Geoscience Canada

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Volume 9, numéro 1, march 1982

URI : https://id.erudit.org/iderudit/geocan9_1art04

Aller au sommaire du numéro

Éditeur(s)

The Geological Association of Canada

ISSN

0315-0941 (imprimé)
1911-4850 (numérique)

Découvrir la revue

Citer cet article

Riddihough, R. P. (1982). One Hundred Million Years of Plate Tectonics in Western Canada. *Geoscience Canada*, *9*(1), 28–34.

Résumé de l'article

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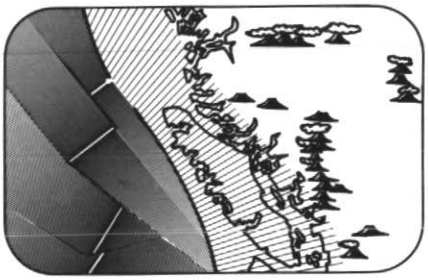

One Hundred Million Years of Plate Tectonics in Western Canada

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Summary

New concepts of western Cordilleran geology involve the assembly of exotic blocks of crust through large northward movements and strike-slip faulting. These can only be valid if the regional plate tectonic framework provides a suitable mechanism. The geometrical reconstruction of global plate motions shows that throughout the last 100 Ma, plate movements along the western margin have been appropriate. Movement has been northward relative to North America at high rates and has alternated between convergence and north-westerly strike-slip faulting. Local details must be compatible but cannot be resolved by such broad reconstructions.

Introduction

The revolution in geological interpretation of the western North American Cordillera (e.g., Coney *et al.*, 1980) sees it as a collage of exotic blocks, pieces and slivers of crust (terranes or micro-plates) rather than a cyclic evolutionary series of subduction zones. According to these new concepts, the last 100 million years has seen the later stages of assembly of many of the constituent pieces of the Canadian Cordillera (e.g., Monger and Irving, 1980; Yorath and Chase, 1981) characterised by large northward movements and predominant right-lateral northwesterly strike slip faulting. If, as is now believed, plate tectonics is the fundamental process of geological evolution, this dynamic assembly must have been the result of regional plate movements. A critical, independent check on the geological concepts can thus be made by examining the extent to which regional plate interactions in the last 100 million years *determined from plate geometry alone*, are compatible with the proposed tectonic models.

The present review surveys three aspects of the subject: the methods and weaknesses of plate tectonic reconstructions for the western margin of North America, the results to date and their limitations in predicting specific geological detail. The review arises from two syntheses presented at the Cascadia Conference (May, 1980) and the 1981 Cordilleran GAC Meeting (February, 1981) and relies heavily on other published work, notably that of Coney (1977), Atwater (1970), Atwater and Molnar (1973), Stone (1977) and Cooper *et al.* (1976).

Sea-floor Spreading and the Farallon and Kula Plates

The first step in plate reconstruction for this region is to determine which plates lay immediately to the west of North America. Because the margin has been predominantly convergent for the whole of the period, these plates have been largely destroyed. Inferences about their motion, size and nature, at least for ages older than 10 Ma, cannot be made directly. The key concept which has to be used is that of sea-floor spreading.

The reconstruction of plates and plate motions using this concept critically depends upon the assumption of symmetrical spreading. Although asymmetric spreading has been recognized on a local scale, in general, equal additions of material do appear to be made to both edges of the plates created at a spreading ridge. The orientation and spacing of magnetic anomalies on one oceanic plate are thus a mirror image of those produced on the other. Spreading rates and directions between the two plates can thus be calculated from distances between dated magnetic anomalies on one plate and the orientation of the appropriate fossil fracture zones. Because plate motions occur on a sphere, this information is further resolvable into a rate of relative angular rotation about a pole.

In the Pacific Ocean (see Fig. 1) symmetrical spreading demands that as much crust must have been created on the eastern flank of the north-south spreading ridge as was created on the west. This eastern crust has been named the Farallon Plate (McKenzie and Morgan, 1969). As the present ridge (East Pacific Rise) is near the eastern margin of the North Pacific, the Farallon Plate must have been almost as large as the present North Pacific ocean floor and have been over-ridden or subducted along the western margin of North America during the last 100-150 Ma. A simple calculation shows that it must therefore have converged with North America at an average rate of 40 mm/yr or 40 km every million years.

Although the North Pacific Ocean floor is dominated by the north-south magnetic anomalies created at the Pacific-Farallon Ridge, a set of east-west magnetic anomalies south of the Aleutian Islands (Fig. 1) implies a further complication: the existence of an east-west spreading centre which created another plate north of the Pacific Plate. This plate, called the Kula Plate by Grow and Atwater (1970), has been almost totally subducted to the north (a relic may be trapped forming the crust beneath the Bering Sea according to Cooper *et al.*, 1976). Assuming symmetric spreading,

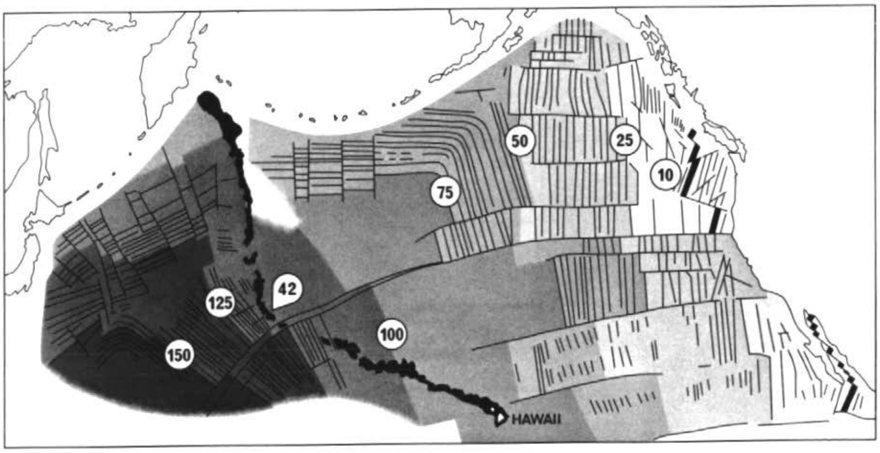

Figure 1 *Magnetic anomalies (shown as black lines) and sea-floor ages (MaBP) of the Pacific Ocean. The Emperor-Hawaii seamount chain and the age of the 'bend' are also shown.*

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the motion of the Kula Plate northwards from the Pacific Plate can be estimated until 55 MaBP (late Palaeocene). Evidence of spreading younger than this does not exist and indeed estimates of the time of disappearance of the Kula Plate as a separate plate vary from 20 MaBP (Grow and Atwater, 1970) to 55 MaBP (Byrne, 1979). Plate geometry further requires that there was a third spreading ridge betwen the Farallon and Kula Plates striking north-east from a ridge-ridge-ridge triple junction between the three oceanic plates (Fig. 2).

The concept of sea-floor spreading thus forms the basis of information about the existence and movement of the Kula and Farallon Plates away from the Pacific Plate at least as far back as there are good records of magnetic anomaly orientation, dating and spacing (c. 150 Ma). Unfortunately, this information is of limited use in determining the interaction of these plates with North America unless the relative motion between North America and the Pacific Plate can also be determined. As these two plates have not been in direct spreading contact, except perhaps in the last few million years in the Gulf of California, this entails the use of three other lines of evidence.

Relative Motions between Pacific and America Plates

Global Sea-Floor Spreading. Atwater and Molnar (1973) used magnetic anomalies and sea-floor spreading to determine Pacific-America motion by encircling the globe westwards from the Pacific plate through a series of spreading ridges of which both flanks are preserved. They measured spreading between the Pacific and Antarctic Plates, the Antarctic and Indian Plates, the Indian and African Plates and the African and American Plates. This process inevitably accumulates a series of errors and uncertainties, particularly those arising from possible deformations between East and West Antarctica and within the Pacific Plate. Nevertheless, Atwater and Molnar's results remain one of the most comprehensive attempts to solve the problem.

Hot-Spots. Another approach used has been to determine the motion of both Pacific and American Plates relative to 'hot-spots'. As developed from Wilson (1963) and elaborated by Morgan (1971), the hot-spot framework is a global system of 'plumes' rising through the asthenosphere over which the lithospheric plates move, leaving a trail of volcanic centres or sea-mounts. This trail provides a measure of the direction and speed of the movement. The Emperor-Hawaii chain on the Pacific Plate, which ranges in age from 80 MaBP at the north end of the Emperor chain to 42 MaBP at the 'bend' and 0 at Hawaii, is one of the most striking examples of this mechanism. The stability of this hot-spot within the framework of other hot-spots affecting the Pacific Plate has been recently tested by both McDougall and Duncan (1980) and Suarez and Molnar (1980) who conclude that it has remained fixed (error < 15 mm/yr) for the last 10 Ma and fixed in latitude relative to the earth's rotation pole (error < 10 mm/yr) for the last 70 Ma. Morgan (1980) and Duncan (1981) conclude that the global hot-spot system has remained internally stable (error < 5 mm/yr) over the last 100 Ma.

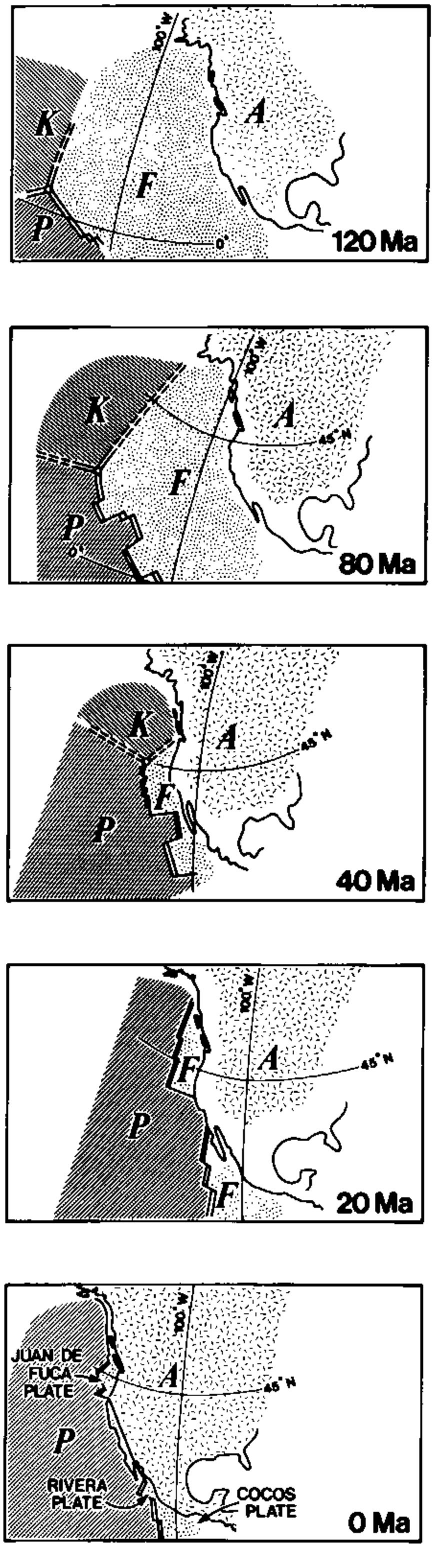

Figure 2 *Plate tectonic reconstructions in the eastern Pacific from 120 MaBP to the present. A - North America plate; F - Farallon plate; K - Kula plate; P - Pacific plate. Principal sources: Coney (1977), Atwater (1970), Atwater and Molnar (1973) and Stone (1977).*

While motion of the Pacific Plate over the hot-spots is well determined, there are very few hot-spot traces within the North American Plate. These (Yellowstone, New England Seamounts, Newfoundland Ridge) have not yet provided a good age progression and may be of questionable stability (Burke *et al.*, 1973). An extension of the method is to connect better determined hot-spot motions on the Africa Plate through to the American Plate by sea-floor spreading information in the Atlantic Ocean. This technique suffers from the complexities and uncertainties of movement between North and South America and the details of spreading in the North Atlantic. Nevertheless Coney (1971, 1977) used this approach to determine interactions within the Cordillera with considerable success. The suggestion raised by Bevier *et al.* (1979) and stressed by Rogers (1981) that the Anahim Volcanic Belt in British Columbia may be the trace of a hot-spot active over the last 25 Ma, holds out the possibility that other hot spot traces may exist and that this method may prove to be the most fruitful approach to the problem.

Palaeomagnetic and 'Mixed' Frameworks. Reference of the Pacific and America Plates to a palaeomagnetic framework suffers both from the inherent longitudinal ambiguity of palaeomagnetic data and the fact that suitable information from the predominantly oceanic Pacific Plate is sparse. Palaeomagnetic data for North America is good and has been combined with other reconstruction methods by a number of authors (e.g., Irving, 1981). Stone (1977) reviewed some of these 'mixed' methods, demonstrating that longitudinal uncertainties of hundreds of km exist for the position of North America.

The problems of combining reconstructions by different methods rather than using only one system must be considered in the light of recent studies which have tried to compare the relative stability of hot-spot, palaeomagnetic and rotation axis frameworks. Suarez and Molnar (1980) concluded that the hot-spot system in the Pacific corresponded with independent latitudinal evidence from sea-floor sediments but that palaeomagnetic data did not. Jurdy (1981) presented evidence that the hot-spots may have moved significantly (10 to 12° in 60 Ma) relative to either the rotation pole or the assumed palaeomagnetic dipole. However, in terms of calculating plate interactions, the work of Morgan (1980) and Duncan (1981) seems to confirm that hot-spots and sea-floor spreading can provide a self-consistent system.

Plate Distribution

Despite the uncertainties, Cooper *et al.* (1976) demonstrated that the broad evolutionary pattern of the plates of the North Pacific region was similar for the three main types of 'mixed' reconstruction routes and frameworks. The general layout and chronology is shown in Figure 2.

At 100 MaBP there were probably three principal oceanic plates in the region -the Pacific, Kula and Farallon Plates. Movement was generally northward for the Pacific Plate and westward for North America. Both the Kula and Farallon Plates were subducted faster than they were created and so slowly diminished in area. Because of the limited amount of magnetic anomaly evidence remaining, one of the greatest uncertainties is the shape and location of the Kula-Farallon ridge and the possible existence of other small plates which have now been totally subducted.

By 30 MaBP the Kula Plate had become very small. Magnetic anomaly evidence has been interpreted by Byrne (1979) as showing that the Pacific-Kula ridge stopped spreading around 55 MaBP and that the Kula Plate moved with the Pacific Plate after that time. Certainly by 20 MaBP, its last remnants had disappeared. At about 30 MaBP, the Farallon Plate became so narrow that a section of the spreading ridge reached the trench off North America and the plate split into two parts separated by a Pacific-America transform - the proto-San Andreas Fault. During the subsequent 25 Ma the northern plate remnant, the Juan de Fuca Plate, continued to reduce in size principally by the migration of the southern triple junction (Pacific-America-Juan de Fuca) northwards to its present position at Cape Mendocino. The last 10 Ma has seen the breaking up of the Juan de Fuca Plate into a series of small subplates near both the northern and southern triple junctions (Riddihough *et al.*, 1982).

Plate Interactions at the Margin

The general plate interactions in the region of the present western Canadian continental margin during the last 100 Ma are convergent. However in detail, their calculation involves a vector addition of all the appropriate plate motions. Because of the chain of motions between North America and the Pacific, Farallon and Kula Plates are particularly long, this addition is subject to a number of uncertainties. The size of the Pacific, Farallon and America Plates makes the determination of relative poles of rotation particularly critical. For example, at 50 MaBP, Pacific Plate motion along the Emperor sea-mount chain (relative to the hot-spot framework was 7° W of N at 86 mm/yr (using the pole of Clague and Jarrard, 1973). At a point on the western margin of the American plate equivalent to the southern end of Vancouver Island, the same Pacific Plate 'absolute' motion resolves to N104° E at 43 mm/yr. Similarly, although Pacific-Farallon motion has been predominantly E-W at the spreading ridge, only knowledge of the pole of relative rotation can permit calculation of Pacific-Farallon motion along the American margin with any degree of certainty.

Given the complexities of plate motion determination discussed above, it is remarkable that the resultant interactions that have been derived for the plates concerned, are essentially similar. A representative selection of Farallon-North America Plate estimates (both published or derived from published estimates of relative plate motions) for a point approximately equivalent to the south end of Vancouver Island are shown in Figure 3. The vectors all show north to north-easterly movement of the Farallon plate relative to North America.

These interactions, plus estimates for Kula and Pacific interactions, are shown in Figure 4 superimposed on plate distribution maps for the region of the Canadian western margin derived from Figure 2. It is important to note that for any time interval there are two separate questions answered in these diagrams: (i) which plates are adjacent to each other?; and (ii) what is the relative motion at their mutual boundary?

Chronological Development

100 to 80 MaBP (Mid to late Cretaceous). Although there are magnetic anomalies covering this period in the western Pacific, the Cretaceous quiet zone of uniform magnetic polarity (85 to 125 MaBP, Ness *et al.*, 1980) makes determination of Pacific-Farallon spreading rates extremely uncertain. A Farallon-Pacific rotation pole to the north was estimated by Franchetau *et al.* (1970) but the northernmost sea-mount of the Emperor chain is dated at 80 MaBP, so that there is no direct 'hot-spot' control over Pacific Plate motion. Duncan (1981) calculates a Pacific Plate motion from African Plate hot-spots and sea-floor spreading data which can be combined with estimates of North

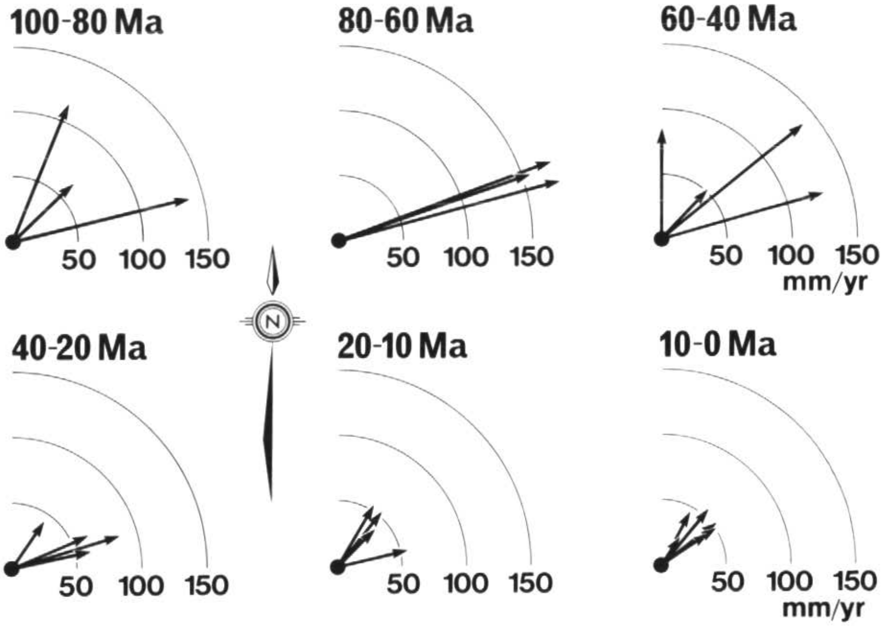

Figure 3 *Relative motion vectors of the Farallon (later Juan de Fuca) plate relative to the North America plate calculated for a point equivalent to the southern end of Vancouver Island. Vectors are calculated from a representative range of the published plate models referred to in the text.*

American motion (westwards to northwestwards; Coney, 1977) to give generally north to north-eastern Farallon-America interaction. Depending on Pacific-Farallon spreading rates, the rate at the equivalent of the position of Vancouver Island, varies between 60 and 120 mm/yr. Coney (1977) estimates 80 mm/yr.

80 to 60 MaBP. (Late Cretaceous to mid-Palaeocene). By this time, the Emperor sea-mount chain is being formed and from this, motions for the Pacific Plate are known. A Pacific-Farallon pole and spreading rate for 70 to 60 MaBP has been calculated by C. Chase (quoted in Cooper *et al.*, 1976) and North American motion estimated at between 30 and 50 mm/yr westwards. These motions give a resultant Farallon-America interaction of from 120-170 mm/yr north-east in various separate estimates.

The Kula Plate was by this time interacting with the American Plate at least along the northern part of the continental margin (Fig. 4). The relative motion vector using the pole of Chase, gives N30° E at 130 to 150 mm/yr near the equivalent position of the present Queen Charlotte Islands.

60 to 40 MaBP (mid-Paleocene to Eocene). Many reconstrucctions suggest that by this time, if the Kula Plate was indeed still independent (Byrne, 1979), the Kula/Farallon/America triple junction had moved southwards along the coast. Coney (1977), Cooper *et al.* (1976) and Stone (1977) estimate that it may have reached as far south as the position of the present Queen Charlotte Islands. However, Atwater (1970) suggested that it could have migrated northwards from southern California at 80 MaBP to a position near Vancouver Island by 40 MaBP.

Farallon/America interaction is still high (100 to 150 mm/yr) in a north-easterly direction. A recent calculation of relative angular velocities at 52 MaBP by Harper *et al.* (1981) gives 100 mm/yr at N57° E near Vancouver Island. Kula/America interaction, which could apply to the Canadian Cordilleran margin at least north of Vancouver Island, is consistently more northerly at between 100 and 150 mm/yr. Harper *et al.* (1981) infer 120 mm/yr at N8° E for the Queen Charlotte Island area.

45 to 40 MaBP (late Eocene). This time appears to be a critical one in the plate tectonic framework as it was the occasion for major plate re-orientation. The outstanding manifestation of this is the Emperor-Hawaii 'bend' now dated at 43 MaBP (Dalrymple, quoted in Butler and Coney, 1981) at which the Pacific Plate changed its motion relative to the hot-spot framework by approximately 50°. Attempts have been made to distinguish changes in Pacific-Farallon or Pacific-Kula motion at the same time but are not yet conclusive. A change in Pacific-Farallon motion at Anomaly 16 was originally dated at 42 MaBP but has been subsequently revised to 38 MaBP (Ness *et al.*, 1980). Butler and Coney (1981) argue that changes and re-alignments in Kula-Pacific-Farallon spreading proposed by Byrne (1979) may also be related. In any case, the effect on the western margin of North America is considerable and interaction rates are reduced to half their previous values.

40 to 20 MaBP (Oligocene to early Miocene). Control of oceanic plate motions from this time becomes tighter although it is still based on the assumption of symmetrical spreading. The Pacific-Farallon rotation pole remains to the north (Hanschumaker, 1978). The most notable event during this interval is the collision of the Pacific-Farallon spreading ridge with the western margin of North America and the initiation of the San Andreas Fault (27 MaBP, Atwater and Molnar, 1973). There is some indication that Pacific-Farallon spreading rates dropped near Anomaly 8 time (27 MaBP); subsequently a number of plate adjustments occurred. As Dickinson and Snyder (1979) pointed out, the Farallon Plate descending beneath North America would remain in one piece until the gap or 'slab window' created by the absence of subduction at the San Andreas Fault reached melting depth. At that time (around 20 MaBP), the northern (Juan de Fuca) and southern (Cocos) portions could begin to move independently. Hanschumaker (1978) related a number of other re-adjustments to the collision including initiation of Galapagos

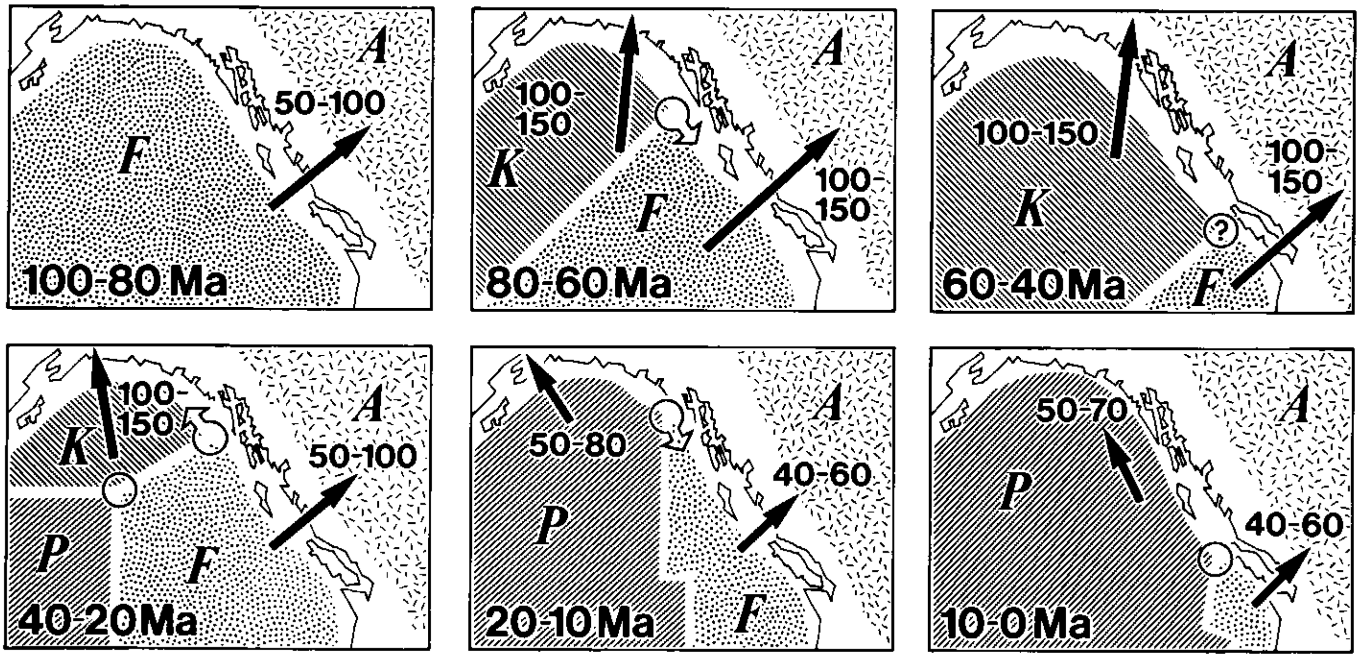

Figure 4 *Plate interactions off western Canada during the last 100 Ma, from a consensus of plate reconstructions (principal sources and Plates are as in Figure 2). Arrows and numbers represent movement relative to America plate in mm/yr or km/Ma. Open circles are triple junction positions with movement where known.*

spreading and clockwise rotations of southern parts of the ridge. Interactions between the Farallon and American Plates were still to the north-east but now varied between 50 and 80 mm/yr. Variations of America Plate motion have been suggested by Molnar and Atwater (1973) which might reduce values to close to 40 mm/yr but still in a north-easterly direction.

The Kula Plate almost certainly disappeared during this interval, the Kula/Farallon/America triple junction migrating rapidly northwards along the Cordilleran margin. Estimated Kula/America interactions are not significantly reduced by the change in Pacific motion if it is assumed that Kula-Pacific spreading remained uniform. Grow and Atwater (1970) suggested that they could be as much as 120 mm/yr in a NNW direction. However, there are no Kula magnetic anomalies of this age that can be used to estimate the pole position, rate or existence of Pacific-Kula spreading.

20 to 10 MaBP (Early to late Miocene). During this period, the Juan de Fuca - Pacific spreading pole is still to the north of the system but spreading rates are diminished considerably from the 80 to 90 mm/yr of the 40 to 20 Ma interval to 50 to 60 mm/yr. This results in a reduced interaction between the Juan de Fuca and America Plates of 40 to 60 mm/yr, still in a north-easterly direction. The Pacific Plate is in contact with the America Plate north of the Juan de Fuca/Pacific/America triple junction which migrates southeastwards along the margin. Pacific-America motion is estimated by most authors at a rate of between 50 and 60 mm/yr to the north-west. However, Atwater and Molnar (1973) suggest that it could be as low as 13 mm/yr. Such a solution would rotate the Juan de Fuca-America interaction vector nearer to N80° E but not significantly reduce its magnitude.

10 to 0 MaBP (late Miocene, Pliocene and Pleistocene). A most significant improvement in geometric plate reconstruction occurs for dates younger than 10 MaBP because it becomes possible to measure magnetic anomaly spacings on both sides of the Pacific-Farallon spreading ridge. Spreading rates continue to decrease during the period and the Juan de Fuca Ridge begins to rotate clockwise. This is associated with a shift of the Farallon (Juan de Fuca) - Pacific Plate rotation pole around 4 MaBP from north of the plate to its present southern position near Tahiti (Riddihough, 1980). The resultant relative clockwise rotation of the Juan de Fuca Plate system results in diminishing north-easterly interaction with the America Plate, rates reducing from 60 mm/yr to 40 mm/yr. During this period the Juan de Fuca/Pacific/America triple junction remained near the north end of Vancouver Island (Riddihough, 1977). Along the margin to the north of the junction, Pacific-America interaction was to the NW or NNW at between 50 and 60 mm/yr. Atwater and Molnar (1973) suggest that it may have been slower before 5 MaBP at about 40 mm/yr.

Geological Implications

One of the most important aspects of these plate tectonic movements in terms of the new ideas in the geological history of the Cordillera is that throughout the last 100 Ma, plate interaction within the region has been predominantly *northerly* (i.e, between north-east and north-west) with respect to the America Plate. It has occurred at rates sufficient that material attached to either the Farallon, Kula or Pacific Plates could have been moved northwards at rates of up to 1000 km in 10 Ma.

The varied movement of triple junctions along the margin also provides a mechanism for the complex sequence of accretion and subsequent strike-slip faulting proposed from the geology. If it is assumed that the margin has been generally oriented in a north to north-westerly direction, much of it has been switched at intervals from northeasterly convergence to northwesterly transform or oblique convergence with the passage of the Kula-Farallon-America or Pacific-Farallon-America triple junctions. This process provides opportunities for exotic material to be brought in, accreted to the margin and then sheared northwards by right-lateral strike slip motion. Considering that the very simple plate tectonic pattern of Figures 2 and 4 is based on limited evidence for the nature of the plates subducted and total ignorance of the geometry of the Kula-Farallon ridge, such episodes could have been much more frequent and complex than implied in Figure 4. If the Kula-Farallon ridge was segmented with transforms in a similar manner to the Pacific-Farallon ridge, then complex interactions of the ridge with the margin may have occurred throughout the 100 to 40 MaBP interval. Figure 5 illustrates an example in which the Farallon Plate becomes segmented with an intervening Kula-America Plate transform analagous to the San Andreas fault system.

The complexity of local response to what at first seems to be a simple tectonic situation has been stressed by Dewey (1975, 1980). It is clear that even at a single plate boundary, the permutation of a limited series of conditions can produce a wide spectrum of tectonic events. Amongst the most fundamental conditions are the local structure of the interacting plates. Although it appears that the Kula and Farallon plates have been predominantly oceanic in nature for much of the last 100 million years, older continental fragments or detached pieces of continental crust (such as that lying west of the San Andreas Fault in California today) could drastically affect local geologic response to their interaction with the America Plate. Similarly the western margin of the America Plate may not always have coincided with a continent-ocean boundary. Five simple models are shown in Figure 6a, any of which could have arisen at the Farallon-America boundary while still fulfilling the broad plate reconstruction framework outlined earlier. The critical importance of the orientation of the boundary between two plates with respect to their direction of relative motion is illustrated in Figure 6b.

Conclusion

As stated in the Introduction, the primary object of this review was to discover if the new tectonic concepts of the western Canadian Cordillera and margin were compatible with the plate tectonic framework that could be deduced from plate geometry alone. There seems little doubt that the plate framework *does give strong support* for the 'collage' concept of Cordilleran geology particularly insofar as the latter requires the importation and accretion of displaced blocks of material from the south and

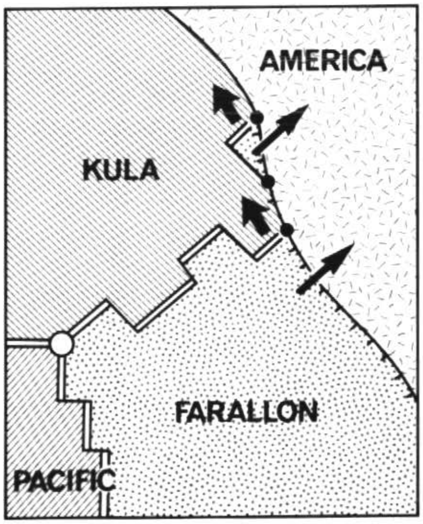

Figure 5 *Sketch of the complexity of interactions at the America margin that could be produced between 100 and 400 MaBP if the Kula-Farallon ridge was segmented in a similar manner to the Pacific-Farallon ridge.*

major episodes of right-lateral strike slip faulting.

Envol

The extent to which geometrical plate tectonic reconstructions for western Canada can be improved without new techniques is limited. Global studies of palaeomagnetism (particularly of the Pacific Plate), of hot-spot stability and marine magnetic anomalies can be expected to steadily improve estimates of relative plate motion over the last 100 Ma. However, the fundamental obstacle remains that the western Cordillera has been the site of plate consumption for most of this period and that much of the detailed sea-floor evidence has been destroyed. Information will have to come from geological and geophysical studies within the western Cordillera which identify sutures, allochthonous blocks, movements, rotation, hot-spots and other features. [For example, the Alert Bay volcanic belt in northern Vancouver Island (Bevier *et al.*, 1979) seems to relate to the recent position of the Pacific/Juan de Fuca/America triple junction. If it has a characteristic petrological or chemical character, it may provide a clue to locating other triple junction positions in the past.] As this work is done, its validity will have to be tested against the broad framework of global plate movements. Preliminary indications are that the geological concepts are compatible. The details will undoubtedly be daunting. Nevertheless, it seems unlikely that a final synthesis that does *not* include large transcurrent movements and the import of exotic blocks of material from the south will prove to be tenable.

A simplified presentation of some of the concepts of this review plus coloured adaptations of Figures 1, 2, and 4 appeared in Geos., v. 10, no. 4, p. 2-5, 1981.

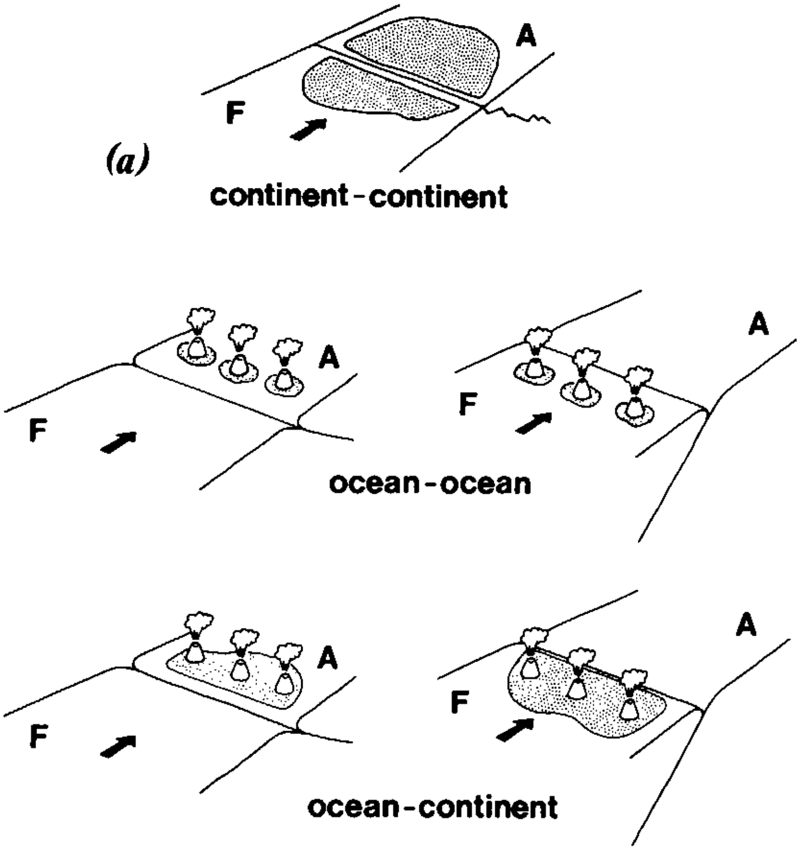

Figure 6 *(a) Sketch illustrating five simple tectonic situations that could arise from the same Farallon-America plate interaction depending on the crust carried on each plate. Each situation would produce different geological, tectonic and geothermal patterns and polarity.*

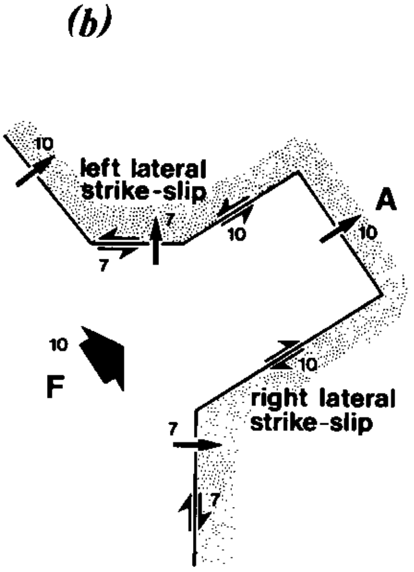

Figure 6 *(b) Variability of Farallon-America interaction depending on the orientation of the boundary between them. Numbers are interaction rates, resolved into parallel and orthogonal components where appropriate.*

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MS received October 27, 1981;
Revised December 4, 1981