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# STRUCTURE AND PETROLEUM POTENTIAL OF THE CONTINENTAL MARGIN BETWEEN CROSS SOUND AND ICY BAY, NORTHERN GULF OF ALASKA

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By

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## ABSTRACT

Major structural features of the Yakutat segment, the segment of the continental margin between Cross Sound and Icy Bay, northern Gulf of Alaska, are delineated by multichannel seismic reflection data. A large structural high is centered on Fairweather Ground and lies generally at the edge of the shelf from Cross Sound to west of the Alsek Valley. A basement uplift, the Dangerous River zone, along which the seismic acoustic basement shallows by up to two kilometers, extends north from the western edge of Fairweather Ground towards the mouth of the Dangerous River. The Dangerous River zone separates the Yakutat segment into two distinct subbasins. The eastern subbasin has a maximum sediment thickness of about 4 km, and the axis of the basin is near and parallel to the coast. Strata in this basin are largely of late Cenozoic age (Neogene and Quaternary) and approximately correlate with the onshore Yakataga Formation. The western subbasin has a maximum of at least 9 km of sediment, comprised of a thick (greater than 4.5 km) Paleogene section overlain by late Cenozoic strata. The Paleogene section is truncated along the Dangerous River zone by a combination of erosion, faulting, and onlap onto the acoustic basement. Within the western subbasin, the late Cenozoic basin axis is near and parallel to the coast, but the Paleogene basin axis appears to trend in a northwest direction diagonally across the shelf. Sedimentary strata throughout the Yakutat shelf show regional subsidence and only minor deformation except in the vicinity of the Fairweather Ground structural high, near and along the Dangerous River zone, and at the shoreline near Lituya Bay.

Seismic data across the continental slope and adjacent deep ocean show truncation at the continental slope of Paleogene strata, the presence of a thick (to 6 km) undeformed or mildly deformed abyssal sedimentary section at the base of the slope that in part onlaps the slope, and a relatively narrow zone along the slope or at the base of the slope where faulting may have occurred. Observed deformation at the base of the slope is primarily related to the late Cenozoic uplift of Fairweather Ground, and to Quarternary folding perpendicular to the Pacific-North America relative convergence vector. No accretionary section or major deformation is observed along the continental slope. The absence of these features suggests that no major subduction of the Pacific plate beneath the Yakutat margin has occurred during the late Cenozoic. However, transform faulting along the base of the slope has occurred, because probable Oligocene oceanic basement is juxtaposed against Mesozoic and Paleogene sedimentary strata of the Yakutat slope. This juxtaposition most likely occurred during late Oligocene and Miocene time. During much of the late Cenozoic, and especially during Pliocene-Pleistocene

time, the Yakutat segment has apparently been moving northward with the Pacific plate.

Dredge samples from the continental slope recovered potential hydrocarbon source and reservoir rocks from the Paleogene sedimentary sequence. Most of the organic matter from these samples is immature to marginally mature. Lopatin calculations suggest that rocks beneath the shelf are likely to be thermally mature at a depth of 4 to 5 km and deeper. In general, the strata at these depths are largely of Paleogene age. Thus, the Paleogene strata may have significant resource potential if source and reservoir rocks similar to those dredged at the slope are present below the shelf. The Paleogene strata are contained primarily within the western subbasin; strata in the east subbasin appear to have little resource potential. Structural traps are apparently present in parts of the basin near and along the Dangerous River zone. These traps are in an updip position from potentially mature strata of the western subbasin, and may hold commercial accumulations of hydrocarbons, if sufficient hydrocarbon generation and migration has occurred to fill such traps and if sufficient reservoir rock is present.

## INTRODUCTION

This report discusses the structure, geologic history, and petroleum potential of the Yakutat segment, the part of the continental margin between Cross Sound and Icy Bay, northern Gulf of Alaska (figs. 1 and 2). As part of a program of geologic and geophysical investigations of the continental margin in the northern Gulf of Alaska, the U.S. Geological Survey collected about 2000 km of multichannel seismic reflection in the study area during 1975, 1977, and 1978 (fig. 3a). In addition, dredge samples from the continental slope were acquired during the 1977, 1978, and 1979 field seasons. Preliminary geological results of the dredge cruises are reported by Plafker and others (1978c, 1979, 1980). The first part of this paper presents an interpretation of the seismic reflection and refraction data, including structural contour maps, isopach maps, and interpreted seismic sections; the second part is a brief discussion of the implications for petroleum potential. The primary area of interest is the continental shelf and slope, but some data from strata at the base of the slope are also included. Some of these data were presented in previous reports by Plafker and others (1978a) and Bruns (1979). The seismic data in the study area for the 1975 cruise are available in an open-file report by Bruns and Bayer (1977).

## REGIONAL SETTING

The Yakutat segment of the continental margin lies in a zone of transition between transform and convergent motion (Rogers, 1977; Plafker and others, 1978; von Huene and others, 1979; Bruns, 1979; Perez and Jacob, 1980; Lahr and Plafker, 1980). To the east of the study area, the Pacific plate is moving laterally past the North America plate along a transform fault system composed of the Queen Charlotte, Fairweather, and related faults (fig. 2). To the west, in the Kodiak Island and Alaska Peninsula regions, plate motion is accomodated by underthrusting of the Pacific plate beneath the continental margin, resulting in the formation of the Aleutian trench and volcanic arc. The northernmost extent of compressional deformation associated with this convergence lies onshore in the complex folds and faults of the Yakataga and Malaspina districts and offshore within the structures of the Yakataga segment of the continental margin along what has been informally termed the Pamplona zone (Plafker, 1971; Plafker and others, 1978b, Bruns, 1979; Lahr and others, 1980; Bruns and Schwab, in press). The Yakutat segment is part of what may be a small crustal plate, informally termed the Yakutat block (Rogers, 1977; Plafker and others, 1978b; von Huene and others (1979), Bruns, 1979; Lahr and Plafker 1980; Bruns and Schwab, in press), that is bounded by Kayak Island on the west, the Queen Charlotte-Fairweather fault system on the north and northeast, and the base of the continental slope on the south (fig. 2).

## REGIONAL GEOLOGY

The study area is bordered onshore by rocks ranging from Mesozoic through Cenozoic age that decrease in age seaward (fig. 2). Rocks of Mesozoic and older age are seen in the high Chugach, St. Elias and Fairweather mountains, and are exposed on the seaward islands of southeastern Alaska north of Chatham Strait. These rocks are characteristically highly deformed, locally metamorphosed and intruded sedimentary and volcanic rocks (Stoneley, 1967; Plafker 1967, 1971; Plafker and others 1975, 1978a; Beikman, 1980).

Cenozoic rocks onshore consist of bedded terrigenous clastic sediments that were deposited primarily in a marine environment. The sequence is broadly divisible into three subdivisions that correspond to major changes in the tectonic and depositional environment of the basin. The subdivisions are: 1) an early Tertiary sequence (Paleocene through early Oligocene) that is characteristically hard, dense, and variably deformed and faulted, and composed of deep-sea fan deposits and associated volcanic rocks of Paleocene age, and continental to shallow marine coal bearing clastic rocks of Eocene to early Oligocene age; 2) a middle Tertiary sequence (middle Oligocene through early Miocene), composed primarily of mudstone and siltstone; and 3) a late Tertiary through Holocene sequence, the Yakataga Formation, a marine diamictite characterized by abundant glacial detritus and composed of mudstone, muddy sandstone and conglomeratic sandy mudstone (Plafker, 1971; Plafker and Addicott, 1976; Plafker and others, 1975; Plafker and others, 1978a; Winkler, 1976). The Yakataga Formation reflects deposition adjacent to the intensely glaciated, high St. Elias-Fairweather mountains, and deposition of these strata probably correlates to of uplift of these mountains (Plafker and Addicott, 1976).

Offshore, strata of Mesozoic through Pliocene age that underlie the continental slope of the Yakutat segment have recently been sampled by dredging (fig.3b; Plafker and others, 1978c, 1979, 1980). These strata can be generalized in much the same way as the onshore strata from oldest to youngest as follows (unit designations are from Plafker and others, 1980): 1) An inferred late Cretaceous sequence consisting of hard graywacke, argillite and possibly intrusive rocks (Unit A). This sequence is found on the continental slope off Fairweather Ground, and probably underlies much of Fairweather Ground. 2) A lower Tertiary sequence consisting of upper Paleocene (?) to lower Eocene (?) sandstone, conglomerate, and shale (Unit B), lower Eocene basalt flows and pyroclastic rocks (Unit C), early to middle Eocene sandstone, conglomerate, siltstone, and shale (Unit D), and upper Eocene and lower

Oligocene (?) shale, tuffaceous shale, siltstone and sandstone (unit E). This sequence is found along parts of the continental slope from Fairweather Ground to about Pamplona Ridge. 3) A middle Tertiary sequence consisting of upper Oligocene siltstone (Unit F) that crops out locally along the upper slope. 4) A middle Miocene (?) and younger clastic sedimentary sequence that includes abundant glaciomarine deposits (Unit G), approximately equivalent to the onshore Yakataga Formation. The Paleogene sedimentary strata (Units B, and D through F) are probably continentally derived, with younger rocks deposited in progressively shallower water. In addition, these rocks differ strikingly in lithology from coeval rocks either exposed in outcrop onshore or penetrated in exploratory wells onshore or offshore (Plafker and others, 1980).

## GEOPHYSICAL DATA

This study is based primarily on 24-fold multichannel seismic reflection data acquired in 1975 from the Geophysical Services, Inc. vessel <u>M/V Cecil H. Green</u> under contract to the U.S. Geological Survey (Bruns and Bayer, 1977), and in 1977 and 1978 from the U.S Geological Survey research vessel <u>R/V S.P. Lee</u>. Tracklines for these three cruises are shown in figure 3. Single channel seismic reflection data across the continental slope south of Icy Bay (von Huene and others, 1975) provide subsurface information between the multichannel lines.

The seismic system on the <u>M/V Cecil H. Green</u> consisted of a tuned array of 22 air-guns with a total capacity of 19.6 P (1,200 cu. in.), a 2,400 m, 48-group streamer and DSF IV digital recording instruments. These data were processed by Petty-Ray Geophysical, Inc. (Bruns and Bayer, 1977). The seismic system on the <u>R/V S. P. Lee</u> consisted of a tuned array of 5 air-guns with a capacity of 21.7 P (1326 cu. in.), a 2,400 m. 24-group streamer, and GUS 4300 digital recording instruments. These data were processed by the U.S. Geological Survey. In all surveys, navigation was by means of an integrated satellite, Loran C, and doppler-sonar navigation system.

Bathymetric, gravity and magnetic data were also acquired during these cruises; maps of these data are available in Schwab and Bruns (1979), Schwab and others (1980), Burkhard and others (1980a, b), Atwood and others (1981), and Bruns and others (1981a, b).

## GEOPHYSICAL INTERPRETATION

### Shelf and Slope

Contour and isopach maps of strata beneath the continental shelf and slope are based on mapping of seismic horizons D and F throughout the seismic grid. Horizon D correlates with the D horizon in the Yakataga shelf to the west (Bruns and Schwab, in press). An additional horizon, horizon E, is mapped on parts of a few seismic lines. These horizons are all at least local unconformities and strong seismic reflectors. In areas where the strata are conformable, mapping is on a seismic horizon interpreted as correlative with the unconformities. Since seismic mapping is on unconformities or the correlative conformity, the mapped horizons have time-stratigraphic significance. Interpretation problems in following the seismic horizons are created by the wide spacing of the data, by poor reflector continuity, and by limited acoustic penetration, especially in the deep parts of the basin. Several factors that limit acoustic penetration and disrupt reflector continuity can be identified or inferred at least locally and include persistent water-bottom and interbed multiples that obscure primary reflectors; coarse or bouldery near-surface and subsurface glacially derived sediments that may scatter or limit penetration of the acoustic signal; and local unconformities and rapid facies or bedding changes within the Yakataga Formation. Because of these problems, and because of the wide spacing of the seismic data, correlation errors may be present in some areas; however, these errors should not seriously change the general basin form shown in the structural contour maps.

The character of the mapped horizons and the seismic reflectors between these horizons is best seen on the slope portions of the seismic sections. The mapped seismic horizons and the reflection character between these horizons are discussed from shallowest to deepest in the following section. The seismic sequence, strata or time interval between any two horizons, as for example between horizons F and D, is referred to as the F-D sequence, strata or time. The seismic lines presented in this report (fig. 3a) are shown in order from west to east in figures 8-16, and then from north to south in figures 17-19.

Horizon D is mapped on a prominent continuous reflector or group of reflectors best observed on the parts of the seismic lines extending across the continental slope south of Icy Bay (seismic lines 404, 916, 906; figs. 8-10) and on lines near and over Fairweather Ground (seismic lines 403, 911, 400; figs. 11, 14, 16). The horizon is moderately well defined throughout the seismic grid, except on the landward ends of the seismic sections where the sedimentary section is thickest.

The relation of seismic reflectors between horizon D and the seafloor (D-SF reflectors) to horizon D appears to be primarily one of concordence. However, on the gently dipping continental slope south of Icy Bay, strata immediately above horizon D show very gentle downlap onto the D reflector, indicating a prograding slope depositional environment (seismic lines 404, 916, 906; figs. 8-10). Onlap of the D-SF reflections onto the D horizon reflector is also seen on seismic sections over Fairweather Ground (seismic line 400, fig. 16). On the steep continental slope between Yakobi Valley and Yakutat Valley, strata of the D-SF sequence are very thin to absent (seismic lines 403, 909; figs. 11, 13).

In general, seismic reflectors between horizon D and the seafloor show variable continuity and are parallel to slightly divergent. Well-defined, high amplitude reflections within the sequence are separated both vertically and laterally by low amplitude to almost reflection-free zones. The reflector configuration generally suggests discontinuous lithologic units and a variable lithology. The D-SF sequence thickens landward from the shelf edge, indicating regional subsidence of the continental shelf (lines 404, 906, 403, 909, 400; figs. 8, 10, 11, 13, 16).

Horizon E is mapped on a prominant, local unconformity on the seaward part of seismic section 403 (fig. 11), but the unconformity cannot be traced with confidence landward or into adjacent seismic lines. Reflectors in the E-D sequence are parallel or subparallel to reflectors in the overlying D-SF sequence. On the seaward part of the line, E-D reflectors onlap horizon E at the base of the sequence; elsewhere these reflectors are concordant with horizon E.

Horizon F is mapped on a strong seismic reflector that is acoustic basement on the seismic lines. The acoustic basement is best seen on line 403 and lines to the east (figs. 3a, 11-16), but can only be discontinuously mapped west of line 403, and is seen only on the slope portion of lines west of line 906, most likely because of insufficient acoustic energy to penetrate through the thick sedimentary sequence present in the area south of Icy Bay. Refraction data (Bayer and others, 1978) give estimates of total sediment thickness in this area, and are used to infer the approximate position of the F horizon contours (fig. 5). Age calls from foraminiferal data from the Colorado Oil and Gas wells near the town of Yakutat (Rau and others, 1977) give the depth to strata correlated to horizons F and D, and are used to estimate the position of the horizons in the area of Yakutat Bay. East of line 909 (fig. 3), horizons F and D merge, as the F-D reflectors are truncated out against a structural high.

Seismic reflections between horizons F and D can best be seen on the continental slope segments of lines 404, 916, 906, and 403 (figs. 8-11); beneath the shelf, the reflectors are partly or totally obscured by multiples generated within the overlying section. Where best seen, reflections in the upper part of the F-D sequence show moderate to poor continuity, and in some places, the sequence is almost reflection free. Reflections are divergent with seaward thickening (lines 906, 403; figs. 10, 11). The reflection configuration suggests a well-bedded, rather uniform lithology. On line 906 the lower part of the sequence is markedly different, with reflections showing good continuity and high amplitude; this difference may reflect the complex character of the basement unit (see following section on geologic correlation of the seismic horizons).

The character of reflections below horizon D suggests two interpretation problems. First, these reflections are low amplitude and, beneath the continental shelf, are usually obscured by multiples. Therefore, the stratigraphic character and internal structure of the F-D sequence strata cannot be well determined even though the top and bottom of the F-D sequence are moderately well defined. Second, the lower part of the F-D sequence on the seaward end of seismic section 906 shows a set of thickening seaward, strong reflectors. The same set of reflectors beneath the shelf would likely not be resolvable, except for the initial reflector at the top of the strong reflector set. Thus, the "acoustic basement" picked on the seismic lines may exclude some strata, and the resulting sediment thickness must be considered a minimum.

## Base of Slope

Seismic data indicate that a well bedded sequence of sedimentary strata is present at the base of the slope (lines 404, 906, 403, 909, 967, 400). Three horizons are mapped and designated as horizons A1, A2, and A3. A multichannel seismic tie to DSDP hole 178 east of Kodiak Island gives estimates of base Pleistocene(?), base Pliocene(?), and top oceanic basalt respectively for the horizons; the ages are queried due to the distance to the drill hole. Horizon A3 (oceanic basalt) is characterized by strong, moderately discontinuous, hyperbolic reflectors. Where sediment overlying the basalt is thick, the reflector is fainter than in other areas and more continuous. The reflection configuration between horizons A3 and A1 is highly variable and in part area dependent, ranging from faint and discontinuous, to strong and continuous. In general, reflectors are parallel to subparallel throughout the interval. This section may include both pelagic units and varying amounts of turbidite deposits. The reflection configuration above horizon A1 is commonly complex and variable, and includes wavey or mounded configurations with low to high reflector continuity. The reflections are suggestive of turbidite fans, with surface and buried channels and levees common. Near the base of the slope, particularly from Yakutat Valley to the west, the sequence is characterized by chaotic reflectors, suggesting rapid deposition.

## VELOCITY DATA

To make structural and isopach maps, seismic time was converted to depth using two types of velocity information, stacking velocities obtained during processing of the multichannel reflection data, and velocities from seismic refraction data. An area-average stacking velocity curve was derived from all the picks from individual seismic lines. Good velocity picks are concentrated in the upper 2 to 3 seconds of the seismic data, in general, corresponding to the data above horizon D. Thus, the stacking velocity picks give good results for the upper 2-3 seconds, but only poorly constrain velocities below about 3 seconds.

Refraction data help constrain the velocity in the deeper sedimentary section. Four unreversed refraction sonobuoys were obtained during the 1977 cruise, using the airgun source. All four sonobuoys are in areas of gentle or no dip (fig. 3a). Two of the sonobuoys are in an area of relatively shallow acoustic basement (sonobuoys 3 and 6), and the basement picks were excluded from the calculation for an average time-depth curve. The other two sonobuoys are in an area with a thick sedimentary sequence (fig. 20).

The area-average stacking velocity curve was converted to interval velocities by use of the Dix formula (Dix, 1955), and the interval curve was used to construct a time-depth curve. This curve was combined with the refraction velocity data, and fitted with a least-squared-error routine to yield a single curve, $z = + 0.695t + 0.296t^2 - 0.02t^3$, where z is the depth in kilometers and t is the two-way travel time in seconds (fig. 21). This curve was used for all time-to-depth conversions. An approximate error range of the resulting curve (fig. 21) was derived by estimating a maximum and minimum bound for the stacking velocities; these bounds were then converted to time-depth picks in the manner given above.

The final area-average time-depth curve is very similar to an independently derived curve developed for the Yakataga shelf to the west (Bruns and Schwab, in press), and closely fits velocity data derived from sonic logs of the Standard Oil Co. of California Riou Bay No. 1 well in Icy Bay, and the Continental Offshore Stratigraphic Test No. 1 well, drilled southeast of Icy Bay on the continental shelf (fig. 21; Bolm and others, 1976; Bruns, 1979; Bruns and Schwab, in press). Both of these wells are in structurally simple areas. The method of derivation of the curve is such that it gives a good depth estimate for the sedimentary section underlying the continental shelf, approximately the section above horizon F, but it is not valid for depth conversion below horizon F or for times greater than about 5 seconds two-way reflection time. In areas of deep water, preliminary examination of stacking velocity data indicates that the sub-seafloor time-depth curve is almost identical with the curve developed for the shelf. Using a single velocity function introduces errors in depth conversion of the contoured horizons and of the seismic lines, but the errors should not affect the basic conclusions of this paper.

## GEOLOGIC CORRELATION OF SEISMIC HORIZONS

The correlation of the mapped horizons to the regional geology (fig. 22) is determined primarily from dredge data from the continental slope (Plafker and others, 1980). Horizon D is approximately correlative with the base of Unit G of Plafker and others (1980), with correlation into the seismic data best defined on seismic sections 404 and 906 (figs. 8, 10). Unit G is in turn correlative with the onshore Yakataga Formation. The horizon can also be correlated to the Riou Bay well at Icy Bay, where the horizon is approximately at the base of the Yakataga Formation (Bruns and Schwab, in press).

Onshore well data (Rau and others, 1977) suggests that much or most of the Yakataga Formation within the study area could be as young as Plio-Pleistocene. In the Riou Bay well, the lower part of the drilled section is of Pliocene(?) age. In the Malaspina # 1A well, the Yakataga Formation is of Pliocene-Pleistocene age and overlies upper Eocene(?) strata. In three Colorado Oil and Gas wells at Yakutat, the early Tertiary section is truncated updip and the Pliocene-Pleistocene Yakataga Formation unconformably overlies Eocene (Narizian) strata in the two seaward wells, and Cretaceous strata in the landward well. Finally, most of the Yakataga Formation at Lituya Bay is of Plio-Pleistocene age. The Yakataga Formation was not extensively sampled during the dredging cruises, so the age of offshore strata (D-SF strata) correlative with the onshore Yakataga Formation is not known, but may be similar to ages known in the wells. Thus, as a possible end member case for horizon D, it could be a major time-stratigraphic break and an erosional unconformity, with Oligocene and older strata below horizon D, and Pliocene and younger strata above the horizon. Alternatively, at the other extreme, the section across horizon D could be continuous with no major breaks in deposition. Both of these cases will be considered later in the report. It is likely that horizon D is intermediate between these cases, with the strata above the horizon comprising a seaward prograding sedimentary sequence, and with the magnitude of the unconformity diminishing towards the coast.

Horizon E is correlated into the dredge data on and near line 403 (fig. 11). On line 403, the horizon is a prominant unconformity, separating dipping F-E sequence strata from overlying more gently dipping E-D strata. The horizon is therefore approximately of middle Oligocene age. The unconformity is not well defined in adjacent seismic lines, and strata appear to be conformable across the horizon over much of the shelf. Dredge samples from the continental slope suggest lower to middle Oligocene strata are unconformably overlain by upper Oligocene strata in the vicinity of line 403 (Plafker and others, 1980). These samples reflect what may be the greatest age difference across horizon E, since they were dredged in an area where uplifted strata in the F-E sequence are overlain by relatively flat-lying, onlapping strata in the upper part of the E-D sequence (line 403). The observed unconformity is interpreted to reflect relatively local deformation of F-E sequence during about middle Oligocene time, followed by onlap of F-D sequence strata from middle to late Oligocene time.

Horizon F is best correlated into the dredge data on line 906 and 403 (figs. 10, 11). On these lines the horizon is correlative with the top of Unit C of Plafker and others (1980), a basalt unit of early Eocene age. Thus, in the area south of Yakutat Bay, the section between horizons F and D includes strata of middle to late Eocene and early to middle Oligocene age (units D, E and F of Plafker and others, 1980).

Horizon F is not correlative everywhere with the top of the basalt. East of line 403, the section between seismic horizons F and D is truncated in the vicinity of the Alsek Canyon against a basement high, informally termed the Dangerous River zone in this report (figs. 4-7). Thus, in the area east of the zone, and generally bounded by the shoreline and Fairweather Ground, horizons F and D coincide. Horizon F in this area coincides at least in part with the top of the Cretaceous strata sampled on Fairweather Ground, although an early Tertiary section may still be present, but not distinguishable on the seismic sections.

In the area west of line 906, and primarily in the vicinity of line 404 (fig. 3a), the relation of seismic horizon F to the dredge data is not clear, as the acoustic basement cannot be clearly mapped beneath the continental shelf. The seismic refraction data of Bayer and others (1978) give an approximate position for the acoustic basement, based on a change of refraction velocity from around 4 km/s to 7 km/s. If horizon F is simply extended seaward, the resulting interpretation is that geologic units B and C lie above the F horizon. This conclusion is considered unlikely since: 1) the units elsewhere form acoustic basement, and 2) this would require uplift and truncation of units D, E, and F, and probably much of unit C below the shelf and upper slope between lines 403 and 404, and the seismic data nowhere suggests that such massive truncation occurs. An alternative interpretation is that a major fault is present in the early Tertiary strata along the lower slope, and a wedge of units D and C has been uplifted seaward of the fault. A further study of this interpretation using modeling studies of gravity and magnetic data is in progress.

In summary (fig. 22) horizon D is correlated with the base of Unit G of Plafker and others (1980). It corresponds to the unconformity at the base of the Yakataga Formation which in the study area separates Oligocene from Miocene(?), Pliocene, and younger strata. Horizon E appears to separate Units E and F of Plafker and others (1980), and is approximately middle Oligocene in age. The horizon is mappable only in the vicinity of line 403, and cannot be mapped throughout the rest of the shelf area. The geologic significance of horizon F is variable. East of the Dangerous River zone, horizon F largely corresponds to horizon D and is on the top of probable Unit A strata,. approximately equivalent to the Cretaceous Yakutat Formation. To the west, horizon F is believed to be at the top of Unit C, an Eocene basalt. In either case, the depth to horizon F gives a minimum thickness for Cenozoic sedimentary rocks for the shelf and upper slope; additional sedimentary strata could be present within or below Units C and B.

## SHELF STRUCTURE

The structure of the Yakutat shelf (figs. 4-7) is characterized by three major elements: 1) a large structural high at the shelf edge centered on Fairweather Ground, 2) a basement uplift, informally referred to herein as the Dangerous River zone, extending north from the western edge of Fairweather Ground towards the mouth of the Dangerous River, and 3) two basins, separated by the Dangerous River zone. These features, and seismic data across these features, will be discussed below.

### Fairweather Ground

The Fairweather Ground high lies at the edge of the continental shelf, roughly between Alsek Valley and Yakobi Valley (figs. 3-5). Dredge hauls (Plafker and others, 1980) and magnetic data (Schwab and others, 1980) suggest that the core of the high and the eastern part of the upper continental slope south of Fairweather Ground consists of pre-Tertiary rocks typical of the Yakutat Group on the adjacent mainland (unit A of Plafker and others, 1980). Tertiary rocks of Eocene through Oligocene age (Units C, D and E of Plafker and others, 1980) are present along the western part of the upper continental slope bordering the high (fig. 4). The early Tertiary strata are also present in the subsurface on the western and northwestern flanks of the high (lines 909, 911, 912; figs. 13, 14, 19). Deep sea deposits, probably hemipelagic sediments and turbidites, onlap the lower continental slope seaward of the high (lines 967, 400; figs. 15, 16). Sedimentary rocks of late Cenozoic age similar to the Yakataga Formation (Unit G of Plafker and others, 1980) occur in isolated basins on the high (Plafker and others, 1980).

On the landward side of Fairweather Ground, seismic data show that Neogene and Quaternary sedimentary strata (D-SF strata) onlap the high and dip toward the coast into the eastern subbasin of the Yakutat shelf. These strata may have surrounded and covered the older rocks, and have been uplifted and truncated at the seafloor over at least part of the high (lines 909, 911 and 912; figs. 13, 14, 19). Lines 909 and 911 (figs. 13, 14, 23, 24) show that much of the uplift occurred during late D-SF time. Little or no thinning of strata is evident in F-D sequence strata or in the lower part of the D-SF sequence strata on these lines, while more pronounced thinning is present in the upper part of the D-SF sequence. On line 911 the D-SF sequence can be divided into two sub-sequences at horizon U. Strata below horizon U show only minor seaward thinning, while strata above horizon U show much greater seaward thinning. Thus, the U horizon marks a change from no or relatively slow uplift of Fairweather Ground to more rapid uplift. The amount of uplift can be estimated by flattening on the U horizon, resulting in the restored section of figure 24. In this section, strata are flat lying to gently seaward dipping, suggesting that little uplift occurred prior to horizon U time. The minimum amount of uplift is estimated from the difference between the restored depth to horizon F and the current depth to the horizon, and is slightly less than 1 km for Line 911. A similar study of line 909 suggests uplift of about 2 km (fig. 23). Uplift may be greater since substantial D-SF strata may have been eroded from the top of the high, and the original dip of horizon U may have been slightly seaward, and the estimate does not include the difference between horizon U and the sea level at horizon U time.

## Dangerous River Zone

The Dangerous River zone is an area where acoustic basement on the seismic data shallows markedly, with structural relief on the acoustic basement horizon of 2 km or more (figs. 4-7). Seismic data show an abrupt geologic change across the zone. The thick Paleogene section present in the area west of the zone is truncated at horizon D, and onlaps and is in part truncated by faulting against acoustic basement along the trend of the zone (Lines 903, 909, 911, 912, 913, 914; figs. 12-19). Paleogene strata are either thin or absent east of the zone, or have markedly different acoustic properties and are part of the acoustic basement. The southern extension of the Dangerous River zone cannot be seismically mapped across the Fairweather Ground high, but the zone trends into an area on the continental slope where, on the basis of dredge data, Paleogene strata are in close proximity to pre-Tertiary strata and may be in fault contact (figs. 4-7; also see fig. 4 of Plafker and others, 1980). The north or northwest extension of the zone is inferred to pass beneath the Colorado Oil and Gas Yakutat wells, where a thick Paleogene section is cut out by truncation or faulting (Rau and others, 1977).

The character of the structural and stratigraphic changes across the Dangerous River zone is variable. On lines 903 and 912 (figs. 18, 19) the Paleogene section appears to thin primarily by erosion at about horizon D time, although some onlap is also apparent. On lines 911 and 913 (figs. 12, 13), the section onlaps the acoustic basement. Finally, on line 909 (figs. 13, 23), the Paleogene strata both onlap the gently dipping acoustic basement (horizon F), and in part buttress against faulted acoustic basement strata (below location 1, fig. 23). Some additional minor deformation is also present in the early Tertiary section and extends into the upper part of the section (below location 2, fig. 23). Strata do not clearly thin landward, as might be expected if faulting occurred prior to or during deposition, and some of the strata in the upper part of the F-D sequence are unfaulted over the fault zone.

The Dangerous River zone appears to mark the subsurface expression of the Paleogene basin edge that Plafker and others (1980) delineated on the continental slope from dredge data. Initial development of the basin started prior to horizon F time. Seismic reflectors in the lower part of the F-D sequence onlap horizon F. Foraminifers from dredged rocks of geologic units D and E show decreasing water depths, from middle to upper bathyal and outer-shelf depths for unit E. Further, considerable transport of shallow-marine sands into deeper marine sediments occurred in unit D (Plafker and others, 1980). Thus, seismic and geologic data indicate deposition into a pre-existing structural low in approximately early to middle Eocene time and infilling of the low during middle to late Eocene and early Oligocene time. Faulting along the zone occurred prior to and during the early stages of deposition of the F-D sequence strata, possibly in middle Eocene time (see following sections for discussion of additional deformation at late Oligocene to early Miocene time).

## Sedimentary Subbasins

The Dangerous River zone separates the Yakutat shelf into two distinct subbasins (figs. 4-7). The eastern subbasin is bounded by the shoreline, the Dangerous River zone, the Fairweather Ground high, and the offshore extension of the Fairweather fault system. Strata in this basin that are resolvable on the seismic data are of late Cenozoic age, and the lower Tertiary strata are missing, thin, or form acoustic basement. The isopach map shows the thickness of the late Cenozoic section and the isopach contours virtually coincide with the structure contours.

The late Cenozoic section onlaps the Fairweather Ground high, and is uplifted and truncated at the seafloor along at least parts of the high. The sedimentary section dips towards the coast, with a maximum thickness of around 4 km east of Dry Bay. The axis of the basin is near and parallels the coast. Marked uplift and folding of the basin strata is present along the shoreline of the onshore Lituya district, where the Yakataga and Topsy Formations crop out with almost vertical dip (Plafker, 1967, 1971). Offshore seismic data indicate flat-lying sediment within 3 km of the coast near Lituya Bay, suggesting a fault or sharp fold with significant deformation and vertical displacement lies near the shoreline. High resolution seismic data and Line 400 (fig. 16) indicate the extension of this fault to the southeast where it merges with the offshore Fairweather fault system (von Huene and others, 1979, Carlson and others, 1980), and it could be a strike-slip fault with significant offset. The fault may extend onshore to the west beneath the thick alluvium of the Yakutat district. In general, the late Cenozoic strata within the eastern subbasin show only regional dip towards the basin axis, and are deformed only along the Lituya district fault zone and its southern extension, and over or around the Fairweather Ground high.

The western subbasin lies between the Dangerous River zone and the compressional folds of the Pamplona zone (figs. 4-7). The structure and isopach maps show that the Tertiary sedimentary section thickens markedly west of the Dangerous River zone to greater than 9 km south of Icy Bay, and includes a thick Paleogene section (F-D sequence strata). South of Yakutat Bay, roughly between the shelf break and the coast, this Paleogene section has a maximum thickness greater than 5 km. In the western part of the subbasin, the thickness and extent of this section is not well defined, since seismic reflection and refraction data give only an approximate position for horizon F, but the section is at least 4.5 km thick. The thickest part of the Paleogene section, as seen in the isopach map (fig. 7), trends roughly northwest, and may define the early Tertiary basin axis. The section is truncated at the continental slope, and thins out over, onlaps, or is faulted out against, the acoustic basement along the Dangerous River zone.

Strata in the Paleogene section were at least locally deformed prior to horizon D time. On seismic line 403 (fig. 11), uplift of strata is evident at what is now the shelf edge (location 1) and a gentle anticline is present in Paleogene strata in the center of the line (location 3). A depth section of this line (fig. 25), with sequential flattening on horizons D, E and a horizon U intermediate between horizons D and E suggests the following history. 1) Strata were initially deposited into an existing basin or onto a subsiding platform, with minor uplift at location 1 prior to U time (fig. 25). Paleontologic data from dredged rocks from the F-D sequence suggest the rocks were deposited in a middle to upper bathyal environments, and shallow marine sediments were transported into the basin (Plafker and others, 1980). Thus, strata were initially deposited into an existing basin. 2) Between horizon E and horizon U time, differential subsidence resulted in the formation of a local structural high (location 3, fig. 25). Prior to horizon D time, uplift of about 1 km at location 1 truncated part of the E-D strata. 3) Finally, deposition of D-SF strata and regional subsidence buried the Paleogene section. Uplift again occurred during middle to late D-SF time, as strata from this sequence are truncated at the seafloor near the shelf edge. The seismic data suggest that major erosion did not occur at horizon E time, since no marked truncation of seismic reflectors in the F-E sequence is seen at the E horizon in the deformed zones on section 403.

Strata in the F-E sequence are unconformably overlain by strata in the E-D sequence. The age difference across horizon E is variable, since successively younger strata in the E-D sequence onlap the E horizon on both the anticline and on the uplifted strata at the shelf edge. The angular unconformity may not be present in other areas of the shelf, as little structure is seen in F-D strata except on line 403 and at the shelf edge between Alsek Canyon and Yakutat valley. Seismic data are insufficient to define the extent of the anticline seen on section 403, but blocks leased during OCS Sale 55, 1980, presumably are on this high and provide some indication as to its extent and to the location of some nearby, smaller structures (fig. 3a).

The structure and isopach maps of strata above horizon D (D-SF strata, figs. 4, 6) show that the depositional axis of the late Cenozoic strata in the western subbasin trends east to west, and lies near the coast. The section increases uniformly in thickness from the shelf edge to the basin axis, with a thickness greater than 5.5 km in the deepest part of the basin. These strata are relatively continuous across the Dangerous River zone into the eastern subbasin, with faulting and folding seen nearshore only along the northern extent of the zone (Line 914, fig. 17).

Adjacent to the structures of the Pamplona zone, the structural contours on horizon D show that the D-SF sequence strata are bowed down into a structural low beneath the continental slope. However, the isopach map shows that the section maintains the same general strike and uniform increase in thickness towards the basin axis as is seen in the rest of the subbasin, instead of showing an increase in thickness in the structural low. Thus, the late Cenozoic section in this area, rather than being deposited into a preexisting structural low, is apparently being bowed down in response to compressional deformation across the Pamplona zone. Elsewhere in the western subbasin, the D-SF strata show regional subsidence towards the basin axis, but are otherwise undeformed.

## SLOPE AND BASE OF SLOPE STRUCTURE

Seismic data crossing the continental slope and adjacent deep ocean show three major features. 1) The early Tertiary sequence (F-D strata) is truncated at the continental slope, and strata above horizon D (D-SF strata) in part prograde seaward over the older rocks. 2) A thick, undeformed or mildly deformed abyssal sedimentary section is present at the base of the slope, and in some areas onlaps the slope. 3) Seismic data show faulting along a relatively narrow zone along the continental slope or at the base of the slope, in part recent high angle reverse or normal faults, and possibly strike-slip faulting. Most of these features can be readily seen on the seismic data accompanying this report (from west to east, lines 404, 916, 906, 403, 909, 400; figs. 8-16).

Both dredge data (Plafker and others, 1980) and seismic data show that the early Tertiary and older strata underlying the continental shelf (strata below horizon D) outcrop on the continental slope throughout the length of the Yakutat segment. Late Cenozoic strata (D-SF sequence strata) are thin or not present on the slope east of about Yakutat Valley, but are truncated at the seafloor on the continental shelf as a result of uplift on the Fairweather Ground high. West of Yakutat Valley, these strata underlie the upper slope, and the lower part of the sequence has prograded seaward over the older strata. The upper part of the sequence outcrops progressively more landward with decreasing age, indicating that the sediment supply has been insufficient to keep pace with subsidence. These strata are flat-lying to gently landward-dipping between Yakutat Valley and the structures of the Pamplona zone, and have been affected only by regional subsidence.

Oceanic crust at the base of the slope is overlain by sedimentary strata that is up to 6 km thick; at least part of the sedimentary sequences appears to be of pre-Pliocene age, in agreement with von Huene and others (1979). In the vicinity of Yakobi Valley, the upper part of the abyssal section appears to onlap the continental margin (lines 400, 967, 909(?), and unpublished seismic sections). Further to the west, these strata may be faulted against the continental margin (lines 404, 916, 906, 403; figs. 8-11). Nowhere can seismic reflectors from the abyssal section be traced beneath the continental slope, and reflectors in general terminate at the base of the slope or onlap the continental slope.

The abyssal strata are undeformed except for uplift in a narrow zone at the base of the slope in areas adjacent to the Fairweather Ground high. Two styles of deformation are present. On seismic lines 906(?), 403, and 909 (figs. 10, 11, 13), the amount of uplift at the base of the slope is a maximum in Pliocene(?) and older sediments (below horizon A1) and decreases upwards in Pleistocene(?) strata (A1-SF sequence); only minor deformation is present in the upper part of the Pleistocene(?) section. Thus, this uplift began prior to horizon A1 time, or approximately during Pliocene(?) time. The magnitude of uplift can be estimated for lines 403 and 909, and is around 1 km and 2 km respectively. Late Cenozoic uplift on the shelf edge and the Fairweather Ground high for these same two lines was earlier estimated as beginning during D-SF time, with these strata being Pliocene and younger, and with magnitudes of around 1 and 2 km respectively. Thus, the time of onset of deformation and the magnitude of deformation for strata on the shelf and at the base of the slope are about the same, suggesting the deformation at the base of the slope is due to uplift of the Fairweather Ground high. The strata of the outer shelf, slope, and base of slope between Yakobi Valley and Yakutat Valley have been warped upwards during Plio-Pleistocene time, with maximum uplift centered on Fairweather Ground. Additional consequences of this uplift may include erosional truncation of strata at the seafloor along the continental shelf and over Fairweather Ground and the steep average gradient of the continental slope, ranging from 8° to 16° with a mean of about 11° (Atwood and others, 1981).

The second style of deformation at the base of the slope is seen southwest of Fairweather Ground. Bathymetric data (fig. 3a; Atwood and others, 1981) show three sub-parallel northwest-trending ridges that are 15 to 30 km long. A seismic line across one of these ridges (line 967, fig. 15) shows that it is a young anticline (post-horizon A1 time) that developed in the late Pleistocene. The ridges trend almost perpendicular to the N. 15° W. relative convergence vector for the Pacific and North America plates (Minster and Jordan, 1978; Chase, 1978) and the geometry suggests that the structures developed in response to this convergence (Atwood and others, 1981).

On all of the seismic lines across the continental slope (figs. 9-16), faulting is likely between the oceanic basalt and the outcropping continental shelf section. As previously discussed, faulting could be in part due to vertical or near vertical faults associated with the Fairweather Ground uplift, or to recent convergence-associated deformation. The lack of other major compressional deformation in strata of the continental shelf or at the base of the slope, and the lack of an accreted section along the continental slope suggests if additional faulting occurs, it is primarily strike-slip, and major subduction of the Pacific Plate beneath the continental margin during the late Cenozoic is unlikely. No features showing strike-slip offset have as yet been observed.

An area of bathymetric relief and structural deformation is present in the area of Yushin Ridge (Atwood and others, 1981) a large northwest-trending ridge or set of ridges subparallel to the base of the slope southwest of Yakutat Valley (fig. 3a; also line 404, fig. 8; see also Plafker and others, 1980, figs. 22, 23; and Atwood and others, 1981, sheet 2). Yushin Ridge is about 5 km wide and 27 km long, and rises more than 800 m above the adjacent seafloor. Seismic and dredge data indicate that Yushin ridge is composed of early Tertiary strata, and that relatively undeformed late Cenozoic sediment surrounds and buries the ridge (Plafker and others, 1980; Atwood and others, 1981). Thus, this feature developed prior to the late Cenozoic and most likely reflects an early to middle Tertiary erosional or tectonic event.

## GEOLOGIC HISTORY AND DISCUSSION

Prior to or about early Eocene time, block or transform faulting along the Dangerous River zone created a structural high to the east of the zone and a basin low to the west. The subsiding basin was floored by early Eocene basalt and interbedded sedimentary rocks. Strata deposited into the basin onlapped the basin floor towards the Dangerous River zone. The basin axis trended generally northwest, cutting obliquely across the current continental shelf (figs. 4-7). Deposition of Eocene and Oligocene strata (F-D sequence strata) occured in increasingly shallower water and the lower part of the sequence is characterized by transport of shallow water sediments into the deeper parts of the basin (Plafker and others, 1980). The Dangerous River zone may mark the early Tertiary basin edge.

West of the Dangerous River zone, local uplift within the Paleogene basin occurred prior to approximately late Eocene to early Oligocene time, as suggested by minor uplift at location 1 on the reconstructed depth section for line 403 (fig. 25). At horizon E time, differential subsidence within the basin formed the gentle structural high seen on line 403. This deformation created a local unconformity at horizon E; the unconformity does not appear to be affected by major erosion. In the rest of the western subbasin, Eocene and Oligocene time is characterized by regional subsidence along the Paleogene basin axis, as no major structures or unconformities are seen in the seismic data. Additional faulting along the Dangerous River zone may also have occurred, resulting in uplift of the area east of the zone. The seismic data leave unclear the timing of early Tertiary faulting along the Dangerous River zone, but faulting occurred prior to and during the early stages of deposition of the F-D sequence strata.

Horizon D is a time-stratigraphic break that may include part or all of Miocene time. West of the Dangerous River zone, seismic reflectors are conformable across the horizon, suggesting that no major deformation occurred during the hiatus. The time interval could be a period of regional uplift and erosion. Uplift along the Dangerous River zone during D horizon time caused truncation of F-D strata at the D horizon. The terrain east of the zone may have undergone major uplift during this time, resulting in erosion and stripping of most of the early Tertiary section.

By Pliocene time, and possibly during Miocene time, deposition of D-SF strata began, initially with these sediments prograding across the continental shelf over the older strata. Gentle uplift began in the Fairweather Ground area during early D-SF time, with more rapid uplift occurring during about the last half of D-SF time (during approximately late Pliocene to Pleistocene time). Maximum uplift in Fairweather Ground is at least 2 km and could be greater. This uplift resulted in truncation of Cretaceous through Pleistocene strata at the seafloor along the uplift zone, deformation of strata at the base of the slope, and possibly faulting along the continental slope between Yakobi Seavalley and Yakutat Seavalley. Throughout the area, the continental shelf is characterized by regional subsidence during D-SF time, with the basin axis near and roughly parallel to the coastline. Reactivation of faults along the Dangerous River zone has resulted in uplift of D-SF strata offshore of the Dangerous River into a gentle anticline. Additional deformation of the late

Cenozoic strata is present along the shoreline near Lituya bay, with marked uplift near the shoreline, and along the offshore extension of the Fairweather fault. Finally, recent deformation of strata at the base of the slope southeast of Fairweather Ground has created anticlines that trend almost perpendicular to the regional North America-Pacific relative convergence vector.

The truncation of Paleogene strata at the continental slope suggests that at some time during the Cenozoic, continental and oceanic crust of very different ages have been juxtaposed at the base of the continental slope. The thickness and extent of the Paleogene section beneath the continental shelf west of the Dangerous River zone suggests that these strata were at one time much more extensive than at present, and that the seaward part of the Paleogene basin is missing. Since the current morphology of the slope is in part a response to late Cenozoic uplift, the seaward part of the basin might be the thick sediment wedge at the base of the slope. The thickness of the Paleogene shelf section at the slope is similar to the thickness of the pre-Pliocene strata at the base of the slope (see lines 906, 403; figs. 10, 11). However, dredge data indicate the shelf strata were deposited primarily in upper bathyal to shelf environments (Plafker and others, 1980), and it seems unlikely that these strata were continuous with the thick sedimentary sequence at the base of the slope. Also, the section at the base of the slope is likely younger than the Paleogene strata of the shelf, as suggested by the seismic age tie to the DSDP hole 178 discussed earlier and by oceanic magnetic anomalies. The oceanic magnetic anomalies on the Pacific plate in near proximity to the shelf are identified as numbers 7 through 14, or Oligocene in age, although this age must in part be inferred across a zone at the base of the slope where the anomalies are severely attenuated (Naugler and Wageman, 1973; Taylor and O'Neill, 1974; Schwab and others, 1980). Thus, the sedimentary strata overlying oceanic crust at the base of the slope are most likely Oligocene and younger, thus requiring juxtaposition of terraine of very different ages.

The time at which this juxtaposition took place is most likely after Oligocene time but prior to about Pliocene time, or during the inferred hiatus across horizon D. Evidence for this is: 1) juxtaposition must have taken place after creation of the Oligocene oceanic crust; 2) Eocene through Oligocene strata of the shelf are truncated at the continental slope; 3) strata above horizon D do not appear to be truncated at the slope (in particular, see lines 404, 916, and 906; figs. 8-10), and have not undergone major deformation during the late Cenozoic, and 4) the upper part of the abyssal section, of Pliocene and younger age, appears to onlap the continental slope (lines 909, 967, 400; figs. 13, 15, 16). The juxtaposition of the continental shelf and oceanic sections could have occurred either by subduction or by transform faulting, but the lack of an early Tertiary accreted section and the lack of major deformation of the Paleogene strata at the shelf edge suggest the most likely mechanism is transform faulting. Transform motion does not appear likely during the late Cenozoic, based on the onlap relationship of Plio-Pleistocene oceanic strata against the continental shelf, and on the absence of deformation of the late Cenozoic shelf and slope strata (strata above horizon D). The shelf and slope of the Yakutat segment have, therefore, been in proximity to the adjacent oceanic section during at least Plio-Pleistocene time, and possibly longer, without major relative motion between the two terrains by either subduction or transform motion during this time period. Thus, the geologic history of the Yakutat segment includes removal of the seaward part of the Paleogene basin, approximately during latest Oligocene or early Miocene time and northwest movement with the Pacific Plate during Plio-Pleistocene time, and possibly part or all of Miocene time as well.

Additional data that support these conclusions include a linear magnetic anomaly, the slope anomaly, that lies along the continental slope of the Yakutat and Yakataga segments (Cross Sound to Kayak Island) and trends across the shelf of the Middleton segment (Kayak Island to the Kenai Peninsula). The source body for this anomaly lies within strata of the continental shelf (Schwab and others, 1980) and is likely to be the Eocene basalt (Plafker and others, 1980), with the anomaly resulting as an edge effect from the truncated basalt. This source body has been subducted beneath the Middleton shelf, and this relation strongly indicates that the continental margin from Cross Sound to Kayak Island is part of a microplate, the Yakutat block, that has moved with the Pacific plate during at least the last 3-5 m.y. (Schwab and others, 1979, 1980; Bruns and others, 1979).

Plafker and others (1980) note that the most probable provenance for the dredged sandstones in the early Tertiary sequence of the Yakutat segment is the plutonic and high grade metamorphic complex of the coastal mountains of British Columbia and Alaska. Such a provenance implies that the dredged strata have been displaced northwest to the Gulf of Alaska by transform faulting along the North America plate margin. If constant movement of the Yakutat segment with the Pacific plate is assumed, then a preliminary finite rotation of the segment shows that in late Oligocene to early Miocene time, the segment lay roughly between the present position of Vancouver and the Queen Charlotte islands, in general agreement with the location favored by Plafker and others (1980). If these interpretations are correct, than the geologic history of the Yakutat segment includes removal of the seaward part of the Paleogene sedimentary sequence and rafting of a combined Yakutat-Yakataga segment (the Yakutat block) from, possibly, a position along what is now British Columbia during late Oligocene to early Miocene time, and movement of the segment northward with the Pacific plate during Miocene to present time. The Yakutat block is now colliding with the North America plate, rather than forming a part of the north America plate and overriding a subducting Pacific plate.

## SUMMARY OF STRUCTURE AND GEOLOGIC HISTORY

The structure of the Yakutat segment is shown by multichannel seismic data to be characterized by three major structural elements. The first of these is a large structural high centered on Fairweather Ground and lying generally at the edge of the shelf from Cross Sound to slightly west of Alsek Valley. Uplift of the high has occurred largely during the late Cenozoic, and at least 2 km of upper Cenozoic strata has been eroded from the crest of the high. The second major element is a basement uplift along the Dangerous River zone, extending north from the western edge of Fairweather Ground towards the mouth of the Dangerous River. Acoustic basement on the seismic data shallows markedly across the zone, with relief of 2 km or more. The Dangerous River zone separates the Yakutat shelf into two distinct subbasins which form the third main structural element. The eastern subbasin has a maximum sediment thickness of about 4 km, and the axis of the basin is near and parallel to the coast. Strata in this basin are largely of late Cenozoic age and generally correlate with the onshore Yakataga Formation. The western subbasin has a maximum of at least 9 km of sediment, comprised of a thick (greater than 4.5 km) Paleogene section overlain by 4-4.5 km of late Cenozoic strata. The Paleogene section is truncated along the Dangerous River zone by a combination of erosion, faulting, and onlap onto the acoustic basement. Within the western subbasin, the Paleogene basin axis appears to trend in a northwest direction across the shelf, while the late Cenozoic basin axis is near and parallel to the coast. Sedimentary rocks throughout the Yakutat shelf show only minor deformation and regional subsidence except in the vicinity of the Fairweather Ground structural high, near and along the Dangerous River zone, and at the shoreline near Lituya Bay.

Seismic data across the continental slope and adjacent deep ocean show truncation at the continental slope of the shelf Paleogene strata, the presence of a thick (to 6 km) undeformed or mildly deformed abyssal sedimentary section at the base of the slope that in part onlaps the slope, and a relatively narrow zone along the slope or at the base of the slope where faulting may have occurred. Deformation is primarily related to the uplift of Fairweather Ground, and to recent, local folding perpendicular to the Pacific-North America relative convergence vector. No accretionary section is present along the continental slope, and no major deformation is observed to suggest that continuous subduction of the Pacific plate beneath the Yakutat margin has occurred during the late Cenozoic. Transform faulting along the base of the slope has probably occurred during the Cenozoic, as indicated by juxtaposition of probable Oligocene basement against Mesozoic, Paleocene (?), and Eocene sedimentary strata of the Yakutat shelf. This juxtaposition most likely occurred during late Oligocene and early Miocene time. During much of the late Cenozoic, and especially during Plio-Pleistocene time, the Yakutat segment has been moving northward with the Pacific plate and colliding with the North America plate, rather than forming a part of the North America plate and overriding a subducting Pacific plate.

## PETROLEUM POTENTIAL

The rocks dredged from the continental slope indicate that potential hydrocarbon source and reservoir rocks are present in the Paleogene sedimentary sequence (Plafker and Claypool, 1979; Plafker and others, 1980). These rocks are immature to marginally mature on the continental slope, but should be more mature beneath the continental shelf. The seismic data show that hydrocarbon traps may be present in the Paleogene strata (F-D sequence strata), but are not likely in the late Cenozoic section (strata above horizon D). This section briefly reviews the results of Plafker and Claypool (1979) and Plafker and others (1980) on source and reservoir rock characteristics and thermal maturity of rocks on the continental slope, discusses trap potential as seen in the seismic data, and uses Lopatin's method (Waples, 1980) to estimate the thermal maturity, petroleum potential and possible petroleum migration history for the strata beneath the continental shelf.

## Source Rocks

Analysis of selected dredge samples from the continental slope (Plafker and Claypool, 1979; Plafker and others, 1980) indicates that rocks with favorable hydrocarbon source rock characteristics are present in the Paleogene sedimentary strata (Units D, E and F of Plafker and others, 1980; F-D sequence strata of this report). Organic matter in selected samples is dominantly herbaceous, with subordinate amounts of humic and amorphous kerogen. Total-organic-carbon content of the analyzed samples ranges from 0.42 to 1.87 percent, and averages greater than 1.0 percent. This average is above the generally accepted minimum value of 0.5 percent for argillaceous hydrocarbon source rocks (Tissot and Welte, 1978). The kerogen composition is of a type that can generate both liquid hydrocarbons and gas (Plafker and Claypool, 1979; Plafker and others, 1980).

## Thermal Maturity

Indicators of thermal maturity show that the dredged samples from Units D, E and F are immature to marginally mature, but that samples from Unit B are mature to overmature (Plafker and Claypool, 1979; Plafker and others, 1980). Oil generation begins at a thermal alteration index (TAI) of about 2 and a vitrinite reflectance value (Ro) of about 0.6 percent; peak oil generation ends at a TAI of around 3 and a vitrinite reflectance of 1.35 percent (Dow, 1977, 1979; Tissot and Welte, 1978). Vitrinite reflectance values for dredge samples from units D, E and F are within the range of 0.3 to 0.6 percent; only a few samples are near or greater than 0.6 percent (see Table 5 and fig. 22 of Plafker and others, 1980). The TAI for these samples ranges from 1.2 to 2.3 with most samples around 1.9 to 2.1 (see Table 4, Plafker and others, 1980). Thus, in general, these rocks are immature, and only a few samples approach thermal maturity. Vitrinite reflectance values from Unit B range from about 0.4 to 3 percent, and TAI values from 2.3 to 3.6 indicating that these rocks are mature to overmature (Plafker and others, 1980).

## Reservoir Rocks

Plafker and others (1980) found that most of the dredged sandstone samples have poor reservoir qualities due to the presence of abundant unstable mineral and rock fragments, common calcite cement, and siliceous, zeolite and clay pore fillings. A few samples of sandstone with permeabilities and porosities sufficient to serve as reservoir rocks were recovered from Units B, D and E during dredging; in these rocks, the permeability and porosity appear to be largely secondary.

## Hydrocarbon Traps

Except for the anticline near the Dangerous River, seismic data do not show any late Cenozoic anticlinal folds on the Yakutat shelf similar to those found on the adjacent Yakataga shelf to the west (Bruns, 1979; Bruns and Schwab, in press). At least one large anticline is present in the early Tertiary section (line 403, fig. 11 and fig. 25, location 2), and the extent of this structure and possibly that of some smaller, similar structures, can be inferred from the blocks leased in the 1980 lease sale 55 (fig. 3). This anticline developed prior to about late Oligocene time and could serve as an effective trap. Additional structures may be present, but not seen in the widely spaced seismic data.

The Dangerous River zone may provide possibilities for stratigraphic and structural traps. Paleogene strata lap onto the acoustic basement and may, in part, be faulted against pre-Tertiary strata along the Dangerous River zone. These potential traps generally are updip from the basin axis, and could trap hydrocarbons migrating out of the basin lows. The Dangerous River zone may have formed the Paleogene basin margin. As noted by Plafker and others (1980), there may therefore be enhanced opportunities for the presence of coarse clastic rocks, up-dip stratigraphic traps, possible Eocene carbonate reefs, and fault seals along the zone. In addition, the overlying late Cenozoic section could provide a seal over the Paleogene strata in same areas.

The uplift of the Fairweather Ground high is unlikely to provide significant trap possibilities, since Tertiary strata around the high generally outcrop at the seafloor, and apparently no effective seal is present. Possible exceptions to this may occur on the west end of the high along the Dangerous River zone.

## Lopatin Calculations On Thermal Maturity

The method of Lopatin (Waples, 1980) can be used to evaluate the thermal maturity of the strata beneath the shelf. This method takes into account the cumulative effects of both time and temperature on the maturation of organic matter. Waples (1980) describes the method in detail, and shows that the time-temperature index of maturity (TTI) that is calculated by this method generally agrees with other indicators of thermal maturity. The threshold values of Lapatin's time-temperature index (TTI), and corresponding vitrinite reflectance (Ro) and thermal alteration index (TAI) values are (see Waples, 1980, Table 5):

| TTI | Ro | TAI | |
|---|---|---|---|
| 15 | 0.65 | 2.65 | Onset of oil generation |
| 75 | 1.0 | 2.9 | Peak oil generation |
| 160 | 1.3 | 3.2 | End of oil generation |
| 1,500 | 2.2 | 3.75 | Wet gas preservation deadline |

Use of Lopatin's method requires estimates of the geothermal gradient and the burial history of the section of interest. In addition, three major simplifying assumptions are made (Waples, 1980): 1) a constant temperature gradient with depth; 2) a constant temperature gradient through time; 3) and a relatively uniform rate of sedimentation for the age units used in the calculation.

The burial history for sediments beneath the Yakutat shelf can be estimated from the seismic data. The mapped horizons give sediment thicknesses throughout the shelf area. Horizon F, lying at least in part on the top of Eocene basalt, is assigned an age of 50 M.Y., or about the age of the basalt as determined by Plafker and others (1980). Horizon E is considered to be on middle Oligocene strata, or about 30 M.Y. Two end member cases are considered for horizon D. First, horizon D is taken as separating Oligocene from Pliocene strata, so that there is a hiatus from about 22.5 to 5 M.Y. (D-horizon unconformity case). The effect of this assumption is that strata remain at a constant burial depth and temperature window for the period 22.5 to 5 M.Y. This case corresponds to age estimates of the shelf strata as discussed earlier in this study, but does not take into account possible deposition of Miocene strata and subsequent stripping during a period of erosion. Maturity could be greater than that calculated. This case gives a conservative estimate of thermal maturity for shelf strata. The second case considers deposition as continuous across horizon D during Neogene and Quaternary time (continuous deposition case). The effect of this assumption is that the calculated maturity is optomized.

The geothermal gradient used for the calculation is 25° C/km, as measured in the Continental Offshore Stratigraphic Test (COST) well drilled southwest of Icy Bay (Bolm and others, 1976). Well logs for Colorado Oil and Gas Yakutat wells #1 and 3 give bottom hole temperatures that yield a gradient as high as 30° C/km, and from the offshore wells southwest of Icy Bay, the gradient may be lower than 20° C/km. The effect of the higher and lower gradients on the calculated results will be discussed later.

Lopatin diagrams for the two cases are shown in figure 26. The reconstruction of burial history is for strata adjacent to the main structure leased during lease sale 55, and is at location 2 on line 403 (figs. 11, 25). The oil generation window is shown by lines corresponding to a calculated TTI of 15 (Ro = 0.6%) and TTI of 160 (Ro = 1.30%). Several conclusions are common to both cases. 1) Only strata in the Eocene sequence have entered or gone through the oil window; and the upper part of the Eocene strata, and Oligocene and younger rocks at this location are likely to be immature. 2) Oil generation within these strata may have started during late Oligocene and Miocene time, with rocks reaching a sufficient depth for peak oil generation (TTI = 75) in Miocene time. 3) Burial had to be greater than about 4 to 4.5 km for oil generation to begin. 4) Only rocks below about 4.5 km (D horizon unconformity case) or 4 km (continuous deposition case) are currently in or below the oil window. 5) The oil generation window is about 1.5 km thick. The main difference between the two cases considered is that the oil generation window is about 0.6 km higher in the section for the continous deposition case than for the D horizon unconformity case. Calculations for geothermal gradients of 20° and 30° C/km move the oil generation window about 1 km deeper or 0.7 km higher, respectively, in the section than discussed above.

Lopatin calculations for other areas of the shelf have been combined to show the oil generation window for 25° C/km in two cross sections (fig. 27; locations shown in fig. 3). Section A-A' is along line 912 and extends on strike to the west to line 404. The section crosses the thickest part of the early Tertiary basin along the inferred early Tertiary basin axis. Section B-B' corresponds to seismic line 906, and crosses the continental margin. These two cross-sections suggest the following conclusions. 1) The top of the oil generation window ranges from about 5.5 to 4 km for the D horizon unconformity case, and is about 0.5 km higher for the continuous deposition case. The average depth is about 5 km and 4.5 km respectively. 2) The base of the oil generation window is about 1.5 km deeper. 3) Potentially mature rocks are primarily of Eocene age. Oligocene strata may be mature only beneath the thickest parts of the Neogene and Quaternary sedimentary basin, primarily in areas beneath the axis and the western quarter of the basin. Neogene rocks are potentially mature only below the axis of the basin. 4) Potentially mature strata are most likely present only west of the Dangerous River zone. 5) Strata at the continental slope are likely to be immature. This conclusion matches observed thermal maturity indicators in the dredged rock samples.

In general, hydrocarbon generation throughout the basin may have begun in Eocene strata in about Miocene time. Migration of these hydrocarbons updip would drive the generated hydrocarbons towards the edges of the basin onshore and at the continental slope where the potential for traps appears to be poor, and east up the basin axis towards the Dangerous River zone and the structures leased during lease sale 55. These structures formed at least in part during Oligocene to early Miocene time, or prior to or during potential hydrocarbon generation and migration, and may thus have good potential for trapping migrating hydrocarbons.

The Lopatin calculations strongly suggest that if suitable source rocks are present in the Eocene strata beneath the shelf, at least some of these strata are mature enough to have generated hydrocarbons. Since the dredge samples suggest source rocks are present in the exposed section, the major unknowns are whether migration has occurred and whether suitable reservoir rocks are present to trap migrating hydrocarbons.

The Lopatin calculations can be combined with volume estimates of sedimentary rocks of the Yakutat shelf and slope to estimate the volume of sediment that may be in or below the oil window. The total volume of sediment can be measured from the structural contour maps. The limits of the area considered are between the Yakobi Trough and the Pamplona zone, and the shoreline (extended across the mouths of the major bays) and the early Tertiary outcrop or subcrop at the continental shelf. In areas where contours are not defined by the seismic data, the contours are estimated by extending them along strike. With these limits and assumptions, the total volume is about 138,500 $km^3$ of which 75,000 $km^3$ or 54% are Eocene and Oligocene strata (F-D sequence strata) and 63,500 $km^3$ or 46% are Neogene and Quaternary strata (D-SF sequence strata). Approximately 90% of the total sediment volume is east of the Dangerous River zone (east of the early Tertiary subcrop line, figs. 4-7). For the D horizon unconformity case and a geothermal gradient of 25° C/km, the average depth to the oil window is about 5 km, and the volume of sediment in or below the threshold for oil generation is therefore about 23% (fig. 28). For the continouous deposition case, averaging about 4.5 km to the oil window, the volume is about 28%. For geothermal gradients of 20° and 30° C/km, the corresponding volume ranges are about 13 to 18% and 34 to 40% respectively. Since almost all the strata in the oil window are of Paleogene age, these volume ranges suggest that from 25% (at 20° C/km) to 70% (at 30° C/km) of the total Paleogene section could be within or below the oil window, depending on the assumptions of burial history and geothermal gradient.

Even though drilling results in the Gulf of Alaska have so far been disappointing, there are still reasons for considerable optimism for the discovery of economic hydrocarbons beneath the Yakutat segment. The major positive consideration is the presence of organic-rich rocks dredged from the continental slope that could be good source rocks beneath the continental shelf. These rocks extend beneath the adjacent Yakataga segment, and are the likely source for the numerous seeps onshore. These strata are untested by drilling that has so far taken place. Thus, the major exploration strategy for the Gulf of Alaska is to search for the Eocene-Oligocene strata in favorable trap locations at drillable depths beneath the Yakutat and Yakataga segments.

## SUMMARY OF PETROLEUM POTENTIAL

Rocks dredged from the continental slope indicate that potential source rocks are present in the Paleogene sedimentary rocks, but these rocks are thermally immature to marginally mature. Sandstones with sufficient porosity and permeability to be reservoir rocks are present within the Paleogene section; the porosity is primarily secondary. Neogene and Quaternary rocks are considered to have poor source reservoir rock potential, as indicated by numerous dry test wells drilled into strata of this age onshore and on the Yakataga shelf (Plafker and others, 1978, 1980). Structural and stratigraphic traps are either known to be present or are likely, primarily along or near the Dangerous River zone, but these traps are generally subtle.

Lopatin calculations (Waples, 1980) for the shelf sedimentary section suggest that strata at a depth of 4 to 5 km and deeper are likely to be in or below the oil generation threshold, with the depth dependant on assumptions of burial history and geothermal gradient (figs. 26-28). In general, the strata within the oil window are primarily of Eocene age, with Oligocene strata thermally mature only in the deepest parts of the basin. About 25% to 70% by volume of the Paleogene section could be thermally mature or overmature depending on assumptions of geothermal gradient and burial history. These strata are contained within the western subbasin of the Yakutat shelf (west of the Dangerous River zone); strata in the east subbasin are likely of Neogene and Quaternary age and have little resource potential. If hydrocarbons have been generated within the Paleogene section, generation would have started during early Miocene time, after formation of the known traps beneath the shelf. Updip migration of the generated hydrocarbons would be towards the edges of the basin onshore and at the continental slope, where potential for trapping the hydrocarbons appears poor, and up the axis of the basin towards the traps near and along the Dangerous River zone. Major unknowns are whether migration of hydrocarbons has filled such traps and whether sufficient reservoir rock is present to allow commercial accumulations of hydrocarbons.

Drilling in the northern Gulf of Alaska has tested the upper Cenozoic strata, but so far has not adequately tested the Eocene and Oligocene strata. The primary exploration strategy for the Gulf of Alaska is now the search for the Eocene and Oligocene strata in the Yakutat segment and the adjacent Yakataga segment. Discovery of economic petroleum is largely dependant on finding these strata in favorable traps, at drillable depths, and with adequate reservoir rocks.

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## FIGURE CAPTIONS

Figure 1. Index map of Alaska showing study area.

Figure 2. Simplified geologic and tectonic setting of the northern Gulf of Alaska showing structural trends and general distribution of Paleozoic, Mesozoic and Cenozoic rocks. Geology after Beikman (1980); Pacific plate-North America plate relative convergence vector (large arrow) from Minster and Jordan (1978). CS-Cross Sound; DF-Denali fault; DRF-Duke River fault; FF-Fairweather fault; FG-Fairweather Ground; IB-Icy Bay; KI-Kayak Island; PZ-Pamplona zone; QC-FF-Queen Charlotte-Fairweather fault system; TF-Totschunda fault; YB-Yakutat Bay; Wrangell Volcs-Wrangell volcanoes and volcanic field.

Figure 3a. Index map of study area showing place names and multichannel seismic reflection tracklines. Heavy, numbered lines are shown in figures 8-19 and discussed in the text. Also shown are OCS Lease Sale 55 tracts, sonobuoy locations (sonobuoy symbol is next to seismic line along which sonobuoy data was recorded), location of depth sections shown in figures 23,24, and 25, and location of sections AA' and BB' shown in figure 27.

Figure 3b. Generalized geologic map showing bedrock outcrop distribution on the Yakutat segment, the outcrop area of pre-Tertiary rocks onshore, areas of thicker unconsolidated deposits, major structural features, and onshore wells. Units G and H not distinguished by patern; contact is at continental slope except in shelf valleys. See text for description of map units. From Plafker and others, 1980.

Figure 4. Structure contours on seismic horizon D, approximately the base of the Neogene sedimentary section. Geology on continental slope is after Plafker and others (1980).

Figure 5. Structure contours on seismic horizon F, approximately the base of the Paleogene sedimentary section.

Figure 6. Isopach between seismic horizon D and the seafloor. Contours show thickness of Neogene sedimentary strata.

Figure 7. Isopach between seismic horizons F and D. Contours show approximate thickness of Paleogene sedimentary strata.

Figure 8. Interpreted seismic section and true scale depth section for line 404. Line crosses the continental margin south of Icy Bay; for location see figure 3. Seismic horizon D corresponds to the mapped horizon of Figure 4. Horizons A, B, and C are additional horizons mapped in the Yakataga segment to the west (Bruns and Schwab, in press). Horizons A1 and A3 are earliest Pleistocene and oceanic basalt respectively. Line intersections indicated at top of section. V.E. about 5:1 at seafloor.

Figure 9. Interpreted seismic section for line 916. Line shows lower slope and base of slope south of Icy Bay; for location see figure 3. Seismic horizons D and F correspond to mapped horizons of figures 4 and 5. Seismic horizons A1, A2, and A3 are earliest Pleistocene, earliest Pliocene, and oceanic basalt respectively. Line intersections indicated at top of section. V.E. about 6.7:1 at seafloor.

Figure 10. Interpreted seismic section for line 906. Line crosses continental margin south of Yakutat Bay; for location see figure 3. See figure 9 for further explanation.

Figure 11. Interpreted seismic section for line 403. Line crosses continental margin south of Yakutat Bay; for location see figure 3. V.E. approximately 5:1 at seafloor. Horizon E is approximately middle Oligocene; other horizons and further explanation as in figure 9.

Figure 12. Interpreted seismic section for line 913. Line crosses Dangerous River zone west of the Alsek Valley; for location see figure 3. See figure 9 for further explanation.

Figure 13. Interpreted seismic section for line 909. Line crosses continental margin along the Alsek Valley; for location see figure 3. Flat-lying, high frequency reflectors below Fairweather Ground (location a) are due to water layer reverberation, and do not indicate sedimentary layers. See figure 9 for further explanation of seismic line.

Figure 14. Interpreted seismic section for line 911. Line crosses eastern subbasin and Fairweather Ground; for location see figure 3. See figure 9 for further explanation.

Figure 15. Seismic section 967. Line crosses the lower slope and base of slope at the base of Fairweather Ground, and shows young anticlinal deformation. For location see figure 3. See figure 9 for further explanation.

Figure 16. Interpreted seismic section for line 400. Line crosses continental margin just west of Cross Sound; for location see figure 3. V.E. approximately 5:1 at seafloor. See figure 9 for further explanation.

Figure 17. Interpreted seismic section for line 914. Line crosses the Dangerous River zone near the shoreline; for location see figure 3. See figure 9 for further explanation.

Figure 18. Interpreted seismic section for line 903. Line crosses the Dangerous River zone in the vicinity of the Alsek Valley; for location see figure 3. See figure 9 for further explanation.

Figure 19. Interpreted seismic section for line 912. Line crosses the 1angerous River zone in the vicinity of the Alsek Valley; for location see figure 3. See figure 9 for further explanation.

Figure 20. Results of refraction sonobuoys, and tentative correlation of velocity layers. Velocities given in km/sec. Locations of sonobuoy lines shown in figure 3.

Figure 21. Time-depth curve used to convert two-way travel time on seismic sections to depth, and interval velocity curve; "z" is subsurface depth in kilometers; "t" is two-way travel time in seconds.

Figure 22. Correlation of seismic horizons D, E, and F from this study to geologic units A-G defined by Plafker and others (1980) from dredge data from the continental slope. Vertical ruled lines indicate a hiatus; diagonal lines indicate no data. Correlation to onshore geologic formations can be determined by comparing this chart to figure 2 of Plafker (1971).

Figure 23. True-scale depth section (top) and restored section derived by flattening on horizon D for a segment of seismic line 909 north of Fairweather Ground. Location of the line segment is shown in figures 3 and 13. Reconstruction at U horizon time shows approximate configuration of early Tertiary strata prior to major uplift of Fairweather Ground. Amount of uplift is about 2 km, and may be about 2.5 km if uplift is mainly after horizon U time.

Figure 24. True-scale depth section top and restored section derived by flattening on horizon U for a segment of seismic line 911 north of Fairweather Ground. Location of the line segment is shown in figures 3 and 14. Reconstruction at horizon U time shows approximate configuration of strata prior to major uplift of Fairweather Ground. Amount of uplift is about 1 km. Age of horizon U is unknown, but is probably Pliocene or younger.

Figure 25. Depth section for part of line 403 and sequential reconstruction of strata configurations at D, U and E horizon times. Reconstructions show history of development of structural highs at locations 1 and 3, and a low at location 2. For location of segment shown see figure 3. Large arrows on each reconstruction indicate subsidence or uplift relative to previous reconstruction See Text for further discussion.

Figure 26a. Lopatin diagram for "D horizon unconformity case", using a geothermal gradient of 25°C/km. Case shown assumes that horizon D separates Oligocene from Pliocene strata, and that no major subsidence or uplift occurred during the hiatus. Diagram shows burial history for strata at location 2, line 403 (figs. 11, 24), and calculated time-temperature index of maturity (TTI) of 15 and 160, corresponding to beginning and end of oil generation (Waples, 1980). Strata beneath horizon F are assumed to have little or no resource potential.

Figure 26b. Lopatin diagram for "continuous deposition case" for same location and geothermal gradient as figure 26a. This case assumes no hiatus at the end of Oligocene time, and continuous deposition across horizon D. The actual burial history probably lies somewhere between that presented in figure 26a and here, and could include both uplift and subsidence at horizon D time.

Figure 27. Cross sections AA' and BB' constructed from seismic data showing depth to the current oil and gas windows calculated by Lopatin's method (Waples, 1980). Diagonal ruling indicates potential oil and gas generating zones for the D horizon unconformity case (see fig. 26a); for the continuous deposition case, zones are shown by dashed lines. Location of cross-sections is shown in figure 3.

Figure 28. Plot of cumulative percent volume versus depth (percent of total volume at or below a particular depth). Oil and gas limits shown are a shelf-wide average based on Lopatin calculations of thermal maturity with a geothermal gradient of $25^{o}$ c/km. The corresponding volume of sediment that may be mature then ranges from around 23 to 28% of the total volume.

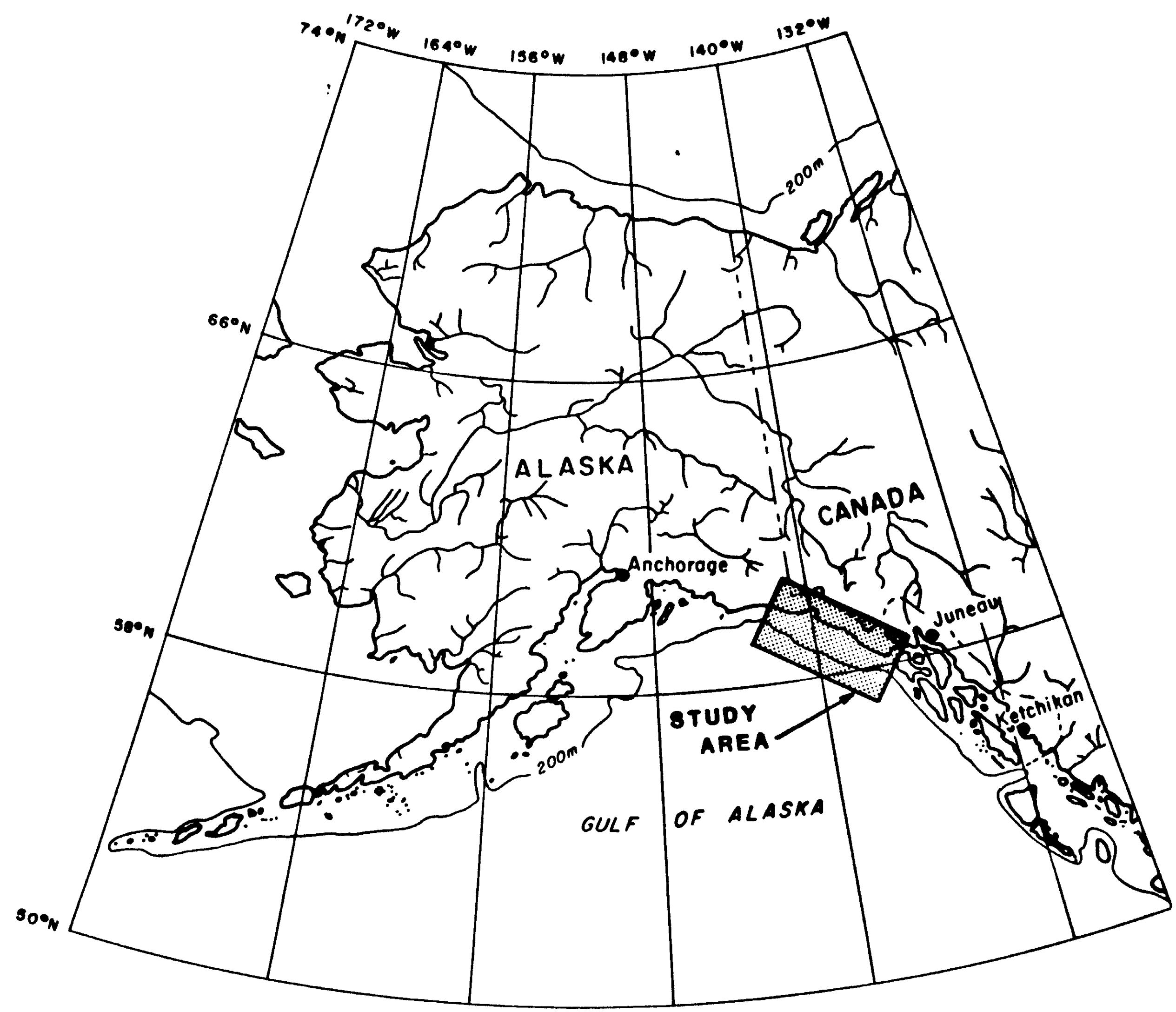

74°N
172°W
164°W
156°W
148°W
140°W
132°W
66°N
58°N
50°N
200m
ALASKA
CANADA
Anchorage
Juneau
Ketchikan
STUDY
AREA
200m
GULF OF ALASKA

Figure 1.

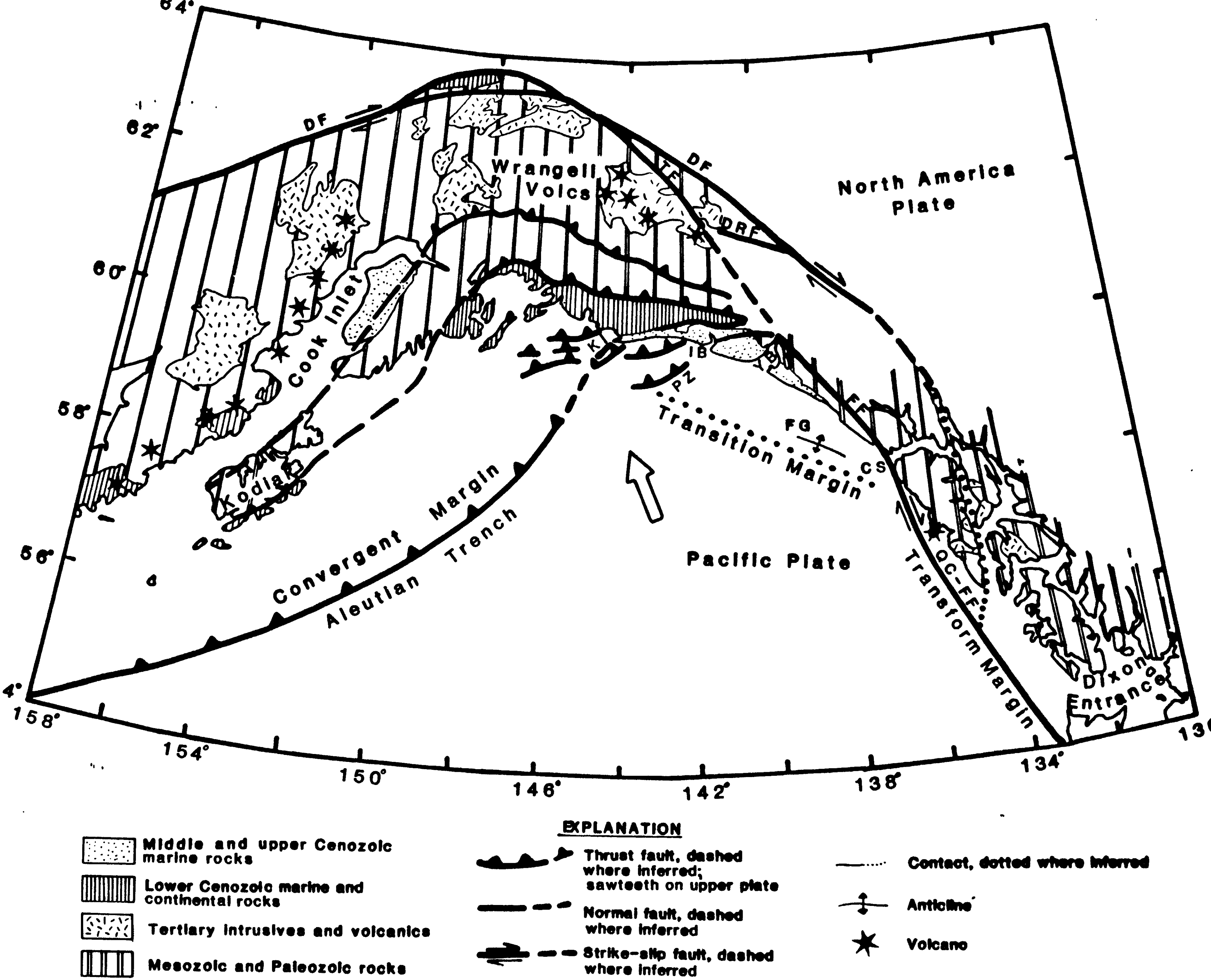

North America Plate
Pacific Plate
Wrangell Volcs
Cook Inlet
Kodiak
DF
TF
DRF
FF
K
IB
PZ
FG
CS
QC-FF
Transition Margin
Transform Margin
Convergent Margin
Aleutian Trench
Dixon Entrance
64°
62°
60°
58°
56°
54°
158°
154°
150°
146°
142°
138°
134°
130°
EXPLANATION
Middle and upper Cenozoic marine rocks
Lower Cenozoic marine and continental rocks
Tertiary intrusives and volcanics
Mesozoic and Paleozoic rocks
Thrust fault, dashed where inferred; sawteeth on upper plate
Normal fault, dashed where inferred
Strike-slip fault, dashed where inferred
Contact, dotted where inferred
Anticline
Volcano

Figure 2.

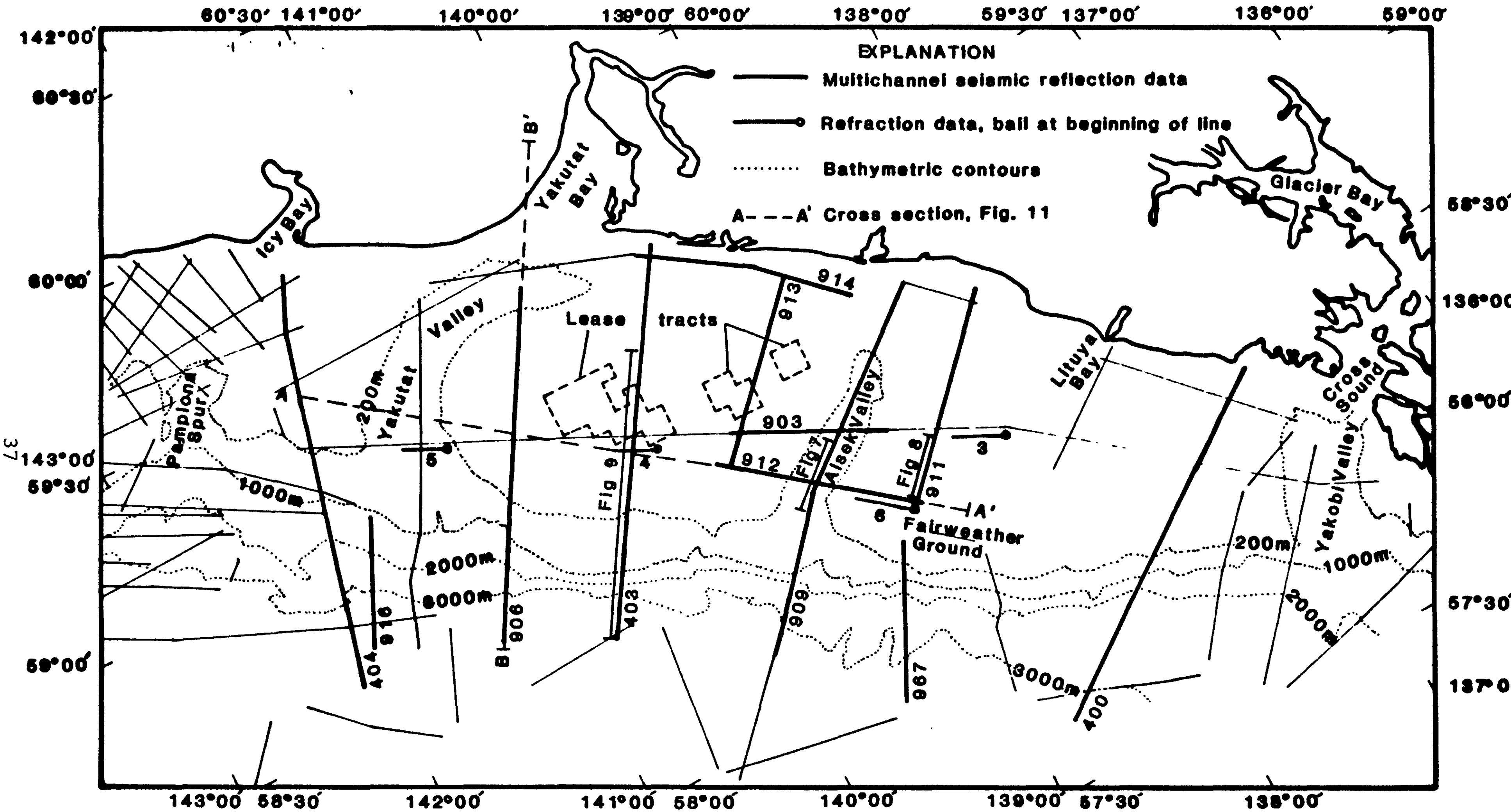

EXPLANATION
Multichannel seismic reflection data
Refraction data, ball at beginning of line
Bathymetric contours
A---A' Cross section, Fig. 11
Icy Bay
Yakutat Bay
Glacier Bay
Cross Sound
Lituya Bay
Lease tracts
Yakutat Valley
Alsek Valley
Yakobi Valley
Pamplona Spur
Fairweather Ground
Fig 7
Fig 8
Fig 9
903
912
913
914
911
909
906
403
404
916
967
400
200m
1000m
2000m
3000m
142°00'
141°00'
140°00'
139°00'
138°00'
137°00'
136°00'
143°00'
60°30'
60°00'
59°30'
59°00'
58°30'
58°00'
57°30'

Figure 3a.

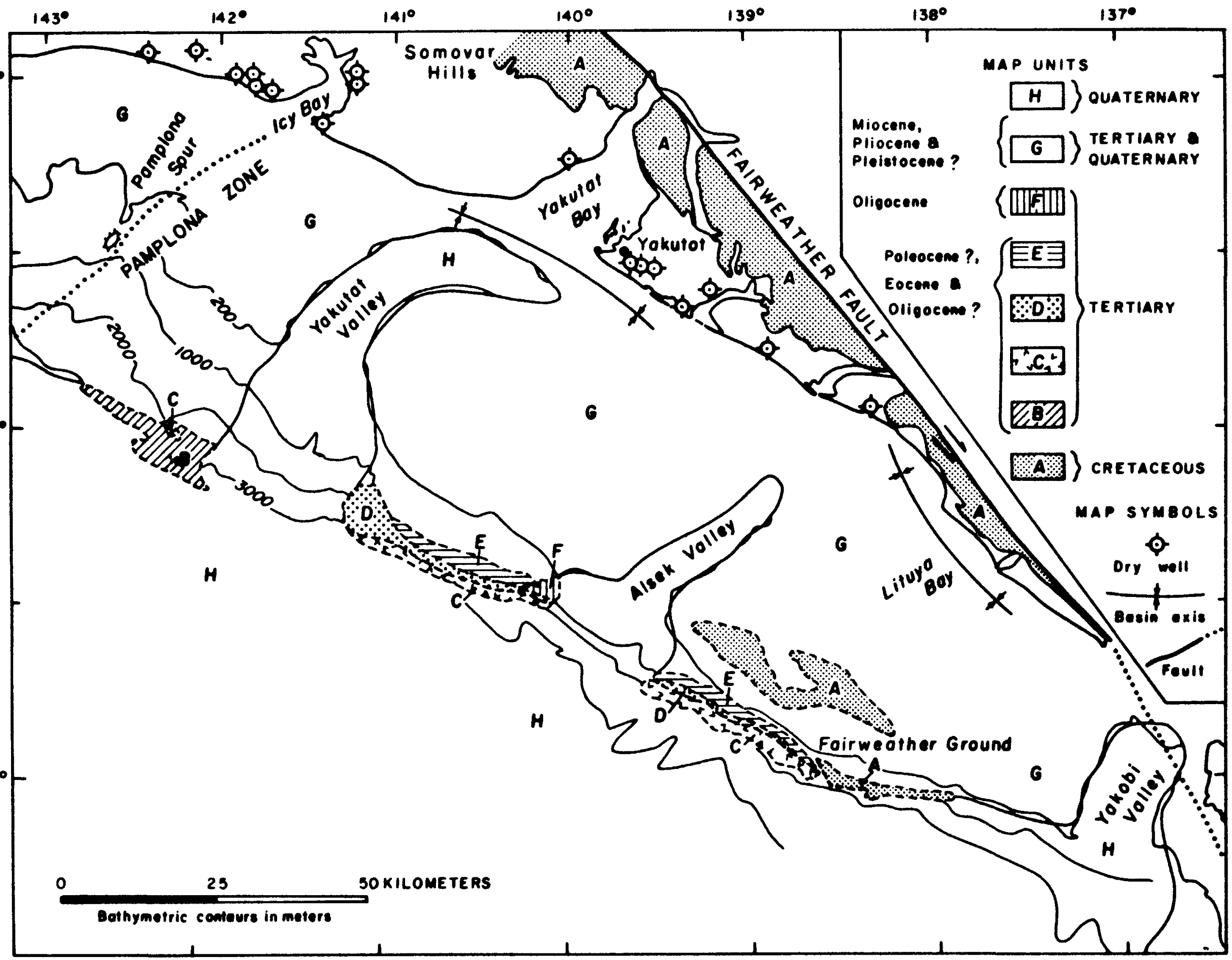

143°
142°
141°
140°
139°
138°
137°
60°
59°
58°
Somovar Hills
Icy Bay
Pamplona Spur
PAMPLONA ZONE
Yakutat Bay
Yakutat
FAIRWEATHER FAULT
Yakutat Valley
Alsek Valley
Lituya Bay
Fairweather Ground
Yakobi Valley
200
1000
2000
3000
0
25
50 KILOMETERS
Bathymetric contours in meters
MAP UNITS
H
QUATERNARY
Miocene, Pliocene & Pleistocene ?
G
TERTIARY & QUATERNARY
Oligocene
F
Paleocene ?, Eocene & Oligocene ?
E
D
C
B
TERTIARY
A
CRETACEOUS
MAP SYMBOLS
Dry well
Basin axis
Fault

Figure 3b.

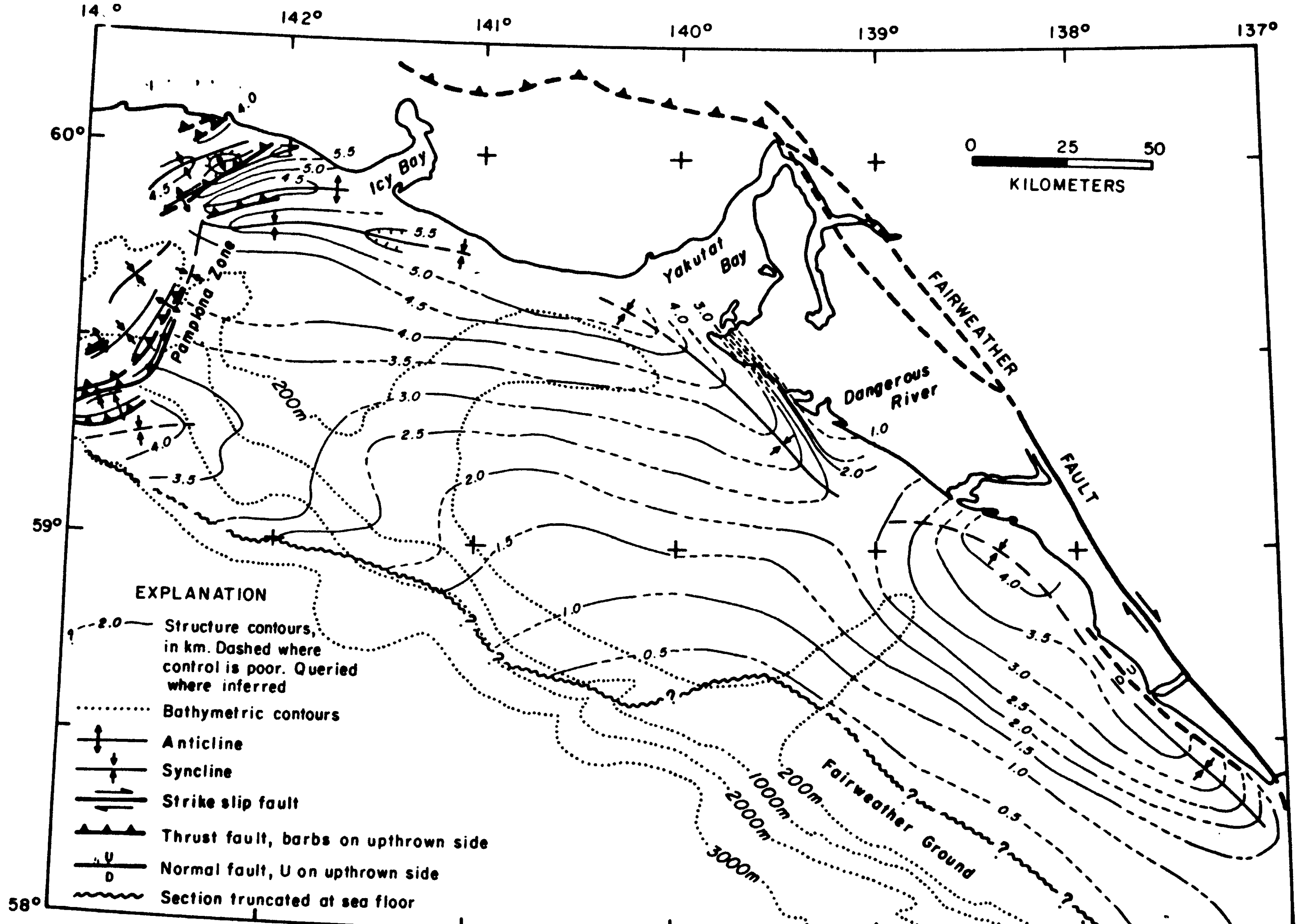
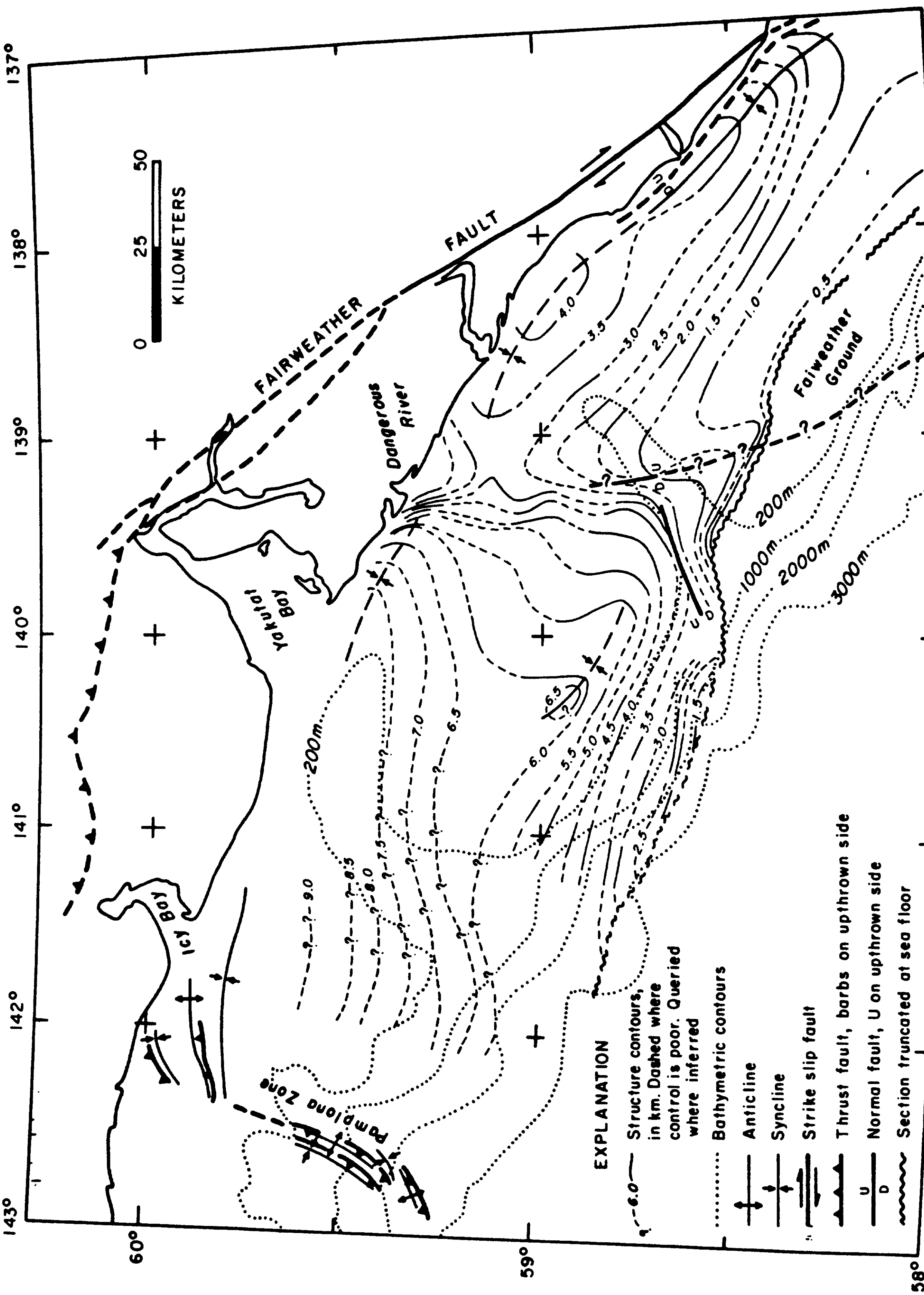

14 °
142°
141°
140°
139°
138°
137°
60°
59°
58°
0 25 50
KILOMETERS
FAIRWEATHER
FAULT
Icy Bay
Yakutat Bay
Dangerous River
Pamplona Zone
Fairweather Ground
200m
1000m
2000m
3000m
EXPLANATION
Structure contours, in km. Dashed where control is poor. Queried where inferred
Bathymetric contours
Anticline
Syncline
Strike slip fault
Thrust fault, barbs on upthrown side
Normal fault, U on upthrown side
Section truncated at sea floor

Figure 4.



FAIRWEATHER FAULT
KILOMETERS
0 25 50
Yakutat Bay
Dangerous River
Icy Bay
Pamplona Zone
Faiweather Ground
200m
1000m
2000m
3000m
137°
138°
139°
140°
141°
142°
143°
60°
59°
58°
EXPLANATION
Structure contours, in km. Dashed where control is poor. Queried where inferred
Bathymetric contours
Anticline
Syncline
Strike slip fault
Thrust fault, barbs on upthrown side
Normal fault, U on upthrown side
Section truncated at sea floor


Figure 5.

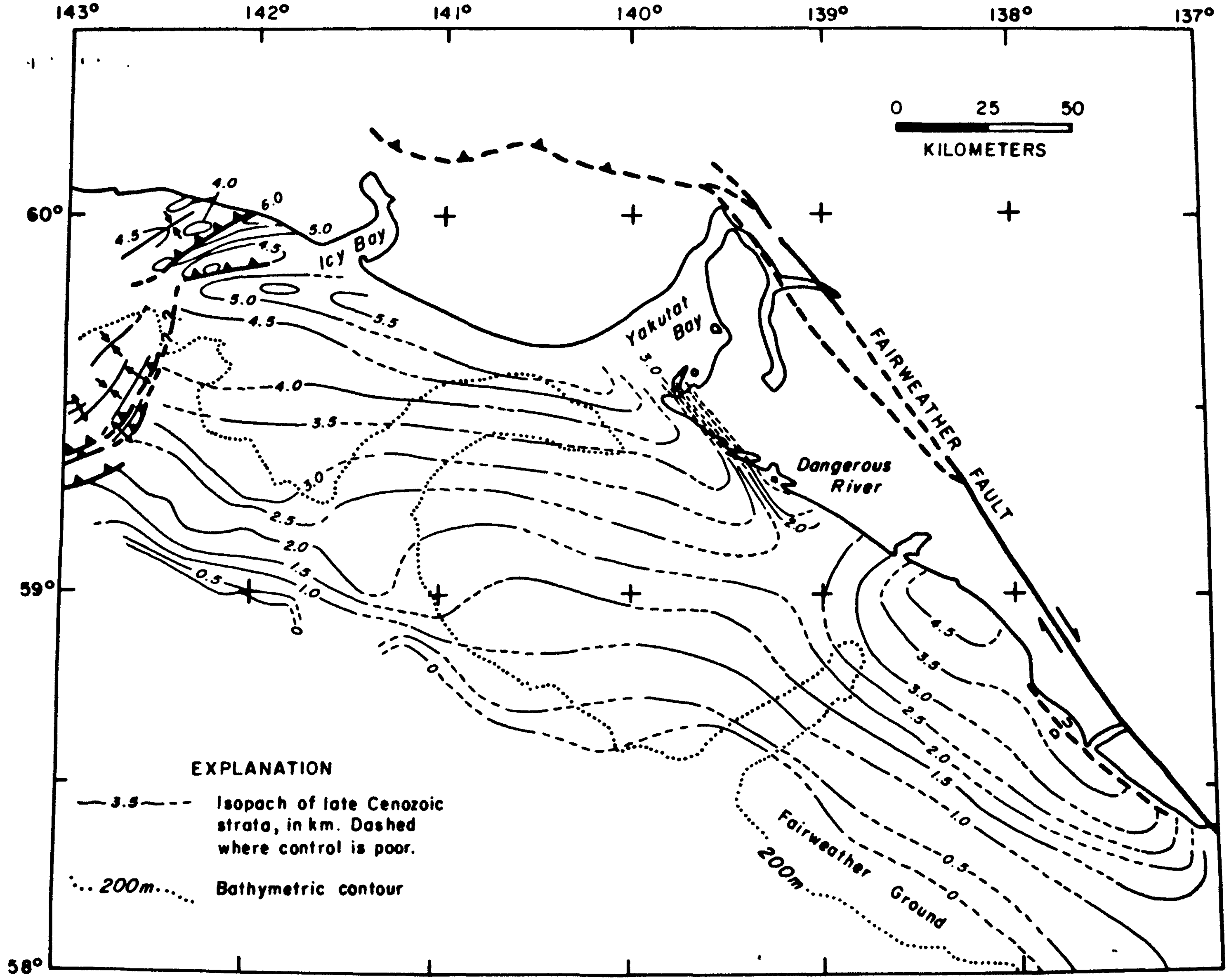

143°
142°
141°
140°
139°
138°
137°
60°
59°
58°
0 25 50
KILOMETERS
FAIRWEATHER FAULT
Icy Bay
Yakutat Bay
Dangerous River
Fairweather Ground
200m
EXPLANATION
Isopach of late Cenozoic strata, in km. Dashed where control is poor.
Bathymetric contour

Figure 6.

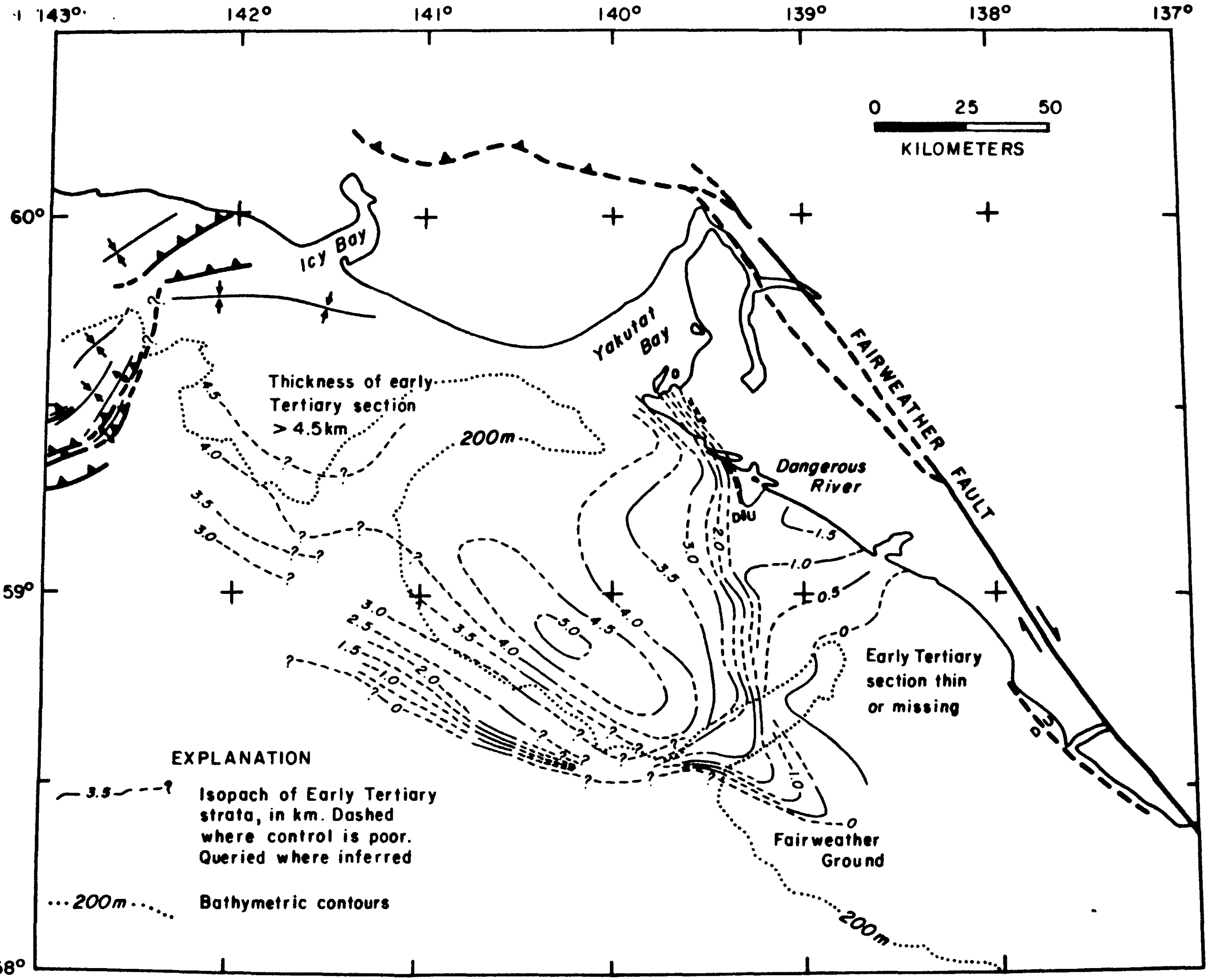

143°
142°
141°
140°
139°
138°
137°
60°
59°
58°
0 25 50
KILOMETERS
FAIRWEATHER FAULT
Icy Bay
Yakutat Bay
Dangerous River
DRU
Thickness of early Tertiary section > 4.5km
200m
Early Tertiary section thin or missing
Fairweather Ground
EXPLANATION
3.5
Isopach of Early Tertiary strata, in km. Dashed where control is poor. Queried where inferred
200m
Bathymetric contours

Figure 7.

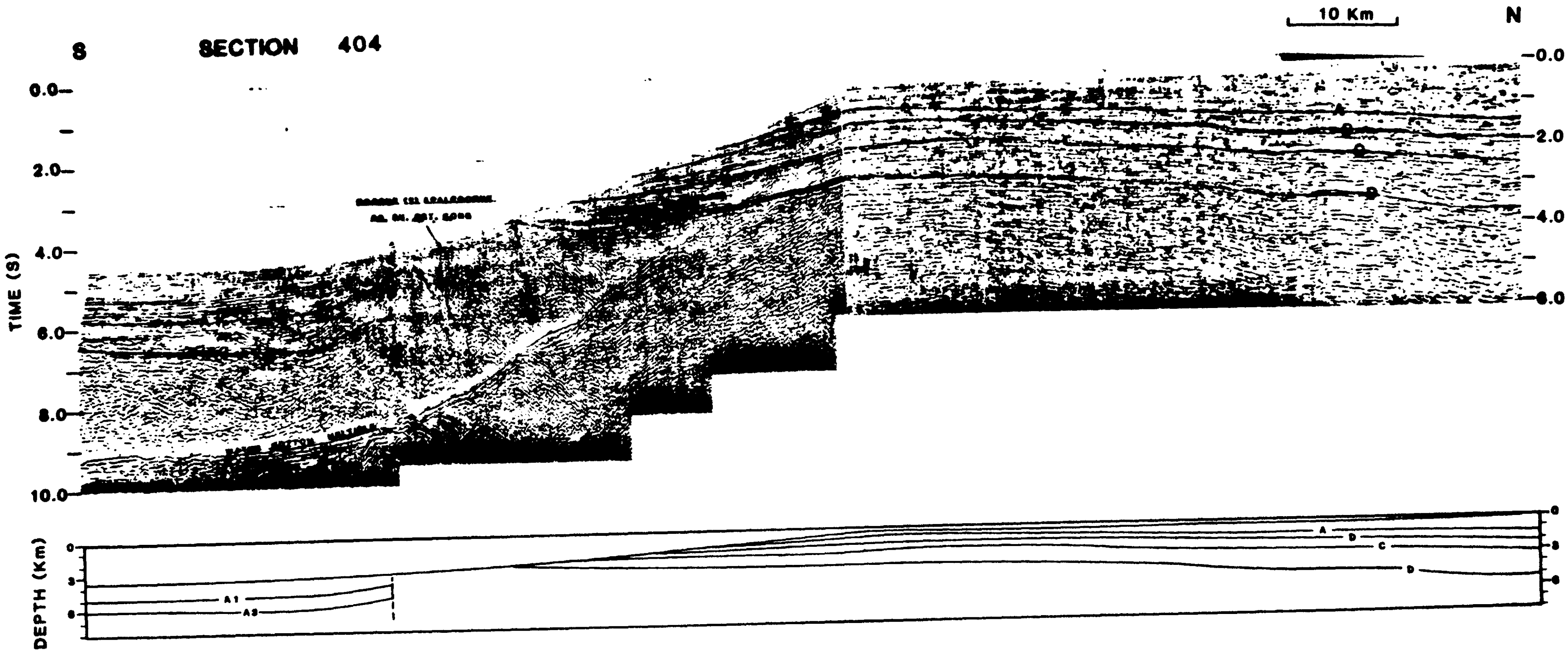



Figure 8.

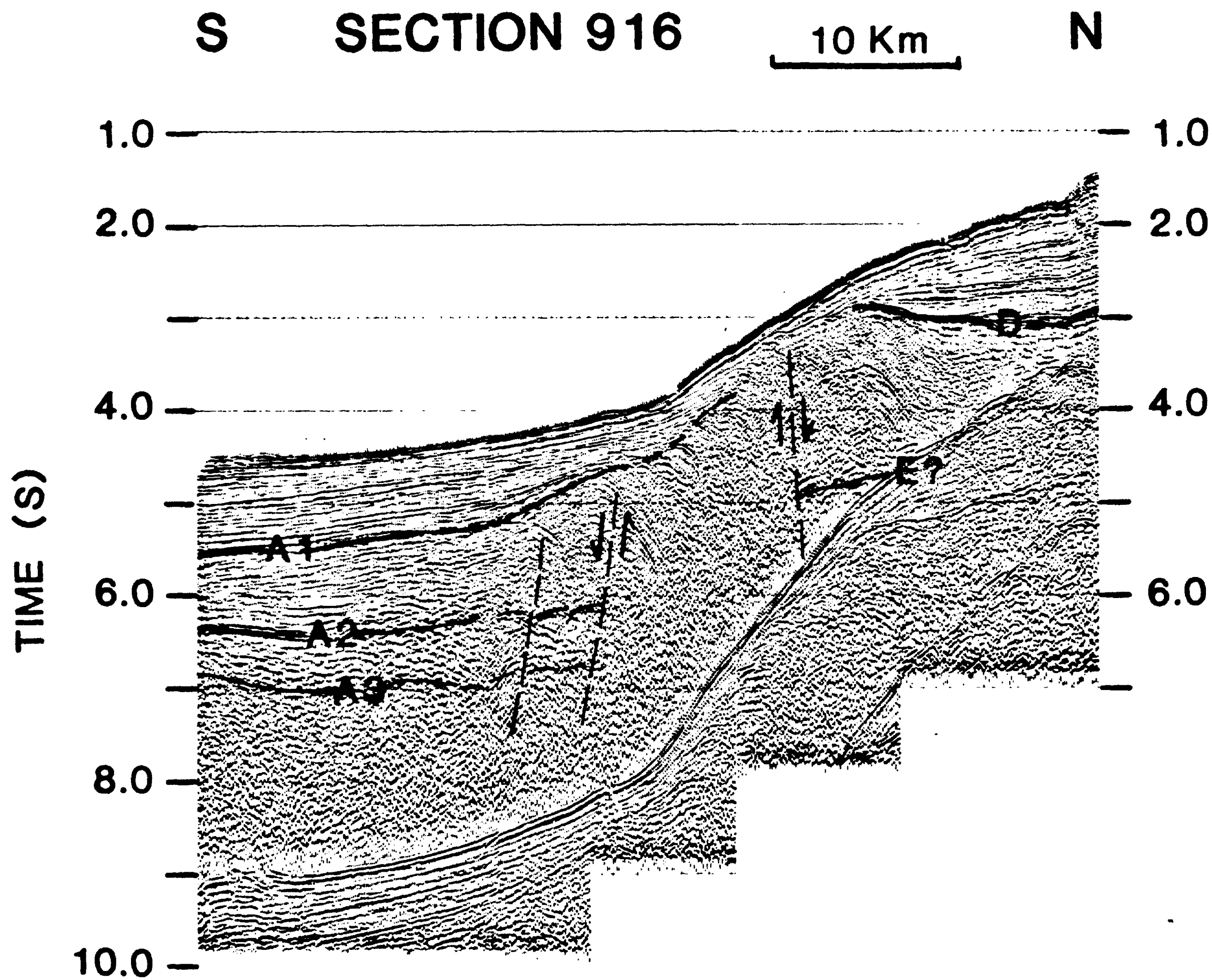



Figure 9.

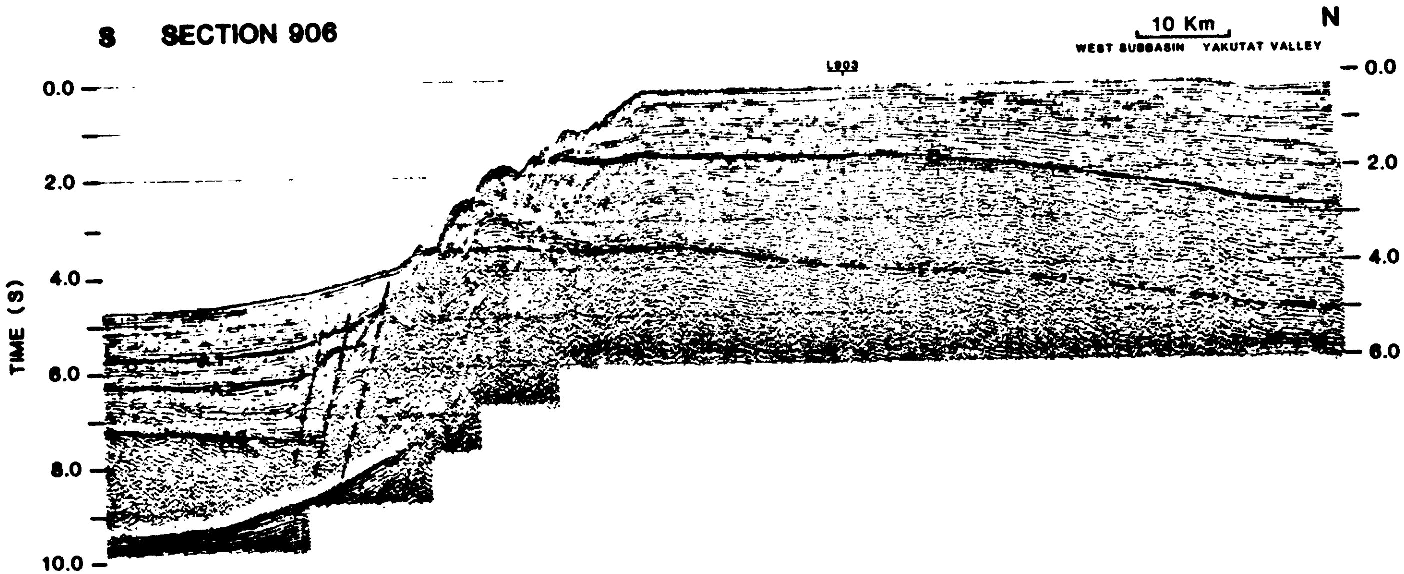

S
SECTION 906
N
10 Km
WEST SUBBASIN
YAKUTAT VALLEY
L903
TIME (S)
0.0
2.0
4.0
6.0
8.0
10.0
0.0
2.0
4.0
6.0

Figure 10.

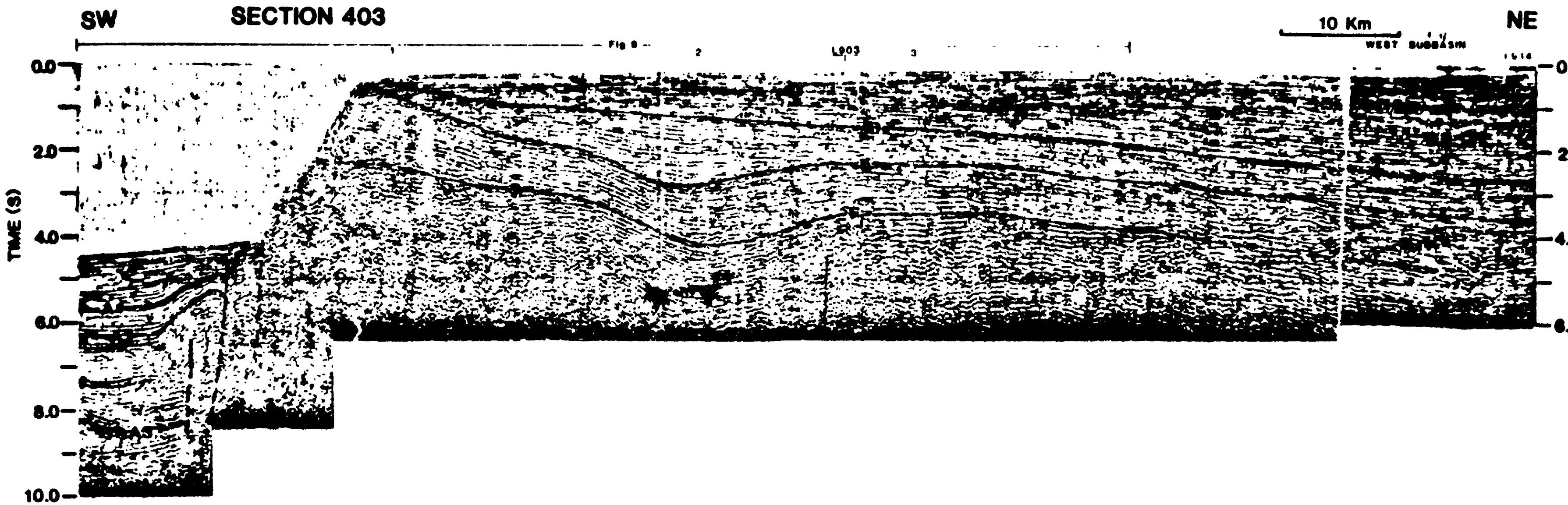

SW
SECTION 403
NE
10 Km
WEST SUBBASIN
TIME (S)
0.0
2.0
4.0
6.0
8.0
10.0
0.0
2.0
4.0
6.0
2
3


Figure 11.

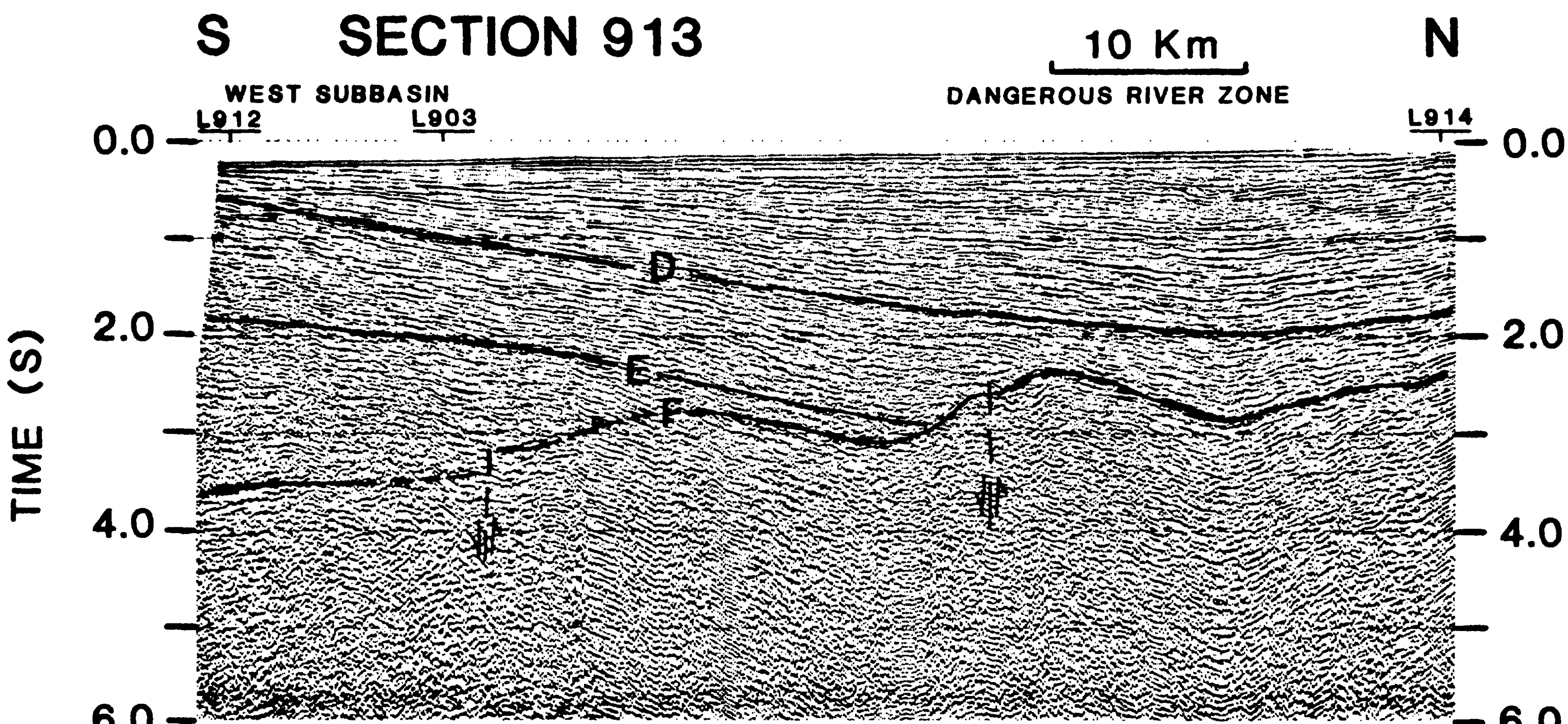

S
SECTION 913
10 Km
N
WEST SUBBASIN
DANGEROUS RIVER ZONE
L912
L903
L914
0.0
2.0
4.0
6.0
TIME (S)
D
E
F

Figure 12.

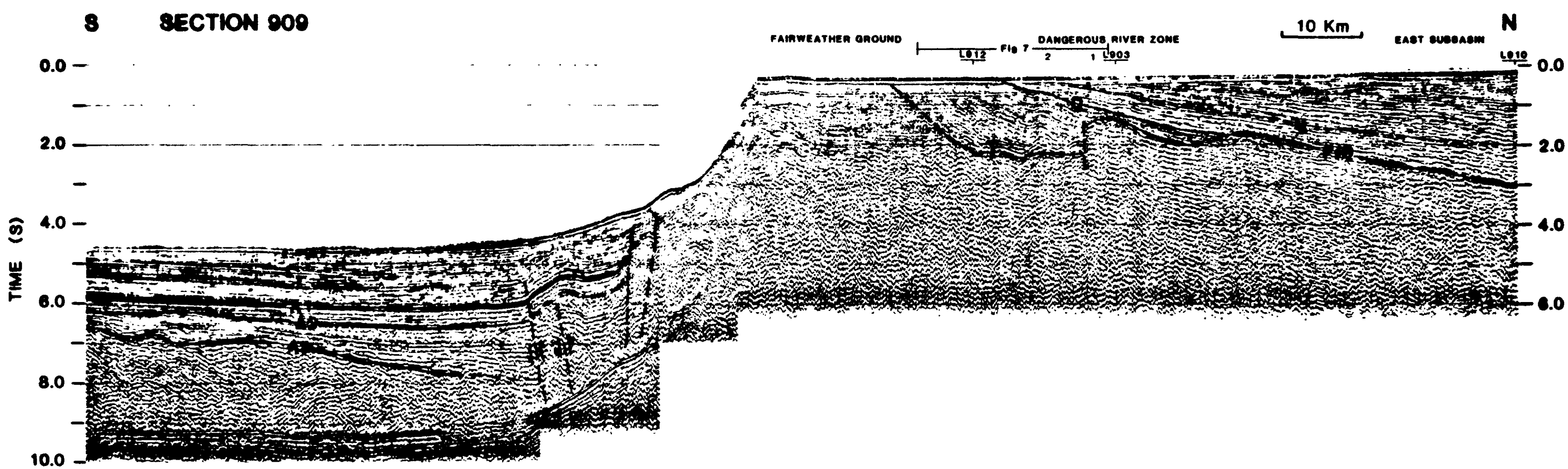

S
SECTION 909
FAIRWEATHER GROUND
L912
Fig 7
DANGEROUS RIVER ZONE
2
1
L903
10 Km
EAST SUBBASIN
N
L910
TIME (S)
0.0
2.0
4.0
6.0
8.0
10.0

Figure 13.

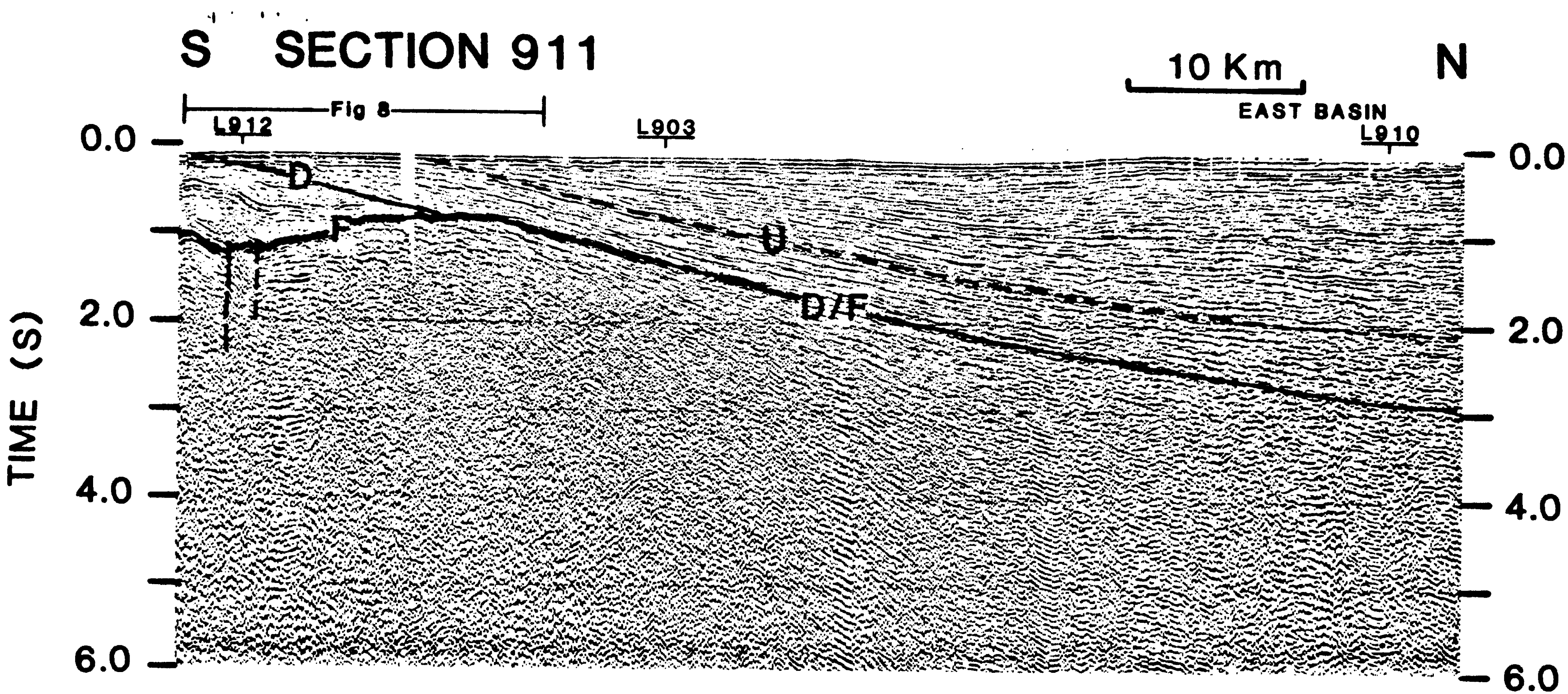

S
SECTION 911
10 Km
N
Fig 8
L912
L903
EAST BASIN
L910
D
U
D/F
TIME (S)
0.0
2.0
4.0
6.0

Figure 14.

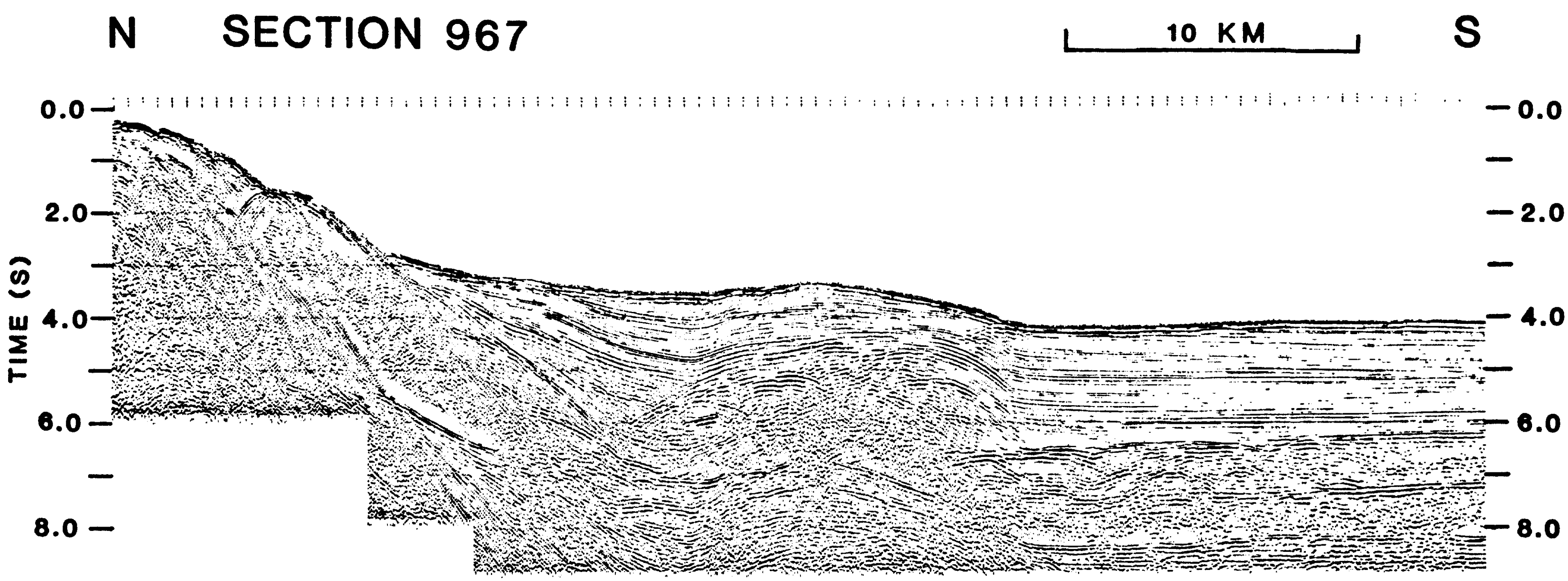



Figure 15.

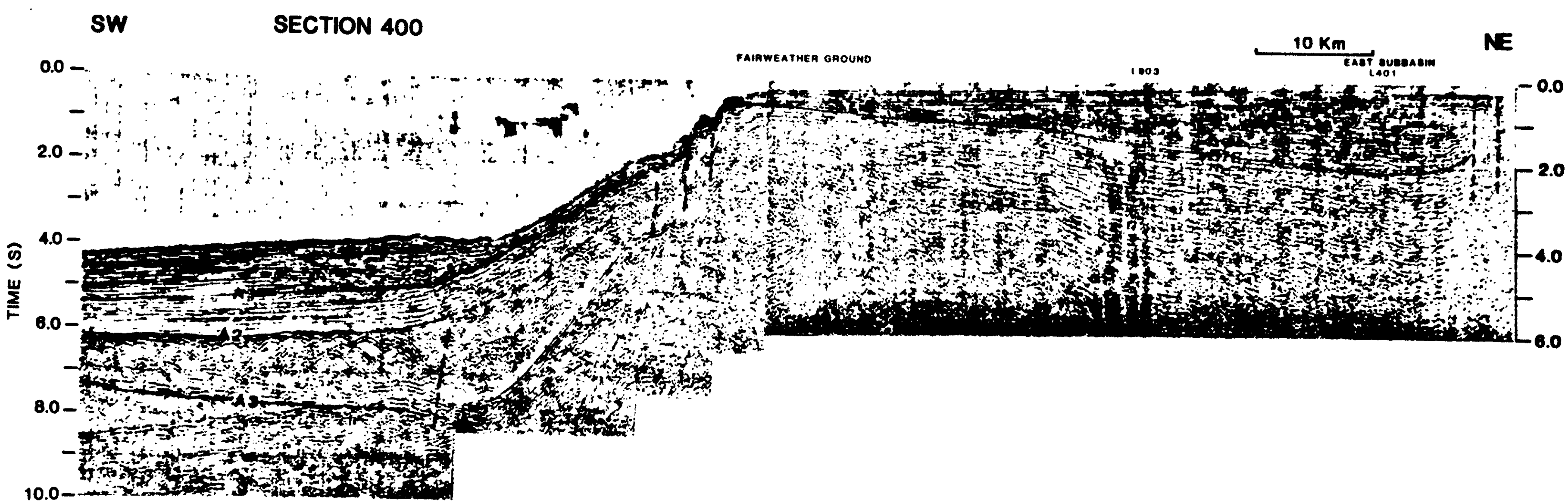

SW
SECTION 400
NE
10 Km
FAIRWEATHER GROUND
1903
EAST SUBBASIN
L401
TIME (S)
0.0
2.0
4.0
6.0
8.0
10.0
A2
A3

Figure 16.

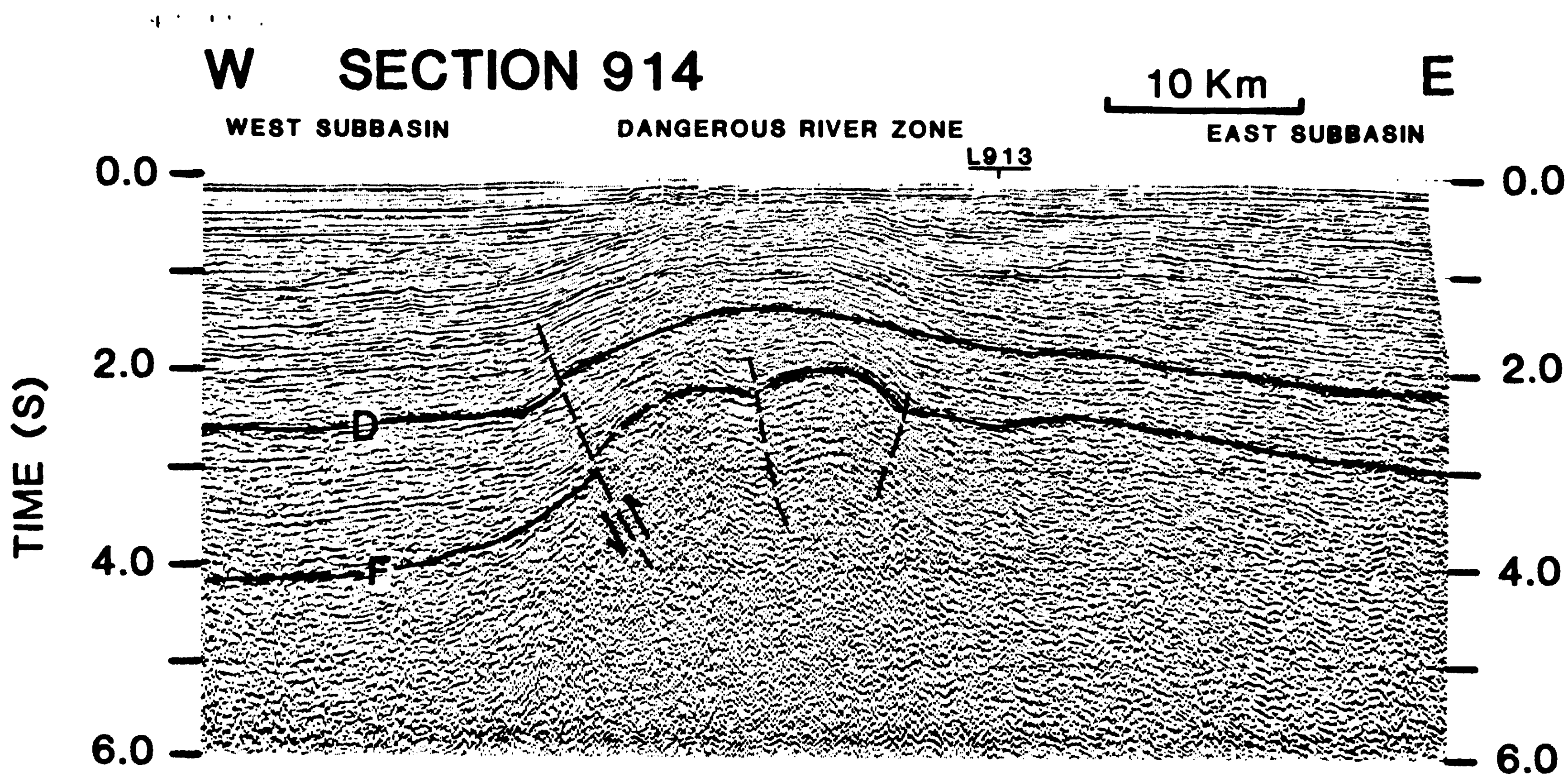

W
SECTION 914
10 Km
E
WEST SUBBASIN
DANGEROUS RIVER ZONE
EAST SUBBASIN
L913
TIME (S)
0.0
2.0
4.0
6.0
D
F

Figure 17.

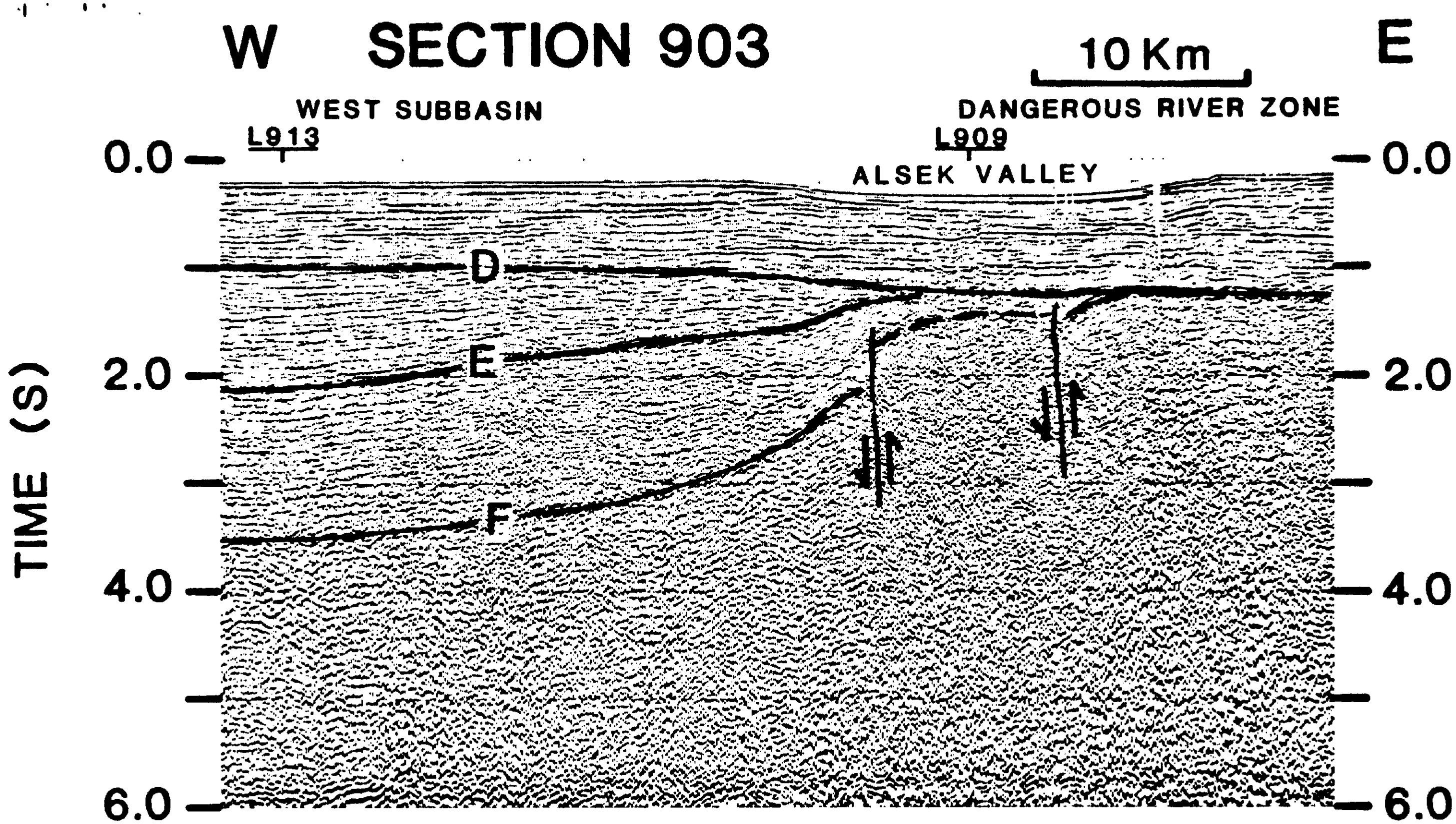

W
SECTION 903
E
10 Km
WEST SUBBASIN
DANGEROUS RIVER ZONE
L913
L909
ALSEK VALLEY
TIME (S)
0.0
2.0
4.0
6.0
D
E
F

Figure 18.

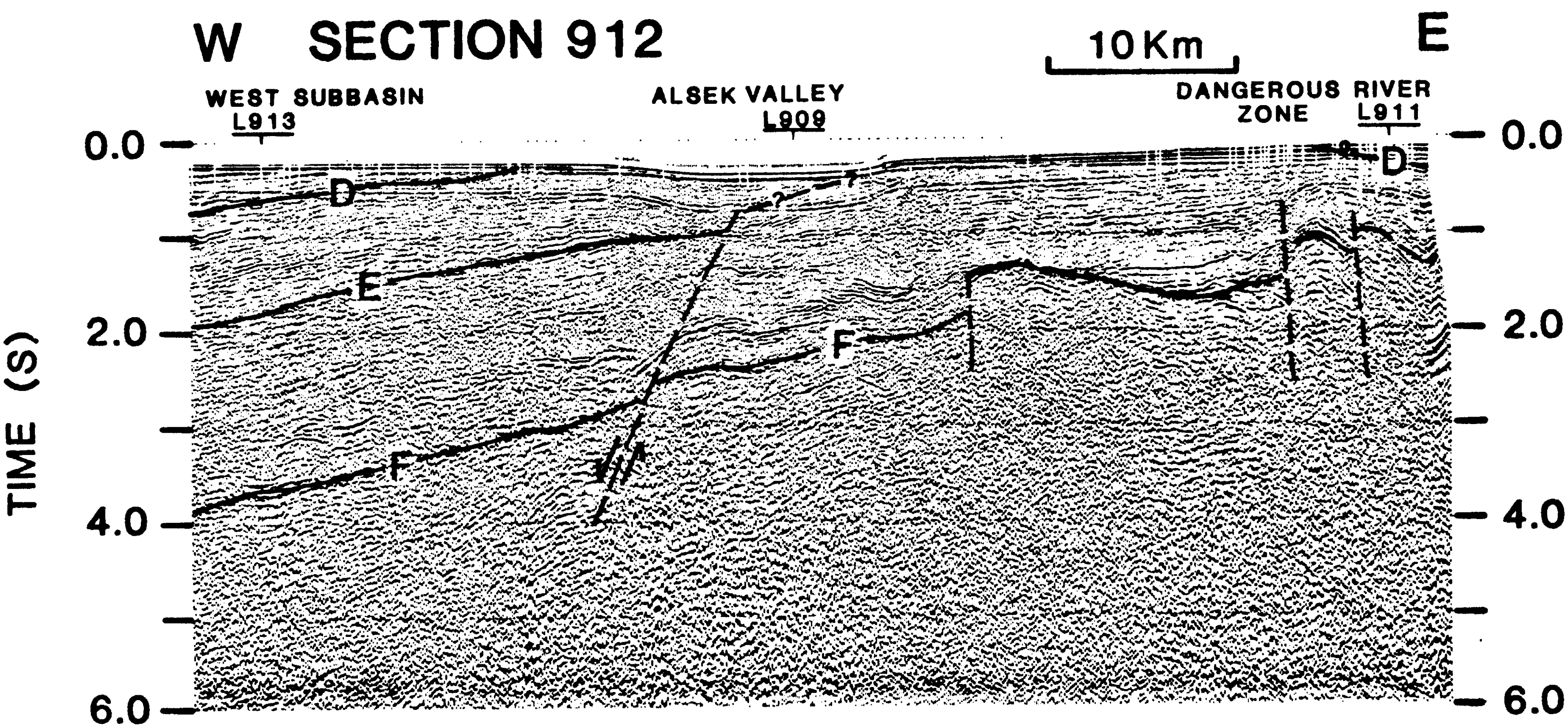

W
SECTION 912
E
10 Km
WEST SUBBASIN
L913
ALSEK VALLEY
L909
DANGEROUS RIVER
ZONE
L911
D
E
F
?
TIME (S)
0.0
2.0
4.0
6.0

Figure 19.

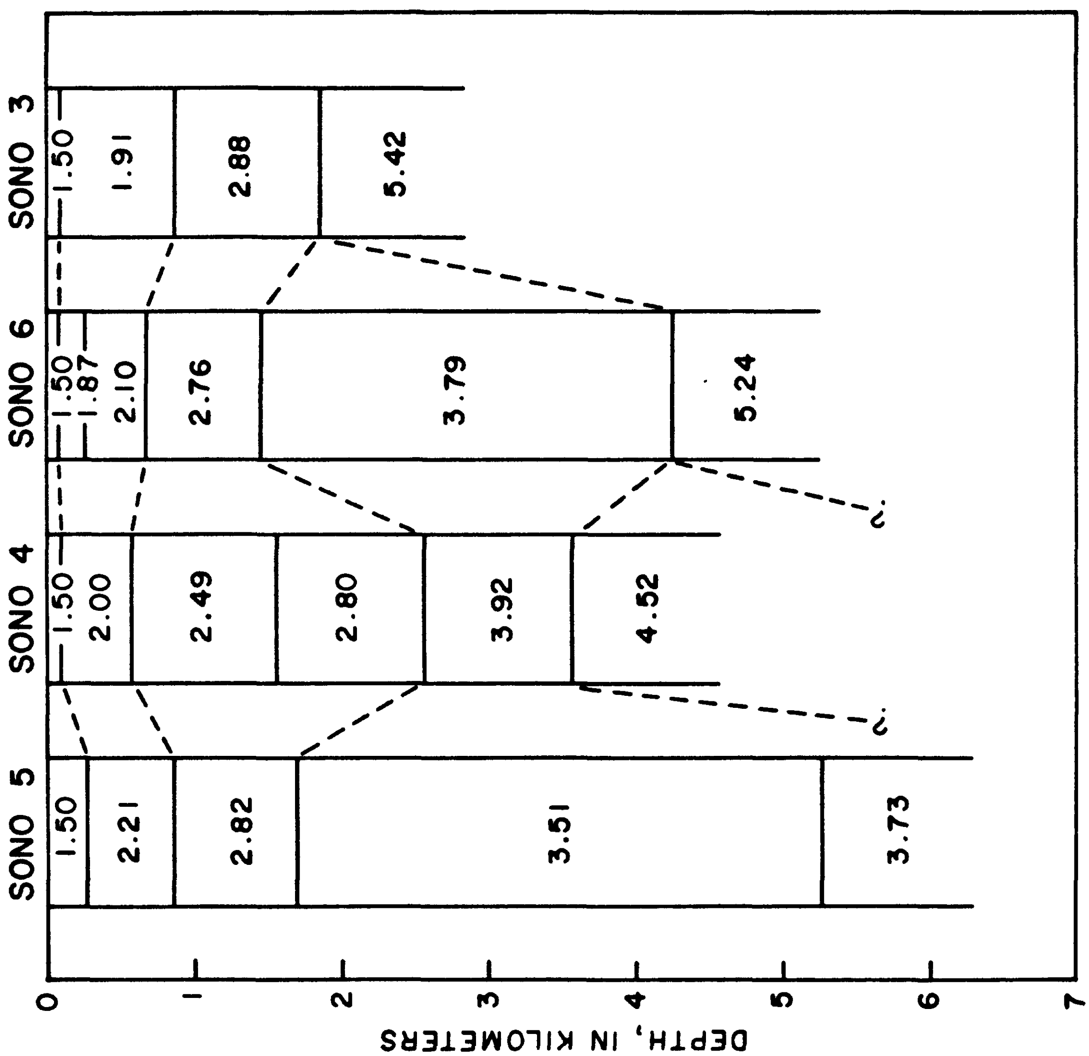
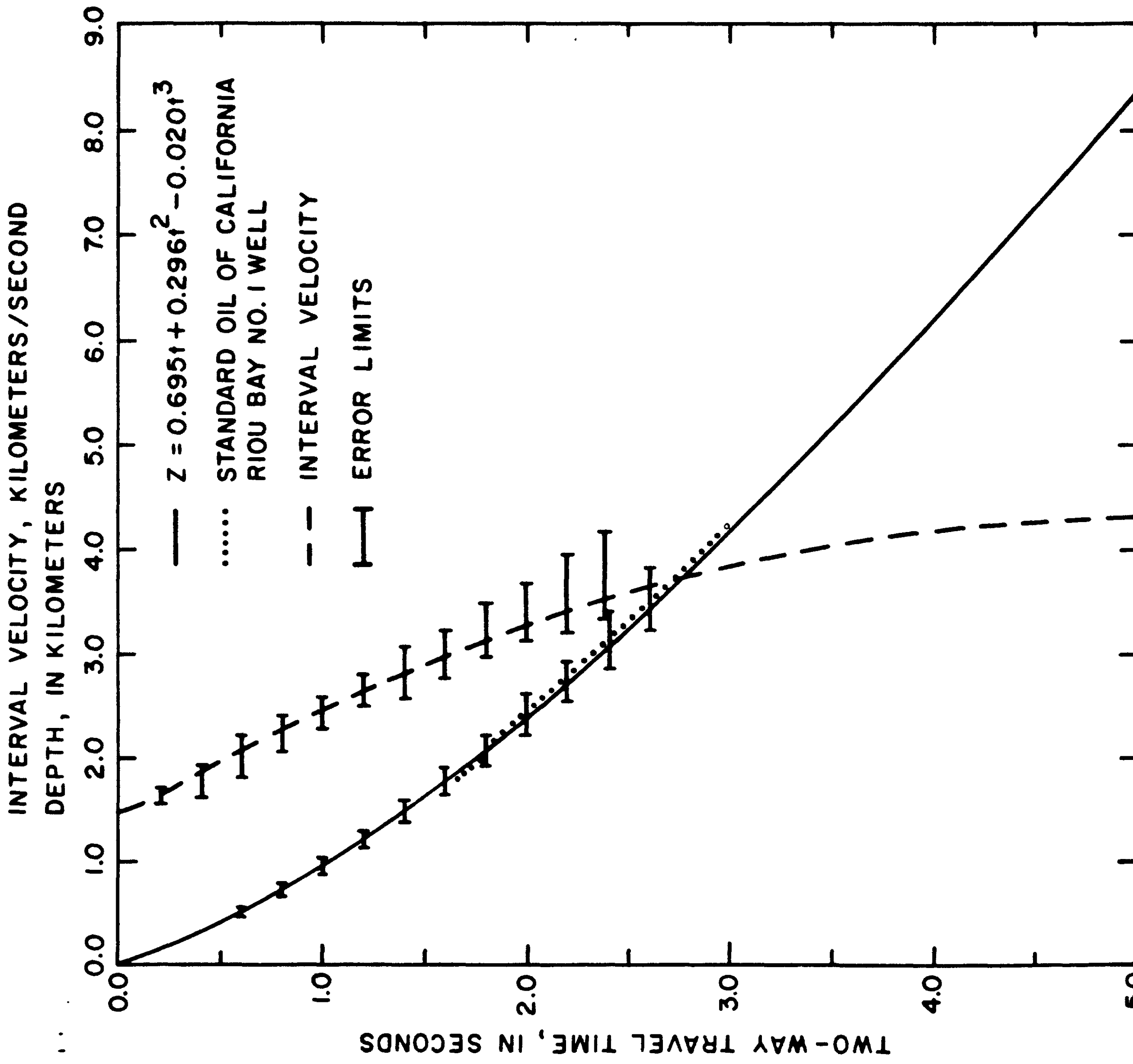

SONO 5
1.50
2.21
2.82
3.51
3.73
SONO 4
1.50
2.00
2.49
2.80
3.92
4.52
SONO 6
1.50
1.87
2.10
2.76
3.79
5.24
SONO 3
1.50
1.91
2.88
5.42
?
?
0
1
2
3
4
5
6
7
DEPTH, IN KILOMETERS

Figure 20.



INTERVAL VELOCITY, KILOMETERS/SECOND
DEPTH, IN KILOMETERS
TWO-WAY TRAVEL TIME, IN SECONDS
Z = 0.695t + 0.296t$^2$ − 0.020t$^3$
STANDARD OIL OF CALIFORNIA
RIOU BAY NO. 1 WELL
INTERVAL VELOCITY
ERROR LIMITS
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0


Figure 21.

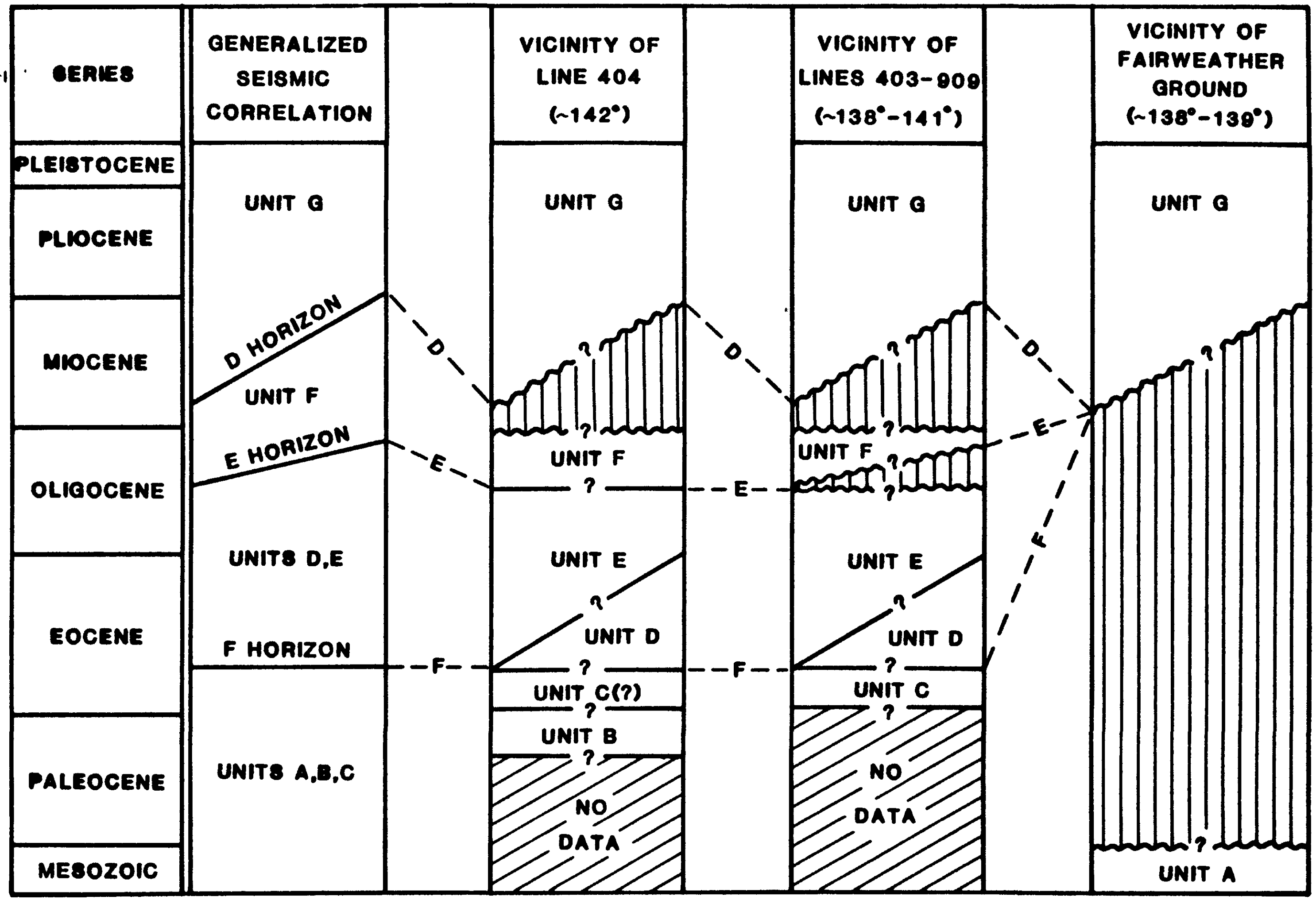

SERIES
PLEISTOCENE
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
MESOZOIC
GENERALIZED SEISMIC CORRELATION
UNIT G
D HORIZON
UNIT F
E HORIZON
UNITS D,E
F HORIZON
UNITS A,B,C
VICINITY OF LINE 404 (~142°)
UNIT G
UNIT F
UNIT E
UNIT D
UNIT C(?)
UNIT B
NO DATA
VICINITY OF LINES 403-909 (~138°-141°)
UNIT G
UNIT F
UNIT E
UNIT D
UNIT C
NO DATA
VICINITY OF FAIRWEATHER GROUND (~138°-139°)
UNIT G
UNIT A
D
E
F

Figure 22.

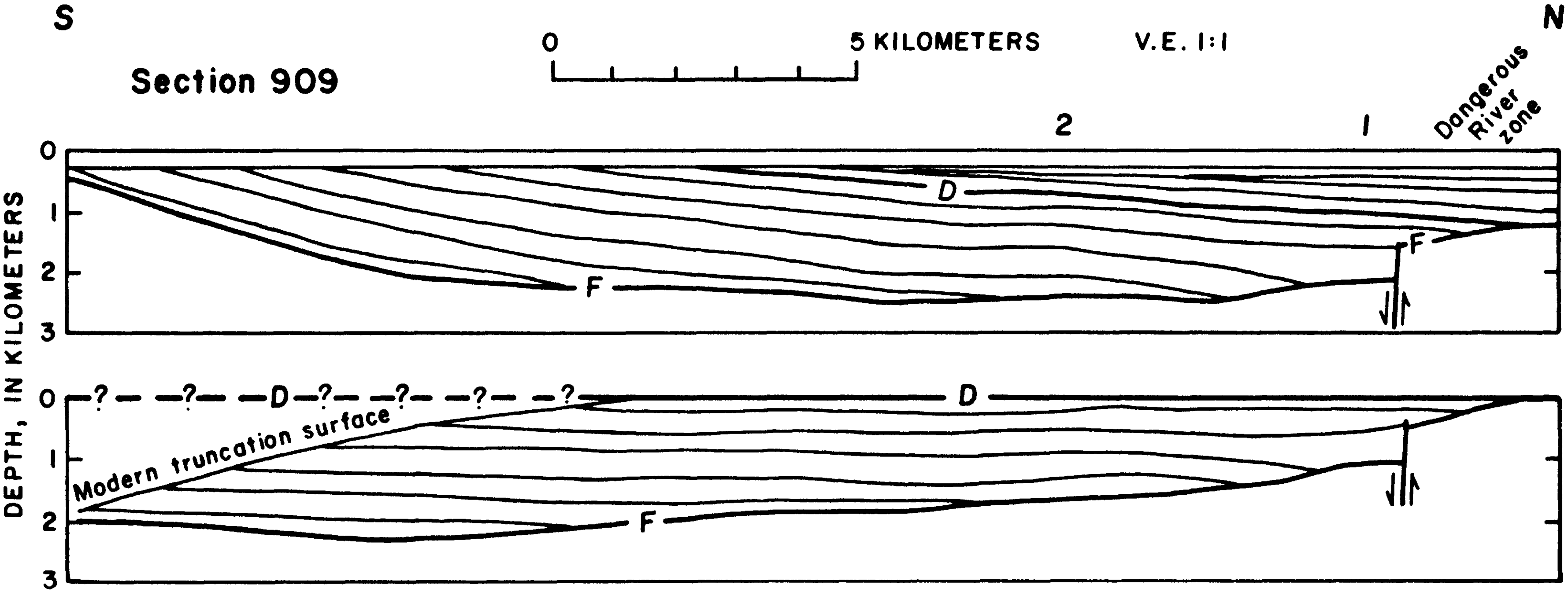

S
N
Section 909
0
5 KILOMETERS
V.E. 1:1
2
1
Dangerous River zone
DEPTH, IN KILOMETERS
0
1
2
3
D
F
Modern truncation surface
?

Figure 23.

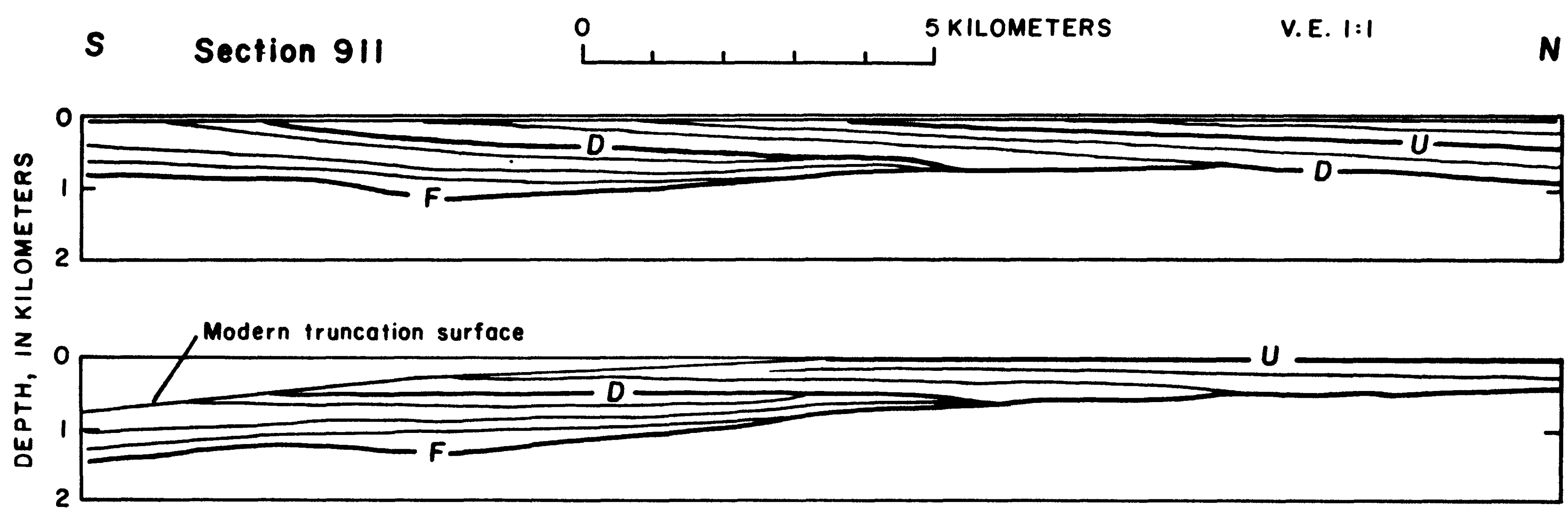

S
Section 911
0
5 KILOMETERS
V.E. 1:1
N
DEPTH, IN KILOMETERS
0
1
2
D
U
F
Modern truncation surface

Figure 24.

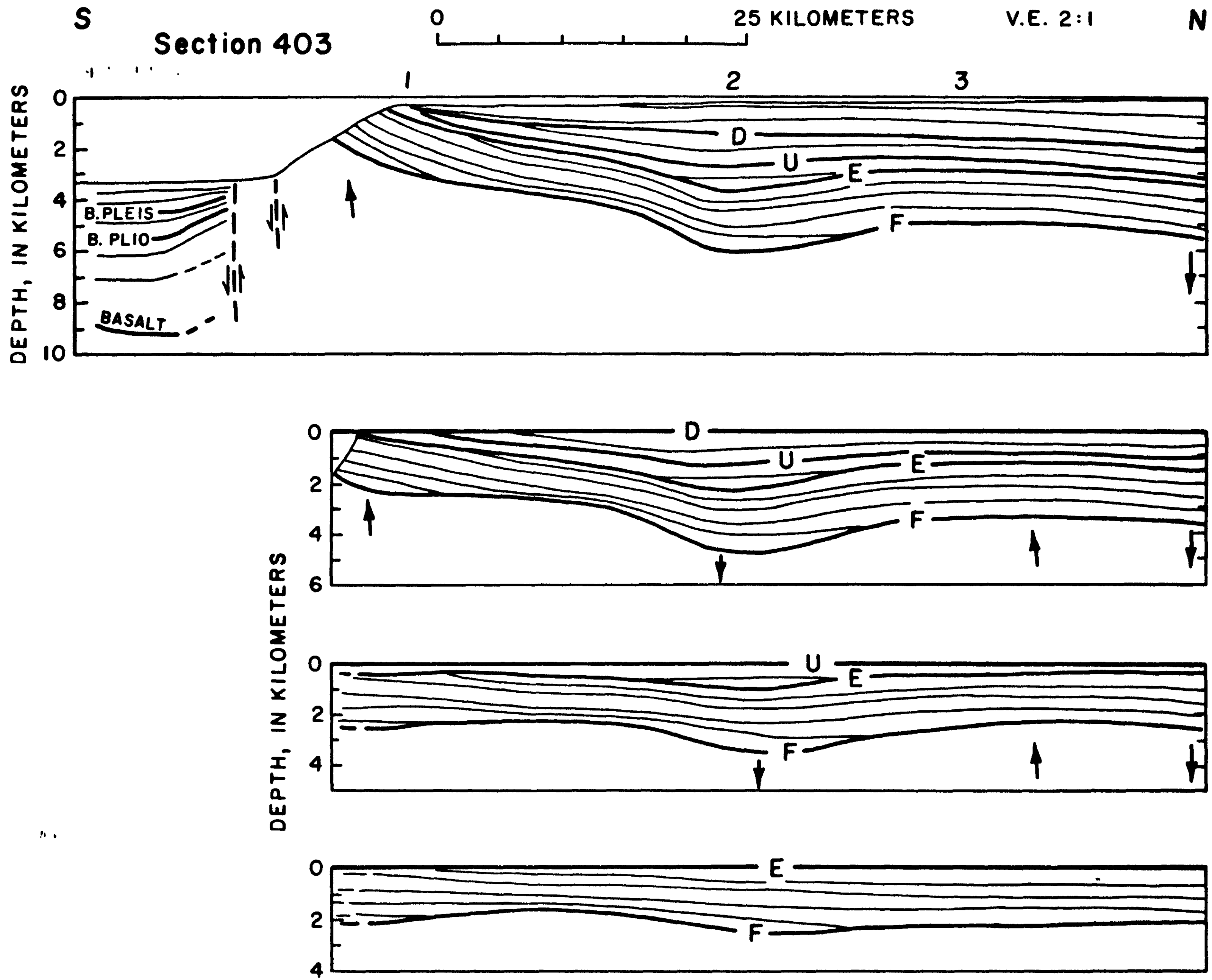

S
Section 403
0
25 KILOMETERS
V.E. 2:1
N
1
2
3
DEPTH, IN KILOMETERS
0
2
4
6
8
10
B.PLEIS
B. PLIO
BASALT
D
U
E
F
0
2
4
6
DEPTH, IN KILOMETERS
0
2
4
E
F
0
2
4

Figure 25.

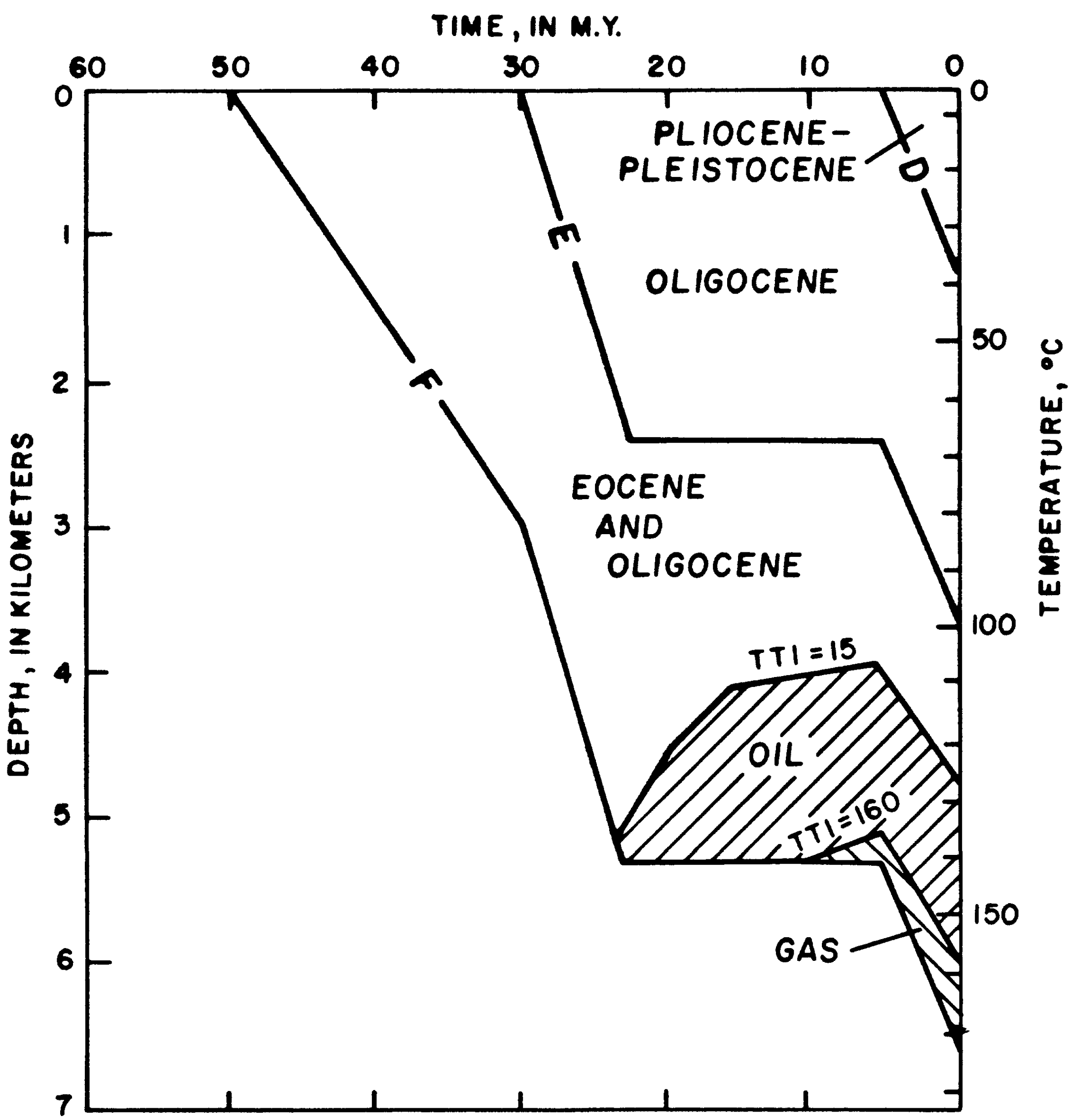
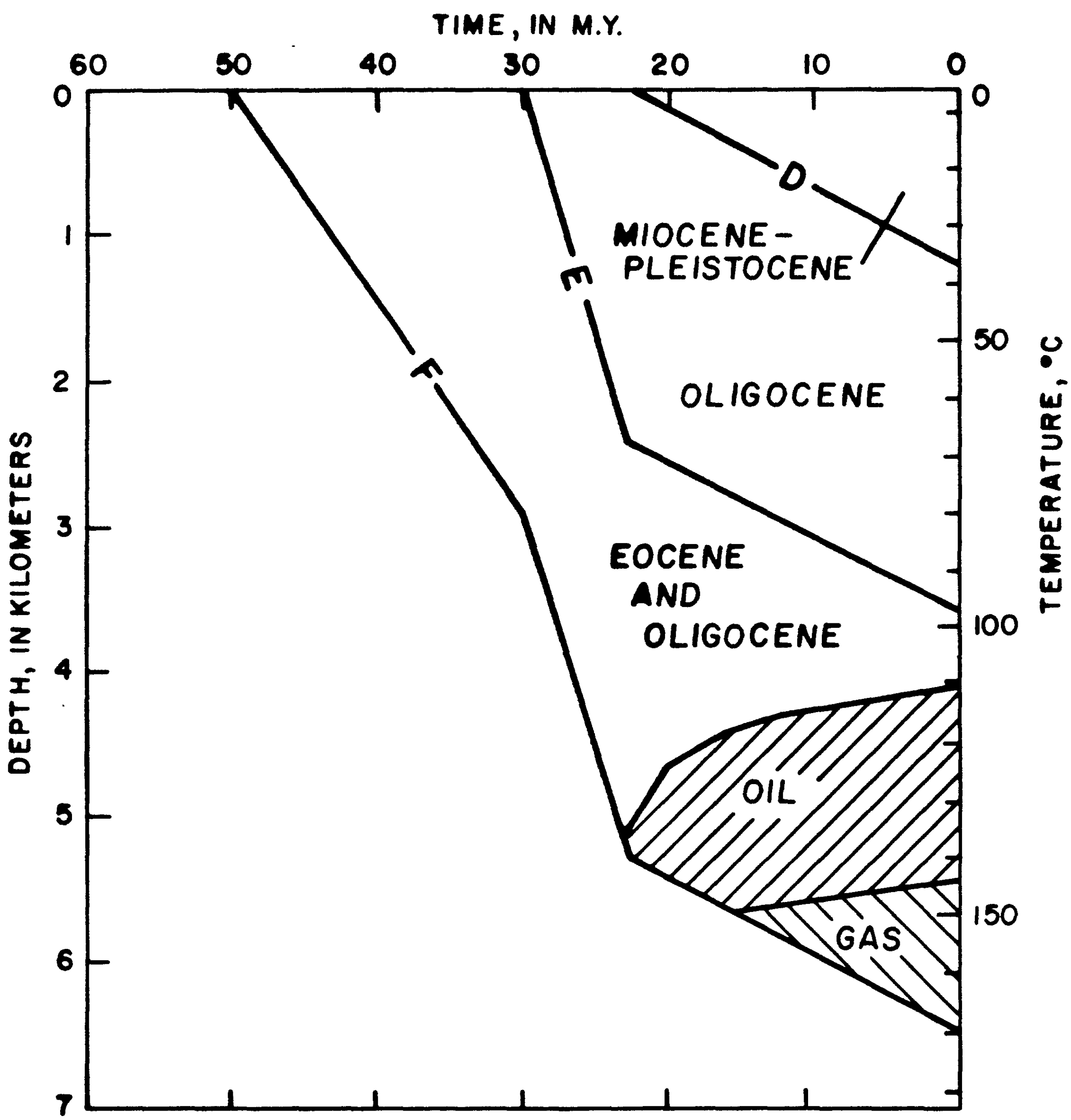

TIME, IN M.Y.
60
50
40
30
20
10
0
DEPTH, IN KILOMETERS
0
1
2
3
4
5
6
7
TEMPERATURE, °C
0
50
100
150
PLIOCENE-
PLEISTOCENE
D
E
F
OLIGOCENE
EOCENE
AND
OLIGOCENE
TTI = 15
OIL
TTI = 160
GAS

Figure 26a.



TIME, IN M.Y.
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
DEPTH, IN KILOMETERS
0
50
100
150
TEMPERATURE, °C
D
E
F
MIOCENE-
PLEISTOCENE
OLIGOCENE
EOCENE
AND
OLIGOCENE
OIL
GAS


Figure 26b.

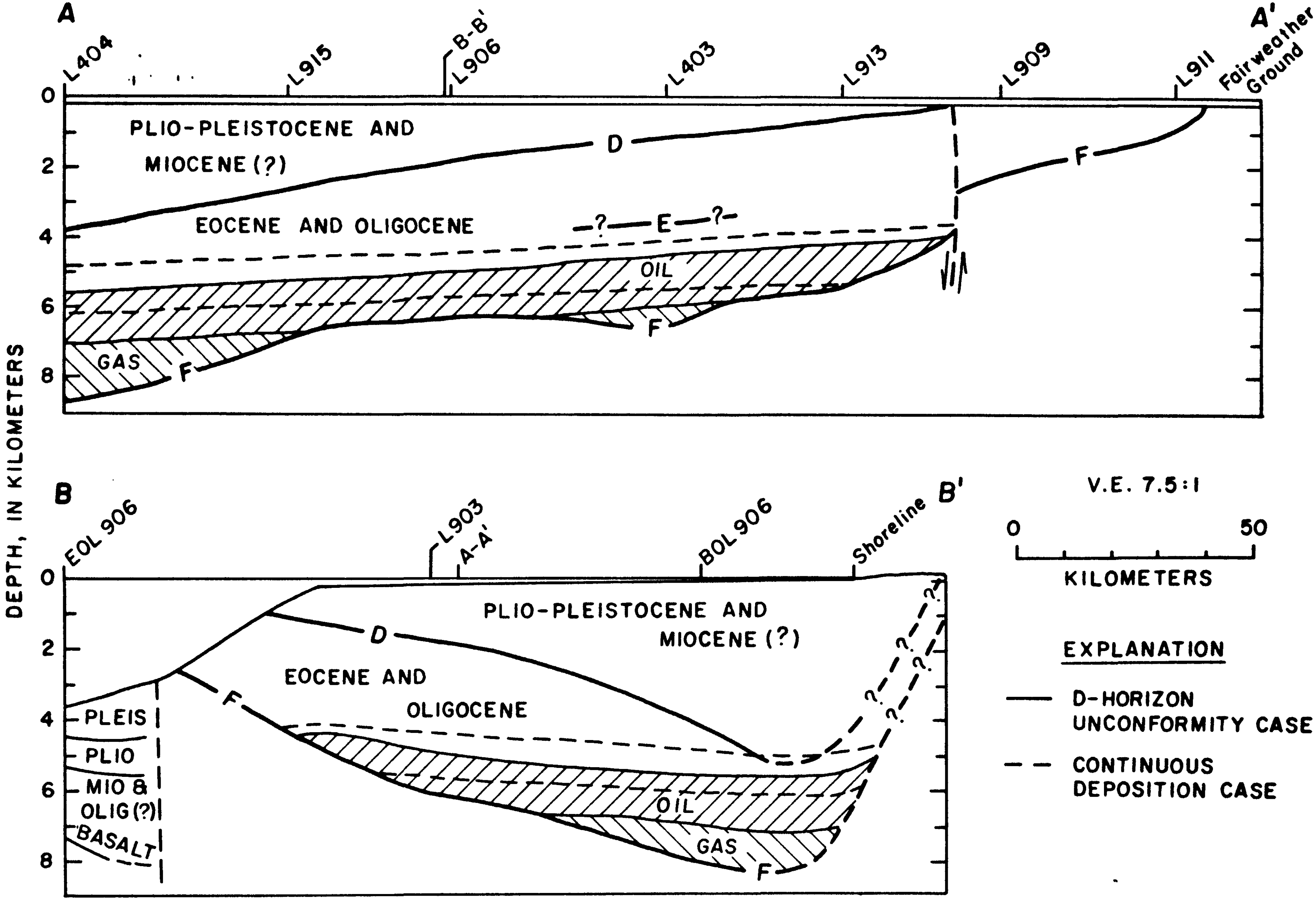

A
A'
L404
L915
B-B'
L906
L403
L913
L909
L911
Fairweather Ground
DEPTH, IN KILOMETERS
0
2
4
6
8
PLIO-PLEISTOCENE AND
MIOCENE (?)
D
F
EOCENE AND OLIGOCENE
?
E
?
OIL
GAS
B
B'
EOL 906
L903
A-A'
BOL 906
Shoreline
PLIO-PLEISTOCENE AND
MIOCENE (?)
EOCENE AND
OLIGOCENE
PLEIS
PLIO
MIO &
OLIG (?)
BASALT
V.E. 7.5:1
0
50
KILOMETERS
EXPLANATION
D-HORIZON
UNCONFORMITY CASE
CONTINUOUS
DEPOSITION CASE

Figure 27.

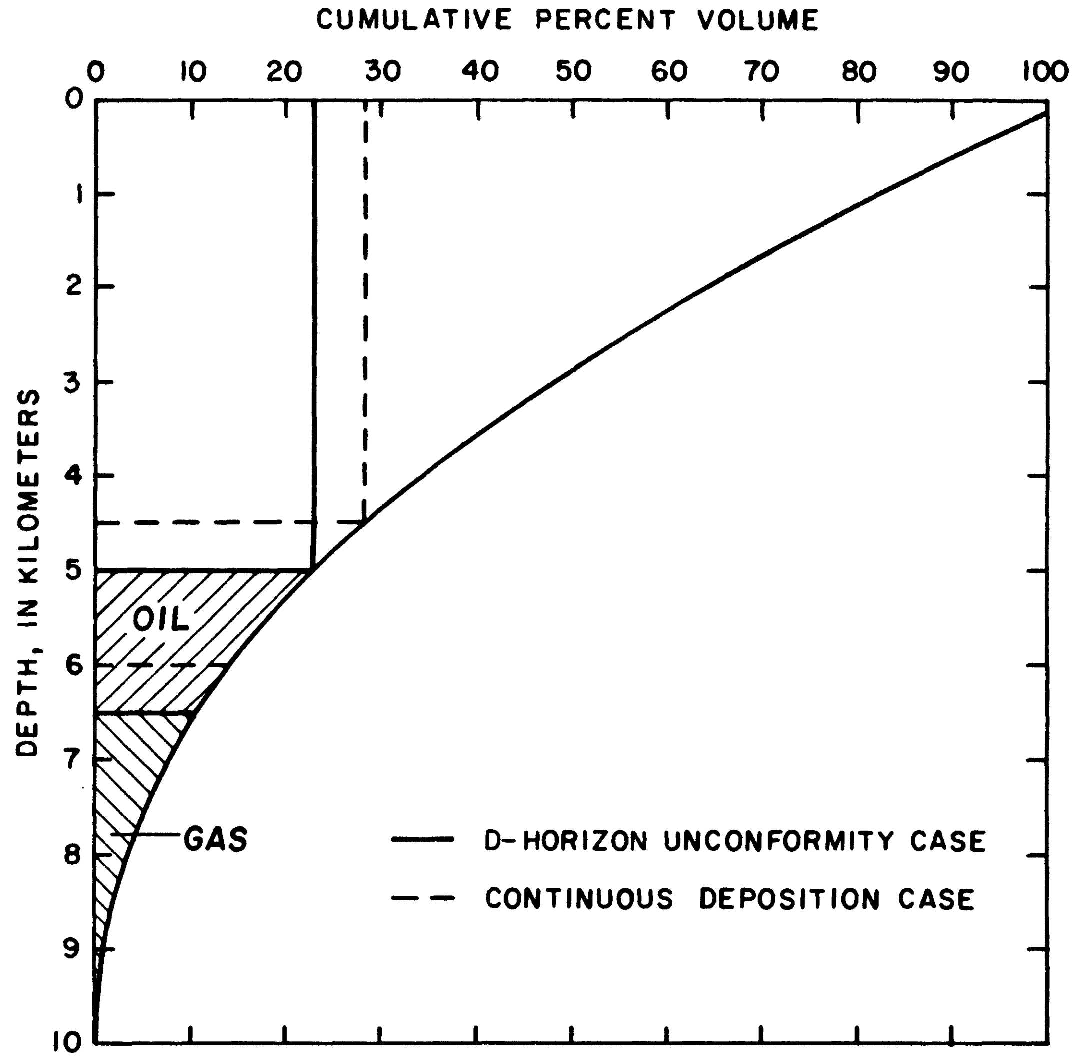

CUMULATIVE PERCENT VOLUME
0
10
20
30
40
50
60
70
80
90
100
DEPTH, IN KILOMETERS
1
2
3
4
5
6
7
8
9
10
OIL
GAS
D-HORIZON UNCONFORMITY CASE
CONTINUOUS DEPOSITION CASE

Figure 28.