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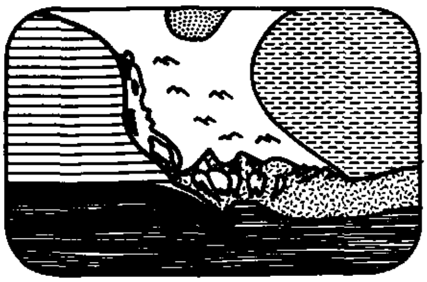

Canada's Active Western Margin - The Case for Subduction

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Summary
We review the evidence for subduction at the continental margin of south-western British Columbia and conclude that, although the pattern is complex and changing, south of 50°N convergence has continued to the present day.

Introduction
Some of the questions that most commonly arise in studies of the recent tectonics of south-western British Columbia are 'when and where has subduction taken place along the continental margin?' and 'is subduction still going on today?'. Being actively involved in both onshore and offshore studies of this region, we felt that it would be useful to review all the important data which bear on these questions. While admitting that our special interests have led us to emphasize particular aspects of the many fields of geology and geophysics relevant to the problem, the exercise has nevertheless considerably clarified our own ideas. It will, we hope, be similarly useful to others whether or not they agree with our conclusions that subduction has occurred and is still occurring.

The ocean floor off western Canada occupies a fundamental position in the development of the theory of plate tectonics. The magnetic anomaly maps of the NE. Pacific by Raff and Mason (1961) (Fig. 1) with their dramatic 'stripes', aroused much of the interest which culminated in the Vine and Matthews (1963) hypothesis that combined seafloor spreading with geomagnetic field reversals. The key publications of Wilson (1965), Vine and Wilson (1965) and Vine (1966) were again concerned with this area and established the presence and basic configuration of an active spreading ocean ridge system off the west coast of Vancouver Island. The theory of the geometrical movement of rigid lithospheric plates on a spherical earth (introduced as the 'paving stone' theory) was first proposed and tested by McKenzie and Parker (1967) using data from the N. Pacific and in the global extension of the theory by Morgan (1968) this region again played a major role. Morgan also concluded that a small block east of the Juan de Fuca ridge (the Juan de Fuca plate, Fig. 2) was moving independently of the main Pacific plate.

The possibility that the Juan de Fuca plate is now underthrusting North America was first suggested by McKenzie and Parker (1967). They noted that consumption of oceanic crust in the area of Washington and Oregon seemed necessary geometrically. This suggestion was reiterated by Tobin and Sykes (1968) in their study of the seismicity of the region and developed in detail by Silver (see 1971) and by Atwater (1970) who showed convergence as a consequence of the ridge and plate geometry of the region.

Nevertheless, the absence of a major bathymetric trench at the foot of the continental slope, the absence of a clearly defined eastward dipping Benioff earthquake zone and the apparently quiescent state of present volcanism have all contributed toward a widespread uncertainty as to whether subduction is currently taking place (e.g., Crosson, 1972; Srivastava, 1973; Stacey, 1973). Past subduction, from several tens of m.y. ago until at least one or two m.y. ago, is more generally accepted and it seems to us that the case for contemporary subduction, in a large part, must be argued upon a continuation into the present of the processes shown to be active in the recent geological past.

In this article we attempt to treat systematically each of the main sources of information on whether or not

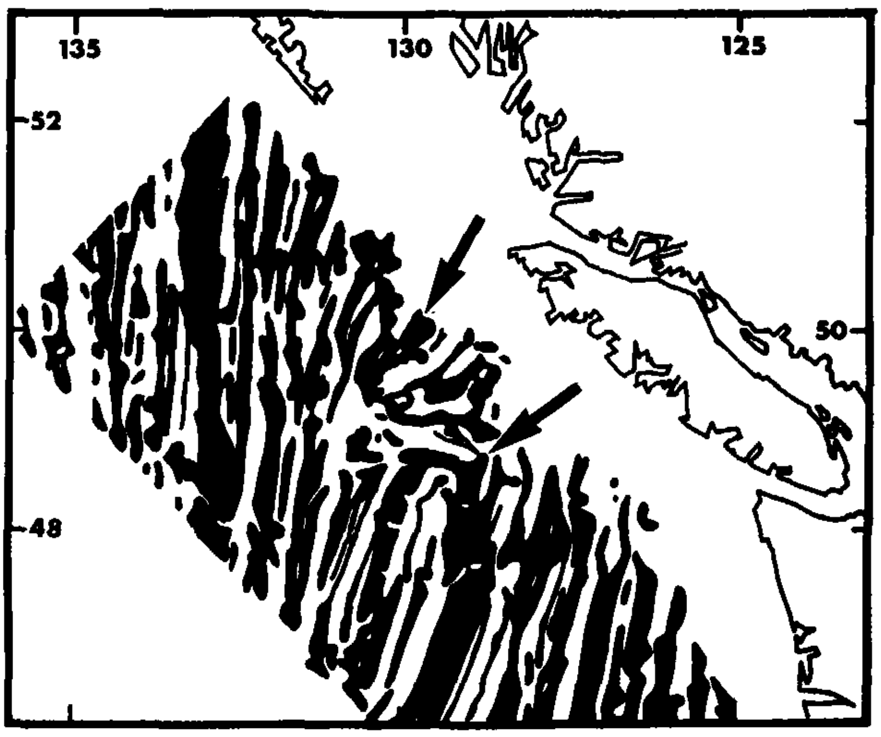

Figure 1
Magnetic anomaly map (black, >0 gamma) from Raff and Mason (1961). Arrows show most recently anomaly.

subduction is taking place. Firstly, the relative motions between the America, Pacific and Juan de Fuca plates over the past 10 m.y. based largely on sea-floor magnetic anomalies; secondly, the indications of subduction at the margin such as sedimentary structures and dip of the oceanic basement; thirdly, the effects of subduction to be expected on the continent such as arc vulcanism, heat flow and gravity; and finally the evidence from seismicity. We feel however that is is important to emphasize that each source of information has a different time scale. The offshore magnetic anomalies, for example, can give information back several tens of m.y. but their time resolution is little better than one m.y.; earthquake data extend only about 50 years into the past and represent a very short, recent, time interval.

Present Plate Configuration

The plate boundaries of the NE. Pacific region have been progressively established by many studies over the past 10 years, principally by marine geophysical surveys (bathymetry, magnetics, reflection seismic and heat flow) and earthquake locations in the area off the Washington, Oregon and British Columbia coast. The plate boundaries based on the most recent data are shown in Figure 2.

Of critical importance for the history of subduction is the location of the point of intersection of three main plates (a triple junction) near the northern end of Vancouver Island. This triple junction is of the transform fault-ridge-trench type and is not necessarily stable in the terms defined by McKenzie and Morgan (1969) and may move with time. The transform fault is the right lateral Queen Charlotte fault which runs northwest along the continental slope west of the Queen Charlotte Islands, meeting the Aleutian trench in southeastern Alaska. The ridge is composed of a complex sequence of en-echelon segments connected by fracture zones running south from the Dellwood Knolls spreading centre, through the Explorer Ridge to the Juan de Fuca Ridge. The trench (although not a bathymetric 'trench') or line of convergence, is near the base of the continental slope off the coast of Vancouver Island and Washington.

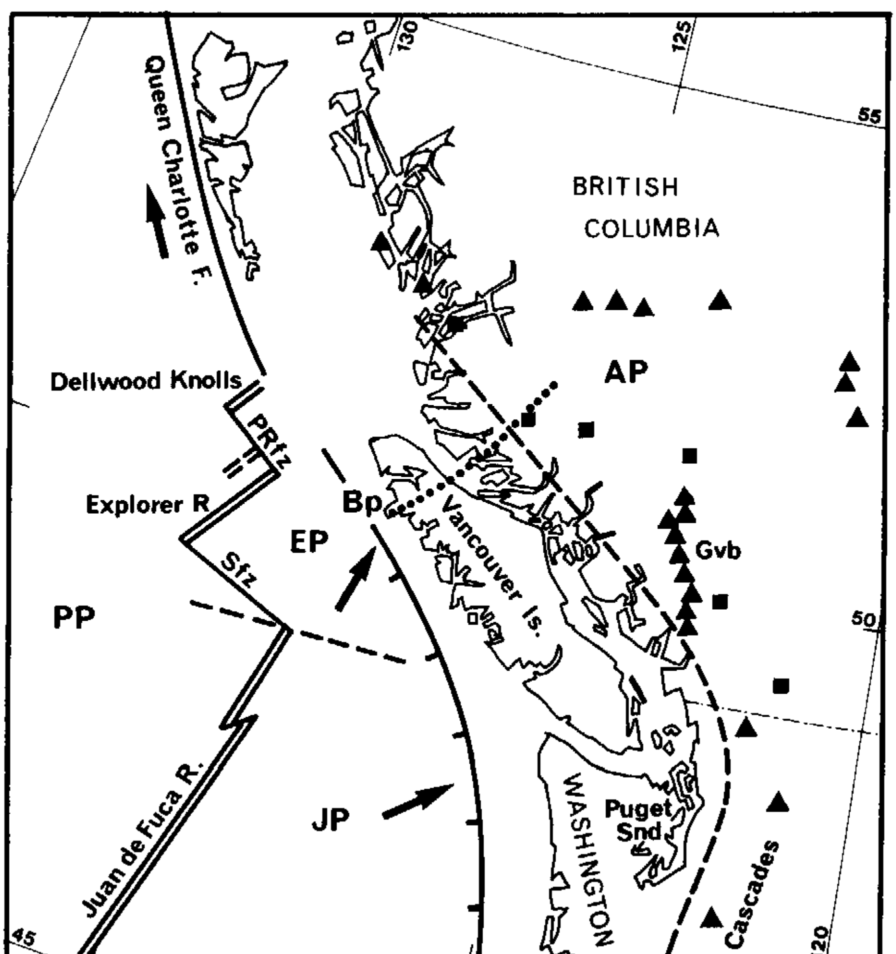

Figure 2
Tectonic features. AP - America plate, Bp - Brooks Peninsula, EP - Explorer plate, Gvb - Garibaldi volcanic belt, JP - Juan de Fuca plate, PP - Pacific plate, PRfz - Paul Revere fracture zone, SFz - Sovanco fracture zone. Dashed line eastwards from SFz is possible Ep/Jp boundary. Dotted line is hypothetical northern edge of subducted plate. Dashed line inland is western limit of volcanism. Triangles - Quaternary volcanoes, squares - Miocene volcanic centres. Arrows are probable plate motions relative to America plate.

Not all of these plate boundaries are equally established and several are in doubt. One complication is the very recent 'ridge jumping' that has been suggested for the northern ends of both the Juan de Fuca and Explorer Ridges. For the former, reflection seismic studies reported by Barr and Chase (1974) and by Davis and Lister (1976) have established that the present axis of spreading is located in the westerly of two spreading centres about 20 km apart. Both spreading centres are expressed by pronounced valleys and a positive magnetic anomaly. The eastern centre was probably active within the past 0.7 m.y. At the northern end of the Explorer Ridge a similar situation has been proposed by Srivastava *et al.* (1971), on the basis of bathymetric, magnetic and heat flow data.

A more radical possibility was suggested by Barr (1974), principally from the evidence of earthquake locations, that the Juan de Fuca - America boundary now extends northeast from the northern end of the Juan de Fuca Ridge and that the Queen Charlotte Fault extends south-eastwards to the same position. This configuration would make the Dellwood Knolls and Explorer Ridge spreading segments inactive. While the absence of any detectable magnetic or bathymetric discontinuity corresponding with an active extension of the Queen Charlotte Fault makes Barr's suggestion unlikely, the existence of a diffuse line of epicentres trending north-east from the northern end of the Juan de Fuca Ridge is confirmed in a recent earthquake compilation (Fig. 3) and may be significant. This is commented upon later.

Clearly, the area is of some complexity. It was described by Vine (1966) as one in which there has been 'faulting and a gradual stifling and re-orientation of the ridge crest'. Menard and Atwater (1968) described the deformation in this offshore region as 'exceptionally complex both because of a continent nearby and because of a relatively recent change in direction of spreading'.

Offshore Magnetic Anomalies and Relative Plate Motions

Through the dating of individual anomalies, magnetic surveys are the most powerful tool available for deducing past motions of the sea floor away from spreading ridges. For the northeast Pacific, the first detailed combining of the magnetic anomaly pattern with the chronology of geomagnetic reversal was presented by Vine (1968). Using a time scale derived from a profile across the East Pacific Rise, Vine established a history going back 15 m.y. The oldest dateable magnetic anomalies east of the Juan de Fuca ridge (now at the margin and parallel to the Washington-Oregon coast) were estimated to be about nine m.y. old. As a complete record older than this lies to the west of the ridge system, subduction must have taken place within the last nine m.y.

A number of authors have subsequently used Vine's analysis to look at the predicted motions in more detail. There is general agreement on spreading rates but the absence of clearly defined transform faults has made the accurate determination of spreading directions more difficult. In different studies spreading has been assumed either to be perpendicular to the magnetic anomaly trend or parallel to the Blanco fracture zone (a difference of between 0° and 20°) From a gradual change in anomaly direction and thus ridge orientation, principally from four to six m.y. ago, a progressive change in spreading direction has been implied. Atwater (1970), taking a right lateral Pacific-American plate motion deduced from the Gulf of California and Juan de Fuca Ridge spreading parallel to the Blanco Fracture Zone at 5.8 $cm\ yr^{-1}$, deduced a present convergence at the continental margin of 2.5 $cm\ yr^{-1}$ in a NE. direction. Silver (1971) subsequently considered the influence of a major NE. transcurrent fault from the ridge to the margin and showed that while it was active (2 to 0.5 m.y. ago) subduction may have been considerably less at the British Columbia margin (approximately one cm/yr) than to the south (3 to 4 cm/yr). Recent more detailed studies of the magnetic anomaly geometry for the southern part of the Juan de Fuca plate off Vancouver Island could have become virtually coupled to the America plate in the recent past.

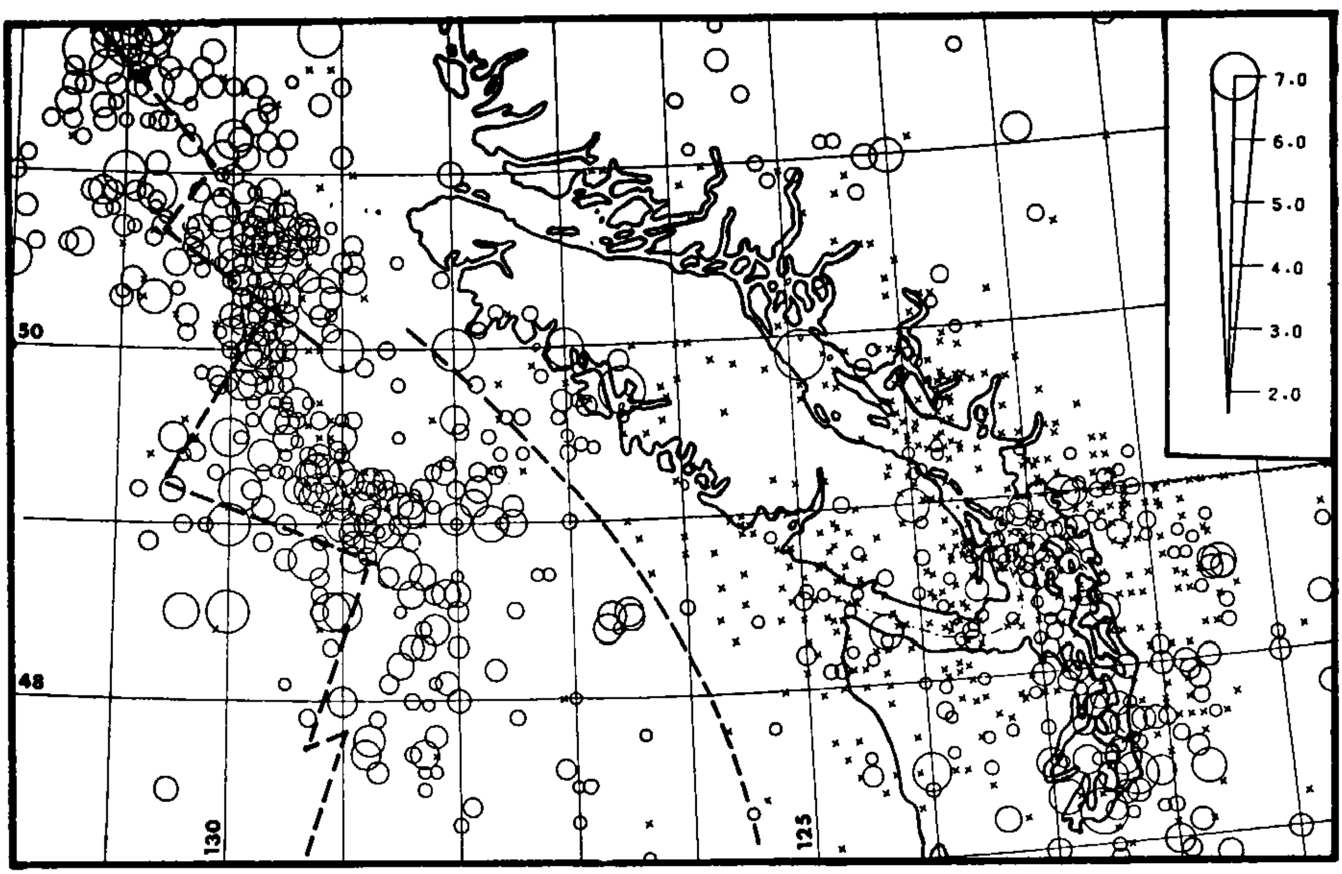

Figure 3
Compilation of earthquake epicentres from Seismological Series, Earth Physics branch, EMR, Canada (see Milne et al., *1976 MS).*

All of the above studies have worked from the southern edge of the Juan de Fuca plate and considered that the Blanco fracture zone defines the direction of relative motion between the Juan de Fuca and Pacific plates. This approach seems to result in particularly large uncertainties in relative plate motions off British Columbia. Working from the northern end of the Juan de Fuca ridge system and making the critical assumption that spreading directions were perpendicular to the magnetic anomaly lineation, Chase *et al.* (1975) recently computed a convergence rate for the Juan de Fuca - America plates of 5.2 cm yr^{-1} at N45°E from 10 to five m.y. decreasing to 4.2 cm yr^{-1} at N43°E from five m.y. to the present. This is a much higher convergence rate than that computed by Atwater (1970) and comes from taking spreading perpendicular to the magnetic anomalies rather than parallel to the Blanco fracture zone. It seems to us that these two approaches may nevertheless eventually prove to be reconcilable through the action of the transcurrent faults mentioned above.

One of us (Riddihough, 1976) has recently re-examined the fine structure of spreading rate variations on the Juan de Fuca and Explorer ridges. Again taking spreading orthogonal to the ridge but using the more recent reversal chronology of Talwani *et al.* (1971), this examination suggests; 1) the Explorer and Juan de Fuca plates (Fig. 2) have moved independently at least since eight m.y. ago and 2) convergence vectors at the continental margin have been variable both in space and time (Fig. 4a). The boundary between the Explorer and Juan de Fuca plates and between the two appropriate convergence regimes has in general terms been an eastward extension of the Sovanco Fracture Zone (Fig. 2) which although now close to 49°N, has moved north at approximately 45 km per million years. South of it the convergence rate at the margin has decreased from 5.5 cm/yr at nine m.y. to 3.6 cm/yr (perpendicular subduction of 3.2 cm/yr) in the past one million years, a result which is similar to that of Chase *et al.* (1975). However, to the north of it (the Explorer plate) convergence at the margin has decreased to a greater extent, from 5.5 cm/yr to about 2.0 cm/yr (perpendicular subduction rate of 1.4 cm/yr) in the same period (Fig. 4b).

The movement of the triple junction or northern limit of subduction off northen Vancouver can be also assessed from estimates of relative plate motions. Atwater (1970) suggested that it has remained close to its present location over the last 10 m.y. Chase *et al.* (1975) calculated that it should have moved 15 km NW. from 10 to five m.y. ago and further 65 km from 5 to 0 m.y. The slow

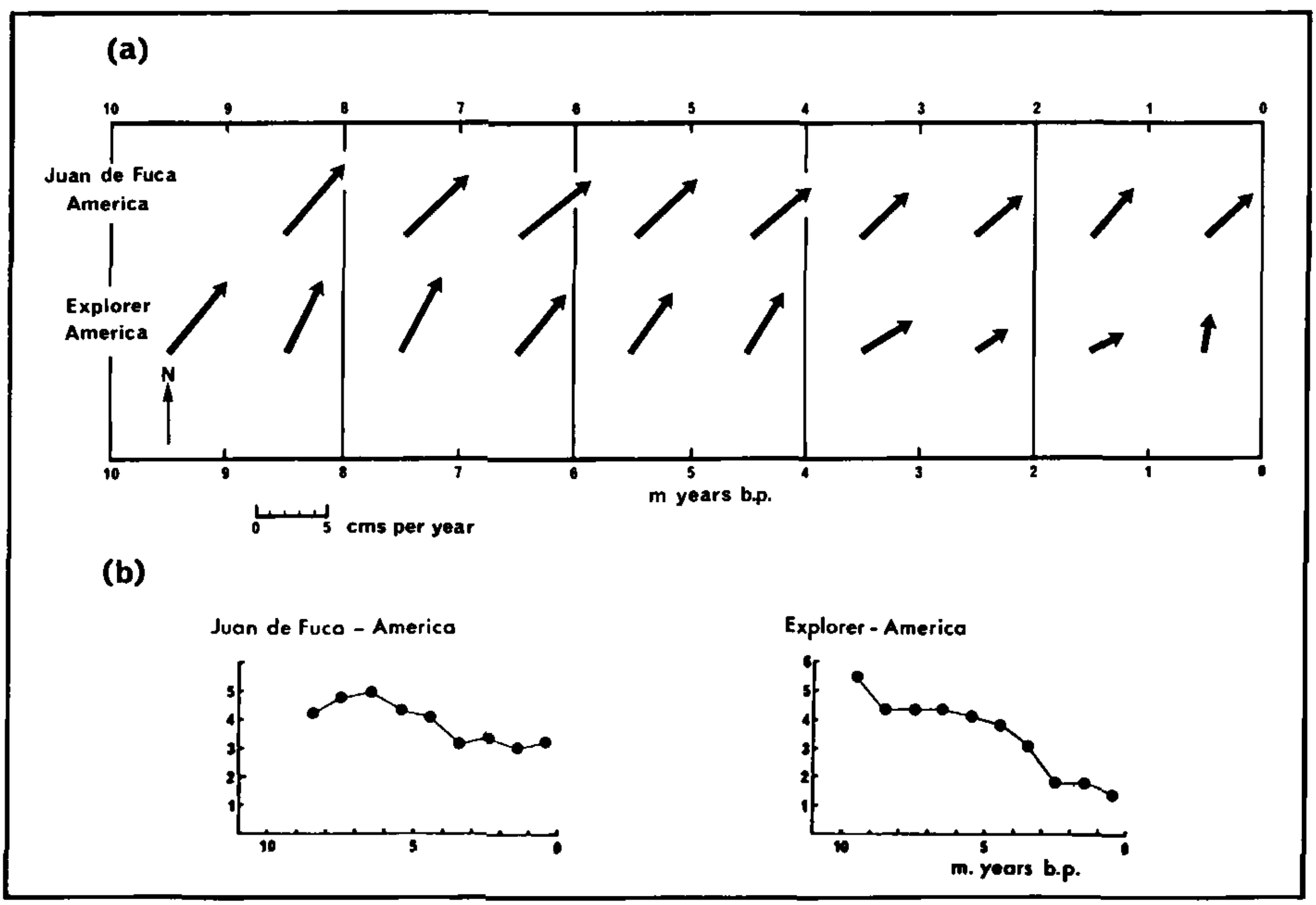

Figure 4
Convergence vectors for Juan de Fuca/America and Explorer/America interactions Subduction rates perpendicular to margin are shown in lower graphs (from Riddihough, 1976 MS).

northward movement is supported by seismic reflection interpretations of sedimentary structures such as those of Tiffin *et al.* (1972) which suggest that the triple junction was stable near Brooks Peninsula (Fig. 2) at least until three m.y. ago. A detailed study of the magnetic anomalies (Riddihough, 1976 MS) using the best estimate of the Pacific-America motion, does confirm that the junction remained stable close to Brooks Peninsula from 10 to 4 m.y. before moving to the northwest at a rate of the order of 1.8 cm yr^{-1}. Using convergence vectors from the detailed spreading history and the above motion of the triple junction, one may obtain a theoretical position for the northern edge of the plate subducted under Vancouver Island during the last 10 m.y. (Fig. 2). The edge strikes northeastward, the plate edge aged 10 m.y. (assuming a 45° dip) now being some 200 km inland from the continental margin.

Bathymetry, Basement Dip and Sediment Deformation at the Margin

Bathymetrically, the Juan de Fuca and Explorer Ridges are evident as broad ridges with central troughs interrupted by transverse ridge/scarp features corresponding with the Sovanco and Revere-Dellwood fracture zones. To the east of the Juan de Fuca Ridge there is an almost featureless plain of low relief, the Cascadia basin, which continues to the edge of the continental slope and contains up to four km of flat-lying sediment. Seismic reflection data (e.g., Tiffin *et al.* 1972; Murray and Tiffin, 1974), the attenuation of magnetic anomalies (Barr, 1974) and gravity measurements (Srivastava, 1973) have all been interpreted to indicate a significant eastward dip of the oceanic basement beneath these sediments and below the continental slope which is attributable to the effect of subduction.

Scholl (1974) regards the region near the foot of the slope as a 'structural trench' which has been filled with land derived sediments. Off the Washington coast this trench fill is represented by a 200 to 500 m thick turbidite sequence apparently accumulated within the past one m.y. Below this is a sequence of landward dipping Miocene to Pleistocene, finer grained, beds which do not thicken appreciably toward the margin. Scholl considers the upper turbidite sequence as a 'true' axial trench deposit because its geometry is controlled by the structural trench, and considers the older sequences to have been deposited on flat lying seafloor further offshore that was later transported eastward and down-warped toward the trench axis.

The continental slope itself changes in character southwards from steep and narrow off the Queen Charlotte Islands and northern Vancouver island to a much wider, irregular slope off southern Vancouver Island, Washington and Oregon. In broad terms this seems to be a symptom of the change in the interaction regime along the margin from transform faulting to compression and subduction.

Details of this interaction, between the sediments at the foot of the slope and the continent, have been studied both off Vancouver Island and off the Washington coast. Off Vancouver Island as far north as Brooks Peninsula, Tiffin *et al.* (1972) and Murray and Tiffin (1974) conclude that up to at least the lower Pliocene (4 m.y. ago), many of the structures of the continental slope are characteristic of compression. They also observe considerable recent faulting and note that deformation increases in intensity along the margin to the southeast. Barr (1974) concludes that deformation continued at least until the late Pleistocene. Off the Washington coast Silver (1972) came to a similar conclusion and suggested a recent convergence rate of two cm yr^{-1} from sedimentary evidence. In the same area, Carson *et al.* (1974) interpret anticlinal ridges in the most recent sediments at the outer edge of the slope as indicating deformation which is continuous up to the present. Both von Heune and Kulm (1973) and Scholl (1974) also deduce that there is good evidence of very recent deformation and uplift in response to compression at the Washington-Oregon slope. Von Heune and Kulm compute a convergence rate of from 1.6 to 2.7 cm/yr.

A typical seismic profile of the base of the continental slope off southern Vancouver Island is shown in Figure 5; the structure revealed compares closely with the deformation of the most recent sediments at an outer anticlinal ridge examined by Carson *et al.* (1974). We conclude therefore, both from the dip of the oceanic basement into a sediment filled trench along from the margin and from deformation of the slope sediments, that there is strong evidence for convergence continuing up to the geological 'present' south of 50°N. However, as the time resolution of sedimentary studies, particularly in the light of extremely high post-glacial sedimentation rates, may be only about 10,000 years, a very recent cessation may not be detectable.

Inland Vulcanism, Heat Flow and Gravity

The subduction of oceanic lithosphere under a continent results in a number of characteristic processes. These extend several hundred kilometres inland of the subduction zone itself and are principally manifested by characteristic patterns of 'arc' or calc-alkaline vulcanism, heat-flow and gravity.

In Washington, Oregon and northern California, the vulcanism resulting from Juan de Fuca plate subduction is well defined by the Cascade chain of volcanoes which occurs parallel to and between 150 and 200 km inland from the continental slope (e.g., Dickinson, 1970). Although there have been few major recorded eruptions in historical times, this chain is clearly active. In northern Washington, its northern trend turns to the northwest and it continues into southern British Columbia up to approximately 52°N. In British Columbia, it is represented by a line of Miocene volcanic centres (the Pemberton volcanic belt, Souther, 1970,

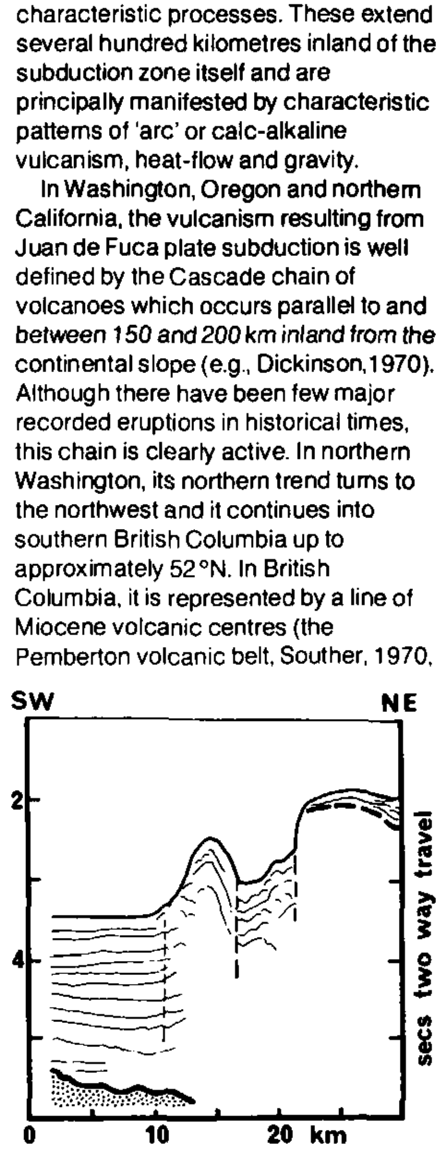

Figure 5
Line drawing of typical seismic profile across the base of the continental slope off southern Vancouver Island (after Barr, 1974). Note deformation of the most recent sediments in the first anticlinal ridge.

1976), Quaternary volcanism being limited to the NNW. Garibaldi volcanic belt which extends only to 51°N (see Fig. 2). The youngest recorded activity in this belt is 2500 years ago. Souther (1976) states that Garibaldi lavas 'are *chemically similar to those of the* Cascade province of western U.S.A., and like the latter, their analyses plot along a typical calc-alkaline trend that is universally associated with Benioff zone magmatism'. Souther relates the changes in trend of the British Columbia volcanic belts to changes in offshore plate geometry and it is interesting to note that the change from the NW. Pemberton belt to the NNW. Garibaldi belt occurred close in time to the sharp 25° change in Explorer-America convergence at four m.y. suggested by Riddihough (1976 MS) (see Fig. 4). Following the same reasoning, it is possible that the present lull is a reaction to the initiation of nearly N-S Explorer-America convergence within the last one m.y. (Fig. 4, 0.5 m.y.)

Estimation of the time scale required for a change in subduction to be reflected in a change in volcanism is difficult. However, if changes are in response to a stress regime, as the above speculations suggest, it may be geologically rapid. Thus the existence of recent volcanism can probably be taken to imply that subduction has occurred and has continued up to at least one m.y. ago. The reduced level of volcanism in the Cascade - British Columbia volcanic belt as compared to volcanic arcs such *as Japan and the Aleutians seems to us* to be broadly explicable by the much slower subduction rates involved (1 to 3 cm/yr as opposed to 5 to 8 cm/yr).

Another observed characteristic of subduction zones is a band of low heat flow on the continental side of the active trench and much higher than normal heat flow further inland (e.g., McKenzie and Sclater, 1968; Hasebe *et al.*, 1970). The 'low zone is produced by the cold oceanic lithosphere which, acting as a heat sink beneath the continent, absorbs *heat that would otherwise reach the* surface (dehydration of hydrated minerals may complement this process). The inland 'high', which commences at the volcanic arc, probably results from upwelling magma derived from the melting of the sinking slab at a depth of several hundred kilometres. The transition at the volcanic arc also corresponds with changes from high to low Bouguer gravity and changes in a number of other geophysical parameters.

There is evidence for this pattern in north-western U.S.A. (Blackwell, 1969, 1975) *and it has been shown by one of* us to be clearly defined in south-western British Columbia (Hyndman, 1976a). A number of authors have produced thermal models that exhibit some of the characteristics of this pattern but the model that most successfully reproduces the observed heat flow pattern is by Hasebe *et al.* (1970). This model fits the data for south-western British Columbia very well, showing a pronounced low just inland of the trench, a plateau of normal heat flow to about 200 km inland and high heat flow beyond (Fig. 6). Heat flow values for most of the models of Hasebe *et al.* are somewhat higher than those observed but reasonable model parameters can be readily found that give good agreement.

The time required for the surface heat flow and other thermally related parameters to respond to a change or termination of subduction is probably several million years for areas near the marginal 'low' and several tens of million years for the inland 'high'. Thus while the heat flow pattern clearly indicates subduction within the last few million

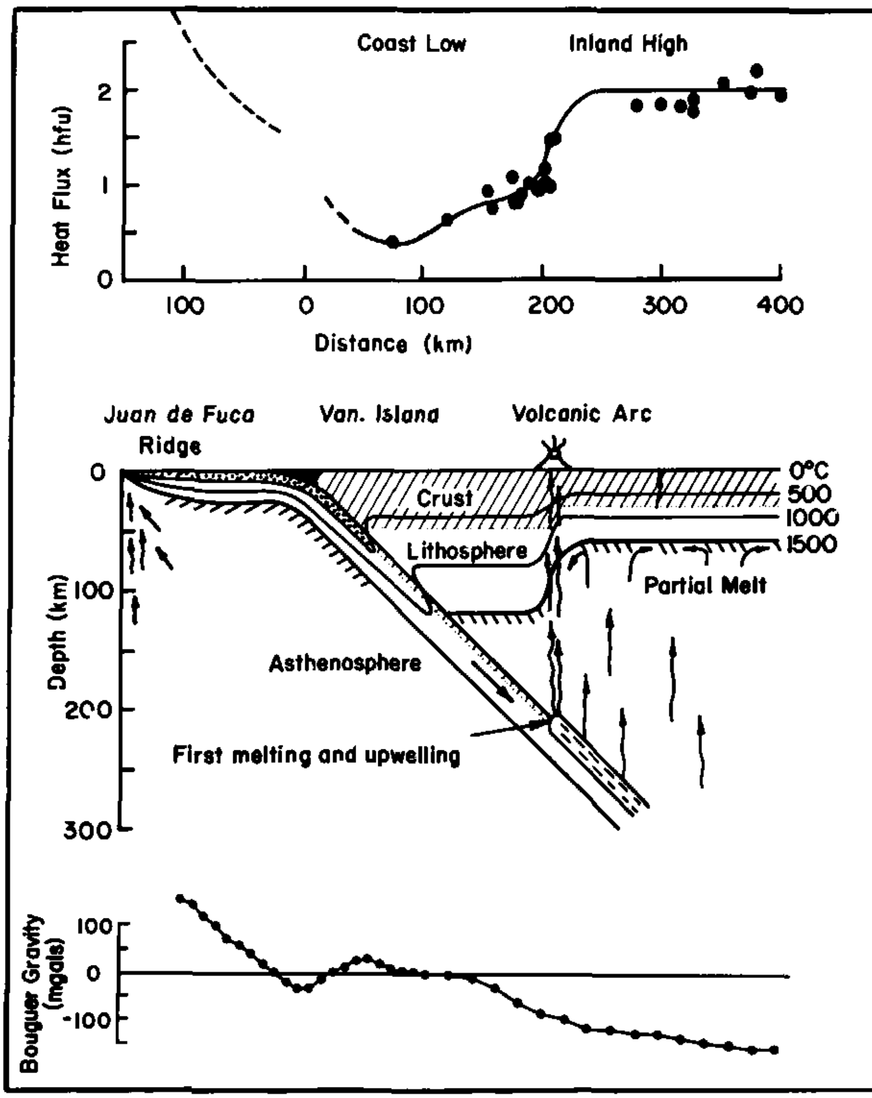

Figure 6
Schematic cross-section of the continental margin of southwestern British Columbia with illustrative isotherms. The dotted area in the sinking slab is below the critical temperature for earthquakes. Heat flow values are shown above and a smoothed Bouguer gravity profile shown below.

years, a recent termination of subduction would not be evident.

A characteristic pattern has been observed in the gravity field across almost all margins where subduction is occurring (e.g., Grow and Bowin, 1975). Previously published interpretations of the gravity field over the continental margin of south-western British Columbia have not in general, considered the existence of a down-going slab and other manifestations of subduction. They are, nevertheless, broadly consistent with it. For example, Couch (1969) postulated a steeply dipping boundary separating high density mantle beneath the continent from lower density mantle beneath the ocean. Similarly, Stacey (1973) showed that the 'plateau' of near zero Bouguer gravity anomaly that lies over Vancouver Island (Earth Physics Branch, 1974) between the oceanic 'high' (>+100 mgal) and the inland 'low' (<-100 mgal) required anomalously high density beneath the island.

One of us (Hyndman, 1976b) has recently shown that the gravity field of the region is compatible with the features expected in an actively subducting situation; the magnitude of the gravity anomalies is however, less than for other subduction zones because the 'trench' is sediment filled and the convergence rate is lower. Figure 6 shows a Bouguer gravity profile across southern Vancouver Island. Profiles across southern Washington and Oregon are similar. The main gravity features are explained qualitatively by the cross-section in the centre of the figure. The zero Bouguer gravity 'plateau' probably arises from the thick cold lithosphere occurring between the trench and the volcanic arc and may reflect a crust and mantle structure rather similar to stable continental areas. Superimposed on this 'plateau' there is a narrow +30 mgal high over western Vancouver Island (also observed near the coasts of southern Washington and Oregon) that is probably associated with high density in the downgoing slab. Grow and Bowin (1975) have shown that such a density contrast must exist and is largely caused by the basalt-ecologite phase transformation in the oceanic crust (an increase in density from 2.9 to 3.5 g/cm^3) and the low temperature of the sinking oceanic lithosphere with respect to the surrounding material. This narrow gravity 'high' coincides with the heat flow minimum.

The Bouguer gravity 'low' (<-100 mgal) which extends eastwards from the volcanic arc is explicable as a result of higher temperatures and partial melt in the mantle. Assuming a mantle density below 60 km which is anomalously low by the order of 0.05 g/cm^3, both the observed gravity effect and the higher average elevation can be explained. Such a result is similar to that of Stacey (1973) and is in conformity with a number of studies of the inland region (e.g., Berry *et al.* 1971; Berry and Forsyth, 1975) which have shown it to have both a thin crust and a thin hot lithosphere underlain by a pronounced asthenosphere.

The response of the density distribution producing the gravity field to change in or termination of subduction is, like heat flow, quite slow. The low gravity inland of the volcanic arc will probably persist for several tens of millions of years although the gravity high nearer the coast may disappear much more quickly, within several million years, as the subducted slab heats and the eclogite reverts to lower density phases.

Seismicity

Major subduction zones around the world are characterized by the presence of a narrow plane of earthquakes, the Benioff zone, steeply dipping beneath of the volcanic arc from the trench to a depth of up to 700 km. The lack of such a Benioff zone under western North America has been held as primary evidence against subduction. We feel, however, that there are strong grounds for concluding that earthquakes deeper than 70 km are not to be expected in this region and that the observed seismicity is, in fact, consistent with continuing subduction.

There is considerable seismicity in the region (Fig. 3) (e.g., Milne, 1967; Milne *et al.* 1976 MS; Crosson, 1972) and, in consequence, little doubt that there is intense tectonic activity of some form. The offshore seismicity generally follows the Queen Charlotte fault, and the Explorer and Juan de Fuca Ridge system. Epicentres, however, are rather imprecisely located on specific ridges or transforms and may be systematically displaced (Wetmiller, 1971; K. Lee, pers. commun.). Accurate determination of the relative plate motions is thus inhibited. A group of earthquakes apparently in the regions of the Paul Revere fracture zone (Azimuth 128°) and the Sovanco fracture zone (Azimuth 110° to 120°) studied by Chandra (1974) indicated right-lateral strike slip motion at azimuths from 152° to 180°. If such directions represented the motion between the Explorer and Pacific plates, the Explorer plate would be moving away from, rather than converging on the American plate. However, as very complex interactions are clearly taking place in this area, we do not believe that such a conclusion is valid.

Within the America plate, Rogers (1976 a, bMS) has analysed the first motions of a number of larger earthquakes and concludes that the region can be divided into two distinct areas. North of 49°, in central Vancouver Island, the earthquakes are shallow and consistent with strike-slip faulting in response to north-south compression. Such faulting could either trend NW. (right-lateral) or NE. (left-lateral). The vector interaction at the margin from offshore magnetic data (Fig. 4) does in fact show N-S convergence between the American and Explorer plates for the most recent (0.5 m.y.) epoch. Analysis of motion along a proposed eastward extension of the Sovanco Fracture Zone (Riddihough, 1976 MS) also suggests that a NE. oriented left lateral fault in the downgoing lithoshpere beneath Vancouver Island is quite probable; the northern edge of the downgoing plate (Fig. 2) is also oriented in the same direction. The crustal earthquakes observed may thus be related to the coupling of one or all of these stresses to the America plate.

South of 49°N, in the Gulf Islands - Puget Sound area a high concentration of earthquakes has been recorded. Although again they are predominantly shallow, deeper earthquakes (down to 60 km) occur which are consistent with a downgoing slab interpretation. Here, McKenzie and Julian (1971), in a study of the travel times from the 1965 Seattle earthquake, proposed the existence of an eastward dipping high velocity slab. Isaacks and Molnar (1971) and Chandra (1974) obtained a depth of about 60 km with extension stress parallel to the dip for the same event. Rogers (1976b MS) finds similar depths and stress regimes for two other events in the area, further supporting continuing subduction to the present although confirming that the geometry of the downgoing slab is probably complex (Fig. 6).

The reason that earthquakes in the region are limited to a maximum depth of about 60 km is, in our opinion, readily seen. The foci of deep Benioff earthquakes are in general limited to the sinking oceanic plate. Such a plate has a long thermal time constant, so that starting cold at the surface, its core will remain cool and seismic instability or brittle fracture occur, to a considerable depth. The surrounding asthenosphere is hot and deforms plastically. The maximum depth of earthquakes is set by the depth below which all of the sinking plate exceeds the critical temperature for seismic instability or fracture. The two most important factors that determine this depth are: 1) the rate of convergence or sinking speed of the plate - the faster the plate is sinking the further it will descend before the critical temperature is exceeded; and 2) the thickness of the subducted plate when it commences to sink - the thicker the plate, the longer its thermal time constant and the further it will penetrate before completely heating above the critical temperature.

Isaacks *et al.* (1968) and McKenzie (1969) showed that the maximum earthquake depth is approximately proportional to the sinking rate; Morgan (in Deffeyes, 1972) showed that the depth depends directly on the age of the sea floor being subducted, the thickness of the oceanic lithosphere being approximately proportional to the square root of its age (e.g., Parker and Oldenburg, 1973). Using relations obtained from compilations of world subduction zones, one of us (Hyndman, 1976b) has estimatied maximum depths for Benioff earthquakes in the region (Fig. 7, and cross-section in Fig. 6). The variation with latitude arises both from variation in sinking rate and in the age (or thickness) of the plate being subducted. The maximum depth of earthquakes of 70 km for a subduction rate of three cm/yr at 45° dip and 10 m.y. old sea floor, is in good agreement with the observed maximum of about 60 km for Washington and Oregon. The predicted maximum depth under Vancouver Island (Explorer plate) is less that 30 km.

We thus conclude that seismicity data supports continuing subduction south of about 49°N, i.e., the Juan de Fuca - American convergence. It supports but is not conclusive, for convergence to the north of 49°N, i.e., between the Explorer and American plates.

Summing-up

From reviewing the aspects of geology and geophysics relevant to subduction under south-western British Columbia, it seems clear to us that there is definitive evidence for convergence and subduction south of a point on the margin near 50 °N, at least until a few million years ago. This evidence is strongest from offshore magnetic anomalies, from sediment deformation along the continental margin and from onshore heat-flow values, gravity anomalies and volcanic activity. As we have stressed, the accuracy of the evidence from these sources for the timing of subduction activity is very variable and could not, in any case, be expected to prove or disprove conclusively the existence of some form of present subduction. Earthquake data however, seem to us to indicate very strongly that at least south of 49°N, subduction of oceanic lithosphere (the Juan de Fuca plate) beneath the continent, *is* continuing.

Between 49°N and Brooks Peninsula, near 50°N, marine magnetic evidence suggests that convergence at the margin may be distinct from that to the south and be controlled by the relative motion between the Explorer oceanic plate and the continent. This interaction appears to have changed in direction very recently and to be rapidly slowing. Earthquake data and recent sediment deformation show evidence for continuing compression and a stress regime compatible with the interaction but no clear evidence for an actively underthrusting oceanic lithosphere. Nevertheless it is of critical importance to realise that because of the very slow sinking rate involved, and the young and very thin oceanic plate being subducted, many of the phenomena normally associated with subduction will be either absent or not readily detectable.

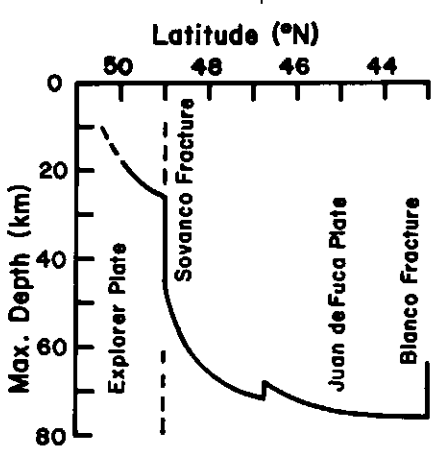

Figure 7
The predicted maximum depth of earthquakes under British Columbia, Washington and Oregon.

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