.* [1989] considered the possibilities of distributed deformation in the islands but rejected this process because the crust is thinner than the global average. We prefer to take the perspective that crust under the islands is thicker than adjacent crust in the mildly compressed continental shelf. On the basis of regional structural trends, *Rohr and Dietrich* [1992] first proposed that distributed deformation from the plate boundary was an important process in Queen Charlotte Basin and that increased compressive deformation toward the northern end of the basin argued for a three-dimensional distribution of stress, not a simple two-dimensional orthogonal partitioning of compression. Compressive deformation of North America in the Pliocene was recognized by *Hyndman and Hamilton* [1993], but they considered the amount of compression absorbed by North America to be negligible.

The model, which proposes a subducting slab, includes a plate boundary which changes dip by 60° or more at some unspecified time interval [*Hyndman et al.*, 1982; *Yorath and Hyndman*, 1983]. Such changes would create large changes in the flexural response of the plates [*Prims et al.*, 1997] if they occurred on timescales longer than the viscoelastic time constant, a few hundred years. If the oceanic plate is only 10 km under North America, its surface under the terrace would be depressed by 6 km; unloading it by rupture along a strike-slip fault would release this depression. A process which involves cyclic loading and unloading should create a recognizable cyclic pattern of angular unconformities on the oceanic plate.

Two angular unconformities are recognizable in the seismic data; one appears to be associated with onset of flexural bending or heavy sedimentation beginning in the Pleistocene and another is associated with deformation on a fault defining the outer edge of the terrace. A cyclic pattern is not currently recognized. If the major fault plane switched dip at rates of less than a few hundred years, we would not necessarily expect to see a flexural response in either plate.

Creating a new transform boundary every so often through the entire Pacific plate seems mechanically inefficient and implausible. Laboratory experiments on rupturing new strike-slip faults in transpressive stress regimes [e.g., *Wilcox et al.*, 1973] show that the new faults form in small irregular to en echelon segments. The current surface expression of the QCF as seen in GLORIA data is of segments nearly 100 km long; the southern segments are parallel to the direction of the pre-Pliocene plates' relative motion [*Hyndman and Hamilton*, 1993; *Rohr and Currie*, 1997]. Thus the large-scale morphology of the QCF argues against this major fault being recreated down to 20 km every now and then.

The three-dimensional consequences of flipping plate boundaries by 60° have not been explored. The 1949 magnitude 8.1 event ruptured roughly 500 km of the Fairweather/QCF, but not the entire QCF, implying that segments of the fault would be out of synch with regard to transcurrent or subduction faulting. Geologic consequences of this phenomenon should be observable.

The structural and mechanical conditions of the plates existing at commencement of transpression are extremely important. A subduction zone with a well-developed slab which undergoes a change in relative motion to oblique underthrusting will probably retain its subduction geometry. Transcurrent faulting in the upper plate is a commonly observed mechanical solution to this stress regime. A transcurrent plate boundary, however, will not instantaneously transmogrify into a subduction zone because the relative motion vector changes gradually by 7°–25°. Initiation of subduction is not a trivial matter especially in young buoyant oceanic plates. The age of the Pacific plate adjacent to the Queen Charlotte Basin at 5 Ma was not significantly different than it is now. In the case of the QCF in which both plates adjacent to the fault are warm and weak, it seems logical that deformation within both of these plates will take up the compression, as is observed. Large amounts of net compression may well initiate subduction, but tens of kilometers do not seem to be large enough. If the brittle-ductile transition in North America was significantly shallower than it is now when transpression began, then it is conceivable that brittle Pacific plate may have intruded the North American ductile zone. Once started, that process would probably continue. However, current seismicity and flexural studies argue against there now being a subducted slab.

Refraction studies of the Queen Charlotte Basin mapped thinned continental crust and relatively flat Moho. Basement under the eastern portions of the islands is ~4 km thicker than under the basin; there was no direct evidence for a subducted slab of Pacific crust in the work of *Spence and Asudeh* [1993] and *Hole et al.* [1993]. In the roughly 30 km between the QCF and the westernmost limit of these studies the authors postulated that a subducted slab might exist, but it would have to dip at angles >20°–26°.

Gravity models across the QCF concur with refraction data that Moho is nearly flat under the islands. However, similar crustal densities in both plates means that gravity models pro-

vide no independent information on whether or not a subduction slab exists. Such a geometry is permissible if the slab merges smoothly with a flat continental Moho along all 400 km of the plate boundary; a vertical fault separating the two plates is equally permissible.

A plate boundary model in which a subduction slab takes up most of the compression predicts that the western side of the Queen Charlotte Islands is substantially uplifted and eroded [*Yorath and Hyndman*, 1983], deepening the level of exposure of crustal rocks to the west. This is not observed [*Thompson et al.*, 1991; *P. D. Lewis et al.*, 1991]; instead, the exposure deepens to the south. Coupled with the up-to-the-south paleomagnetic tilts and focal mechanisms showing north to northeasterly compression, the case for historical and present-day northerly compressive deformation of the islands is clear.

6.2. Strength of Plate Boundary and Seismicity

On many transform plate boundaries, deformation appears to be partitioned between pure strike-slip and pure compressive motion, indicating that the main fault itself is weak relative to the plate [*Mount and Suppe*, 1987]. In the Queen Charlotte region, fault mechanisms from the Pacific and North American plates have oblique slip as well as pure thrust, extension, and strike-slip motion. The evidence given above that the Queen Charlotte Islands are being pushed north into Dixon Entrance which is being pushed into the Alaska panhandle suggests that a simple two-dimensional partitioning of motion is not occurring in this portion of North America.

Seismicity can also indicate the relative strength of a fault. *Bird* [1997] has calculated that between 1951 and 1981 the moment release rate was about 4×10^{18} N m/yr. If seismicity takes up all of the relative plate motion, then the QCF from the Tuzo Wilson Seamounts to the Alaska border (400 km) has a shear modulus of 10 GPa for a 20-km-deep seismogenic zone, which is quite weak. If the shear modulus has values of 20–30 GPa, a value considered typical for hot mafic plates [*Kreemer et al.*, 1998], then the amount of strain accommodated by earthquakes is 30–50%. It may be that the difference between the strength of North America and the main fault zone is not great enough to produce strain partitioning.

The concept that strain partitioning (or lack thereof) is a unique indicator of fault strength may be oversimplified. Pre-existing geometry of the plate boundary and heterogeneities within the plates may override such effects during deformation. The fact that compression within Hecate Strait occurs most visibly by inversion of Miocene extensional faults indicates that preexisting structures have strongly influenced regional deformation.

The model proposed here argues that a “megathrust” event between underthrust oceanic and overriding continental plates as predicted by *Yorath and Hyndman* [1983] and modeled by *Smith et al.* [1998] is highly unlikely. The model proposed here can explain current seismicity in Graham Island and adjacent Hecate Strait as deformation which is propagating northward from the hinterland, Graham Island. To date, intraplate earthquakes are typically smaller than magnitude 5. It should be noted, however, that blind thrusts in the “big bend” of the San Andreas Fault system have produced earthquakes of magnitude 6.7 [*Southern California Earthquake Committee and U.S. Geological Survey Staff*, 1994].

6.3. Comparison to Other Regions

The Pacific-North America plate boundary to the south of the region that we considered lies entirely within younger, weaker oceanic material. Adjustment to the change in relative motions from 8 to 5 Ma has occurred by ridge migration, jumps, and, currently, deformation in a wide shear zone [Rohr and Furlong, 1995; Kreemer *et al.*, 1998]. To the north the amount of transpression is smaller; the terrace is less distinct [Bruns and Carlson, 1987], and there is little obvious deformation in North America [Gehrels *et al.*, 1987]. The Pacific plate is older and stronger, and in North America the crust changes from the Wrangell to the Alexander terrane, which did not experience the same degree of warming and extension in the Miocene [Gabrielse and Yorath, 1991].

Regions of transpression which are currently being studied with modern seismic techniques are New Zealand and California. Net compression along the central San Andreas Fault has been estimated to be 28–72 km, and all of it is thought to be accommodated by intraplate deformation on both sides of the San Andreas Fault [Crouch *et al.*, 1984] as well as delamination [Wallace, 1990], although the exact structures are not well known. Inversion structures similar to those in Hecate Strait are observed east of the San Andreas Fault in the Kettleman Hills and Coalinga Anticline [Namson and Davis, 1988]. In the Transverse Ranges a large high-velocity anomaly in the mantle [Humphreys *et al.*, 1984; Kohler, 1999] has been interpreted to be ductile continental plate bowed into the mantle by transpression. In New Zealand, interpretations have included the idea that a plate can be delaminated [Walcott, 1998]; its upper brittle part is peeled off and forced upward, while the lower section sinks under the adjacent plate. More recently, extensive seismic measurements show both extensive anisotropy [Klosko *et al.*, 1999] and a high-speed velocity anomaly in the mantle beneath New Zealand [Molnar *et al.*, 1999]. These results have been interpreted to indicate that the mantle is deforming in a wide shear zone and not in a subduction geometry. It should be noted that both regions are dominantly silicic in the crustal domain and the plate may have a layer of very weak crustal material above stronger mantle. This mechanical profile, as contrasted with the simpler profile of mafic plates would affect the plates' response to transpressive stresses.

Oceanic transforms are the most abundant examples of strike-slip interaction between mafic plates, but little is known about possible crustal thickening or uplift caused by transpressional forces. Transform ridges in long offset fracture zones can be 30–100 km wide, but uplift may also be caused by extensional forces [Pockalny *et al.*, 1996]. Local thickening under a transform ridge at the Clipperton Fracture Zone has been attributed to transpressional forces [Van Avendonk *et al.*, 1998; Pockalny *et al.*, 1997]. Krause *et al.* [1998] suggest that the 400-km-long Mendocino ridge formed by obduction during transpression in the last 19 Myr. Anomalously aged basalts testify to transfer of crust from one plate to another, although the exact nature of the structures which accommodate the transfer is unknown. Previous uplift of the ridge is shown by the presence of wave-worn cobbles on the crest of the ridge.

A significant difference between the Queen Charlotte region and an oceanic transform is that between spreading centers the plates age and change mechanical behavior along strike more quickly than in the example studied here. Plate being created at the ridge itself is expected to adjust instantaneously to

changes in relative plate motions [Pockalny *et al.*, 1997]; the adjacent very young plate will deform easily, and the oldest plate along the transform will be more resistant to deformation during transpression. The QCF strikes at a low angle to the trend of magnetic anomalies resulting in a slow change in plate age along strike, and the flexural anomalies of North America suggest that little change in mechanical behavior occurs along strike.

7. Conclusions

Transpression across the Pacific-North America plate boundary of western Canada is most likely accommodated by strike-slip motion along the QCF and both strike-slip and compressive deformation within each plate. The QCF is a long-lived transform plate boundary separating two warm mafic plates. The oceanic plate is 7–15 Myr old and North America consists of the mafic Wrangell terrane that was heated by Miocene extension. The brittle-ductile transition in both plates is currently between 13 and 21 km depth. The three-dimensional interaction of the plate boundary and the relative motion vector puts most of the deformation in North America. A small amount of transpression in the oceanic plate is accommodated within the terrace, an ~30-km-wide region of duplexed oceanic plate and folded sediments; lowered crustal velocities attest to the deformation of basement material. In North America, uplift and compression of Miocene extensional basins attest to distributed deformation. The portion of the plate lying in the region of predicted overlap east of the QCF is under northerly directed compression and its crust is being thickened to form the Queen Charlotte Islands.

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