PATTERNS OF DEFORMATION, SEDIMENTATION AND TECTONISM SOUTHWESTERN CANADIAN CONTINENTAL MARGIN

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(10 figures dans le texte)

RÉSUMÉ

Des dragages, ainsi que l'enregistrement de profils sismiques sur la bordure continentale du Canada occidental, ont révélé la présence de deux bassins sédimentaires bien distincts que sépare une zone tectonique submergée : la « Kyuquot Uplift-Brooks Fracture Zone ». Le Bassin septentrional ou Winona Basin s'individualisa à l'Eomiocène et renferme une épaisseur estimée à 4000 mètres d'argillites, de grès, de conglomérats et, dans une moindre mesure, de charbons. Le Bassin de Toffino, au sud, s'individualisa quant à lui au Néoécène et renferme une épaisseur de sédiments estimées à 3200 mètres, principalement des argillites.

Dans le Bassin de Winona, les couches, à disposition homoclinales, apparaissent intactes sur le shelf, mais sont dérangées sur le talus continental par un faillage à grande échelle. Au delà du talus continental apparaissent des plis de direction N.W. associés à un système de failles également N.W. Au Sud du Kyuquot Uplift, sur le plateau continental du Bassin de Toffino, apparaissent des plis de direction N.W. associés à un diapirisme localisé dans les argillites. Ici, le talus continental ne montre pas le système de failles rencontré dans le Bassin de Winona, mais s'appuie généralement sur des plis de direction N.W.

La déformation a induit un relief considérable dans le bassin, relief qui a eu un effet prononcé sur la sédimentation.

Les caractéristiques tectoniques et sédimentaires observées semblent être en liaison avec la configuration actuelle et/ou antérieure de centres d'expansion situés au larges, de plaques et de failles transformantes.

ABSTRACT

Dredging and seismic profiling on the Western Canadian continental margin has revealed two distinct Tertiary sedimentary basins separated by a submerged tectonic feature, the Kyuquot Uplift-Brooks Fracture Zone. The northerly Winona Basin was initiated in Early Miocene time and contains an estimated thickness of 4 kms of mudstone, sandstone, conglomerate and minor coal. The Tofino Basin, to the south, however, was initiated in Late Eocene time and contains an estimated 3.2 kms of sediment, principally mudstone. In the Winona Basin, homoclinally dipping strata rest undisturbed on the shelf, but are disrupted by large scale faulting on the continental slope. Beyond the continental slope, however, northwesterly trending folds are present, associated with a northwesterly striking fault system. Southeast of the Kyuquot Uplift on the Tofino Basin continental shelf, northwesterly striking folds, associated with mudstone diaprism, are

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present. Here the continental slope lacks the large scale faulting characteristically developed in the Winona Basin and is commonly underlain by northwesterly trending folds.

Deformation has created considerable topography in the basin which has had a pronounced effect on sedimentation. This deformation was at least partly contemporaneous with deposition.

The tectonic and depositional features observed appear to be related to present and earlier configurations of nearby offshore spreading centres, plates and transform faults.

INTRODUCTION

A Tertiary depositonal site off the west coast of Vancouver Island, Canada, extending from the Scott Islands in the north to Juan de Fuca Canyon in the south was named the Tofino Basin by Murray and Tiffin (1969). Subsequent work has revealed two distinct sedimentary basins in the region (Fig. 1), separated by a submerged tectonic feature, the Brooks Fracture Zone — Kyuquot Uplift. We now propose to restrict the name Tofino Basin for the more southerly region and include that sedimentary basin north of the Kyuquot Uplift — Brooks Fracture Zone in the Winona Basin (Fig. 1). Scattered Tertiary outcrops of limited extend occur along the west coast of central Vancouver Island, marking the eastern margin of the Tofino Basin, but the western limit of this basin is ill-defined. The eastern limit of the Winona Basin is submerged beneath the waters of the continental shelf, but the western limit is a well defined topographic and tectonic feature, the Paul Revere Ridge (Fig. 1).

Some 2500 kilometers of continuous seismic reflection profiling have been completed over the continental shelf, slope and rise using sparker and air gun sources. Approximately 140 dredge hauls have also been recovered from sea floor outcrops on the shelf and slope. In addition, dart cores and rotary sample cuttings from offshore exploratory boreholes have been generously supplied by Shell Canada Limited. Locations of seismic profiles, exploratory borehole sites and some selected dredge localities are shown in Figure 2. Continuous seismic profiles used as illustrations in this paper are darkened.

WINONA BASIN

The Winona Basin (Fig. 1), a name first proposed for the deep basin at the foot of the slope (Srivastava, et al, 1971), consists of two distinct parts. The eastern part underlays a narrow shelf 18 to 22 kilometers wide (Fig. 2), which is terminated by a steeply dipping continental slope. A wedge of monoclinally seaward dipping strata underlies the outer shelf and thickens seaward over an unconformable lower contact as seen in continuous seismic profiles of which Figure 3 is typical for this area. Dredging on the slope indicates Lower Miocene rocks occur near the base of the monoclinal section while Upper (?) Miocene and Pliocene rocks occur stratigraphically higher (Cameron, oral comm. 1972). Pleistocene sediments, we believe, compose the cap of surficial sediments evident on the profile resting over the outer shelf break. Insufficient sampling has been done to resolve the age of rock below the unconformity. However, quartzites and conglomerates of possible Lower Cretaceous age (Muller, oral comm., 1969) have been dredged from four inshore sites. Complex shoreline geology (Muller, 1971) suggests pre-Cretaceous meta-sedimentary and volcanic rocks may be represented below the unconformity.

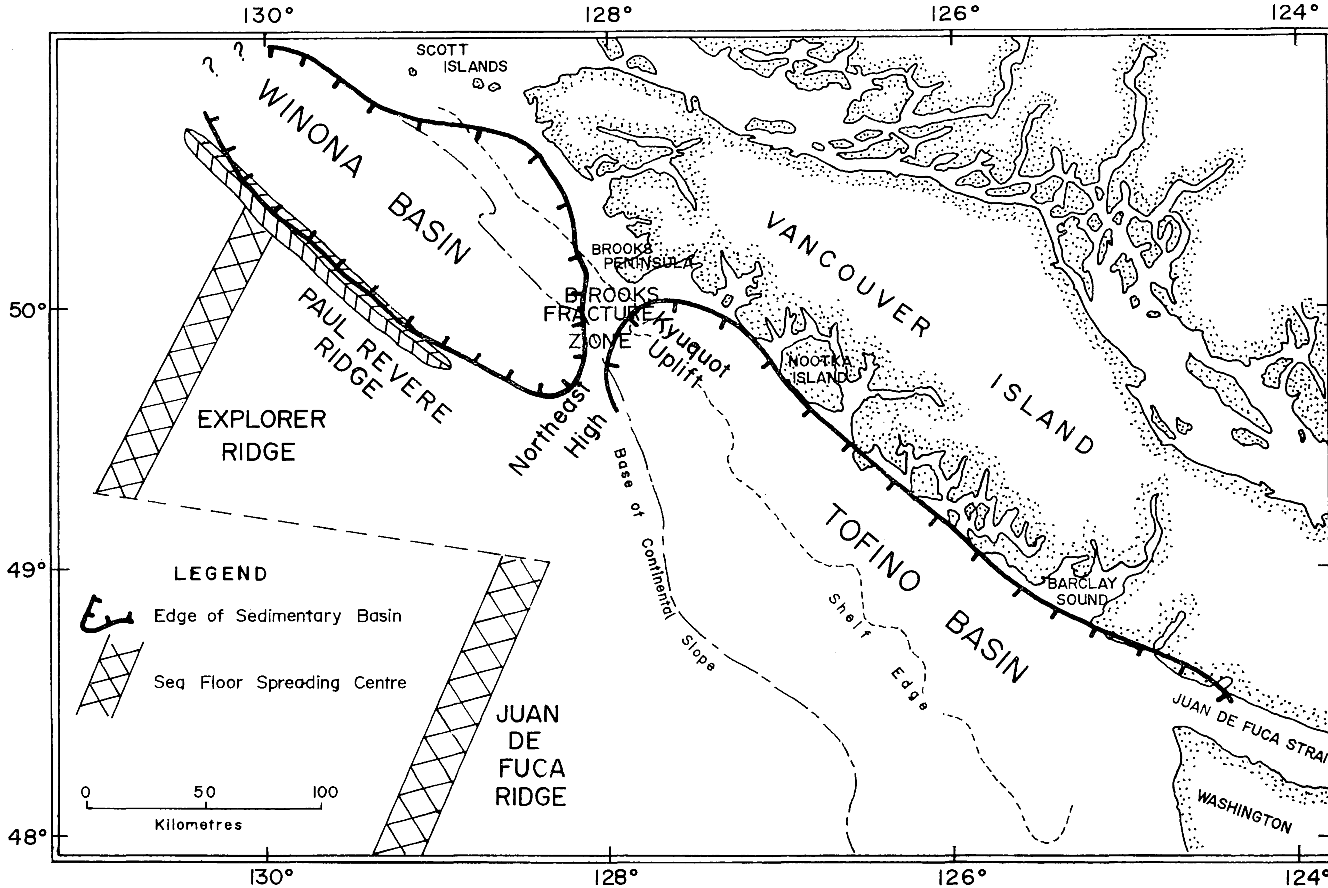

Fig. 1. — Locality map of southwestern Canadian continental margin showing Winona Basin, Brooks Fracture Zone-Kyuquot Uplift and Tofino Basin.

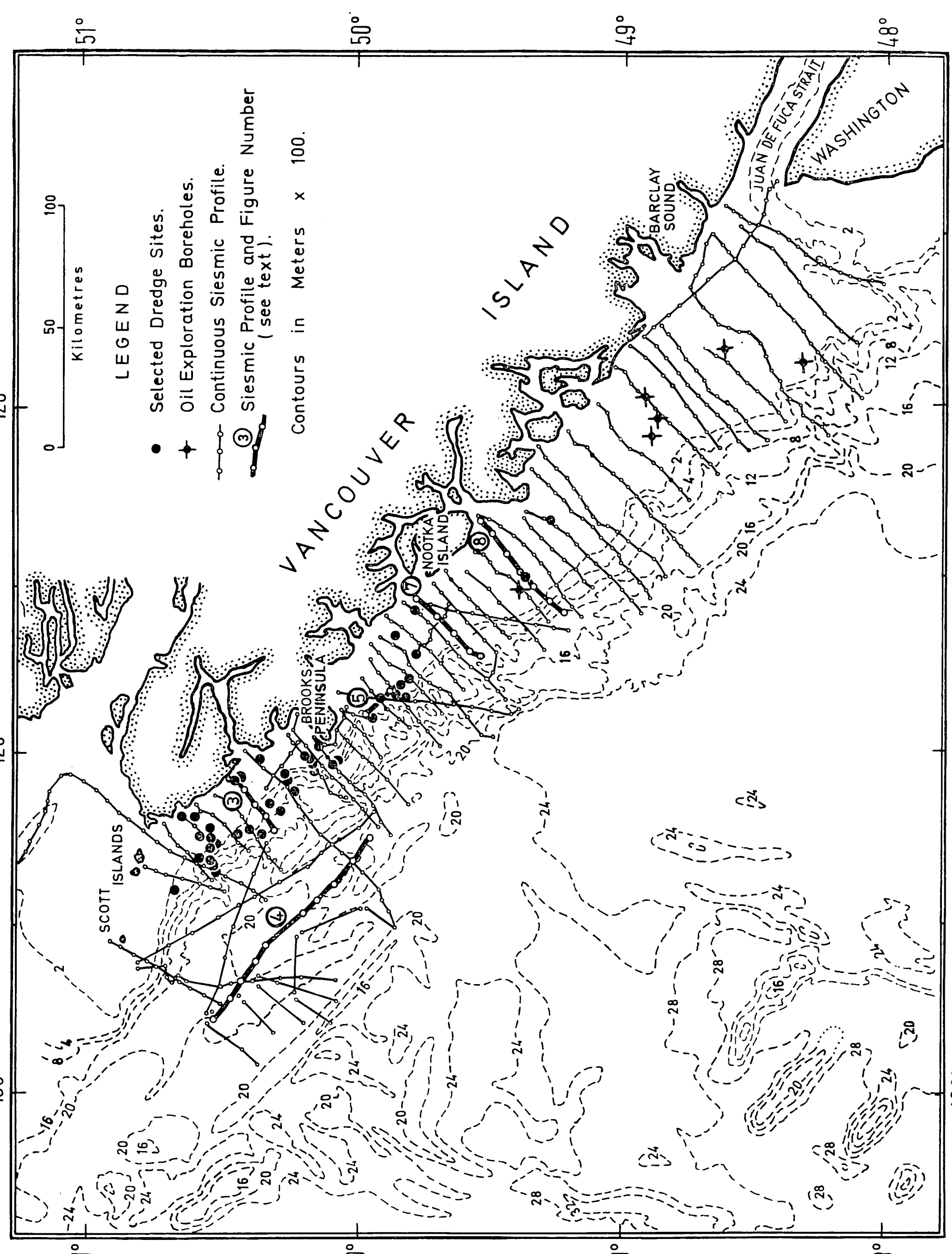

Fig. 2. — Location of seismic profiles, exploratory boreholes and selected dredge sites. Circled numbers refer to figures of seismic profiles used in text. Bathymetry adapted from Mammerickx and Taylor (1971).

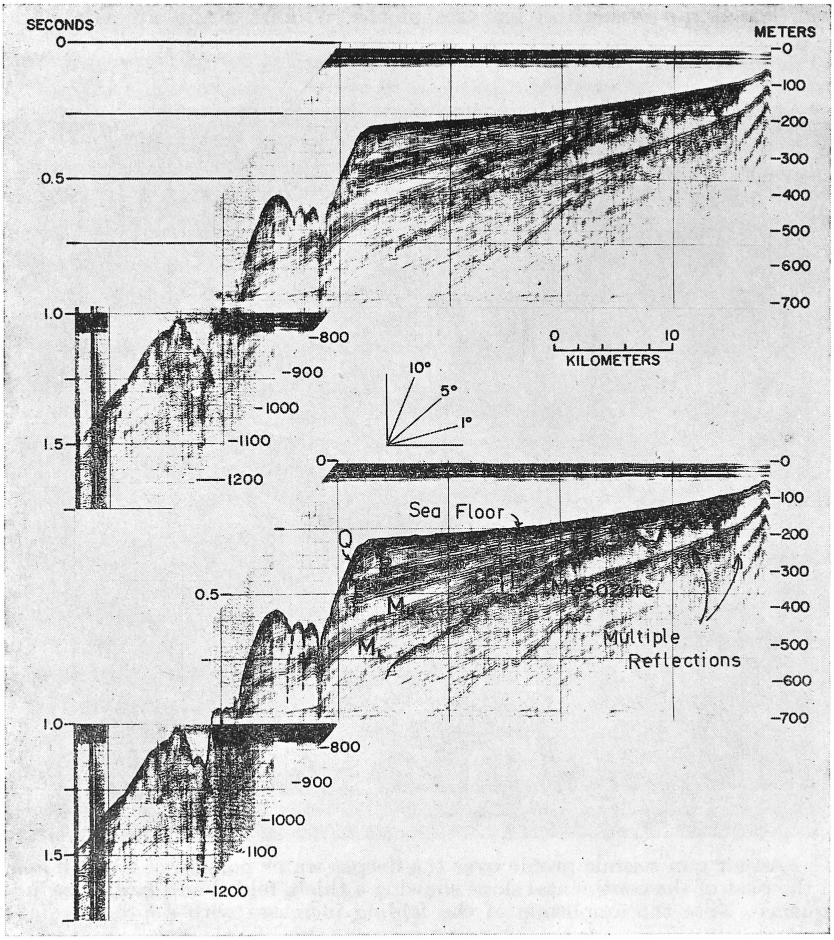

Fig. 3. — A sparker seismic profile illustrating shelf and slope structures and faulting typical on the continental margin in the Winona Basin. P = Pliocene, M_U = Upper Miocene, M_L = Lower Miocene, Q = thin Quaternary cover. Vertical Exaggeration = 12 ×.

The structure of the deeper water, central and western part of the Winona Basin, extending from the base of the continental slope to Paul Revere Ridge (Fig. 1), is characterized by folding and faulting. This part of the basin is underlain in its deeper parts by an estimated 4 kms of mudstone, sandstone, conglomerate and minor coal of definite Pliocene and Pleistocene age (Tiffin, 1973). The presence of Miocene rocks in this deeper part of the basin is unproven and doubtful as will be shown later. The strata are deformed into northwesterly and northerly striking folds whose amplitudes increase with depth of burial (Fig. 4). In addition, major northwesterly striking faults extend for considerable distances parallel to the continental margin. This area has been called Scott Island Fracture Zone (Dehlinger et al, 1970). The major fault of the area, the Revere-Dellwood transform fault (Srivastava et al, 1971), and the related Paul Revere ridge form the western edge of the basin. The abundance of earthquake epicentries in the region support the concept of Recent faulting. The major structural features of the Winona Basin are summarized on Figure 5.

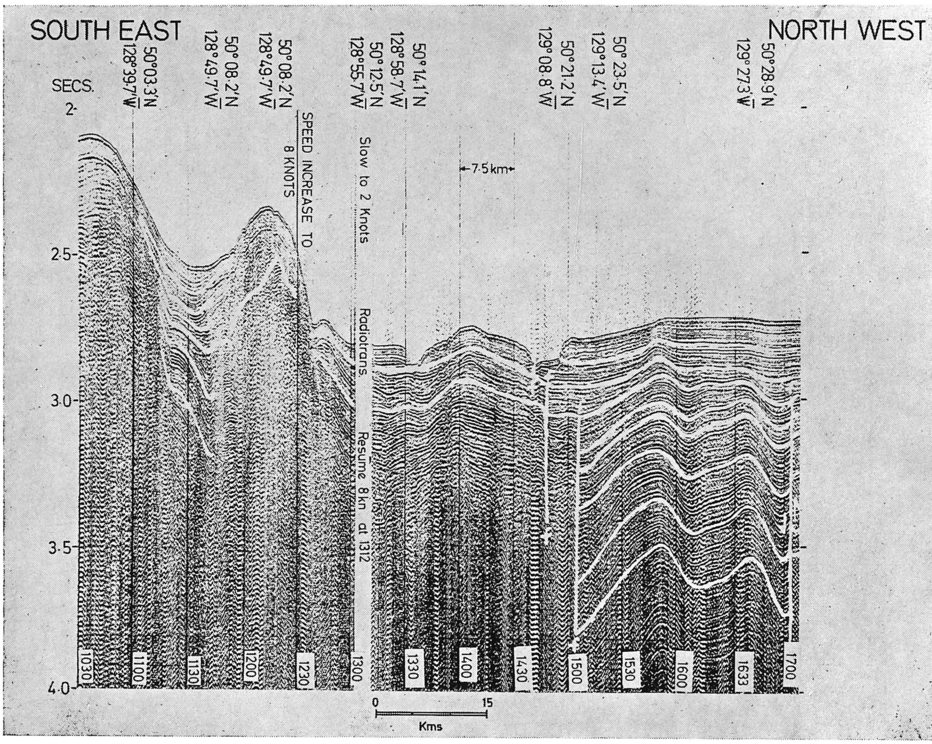

Fig. 4. — An air gun seismic profile over the deeper water portion of the Winona Basin beyond the base of the continental slope showing a thick, folded and faulted sedimentary sequence. Note the amplitude of the folding increases with depth. f = fault.

KYUQUOT UPLIFT — BROOKS FRACTURE ZONE

A northeasterly trending fault is presumed to extend from the Brooks Peninsula (Fig. 5) to the offshore. This important fault intersects and terminates other important faults in the region (Fig. 5), as well as the sediments of Tofino Basin. Widespread faulting in the area is expressed topographically by irregular bottom topography. Because of the importance of the faulting on the shelf and slope, the name Brooks Fracture Zone is proposed for this area.

South of the Brooks Peninsula the structure of the continental shelf is characterized by a broad uplift which exposes Upper Eocene to Oligocene sediments across the entire shelf width. This feature was recognized and named by Tiffin, Cameron and Murray (1972) as the Kyuquot Uplift.

The Upper Eocene to Oligocene sediments exposed on the Kyuquot Uplift dip southwesterly and are unconformably overlain on the northwest shelf edge by younger rocks of Pliocene and probably Late Miocene age. The latter dip northwesterly, reaching a thickness of at least 600 metres before being truncated by faulting along

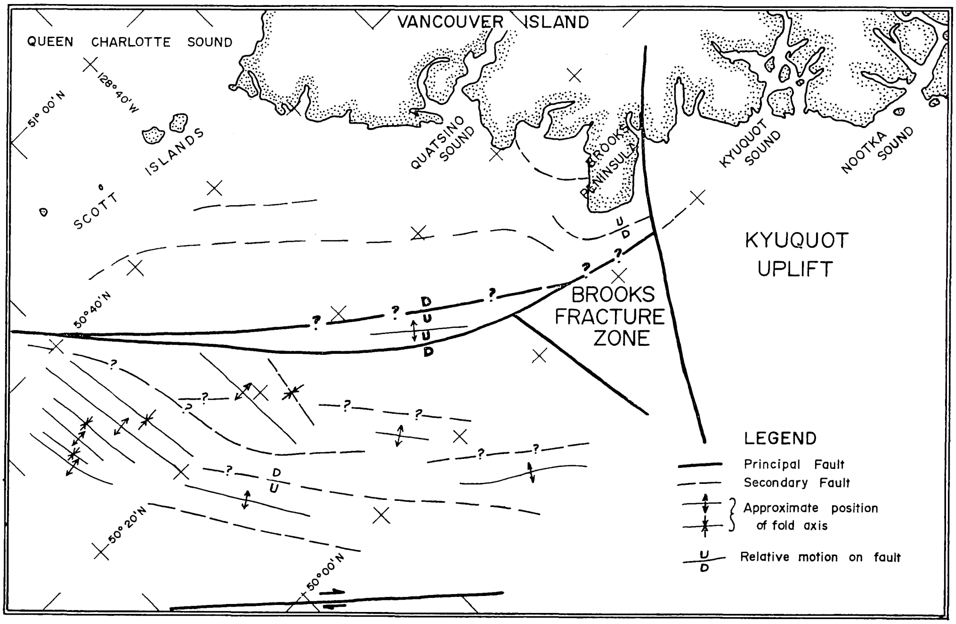

Fig. 5. — General structural features of the Winona Basin and adjacent Brooks Fracture Zone.

the slope (Fig. 6). The angular unconformity between Upper Eocene-Oligocene and younger Tertiary sediments indicates a period of deformation, uplift and erosion occurred prior to Late (?) Miocene (Tiffin et al., *op. cit.*). Thinning of younger sedimentary units can be observed towards the centre of the uplift (Fig. 6) suggesting uplift contemporaneous with sedimentation. Erosion of both younger and older Tertiary strata (Fig. 6) indicates a later stage of uplift, accompanied or followed by faulting on the shelf edge, occurred in later Pliocene or post-Pliocene time.

Extensive dredging and micropaleontological studies (Cameron, oral comm., 1972) indicate the Upper Eocene-Oligocene strata are terminated south of the Brooks Peninsula. In addition, no evidence of marine sediments of this age has been found either in the Winona Basin or in the Queen Charlotte Basin (Shouldice, 1971) northwest of Vancouver Island. It is possible the Brooks Peninsula is related to an older structural or stratigraphical termination of the Tofino Basin since all Tertiary sediments known north or west of this feature are younger.

TOFINA BASIN (NORTHERN PART)

An angular unconformity dips southward from the Kyuquot Uplift and undoubtedly correlates with the mid-Miocene unconformity on the northwest side. On the south of the uplift the unconformity separates Late Eocene-Oligocene from overlying Late Miocene (?) — Pliocene rocks. The latter thicken to the southeast and near the Kyuquot Uplift are gently folded over the unconformity (Fig. 7) which may act as a plane of decollement. Small scarps on the outer shelf are evidence of recent fault movement (Fig. 7). Farther to the south, folding becomes more intense

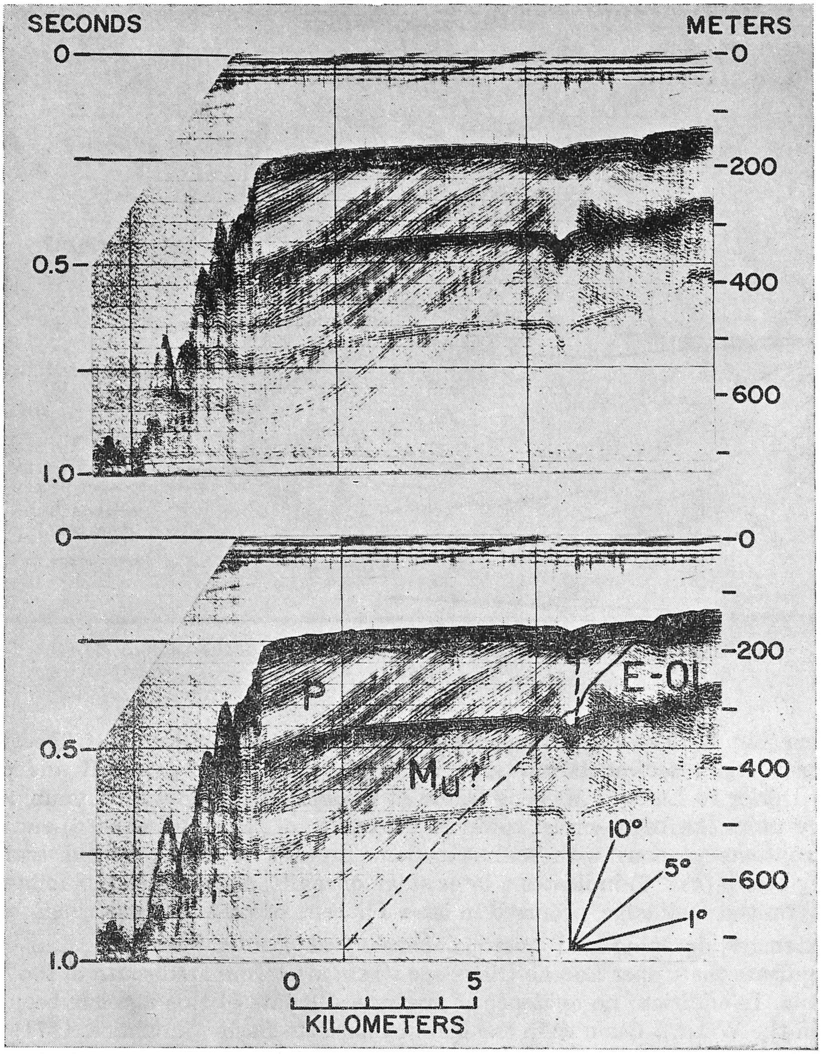

Fig. 6. — Pliocene (P) and possible Upper Miocene (M_U) strata dip northwest and unconformably overly southwesterly dipping Eocene-Oligocene strata (E-O1) of the Kyuquot Uplift. V.E. = 12 ×.

until, near Nootka Sound, mudstone diapirism is common (Fig. 8). The evolution of disharmonic, compressive folds into northwest-southeast trending diapirs suggests compressive stresses increase in intensity south of Kyuquot Uplift. Such stresses may be related to continuing plate movements associated with oceanic spreading centers situated within 100 to 200 kilometers of the coast. Topographic relief of twenty to thirty meters over the exposed cores of some diapirs, in contrast to the otherwise smooth sea floor around them, is proof of post-Pleistocene movements (Fig. 8). Shelf edge folding, possibly associated with diapirism, occurs farther seaward. Minor unconformities are present on the flanks of the diapirs while major unconformities, one of which separates Upper Eocene-Oligocene rocks from younger Tertiary strata, occur shoreward of the diapirs. Beneath the shoreward unconformities, older strata are more highly deformed.

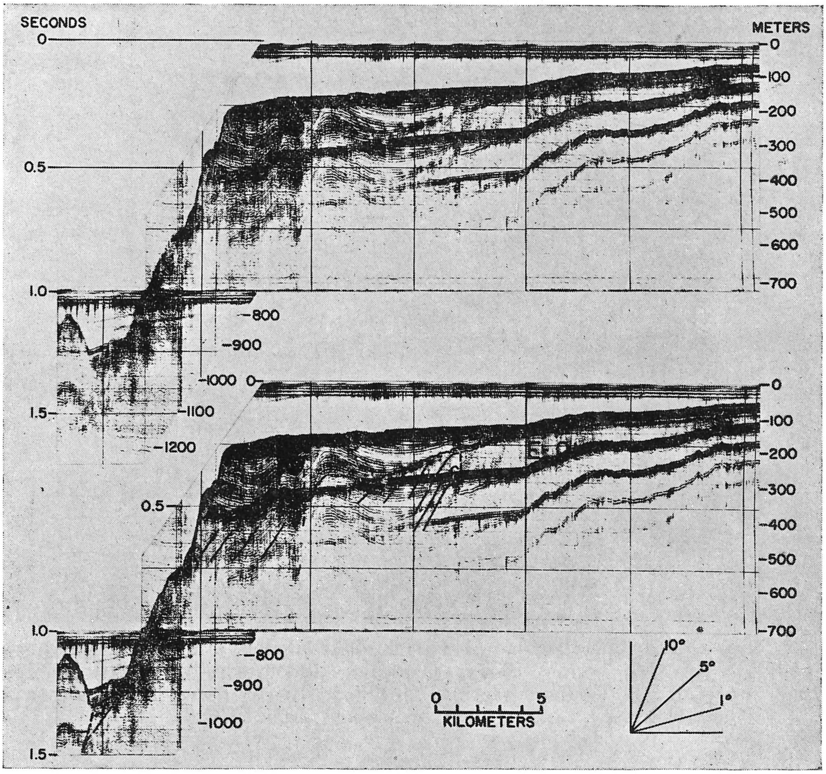

Fig. 7. — On the southern side of the Kyuquot Uplift, gentle deformation occurs in Late Tertiary sediments overlying an unconformity. The inconformity may act in part as a plane of decollement. Faults are evident on the shelf edge. V.E. = 12 ×.

The region of diapirs extends over an area approximately 75 kilometers long and 20 kilometers wide. Figure 9 shows the distribution of the diapirs and other major structural features in the Tofino Basin.

TOFINO BASIN (SOUTHERN PART)

Much of the area south of the main diapiric region has undergone extensive glaciation. Ice scouring and erosional channels are evident in the seismic records as surficial and buried features. These are present in the nearshore areas and off the mouths of most inlets, but they are particularly predominant in the area near Juan de Fuca Strait. Probable Pleistocene sediments extend to the shelf edge in this area and beyond. Folding is common on the outer shelf. In some areas the folds may be associated with diapirism although such structures cannot be as positively identified as in the adjacent area to the north. Diapirs do appear south of this area on the continental shelf west of Washington State (Bennett, 1969; Grim and Bennett, 1969) and at one locality on sea cliffs (Rau, 1970) of the Olympic Peninsula. Some of the structural features of this area are illustrated in Figure 9.

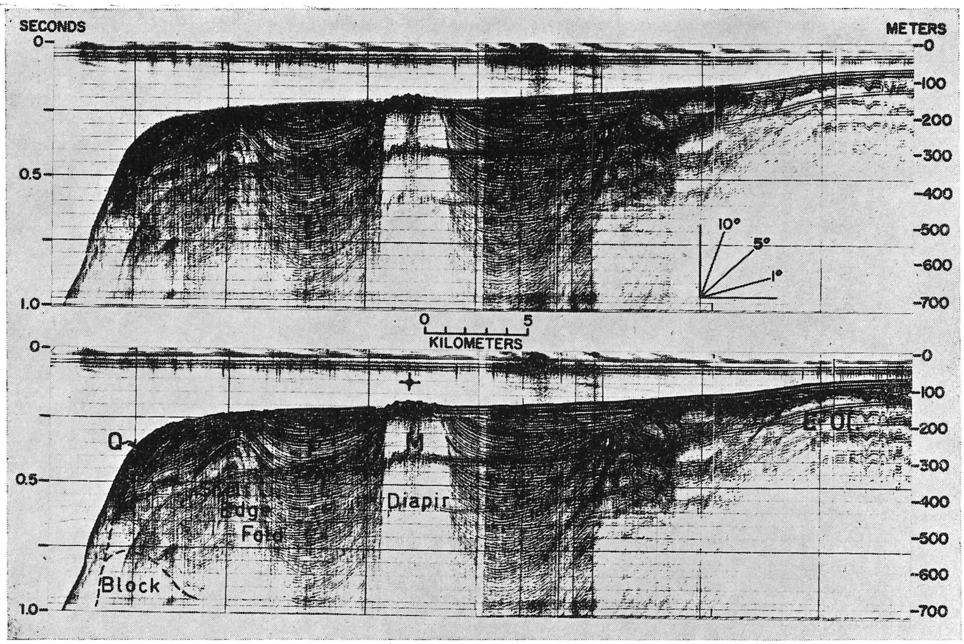

Fig. 8. — Deep-seated diapirism coupled with shelf edge folding occurs in this area of thick sediment in the Tofino Basin. Complex unconformable relationsships exist throughout much of the Tertiary section. Unlike in the Winona Basin, strata are not truncated by faulting on the upper slope. V.E. = 12 ×.

TECTONIC DEVELOPMENT OF THE CONTINENTAL MARGIN

The effect of tectonics on the Winona Basin and on the Tofino Basin are markedly different. Briefly summarized these are : (a) in the Winona Basin, homoclinally dipping strata rest undisturbed upon the shelf, broken only by faulting along the shelf edge. In the deeper water parts of the basin, however, the strata are both folded and faulted; (b) South of a zone of intense faulting, called the Brooks Fracture Zone, the Kuyquot Uplift exposes southwesterly dipping Late Eocene-Oligocene strata across the shelf, overlain on the nothwest and south by Miocene to Pliocene strata. In this area a post Oligocene to pre-Late Miocene period of uplift and deformation was followed by Later Miocene and Pliocene sedimentation, with another period of uplift in post-Pliocene evident from truncation of Pliocene strata on the shelf; (c) In the Tofino Basin, southeastward of the Kyuquot Uplift, younger Tertiary strata, separated from the Upper-Eocene-Oligocene by an unconformity, thicken and become folded. Folding intensifies southward where it is associated with mudstone diapirism; (d) Folding and possible diapirism is also present in the southern area off Juan de Fuca Strait. Structural interpretation of this area is made more difficult by a heavy blanket of Pleistocene cover.

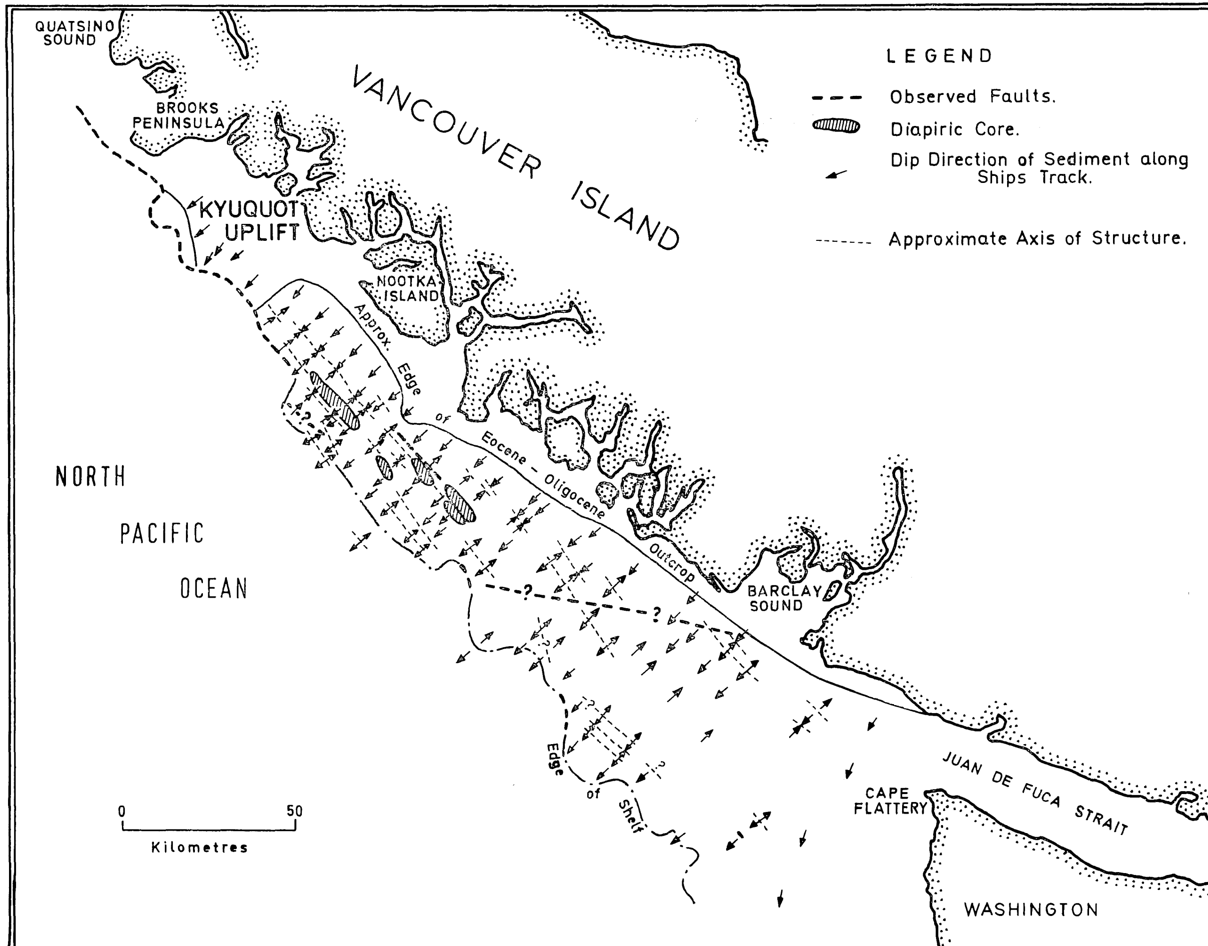

Fig. 9. — Some of the major structural features of the Tofino Basin showing area of diapiric intrusion, folds and faults. Dip symbols are apparent dips along seismic lines.

Most of the Tertiary strata in the Winona Basin and Tofino Basin are marine, although Chase (1971) has reported the occurrence of coal on Paul Ridge (Winona Basin) 100 kms from shore and in water 2000 meters deep. Considerable controversy surrounds the postulated environment of deposition of the rocks in the Tofino Basin. Cameron (1971; 1972) has suggested the rocks of the outcrop area on the eastern Tofino Basin margin were deposited in bathyal water depth. This suggestion has. been challenged by Jeletzky (1973) who contends that only the middle part of the Tertiary sequence is of bathyal depth.

The structural variations from north to south in the region, and between early and late Tertiary may be a result of plate movement near the continental margin. The most active nearby tectonism, and one that must have had considerable influence on the margin, is associated with sea floor spreading and plate movement. Spread-ridges are presently positioned close by the continent on the Northeast Pacific (Fig. 10). These strike toward the continent at an angle of approximately N. 15°. The Juan de Fuca plate, laying between Juan de Fuca and Explorer Ridge segments and the continental margin, is considered to be a remnant of a much larger plate, the Farallon Plate (Atwater, 1970), wihch has mainly disappeared, presumably by crustal shortening and/for subduction under the continental America Plate. In the subduction process, compressional forces may have developed to fold and uplift sediments along the continental margin as suggested by Byrne et al. (1966) off the Oregon coast, and Silver (1971, 1972), off California and Washington. Accepting a deeper water origin for most of the Tofino Basin sediments, which we do, then it is possible uplift of bathyal sediments occurred in mid-Miocene time and again in Upper Pliocene-Pleistocene time. Uplift on the continental shelf may have ceased in Pliocene time but deformation is most probably continuing.

If plate movements have produced the uplift and deformational pattern of the shelf, the question remains as to why there exists a variation in intensity and style or deformation from north to south. The shelf north of Brooks Peninsula has undergone little, if any, vertical movement and no folding, but is truncated by a large fault which probably extends from at least the Scott Islands to the Brooks Fracture Zone. However, in the deeper water beyond the base of the continental slope folding is common. Similarly, in the Tofino Basin there exists a southward increase in intensity of folding and deformation. A reasonable hypothesis which explains these facts is that the Winona Basin shelf has been adjacent to a transform fault system which separated the America and Pacific plates just as the Queen Charlotte Fault (Chase and Tiffin, 1972) does at the present time 75 kms to the north. This implies the triple junction of the three crustal plates, Pacific, Juan de Fuca and America plates (Fig. 10) was, until relatively recently, south of Brooks Peninsula or in the immediate vicinity. The Pacific plate is moving north relative to the America plate (Wilson, 1965; Tobin and Sykes, 1968; Chase and Tiffin, 1972) along the Queen Charlotte transform, resulting in a faulted continental margin north of the triple point, but relatively unfaulted to the south. We believe, from our data, that the triple point has moved northward with time in Late Tertiary. Because new sea floor is generated at the spreading ridges, the northward movement of the triple point is not required to be as fast as the relative movement along the transform fault. In fact, the triple point may have been almost stationary for some time throughout Early Tertiary with respect to the America plate (Atwater, 1970). However, a rotation of the Juan de Fuca plate which began about 7 million years ago (Atwater, 1970; Menard and Atwater, 1968) may have led to a migration northward of the Explorer segment of ridge and the triple point to its present position relative to the Juan de Fuca segment, beginning, possibly, as late as 4 million years ago. If the present position of the Juan de Fuca segment is projected northeastward, it bisects the continent at the Brooks Fracture Zone. The former presence of the ridge in the area of Brooks Fracture Zone may have led to the formation of this feature and to the uplift of the Kyuquot Arch If the ridge moved northward from that area, the crust under the western part of Winona Basin is then 4 million years old, or less, and any Miocene sediments which may have been deposited in this region must have either been subducted or accreted to the continent.

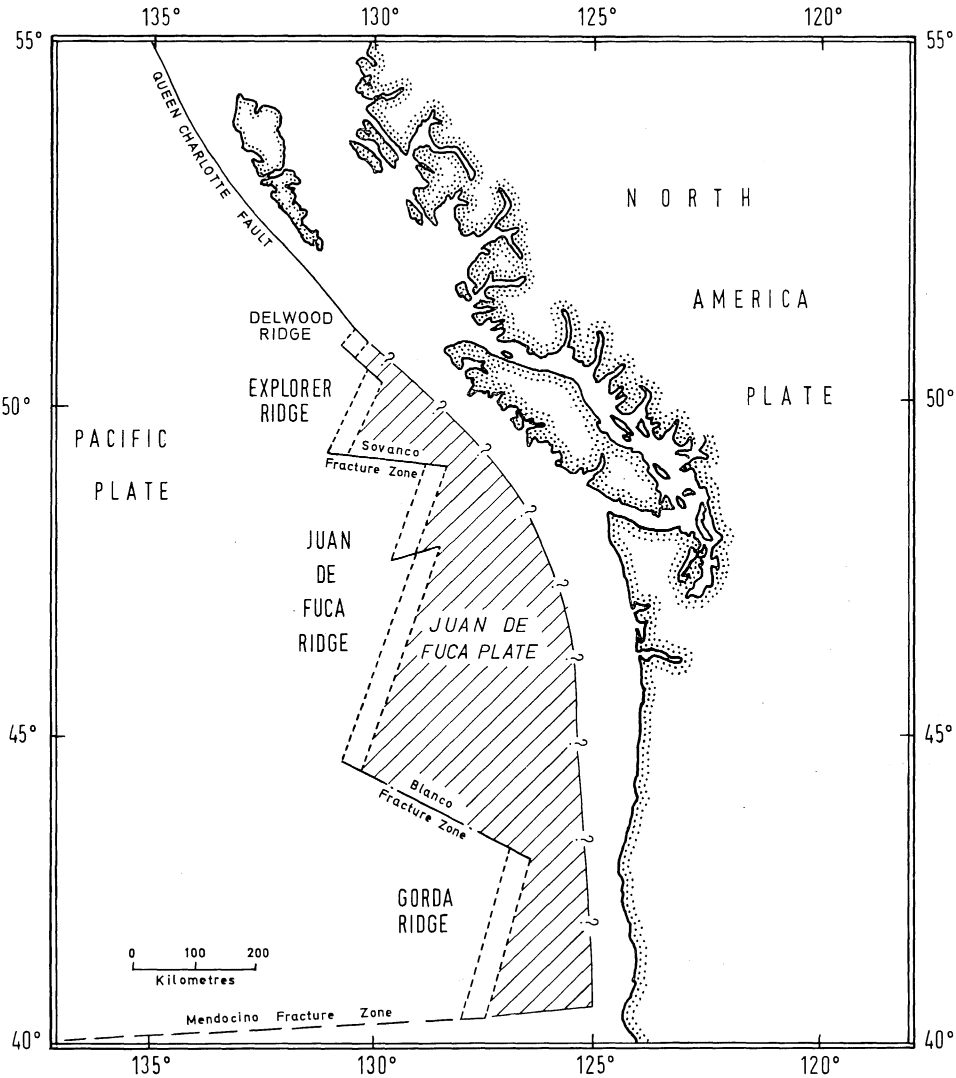

Fig. 10. — Regional tectonics showing the position of the three crustal plates, spreading centres, transform faults and fracture zones whose movements probably influenced the tectonic develoment of the continental margin off Vancouver Island. The boundary between the Juan de Fuca Plate and America Plate is speculative.

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