THE CANADIAN CORDILLERA

ROGER A. STACEY*

RESUMEN

Se discuten las subdivisiones fisiográficas y geológicas de la Cordillera del Canadá, y se definen los límites actuales entre las Placas de las Américas, del Pacífico y de Juan de Fuca. Se propone una interpretación preliminar de la historia geológica de la Cordillera desde el Proterozoico, en base a la teoría de placas. Se pasa revista a las mediciones aeromagnéticas, de variación magnética, de gravedad y de flujo térmico, a los experimentos de refracción sísmica y a los estudios sismológicos en la región cordillerana y el Océano Pacífico adyacente, y se presenta una tentativa de relacionar estos datos con la historia tectónica de la Cordillera. Los temas de mayor interés son los límites actuales entre las placas de las Américas, del Pacífico y de Juan de Fuca, y la historia reciente del punto triple entre estas placas que se encuentra al NW de la Isla Vancouver. Al interior de la Cordillera los problemas de especial interés son las evidencias de antiguos límites de placas, y el estudio de las características físicas de la corteza y del manto superior.

ABSTRACT

The physiographic and geologic subdivisions of the Canadian Cordillera are reviewed and the present boundaries between the American, Pacific and Juan de Fuca plates are defined. A preliminary interpretation of the geological history of the Cordillera since the Proterozoic is presented in terms of plate theory. The results of aeromagnetic, magnetic variation, gravity and heat flow measurements, refraction seismic experiments and seismology studies over the Cordilleran region and the adjacent Pacific Ocean are reviewed and an attempt is made to relate these data to the tectonic history of the Cordillera. Areas of special interest are the present day boundaries between the American, Pacific and Juan de Fuca plates and the recent history of the triple junction between these plates northwest of Vancouver Island. Within the Cordillera interest is focused on the recognition of older plate boundaries and the study of the physical characteristics of the crust and upper mantle.

* *Department of Energy, Mines and Resources, Ottawa, Canada.*

INTRODUCTION

The purpose of this paper is to present a broad section through western Canada between 49°N and 56°N that extends from the Interior Plains, through the Cordilleran mobile belt to the Pacific Ocean. We shall look at the physiographic, geological and geophysical characteristics of each of the main regions: the Interior Plains, the Cordillera and the Pacific, and at the nature of the transitions between them. The main episodes in the geological history of the Cordilleran mobile belt from the late Proterozoic to the present will be interpreted in terms of the interaction between oceanic plates of the Pacific area and the western margin of the American continent.

PHYSIOGRAPHIC AND GEOLOGICAL DIVISIONS

1. *The Interior Plains*

In the east the Plains extend over 1 000 km from the Canadian Shield of central and eastern Canada to the Rocky Mountain front (Fig. 1). Elevations range from near sea level around Hudson Bay in the east to about a kilometer near the Rocky Mountains. Geologically, the Plains are a westward thickening wedge of late Proterozoic to early Cenozoic sediments overlying the Canadian Shield. The maximum thickness of the sediments is about 5 km below the axis of the Rocky Mountain thrust belt. Within the last 25 years oil and gas deposits have been discovered thoughout the western part of the Plains in rocks ranging in age from Devonian to Cretaceous. This region, underlain by the Precambrian Shield, can be regarded as the stable craton when considering events to the west.

2. *The Cordilleran Mobile Belt*

The southern part of the Canadian section of the Cordillera is 800 km wide and lies between the Precambrian craton and the Pacific Ocean. The region, which appears to have been most active from the mid-Mesozoic to the early Cenozoic, can be sub-divided on physiographic and geological grounds into five distinctive units. These are from east to west:

a) The Rocky Mountain thrust belt formed during the Cretaceous and early Tertiary and probably overlying the western part of the Precambrian craton,

b) The Columbia Mountains metamorphic belt which developed between the late Triassic and the early Cretaceous along the continental shelf marking the western margin of the craton during the Paleozoic and early Mesozoic,

c) The predominantly Mesozoic volcanic and sedimentary sequences of the Interior Plateau – now largely covered by Cenozoic lavas,

d) The late Jurassic to early Tertiary Coast Mountains metamorphic complex, and

e) The Insular Belt which includes the predominantly Mesozoic volcanic areas of Vancouver Island and the Queen Charlotte Islands and the intervening Cenozoic sedimentary basins of the continental shelf. The search for oil on the continental shelf has begun but nothing has been found so far.

These zones contain evidence of orogenic activity extending from the late Proterozoic to Recent times. An attempt has been made to interpret the geological history of the Cordillera in terms of plate tectonics. We will retur to this later.

3. The Pacific Ocean

Off western Canada the continental shelf is generally less than 50 km wide and the ocean beyond is about 3 km deep, obscuring two important geological units –the large Pacific plate moving northwestwards relative to the American continent along the Queen Charlotte transform fault, and the small Juan de Fuca plate lying between the Juan de Fuca ridge and Vancouver Island. The Pacific plate is characterized by a fairly uniform sedimentary cover interrupted by occasional northwest trending seamount chains. The Juan de Fuca plate is completely covered by sediments along the foot of the continental slope. The sediments along the foot of the continental slope may fill a trench which marked a late Cenozoic subduction zone between the Juan de Fuca and American plates. The triple junction between these plates appears to be a region of closely spaced transform faults along the continental margin between the northern end of Vancouver Island and the southern end of the Queen Charlotte Islands.

GEOPHYSICS

In this section we shall discuss the available magnetic, gravity and seismic data, their interpretation and their relationship to the regional geology of the Plains, the mobile belt and the oceanic area.

1. Regional Magnetic Measurements

Aeromagnetic measurements at 5.5 km elevation (Fig. 2) show:

a) Broad northeasterly trending anomalies of 500 γ or more east of the Rocky Mountain Trench. These anomalies must be related to the Precambrian basement as there is no magnetic material within the 3 – 5 km of sedimentary cover. Abnormally high magnetisation values are required to account for the amplitude of some of these anomalies.

b) Within the mobile belt anomalies trend northwesterly and there are two "flat" zones corresponding to the Columbia and the Coast Mountain metamorphic belts. A strong positive anomaly of up to 800 γ follows the coast of the mainland.

c) Over the Pacific the north-south trending pattern of parallel anomalies associated with ocean floor spreading can be recognised.

2. Magnetic Variation Measurements

Simultaneous measurements of the H, Z and D components of the Earth's magnetic field at up to 40 stations show a marked decrease in the amplitude of the Z variations west of the Rocky Mountain Trench. This change has been explained by an increase in the electrical conductivity of the upper mantle –probably with a corresponding increase in the temperature gradient west of the Trench. The transition from normal to low amplitude Z variations has been associated with the edge of the Precambrian craton in Canada, the United States and elsewhere.

3. Regional Gravity Measurements

There are about 8 000 land and underwater gravity observations in southwest Canada plus about 2 000 line kilometers of surfacemeter data off the coast. As expected, the free air anomalies show a strong correlation with local topography, being up to +100 mgal on mountain peaks and –100 mgal in the valleys. Bouguer anomalies show a correlation with regional changes in elevation, decreasing at approximately 100 mgal per kilometer increase in elevation. Although local anomalies related to density changes in the surface rocks can be recognised on the Bouguer map, the anomalies are often distorted by the correlation between the Bouguer values and elevation. The best way of demonstrating gravity changes in mountainous regions is to compute the isostatic anomalies which, in theory, should not be related to changes in elevation (Fig. 3).

The Airy-Heiskanen form of compensation has been assumed with the crust thicker than normal below mountains and thinner than normal for oceanic areas. In this case, a normal crustal thickness of 30 km has been assumed with a density contrast between the crust and upper mantle of 0.4 g/cm^3. Despite the simplification necessary in the diagram, it is evident that there are northeast trending positive anomalies east of the Rocky Mountain Trench which correspond to the areas of positivie magnetic anomaly. The partially defined +40 mgal anomaly over the highest part of the Rocky Mountains thrust belt can be related to a repeated sequence of dense lower Paleozoic limestones. Within the Cordillera positive anomalies generally correspond to volcanic sequences and negative anomalies to granitic rocks. Along the coast there is a belt of positive anomalies which coincides with the positive magnetic anomaly along the coast. Regional geological mapping of the Coast Mountains is almost complete and specific gravity measurements on several thousand samples confirm that the western part of the complex is denser than the central and eastern parts. The magnetic properties of these samples have not yet been determined. The positive gravity anomaly along the coast is interrupted by an east-west negative at 52°N which extends across the continental shelf and through the Coast Mountains metamorphic complex. The magnetic anomaly shows no such interruption at this latitude so it is possible that the source of the east-west gravity anomaly is deep seated and related to the Juan de Fuca plate underlying the continental area south and east of the triple junction off the continental margin at this latitude.

Between Vancouver Island and the mainland and between the Queen Charlotte Islands and the mainland the negative anomalies correspond to Tertiary sedimentary basins. Both Vancouver Island and the Queen Charlotte Islands are characterised by 20 to 40 mgal positive anomalies with large negative anomalies on the shelf and slope west of Vancouver Island and at the foot of the slope west of the Queen Charlotte Islands. The wavelength of these anomalies is much greater south of the triple junction than it is to the north across the Queen Charlotte transform fault. Between these islands in the vicinity of the triple junction and the east-west negative anomaly mentioned earlier, there is no well-defined positive or negative anomaly near the shelf break. To the west over the Pacific Ocean anomalies are generally about +10 mgal except in the vicinity of seamounts where they are strongly positive.

4. Seismic Experiments

The results of refraction and reflection seismic experiments have been superimposed on the Airy-Heiskanen compensated crustal model used to compute the isostatic anomalies (Fig. 4). Below the Plains the seismic data show a layered crust with the M-discontinuity at 47 km considerably deeper than in the gravity model. Within the mobile belt no crustal layering has been detected from the seismic data and there is a much better agreement between the crustal models. The same is true for the continental shelf north of the triple junction, but to the south of the junction the M-discontinuity has been estimated from seismic data to be at least 50 km deep with an abnormally low P_n velocity. The crust of the Pacific plate west of the Queen Charlotte Islands is about 11 km thick –surprisingly thin considering that there is only 3 km of water in this area, and very much thinner than the crust in the gravity model.

5. Discrepancies Between the Gravity and Seismic Crustal Models

The differences between the compensated crustal model used to compute the isostatic anomalies and the thickness of the crust determined by seismic techniques may be interpreted in a number of ways:

a) The areas of discrepancy may not be in isostatic equilibrium,

b) Compensation for the topography may not be in the form of roots,

c) The base of the compensated crust may not correspond to the M-discontinuity,

d) The assumed normal thickness of the crust and density contrast between the crust and the upper mantle may not be valid for all regions and the density of both the crust and the upper mantle may vary from one region to another.

Stacey (1973) has interpreted the gravity data on the assumption that the area is in isostatic equilibrium and that the compensation for the topography is in the form of roots and that the base of the crust corresponds to the M-discontinuity. Residual anomalies, after the effects of the surface geology have been filtered out, have been related to changes in the density of the crust and the upper mantle to a depth of 100 km (the average thicknes of the lithosphere). Below this level it has been assumed that the asthenosphere cannot maintain lateral variations in density. Two possible models for the Cordillera at 50°N which reconcile the seismic and the gravity data are shown in Fig. 5. In both cases the crust and the upper mantle below the Plains region underlain by the Precambrian Shield are denser than the crust and upper mantle below the mobile belt and the oceanic area to the west. The residual gravity anomaly over Vancouver Island can be interpreted as either abnormally high density crust or as abnormally low density mantle. In either case, the anomaly is probably related to the presence of the underthrust part of the Juan de Fuca plate.

6. Seismicity and Magnetic Measurements in the Oceanic Area

In the oceanic region, seismicity (Fig. 6) gives us some idea of present day tectonic activity, while the linear magnetic anomalies associated with ocean floor spreading from the Juan de Fuca ridge give us information on the late Cenozoic history of the region. Starting with the seismicity, we can see it is related to the Queen Charlotte and Blanco transform faults. The scattering of epicenters off Vancouver Island is due partly to poor locations, but it is probably adequate to suggest movement is occurring along several closely spaced transform faults near the triple junction. Although the triple junction appears to be of the ridge-fault-trench type, there are, at present, no deep earthquakes below the American continent east of the Juan de Fuca plate –this point will be returned to later. The magnetic anomalies (Fig. 7) show the position of the ridge axis and displacement of the magnetic lineations within the Juan de Fuca plate suggests fracturing has occurred in the recent past. Lineations within the Juan de Fuca plate trend north-northeast rather than north-south as they do in the main Pacific plate, suggesting either a change in the spreading direction about 10 m.y. ago or a very recent clock-wise rotation of the Juan de Fuca plate.

GEOLOGICAL HISTORY

The review of the main events in the tectonic history of the Canadian section of the Cordillera which follows is based on the reconstruction by Monger *et al* (1972).

a) *Proterozoic and Paleozoic (1 600 – 200 m.y.)*

For most of this period (Fig. 8a), there was a prograding continental shelf along the western edge of the Precambrian Shield. The shelf extended as far west as the Interior Plateau with oceanic crust for an unknown distance further west. This broad concept was interrupted from time to time as evidenced by changes in the character of the sediments and occasional periods of volcanicity and intrusive activity. For instance, the late Proterozoic Racklan-East Kootenay period of intrusive activity, and again during the mid-Paleozoic there may have been a period of obduction with oceanic crust being thrust onto the continental shelf which corresponded to the Antler orogeny recognised in the United States.

b) *Triassic (200 m.y.)*

The first recognisable island arc developed during the late Triassic and today marks the boundary between the Columbia metamorphic belt and the Interior Plateau (Fig. 8b). Monger *et al* believe it was associated with an eastward dipping subduction zone along what was then the continental margin. It is possible that the late Paleozoic suite of limestones, cherts and ultrabasic rocks exposed west of the volcanic arc represents oceanic crust. The sub-volcanic plutons exposed today within this arc are important sources of copper. According to this reconstruction the Columbia metamorphic belt represents the altered remnants of continental shelf deposits and may include part of the Precambrian crystalline basement.

c) *Mid-Jurassic to Mid-Cretaceous (170 – 100 m.y.)*

Between the end of the Triassic and the mid-Jurassic it appears that the subduction zone jumped or gradually migrated westwards to a position near the present continental margin (Fig. 8). This new arc probably developed some distance west of the continental margin and its roots are now exposed in the Coast Mountains metamorphic complex. As subduction below the Triassic arc ceased and the boundary between the American and the oceanic plates moved westwards, uplift of the Columbia metamorphic belt began –culminating in the Cretaceous and early Tertiary with the Laramide orogeny and the development of the Rocky Mountains. One can visualize the sediments overlying the rising core zone of the metamorphic belt sliding eastwards under the influence of gravity to form the Rocky Mountain thrust belt. The predominantly eastward motion possibly being a reflection of the asymmetric structure of the original subduction zone.

Between the new arc and the rising Columbia metamorphic belt a number of short-lived basins developed in different parts of what is now the Interior Plateau. At the same time a number of northwest trending right lateral wrench faults were active in the central part of the Cordillera, but their importance in the tectonic development of the Cordillera is not clear. As motion on these faults ceased during the early Tertiary, motion in the same sense began along faults on the Queen Charlotte Islands which can probably be related to the transform fault system marking the continental margin.

d) *Tertiary to Recent (80 m.y. to the present)*

The initial uplift of the Coast Mountains metamorphic complex occurred during the Cretaceous and may have been related to a change in the relative motion of the American and the oceanic plates-possibly the beginning of the northerly motion of the Pacific plate (Fig. 8d). Volcanic activity in the Cordillera continued throughout the Cenozoic, ranging from explosive eruptions during the early part of the Tertiary to the quiet effusion of plateau basalt during the Miocene and Pliocene and the construction of nearly 150 cinder cones and stratovolcanoes during Pleistocene and Recent times. At the same time, sedimentary basins developed on the continental shelf.

Today, off the west coast of Canada, we have a ridge-fault-trench type triple junction between the Pacific, American and Juan de Fuca plates. Considering first the Queen Charlotte transform fault between the Pacific and American plates, fault plane solutions for some of the major earthquakes indicate that the Pacific plate is moving northwestwards with respect to the American. Reflection seismic lines across the Queen Charlotte fault (Fig. 9a) show a narrow continental shelf, a very steep slope and evidence of faulting involves the oceanic basement. To the west, the sediment cover of the Pacific plate appears to be fairly uniform.

The northern end of the Juan de Fuca ridge has been offset to the north by a number of transform faults approximately parallel to the main Queen Charlotte fault. The first segment of the ridge to be offset is generally referred to as the Explorer ridge and is an area of rugged topography, high heat flow and recurrent seismicity. The local magnetic anomalies associated with the many seamounts in the region destroy the linear pattern of anomalies that might be expected either side of the ridge. The axes of the small ridge segments at the northern end of the Juan de Fuca ridge appear to have been rotated clockwise and now trend northeast-southwest approximately perpendicular to the transform faults, rather than north-northeast parallel to the main Pacific and American plates.

Over the "trench" boundary between the Juan de Fuca and the American plates a seismic reflection profile off Vancouver Island (Fig. 9b) shows a prograding continental shelf with at least two kilometers of sediment at the foot of the slope. This sedimentary basin extends as far west as the Juan de Fuca ridge which has acted as a barrier to further distribution. Seismic activity along the western margin of the American plate opposite the supposed subduction zone is sporadic and shallow (the deepest event recorded being 60 km near Seattle), there is no indication of a Benioff seismic zone. However, the seismic activity represents only the present situation, the geological evidence strongly suggests an east dipping subduction zone existed opposite the Juan de Fuca plate during the Cenozoic. There is a volcanic arc approximately 200 km east of the continental margin that extends south from the triple junction and was active during this period but is now dormant, there is a trench at the foot of the continental slope, which is now filled with sediments and a low heat flow zone has been outlined in Canada between the trench and the arc. Together these observations indicate that the Juan de Fuca plate was being destroyed below the western margin of the American plate during the latter part of the Cenozoic and possibly even earlier. The apparent absence of subduction today could be related to the rotation of the Juan de Fuca plate indicated by the difference in the orientation of the magnetic lineations within the plate as opposed to those of the Pacific plate. The present seismicity in the vicinity of the triple junction could then be related to compression between the rotating Juan de Fuca plate and the American plate as well as northwesterly translation of the oceanic plates. If oceanic crust is still being generated along the Juan de Fuca ridge despite the lateral movement produced by rotating the plate, then the area should be of fundamental interest in the study of mechanisms for producing oceanic crust along ridges.

SUMMARY

Fig. 10 shows what I believe is the present tectonic situation on the west coast of Canada. The present plate arrangement is superimposed on a late Mesozoic-early Cenozoic configuration in which a plate (the Farallon?) dipped under the American between Alaska and the United States-Canada border at 49°N. This plate was related to the development of the Coast Mountains metamorphic belt. Previous to this, during the early Mesozoic, there was an east dipping plate along the Paleozoic continental margin between the Yukon and Idaho which gave rise to the Columbia metamorphic belt. The initiation of this plate may have coincided with the break-up of the Atlantic Ocean which also occurred during the early part of the Mesozoic. Throughout most of the Paleozoic and the late Proterozoic there was an Atlantic-type continental shelf along the western margin of the Precambrian craton.

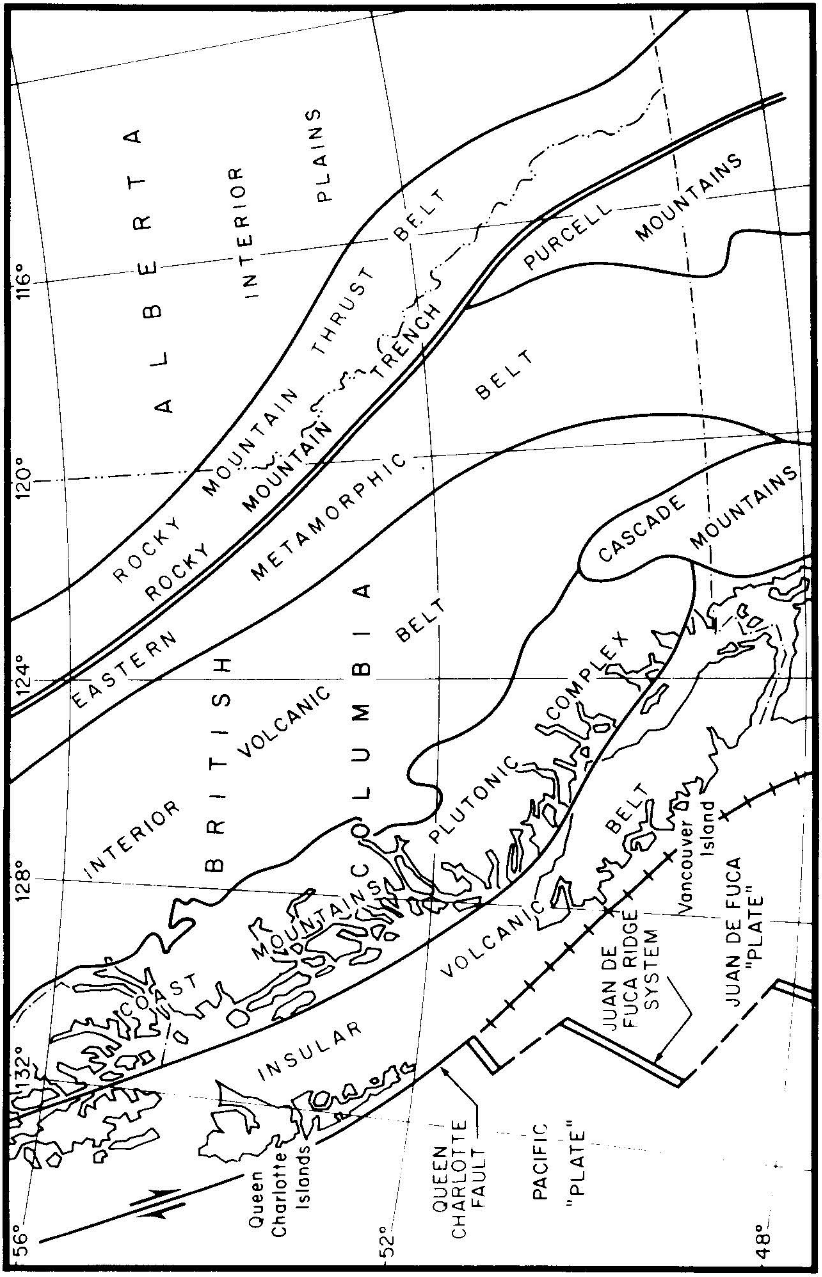

Figure 1. Physiographic and geological divisions of the Canadian Cordillera.

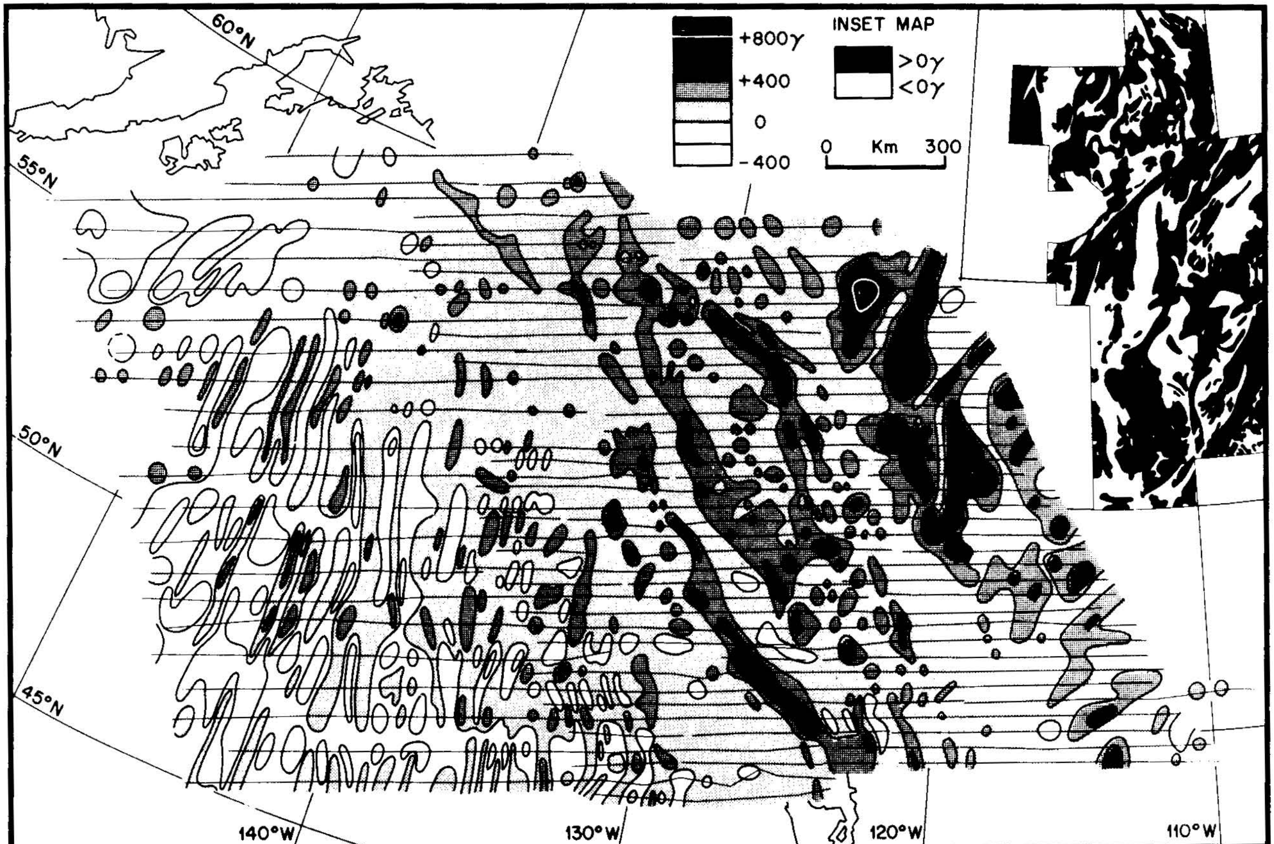

Figure 2. The vertical component of the magnetic field relative to the IGRF for the Canadian Cordillera and the adjacent Pacific Ocean. Insert shows the total magnetic field anomalies from GSC Map 1255A. (Haines *et al*, 1971).

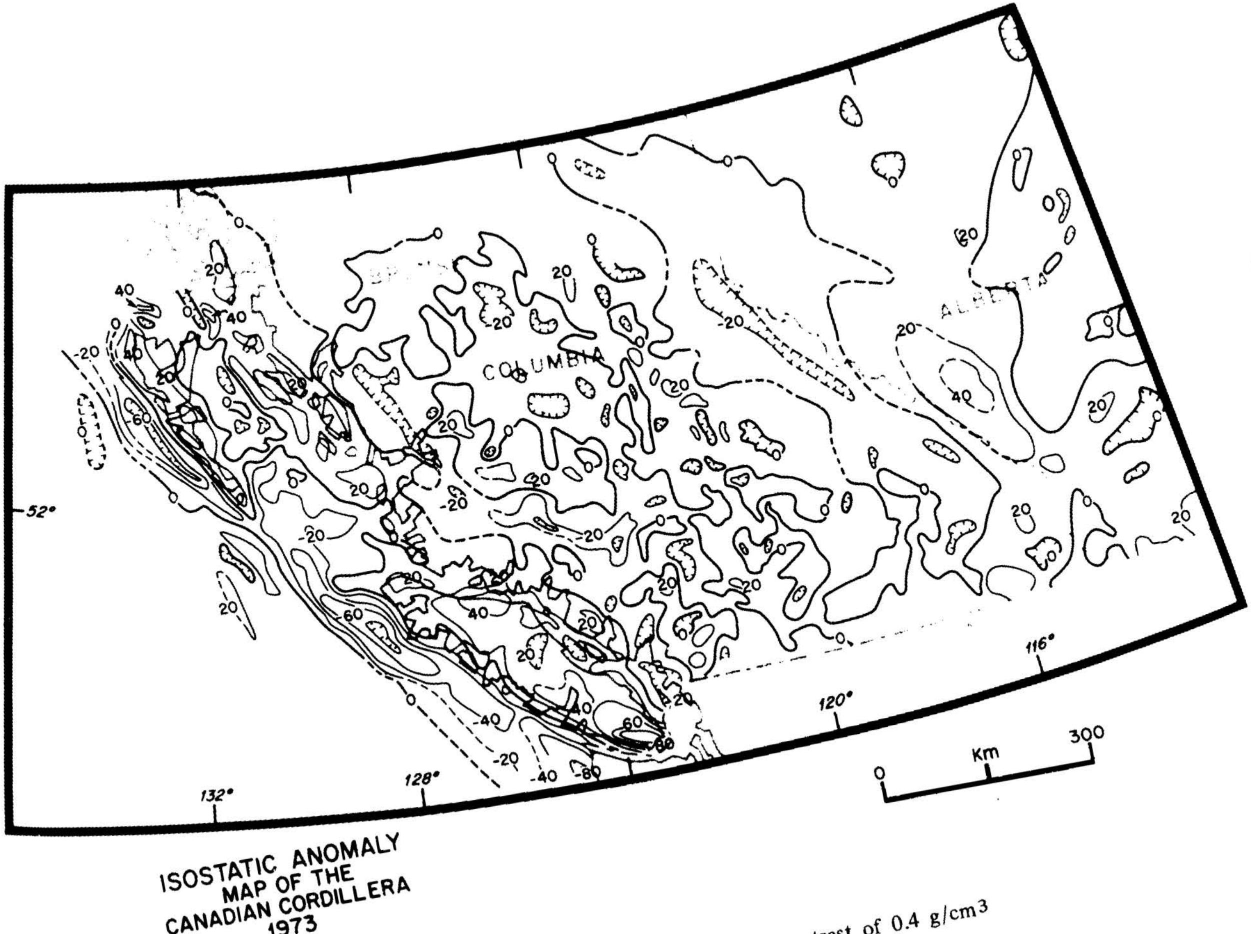

Figure 3. Airy-Heiskanen isostatic anomalies for T = 30 km and a density contrast of 0.4 g/cm3

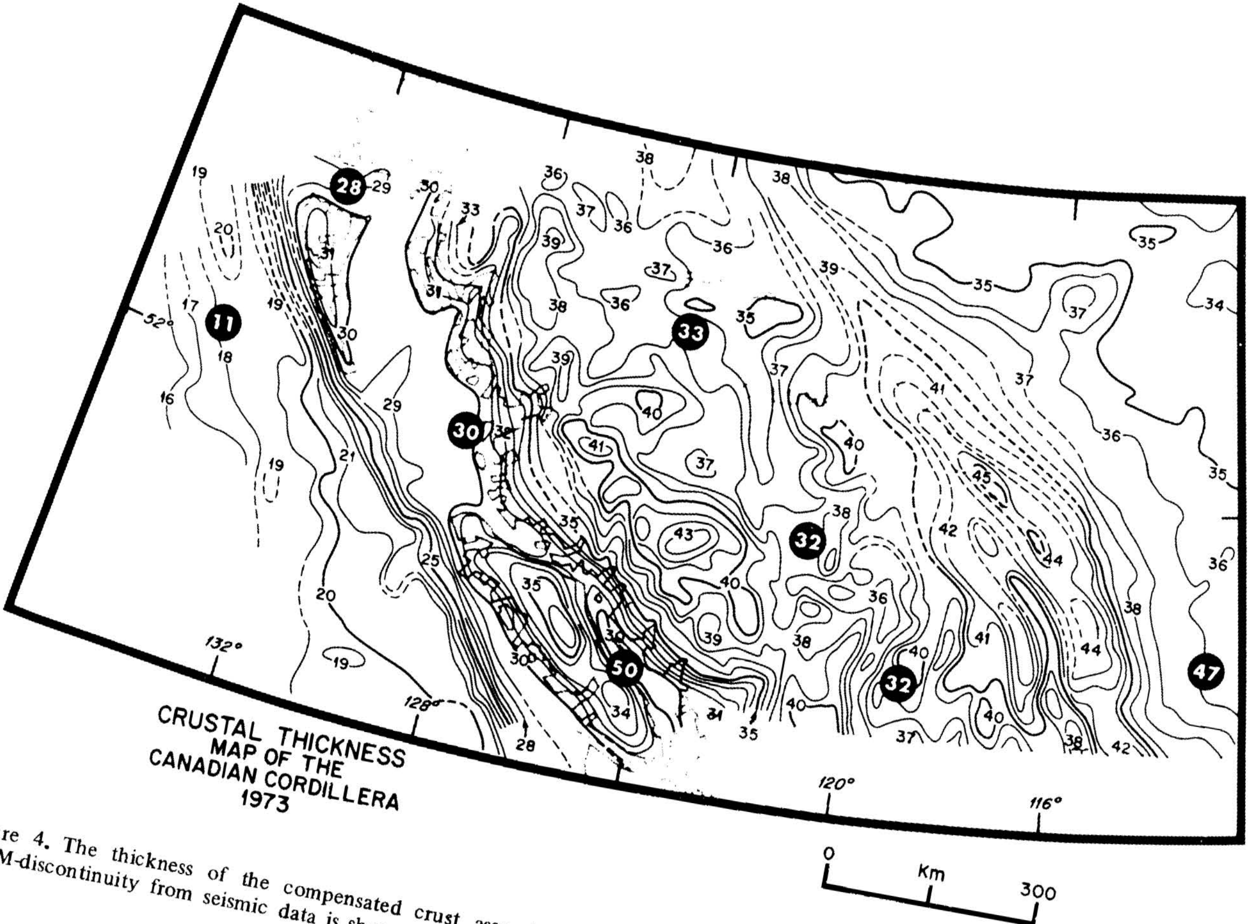

Figure 4. The thickness of the compensated crust assuming T = 30 km and a density contrast of 0.4 g/cm^3. The depth to the M-discontinuity from seismic data is shown in the large figures.

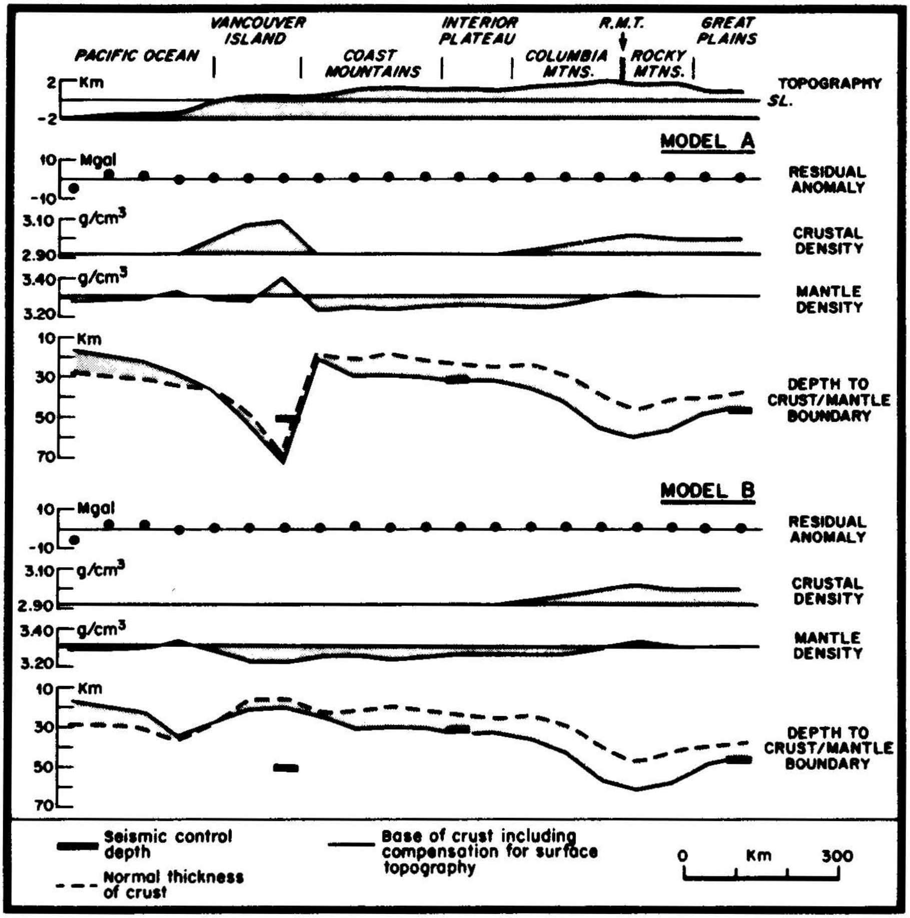

Figure 5. Two possible models for the crust and upper mantle at 50° N (Stacey, 1973).

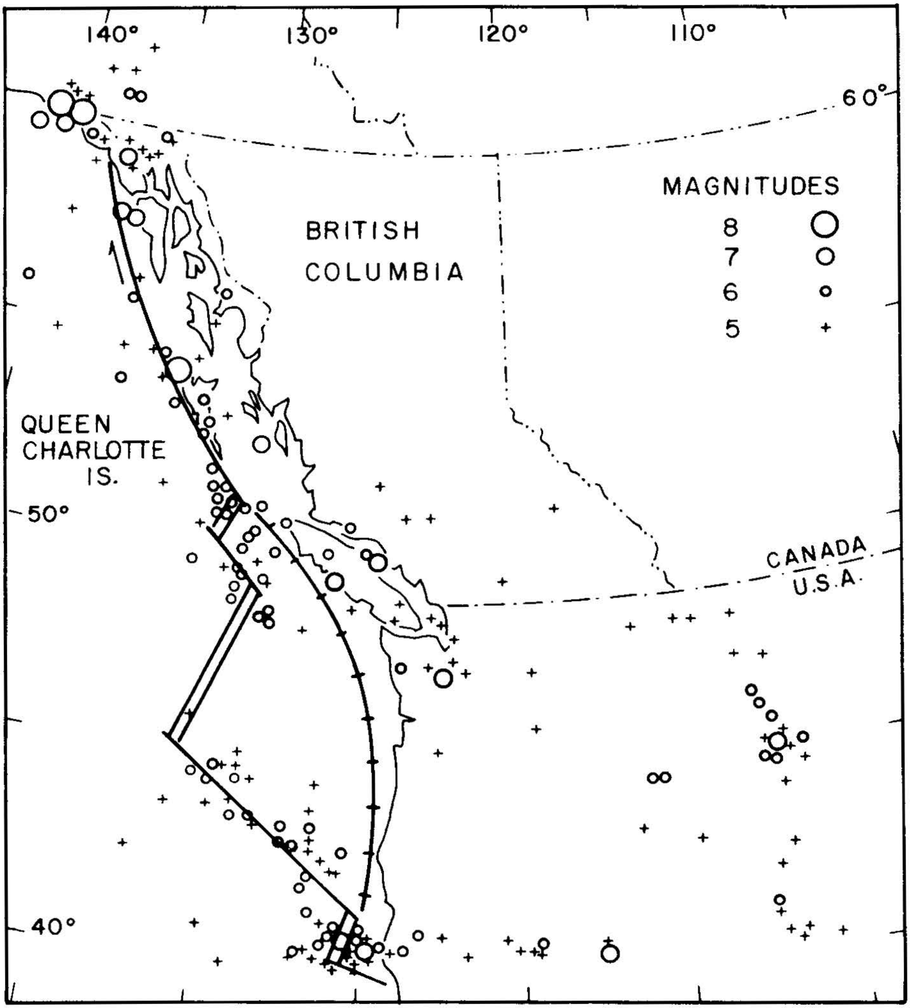

Figure 6. Epicentres in western Canada (modified from Milne *et al*, 1967).

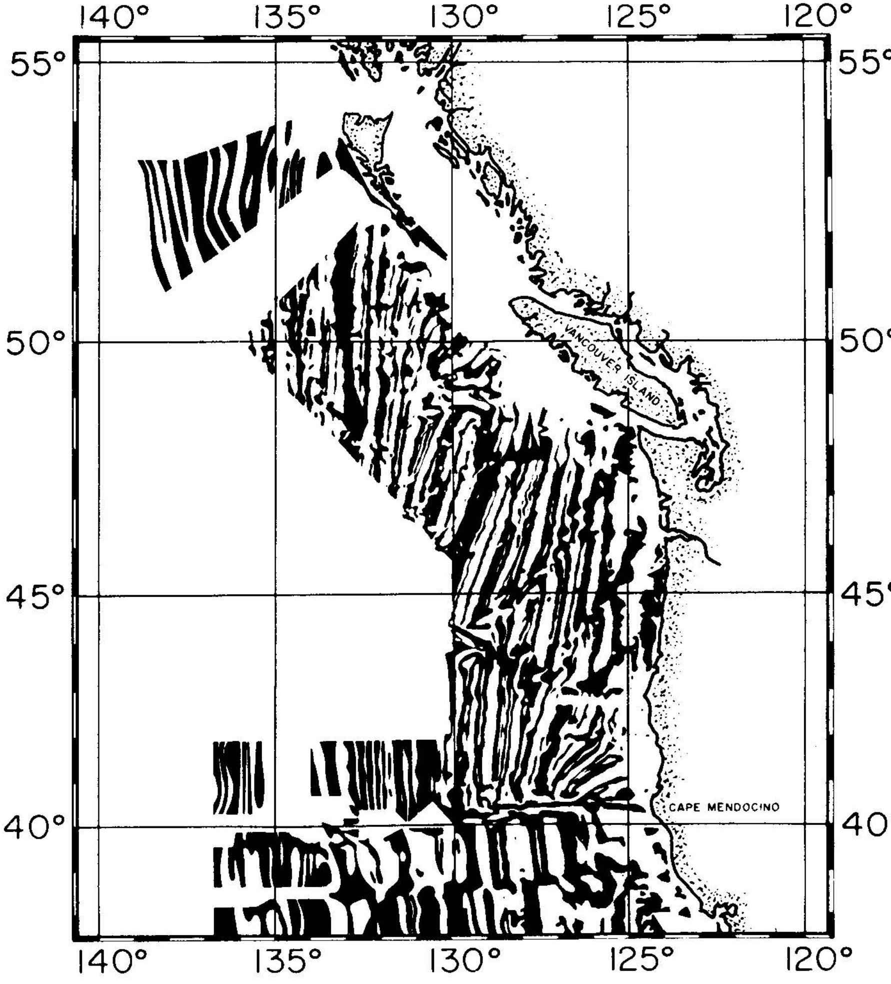

Figure 7. Total magnetic field anomalies over the Pacific Ocean off Canada and the northwestern United States (Dehlinger *et al*, 1970).

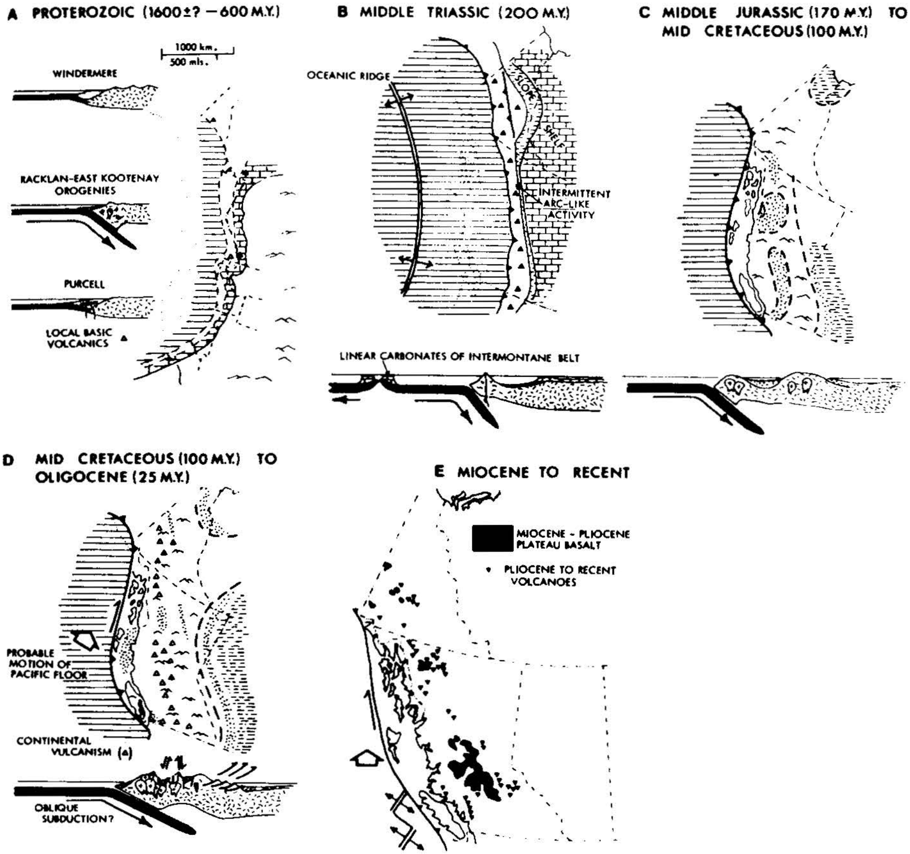

Figure 8. The main episodes in the development of the Canadian Cordillera (Monger *et al*, 1972).

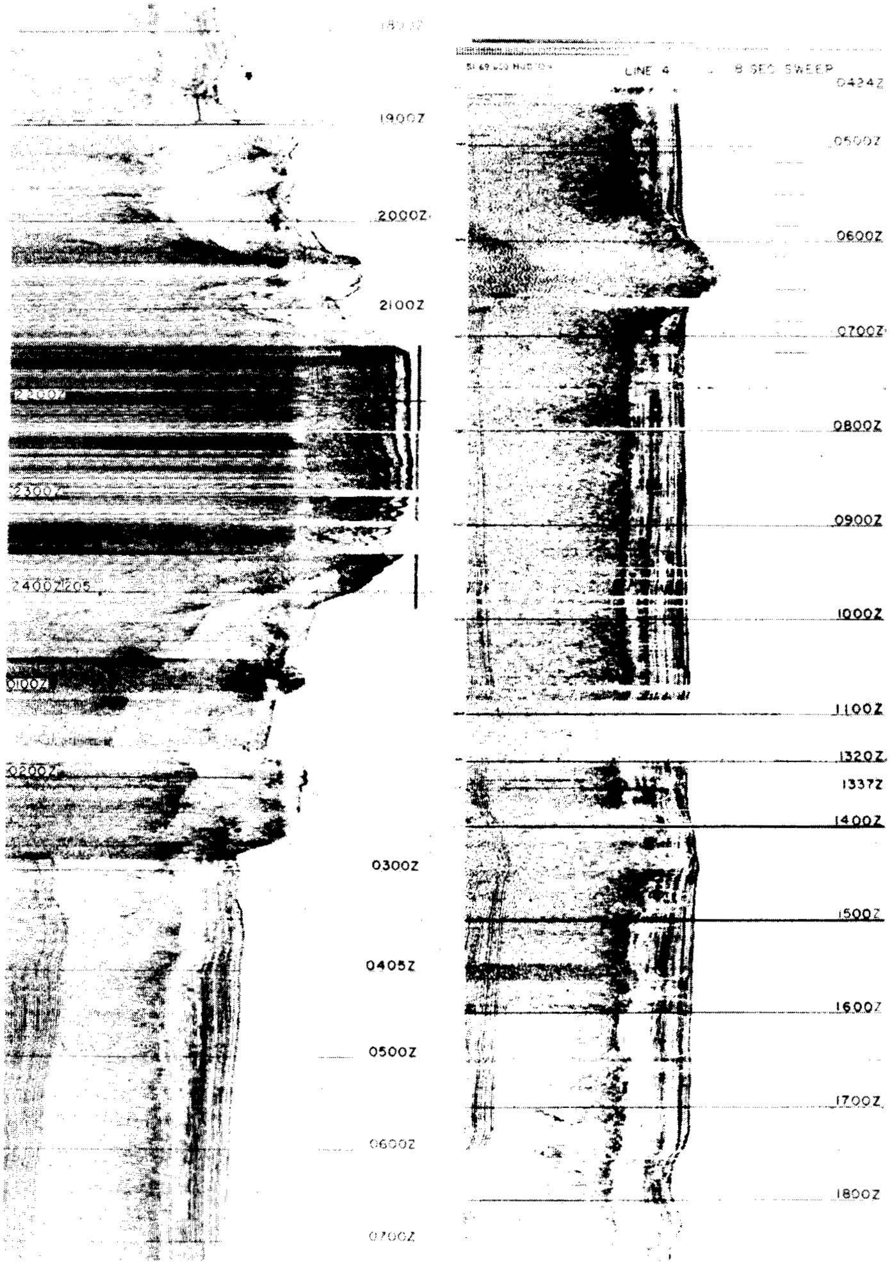

Figure 9a. A seismic reflection profile across the Queen Charlotte fault at 52°15'N (Srivastava *et al*, 1971).

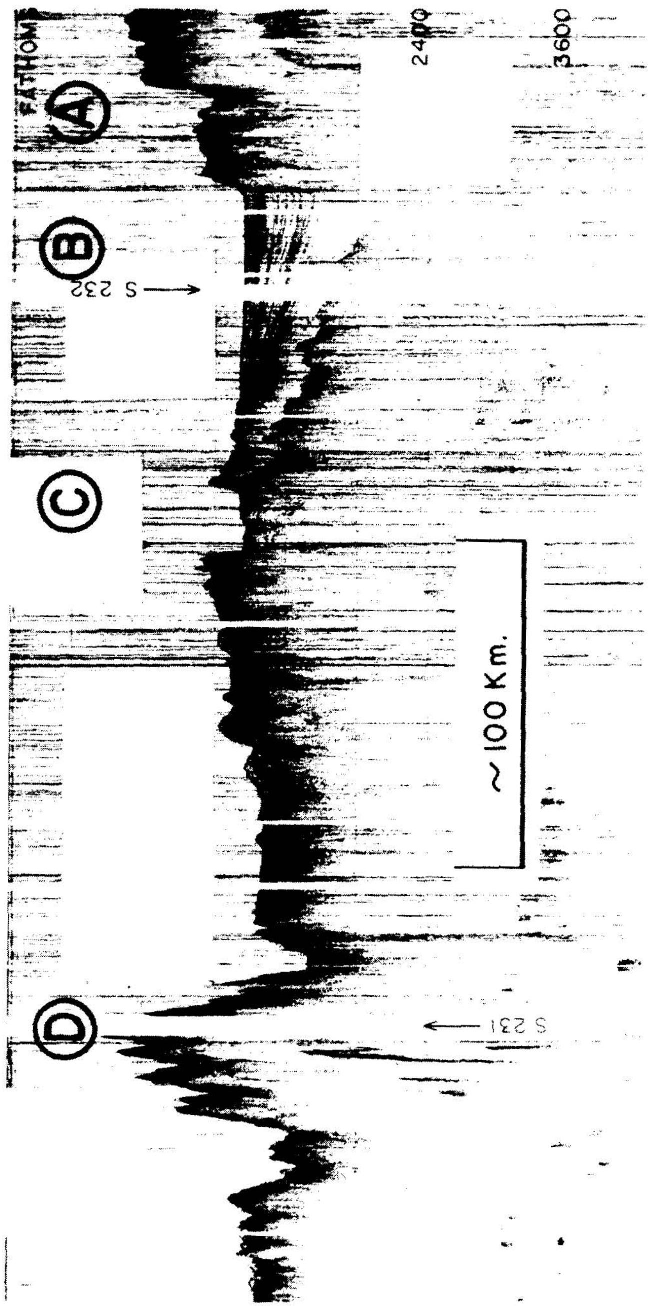

Figure 9b. A seismic reflection profile off southern Vancouver Island at approximately 48°30'N (Hayes and Ewing, 1970). "A" is the continental margin. "B" the sediment covered Juan de Fuca plate and "C" the end of the Juan de Fuca ridge "D" the explore ridge.

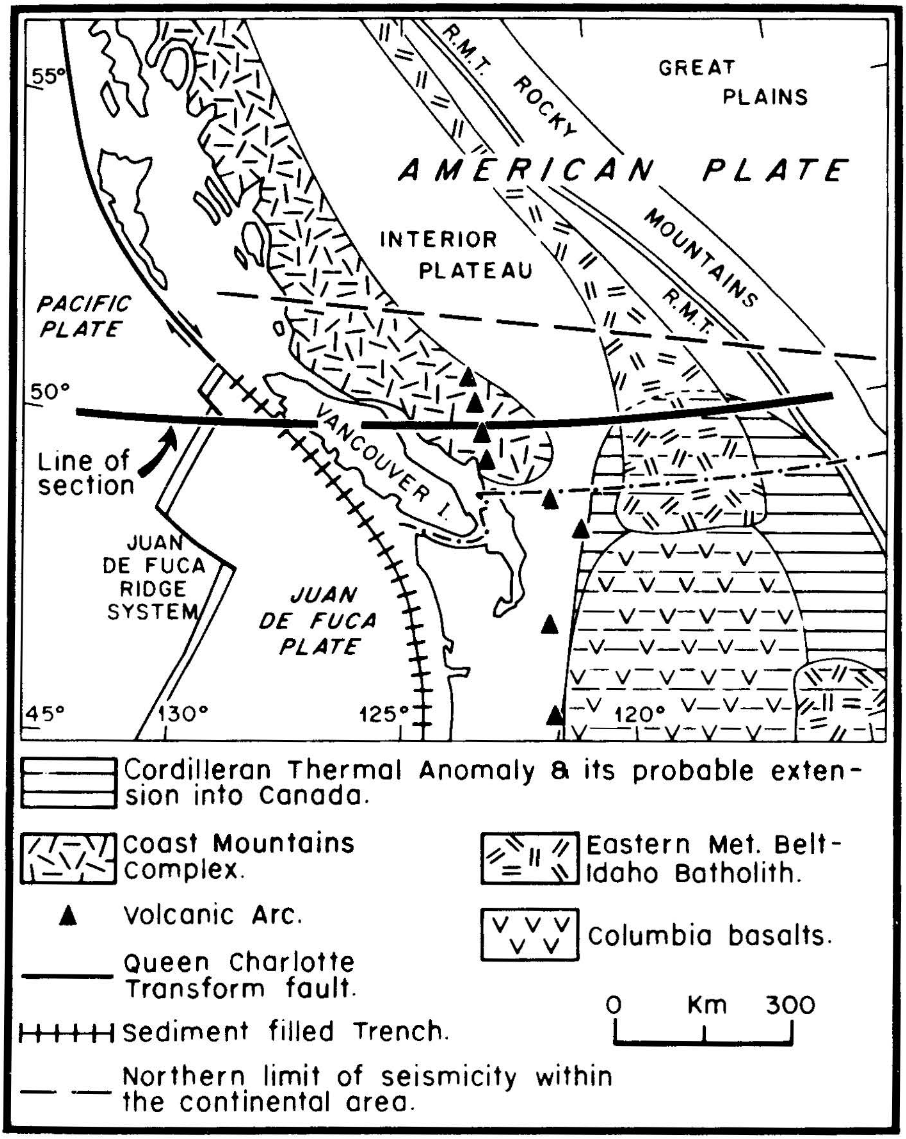

Figure 10. The present tectonic setting of the southern Canadian Cordillera (Stacey, 1973). The line of section refers to the models in Fig. 5.

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