A STUDY OF THE WESTERN WASHINGTON-OREGON MARGIN AND ADJACENT JUAN DE FUCA PLATE

Submitted to

Washington Public Power Supply System
Richland, Washington

by

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by

Vern Kulm

1.0 Introduction

The Juan de Fuca plate is being created at the spreading Juan de Fuca Ridge (Vine and Wilison, 1965; Atwater, 1970;) which is situated some 370 km to the west of the Oregon-Washington continental margin (Fig. 1.0). Recent plate motion studies indicate that this young oceanic plate is converging with the North American plate (Oregon-Washington continental margin) (Riddihough, 1977). Oblique subduction has characterized the relative motion between these two plates with the convergence direction remaining between N 35°E and N 50°E for the last 9 my. The convergence rates decreased from 5.5 cm/yr at 8.5 my ago to 4.5 cm/yr at 4.5 my and then decreased rapidly to 3.4 cm/yr for the past 4.0 my. The subduction rate orthogonal to the Washington margin shows a decrease from 4.9 cm.yr at 6.5 my to 3.2 cm/yr during the past 1.0 my (Riddihough, 1977).

The Juan de Fuca plate exhibits a rather thick sediment cover, which is composed primarily of terrigenous material derived from the adjacent landmass. A thick sedimentary wedge occurs at the base of the continental slope in an elongate depression that normally marks the position of an oceanic trench. Two large submarine fans (Fig. 1.0) fill this depression precluding the formation of a topographic trench.

1.1 Definition of the Task

Existing data for the continental slopes of Washington and Oregon are to be examined for evidence of Quaternary faulting and other deformation. This work will principally examine the morphologic and structural data off Oregon and Washington and where possible, compare these observed features with existing data on the morphology and structure along active and inactive segments of other major subduction zones. The information is intended for use in evaluating seismic hazards along the Juan de Fuca subduction zone in western Washington.

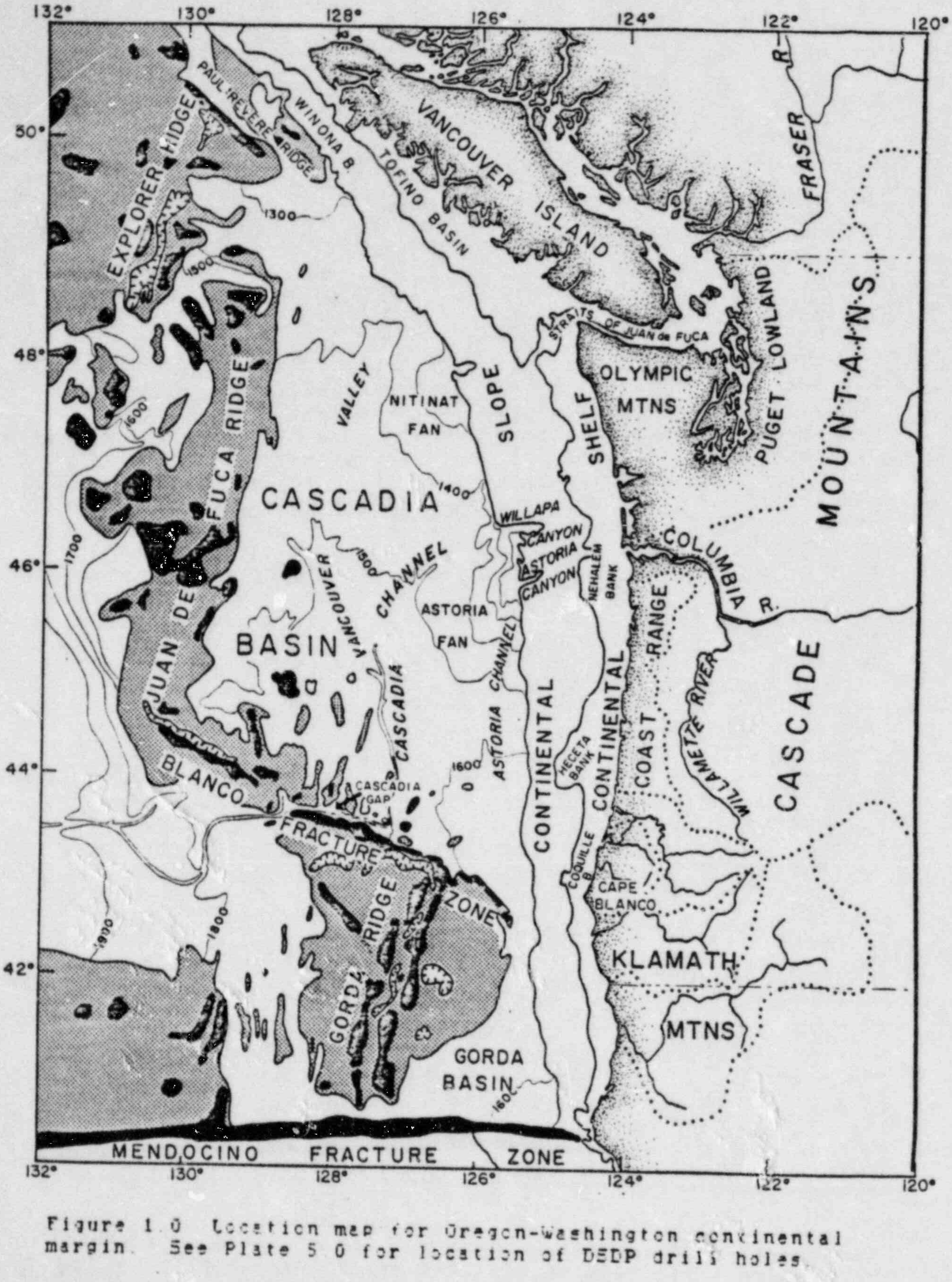


Figure 1.0 Location map for Oregon-Washington continental margin. See Plate 5.0 for location of DSDP drill holes.

1.2 Methods

Most marterials used in this report were obtained from the published literature in journals or from Masters and PhD theses available at various academic institutional libraries. The specific use of these materials is described and documented in the following sections of the report. The methods of analysis are also indicated in each section of this report. Copies of the original single channel seismic reflection records were used in a number of cases and these records are available to the general public in various oceanographic archieves. Most of these records have been published as line drawings by numerous authors. The author of this report made line drawings of a number of these original records and these drawings are his interpretation of the original records.

1.3 Final Report

This document is the Final Report of Vern Kulm, consultant, and it is being submitted to the Washington Public Power Supply System (WPPSS) on the work entitled "A Study of the Western Washington-Oregon Margin and Adjacent Juan de Fuca Plate". Six copies of the Final Report are being submitted to Mr. Ronald A. Chitwood, Techinical Representive of the Washington Public Power Supply System, Richland, Washington.

This study was conducted under WPPSS Contract C-20032 to Vern Kulm, consultant to WPPSS.

2.0 Morphology and Physiography

The morphology of the Oregon-Washington continental shelf and slope has been studied by a number of investigators during the past two decades. A variety of bathymetric maps has been produced from precision depth records (PDR) generated by academic investigators and Federal mapping agenices (eg: Oregon--Byrne, 1962, 1963a, 1963b; Maloney 1965; Carlson 1968; Spigai 1971; Kulm and Fowler, 1974; and Washington --Barnard, 1973, 1978). Most of the positioning was done with the aid of Loran A navigation. The bathymetric maps used in this study for Oregon are maps of ESSA (C&GS, 1968), U.S. Geological Survey Open File Map 81-443 (Plate 2.0); and for Washington the same open file map and the map compiled from Barnard (1973, 1978; Plate 2.1), which is the most detailed map published of the Washington margin. The most recent, non-classified, detailed bathymetric data obtained on the slope is the SEABEAM data (swath mapping multibeam bathymetry) acquired by the oceanographic vessel SURVEYOR of the National Ocean Survey, National Ocean and Atmospheric Administration in a joint NOAA-Oregon State University study of the central Oregon continental slope and southern Washington continental slope in 1981 and 1982, respectively. These data are not yet available in the published literature.

All of the aforementioned published data were used to construct the physiographic and morphologic maps presented in this report (Plates 2.2 and 2.3, respectively).

2.1 Continental Shelf

The combined width of the continental shelf and slope off Oregon and Washington ranges from about 75 km off southern Oregon to about 135 km off northern Oregon and off portions of Washington (Plates 2.0, 2.2). The shelf varies in width from a minimum of about 17 km off southern Oregon to a maximum of about 70 km off central Oregon; portions of the shelf off northern Oregon and most of Washington are 52 to 60 km in width. The shelf is characterized by its sinuous shape along the shelf-slope break which occurs at a depth ranging from about 145 to 185 m (Plates 2.0, 2.1). Prominent submarine banks, Nehalem, Heceta, and Coquille off Oregon (Plates 2.3), occur near the outer edge of the shelf and may have as much as 75 m of relief. Seismic reflection profiles, bottom photographs, and bottom sampling show that bedrock crops out on these banks (Byrne et al.,1966; Maloney, 1965; Muehlberg, 1971; Kulm and Fowler, 1974). Bedrock also crops out on the inner shelf, especially between Coos Bay and Rouge River (Plate 2.3; Folwer et al., 1971). Similar submarine banks have not been reported on the Washington margin although diapirs containing probable siltstone or mudstone show some relief on the shelf (Snavely et al., 1977).

2.2 Continental Slope

The morphology off the continental slope along Oregon-Washington is quite variable and the slope is most commonly divided into an upper and lower slope region (Plates 2.2, 2.3). Off Oregon the upper slope extends from the shelf break to water depths of about 1500 m. The upper slope (180-900 m) is characterized by benches and low relief hills (Plate 2.3). The largest bench is situated in the north between Cascade Head and Tillamook Bay and is 400 to 600 m deep (Kulm and Fowler, 1974). Another bench is located in the south between Cape Sebastian and the California border and lies between 500 and 700 m; it is a northward extension of the Klamath Plateau found on the upper slope off northern California (Silver, 1971; Spigai, 1971). Steep escarpments frequently occur immediately seaward of the submarine banks described previously indicating a possible structural origin (Plates 2.0, 2.3). Narrow benches, small hills, and valleys characterize the lower slope from the California border to Cascade Head off central Oregon.

The morphology of the lower slope changes dramatically from a region of relatively steep escarpments off southern and south central Oregon to prominent elongate north-northwest trending ridges and intervening basins that commence at about 44°30'N off central Oregon and extend northward along the entire length of the lower continental slope off Washington, terminating at about 48°15'N (Plates 2.0, 2.1, 2.2; Fig. 2.0). Off Oregon these ridges are 10-75 km long with as much as 1150 m of relief and the floors of the basins lie at water depths of from 2000 to 2165 m. With some exceptions, these ridges are rather symmetrical.

Off Oregon two prominent submarine canyons head at the outer edge of the shelf and meander through the slope topography to the abyssal plain. Astoria Canyon is situated off the Columbia River and connects with Astoria Fan, a large submarine fan, at the base of the slope (Plates 2.0, 2.2). The Rouge Canyon lies to north of the Rogue River and terminates at the base of the slope with no apparent relation to the adjacent abyssal plain.

Off Washington the upper slope extends from the shelf break to a water depth of about 1500 m (Barnard, 1973, 1978) as it does off Oregon; it is about 25-35 km wide between the eight submarine canyons that cut the continenal slope (Plates 2.0, 2.1, 2.2). Most canyons are located near major rivers but only Juan de Fuca Canyon extends across the continental shelf to the shoreline as a morphological feature. Unpublished seismic reflection records on the continental shelf show that the few canyons surveyed were connected to the rivers during lower sea level as evidenced by the cut and filled channels on the shelf. Small hills or ridges occur randomly over the upper slope. The upper slope either descends gently westward from the shelf break to the lower slope or it is interruped by relatively short plateau-like features before descending to the lower slope (Fig. 2.0, Plates 2.0, 2.1; Barnard, 1978).

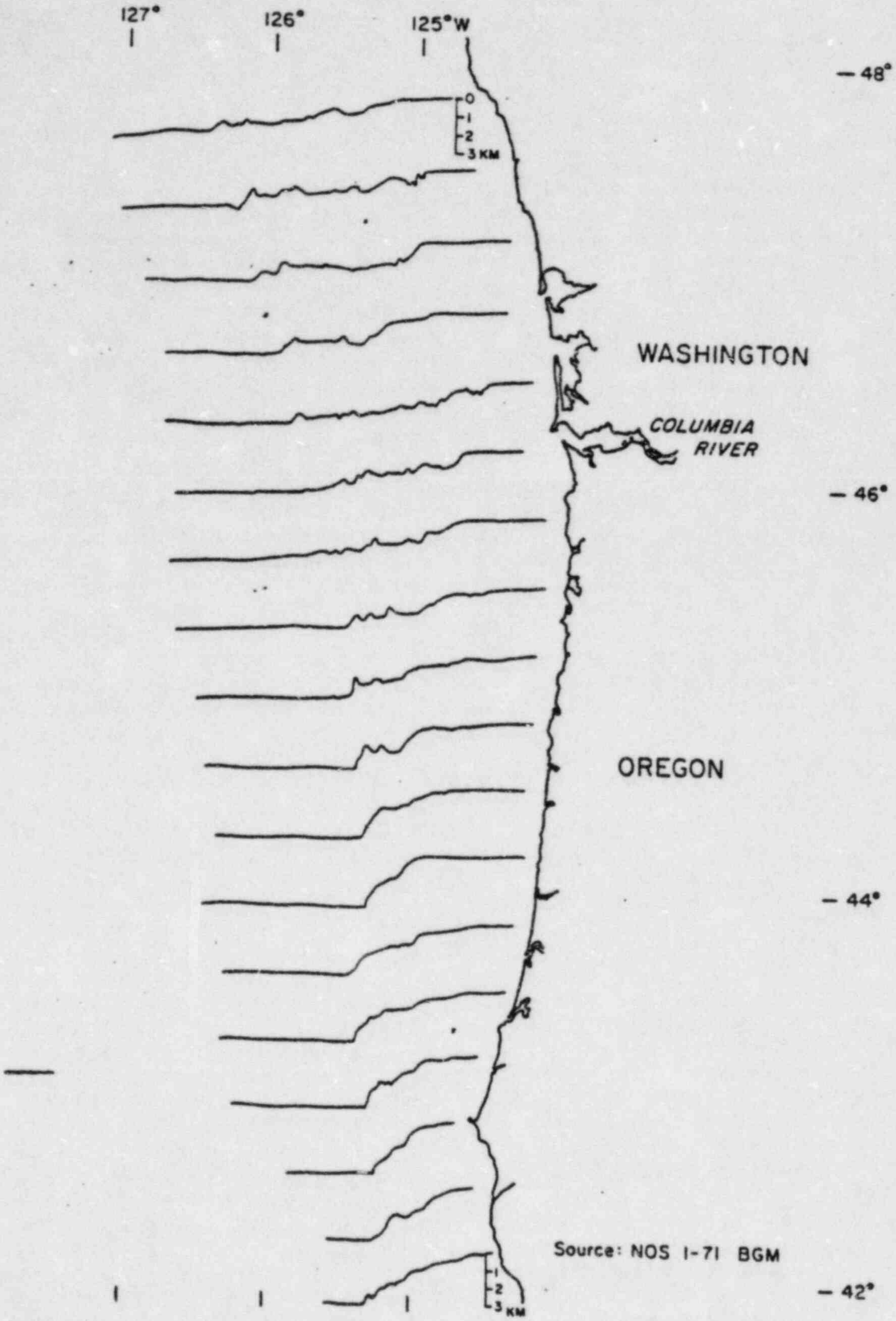


Figure 2.0 Bathymetry of the Oregon-Washington continental shelf and slope and adjacent Cascadia Basin. Note ridge and basin province off northern Oregon and Washington (see Plate 2.3).

The upper slope merges into the lower slope at depths ranging from 1400 to 1800 m (Plates 2.0, 2.1). The lower slope is referred to as the borderland by Barnard (1973,1978), but this term will not be used in this report because of it common association with structural features in other areas of the world that are of dissimilar origin to those described for the Oregon-Washington margin. As was noted off northern Oregon, several elongate north-northwest trending ridges with low gradient intervening basins characterize the lower continental slope (Plate 2.3; Fig. 2.0). These ridges rise from less than 100 m to about 800 m above the surrounding basin floor; they are, in general, lower relief features than they are off Oregon (Plate 2.0). These ridges appear to range in length from a few kilometers to less than 40 km based upon the most recent bathymetric map published to date (Plate 2.1; Barnard, 1973, 1978). This basin and ridge morphology is about 40-45 km wide from just south of Astoria Canyon northward to the vicinity of Grays Canyon; it increases in width to about 60 km north of Quinault Canyon and gradually narrows until it terminates near 48°15'N (Plate 2.3; Barnard, 1978). This basin and ridge morphology extends over a total distance of about 410 km off Oregon-Washington. Barnard (1973,1978) defines three and possibly six semi-continuous ridges with flank slopes of 8 degrees to 30 degrees. The best developed ridge and apparently continuous ridge lies between Willapa and Juan de Fuca canyons and is named the Quinault Ridge (Plates 2.2, 2.3).

2.3 Cascadia Basin

The lower continental slope merges with Cascadia Basin as a smooth gradient where the sediments of the submarine canyons are transport by turbidity currents through the ridge and basin topography of the lower slope. Between the canyons, especially off Washington, the crest of the outermost ridge drops 400-700 m into Cascadia Basin with a gentle gradient where asymmetric ridges torm the interface or more abruptly where the ridge is more symmetrical (Plate 2.1; Fig. 2.0). The lower slope basin floor is situated about 700 m above the general level of Cascadia Basin off Washington; whereas, the lower slope basin floor off northern Oregon lies only about 200 to 400 m above the Basin, possibly reflecting a higher rate of sedimentation off Washington because of the numerous submarine canyons that act as avenues of sediment dispersal. Cascadia Basin forms an abrupt interface with the lower slope off southern and south central Oregon where the slope is characterized by relatively steep escarpments.

Two submarine fans, Nitinat and Astoria, produce large convex features that rise several hundred meters above the the regional depth of Cascadia Basin (Plates 2.0, 2.2, 2.3). These fans are characterized by one major fan channel and several minor channels originating from the apex of the fan (Nelson, 1968). Well-developed leeves characterize the main channel which may have as much as 300 m of relief. A small channel frequently occurs at the base of the continental slope.

3.0 Structure and Stratigraphy

A structure map was compiled for the Oregon and Washington continental shelf and slope (Plate 3.0, see also Plate 3.1 for selected tracklines of figures) using existing structure maps and seismic reflection records presented collectively in various publications such as Johnson, et al., 1983, 1983a; McClain and Peper, 1983; Snavely et al., 1982; Snavely et al., 1980; Seely, 1977; Carson 1977; Snavely et al., 1977; Carson et al., 1974; Seely et al., 1974; Barnard, 1973 and 1978; Kulm and Fowler, 1974; Silver, 1972; Spigai, 1971; Muehlberg, 1971; Fowler, et al., 1971. Some additional unpublished structural data were compiled from seismic reflection records obtained from oceanographic archives. The major anticlinal and synclinal fold axes for the continental shelf and slope are shown on the map (Plate 3.0). Small synclinal basins frequently occur between the anticlines on the slope, but they are not shown on this map. Faults are indicated on the map with the downthrown side indicated by the hatchured line. Seismic reflection records, mainly single channel and a few multichannel seismic records, were used by all previous investigators and the author of this report to determine the structure of the continental margin. In some cases the biostratigraphy and paleodepths of the sedimentary rocks were used to determine the occurrence of faults, especially in complex terrains, and the direction of throw on the faults.

Criteria for the recognition of faults in the seismic records include the offset of reflectors, termination of horizontal reflectors at steep dips, diffractions from point sources and other crtieria commonly used in such analysis.

3.1 Structure of the Continental Shelf and Upper Slope

Several sedimentary basins with several thousand meters of sediment occur on the continental shelf and upper continental slope off Oregon and Washington (Connard et al., 1983; Snavely et al., 1980; Braislin et al., 1971). Broad folds characterize the late Cenozoic structures in these basins in many areas (Plates 3.0, 3.2; Figs. 3.11, 3.12, 3.13). However, the Upper Miocene to Pliocene strata may be intruded by shale diapirs, particularly off Washington, which produce antiformal dips in the young strata (Fig. 3.14; Snavely et al., 1977) or they may be tightly folded into steeply dipping anticlines (particularly off Oregon) that are truncated at the seafloor (Fig 3.15, Sp-106; Kulm and Fowler, 1974; MacKay, 1969). The fold axes of the outer continental shelf and uppermost continental slope roughly parallel the north-northwest trending ridges that comprise the ridge and basin province found off northern Oregon and Washington and the trend of the continental slope-Cascadia Basin interface (Plates 2.3, 3.0, 3.2). Fold trends of these Upper Miocene and Pliocene strata on the inner continental shelf from south central Oregon to northern Washington more closely approximate the trends of the older Cenozoic strata as seen in the maps complied by Johnson et al., (1983, 1983a) and Snavely et al., (1977). Off southern Oregon some of these same strata have a similar trend to those found to the north, but other strata strike in an east-west direction which may reflect the structural trends of older Cenozoic and possibly Mesozoic strata (Plate 3.0 and as seen in the maps of Johnson et al., 1983, 1983a and inferred by the data of Kulm and Folwer, 1974; Fowler et al., 1971; Spigai, 1971). The most continuous structural feature on the continental is a sinuous, 300 km-long syncline which occupies the inner continental shelf off central to northern Oregon and southernmost Washington (Plate 3.0); subsidence of the inner shelf is indicated by the several subsurface angular unconformities separating the various synclinal basins.

The Oregon continental shelf is characterized folded and faulted structures, the most prominent of which occur in the vicinity of the submarine banks (Nehalem, Heceata, and Coquille Bank) along the outer edge of the shelf (Fig. 3.15; Plate 2.3). Pleistocene to pre-Miocene strata are exposed on these banks with the oldest known sediment occurring on the upthrown side of faults in the vicinity of Heceta Bank. A large positive free-air gravity occurs beneath Heceta Bank indicating a mass excess (Kulm and Fowler, 1974) which is believed to be Middle to Lower Eocene volcanics underlying this portion of the continental shelf and the adjacent Coast Range (Snavely et al., 1980; Seely et al., 1974; Braislin et al., 1971).

A series of interconnecting shallow synclines occurs between the shoreline and the outer shelf banks off southernmost Washington and northern and central Oregon (Kulm and Fowler,

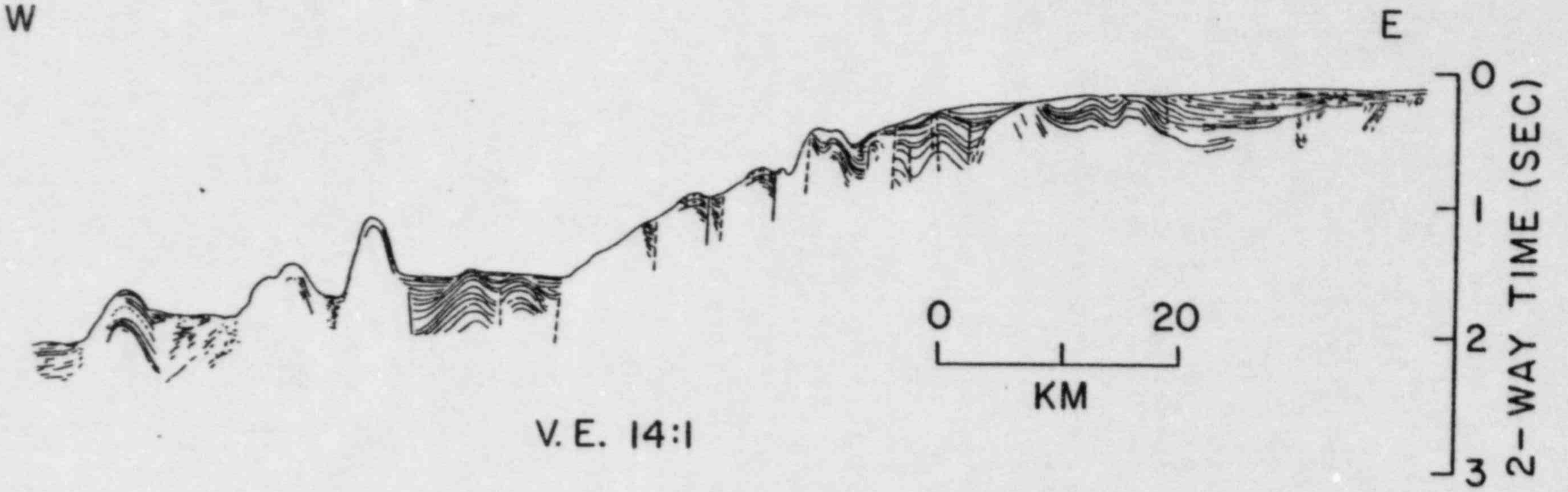


Figure 3.11. Line drawing of seismic reflection profile (Sp-104) of northern Oregon continental shelf and slope. See Plate 3.1 for location.

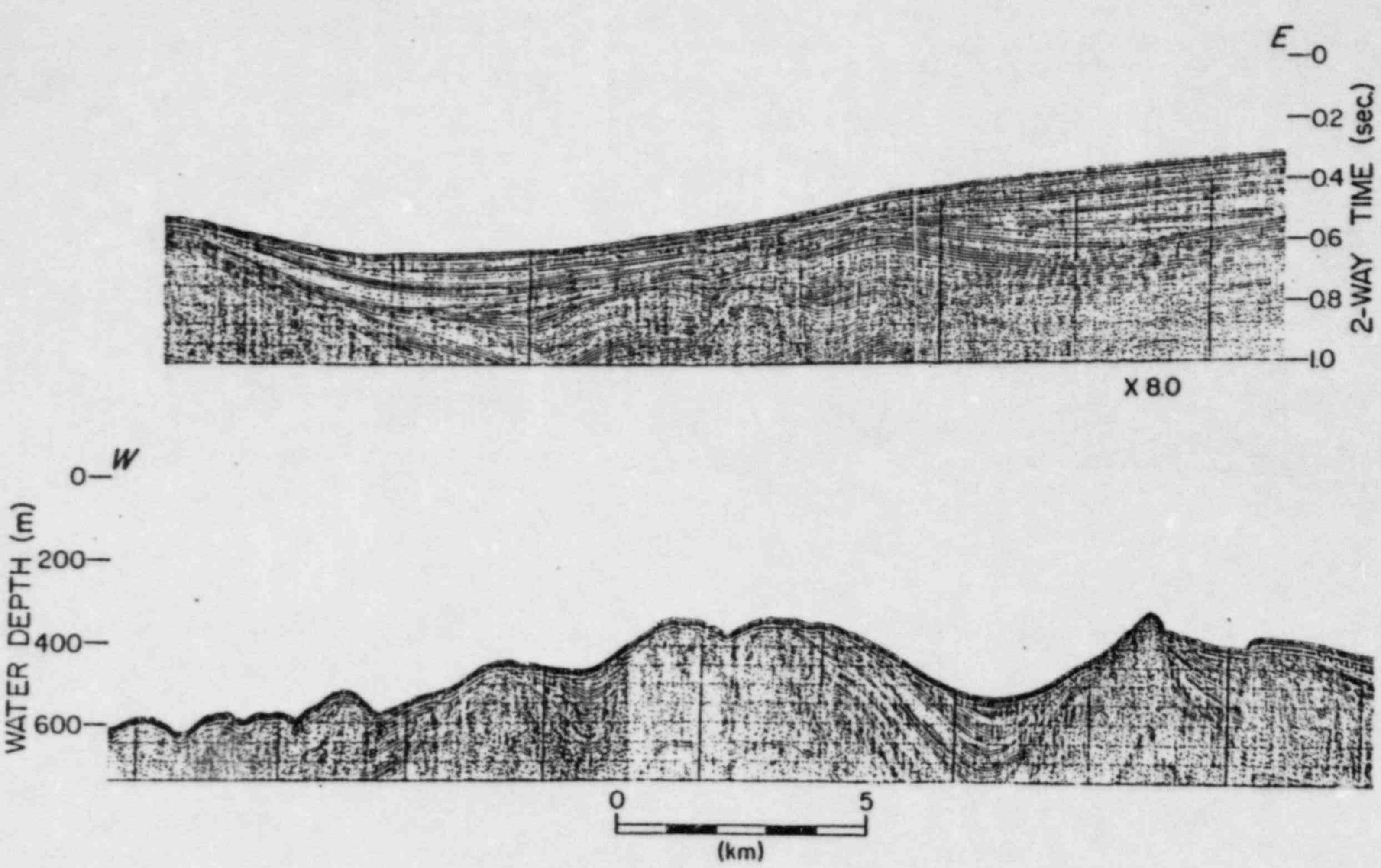


Figure 3.12. Single channel seismic reflection record (Sp-56) of outer shelf and upper slope off north central Oregon. Note fold structures and migrating depocenters in basins ponded behind structures. See Plate 3.1 for location.

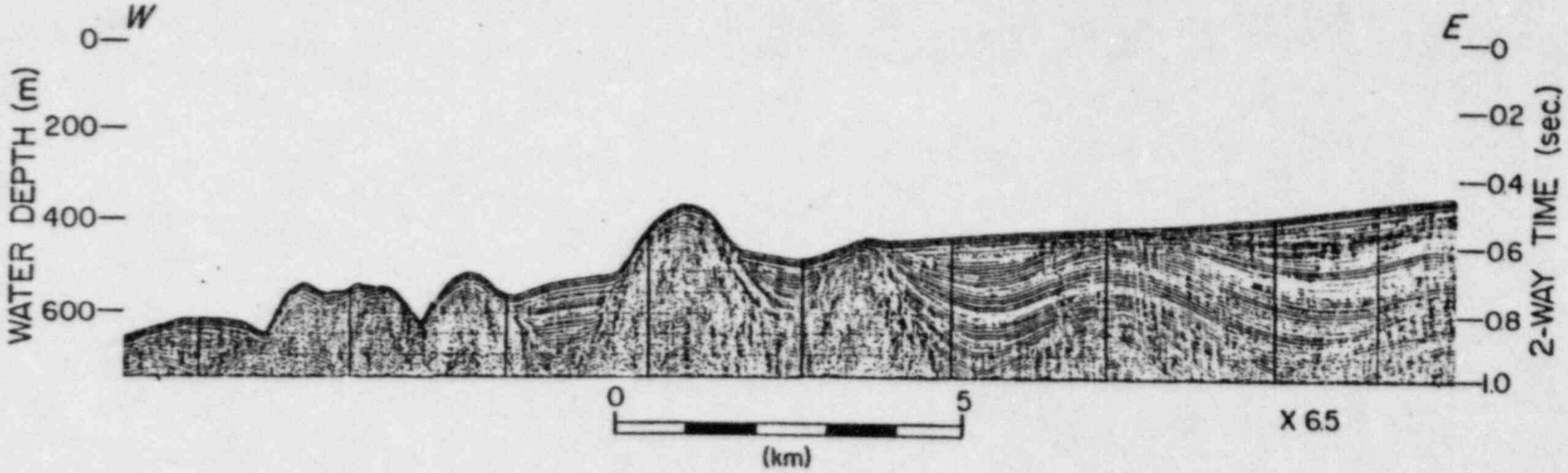


Figure 3.13. Single channel seismic reflection record (Sp-54) of the upper continental slope off central Oregon showing fold structures and ponded basins. See Plate 3.1 for location.

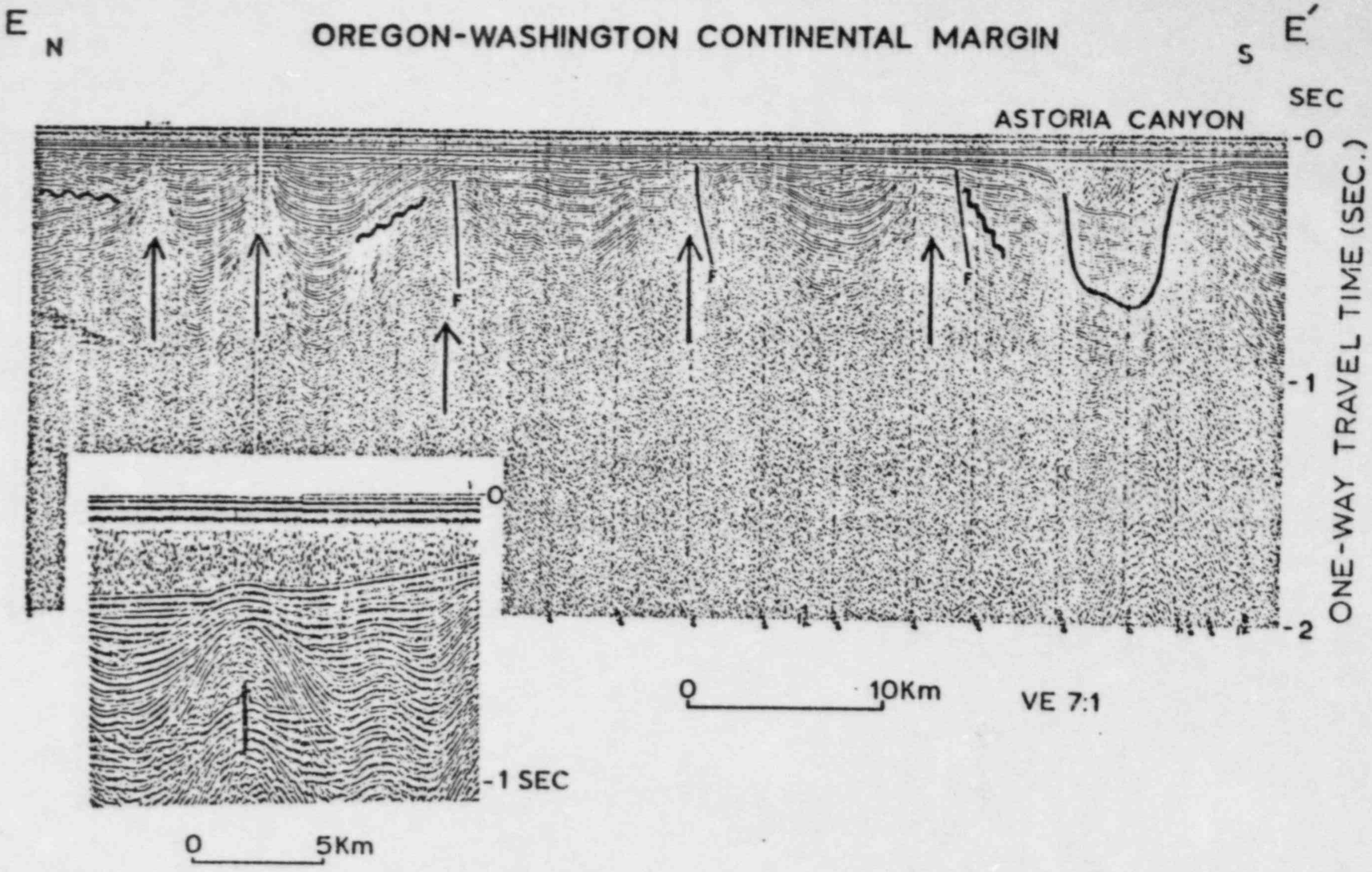


Figure 3.14. Siltstone diapirs on the inner shelf off southern Washington. Note growth faults (F) and local unconformities on flanks of diapirs. Insert shows warping of seafloor above diapir. See Plate 3.1 for location of section E-E´. (From Snavely et al., 1977).

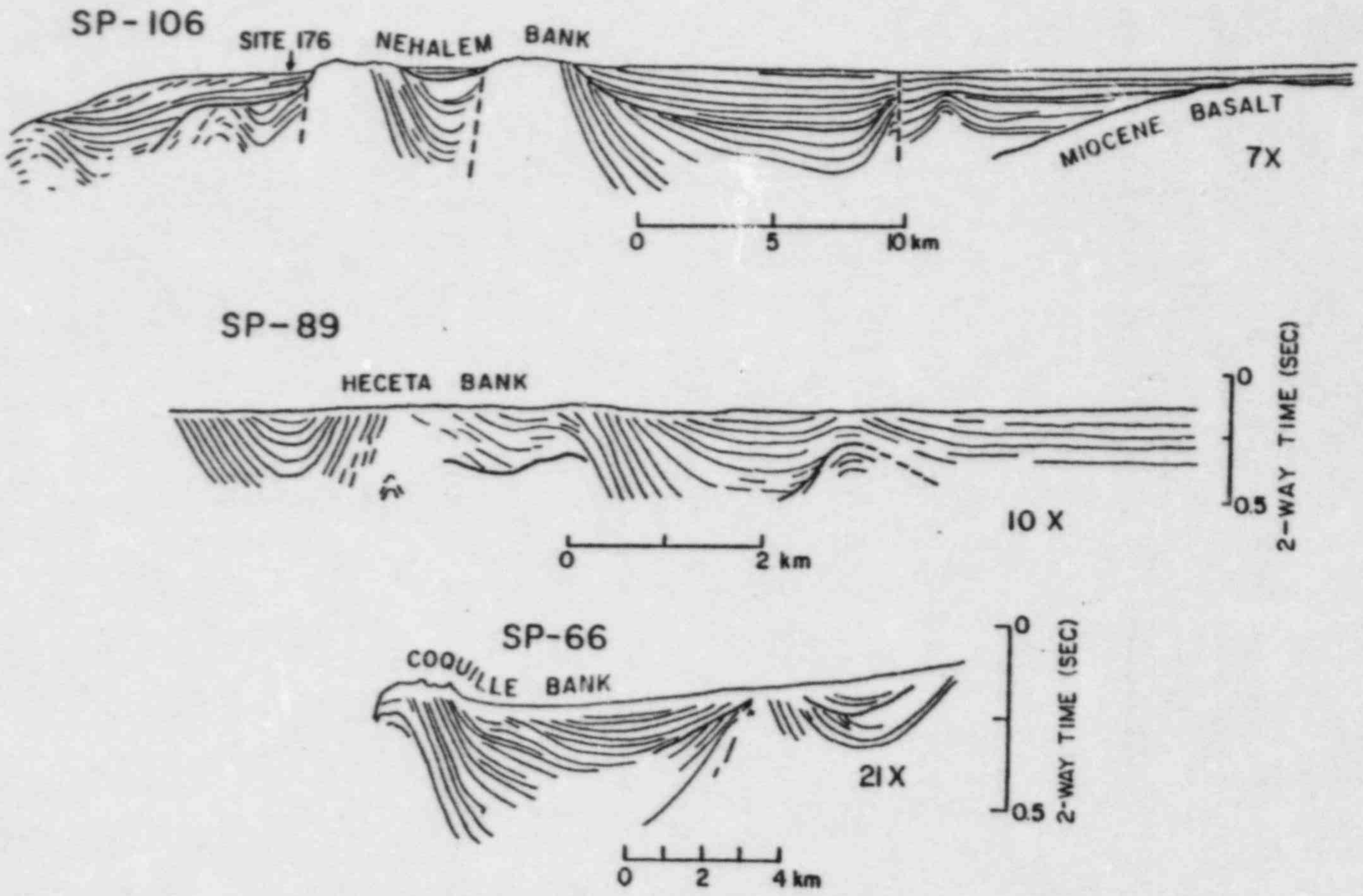


Figure 3.15. Line drawings of seismic reflection records made over submarine banks on the outer continental shelf off Oregon (modified from Kulm and Fowler, 1974). See Plate 3.1 for location. Note DSDP Site 176 was drilled on the seaward flank of the Nehalem Bank. Miocene basalt is extrapolated from outcrops onshore.

1974). Angular unconformities frequently separate these synclinal sediments at depth indicating a history of uplift and subareal erosion. The largest and most recent syncline forms a broad basin and is centered off Cascade Head (Plate 3.0; Fig. 3.12). Subsurface folds along the seaward limb of the syncline serve as a structural barrier to the seaward bottom transport of sediment; the sediments are ponded behind and overlap these subsurface folds (Figs. 3.13). The folds may rise to the surface on the upper continental slope where the sediment ponds are not yet filled (Fig. 3.13). The youngest synclines involve Pleistocene sediments that nearly everywhere overlie older units unconformably. The synclines are generally best developed in the offshore regions where thick late Paleogene and early Neogene sections occur on land and trend offshore (Kulm and Fowler, 1974).

Off southern Oregon, between Coos Bay and Cape Sebastian, the inner shelf consists of intensely folded and fautlted sedimentary strata (Kulm and Fowler, 1974; Mackay, 1969; Bales and Kulm, 1969). Most of these older structures have been truncated and covered by a thin veneer of Pleistocene sediment which occurs in basin lows or in downfaulted blocks between Coos Bay and Cape Blanco. However, the Pleistocene sediments occur in a shallow basin and are essentially undeformed between the Rogue River and the California border. South of the Rogue River the north-northwest trending structures change their strike to a roughly east-west trend (Plate 3.0), possibly reflecting the orientation of the deeper Mesozoic strata found in the coastal and nearshore region (Hunter et al., 1970).

Submarine banks off Oregon record some of the most recent tectonic movements along the continental shelf because the banks can be sampled to determine the ages of the sedimentary deposits comprising the folded and faulted structures. Anticlinal folds have developed in the Pliocene siltstone and claystone that underlie Nehalem Bank (Plates 2.3, 3.0; Fig. 3.15, Sp-106) and have been truncated during lower sea level stands of the Pleistocene and subsequently overlapped by the younger Pleistocene deposits (Kulm and Fowler, 1974). Linear trends in the bathymetry, structures seen in seismic reflection records, and fanual stratigraphy indicate that this bank is a fault controlled feature with the western flank of the bank being downthrown. Deep-sea drilling on the seaward flank of this bank shows that the Pliocene shale recovered below an angular unconformity was originally deposited on the upper continental slope and has since been uplifted at least 500 m, truncated during a former lowering of sea level, and has since subsided more than 100 m (Fig. 3.15, Sp-106; Kulm, von Huene et al.,1973). A similar history is implied for Coquille

Bank which is a north-south trending anticline (Fig. 3.15, Sp-66). A thick section of Pliocene and Pleistocene siltstone and claystone forms its eastern limb but ths section is absent on the western limb; a normal fault is inferred along the straight searward edge of the bank with the downthrown side to the west (Kulm and Fowler, 1974; Mackay, 1969).

Heceta Bank is a structurally complex feature whose strata form steep dips and are offset by faults that are downthrown in an easterly or westerly direction (Fig. 3.15, Sp-89; Kulm and Fowler, 1974; Muehlberg, 1971; Maloney, 1965). The older strata, probably the pre-late Miocene rocks, are more intensely deformed than the younger strata.

The upper continental slope off southern and northern Oregon is frequently characterized by structural benches or plateaus that occur in the vicinity of the Klamath Plateau, Cape Blanco and Cascade Head (Plate 2.3; Kulm and Fowler, 1974; Spigai, 1971). In general the benches are formed by the ponding of sediments behind anticlinal folds (Figs. 3.12, 3.13). The ponded sediments may form a synclinal basin if there has been subsequent or contemporaneous movement of the structures flanking the basin. The depocenters shift either landward or seaward in response to these relative movements (Fig. 3.12). Uplift of the seaward flank is indicated by the landward shift of depositional centers in most basins. The western flank of the Klamath Plateau is believed to be a normal fault downthrown to the west (Plates 2.3, 3.0); Spigai, 1971). Normal faults are also noted especially within the benches located off southern Oregon (Plates 2.3, 3.0).

Off Washington the continental shelf strata are generally broadly folded (Plate 3.2) with angular unconformities present south of 47°N (Grays Harbor), which are similar to those described on the northern Oregon shelf and upper slope, but no unconformities are apparently present on the shelf north of 47° N (Silver, 1972; Barnard, 1978). The upper continental slope between Astoria and Willapa Canyons is tightly folded and displays unconformities, whereas the upper slope north of Willapa Canyon is gently folded with no apparent unconformities (Plate 3.0). Continental shelf strata are intruded by shale/siltstone diapirs which produce antiformal dips in the young strata as shown in figure 3.14 (Snavely et al., 1977). The sea floor may be warped above the diapirs. Growth faults and local angular unconformities are seen in the seismic reflection records of these diapirs. The youngest sediments (Holocene) on the seafloor of the inner continental shelf are offset about 7 m by a fault seen in a high resolution seismic record made just north of Grays Harbor (Fig. 3.16; Snavely et al., 1977). It is not possible to determine the strike or the length of this fault from the single crossing, although the downthrown side apparently lies in a northerly direction.

Uplift and subsidence are inferred from the prominent structures and angular unconformities displayed in the seismic reflection records collected over the continental shelf and upper slope off Oregon and Washington (Figs. 3.11, 3.12). At least two prominent angular unconformities, Pliocene-Pleistocene and middle to late Miocene, are widespread on the Oregon continental shelf (Kulm and Fowler, 1974). The youngest and most widespread of these two unconformities is traced on seismic reflection profiles and occurs beneath most of the Oregon shelf. It probably occurs over the southern Washington shelf (ie: south of 47°N latitude), considering the similarity of structure in this area with that of the northern Oregon shelf and upper slope. Strata punched cored and drilled on the submarine banks were used to date this unconformtiy (Kulm and Fowler, 1974). Significant uplift and erosion occur over the continental shelf during late Pliocene to Pleistocene time; middle to late Pleistocene age (maximum age 1.3 my) unconsolidated sediments overlie uplifted Pliocene shale in the unconformity drilled at DSDP Site 176 on the seaward flank of Nehalem Bank (Fig. 3.15, Sp-106). A significant middle to late Miocene unconformity occurs in an industry dill hole on the central Oregon shelf (Snavely et al., 1980; Kulm and Fowler, 1974; Braislin et al., 1971;) and is detected in seismic reflection records in this area (Muehlberg, 1971).

The youngest of these unconformities occurs between the folded and subsequently Pleistocene strata and the horizontal overlying Holocene strata along the outer continental shelf (Fig. 3.17; Snavely et al., 1977; Kulm and Fowler, 1974).

Uplift of as much 1 km has been reported for the central Oregon shelf and upper slope (Byrne et al., 1966; Kulm and Fowler, 1974); while uplift has occurred on the Washington shelf, the amounts have not been documented. The largest amounts of uplift (900-1000 m) involves the late Miocene and early Piocene strata in the vicinity of Heceta Bank (Plate 2.3; Fig. 3.18). Early to middle Pliocene rocks on Nehalem and Coquille banks have been uplifted as much as 500-600 m while Pleistocene strata show 0-100 m. In contrast, up to 200 m of downwarp of the outer shelf is documented on seaward flanks of Nehalem and Coquille banks and on the upper slope off the Rogue River. The average rates of uplift range from 100 to less than 200 m with the highest rates associated with the older rocks (Fig. 3.19); a rather uniform rate of uplift has occurred over much of the shelf during late Cenozoic time (Kulm and Fowler,

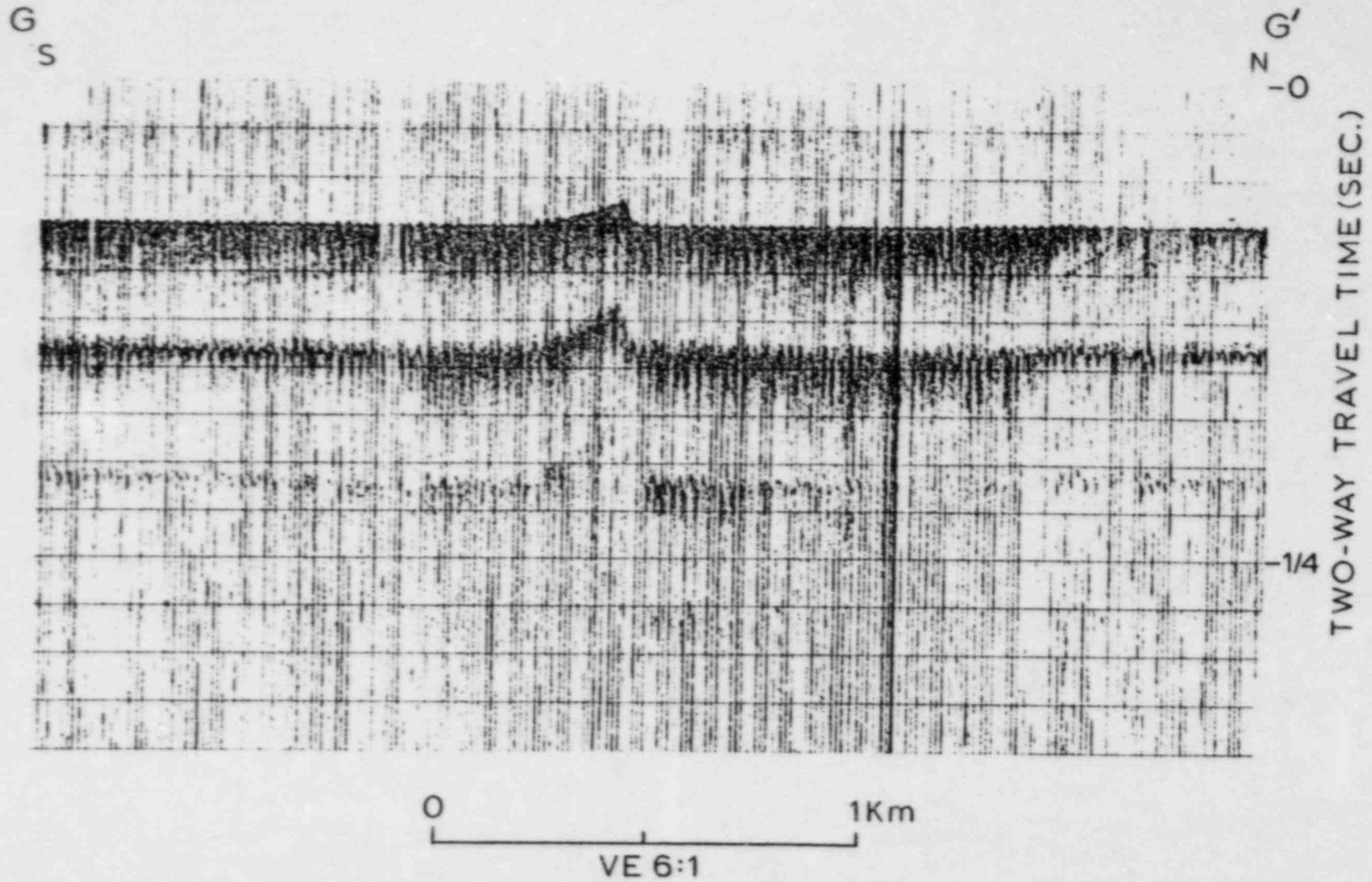


Figure 3.16. High-resolution seismic profile G-G′ showing fault on inner continental shelf off southern Washington. Fault offsets the seafloor sediments about 7 m. See Plate 3.1 for location of profile.

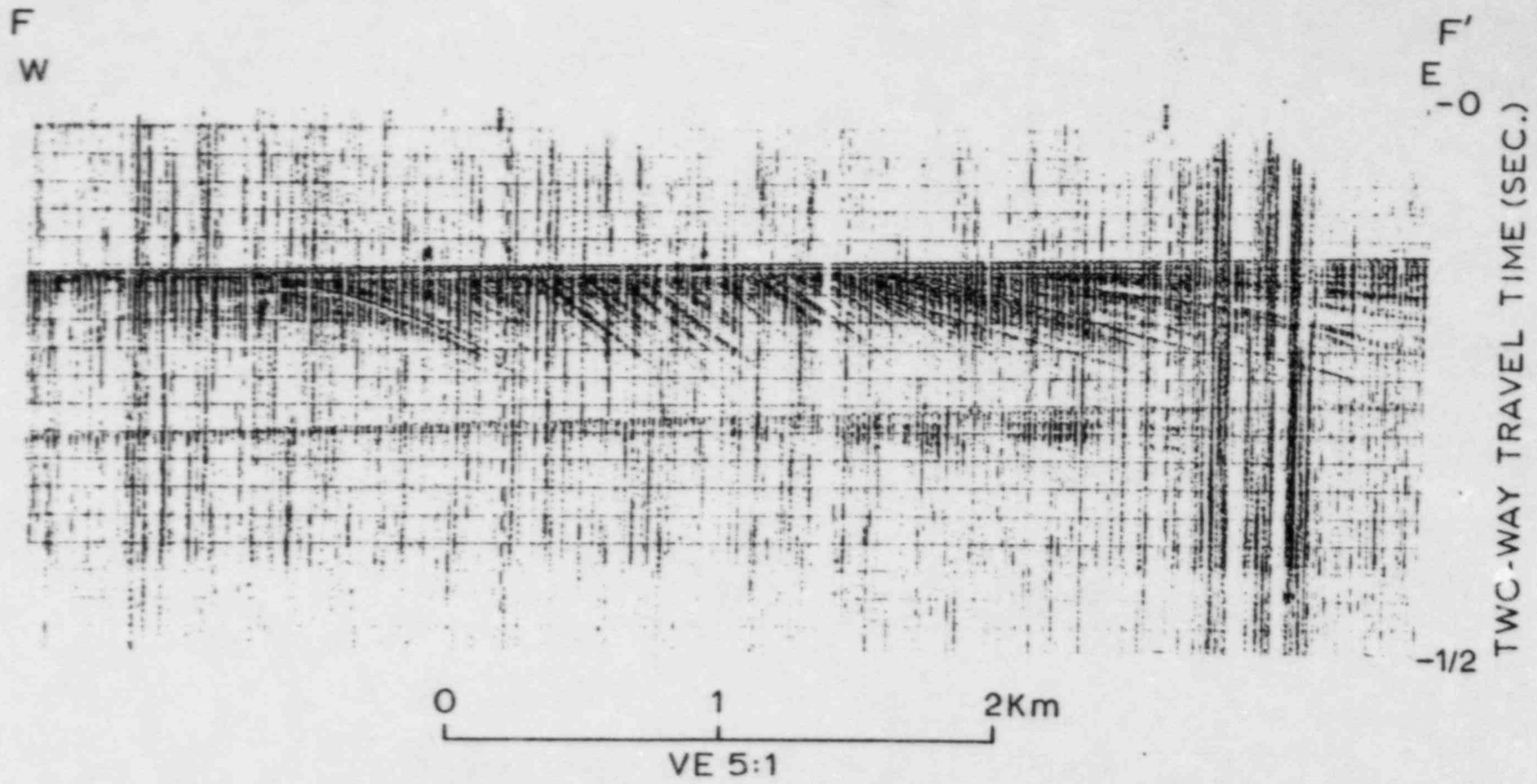


Figure 3.17. High-resolution seismic profile F-F′ showing unconformities in Pleistocene and Holocene strata on the west flank of a broad anticline on the Washington shelf. See Plate 3.1 for location.

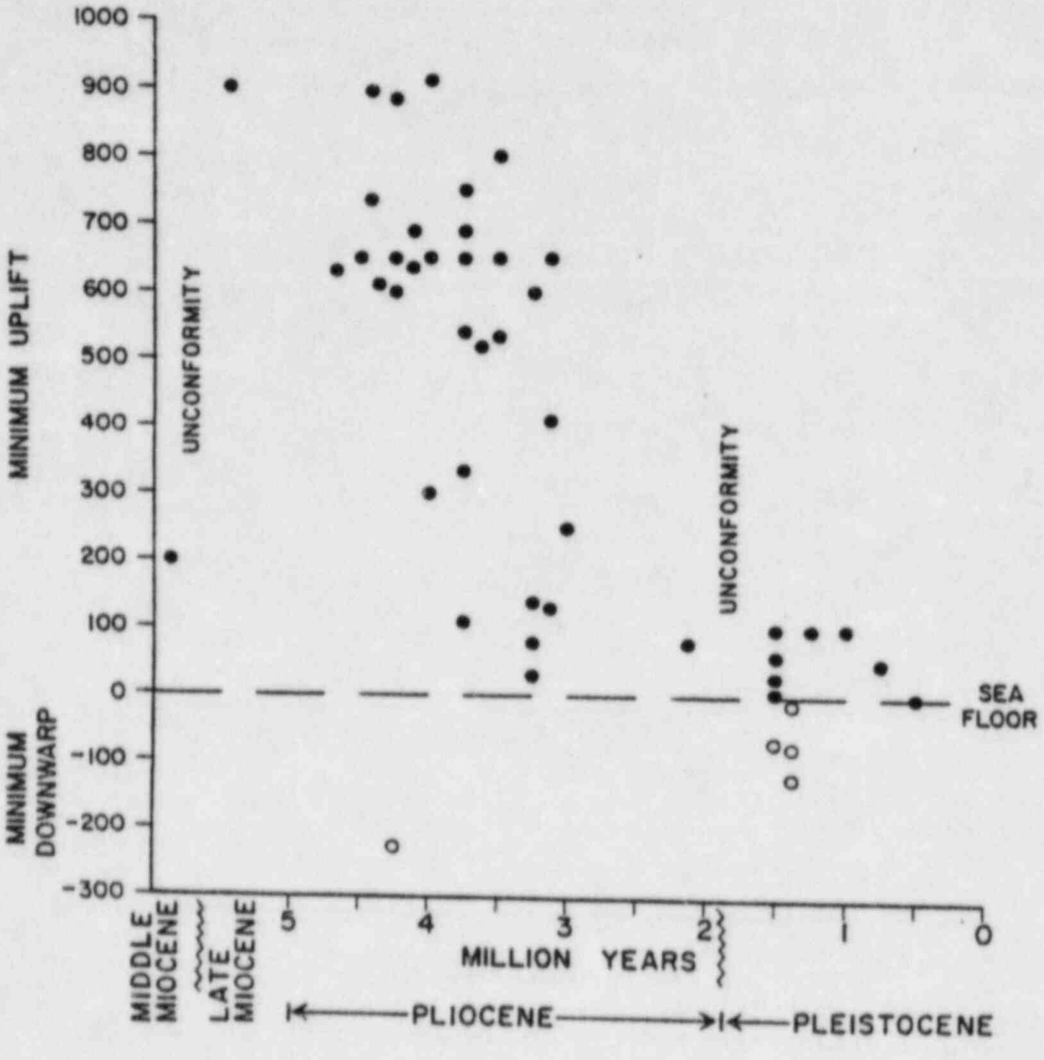


Figure 3.16. Amount of relative tectonic movement in meters on the Oregon margin during late Cenozoic time. Note unconformities in the sections. Subsidence is indicated on seaward flank of submarine banks (Fig. 3.15). Time scale after Berggren (1971). (From Kulm and Fowler, 1974).

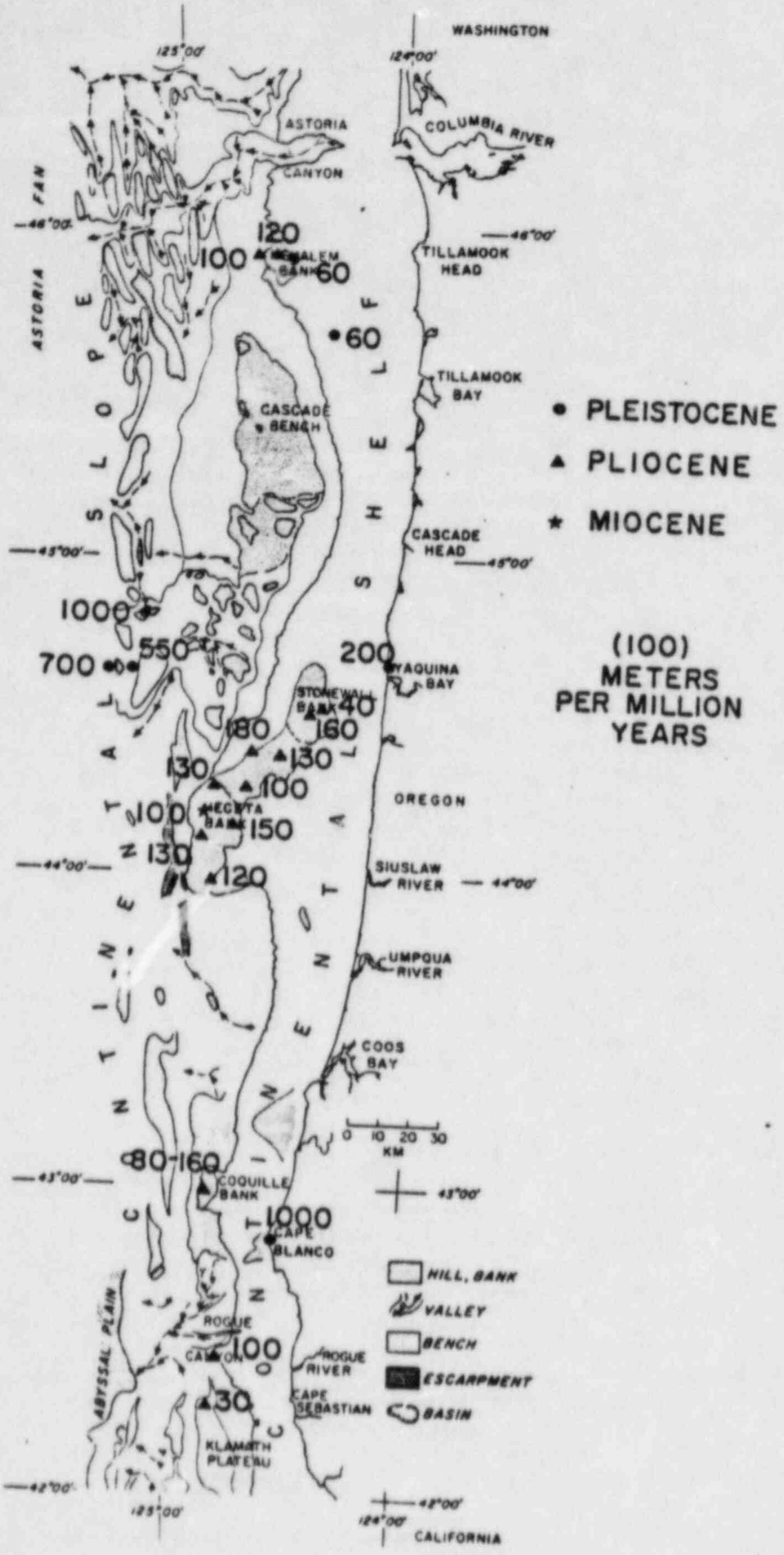


Figure 3.19. Minimum rates of uplift (m/my) on the Oregon continental margin. (From Kulm and Fowler, 1974).

1974).

3.2 Lower Continental Slope and Ridge Structure

Two main types of structural styles, seaward vergence (Fig. 3.22, thrust faults dipping toward the continent) and landward vergence (Fig. 3.23, thrust faults dipping toward the oceanic plate) of sedimentary sequences, are recognized along the lower continental slope off Oregon and Washington (Snavely et al., 1980; Barnard, 1978; Seely, 1977; Seely et al., 1974; Kulm and Fowler, 1974; Carson et al., 1974; Kulm et al., 1973; von Huene and Kulm, 1973; Silver, 1972). These structures are characterized by an underthrust and an overthrust structural framework, respectively. In both cases the clastic terrigenous sediments of the subducting Juan de Fuca plate (Cascadia Basin) are being offscraped to form an accretionary prism, which comprises a large portion of the sedimentary deposits of the continental slope. These accreted deposits are being covered by clastic terrigenous sediments derived from the adjacent continental drainage basins and transported largely by the Columbia River to the shoreline where they are carried to the continental slope and to the Cascadia Basin by suspension through the water column and by turbidity currents originating on the continental slope. Deformation (ie: dewatering, folding, and faulting) of the accretionary prism (ridges) is documented in the basin deposits that overlie the prism (offscraped deposits). These basin deposits are frequently warped in response to the continuning movement of the underlying prism. The depocenters of the basin deposits shift either landward or seaward in response to the relative uplift of the structural ridges that flank of the basins. If the tectonic movements of the prism are of sufficient magnitude, faults may develop within the basin deposits.

The structure of the lower continental slope is often difficult to decipher because of the steep escarpments and the apparent steep dips of the strata. Off southern Oregon the lower slope apparently consists of small-scale, north-south trending anticlinal folds and faults downthrown to the west (Spigai, 1971; Plate 3.0). Silver (1969) has described similar structures off northern California on the lower slope. Off south central and central Oregon little structural information was obtained from the single channel seismic reflection profiles because of the steep escarpments comprising the lower slope.

Multichannel seismic reflection data obtained off central

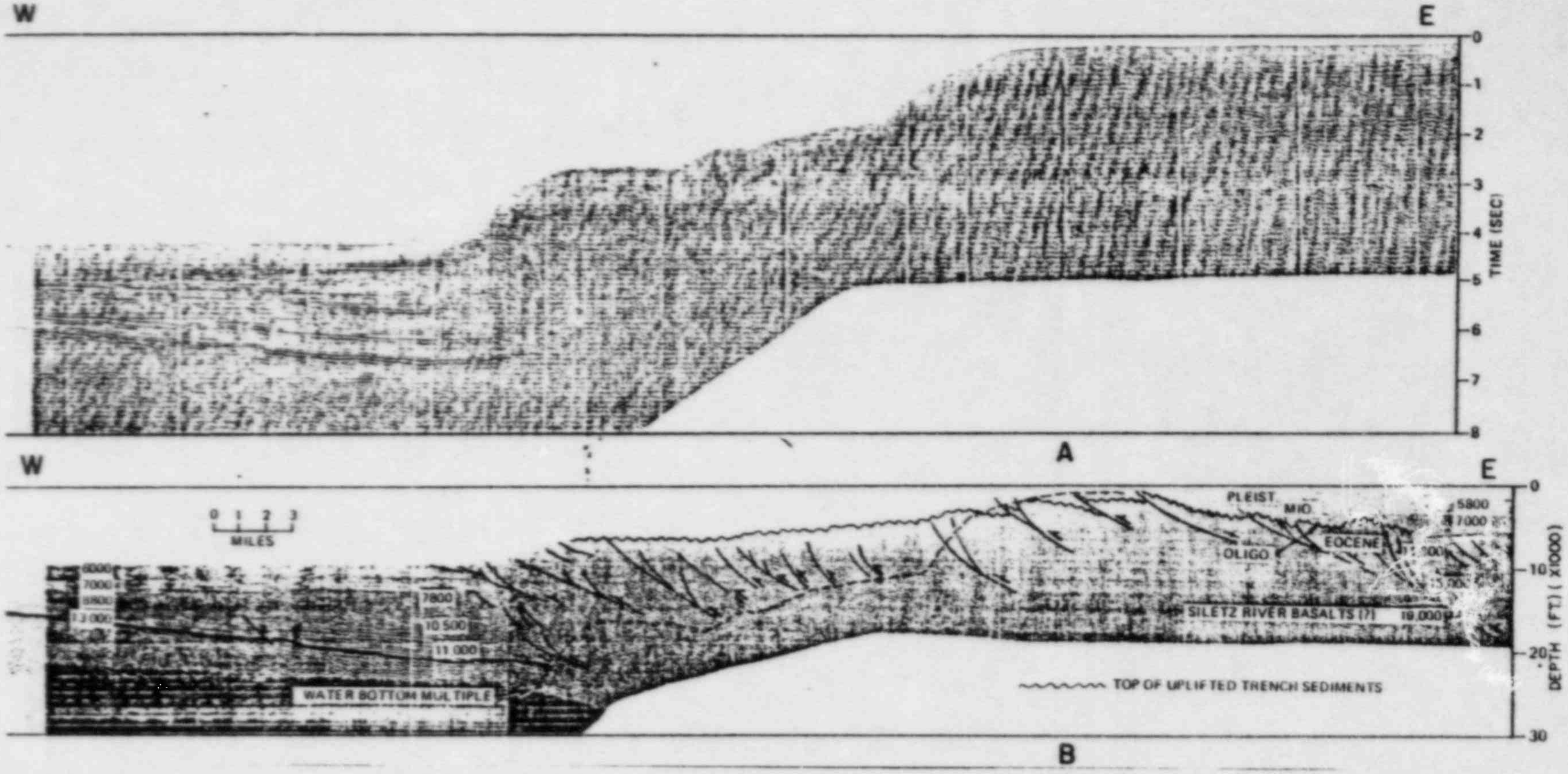


Figure 3.22. Seaward vergence sequence interpreted off central Oregon by Seely et al., 1974 and confirmed biostratigraphically by Kulm, von Huene et al., 1973 and Kulm and Fowler, 1974. (A) multichannel seismic record, time section and (B) non-migrated depth section of A. (Modified from Seely et al., 1974). See Plate 3.1 (ie: Exxon 1) for location.

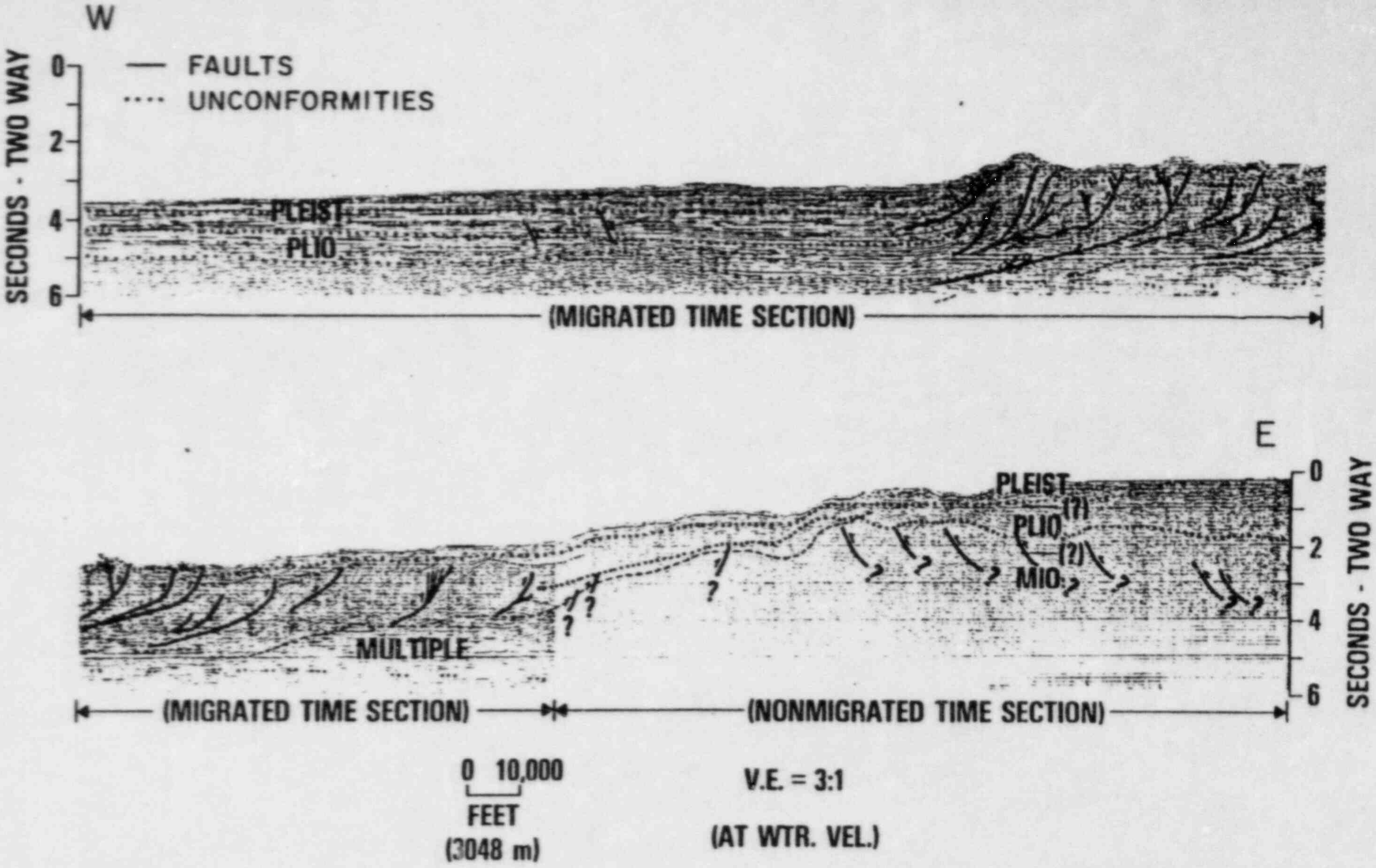


Figure 3.23. Landward vergence sequence interpreted off northern Washington by Seely, 1977. Top multichannel record shows Cascadia Basin with the formation of the marginal ridge to the right side of record. Bottom multichannel record continues up the continental slope. See Plate 3.1 (ie: Exxon 2) for location. (From Seely, 1977).

Oregon (44°N latitude) are interpreted to be imbricate thrust faults which display a seaward verging sedimentary sequence (Fig. 3.22; Seely et al., 1974). A similar interpretation is made for the multichannel seismic sections acquired at 45°N latitude (Snavely et al., 1980). However, the best example of a seaward verging, imbricate thrust sequence along the Oregon-Washington margin is seen on the lowermost continental slope off northern Washington (Fig. 3.24). The sediments of Cascadia Basin are in the initial stage of being faulted, offscraped, and tilted back toward the continent, while the sedimentary sequence above is in a more advanced stage of being tilted at a steeper angle in the same direction. The most recently deposited sediments (late Pleistocene to Holocene) of Cascadia Basin are apparently being deformed and faulted. A sedimentary basin is forming behind the upper thrust sequence and even the basin deposits are being upwarped as the thrust sequence rises along the seaward flank of the basin. This is a classic example of a seaward verging sequence and accretionary basin (ie: formation of a basin on the accreting sediment prism) first described by Seely et al., 1974 for subducting margins (see also Dickinson and Seely, 1979; Seely, 1977). A similar seaward verging underthrust setting has been confirmed rather conclusively off Barbados by deep sea drilling and multichannel seismic records (Moore et al.,1982) and is strongly implied off southern Mexico (Moore, et al., 1982) using similar techniques.

In marked contrast, several areas along the lowermost slope off both Oregon and Washington exhibit a landward verging sequence where the offscraped Cascadia Basin sediments are thrust over the top of the pre-existing slope deposits of the overriding continental plate. Multichannel seismic records made off northern Washington are interpreted as a landward verging sequence (Fig. 3.23; Seely, 1977). Perhaps a better example of this process is seen in single channel seismic reflection records which show the most recently deposited sediments (late Pleistocene and Holocene) of Cascadia Basin can be traced continuously from the basin as the western limb of an anticlinal fold that rises to form the marginal ridge of the lowermost continental slope off north central Oregon (Fig. 3.25). The eastern boundary of this fold is characterized by diffractions which suggest that this limb of the anticline is bounded by a fault. This is the only known occurrence of a landward verging sequence off Oregon. Other examples of this type of deformation and faulting is seen along tracklines 79-1 and 79-4 (Fig. 3.26, see Plate 3.1) from central and southern Washington In some cases, there has been some deposition of sediment in Cascadia Basin since the anticlinal fold developed.

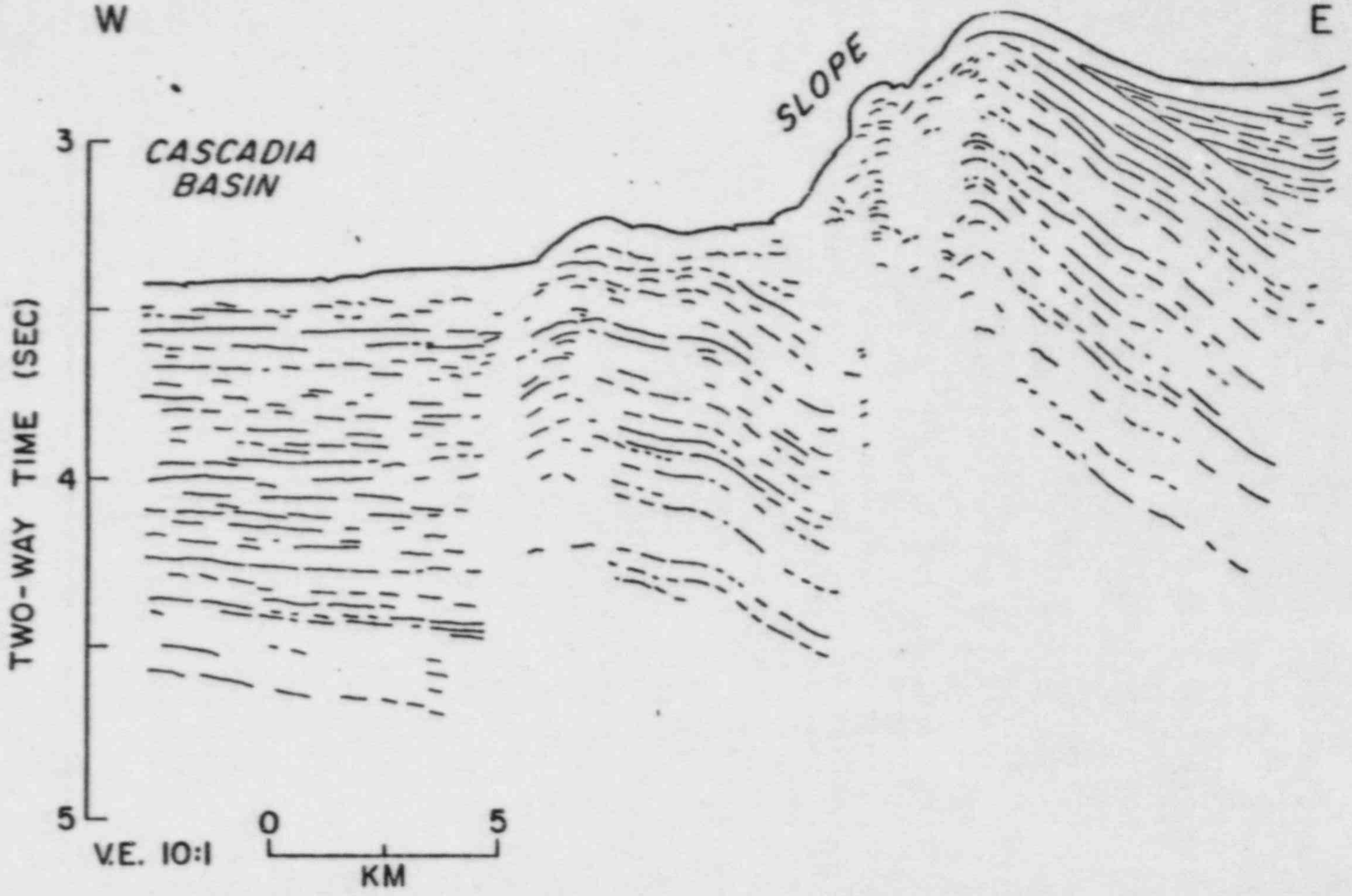


Figure 3.24. Line drawing of single channel seismic record (59-60) across the lower continental slope-abyssal plain (Cascadia Basin) interface. Note seaward vergence of strata expecially the most landward structure. See Plate 3.1 for location.

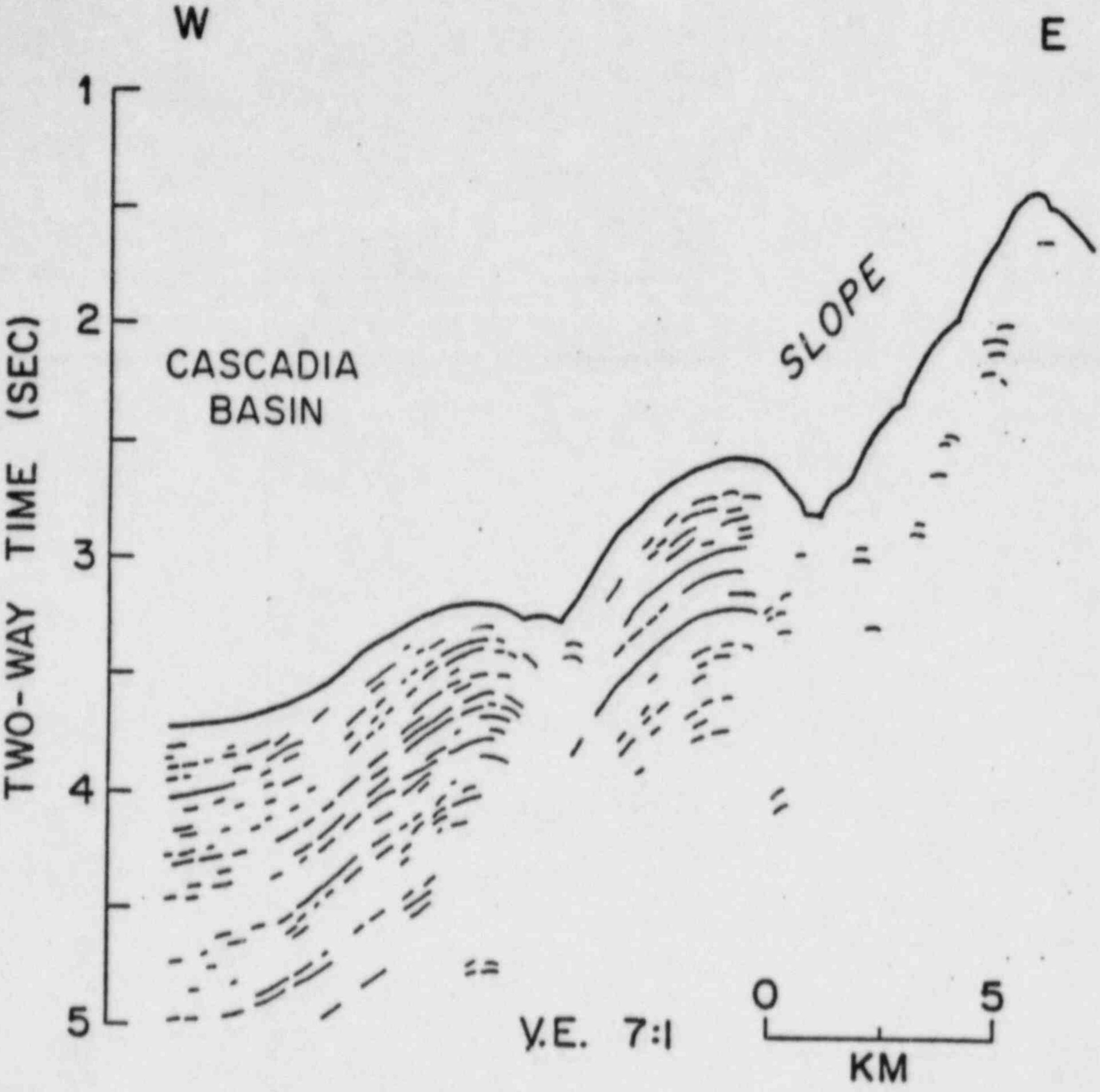


Figure 3.25. Line drawing of single channel seismic record (90-4) across a landward verging sequence of Cascadia Basin sediments off northern Oregon. See Plate 3.1 for location.

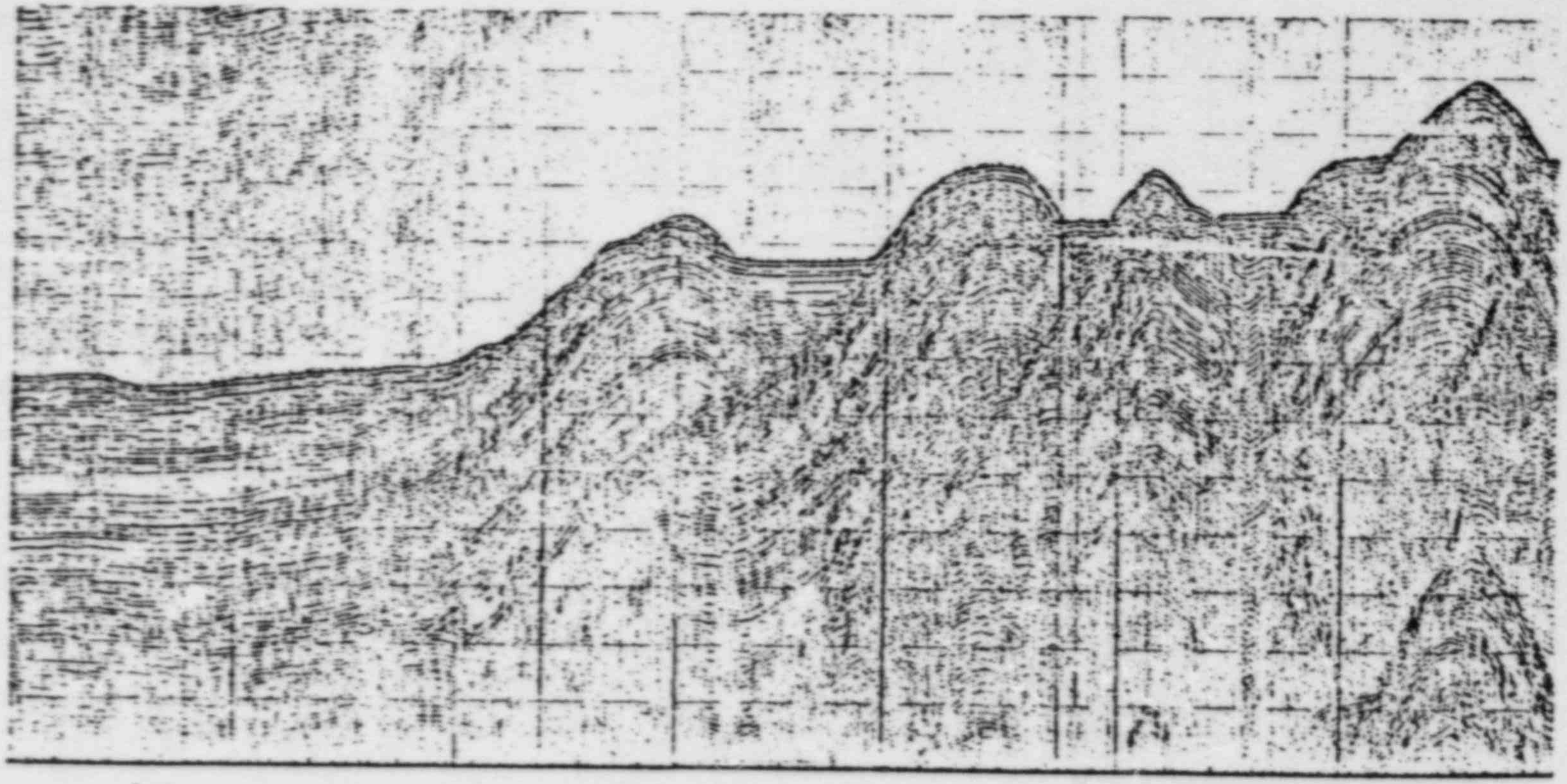


Figure 3.26. Single channel seismic record (79-4) of landward verging sequence off central Washington. See Plate 3.1 for location.

A deep-towed seismic reflection study of the marginal ridge off the southern Washington shows considerably more detail of the structure in the vicinity of basin-marginal ridge interface (Lewis, 1983). These processed digital data outline an escarpment along the western flank of the ridge, which is presumed be a fault, dipping in a seaward direction (Figs. 3.27, 3.28). Gently warped strata approximately 3 km wide occur between the scarp and the seaward dipping strata to the east. Another seaward dipping fault separates these two sedimentary sequences forming what appears to be an overthrust (Lewis, 1983). The fault appears to sole out above the oceanic basement. The reflectors of Cascadia Basin do not appear to be continuous with those comprising the first fold (ie: marginal ridge) although the seismic section does not extend far enough to the west to determine the exact relationship between these two sedimentary units. All of this deformation and faulting has occurred during late Pleistocene and Holocene time based upon the surface faulting and age dating of the deposits comprising the marginal ridge (see section 5.0, Plate 5.0).

While we have presented the two major tectonic styles occurring along the lowermost continental slope, there are many other areas of the slope where the style of deformation is quite obscure because of the steep dips and/or internal deformation of the strata. The deep-towed seismic technique offers the best solution to the definition of these complex structures associated with sediment offscraping and subduction of the Juan de Fuca plate beneath Oregon and Washington.

3.3 Slope basin structure

The sedimentary basins in the ridge and basin province form as a result of the deformation of the accretionary prism and document the tectonic movements of the prism throughout the geologic history of an individual basin (Plate 3.2 and following figures). Although there is a complex interplay between the rate of depostion and tectonism, recent movements of the prism are usually seen to varying degrees in the folded and faulted basin deposits. The basins are bounded to the east and west by anticlinal folds, faults, or chaotic sediment masses whose structure can not be resolved on seismic reflection records because of the steep dips or intense internal dispruption. Movement of the boundary features that flank the synclinal basins produces unconformable contacts between two juxtaposed sedimentary sequences laid down largely by turbidity currents with intervening hemipelagic deposition.

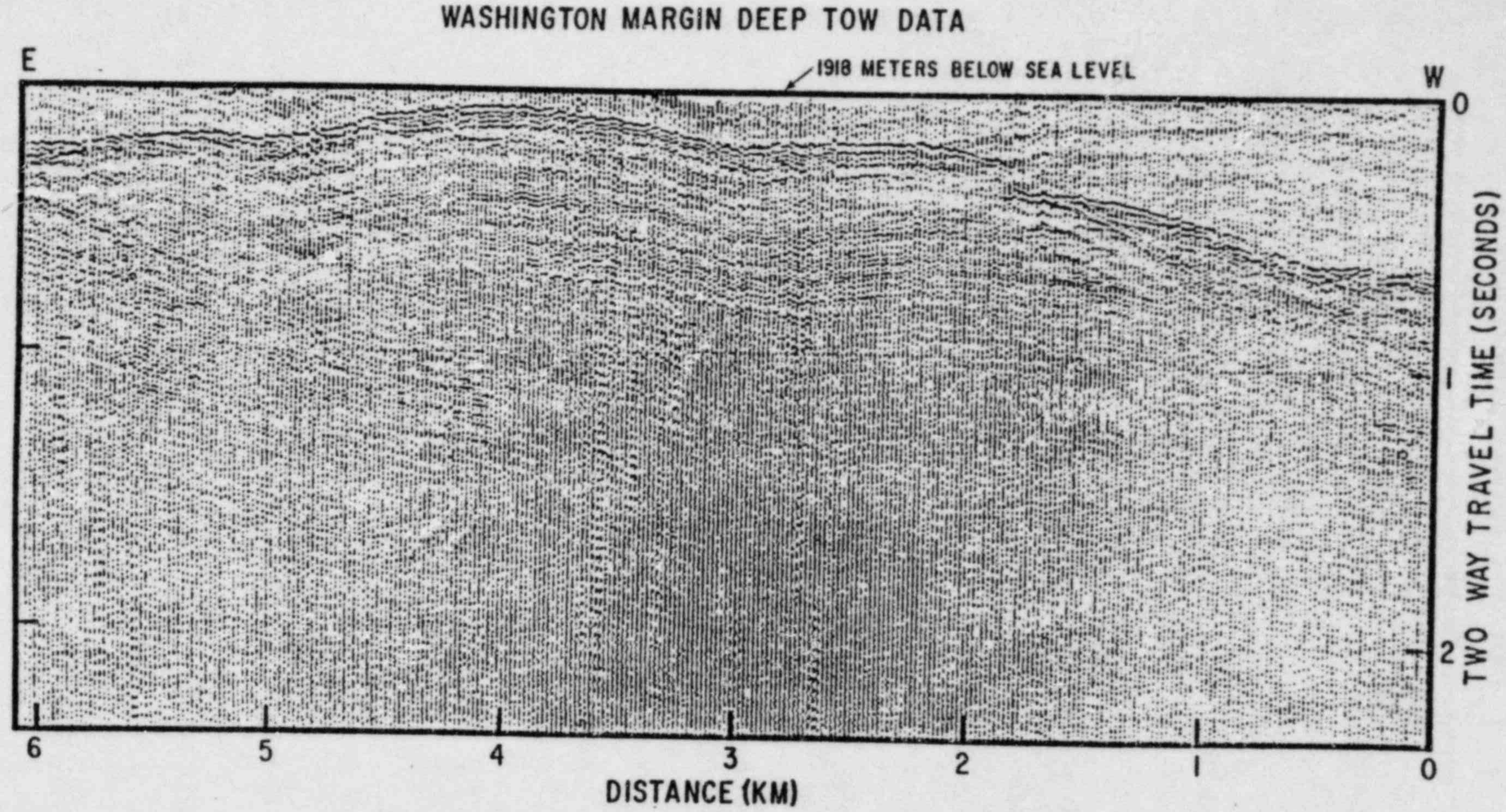


Figure 3.27. Deep-tow seismic reflection record from the southern Washington lowermost continental slope (left side) and adjacent abyssal plain (right side) near 47°N latitude. No vertical exaggeration. See figure 3.28 for interpretation. (From Lewis, 1983).

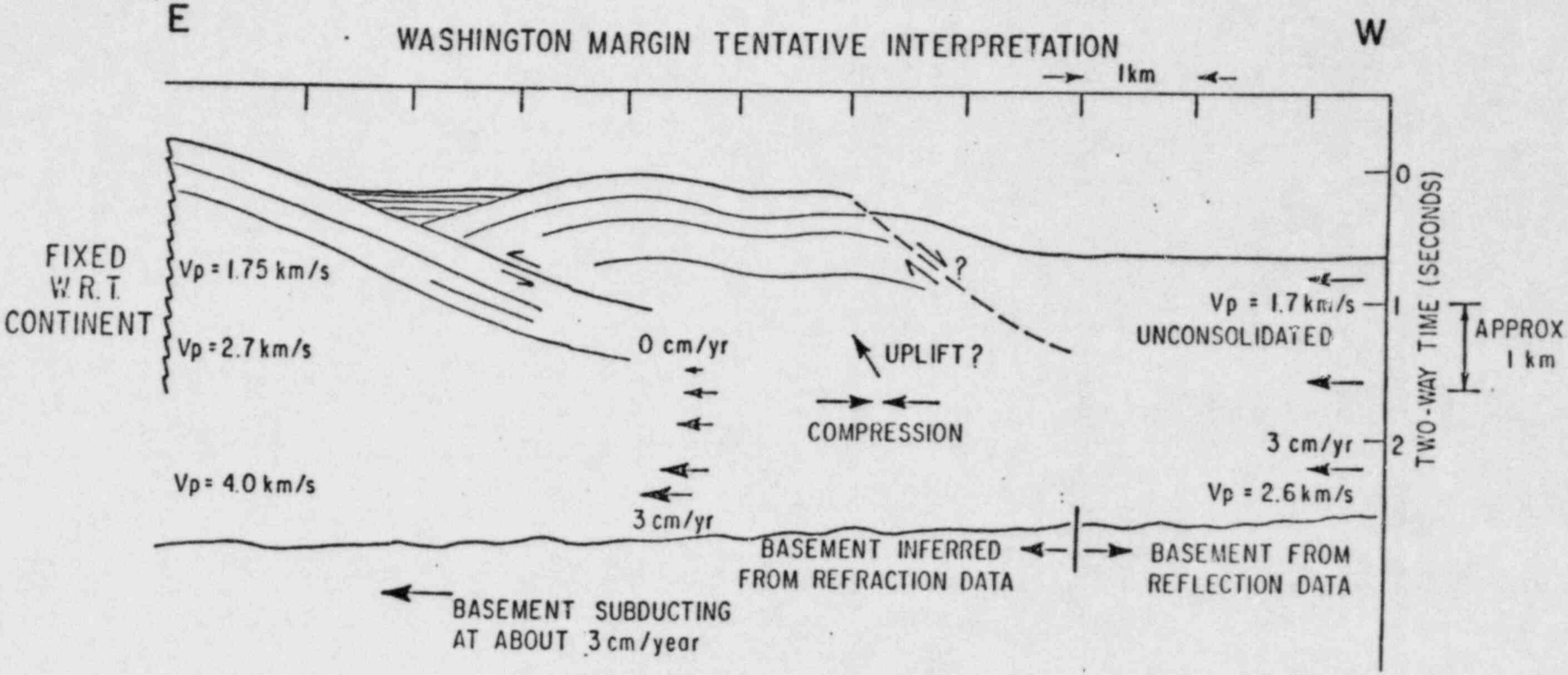


Figure 3.28. Interpretation of deep-towed seismic record shown in figure 3.27. (From Lewis, 1983). Note position of possible faults and apparent offset of the surface sediment on the marginal ridge to the west. (From Lewis, 1983).

Turbidity currents tend to fill in the low topographic areas and create horizontal lying deposits; any deviation from horizontality usually can be attributed to deformation of the sedimentary sequence. As the boundary features are uplifted or subside relative to one another, the depocenters of the basins may migrate either landward or seaward with regard to the relative movement of the bounding feature.

Several types of deformation occur in these lower slope basin settings. They include the following:

(a) basin deposits with migrating depocenters (ie: in a landward or seaward direction) with no major internal faults within the basin sediments off northern Oregon (figure 3.11; tracklines 90-1 and 90-2 in figure 3.30 and Plate 3.1), southern Washington (trackline 6-7, Plate 3.1), and northern Washington (Fig. 3.24). Several migrations of depocenters within a vertical sequence of a given synclinal basin are most prominently displayed in the aforementioned areas. While depocenters do migrate in other basins on the Washington slope, they are do not record as many movements of the bounding structures or they are frequently absent. These synclinal basins may have anticlinal folds rising within a larger basinal setting tending to divide it into more than one basin (Fig. 3.11). Basins displaying several migrating depocenters are located just to the north and south of the Columbia River, which supplies a large amount of sediment to the continental slope, especially during lower sea level stands during the Pleistocene when the river flowed across the continental shelf and discharged its sediment into the heads of submarine canyons on the slope (Kulm and Scheidegger, 1979). The bulk of these sediments was dispersed by turbidity currents that found their way through the structural ridges, finally depositing their sediment load into the accessible topographic lows (Kulm and Scheidegger, 1979; Barnard, 1978). Because of the high sedimentation rates (largely turbidite deposition) in this area, episodic tectonic movements are recorded with a higher degree of resolution in the strongly reflecting acoustic sequences than in areas where sedimentation rates are quite low or where the basin filling deposits are mainly acoustically transparent hemipelagic sediment. Profile 60-59 (Fig. 3.24) off northern Washington shows how the depocenters migrate in only one direction (landward) because of the rising structural high created by the seaward verging sedimentary sequence. This style of deformation is typical of active margins (Seely, 1977) and is well documented in the Winona Basin off Vancouver Island by seismic reflection records and deep-sea drilling on Paul Revere Ridge (Kulm, von Huene, et al., 1973).

(b) basin deposits exhibting former periods of warping, folding, and occasional faulting followed by relatively undisturbed horizontally layered sedimentary sequences (Fig. 3.31; tracklines 12-13, and 8-9, Plate 3.1). Most of these basinal settings are found off central Washington on the lower continental slope. The apparent absence of deformation in the most recently deposited sediments suggests a period of relative stability for these basins, although in some of these younger basins, the deposits are weakly reflecting or nearly transparent, indicating hemipelagic rather than turbidite deposition. Structural barriers (eg: anticlinal folds and chaotic sediments masses) preclude bottom transport in the more recently formed basins on the lowermost continental slope where mainly hemipelagic sediment accumulates (eg: Site 175, Plate 5.0); these deposits are not as likely to record the tectonic movement of the underlying deposits.

(c) basin deposits with internal faults that surface on the seafloor (Figs. 3.32, 3.33). Faults that offset the most recently deposited surface sediment in basins are observed in two widely separated areas of the lower continental slope (Figs. 3.32, 3.33). The older sediments in the basins are usually tilted and faulted with a slight angular discordance occurring between these deposits and the overlying younger, less deformed deposits. Acoustically incoherent structures and anticlinal folds appear to be rising beneath the basin deposits causing much of disturbance. One major fault appears to offset all strata including those at on the seafloor. These basins are located immediately landward of the marginal ridge that forms the boundary betweeen the slope and the abyssal plain; the faults are located 10 km (Fig. 3.32) and 15 km (Fig. 3.33) landward of the slope-plain interface. The length of the faults is more difficult to determine because of the line spacing of the seismic records and the inherent errors in Loran A navigation. Despite these reservations, it is possible that the basin fault shown in figure 3.34 is the same one noted in figure 3.32, since it also is located about 10 km landward of the slope-plain interface, although it has not yet surfaced as seen in the former seismic record. If this is the same fault in both of these records, it is about 5 km long based upon the trackline spacing.

(d) basin deposits with titled strata (usually at depth) that terminate with a fault. These deposits are turbidites that have been titled, producing a discordant contact with the overlying strata. Subsequent warping and faulting have created rather complex basin structures (Figs. 3.34, 3.35, 3.36). Some of basin faults appear to be growth faults.

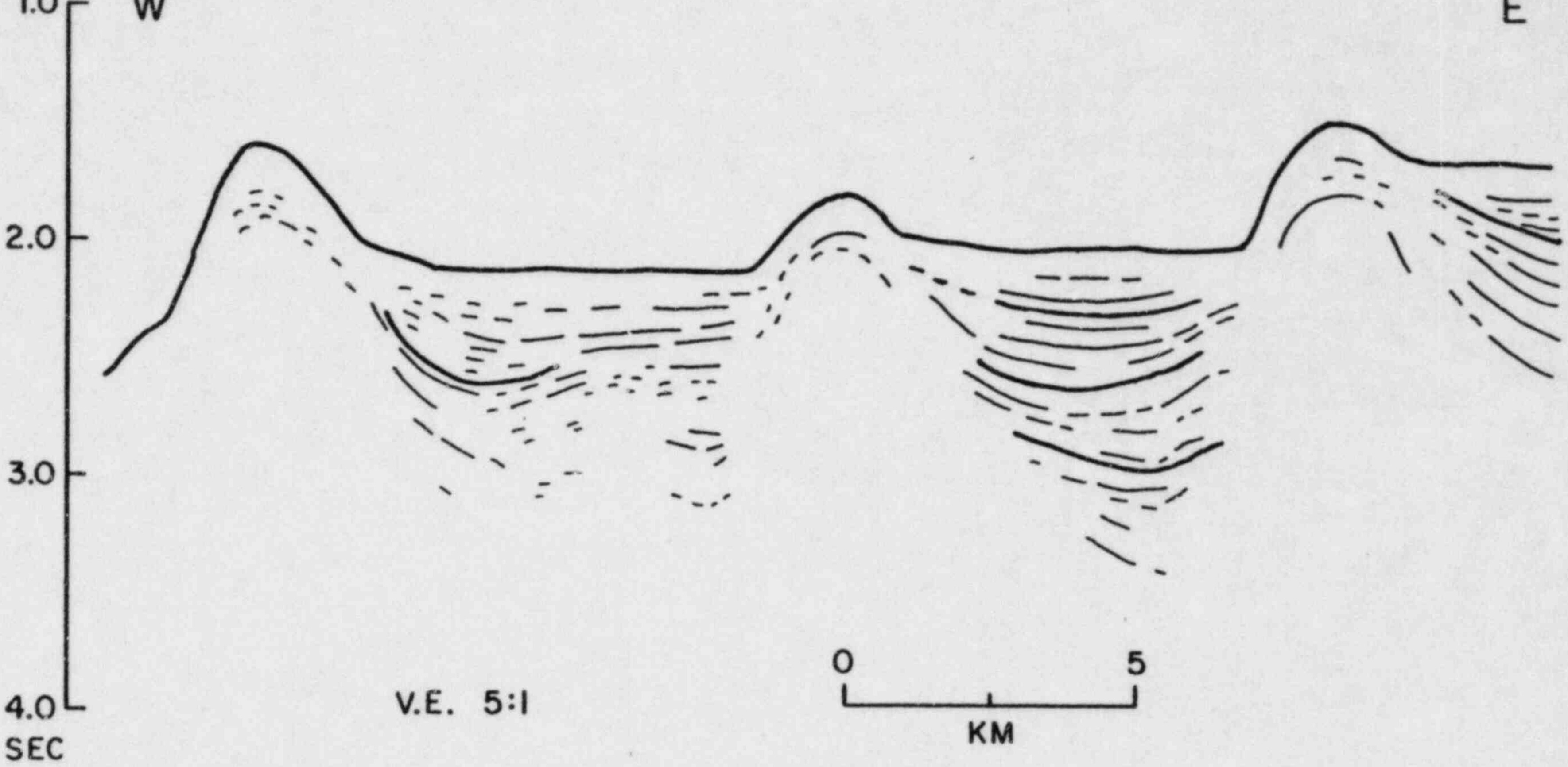


Figure 3.30. Line drawing of seismic record (90-1) of lower slope region showing migrating depocenters of basin deposits flanked by rising ridges (seismic record from Carson, 1978).

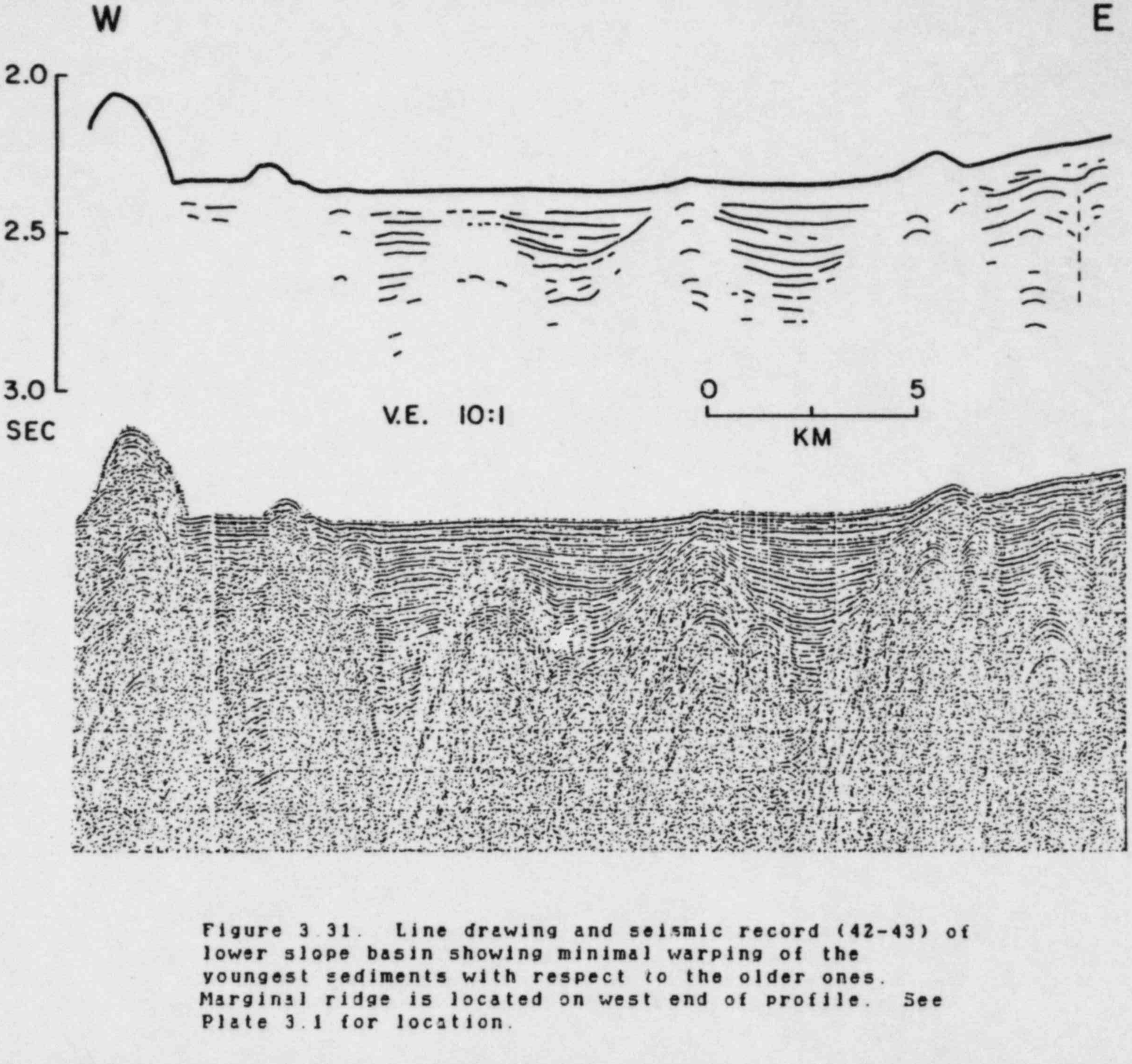


Figure 3.31. Line drawing and seismic record (42-43) of lower slope basin showing minimal warping of the youngest sediments with respect to the older ones. Marginal ridge is located on west end of profile. See Plate 3.1 for location.

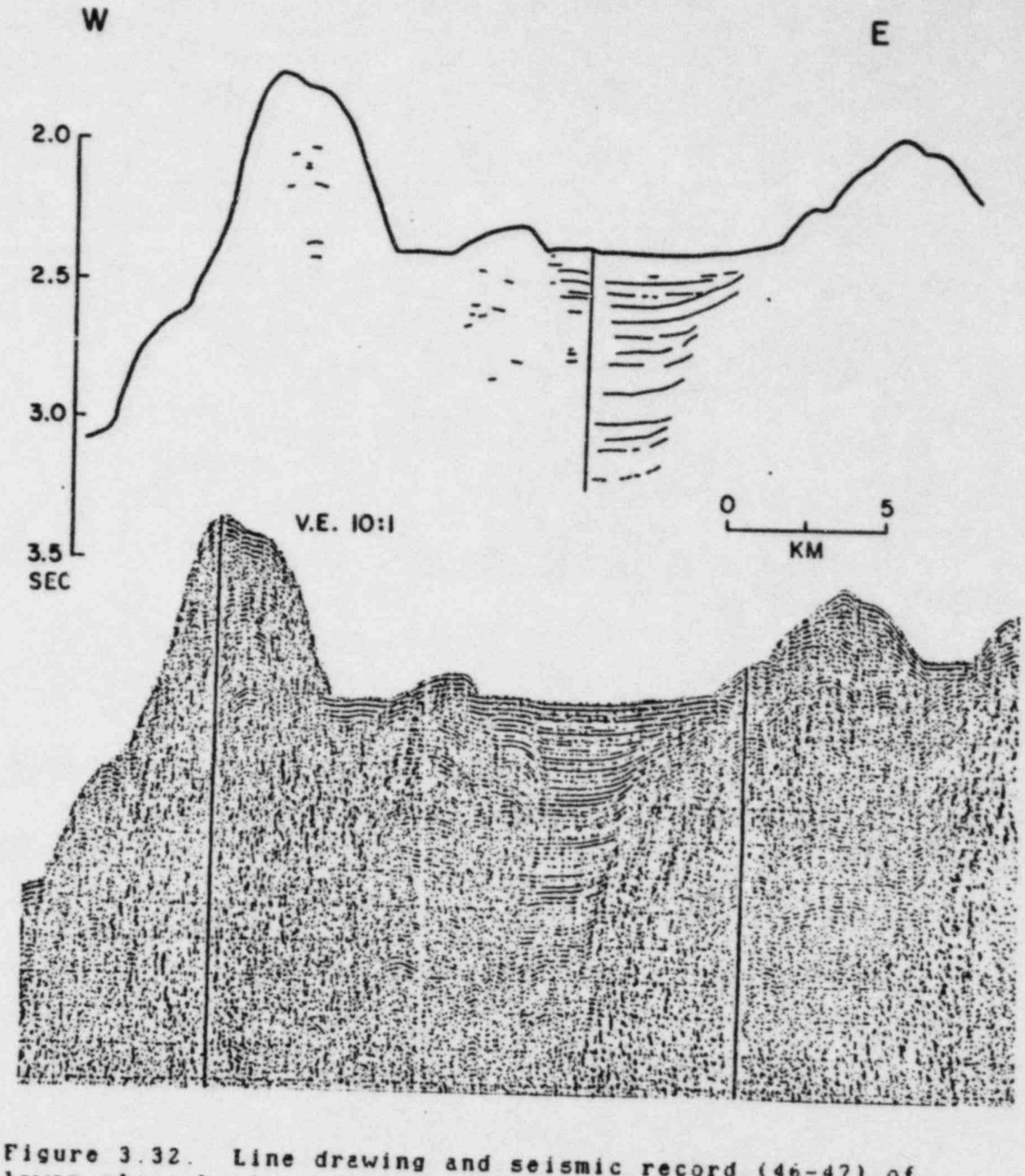


Figure 3.32. Line drawing and seismic record (46-47) of lower slope basin showing fault that offsets the sediments of the seafloor. Marginal ridge is situated to the west. See Plate 3.1 for location.

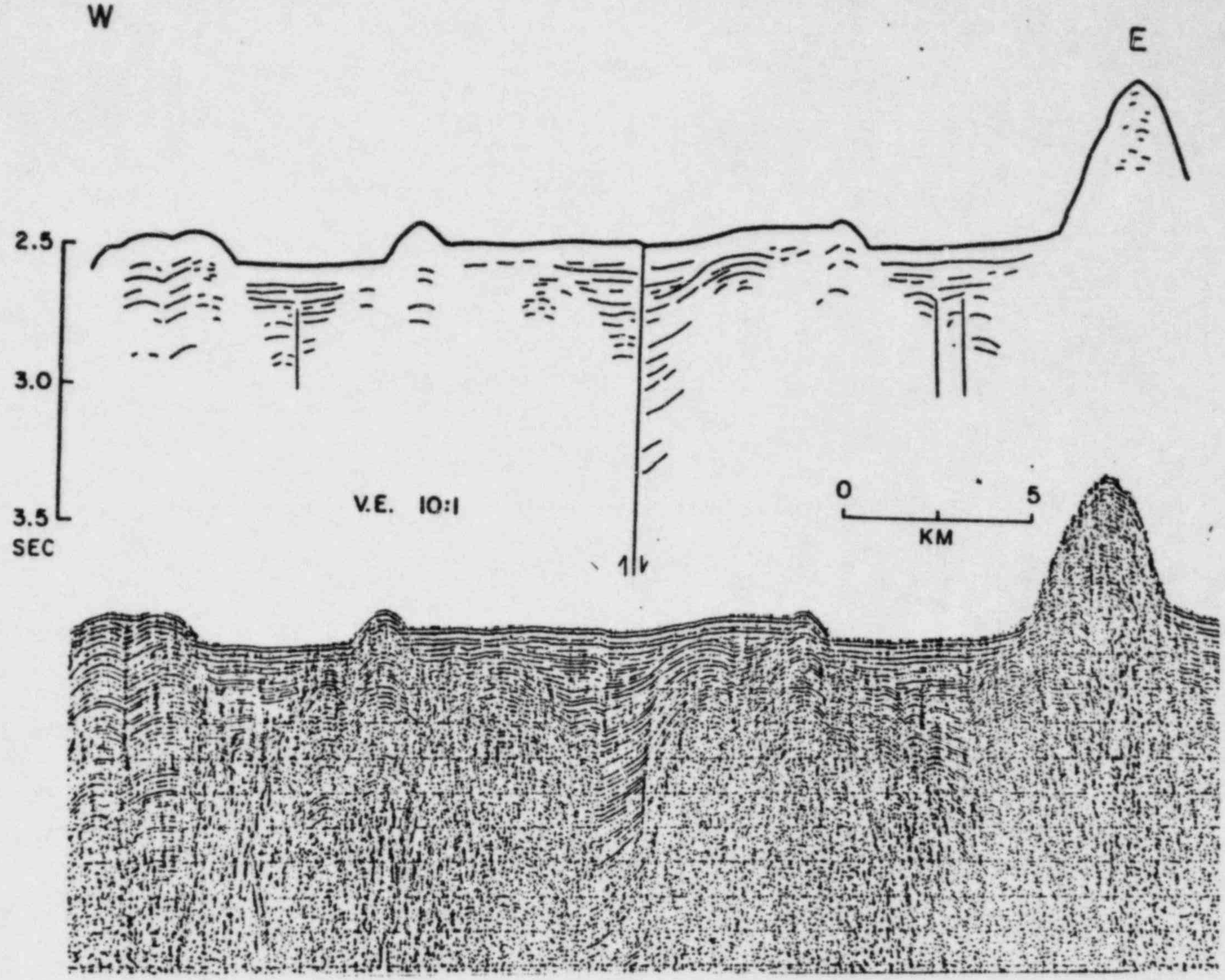


Figure 3.33. Line drawing and seismic record (13.5-14) of lower slope basin showing fault that offsets the sediments of the seafloor. Marginal ridge located to the west. See Plate 3.1 for location.

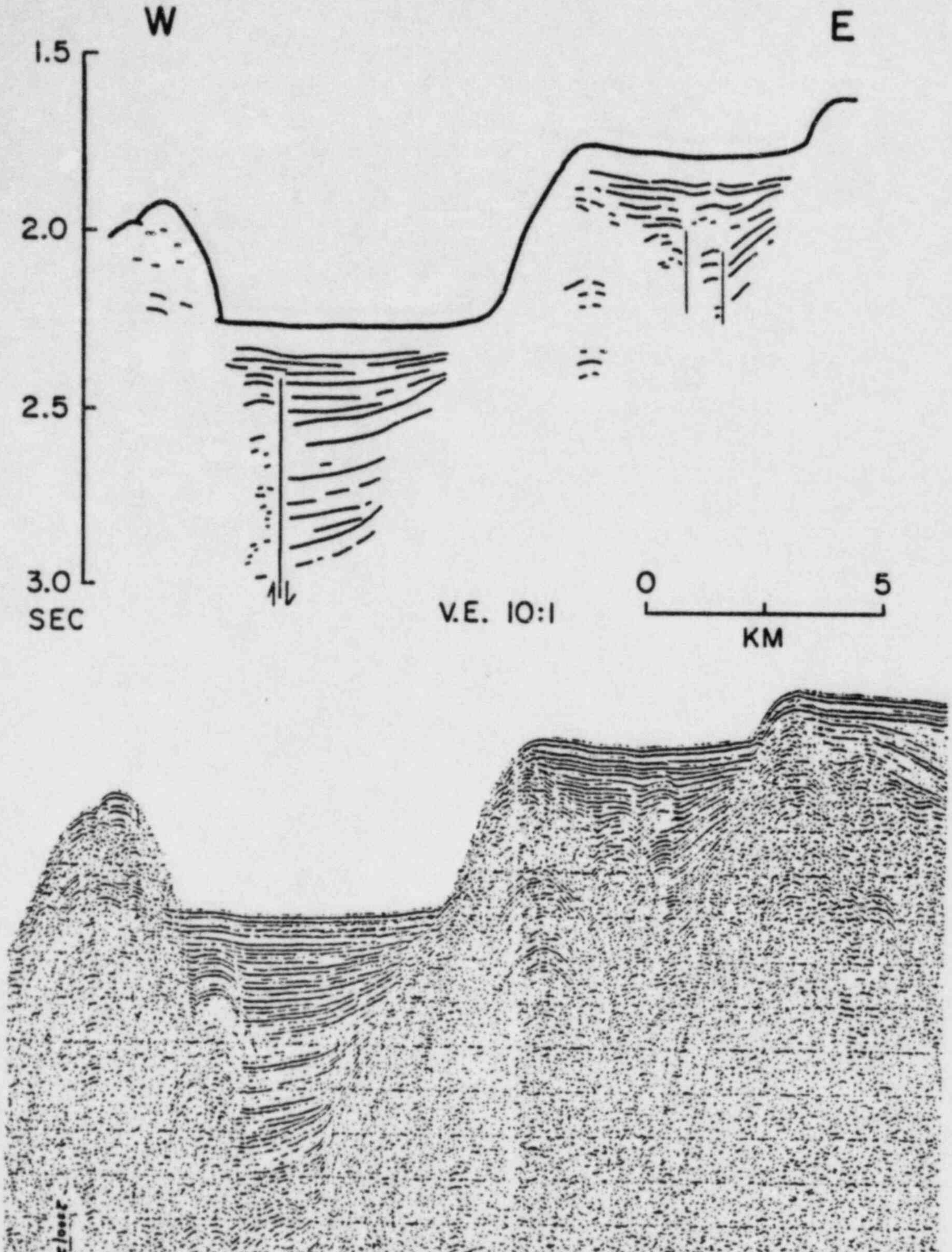


Figure 3.34. Line drawing and seismic record (48-49) of lower slope basin showing internal faults and uplifted basin deposits. See Plate 3.1 for location.

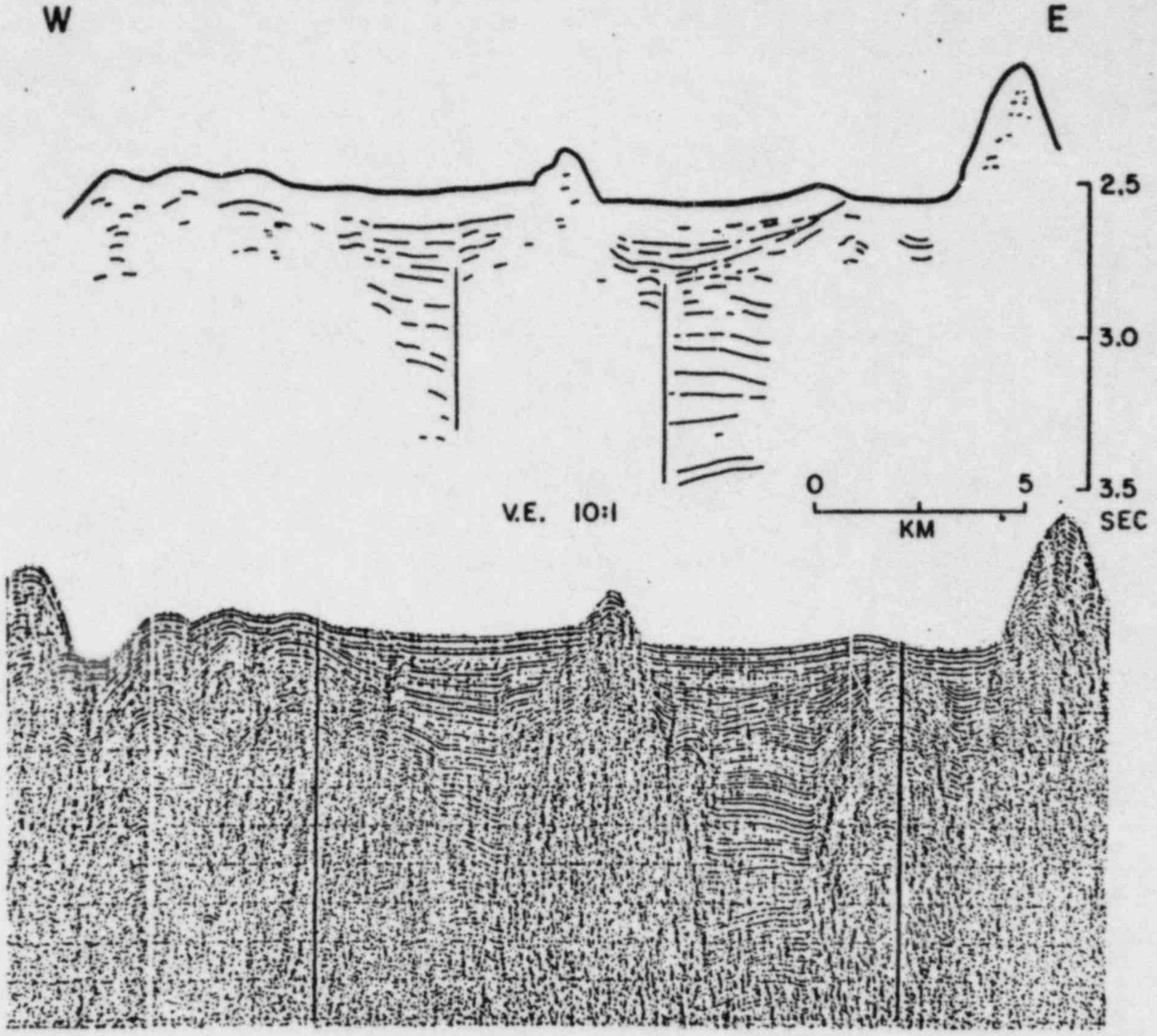


Figure 3.35. Line drawing and seismic record (36-37) of lower slope basin showing different stages of warping of basin sediments and possible faults. See Plate 3.1 for location.

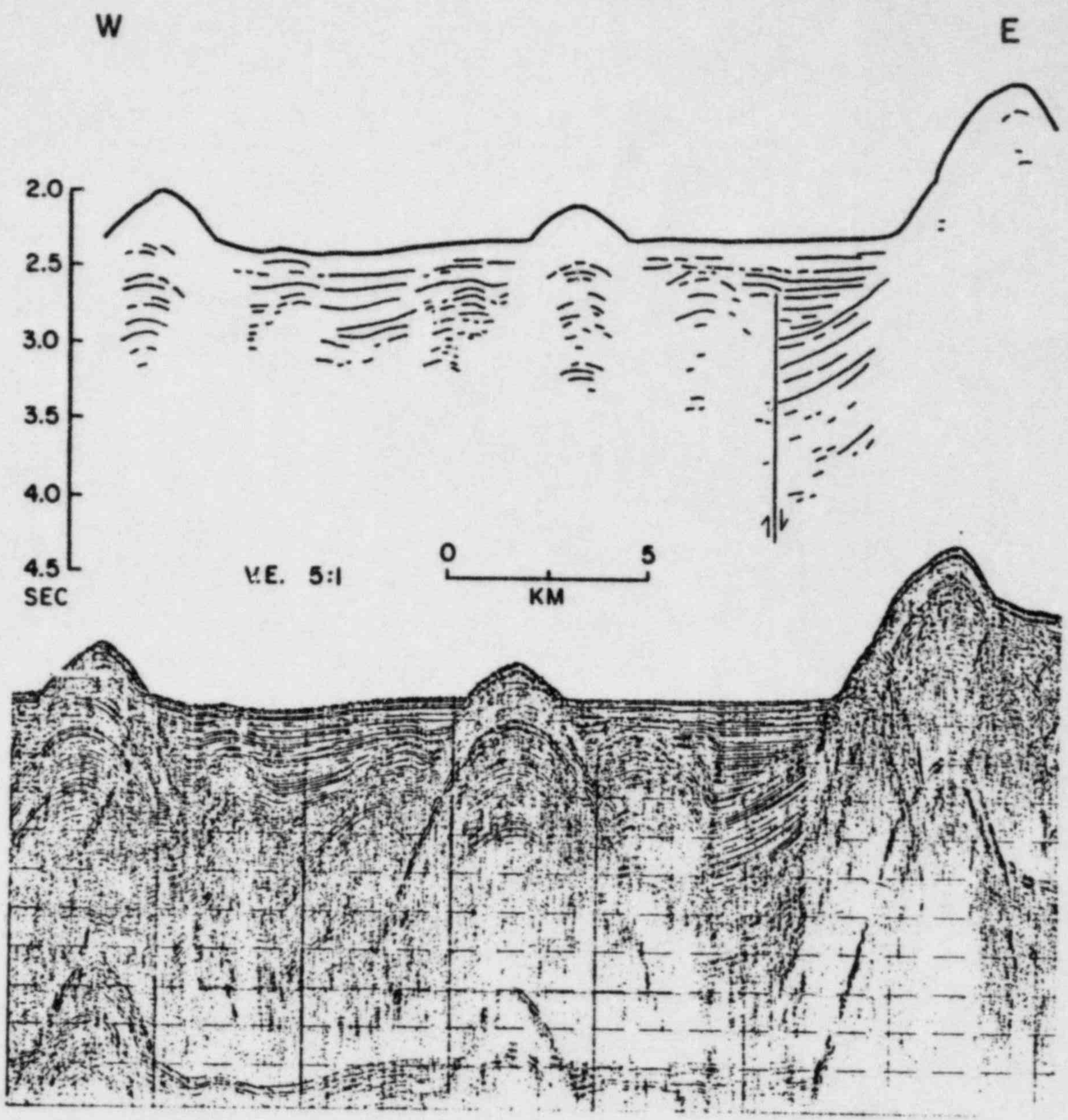


Figure 3.36. Line drawing and seismic record (79-4) of lower slope basin showing warped and tilted strata. In at least one case the titled basin sediments apparently terrminate at a basin fault. See Plate 3.1 for location.

It is difficult to determine whether the entire ridge and basin province of the lower slope is experiencing continuning tectonism or whether this tectonism is more intense along the deformation front (marginal ridge). The most extreme changes in the physical properties of the sediments occur in the vicinity of the marginal ridge, but warping and faulting also occur in the basin deposits overlying the older, previously accreted ridge material. Those basins characterized by rapid turbidite deposition and little of no deformation of the youngest deposits may appear to be stable in the recent past, but this may be an artifact of the high sedimentation rates and/or episodic tectonism.

3.4 Cascadia Basin Structure

A thick wedge of sediment occurs at the base of the continental slope in an elongate basement depression that extends from the Mendocino fracture zone in the south to Paul Revere Ridge in the north forming the eastern boundary of the Juan de Fuca-Gorda plate (see Fig. 1 and Plate 3.2). The wedge is thickest (about 2.5 km) in the vicinity of the apecies of the Astoria and Nitinat submarine fans and thins westward toward the spreading Juan de Fuca and Gorda ridges. A seismic dicontinutiy occurs within the sedimentary wedge separating the fan deposits above from the abyssal plain deposits below (Kulm et al., 1973). Fan deposition produces a time transgressive onlap onto the abyssal plain deposits, creating a slight angular discordance between the eastward dipping abyssal deposits and the overlying horizontal fan deposits. Complex sedimentary sequences are seen within the fan deposits because of the shifting fan channels that transport sediment to the more distal portions of the fans. The fans are somwhat asymmetric and hook to the left, lenghtening in the direction of regional dip to the south.

Deep-sea drilling at Site 174 (Plate 5.0) shows that the sand turbidites and interbedded muds of Astoria Fan are no older than middle to late Pleistocene (0.4 to 1.0 my) in age (Kulm, von Huene et al., 1973); the last major fan deposition by turbidity currents is documented during the last major lowering of sea level, about 20,000 years ago (Nelson, 1968). Sedimentation rates for Astoria Fan probablity range from 275 to 550 m/my (Kulm et al., 1973). The underlying abyssal plain silt turbidites and interbedded muds range in age from Pliocene to middle Pleistocene. The deposits of Nitinat Fan and the underlying abyssal plain deposits are believed to be of similar age and lithology.

The structure of eastern Cascadia Basin deposits was studied using available seismic refection records. Emphasis was placed on those structures that were likely to result from the convergence between the Juan de Fuca and North American plates. Any folding or faulting, which disrupts the most recent sediments of the basin, would have occurred within the past few thousand or, at the most, tens of thousands of years based upon the basin stratigraphy described above. Several different types of structures were identified along the plate boundary (ie: continental slope-abyssal plain interface) and just seaward of this boundary that can be linked to the basin by seismic reflectors. The most prominent rupture zone within the Cascadia Basin (ie: in Nitinat Fan) deposits occurs 4 to 6 km seaward of this interface, as seen in a series of east-west seismic reflection profiles (Fig. 3.41 A-F), and extends from 47°38′N to 47°05′N latitude off central Washington (Plate 3.1, trackline A-A′). Although the character of the rupture zone varies from north to south, the sediment deformation commences to the west as a monclinal-like fold or flexure that apparently terminates in a fault to the east (Fig. 3.41 C and E). The sediments may be upwarped between the fault and the slope-plain interface creating a complicated and undefined boundary with the more highly folded and faulted continental slope structures. This flexure involves the most recent sediments of the fan and forms a structural high on the seafloor; the fault appears to surface where the flexure has its most pronounced effect on the seafloor (Fig. 3.41D). A northwest-southeast seismic profile clearly shows the folding and faulting of the fan deposits (Fig. 3.42; Plate 3.1). An anticlinal fold is well developed on the northern end of this line but becomes less pronounced near the surface where the onlap indicates either rapid deposition of the near surface sediments or less intense folding near the surface. Folding becomes less intense to the south of the fault. Two additinal faults occur in the section as indicated by the offset of reflectors and the diffraction patterns. These faults appear to extend to the surface cutting the most recently deposited sediments on the fan. The folded portion the profile is about 25 km long; the entire deformed zone extends over a distance of 62 km.

4.0 Consolidation and Cementation of Continental Slope Sediment

4.1 Tectonic Consolidation of Slope Sediments

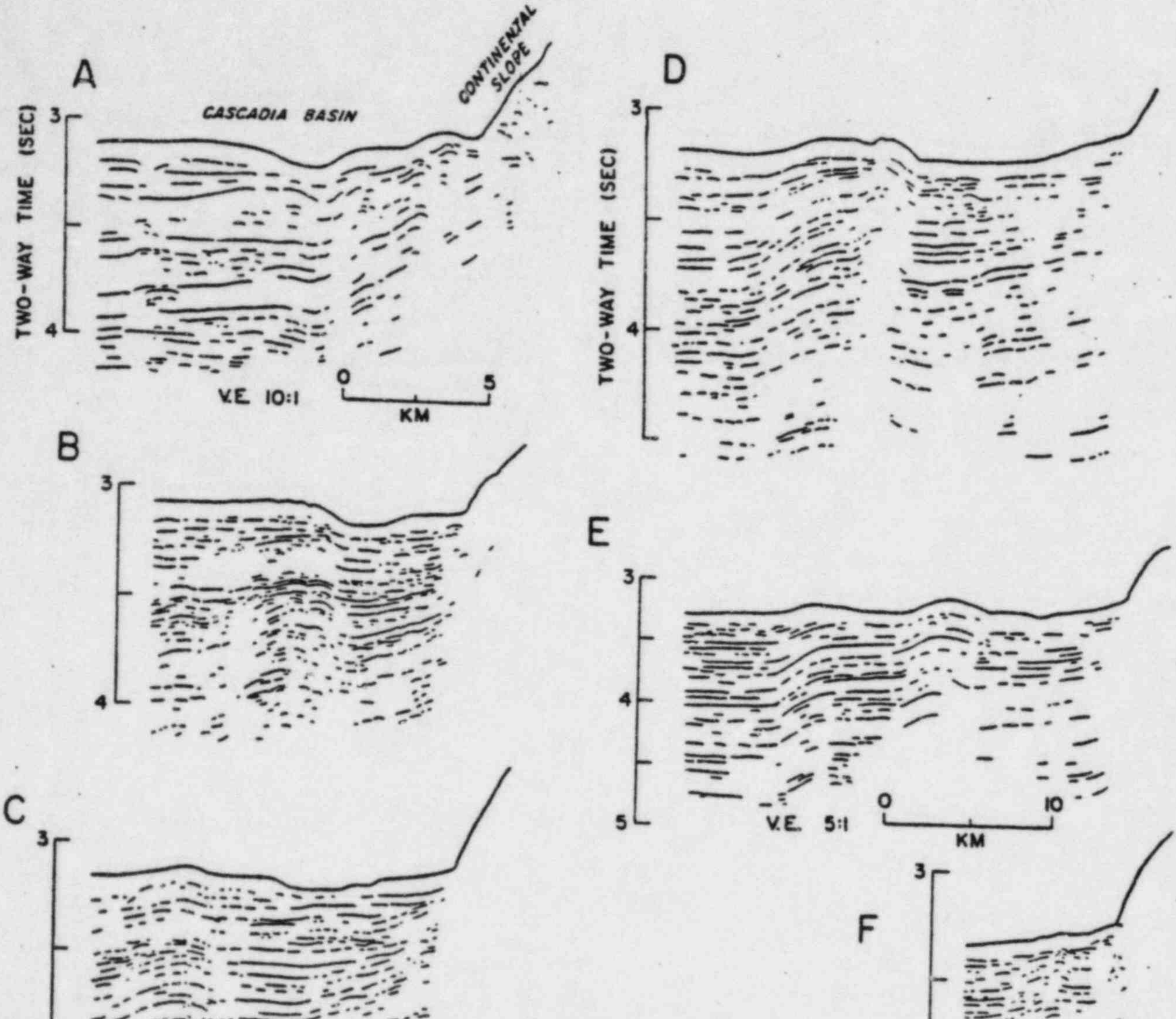


Figure 3.41. Line drawings of seismic reflection records near the base of the continental slope in Cascadia Basin off southern Washington. These east-west trending profiles cross the northern one-half of section A-A′ given in figure 3.42. See text for explanation. Seismic records shown here are located between 47°38′ N and 47°05′ N latitude (see Plate 3.1).

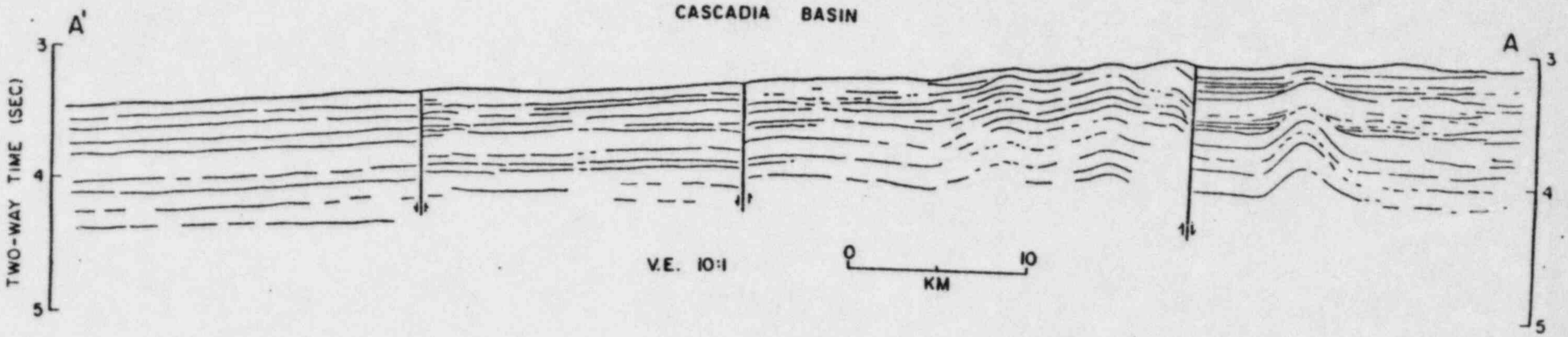


Figure 3.42. Line drawing of seismic reflection record made parallel (ie: northwest-southeast trending) to the base of the continental slope in Cascadia Basin off southern Washington. The section A-A' was made perpendicular to the records shown in figure 3.41. See Plate 3.1 for location.

The physical properties of the deformed, near surface sediments of the ridges on Oregon-Washington continental slope show that these deposits are highly overconsolidated with respect to the undeformed sediments of the adjacent Cascadia Basin (Carson, 1977) and the relatively undeformed, ponded basin sediments that overlie the deformed ridge deposits (McDonald, 1982; this study). Consolidation of sediments may occur by (1) vertical loading through sedimentation with the resulting overburden pressure causing dewatering and consolidation or (2) lateral loading due to tectonically induced deformation also causes dewatering and consolidation (Shepard and Byrant, 1980; Carson, 1977; Moore and Karig, 1976; Trabant et al., 1975; Lee, et al., 1973). Cementation may further complicate the consolidation process, although such activity is not a true consolidation process, and produces a number of distinctive physical properties (ie: increased density, lower water content and porosity) usually associated with consolidation by vertical loading.

As the unconsolidated sediments of Cascadia Basin are accreted to the continental slopes off Oregon and Washington, they are mechanically consolidated, producing mudstones and sandstones which have water contents between 17-30 % wet weight, void ratios of 0.4-1.2, and preconsolidation (maximum past) pressures of 0.8-8.2 kPa (Figs. 4.11, 4.12). In marked contrast, the undeformed sediment of Cascadia Basin have water contents of 55-70 % wet weight, void ratios of 1.1-1.9, and maximum consolidation is <2.0 kPa. and the relatively undeformed sediments in the ponded basins that overlie the deformed (accreted) sediments have values of 44-60 %, 0.6->3.0 and 0.03-0.078 kPa, respectivley. The deep sea drilling site 175 shows a range in water contents in the upper 100 m of sediment in one of the ponded basins overlying the accretionary prism; the upper portion of the deposits exhibit a similar water content to the near-surface basin deposits (see x symbols of figure 4.11). The accreted deposits in the lower section of site 175 have water contents similar to the those of the deformed ridges. The deforming ridges may cause some additional dewatering of the overlying basin deposits, although this is difficult to document except for the fact that the Cascadia Basin deposits have a slightly higher water content than the slope basin deposits (Fig. 4.11). However, textural differences between these two deposits may account for the observed differences in water content.

Shear strength determinations for the near-surface ridge deposits range from 90 to 416 kPa (Fig. 4.12). In general, the shear strenghts are significantly greater for the slope ridge

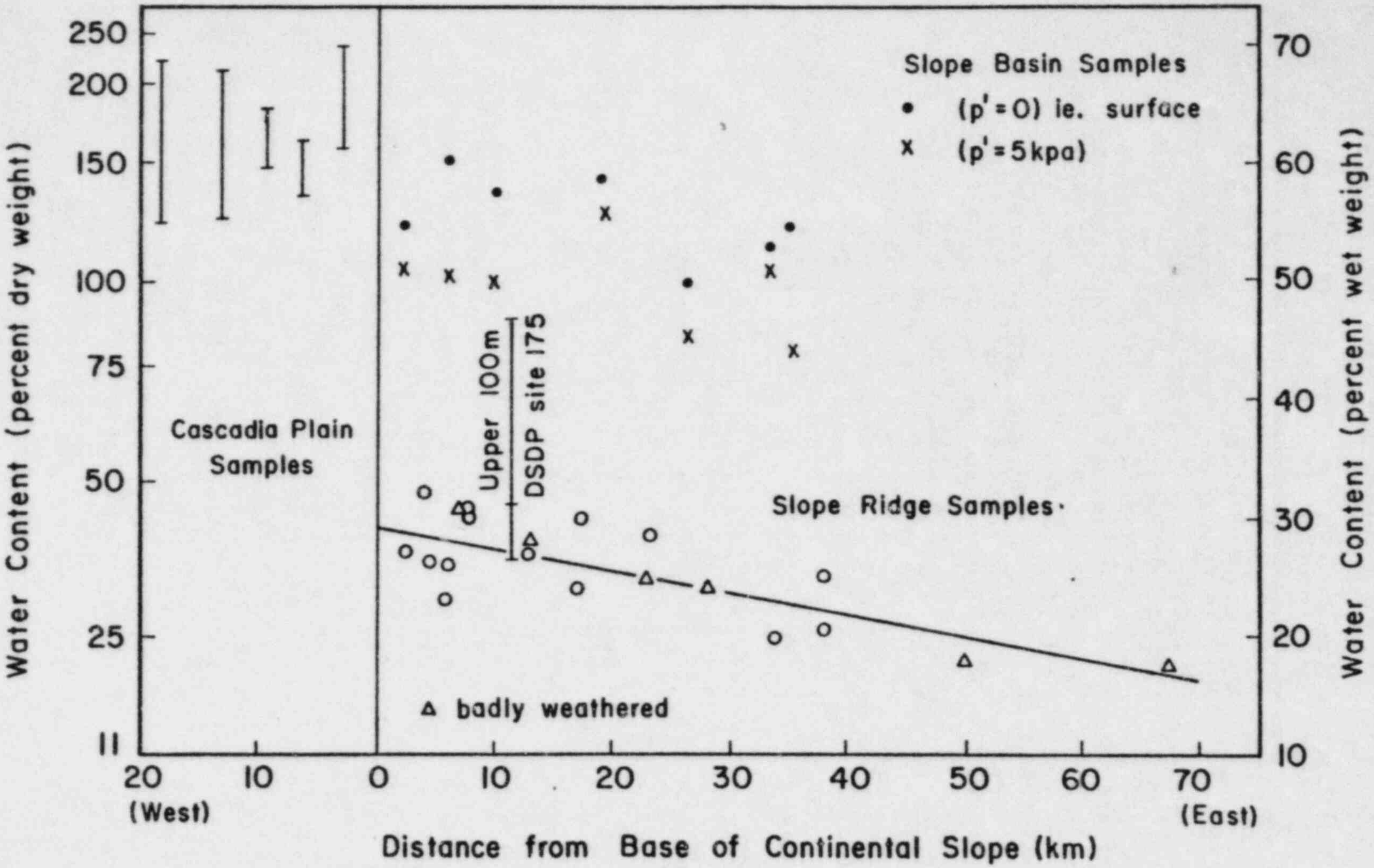


Figure 4.11. Water content with distance from the base of the continental slope (Modified from Carson, 1977). Samples with triangles from Barnard (1973); open circles, Cascadia Plain (Basin) and drill site 175 from Carson (1977); closed circles and letter x from McDonald (1962) in northern Oregon lower slope basins. Water contents of Cascadia Basin sediment were taken from upper one meter of gravity cores. McDonald's samples taken with kasten cores.

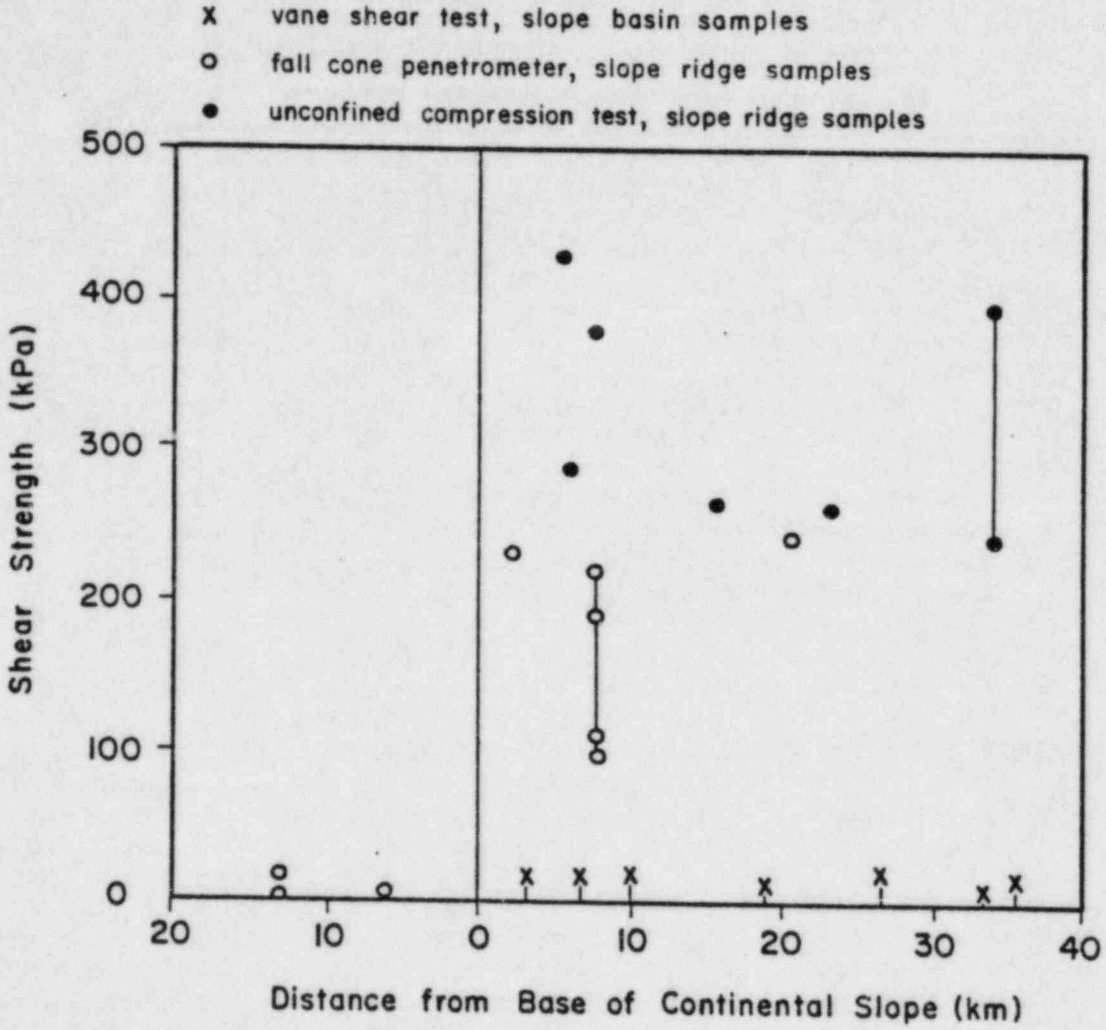


Figure 4.12. Shear strength with distance from base of slope (Modified from Carson, 1977). Solid circles indicate unconfined compression tests. Open circles are fall cone determinations. Cascadia Basin lies to the left of zero distance; samples are from upper one meter of sediment. Letter x indicates data from McDonald (1982) in northern Oregon lower slope basins.

deposits than the equivalent deposits found in Cascadia Basin and in the ponded slope basins. Hemipelagic terrigenous sediments normally have shear strengths of from 0.0 to 59 kPa in <100 m of near sediment in the deep ocean environment (Bouma and Moore, 1975).

Water content is the only property that shows a definitive trend with respect to the development of the slope ridges. The bulk of the dewatering occurs during the initial stages of deformation (ie: within the past 2 my), near the slope-plain interface, and progresses more gradually landward as the ridges undergo continued deformation and uplift. Because the ridges become progressively older in a landward direction, the sediments apparently become more dewatered with age.

In summary, burial of sediment in Cascadia Basin to depths of 2.5 km (approximate maximum thickness of sediment overlying the oceanic basaltic crust) could not account for the high degree of consolidation noted in the near-surface sediments collected from the deformed slope ridges in the ridge and basin province. Therefore, most of the consolidation is attributed to the tectonically induced horizontal stress associated with the convergence of the Juan de Fuca and North American plates whose boundary lies near the Cascadia Basin-continental slope interface off Oregon and Washington.

4.2 Foliation in Mudstones

The effects of sediment deformation in the slope ridges is seen in the development of foliation in the mudstones recovered from the ridges (Berglund, 1980). Small (10-150 mm wide, 10 cm long) fractures/veins spaced 1.5-2.0 cm apart define a spaced cleavage which apparently limits the shear strength of the mudstones to values of <450 kPa. Movement along the foliae may accommodate much of the tectonic strain after consolidation (Berglund, 1980). Fluid movement through the accretionary prism during dewatering may be enhanced by these veins and fractures (Arthur, Carson, and von Huene, 1980), especially if the sedimentary section is overpressured as suggested by Seely (1977).

4.3 Cementation of Deformed Ridge Sediments

Carbonate cementation occurs in the dewatered sediments that comprise the ridges found in ridge and basin province. When cementation occurs in the mudstones and sandstones, it is invariably composed of secondarily precipitated microcrystalline calcite, aragonite, and /or proto-dolomite (Scamman, 1981). The sands in the turbidites, derived largely from the submarine fans (Kulm and Fowler, 1974) are preferentially cemented relative to interbedded muds. The detrital sand grains are carbonate supported, filling the voids originally occupied by interstitial fluids (Scamman, 1981). Laboratory experiments show that large-scale fluid movement takes place in the dewatering accretionary prism (Carson and Berglund, 1983); these deep-seated fluids are most likely the source of the calcium and carbonate ions. Scamman (1981) suggests that the carbonate cementation occurs in the Cascadia Basin deposits just prior to uplift and accretion to the continental slope. Carbonate content of the sediments is limited by the porosity of the detrital sediment at the time of cementation. Comparison of the carbonate content to the texture of the sediment indicates that the host sediment is largely uncompacted at the time of cementation.

In contrast, the sediments of Cascadia Basin do not exhibit any appreciable cementation as noted at deep-sea drilling Site 174 located about 100 km from the base of the continental slope in the distal portion of Astoria Fan (Kulm, et al., 1973). However, one encounters varying amounts calcium carbonate in the Pliocene calcareous mudstone in the abyssal plain silt turbidites underlying the fan sands, but the fans sands are devoid of any appreciable carbonate and they are not cemented.

5.0 Ages and Rates of Vertical Movement on Continental Margin

The age of the terrigenous clastic deposits (siltstone, sandstone, and mudstone) comprising the continental shelf are known from a series of holes drilled by industry on the shelf (Plate 5.0). These deposits range in age from Pleistocene to early Eocene. Eocene basaltic crust apparently underlies a portion of the shelf based upon geophysical data and extrapolation with land strata in areas off Oregon and younger basalt is interbedded with the clastic rocks off central Oregon. Oligocene (?) melange forms the foundation of the shelf off portions of Washington.

The deformed and dewatered sediments collected on the ridges in the ridge and basin province range in age from late Pliocene to late Pleistocene based largely upon radiolarian biostratigraphy (Plate 5.0; Carson, 1977; Kulm and Fowler, 1974). The westernmost marginal ridge off Oregon and

Washington is characterized by the youngest sediment (0.3 to 0.5 my). Ridges situated 10 to 28 km to the east of the marginal ridge generally range in age between 0.4 to 2.0 my. The limited number of age dates indicates that the ridges become progressively older east (landward) of the most recently formed ridge that marks the boundary between the lowermost continental slope and the abyssal plain. This progression of ages indicates that successively younger material is being accreted to the lowermost continental slope in the form of marginal ridges. These relatively young, deformed sediments exhibit the highest rates of vertical movement of any of the sedimentary deposits on the continental margin. Calcualted minimum rates of uplift range from 550 to 1000 m/my for these Pleistocene to Holocene deposits (Fig. 3.19).

Mudstones and a lithic wacke dredged in the vicinity of the structural benches on the upper continental slope off southern Oregon are late Miocene in age (6.5 to 8.5 my, Plate 5.0; Spigai, 1971). These lithologies were dated using benthic and planktonic foraminiferal assemblages. The benthic assemblages indicate minimum rates of uplift of 30 to 100 m/my and subsidence of 26 m/my since late Miocene to the present (Fig. 3.19; Kulm and Fowler, 1974; Spigai, 1971).

The stratigraphy of the lower continental slope was determined through deep-sea drilling at site 175 off central Oregon. This drill site is situated about 10 km landward of base of the continental slope in a narrow basin between two ridges in the southernmost part of the Ridge and Basin province (Fig. 1.0 and Plate 5.0; Kulm and Fowler, 1974). This section consists of middle to late Pleistocene (1.2 to 0.6 my) silty clays, with interbedded silt turbidites, which grade upward into late Pleistocene (0.6 my to present) hemipelagic silty clays (Plate 5.0). Benthic foraminifera in the silt turbidites and their age indicate uplift (about 800 m) of these former abyssal plain deposits between 0.3 and 0.45 my ago (Kulm, von Huene et al., 1973). Folding of younger deposits has since produced the anticlinal fold seaward of the uplifted deposits drilled at Site 175.

6.0 Crustal Velocity Structure and Heat Flow

Seismic refraction studies off the continental margin (Shor et al., 1968) show that oceanic crustal velocities of 6.6 km/sec occur at a subsurface depth of 10 km on the continental shelf off central Oregon. Cenozoic sedimentary and volcanic rocks overlie what is apparently remnant Eocene oceanic crust that was emplaced during a former period of underthrusting. This crust and the overlying deep water sediments have been uplifted to form the structural highs along some portions of the outer continental shelf (Braislin, et al., 1971; Kulm and Fowler, 1974; Snavely et al., 1980). Mantle depths range between 14 and 20 km for western Oregon (Shor et al., 1968; Berg et al., 1966; Thiruvathukal et al., 1970; Dehlinger et al., 1968;) which are much shallower than normally associated with continental crust.

In Cascadia Basin, at the base of the continental slope, the mantle is at a depth of 10-11 km and is overlain by a 5.0-6.9 km/sec crystalline oceanic layer 5 to 6 km thick, which is typical for normal oceanic crust. However, the thick sedimenatry deposits (about 2.5 km) of the submarine fans and underlying abyssal deposits should produce regional compensation and thus a deeper mantle. According to Shor et al. (1968), the shallow mantle may be related to the low-density mantle that exists beneath the young crust of the Juan de Fuca Ridge and Cascadia Basin (see also Dehlinger et al., 1968).

The low density upper mantle may be due to the high heat flow in Cascadia Basin (ie: Juan de Fuca plate) which ranges from 100 to 300 mW/m^2 (Connard et al., 1983; Fig. 6.1), these heat flow values are much higher than those found in the older oceanic plates that generally enter subduction zones. High heat flow (100-500 mW/m^2) occurs in the vicinity of the Juan de Fuca Ridge and in the sediment covered portions of Cascadia Basin (100-300 mW/m^2) (Fig. 6.1). Higher than normal temperatures in the sediment on the young subducting Juan de Fuca plate are expected due to the thick terrigenous turbidites and hemipelagites that cover the basaltic crust virtually as soon as it forms at the spreading center Scheidegger (1983). Connective processes such as hydrothermal circulation are impeded by the sediment insulation and the warm lithosphere that has just formed at the spreading ridge continues to cool slowly by conduction. Because of these processes, McClain (1981) suggests the lithosphere is only about 30 km thick over this young (less than 8 my old) Juan de Fuca plate.

This relativly high heat flow continues onto the lower continental slope where values of 40-142 mW/m^2 occur in the thick sedimentary deposits comprising the lower slope off central Oregon and no doubt elsewhere along the Oregon-Washington outer margin (Fig. 6.1). These heat flow values are a factor 2 to 3 higher than those normally associated with the so-called "cool" forearc regions of the world. Temperature calculations by McClain (1981) from

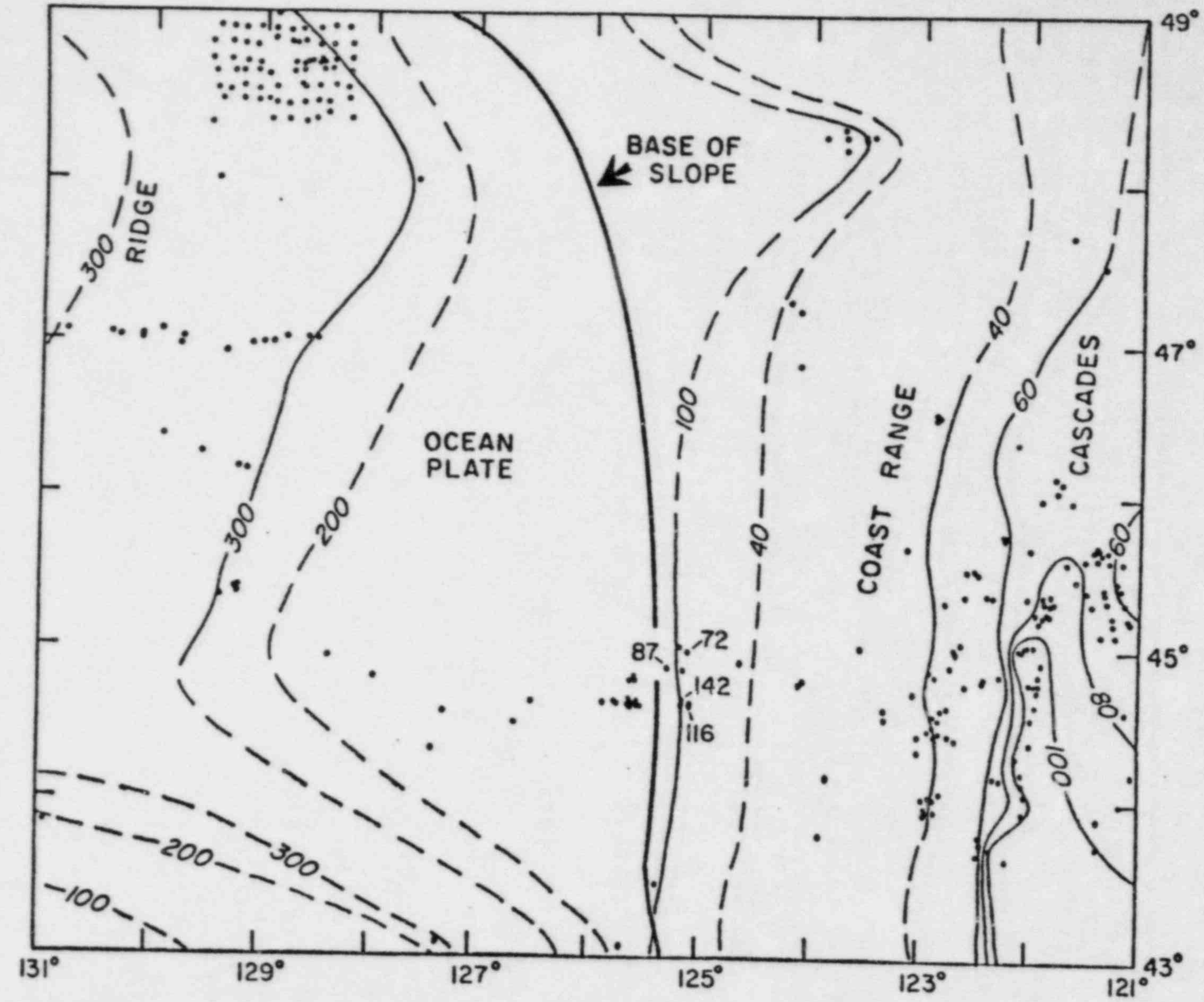


Figure 6.1 Heat flow of the Juan de Fuca plate, adjacent continental slope and continental land area (From Connard et al., 1983). Heat flow expressed in mW/m^2 in contours and isolated values on slope. Heat flow is extremely variable and contours are generalized.

existing heat flow data show that with 2 km of sediment near the base of the continental slope in Cascadia Basin the temperature ranges between 134-200° C. For the lower continental slope, the sediment thickness is 2.8 km and the resultng temperature is 188-280° C. As noted by McClain, the added 800 m of sediment insulation on the already warm oceanic crust raises the temperature 60-80° C. Such elevated temperatures are conducive to greenschist metamorphism (ie: at temperatues above 150° C) and it is possible that oceanc layer 2 has been metamorphosed to greenschist prior to subduction (Scheidegger, 1983).

The most recent and most detailed seismic refraction studies of the crust have been conducted on the lower continental slope off southern Washington by McClain (1981; Fig. 6.2 and Plate 3.2). While early seismic refraction data showed sediment velocities of 1.8-2.3 km/sec above the oceanic crust in the Cascadia Basin near the base of the continental slope, McClain's work shows a 4.0 to 4.5 km/sec layer 500 m thick sandwiched between the oceanic crust (>5.0 km/sec) and overlying sediments having velocities of 2.0-2.7 km/sec (Fig. 6.2). Seismic refraction data from Clowes and Knize (1979) at 48°30′N latitude at the base of the slope in Cascadia Basin discovered 1.8 km of sediment with a velocity of 2.4 km.sec underlain by 0.5 km of sediment with a velocity of about 3.1 km/sec. Published and unpublished multichannel seismic reflection data also show that a relatively high velocity layer (2.7-3.4 km/sec) begins to form above the young oceanic crust approximately 30-50 km seaward of the base of the slope in Cascadia Basin (Seely et al., 1974). The 4.0-4.5 km/sec layer beneath the lowermost slope may be a landward extension of the basin layer, but the increase in seismic velocities under the slope probably result from a decrease in porosity through mechanical consolidation or through chemical consolidation by cementation. If metamorphism is important in the oceanic crust, its influence would most likely decrease the porosity of sediments and increase the seismic velocities which are documented for the deepest sediment beneath the slope.

The velocity structure of the marginal ridge appears to be similar in a north-south direction because the velocities are the same at both ends of the refraction lines. The east-west refraction lines crossed several elevated and buried ridges (eg: Fig. 3.33) and show a more complicated velocity structure, although there is a general increase in velocity landward from the marginal ridge (outermost ridge).

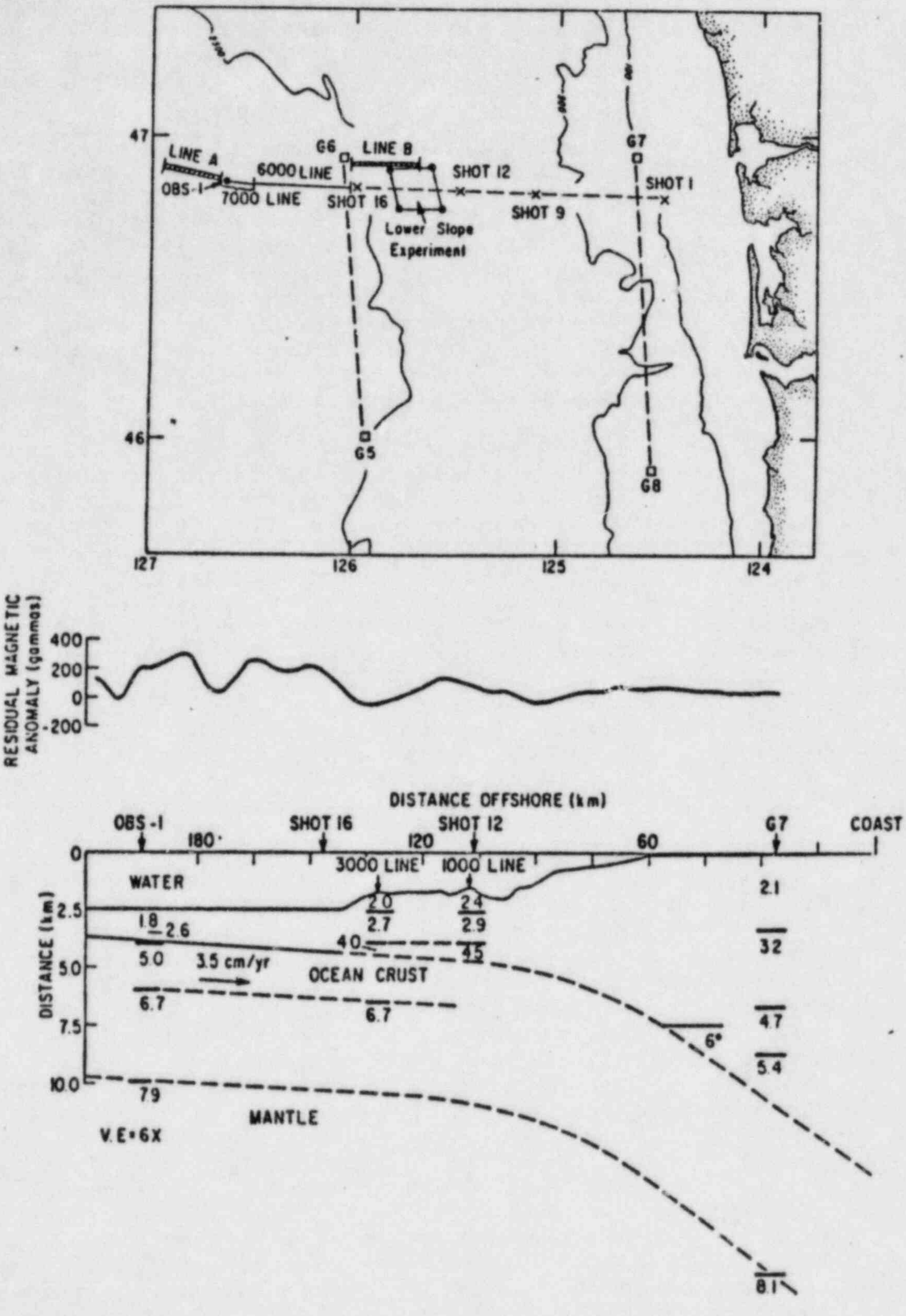


Figure 6.2. Seismic refraction data from McClain (1981). Top: location of seismic refraction study across the southern Washington margin and adjacent Cascadia Basin. Bottom: crustal section showing velocities and thickness of crustal layers. Note 4.0-4.5 km/sec layer identified beneath lower slope in detailed experiment. See text for explanation.

This increase in velocity is consistent with the increase in dewatering that occurs from the marginal ridge landward (Fig. 4.11).

7.0 Margin Comparisons

Several different convergent continental margins of the world were considered for comparison with the Oregon-Washington margin. The criteria used for such a comparsion were the morphology, structure, and styles deformation of these margins since this is the primary task being conducted on the Oregon-Washington margin. The sedimentary framework of the subducting plate also was taken into account since the morphology and structure of the Oregon-Washington margin is beleived to be related, at least in part, to the thick sediment cover of the Juan de Fuca plate. This narrowed the choices of active margins to select regions of the world, that is, those margins and subducting plates that have experienced high rates of sedimentation and deformation during Cenozoic time and especially since Quaternary time. Although other factors, such as the age of the subducting plate, the rate of subduction, the direction of convergence and subduction, and the seismicity, may be important in such a comparison, only a few of these parameters are discussed here due to the author's time contraints on the various tasks pursued under this contract.

Three active margins, southern Barbados fore arc, Makran fore arc off Pakistan and Iran in the Gulf of Oman, and northern Sunda fore arc (ie: Andaman and Nicobar islands), were selected for the comparison with the Oregon-Washington fore arc. Another region, the South Chile margin, also fits the criteria listed above although there is not as much information available for this active margin nor is the seismicity as well known as in the other three cases.

All three of the regions studied are characterized by active subduction zones and relatively thick to extremely thick terrigenous sediment cover on the subducting oceanic plate as well as in the adjacent forearc region. The rates of plate convergence range from about 2.0 to 5.6 cm/yr. with the northern Sunda arc exhibiting oblique subduction. There is documented evidence of deformation of all forearc regions, including deformation of the deposits on the adjacent subducting plate. None of the regions has a topographic trench due to the thick accumulation of sediments and, submarine fans, Nicobar and Bengal fans, occupy the trench in the northern Sunda arc. While the seismicity in the three areas was not investigated as part of this report, it appears that the Gulf of Oman (Nowroozi, 1976) and Barbados (Tomblin, 1975) regions identified above may only exhibit shallow to intermediate depth earthquakes. In these three regions, many of the sedimentary and structural characteristics of the subducting plate, as well as certain structural aspects of the adjacent forearc, are similar to those observed for the subducting Juan de Fuca plate and the adjacent Oregon-Washington fore arc.

The structure and morphology of the forearc off the Makran in the Gulf of Oman has been compared with that observed (and described in this report) for the Washington continental margin (White and Kiltgord, 1976; White and Ross, 1979; White, 1977; White and Kiltgord, 1976). The Makran continental margin is characterized by an accretionary prism that is created by the subduction of the Arabian oceanic plate beneath the Eurasian plate at a rate of about 4 cm/yr. Deep Sea Drilling Project hole 233 (18°45'N and 60°08'E) drilled through deep marine sediments and bottomed in Paleocene basalt (Witmarsh et al., 1974), which suggests that the crust in the Gulf of Oman is at least Paleocene in age (Farhoudi and Karig, 1977). The Gulf of Oman is covered by more than 6 km of sediment (White and Kiltgord, 1976). The morphology of the the lower continental slope off the Makran (Fig. 7.1) is virtually identical to that observed in the ridge and basin province (Plates 2.2 & 2.3) located on the lower slope off northern Oregon and Washington. In both regions, the ridges with intervening basins rise to elevations of about 800 m above the adjacent abyssal plain of the oceanic plate, forming a broad platform whose depth remains rather constant over several tens of kilometers. Off the Makran seismic reflection records show a sequence of folds that are oriented parallel to the coast; they form a system of ridges and troughs that step up towards the coast (Fig. 7.2; White, 1982; White and Kiltgord, 1976). Initial deformtion of the frontal or marginal fold is shown in figure (Fig. 7.3). The direction of vergence appears to be seaward in the frontal fold. This type of deformation is similar to that observed off northern Oregon (Fig. 3.11) along the lower slope and along portions of the Washington margin (Figs. 3.26, 3.36), except the marginal ridge of the latter margin is frequently more asymmetrical and may reflect either seaward or landward vergence with an apparent fault bounding the seaward side and landward side respectively, of the anticlinal fold. However, recent deformation and sediment offscraping of the subducting oceanic plate sediments are occurring in both regions and the deformation front is migrating seaward with the addition of each ridge (White, 1982; Silver, 1972; Carson et al., 1974; this report). The frontal or marginal fold is then incorporated into the accretionaly prism by uplift along a thrust fault. Off the Makran the intial buckling is confined to the uppermost 2.5 km above the decollement zone and there is

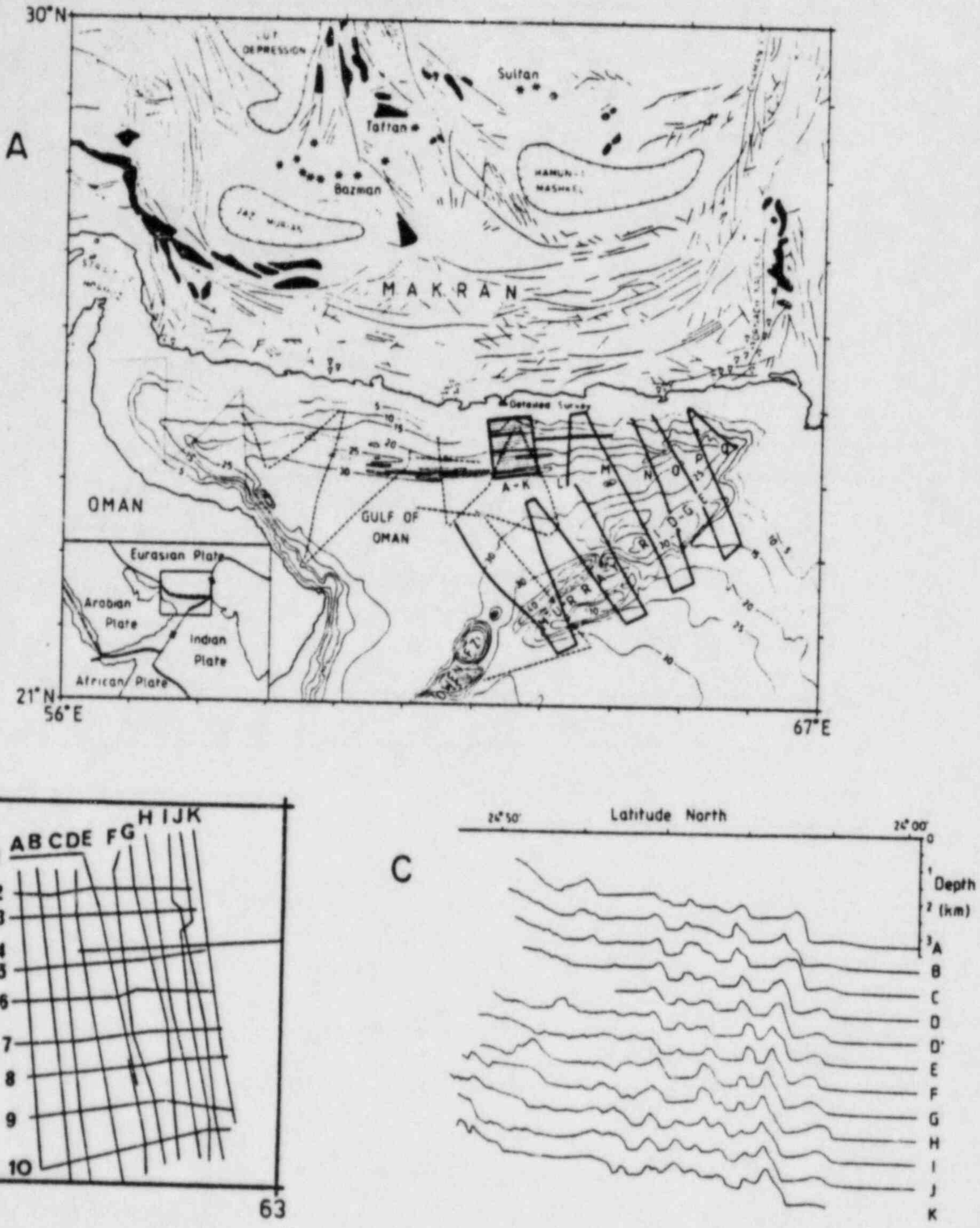


Figure 7.1. (A) location of Makran fore arc and seismic reflection records. (B) detailed seismic lines (see ruled box in A). (C) bathymetry profiles of abyssal region and continental slope, profiles located in B. (Figures after White, 1982)

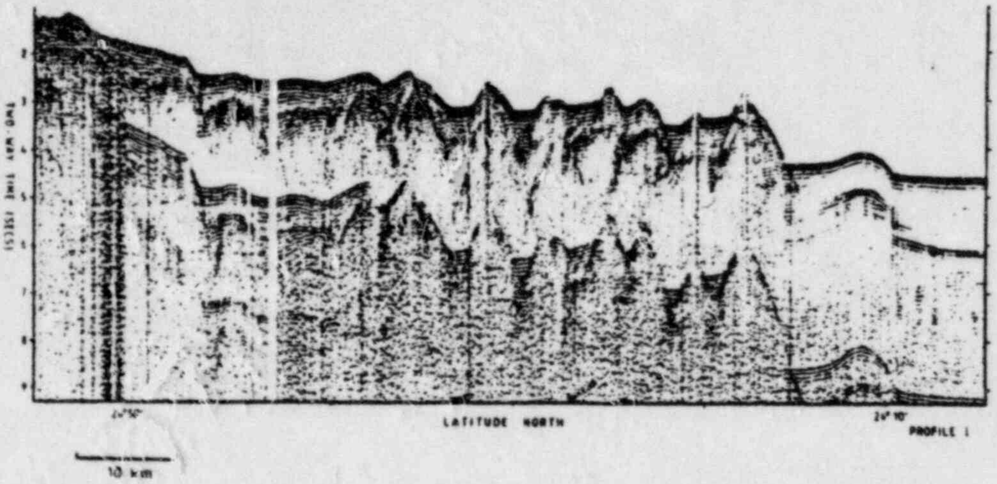


Figure 7.2. Continuous seismic reflection profile taken along line I in figure 7.1 (diagram B); profile taken perpendicular to strike of fold belt. Vertical exxageration is about 7:1. (From White, 1982).

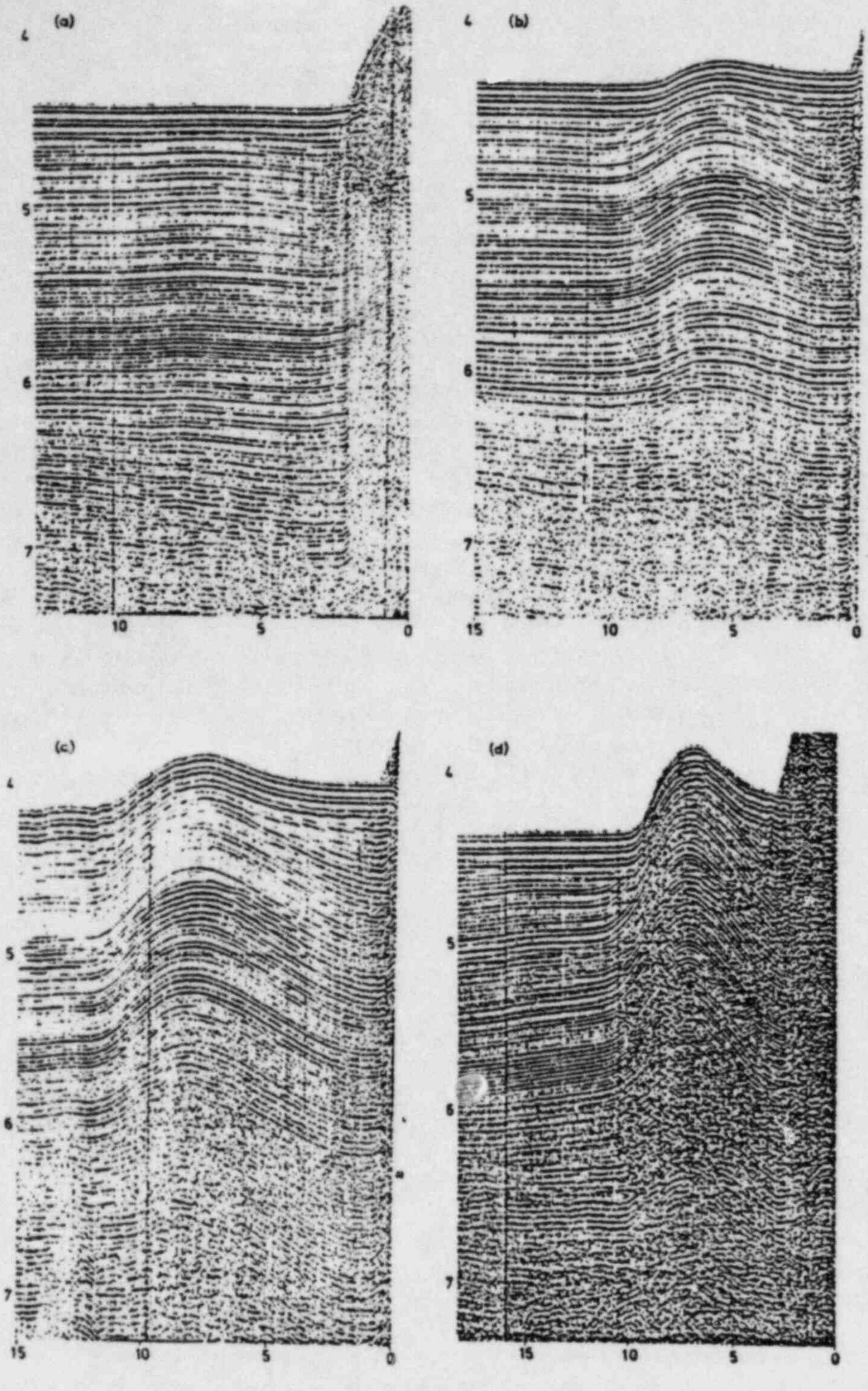


Figure 7.3. Seismic reflection records across the frontal folds of Makran fore arc shown in figure 7.2. Folds shown in increasing order of deformation (ie: A to D) from several localities. Horizontal scale in kilometers; vertical exaggeration about 10:1. (From White, 1977)

evidence of small-scale diapirism (White, 1977, 1982). Deformation may be facilitated by overpressuring of the clays that are buried within the rapidly accumulting, thick sedimentary sections (White, 1977; Seely, 1977).

The oceanic plate (ie: Indian plate) off the northern part of the Sunda fore arc in the vicinity of the Andaman and Nicobar Islands is characterized by a thick sedimentary cover which is produced by rapid deposition on the Nicobar and Bengal fans (Fig. 7.4). The turbidite deposits of the Nicobar Fan thicken to the north, increasing from 1 in the south to more 2 km in the north (Moore et al., 1980; Curray and Moore, 1974; McDonald, 1977: Bowles et al., 1978). Convergence is slightly oblique in the South and Central Sumatra province (area II of figure 7.4) and the component of subduction rate perpendicular to the trench decreases from 7.0 to 5.7 cm/yr northward (Moore et al., 1980. A migrated seismic profile at the base of the lower trench slope indicates the deformation occurs as a monoclinal flexure that may produced by a landward dipping thrust fault (ie: a seaward vergence sequence). The morphology of this province exhibits ridges that approximately parallel the continental slope and small basins with variable amounts of sediment fill; basins closest to the trench have the least amount of sediment. These ridges and basins do not have the same morphology as the ridge and basin province found off northern Oregon and Washington.

Moving northward into the North Sumatra-Nicobar provice, the convergence (area III of figure 7.4) along the province is highly oblique and the perpendicular component of subduction decreases northward from 5.6 to 4.1 cm/yr (Moore et al., 1980). The relatively thick deposits of the oceanic plate at the base of the slope are deformed into a fold structures, some of which display apparent seaward vergence. However, Moore et al., 1980 observed landward vergence in these slope structures on industry seismic records made in this area. If this is correct (no records are shown in their paper), it would be one of the few occurrence of landward vergence reported for active margins with the exception of such occurrences documented for the Oregon-Washingon margin as described in this report. In both cases, landward vergence is associated with thick sedimentary deposits on the subducting oceanic plate. Thick submarine fan deposits may cause overpressuring of the underlying abyssal plain deposits as postulated by Seely (1977) for northern Washington and as discussed for the Makran fore arc.

Convergence is also highly oblique in the Andaman province (area IV of figure 7.4) with the perpendicular component of subduction being 0.7 to 2.1 cm/yr. The component of

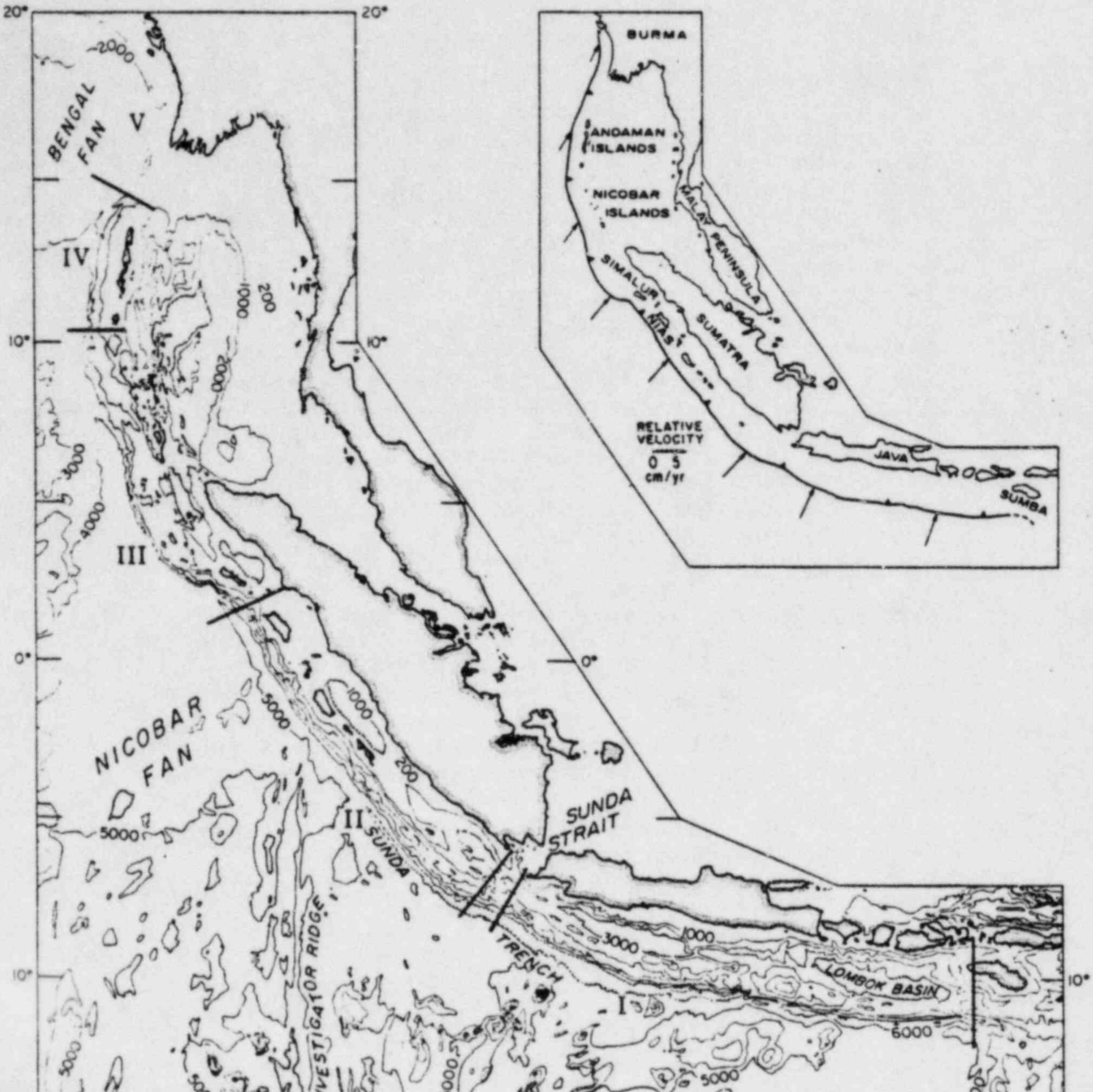


Figure 7.4. Bathymetry (meters) and location of Sunda arc. Tectonic provinces (II) indicated. Directions and rates of plate convergence shown in inset. (From Moore et al., 1980).

perpendicular subduction in this and the province to the south is both higher and lower than the perpendicular rate of subduction indicated for Oregon-Washington (ie: 3.2 cm/yr) as discussed elsewhere in this report. A well developed ridge and trough morphology occurs on the inner trench slope in the Andaman province, but the ridges with their ponded basins are elevated in steps (figure 7.5; Moore et al., 1980) several hundred meters above the ridge and basin set forming to the seaward; the ridges parallel the slope. A tight fold has developed as a marginal ridge uplifting the trench and Bengal Fan sediments and exhibits a slight landward dip which suggest a seaward vergence of the sedimentary sequence. Father north in the Burma province (area V), the trench has no expression at the base of the continental slope and the seafloor is about 3 km deep. A seismic section in this area shows the thick sediments are broadly warped into a fold (Fig. 7.6; Moore et al., 1980) which is similar to that of the marginal fold described for the Makran (White, 1977; Fig. 7.4) and off northern Washington. Subduction is highly oblique here approaching strike-slip motion. While this portion of the Sunda fore arc has several charactersitics of individual features of the Oregon-Washington lowermost continental slope, the overall accretion pattern across the fore arc is different than that noted in the ridge and basin province of the latter region. However, the uplifting and tilted basins behind the ridges in figure 7.5 are similar to some of those seen in central Oregon and northern Washington (see Figs. 3.11, 3.24).

While the morphology and perhaps the structure of the Barbados fore arc varies along its length (Westerbrook, 1982), the southern portion (about 11° to 14°N latitude) of the forearc exhibits the anticlinal ridges noted off regon and Washington (Fig. 7.7; Fig. 7.8, Biju-Duval et al., 1982). The trench is absent here and the oceanic plate has a thick sediment cover. The rate of convergence is about 2 cm/yr in a westerly direction (Minster and Jordan, 1978). Deformation of the basin deposits behind the folds, along the lowermost slope, is not as clear as noted in the other forearc regions discussed here, but a seaward verging underthrust sequence is clearly documented along the leading edge of the fore arc at 15°30'N latitude by Deep Sea Drilling Sites 541 and 542 (Moore et al., 1982).

8.0 Conclusions

1. The structure, stratigraphy, morphology, and sediment

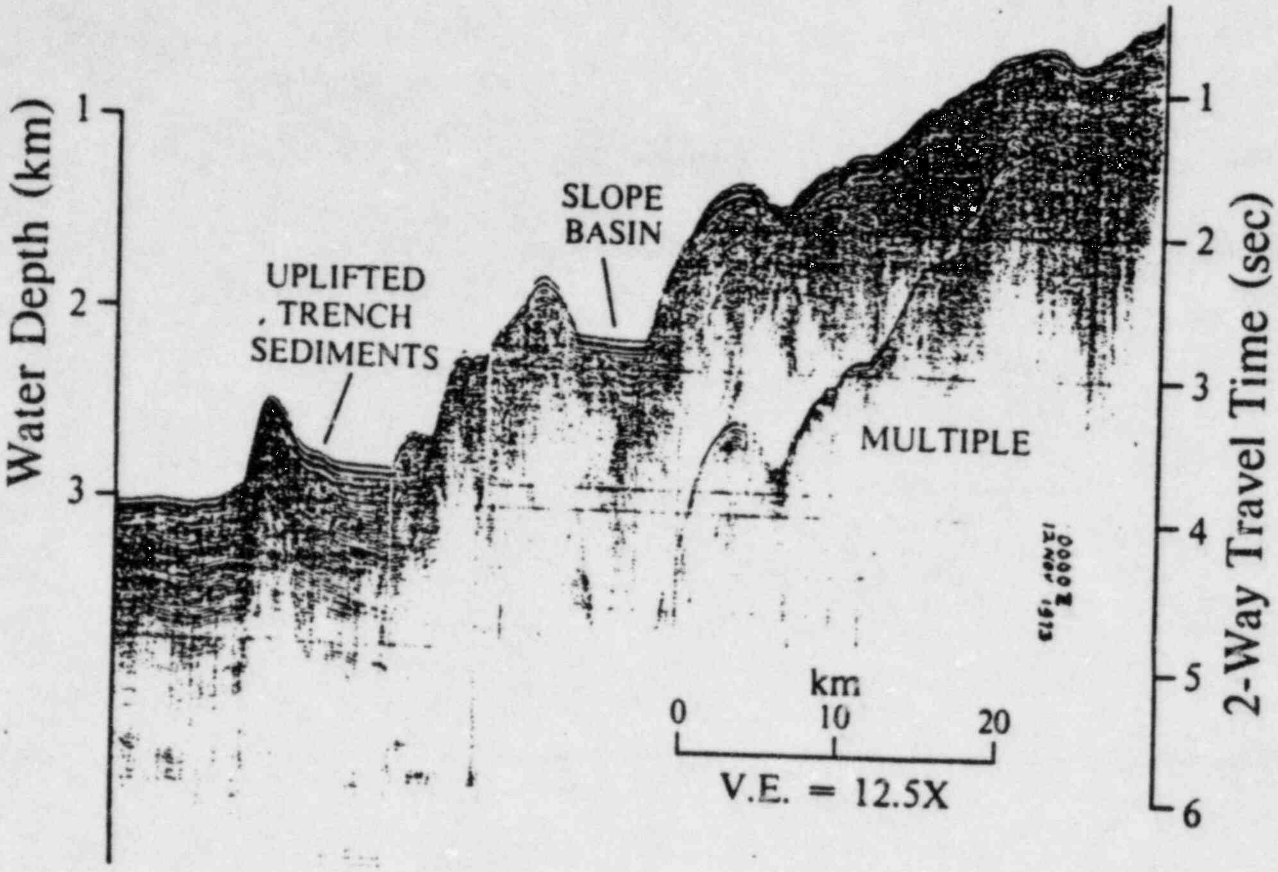


Figure 7.5. Seismic record showing deformation of Bengal Fan west off Andaman Islands. Note marginal ridge and uplifted basin to the landward. (From Moore et al., 1980).

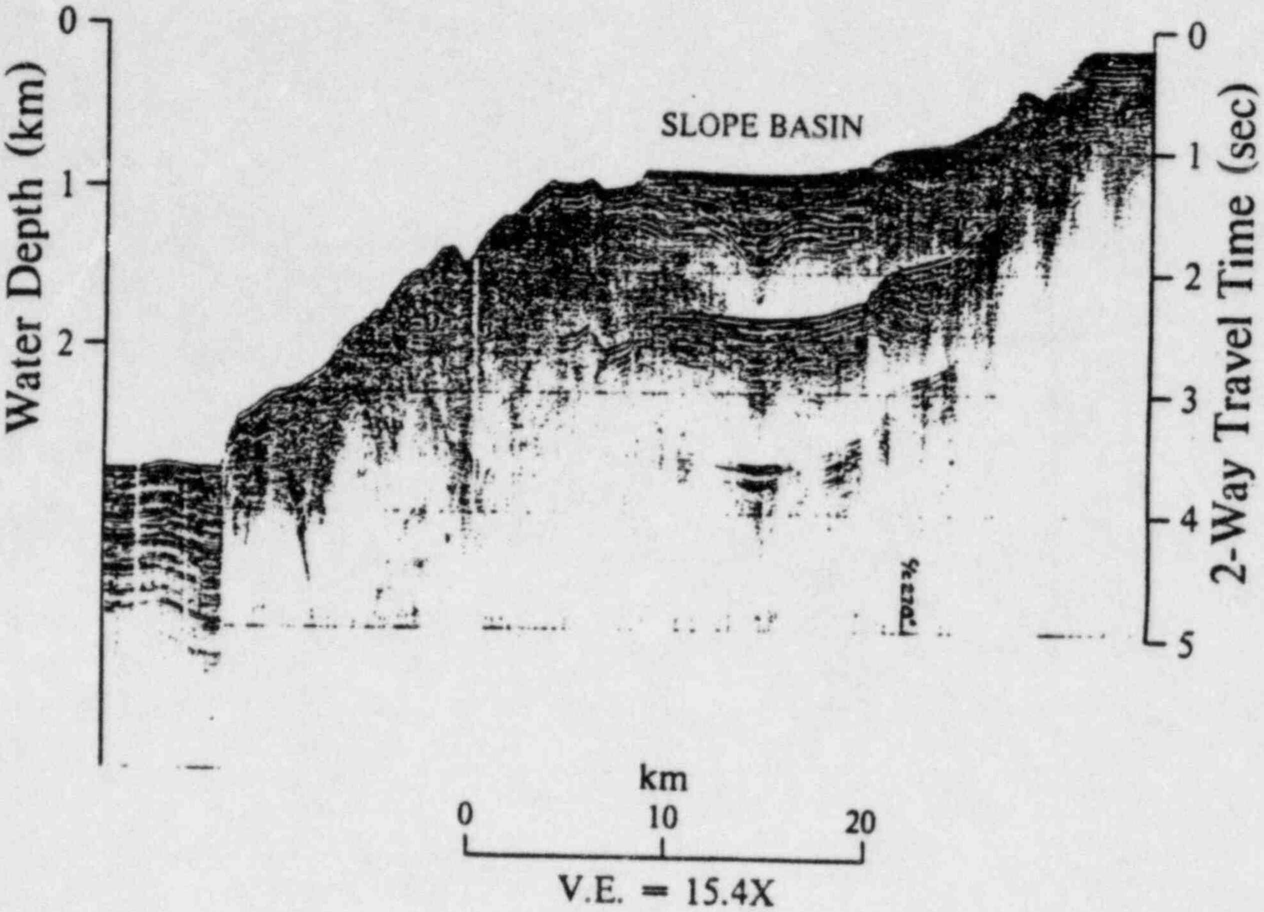
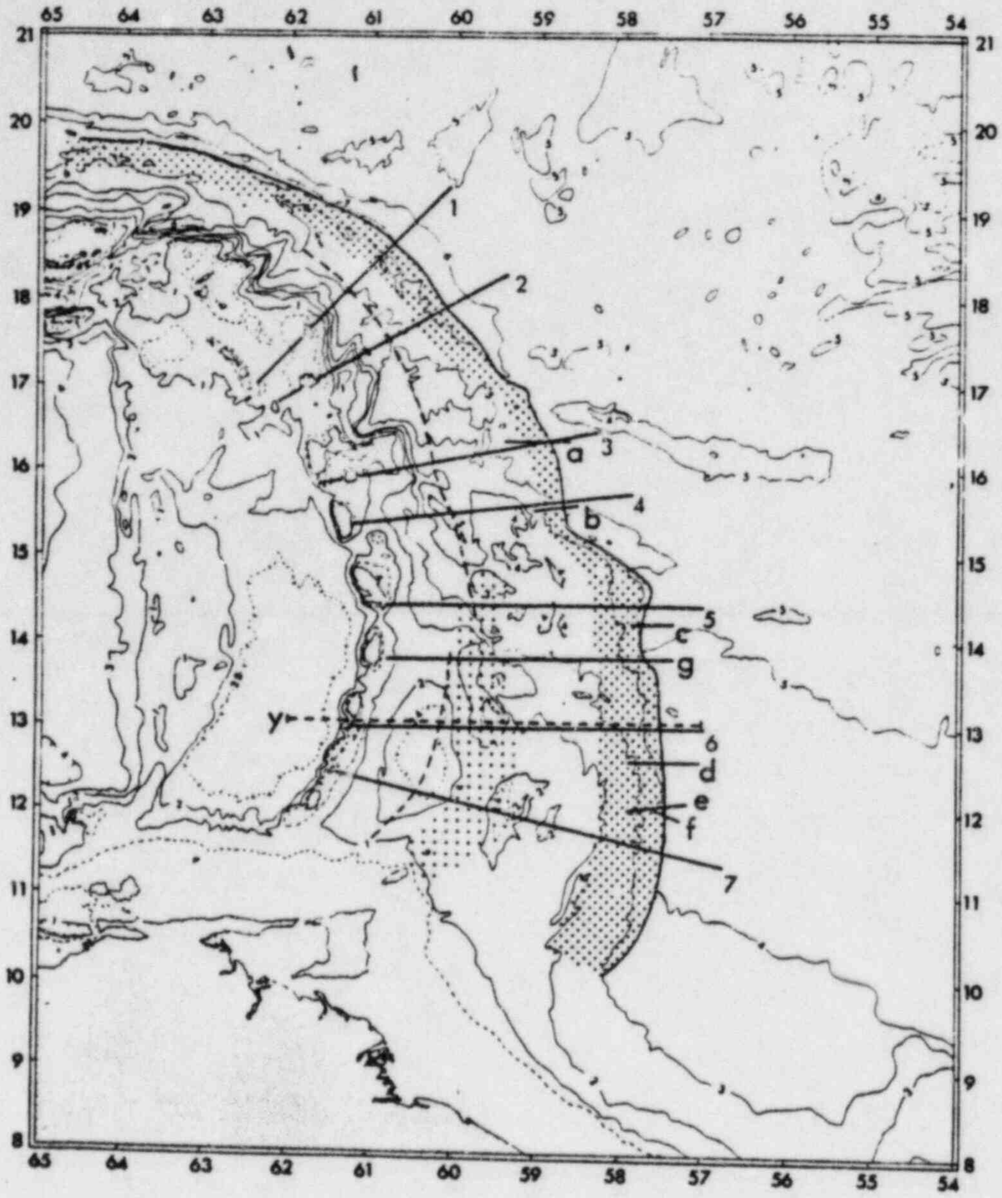


Figure 7.6. Seismic record showing folded strata near base of continental slope off the southwest coast of Burma. (From Moore et al., 1980).



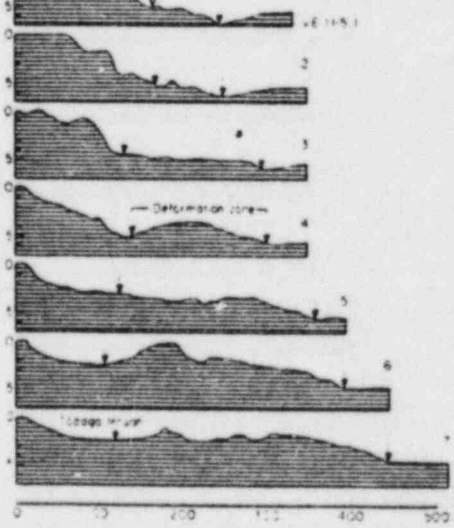


Figure 7.7. Location map of Barbados fore arc (top) and bathymetric profiles (right). See profile numbers on location map. (From Westerbrook, 1982).

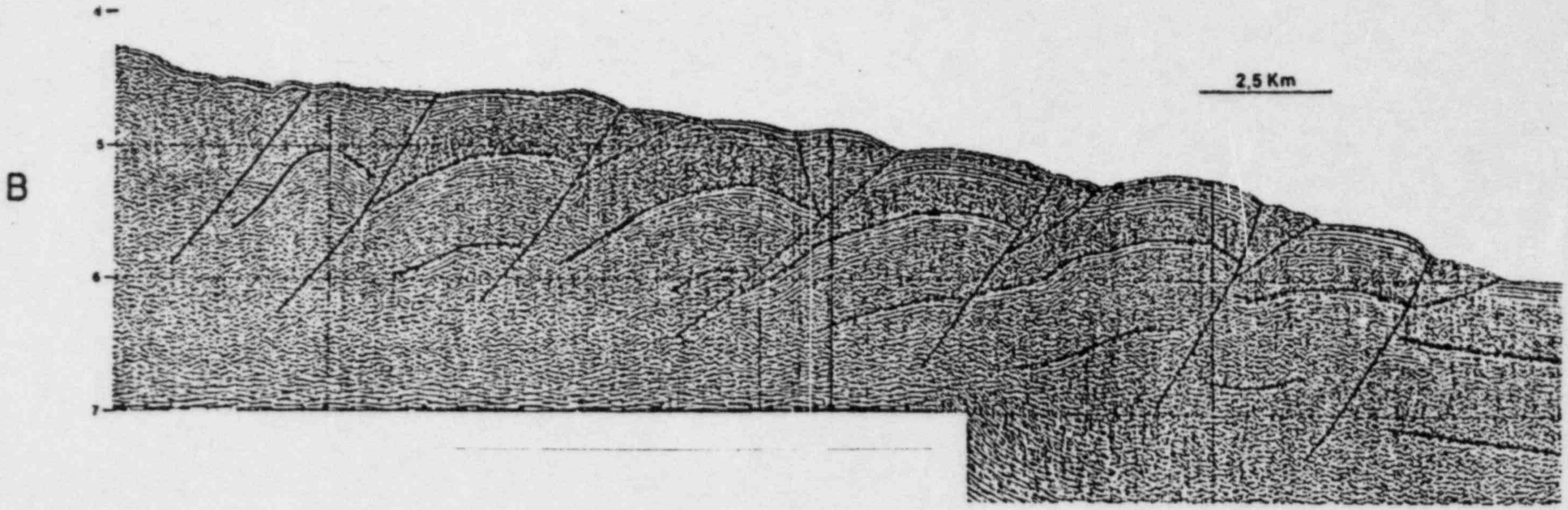


Figure 7.8. Migrated time section of multichannel seismic record (B) from the southern Barbados fore arc: location about 12 N latitude extending from the abyssal plain to the middle continental slope. (From Biju-Duval et al., 1982).

physical properties of the Oregon-Washington continental margin and adjacent Cascadia Basin indicate that the Juan de Fuca plate has been converging with the North American plate during late Cenozoic and Quaternary time. The late Cenozoic sedimentary deposits of the Oregon-Washington continental shelf and slope (fore arc) show abundant evidence of sediment deformation such as warping, folding, and faulting. This deformation continues upward into the Quaternary deposits in several areas of the continental shelf and slope. These tectonic processes have produced a series of ridge and basin structures which comprise the outer continental margin off central and northern Oregon and off Washington. Quaternary sediments of the adjacent Cascadia Basin (Juan de Fuca plate) also are folded and faulted immediately seaward of the base of the continental slope. Some of the most extensive and prominent regions of deformation in Cascadia Basin occur off central and south central Washington between 47°38' N and 47°05' N latitude where a variety of deep deformational features extend upward into the sedimentary section to offset and deform the most recently deposited sediments near the base of the continental slope. Sediment dewatering characterizes the late Pleistocene deformed sediments comprising the marginal ridges and their predecessor ridges along the lower continental slope off Oregon-Washington and indicates tectonic-induced deformation under horizontal compression. This widespread and continuning dewatering process most likely results from the convergence between the Juan de Fuca and North American plates, and the evolving marginal ridge (ie: deformational front) marks the boundary between these two plates at a given time.

The Oregon-Washington continental margin exhibits many of the structures and stratigraphic relationships commonly associated with an active subduction zone where sediment offscraping and large-scale accretion of the sedimentary deposits occur as the subducting oceanic plate passes beneath the overriding continental plate. Seaward vergence of Pleistocene structures comprising the lower continental slope shows that underthrusting is the dominant tectonic process in many areas of the Juan de Fuca-North American convergence zone described above. Landward vergence of Pleistocene structures is particularly prominent in several areas of the Washington and in one area of the Oregon convergence zone. This sequence of structures occurs where several hundred meters of the Pleistocene sediments of Cascadia Basin are thrust over the existing lower continental slope deposits, most noticeably in the vicinity of the marginal ridge along the lowermost continental slope. Both the underthrusting and overthrusting processes have facilitated the progressive accretion of Juan de Fuca plate sediments to the lowermost continental slopes off

Oregon and Washington throughout Quaternary time. A substantial portion of the Juan de Fuca plate deposits, especially the deeper 3.0 to 4.5 km/sec velocity material, was probably subducted during this time. Whlie it is not possible to determine if subduction is continuous or episodic, the bulk of the ridge and basin province (see item 2 below) appears to have been accreted to the continental margin during Quaternary time.

2. The morphology of the Oregon-Washington continental shelf and slope exhibits several positive relief features that suggest they are structurally controlled. Prominent submarine banks occupy portions of the outer continental shelf off Oregon; the seaward flank of these banks are rather straight and may terminate with a steep escarpment (Plates 2.0, 2.3). Rock outcrops have been photographed on these banks. Benches and plateaus frequently occupy the upper continental slope. The headward portions of numerous submarine canyons are located near the shelf-slope break and extend down the continental slope. A major change in the inclination of the continental slope occurs at a water depth of about 1500 m off northern Oregon and most of Washington. The rather steep upper slope merges into the lower slope, which is characterized by a ridge and basin province. This province appears as a low relief plateau that is elevated above the adjacent abyssal plain of Cascadia Basin; the north-northwest trending ridges rise from 100 to 800 m above general level of the plateau. The ridge and basin province ranges up to 45 km in width and is about 410 km in length. The lower slope merges smoothly with Cascadia Basin where submarine fans occur at the base of the continental slope or may form an abrupt interface with the slope in other areas. The rather straight abyssal plain-continental slope interface suggests that it is structurally controlled.

The lower slope basins in the ridge and basin province contain variable amounts of sediment which is generally related to the age of formation of the basin. The most recently developed basins behind the marginal ridge have only a thin covering of sediment whereas those older basins landward may have up to several hundred meters of sediment. If the basins are accessible to turbidity current flows, deposition is rapid with resulting thick accumulations. Structurally isolated basins, usually those near the marginal ridge, are characterized by hemipelagic sediment deposition through suspension in the water column until they come under the influence of turbidity current deposition. Basins with turbidite deposition best record the tectonic movements of the under lying folded and faulted structures of the evolving accretionary prism.

3. The late Cenozoic deposits on the continental shelf and the upper continental slope off Oregon and portions of the Washington are characterized by folded and faulted structures. Broad folds occur within the several interconnecting synclinal basins that occupy the shelf and upper slope. Shale diapirs are especially prominent off Washington and truncated anticlinal folds are common off Oregon on the shelf. Biostratigraphic data and seismic reflection records indicate that the Pleistocene and older strata are folded and faulted especially in the vicinity of the uplifting submarine banks that occupy the outer shelf off Oregon. The western (seaward) flank of the bank may subside relative to the uplifted eastern flank. Several hundred meters of uplift are recorded in these late Cenozoic deposits with the greatest amount occurring in the older Miocene and Pliocene strata; the Pleistocene strata record a lesser amount of uplift. Prominent angular unconformities, particularly Pliocene-Pleistocene and middle to late Miocene, occur within the synclinal basins of the shelf and document periods of uplift and subareal erosion followed by subsidence. Some upper slope basin deposits off northern Oregon exhibit discordant contacts between sedimentary units. These units represent migrating depocenters, which usually shift landward, in response to the uplifting deep water deposits of the middle to upper slope region. The most recently deposited sediment in these outer shelf and upper slope basins is frequently warped which suggests ongoing deformation of the underlying deep-water deposits.

Recent faulting of the inner shelf off southern Washington is indicated by vertical offset of the Holocene sediments on the seafloor.

4. Lower slope basin (ie: ridge and basin province) deposits show migrating depocenters that commonly shift landward in response to the uplift of the seaward ridge. More complex tilting of the basin strata with discordant contacts between succeeding sedimentary units are observed in several areas; the tilted strata may terminate against a fault within the basin. Some of he basin faults offset the seafloor and extend through the basin deposits downward to the highly deformed strata below. It is difficult to determine the length of the fault zones because of the wide trackline spacing of the

seismic reflection records. Tentative correlation of one fault in adjacent records suggests that it is at least 5 km long. The fault surfaces in one record, but terminates in the subsurface in the adjacent record. While there are many examples of faulting and warping of the basin deposits, some basins exhibit a previous history of tectonism followed by a more recent history of deposition without structural adjustments. These basins generally have a thin sediment cover.

The interface between the Cascadia Basin deposits and those forming the lower slope structural ridges (ie: marginal ridges) is a structurally complex region. Two structural styles, a seaward vergence sequence (underthrust) and a landward vergence sequence (overthrust), occur along this interface although there are many areas where the style of deformation is obscure because of the steep escarpments and possibly intense deformation. In both cases the sediments are highly dewatered and display other physical properties that indicate tectonic consolidation of the most recently folded and faulted deposits of Cascadia Basin. The dewatering process apparently occurs because of the horizontal compression induced by the convergence of the Juan de Fuca and North American plates.

Although the sediments lying a few kilometers seaward of this interface are generally undeformed, there are some striking examples of folding and faulting of these deposits. The most prominent fold and fault region occurs from 4 to 6 km seaward of the base of the continental slope between 47°38′N and 47°05′N over a distance of 62 km off central and southern Washington. There is insufficient data to determine if this is one continuous rupture zone or several separate zones; the strike of the faults and folds is also unclear at this time.

5. Evidence of continuing deformation along the outer Oregon-Washington margin is seen in the dramatic changes in physical properties observed in the sediment forming the ridges in the basin and ridge province. The youngest sediments (late Pleistocene, less than 0.3 my) of the marginal ridge have been dewatered to less than one-half of their original water content due to tectonic consolidation, induced by sediment offscraping of Cascadia Basin (ie: Juan de Fuca plate) deposits onto the continental slope. The sediments become progressively more dewatered (55-70% to 17-30% wet weight) in a landward direction and with age although the degree of dewatering is small compared to that occurring along the initial deformation front at the base of the continental slope. Void ratios show a

corresponding decrease (1.1-1.9 to 0.4-1.2) after the initial stage of deformation. Preconsolidation (maxium past) pressure values of <2.0 kPa are typical of unconsolidated deposits whereas values of 0.8 to 8.2 MPa are found in the deformed deposits. Foliation occurs in the mudstones; movement along the foliae may accommodiate much of the tectonic strain after consolidation. Additonal evidence of fluid movement is seen in the carbonate cement that occurs preferentially in the sandstones, relative to the mudstones, comprising the ridges.

6. Several different convergent margins were investigated for a comparison with the Oregon-Washington margin. Three subducting margins, Makran fore arc off Pakistan and Iran in the Gulf of Oman, northern Sunda fore arc, and the southern Barbados fore arc, have various aspects of morphology and structure that resemble those described for the Oregon-Washington fore arc. All three regions are characterized by relatively thick to extremely thick deposits on the subducting oceanic plate as well as in the fore arc area. The trench is absent (ie: completely filled with sediments) or of limited depth due to sediment fill. The Niocbar and Bengal Fan deposits are being accreted to the fore arc in the Sunda arc, which is similar to the Astoria and Nitinat Fan setting of the Oregon-Washington region. The rate of convergence for these areas ranges from 2.0 to 7.0 cm/yr; the Sunda arc is characterized by oblique to highly oblique convergence. Northern Oregon and Washington also experience oblique convergence with the Juan de Fuca plate. The rate of subduction perpendicular to the fore arc ranges from 0.7 to 7.0 cm/yr for these three areas; the rate of subduction off southern Washington is 3.2 cm/yr.

The Makran fore arc exhibts many of the morphologic and structural characteristics of the Oregon-Washington fore arc. The most prominent characteristic of the Makran outer fore arc is the ridge and basin structures that form a low plateau-like feature consisting of ridges and intervening basins, similar to that seen in Oregon-Washington ridge and basin province. The sediments of the abyssal plain are being folded immediately ahead of the marginal ridge that forms the base of continental slope. The vergence direction is not as clear in these most recently formed folds because they are rather symmetrical. However, seaward vergence is suggested in one seismic record. The basin deposits between the ridges do not exhibit the migrating depocenters, degree of warping, and internal basin faults as noted off Washington; at least, it can not be seen in the published seismic records. Despite these differences between the two fore arcs, the Makran region is a likely comparison with Oregon-Washington.

The submarine fans and the marginal ridge of the northern Sunda fore arc display similar characteristics to those of central Oregon and northern Washington (ie: a possble seaward vergence sequence). The sediments of the Bengal Fan are warped at the base of the continental slope and the trench is filled with fan deposits. The central to northern Sunda arc is characterized by varying degrees of oblique convergence, as noted off Oregon-Washington, but there is insufficient information to attempt to relate the morphology and structure to this oblique convergence.

9.0 References

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