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GEOPHYSICAL MEASUREMENTS IN BRITISH COLUMBIA

with maps: No. 120 — Strait of Georgia
No. 121 — Juan de Fuca Strait

R. A. Stacey and J. P. Steele

DEPARTMENT OF ENERGY, MINES AND RESOURCES

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WITH MAPS

120 STRAIT OF GEORGIA

121 JUAN DE FUCA STRAIT

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GEOPHYSICAL MEASUREMENTS IN BRITISH COLUMBIA

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ABSTRACT - Bathymetric, gravity and magnetic measurements are presented for the Strait of Georgia between Vancouver Island and the mainland of British Columbia, and for Juan de Fuca Strait between Vancouver Island and Washington, U.S.A. It has been concluded from the bathymetric data for the Strait of Georgia that most of the submarine topography dates from the Pleistocene epoch, although some of the larger channels may correspond to important faults which are probably older than Pleistocene. The majority of the Strait appears to be underlain by Cretaceous - Tertiary sediments concealed beneath a veneer of glacial debris. Below the Cretaceous - Tertiary sediments on the Vancouver Island side of the Strait are the largely volcanic sequences of Mesozoic age typical of the Island, and below the sediments on the mainland side of the Strait are plutonic rocks typical of the Coast Mountains complex. The boundary between the volcanic sequences and the plutonic rocks is marked by a prominent magnetic gradient along the centre of the Strait, and corresponds to a submarine topographic feature which suggests that a fault has been active since the early Tertiary. In the Juan de Fuca region, the geophysical evidence indicates that the east-west faults on Vancouver Island may extend across the continental shelf at the western end of the area and may have controlled the formation of the Juan de Fuca submarine canyon. A minor fault along the axis of the Strait can be inferred from submarine geology, but this cannot easily be related to the major crustal change indicated by the gravity results.

RÉSUMÉ - Le présent ouvrage donne des mesures bathymétriques, gravimétriques et magnétiques pour le détroit de Géorgie, entre l'île Vancouver et la partie continentale de la Colombie-Britannique, et pour le détroit de Juan de Fuca, entre l'île Vancouver et l'État de Washington (É.-U.). Les données bathymétriques relatives au détroit de Géorgie ont permis de conclure que la plus grande partie de la topographie sous-marine date du Pléistocène, bien que certains des plus grands chenaux peuvent correspondre à des failles importantes, probablement antérieures au Pléistocène. La plus grande partie du détroit semble reposer sur des sédiments du Crétacé-Tertiaire, recouverts d'une couche superficielle de débris glaciaires. Sous les sédiments du Crétacé-Tertiaire de la partie du détroit du côté de l'île Vancouver se trouvent des séquences en majorité volcaniques datant du Mésozoïque, et qui sont typiques de l'île; sous les sédiments du côté continental du détroit se trouvent des roches plutoniques typiques du complexe de la chaîne Côtière. La limite entre les séquences volcaniques et les roches plutoniques est marquée par un gradient magnétique important qui suit le centre du détroit; elle correspond à un trait topographique sous-marin qui suggère l'existence d'une faille à cet endroit depuis le début du Tertiaire. Dans la région de Juan de Fuca, les éléments géophysiques indiquent que les failles orientées d'est en ouest sur l'île Vancouver peuvent s'étendre à travers le plateau continental à l'extrémité ouest de la région et peuvent avoir eu un rôle prépondérant dans la formation du canyon sous-marin de Juan de Fuca. La géologie sous-marine permettrait de soupçonner l'existence d'une faille plus petite le long de l'axe du détroit, mais il est difficile de la relier à l'importante modification corticale indiquée par les mesures gravimétriques.

INTRODUCTION

The Strait of Georgia occupies a low-lying area between Vancouver Island and the mainland of British Columbia and Juan de Fuca Strait lies between the south end of Vancouver Island and the Olympic Peninsula of northern Washington (Figure 1). Bathymetric, gravity and magnetic measurements together with continuous reflection seismic profiles were made from the C. S. S. Parizeau during September 1968 in an attempt to determine the structure and submarine geology of these two areas.

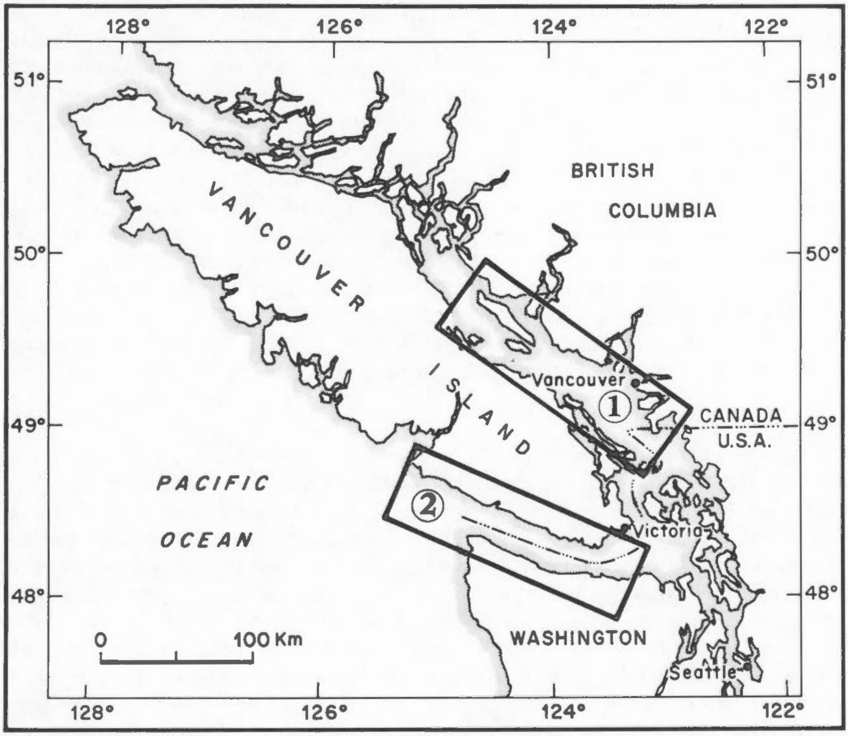

Figure 1. Location map. 1 - Strait of Georgia, 2 - Juan de Fuca Strait.

The Georgia depression is bounded to the east by the late Mesozoic plutonic complex of the Coast Mountains and to the west by the largely Mesozoic volcanic and sedimentary sequences of Vancouver Island. Recent volcanism in the Coast Mountains north of Vancouver, coupled with the numerous shallow seismic events recorded throughout the area, suggest that tectonic activity may be continuing at present.

Juan de Fuca Strait between Vancouver Island and the Olympic Mountains of northern Washington has Tertiary volcanics and sediments along both shorelines. Again, seismic evidence suggests that the area is tectonically active and it has been recently demonstrated that thrust sheets of Eocene rocks overlie later rocks along the Washington shoreline of the Strait (McWilliams, 1970). Gravity measurements on Vancouver Island and in northern Washington show a considerable gravity gradient between the two areas which has been related to a major crustal fracture below the Strait (Walcott, 1967).

Earlier geophysical measurements in the area in addition to those of Walcott, include gravity measurements by Dehlinger, Gemperle, Couch and Hood (1966) and Stacey and Stephens (1969). Refraction seismic experiments have been reported by Milne and White (1960) for southern Vancouver Island and by White and Savage (1965) and Tseng (1968) for the Strait of Georgia. Tiffin (1970) has discussed the results of continuous reflection seismic profiling carried out in the Strait of Georgia prior to 1968. Milne (1963) has summarized the seismic activity of the area and has recognized certain areas where earthquakes are most common but he had difficulty in relating the disturbances to the surface geology. Deep resistivity measurements in the Fraser Valley near Vancouver have been reported by Samson (1969).

The shoreline geology for the Strait of Georgia has been taken from various maps published by the Geological Survey of Canada, in particular the map of Vancouver Island by Muller (1967). The geology of the Washington coastline has been taken from the 1:500,000 geological map of the state published by the Department of Conservation (1961).

REDUCTION OF THE DATA

The control line spacing in the Strait of Georgia is generally 4.6 km (2.5 n.m.) with the lines parallel to the magnetic meridian - N22°E or its reciprocal S22°W. The tie lines are approximately perpendicular to these lines and have been made wherever possible along the centre and along either side of the Strait. The ship was generally travelling at 13 km/hr (7 knots) on control lines with the continuous seismic reflection equipment operating, but along tie lines the seismic gear was not used and the ship travelled at 26 km/hr (14 knots). In Juan de Fuca Strait the data are generally along zig-zag tracks made en route to and from the Pacific from the ship's base at Esquimalt on Vancouver Island. The average line spacing in this Strait is about 5.6 km (3 n.m.) and as the seismic equipment was not used except on one profile across the Strait, the ship was generally travelling at 26 km/hr (14 knots). Tie lines in this area were made on either side of the Strait as close as possible to the shorelines.

The distance from the mainland to Vancouver Island across the Strait of Georgia is approximately 20 km (10 n.m.) and across Juan de Fuca Strait from Vancouver Island to Washington the distance is about 15 km (7.5 n.m.) and in both cases the position of the ship was determined relative to the nearest shoreline by radar. The mean course and speed of the ship on different segments of the track were determined by fitting a straight line to the observed positions by least squares. The average distance between the observed positions of the ship from the radar fixes and the positions derived from the straight line track is in the order of 200 m (0.1 n.m.) for both areas. The unsmoothed ship's track appears on maps 120 and 121 enclosed.

Bathymetric Measurements

The sounding equipment on the C.S.S. Parizeau consisted of a hull mounted Simrad transducer keyed by a Gifft recorder with a 75-cm (19-inch) wet chemical display unit. The Gifft generated time marks on the record at 30-second and five minute intervals and these were periodically identified by the watchkeeper. The sounding data have been digitized at five-minute intervals (corresponding to a distance of 1.1 km at 13 km/hr or 7 knots) and the time of each digitized value has been related to a position on the straight line approximation to the ship's track. The sounding equipment was calibrated for a velocity of sound in water of 1,585 m/sec (4,800 ft/sec). Tiffin (1970) has studied the temperature and salinity data for the Strait of Georgia and concluded that this velocity is correct for the intermediate and lower layers but, depending on the time of year, small variations in the temperature and salinity of the surface layers will introduce small errors in the depths. As the bathymetric data for this report are in-tended to show only the major features of the submarine topography, no account has been taken of possible variations in the velocity, nor has any correction been applied for the slope of bottom. In some areas in both the Strait of Georgia and Juan de Fuca Strait, the digitizing interval of five minutes and the line spacing of about 5 km are too great to bring out the details of the topography. Therefore, in the bathymetric maps for both areas no attempt has been made to contour the bottom where the depths are less than 200 m (100 fm). The mean difference in the depth at 90-track intersections in the Strait of Georgia is 10 m (5.3 fm) and the histogram of these discrepancies is given in Figure 2(a). The corresponding analysis of the Juan de Fuca data has not been made but as the survey conditions were similar in both areas, the errors at track intersections should be approximately the same.

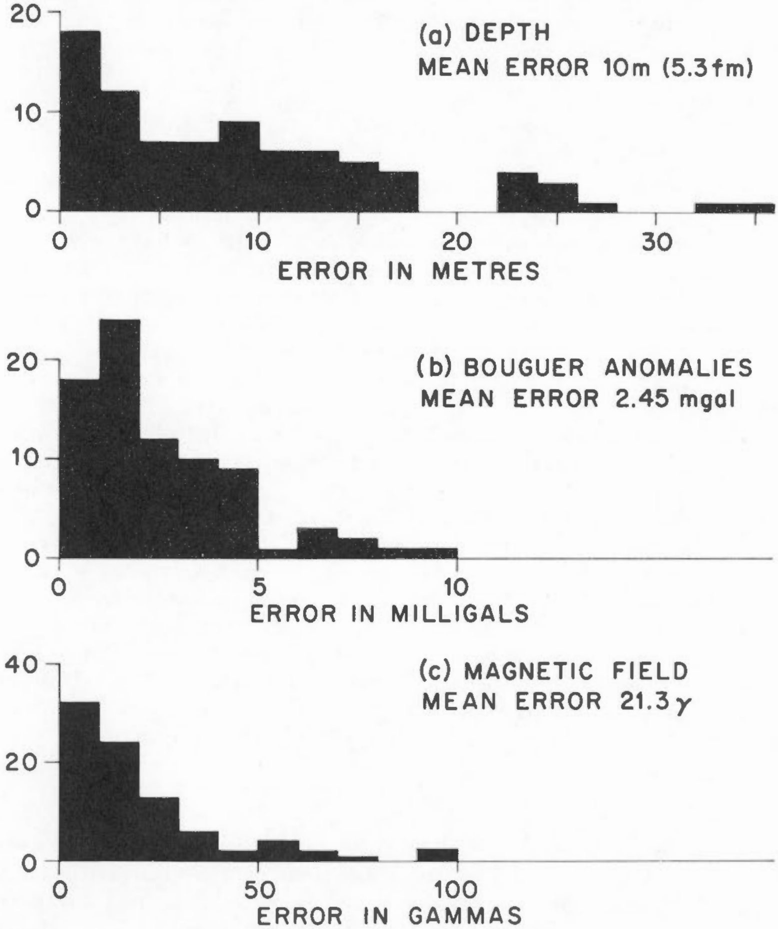

Figure 2. Histograms showing the errors in (a) depth, (b) Bouguer anomaly and (c) magnetic field at track intersections in the Strait of Georgia.

Gravity Measurements

The variations in the Earth's gravity field were measured using a LaCoste and Romberg air/sea gravity meter (number S-35) with analogue and digital recording facilities. The layout of the lower deck aboard the C.S.S. Parizeau is such that the gravity meter and stabilized platform can be installed in an ideal position on the fore and aft centreline of the ship, close to the waterline and close to the axis of pitch.

The digital recording unit did not operate satisfactorily while the ship was at sea so the analogue record corresponding to the gravity variations was picked at five-minute intervals whenever the cross-coupling was less than 15 mgal and the record showing the position of the beam in the gravity meter was steady. Other records, showing the long and short period deviations of the levels corresponding to pitch and roll of the stabilized platform from the horizontal, were checked to ensure that the platform was operating satisfactorily. The instrument readings were converted to their milligal equivalent using the tables provided by the manufacturer for instrument number S-35, and the actual values of the Earth's gravity field corresponding to these converted readings were computed relative to the gravity base station on the C.S.S. Parizeau's dock at Esquimalt. (Base number 9600-68, g = 980.97712 cm/s^2, established by the Earth Physics Branch of the Department of Energy, Mines and Resources, Ottawa.) As the instrument reading at this base did not change throughout the survey, no drift correction was required.

The time of each digitized value has been corrected by -1.5 or -3.0 minutes, depending whether the reading had been averaged over a period of three or six minutes (LaCoste, 1967) and then related to a position on the straight line approximation to the ship's track. The ship's mean speed and heading over the period of the straight line segment of the track containing the time of the reading, plus the latitude at the time of the reading, are used to compute the Eötvös correction. Most of the gravity measurements have been made along tracks orientated at N22°E with the ship travelling at 13 km/hr (7 knots). The accuracy of the Eötvös correction for these lines is estimated from nomograms published by Glicken (1962) to be about 1 mgal, if it is assumed that the ship's speed and course are known to within 0.5 km/hr (0.25 knot) and 0.5° respectively.

The free-air anomaly is the difference between the observed gravity value corrected for the Eötvös effect, and the theoretical gravity value at the latitude of the observation derived from the International Gravity Formula of 1930. For the Bouguer correction the water below the ship is replaced by rock in the form of an infinite horizontal slab with thickness equal to the depth of water and density 1.64 g/cm^3 - the difference between the standard density of 2.67 g/cm^3 for the Earth's crust and that of seawater, 1.03 g/cm^3. The depth of water for this correction is found by interpolating between the depths (which are at five-minute intervals) immediately before and after the time of the gravity observation.

The mean difference between the Bouguer anomaly values on different tracks at 81 intersections in the Strait of Georgia is 2.45 mgal. Approximately 1 mgal of this can be attributed to errors in the Eötvös correction, and the remainder to navigation errors, rounding errors introduced when digitizing the analogue record (these were read to the nearest milligal) and the effect of changes in gravity during the three or six-minute averaging period due to abrupt changes in the water depth. The mean difference between Bouguer anomaly values established during earlier surveys at 16 points in the Strait of Georgia using LaCoste and Romberg remote controlled underwater gravity meter (Stacey, Stephens, Cooper and Brule, 1969) and the interpolated surface gravity meter value is +0.24 mgal which suggests that there are no systematic differences between the two methods. The mean of the absolute values of the differences in 1.85 mgal which is of the same order as the mean for the Bouguer anomaly differences at the track intersections.

Magnetic Measurements

A Varian proton precession marine magnetometer (model V-4937) was used to measure the total intensity of the Earth's magnetic field which in the area of the survey was approximately 57,800 gammas with a declination N22°E and a dip of 70°. The magnetometer was equipped with a Dymec data logging system (DY-6870) which provided time marks for both punched paper tape output of the magnetic intensity in gamma and the chart record accompanying the Varian magnetometer. After editing the time information and the magnetic field values on the punched paper tape, the data were transferred to magnetic tape and the time of each magnetic value (usually at one-minute intervals) was related to a position on the straight line approximation of the ship's track. The magnetic values at these positions were then plotted and the results contoured (maps 120 and 121). No correction has been made for the International Geomagnetic Reference Field (I.G.R.F.) although it has been plotted on the sections A - B, C - D and E - F (Figures 4, 5 and 7). The magnetic field records from the Dominion Astrophysical Observatory, Victoria have been checked and they show the normal diurnal variation during the period of the survey to be between 15 and 20 gammas in any 24-hour period. No major magnetic disturbances occurred during the survey period. The histogram of the differences in the magnetic field values at 87-track intersections is given in Figure 2(c). The mean value of the differences at these 87 intersections is 21.3 gammas, which is of the same order of magnitude as the diurnal changes. No corrections have been made for these variations as they are generally small compared with the measured change of several hundred gammas due to geological effects.

STRAIT OF GEORGIA

General Description

The Strait of Georgia lies in a depression between two major geological provinces - the Jurassic-Cretaceous Coast Mountain plutonic complex on the mainland and the predominantly volcanic and sedimentary sequences of Vancouver Island which range in age from Late Paleozoic to Tertiary. In the southeastern part of the area the Coast Mountains end abruptly north of Vancouver and the bedrock geology farther south is obscured by many thousands of feet of Cretacous to Recent sediments in the Fraser River valley. At the northwestern end of the survey area the geology of Texada and Lasqueti Islands is more akin to that of Vancouver Island than the mainland, suggesting that the boundary between the two provinces lies between Texada Island and the mainland. Cretaceous sediments of the Nanaimo group are exposed on the coast of Vancouver Island and on the adjacent islands in the Strait of Georgia. The basin containing these sediments appears to deepen towards the Strait and the rocks exposed at the surface become progressively younger in the same direction. Pre-Nanaimo group rocks outcrop north of the town of Nanaimo along a north-south structural high.

In the following sections the geophysical measurements made during the cruise of the C.S.S. Parizeau provide the basis for an attempt to extend the shoreline geology across the Strait of Georgia and to identify the boundary between the plutonic complex of the mainland and the volcanic and sedimentary sequences of Vancouver Island.

Interpretation

(i) Bathymetric measurements

The conclusions drawn from the bathymetric data for the central and southern areas of the Strait of Georgia do not differ significantly from those of Cockbain (1963) and Tiffin (1970). The main geomorphological features are the flat bottomed Malaspina and Ballenas basins (1 and 2 on map 120) about 210 fm deep and lying north and south of Sangster ridge (3), and the Fraser River delta (4) which dominates the southeastern part of the Strait. The two basins appear to be typical U-shaped glaciated valleys with indications of hanging valleys on either side.

Between the Malaspina basin (and its southward extension into the Ballenas basin) and the mainland to the north is an area of banks less than 125 fm deep (5). During the C.S.S. Parizeau cruise in 1968 the seismic profiling data were obtained using more powerful equipment than was available in 1963 and are at present being interpreted by students of the Department of Geology at the University of British Columbia. These results, plus the detailed interpretation of the magnetic data presented in map form with this report, by the Department of Geophysics at the same university, should permit a reasonably sound geological interpretation of the data, not only for the area of banks, but elsewhere in the Strait of Georgia.

Farther north between Lasqueti and Vancouver Islands, the Hornby basin (6) is approximately 180 fm deep. This appears to be the upper part of the Ballenas basin (Cockbain, 1963) and is terminated by Hornby Island to the north and by a low ridge between Hornby and Lasqueti Islands to the northeast. North of this low ridge is an area with an average depth of 75 fm (7) and close to Texada Island is a channel with depths greater than 175 fm which extends from outside the area in the north, towards Sabine Channel between Texada and Lasqueti (8). The possible geological significance of this feature will be discussed later in this report.

(ii) Gravity measurements

The average Bouguer anomaly over the axis of the Coast Mountains between Prince Rupert in the north and Vancouver in the south is less than -100 mgal, increasing to near zero values west of the mainland coastline (Stacey et al., 1969). This regional trend is observed also in the Strait of Georgia where the Bouguer values are generally lower on the mainland side of the Strait than they are over Vancouver Island. Most of this decrease can be attributed to isostatic compensation at depth for the Coast Mountains. If compensation occurs within the crust one would expect the M discontinuity to be deeper below the Coast Mountains than below the Strait of Georgia. However, the theory of plate tectonics and the geological history of the Cordilleran region suggest that ocean crust was being destroyed in the vicinity of Vancouver Island during the late Mesozoic and Tertiary periods and it might be expected that any remnant of such a plate in the upper mantle today would affect the gravity field at the surface (Hamilton, 1969). Detailed discussion of this point is considered to be beyond the scope of this Gravity Map Series report and will be reserved for a later paper.

Superimposed on this general decrease in the Bouguer anomaly from southwest to northeast are local anomalies related to density changes in the surface and near-surface rocks. The available density information is summarized in Table I. It has been noted elsewhere (Stacey et al., 1969) that the Bouguer anomaly values are generally higher over the basalts of the Karmutsen formation of the Vancouver group and low over the Nanaimo group sedimentary basins. There does not appear to be any obvious correlation between the Bouguer values and the Sicker group, the Quatsino and Bonanza formations and the plutonic rocks exposed on Vancouver Island. On the mainland any anomalies that could be related to density changes in the plutonic complex of the Coast Mountains are obscured by the rapid decrease of the anomaly values from near zero on the coast to less than -100 mgal inland from the Strait of Georgia.

TABLE I

Summary of the Available Density Information

(from Stacey and Stephens, 1969)

Age	Formation or Group	Lithology	No. of samples	Range of densities	(g/cm^3) Mean density	Source*
VANCOUVER ISLAND - DENSITIES FOR SEDIMENTARY AND VOLCANIC ROCKS						
Early Tertiary	Metchosin	Pillow basalts		2.41 - 3.02	2.80	W
Late Cretaceous to Early Tertiary	Nanaimo	Sandstone, conglomerate, coal and shale	23	2.46 - 2.63	2.55	W
Late Jurassic to Early Cretaceous		Marine sandstone, shale and conglomerate	11	2.67 - 2.75	2.71	W
Early Jurassic to Mid-Jurassic	Bonanza	Porphyritic andesite, tuff and some sediments	13	2.55 - 2.82	2.69	E. P., G. S. C.
Late Triassic to Early Jurassic	Quatsino	Limestone	8	2.69 - 2.85	2.76	W
Triassic	Karmutsen	Marine sodic basalts	82	2.83 - 3.14	2.96	W., G. S. C.
Permo-Pennsylvanian	Sicker	Marine basalt, graywacke chert, limestone, argillite	8	2.73 - 2.85	2.77	W
VANCOUVER ISLAND - DENSITIES FOR PLUTONIC AND METASEDIMENTARY ROCKS						
Post-tectonic phase		Granodiorite	24	2.56 - 2.82	2.68	W., E. P.
Syn-tectonic phase		Diorite and metasediments	43	2.65 - 3.01	2.78	W., E. P.
BRITISH COLUMBIA MAINLAND - DENSITIES FOR PLUTONIC ROCKS						
Mainly Jurassic - Cretaceous		Range from diorite to granite	3000	2.55 - 2.99	2.73	G. S. C.

*W - Walcott (1967)
G. S. C. - Muller and Roddick (personal communication, 1968)
E. P. - Earth Physics Branch

The north-south structural high exposing late Paleozoic rocks northwest of Nanaimo appears to extend across the Strait to the eastern end of Texada Island where rocks of similar age are seen at the surface. Although the Bouguer values over this feature are normal, there are two elongate areas of high values to the east and west of the structure that can be related to the Karmutsen formation if the structure is assumed to be in the form of an anticline. This concept is strengthened by the presence of the Karmutsen formation volcanics on Lasqueti Island and what is believed to be their metamorphosed equivalent on South Thormanby Island near the mainland on the opposite side of the structure (Figure 3).

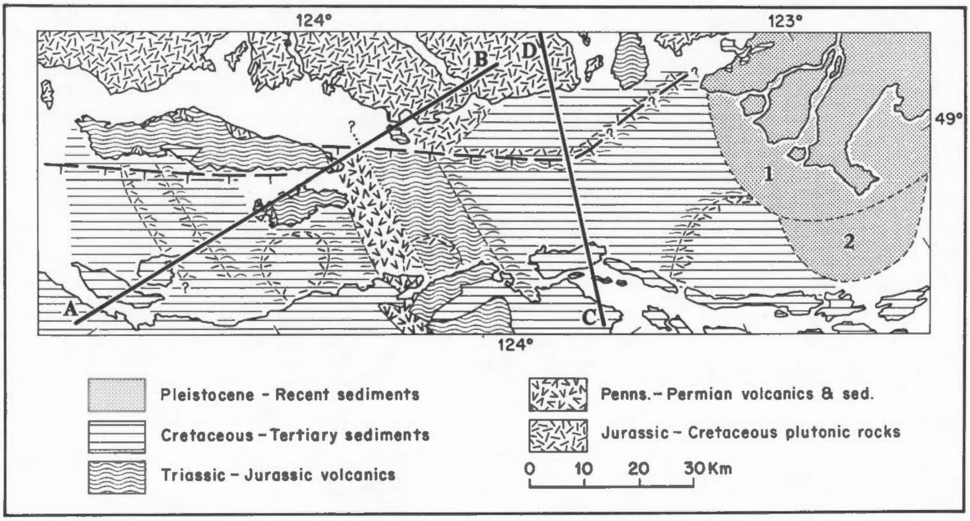

Figure 3. Inferred geology for the Strait of Georgia. Boundaries below the sediments are indicated by short dashes and faults by long dashes.

The low between Texada Island and Hornby Island can be attributed to comparatively light Cretaceous and possibly Tertiary sediments, probably overlain by a blanket of glacial debris. This anomaly is bounded to the northeast and the east by steep gradients which indicate a sharp lateral density change - possibly this could be related to faulting along these two margins of the basin (particularly to the northeast where there is a deep trough along the coast of Texada Island). A shallower basin of similar age may exist between Lasqueti Island and Vancouver Island as there is a small decrease in the anomaly values in this vicinity.

Farther south, Sangster Ridge has little effect on the Bouguer anomaly implying that its density does not differ significantly from that used in the Bouguer reduction ($2.67\ g/cm^3$). This rules out the possibility that the ridge is due to Karmutsen volcanics which resisted glacial erosion because these rocks would give high Bouguer values. To the east, over the area of banks defined earlier, the low Bouguer values suggest that this part of the Strait is underlain by a varying thickness of Cretaceous and possibly Tertiary sedimentary rocks - the latter being an extension of the Tertiary rocks exposed in the vicinity of Vancouver (Tiffin, 1970). The numerals "1" and "2" in Figure 3 refer to the Recent and Pleistocene positions of the Fraser Delta respectively according to Tiffin (1970). The Bouguer values are generally low over the delta (-70 mgal) and a density contrast between the sediments and the country rock of -0.25 g/cm^3 gives good agreement between the thickness of sediments from the gravity data and those obtained from deep resistivity (Samson, 1969) and drilling results.

(iii) Magnetic measurements

The total field isodynamic chart (Dom. Obs., 1965) shows the normal earth field values to be approximately 56,800 gammas on the Vancouver Island side of the Strait, increasing at 4 gammas/km in a direction N45°E to 57,000 gammas on the mainland. From the magnetic map with this report it is apparent that the field increases from near normal values on the Vancouver Island side of the Strait at approximately 22 gammas/km to a region of strong magnetic anomalies (average value approximately 57,400 gammas) on the mainland side.

The aeromagnetic map of the Nanaimo area (G.S.C. Geophysics paper 5322) shows that the majority of the areas of strong magnetic anomalies coincide with areas of intrusive rock - usually quartz diorite. Intrusive rocks of this composition are found on the mainland and on Texada Island and there is a noticeable correlation between these areas and those of strong magnetic anomalies which lie immediately off-shore. Based on the aeromagnetic evidence from the Nanaimo area it is concluded that the steepest part of the regional gradient across the Strait of Georgia, which coincides with the northern side of the Malaspina basin and its extension into Ballenas basin, marks the boundary between the predominantly sedimentary and volcanic sequence of Vancouver Island and the complex intrusive mass of the Coast Mountains which has an average composition of quartz diorite (Roddick, Baer and Hutchinson, 1966). This boundary has been suggested earlier by Cockbain (1963) in his study of the submarine topography of the Strait. The areas of high magnetic values between Lasqueti and Vancouver Islands and off Galiano Island have been tentatively related to intermediate intrusive rocks at some depth below the floor of the Strait (Figure 3).

Section A - B (Figure 4)

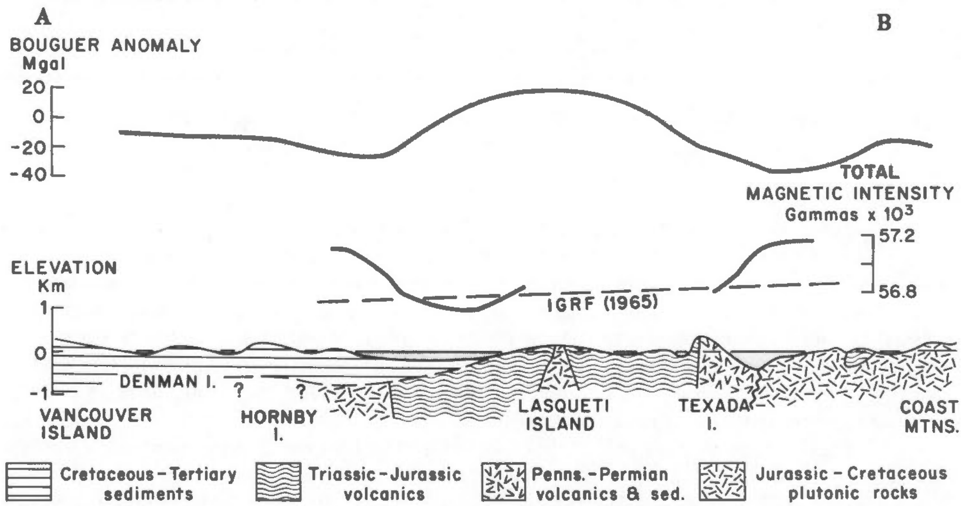

Figure 4. Geophysical data and inferred geology along section A - B, Strait of Georgia.

The surface rocks on Vancouver Island at the western end of the profile are all Nanaimo group sediments, generally becoming younger to the east on Hornby Island. Sediments believed to be Tertiary in age are seen on Lasqueti Island just to the north of the profile (Muller and Carson, 1968). The remainder of Lasqueti Island, apart from a small area of Jurassic - Cretaceous plutonic rocks is covered by Karmutsen volcanics of the Vancouver group. On Texada Island, the Late Paleozoic Sicker group is seen below the rocks of the Vancouver group. Farther east the metavolcanics on the Thormanby Islands are believed to be equivalent to the volcanics of the Karmutsen formation. The rocks of the mainland area have not been completely mapped but they are mainly plutonic rocks of Jurassic - Cretaceous age.

Between Hornby and Lasqueti Islands the low Bouguer values suggest that the Nanaimo group sediments reach a maximum thickness of about one kilometre. The high magnetic values suggest that the sediments seen on Hornby Island are underlain by plutonic rocks similar to those exposed south of the profile on Vancouver Island. The high Bouguer anomalies over Lasqueti Island together with the lack of expression in the magnetic values suggest that the Vancouver group underlies the Nanaimo group which thins towards Lasqueti Island.

The Sicker group rocks exposed on the south end of Texada Island appear to be part of the north-south structural high mentioned earlier which brings similar rocks to the surface on Vancouver Island south of the section line. These rocks are generally related to comparatively low Bouguer anomaly values (Stacey and Stephens, 1969) with the minimum gravity values lying along the axis of the structure. However, part of the low between Texada Island and the Thormanby Islands may be due to Cretaceous - Tertiary sediments (not shown in section A - B). The increase in the magnetic values along this part of the section suggests that the eastern part of the Strait is underlain by plutonic rocks of the Coast Mountains complex. The magnetic data do not preclude the possibility that these rocks are overlain by later sediments. At the eastern end of the profile the increase in the gravity values over the Thormanby Islands is probably due to the presence of metavolcanic rocks which are denser than the surrounding plutonic rocks.

Section C - D (Figure 5)

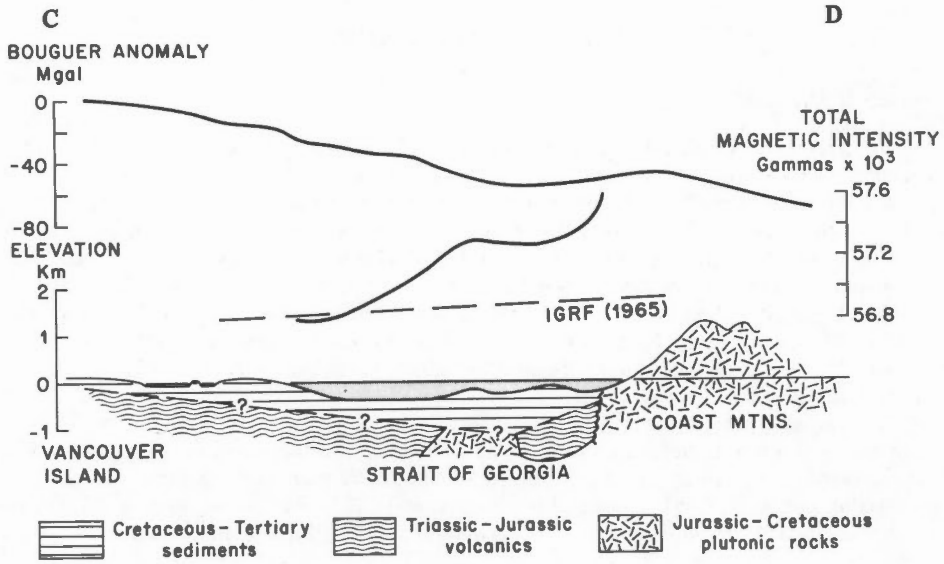

Figure 5. Geophysical data and inferred geology along section C - D, Strait of Georgia.

This north-south section extends from Vancouver Island, across Galiano Island to the mainland. Cretaceous sediments of the Nanaimo group are exposed on Vancouver and Galiano Islands and plutonic rocks of the Coast Mountains complex are seen on the mainland. The Bouguer anomaly decreases from 0 mgal over Vancouver Island to -60 mgal over the mainland. The geology at the south end of the profile suggests that the

Nanaimo group thickens towards the centre of the Strait, possibly with the addition of later Tertiary sediments and the local minimum in the gravity values about 10 km off the mainland coast is believed to coincide with the maximum thickness of these sediments. Refraction seismic data interpreted by Tseng (1968) indicates 2 km of sediments near the centre of the Strait which is in good agreement if the density contrast between the sediments and the bedrock is taken to be $-0.3\ g/cm^3$. Tiffin (1970) has also concluded from continuous seismic profiling data that sediments of Tertiary age underlie the glacial debris off the mainland coast and suggests that they are equivalent to the Tertiary sediments seen in the vicinity of Vancouver to the southeast of the profile.

The featureless gravity field and the lack of magnetic data over the southern end of the profile make it very difficult to determine the nature of the rocks below the Nanaimo group sediments. On Vancouver Island beyond the southern end of the profile, the sediments overlie rocks of the Vancouver and Sicker groups and it has been tentatively assumed that these units extend northwards below the Nanaimo group as far as the centre of the Strait of Georgia. At this point the magnetic values begin to increase rapidly to the north, indicating that the magnetic basement is approaching the surface in this direction. This basement is assumed to be the Coast Mountains complex because the increase in the magnetic field values occurs throughout the area towards the mainland. The line of this gradient follows the topographic feature marking the northern margin of the Malaspina - Ballenas basin which, as has already been suggested, may be a fault, or simply the transition from Vancouver Island rocks to those of the Coast Mountains complex. The decrease in the magnetic values close to the mainland may be related to the gravity minimum in the same area, or it may reflect a change within the magnetic basement rocks.

JUAN DE FUCA STRAIT

General Description

Juan de Fuca Strait lies between southern Vancouver Island and the Olympic Peninsula of northwest Washington. The Eocene volcanics of the Metchosin formation on southern Vancouver Island appear to be part of the Tertiary geosyncline which extended south from the Strait along the Pacific coast of Washington and Oregon. The northern limit of the geosyncline can probably be related to the east-west San Juan and Leech River faults on Vancouver Island (Figure 6). North of the San Juan fault the geology is typical of Vancouver Island, but between the faults the greywackes and siltstones of the Leech River formation have presented a problem to geologists and estimates of the age of this formation range from Pennsylvanian (Muller, 1967) to late Jurassic (Sutherland Brown, 1966).

The extreme linearity of the Vancouver Island side of Juan de Fuca Strait has prompted geologists to draw in a fault along the Strait and the steep gravity gradient between Vancouver Island and the Olympic Mountains has tended to substantiate this supposition (Walcott, 1967; Couch, 1969). However, it is still possible that the linearity of Juan de Fuca Strait is due to glacial action during the Pleistocene.

Interpretation

(i) Bathymetric measurements

The line spacing during the C.S.S. Parizeau cruises in this area was too large to construct an adequate map of the floor of Juan de Fuca Strait so the data gathered during the cruise have been merged with data on Canadian Hydrographic Services chart No. 3607 (Juan de Fuca Strait).

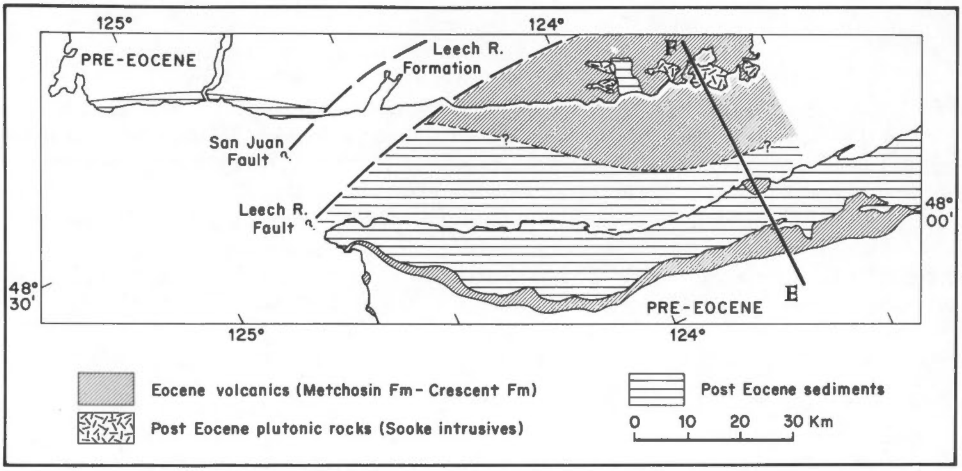

Figure 6. Inferred geology for Juan de Fuca Strait.

Juan de Fuca Strait has the typical U-shaped cross section of a glaciated valley with an average depth close to 100 fathoms. The channel gradually deepens westwards and a narrow central valley which marks the head of the Juan de Fuca submarine canyon becomes more and more pronounced. Approximately 10 km northwest of Cape Flattery the axis of this trough turns abruptly from northwest to southwest and continues across the continental shelf to the foot of the slope (Carson and McManus, 1969). The southwest-trending section follows the line of steepest slope across the shelf to the shelf-break. However, there may also be some geological control which will be discussed later.

(ii) Gravity measurements

The Bouguer anomaly field is dominated by the gradient between the Sooke high over southern Vancouver Island and the Olympic low in northwest Washington. The average gradient between the Sooke high where the Bouguer anomaly values are between 60 and 65 mgal, and the Olympic Mountains where the Bouguer anomaly is -60 to -70 mgal, is approximately 2 mgal/km. Across Juan de Fuca Strait this gradient attains 4 mgal/km. This increase in the gradient can be related to the transition from the comparatively heavy basaltic and gabbroic rocks of the Metchosin formation and the Sooke intrusives (average density between 2.8 and 2.9 g/cm^3) (Figure 6) to the later and less dense sediments (average density 2.4 to 2.5 g/cm^3, Walcott, 1967) farther south. This effect can also be seen in the deflection of the isogals west of Sooke.

At the western end of the Strait, between Cape Flattery and Port San Juan, the Bouguer anomaly values tend to be lower and this has been related to the outcrop of the greywackes and siltstones of the Leech River formation between Leech River and San Juan faults.

(iii) Magnetic measurements

The area of strongest magnetic anomalies which lies northeast of a line from Sombrio Point on Vancouver Island to Low Point on the Washington side of the Strait probably corresponds to the outcrop of the lower Eocene Metchosin formation basaltic volcanics and the Upper Eocene or Oligocene gabbroic Sooke intrusives.

Farther west the magnetic measurements show that the Leech River fault continues across the Strait at least as far as a point 7 km north of Cape Flattery. The area between this fault, the postulated limit of the Metchosin formation outcrop, and the Washington coast is probably occupied by post-Eocene sediments. West of the Leech River fault there are few magnetic measurements but it appears that the San Juan fault could continue westward in the same way as the Leech River fault. The area of comparatively featureless magnetic field thus enclosed would correspond to the Leech River formation slates and greywackes. North of the San Juan fault a pronounced magnetic gradient marks the extension of the early intrusive rocks near Nitinat Lake, seawards below the Tertiary sandstones of the Carmanah formation.

Section E - F (Figure 7)

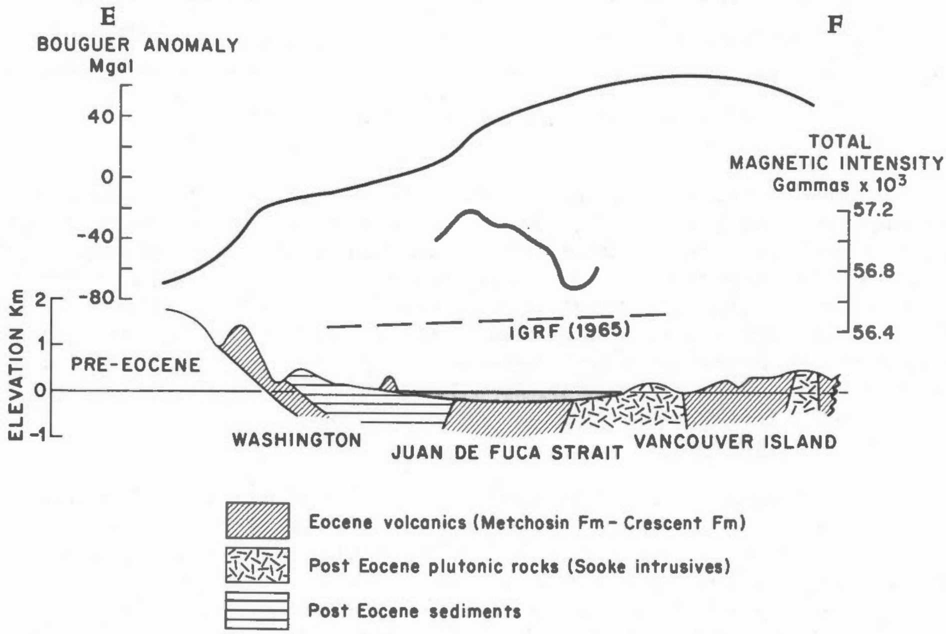

Figure 7. Geophysical data and inferred geology along section E - F, Juan de Fuca Strait.

This north-south section across Juan de Fuca Strait extends from Washington where a north-dipping sequence of Tertiary rocks ranging from Eocene to Miocene is exposed, to Vancouver Island where early Eocene volcanic rocks which have been intruded by later plutonic rocks are seen at the surface. The early Eocene volcanic rocks of the Crescent formation in Washington have been correlated with the Metchosin volcanics of similar age on Vancouver Island (Clapp, 1912 and 1913), suggesting that Juan de Fuca Strait lies along the axis of an asymmetric synclinal structure with the steepest limb on the Washington side.

The interpretation of the gravity data has been discussed in general terms by Walcott (1967) and he suggested that the decrease in the Bouguer anomaly values to the south was due to a decrease in the thickness and density of the crust below Washington relative to that below Vancouver Island. The gravity measurements presented here confirm the general trend of the Bouguer anomalies and in conjunction with the magnetic data, it is possible to recognize the southern margin of the Metchosin formation of Vancouver Island. This junction (Figure 6) which is believed to be between Metchosin lavas and later sediments to the south, lies close to the Vancouver Island side of the Strait at its western end and crosses the Strait obliquely towards the Washington side near the eastern limit of the survey. This line, although apparently interrupted by the San Juan and Leech River faults, may be the southward continuation of the fault believed to lie very close to the west coast of Vancouver Island. To the north, refraction seismic results suggest that the Metchosin formation thickens to about 4.5 km (Milne and White, 1960).

In a recent note by McWilliams (1970) the Crescent formation volcanics on the Washington coast cut by the section E - F are recognized to be a thrust plate overlying more recent Oligocene/Miocene sediments. Assuming this to be true, the plate could have arrived at its present position by gravity sliding from the Olympic Mountains to the south or the fracture proposed below the Strait could be a thrust fault dipping northwards below Vancouver Island, in which case the volcanic rocks on the Washington coast could be an outlier of the Metchosin formation. It will probably be impossible to distinguish between these two possibilities until the geology along the shorelines of the Strait is better known or the nature of the proposed fracture below the Strait is clarified.

SUMMARY AND CONCLUSIONS

The preliminary interpretation of the geophysical results suggest that in the Strait of Georgia the Bouguer anomaly values are low over the Cretaceous and Tertiary sedimentary sequences and high over early Mesozoic basic volcanic sequences such as the Karmutsen formation. Volcanics and sediments of the Permo-Pennsylvanian Sicker group, the Jurassic and lower Cretaceous sequences and the majority of the intrusive rocks have an average density of about 2.7 g/cm^3 and are consequently indistinguishable from one another by gravity measurements alone. In the same area, the magnetic field appears to be most disturbed over the Jurassic intrusives which have an average composition of quartz diorite. By combining the magnetic and gravity results, delineation of the gross features of the geology of the Strait of Georgia has been attempted and it appears that the transition from typical Vancouver Island geology to that of the Coast Mountains is complex.

In Juan de Fuca Strait it is apparent from the magnetic results that the early Eocene volcanics extend from Vancouver Island to the Washington Coast and are probably exposed in the east and buried below later sediments in the west. Similarly, the Leech River and San Juan faults seem to continue across Juan de Fuca Strait and the Leech River formation between the faults may have influenced the development of the upper part of the Juan de Fuca submarine canyon off Cape Flattery. From the magnetic data there appears to be no direct evidence for a major fault along the Strait despite the straightness of the coastlines and the gravity gradient between southern Vancouver Island and the Olympic Mountains in Washington. However, the structure may have developed prior to or contemporaneous with the volcanic activity at the beginning of the Tertiary period and thus may be obscured by later lavas and sediments.

The regional decrease in the Bouguer anomaly values from Vancouver Island towards the mainland and towards the Washington peninsula is believed to indicate that the crust east and south of Vancouver Island is thinner and less dense than that below the Island. This interpretation is in good agreement with the crustal models derived from refraction seismic data. The lack of clear expression of this transition in the surface geology suggests that the present relationship between the different crustal blocks has existed since the early Cretaceous and may be even older.

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REFERENCES

Carson, B., and D.A. McManus, 1969. Seismic reflection profiles across Juan de Fuca. J. Geophys. Res., 74, pp. 1052-1060.

Clapp, C.H., 1912. Southern Vancouver Island. Geol. Surv. Can., Mem. 13.

Clapp, C.H., 1913. Geology of Victoria and Saanich map-areas, Vancouver Island. Geol. Surv. Can., Mem. 36.

Cockbain, A.E., 1963. Submarine topography and sediment thickness in the southern Strait of Georgia. Univ. British Columbia Inst. Oceanog., Report No. 14 (unpublished).

Couch, R.W., 1969. Gravity and structures of the crust and subcrust in the northeast Pacific Ocean west of Washington and British Columbia. Ph.D. thesis, Oregon State University.

Dehlinger, P., M. Germperle, R.W. Couch, and D.W. Hood, 1966. Free-air gravity anomalies along the inside passage of British Columbia and Alaska. J. Geophys. Res., 71, pp. 6011-6015.

Glicken, M., 1962. Eötvös corrections for a moving gravity meter. Geophys., 27, pp. 531-533.

Hamilton, W., 1969. Mesozoic California and the underflow of Pacific mantle. Bull. Geol. Soc. Am., 80, pp. 2409-2430.

LaCoste, L.J.B., 1967. Measurement of gravity at sea and in the air. Rev. Geophys., 5, pp. 477-526.

McWilliams, R.G., 1970. Evidence for thrust faulting in northern Olympic peninsulas, Washington. Am. Ass. Pet. Geol., Bull. 54, pp. 344-356.

Milne, W.G., 1963. Seismicity of western Canada. Bol. Biblio. Geofis. y Oceanog. Am., 3, pp. 17-40.

Milne, W.G., and W.R.H. White, 1960. A seismic survey in the vicinity of Vancouver Island, British Columbia. Pub. Dom. Obs., 24, pp. 145-154.

Muller, J.E., 1967. Geological sketch map of Vancouver Island and the Gulf Islands. Open file Geol. Surv. Can.

Muller, J. E., and D. J. T. Carson, 1968. Geology and mineral deposits of Alberni map-area, British Columbia (92F). Geol. Surv. Can., Paper 68-50.

Roddick, J. A., A. J. Baer, and W. W. Hutchinson, 1966. Coast Mountains project. Geol. Surv. Can., Paper 66-1, pp. 80-85.

Samson, J. C., 1969. Deep resistivity measurements in the Fraser Valley, British Columbia. Can. J. Earth Sc., 6, pp. 1129-1136.

Snavely, P. D., and H. C. Wagner, 1963. Tertiary geologic history of western Washington. Div. Mines and Geology, 22, 25 pp.

Stacey, R. A., and L. E. Stephens, 1969. An interpretation of gravity measurements on the west coast of Canada. Can. J. Earth Sc., 6, pp. 463-474.

Stacey, R. A., L. E. Stephens, R. V. Cooper, and B. G. Brule, 1969. Gravity Map Series, Dom. Obs. No. 88 - British Columbia Coastal area.

Sutherland Brown, A., 1966. Tectonic history of the Insular Belt of British Columbia. CIMM, 8, pp. 83-100.

Tiffin, D., 1970. Continuous seismic reflection profiling in the Strait of Georgia, British Columbia. Ph.D. thesis, Univ. British Columbia, Inst. Oceanog.

Tseng, K-H., 1968. A new model for the crust in the vicinity of Vancouver Island. M. Sc. thesis, Univ. British Columbia.

Walcott, R.I., 1967. The Bouguer anomaly map of southwest British Columbia. Univ. British Columbia Inst. Earth Sc., Report 15.

White, W. R. H., and J. C. Savage, 1965. A seismic refraction and gravity study of the Earth's crust in British Columbia. Bull. Seis. Soc. Am., 55, pp. 463-486.