33. TECTONIC SUMMARY OF LEG 18[1]

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INTRODUCTION

On Leg 18, a group of sites were drilled to see if evidence relating to subduction could be found at the continental margins off Oregon and Alaska. Furthermore, any indication of the rate of subduction was sought for comparison with the rates proposed in north Pacific plate tectonic models (Atwater, 1970; Hayes and Pitman, 1970). Interactions between lithospheric plates—a simple theortical concept—produce complex relations along the continental margins of the north Pacific. As with other developing geologic theories, there is a need to check the theory with field observations, where discrepancies between theory and observation seem to occur. For instance, the 6 cm/yr subduction under western Alaska required by present north Pacific models is difficult to reconcile with the lack of large compressional structures in sediments filling the Aleutian Trench and the steep faults and open folds of Neogene age on the continental shelf (von Huene et al., 1972). The absence of a Benioff zone beneath the continental margin off Oregon and Washington seems to indicate that subduction is not taking place, yet some observations are enticingly suggestive of subduction, such as the folded Pliocene and Pleistocene sediments of the Oregon lower continental slope. Similarly, off Alaska, the deformation during the great 1964 earthquake and the results of focal-mechanism studies are most easily explained by underthrusting (Plafker, 1969; Stauder and Bollinger, 1966). Thus some field observations support the theory and others conflict with it. A strong attraction for favoring underthrusting is its association with the popular theory of plate tectonics, but from observations along most continental margins the possibility of other tectonic mechanisms such as vertical uplift or massive slumping are not easily excluded. The apparent contradition between the proposed rates of subduction and the general absence of compressional structures prompted selection of the Leg 18 sites. Rapid sedimentation can bury many structures and rates of sedimentation are easily verified by deep sampling. Furthermore, from studies of cores, we thought we might establish whether ocean floor sediments are incorporated into the continental slope. These were some of our thoughts as we began Leg18.

[1]Publication authorized by the Director, U. S. Geological Survey.

LATE CENOZOIC HISTORY OF CASCADIA BASIN AND THE ADJACENT CONTINENTAL MARGIN

A group of sites (174, 175, and 176) were drilled to elucidate the geologic history of the Oregon continental margin and the adjacent oceanic Cascadia Basin. This history should reflect plate movements, because a subduction zone is postulated to form the juncture between oceanic and continental areas (Atwater, 1970; Silver, 1969, 1971). From the sediment sequence at each site a part of the geologic history can be inferred, and a summary of the three holes provides information on the tectonic history.

Distal Edge of Astoria Fan, Site 174

At Site 174, a sequence of abyssal silt beneath the distal edge of Astoria Fan was sampled to determine the age and lithology of the fan (Figure 1). Astoria Fan fills the upper part of a trench-like depression that borders eastern Cascadia Basin (Figure 2). The depression formed by eastward tilting of acoustic basement and the overlying abyssal plain sedimentary sequence (Figure 2) before the fan began forming, or as it formed. A seaward transgression of fan sediment is seen in the reflection record of Figure 7 in Appendix 1 (Kulm et al.), where the vertical scale of a seismic record has been highly exaggerated. Figure 7 also shows the complexity of bedding within Astoria Fan, which probably results from the deposition of sand and silt along the banks of shifting distributary channels on the fan. The angular contact between Astoria Fan turbidites and the underlying abyssal silt probably resulted when a hemipelagic facies changed laterally to a fan turbidite facies during a time-transgressive onlap (Figure 2).

The lithology, mineralogy, and rates of sedimentation at Site 174 indicate an initial, slowly deposited pelagic deep-ocean sediment followed by increasingly greater amounts of deep-ocean turbidites, and finally by the turbidites of Astoria Fan. Sampling of the basement was prevented by drilling difficulties, but from seismic records and measured sound velocities the basement is estimated to be 911 meters deep or about 32 meters below the bottom of the hole. The oldest sediment above basement is inferred to be 8 m.y. old because Site 174 is located on anomaly 5 (Heirtzler et al., 1968). This older section is known from two cores of muddy limestone containing clay minerals that were probably derived from local submarine detritus. The limestone was deposited at a rate of approximately 60 to

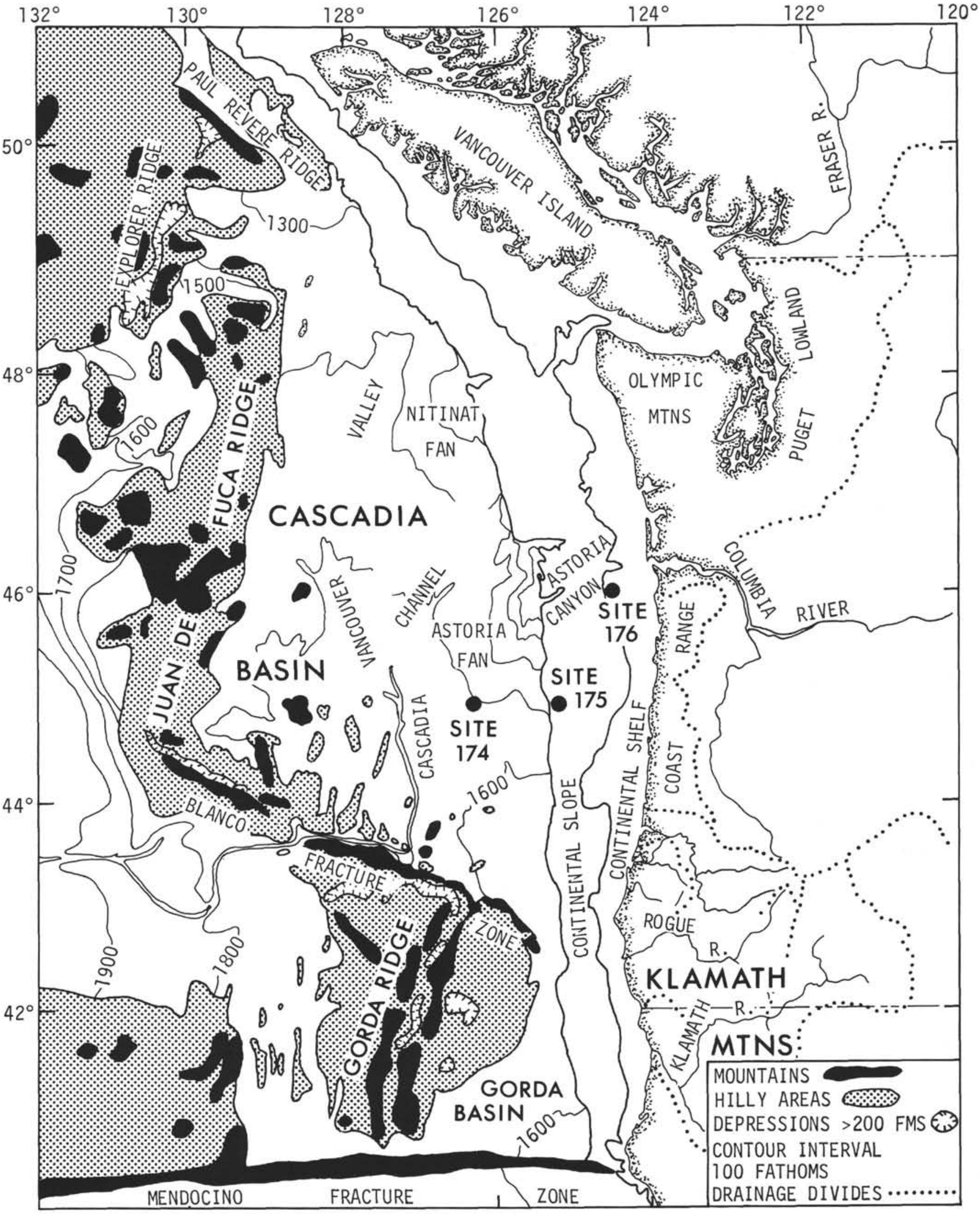
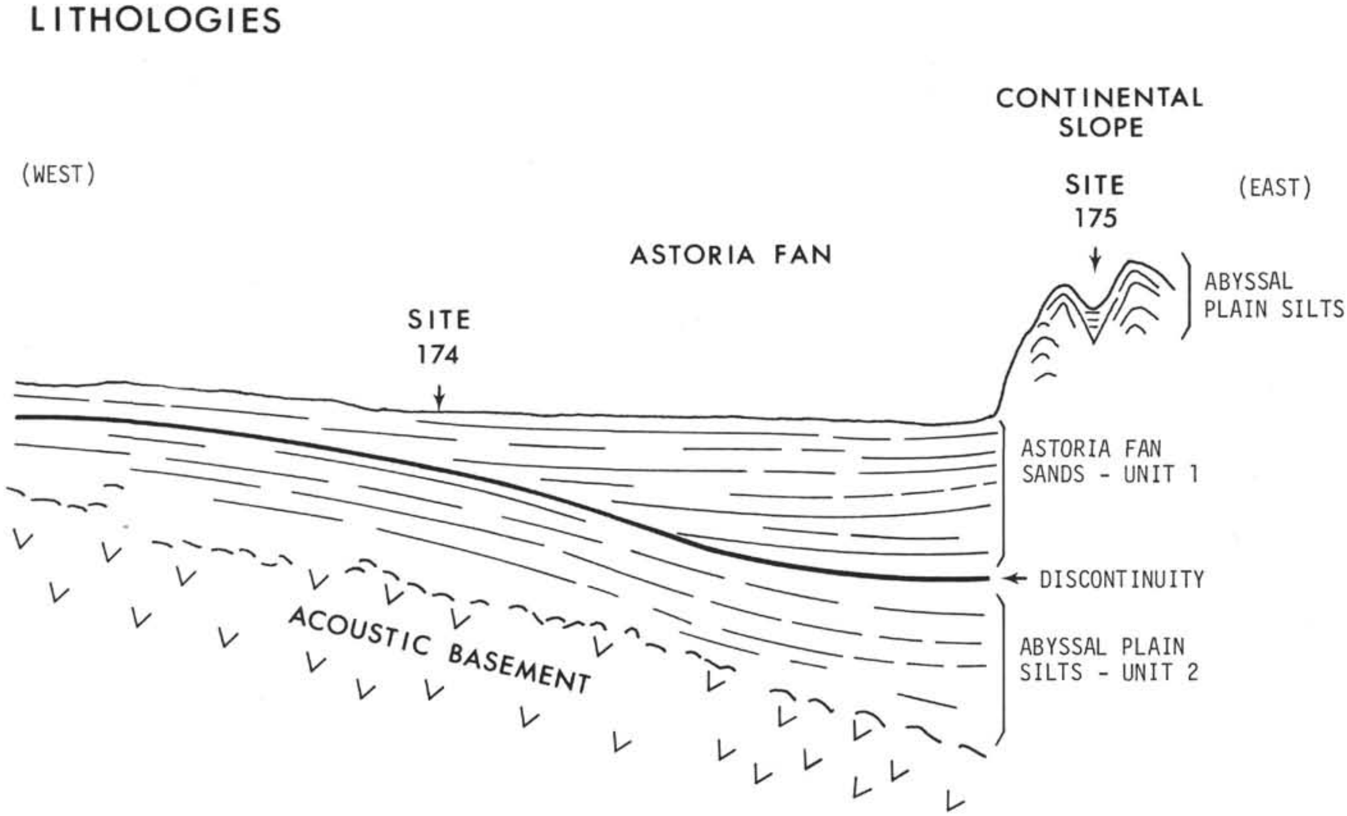


Figure 1. *Location map of Gorda-Juan de Fuca plate (Cascadia and Gorda basins), adjacent continental margin, and Pacific northwest. Note locations of Sites 174, 175, and 176.*



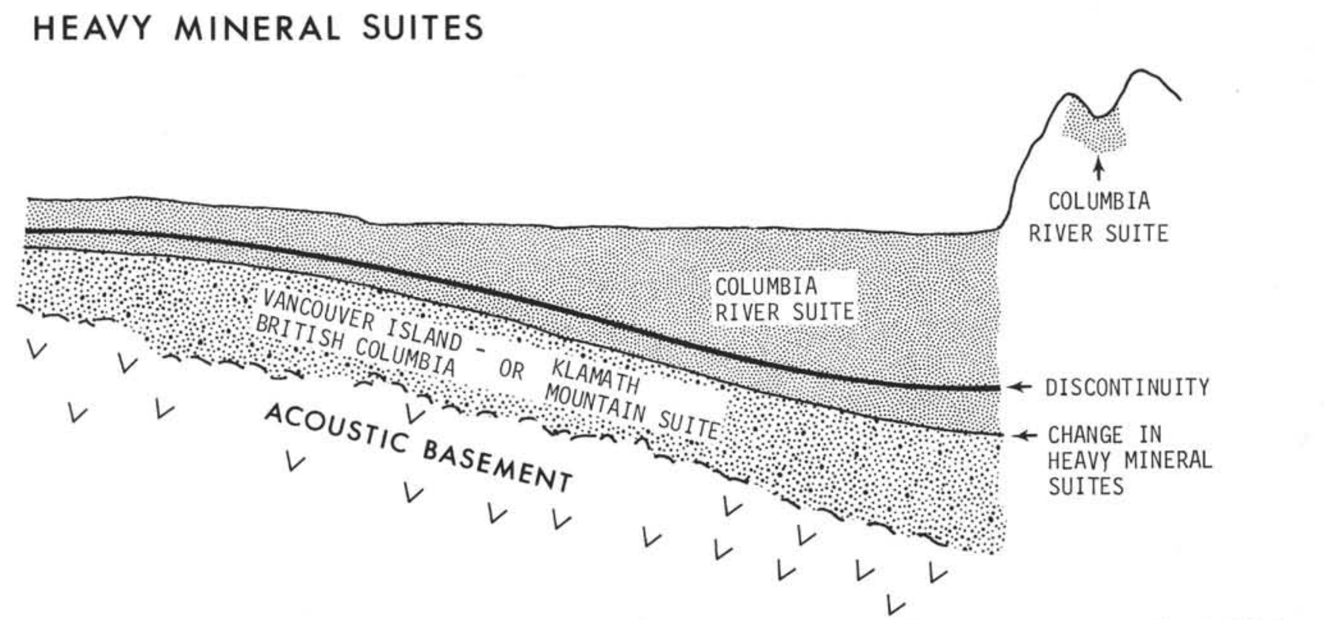


Figure 2. *Diagrammatic sketch of seismic reflection profiles. Upper: correlation of lithologies at Sites 174 and 175. Lower: heavy mineral suites. Note how mineralogy changes below the seismic discontinuity.*

80 m/m.y.[2]. The sediment appears to have been deposited in a deep ocean environment beyond the influence of coarse terrigenous sedimentation. This sequence is overlain by Pliocene and Pleistocene silty clay beds with graded silt bases composed mainly of terrigenous clay minerals. They accumulated at rates between 140 and 220 m/m.y., and their lithology indicates a terrigenous influence. The top 284 meters is the late Pleistocene sequence of graded sand beds that make up the Astoria Fan; these beds accumulated at a rate of between 370 and 940 m/m.y.

Heavy mineral suites at Site 174 (Scheidegger et al., Chapter 25) indicate that Pliocene silt turbidites between 370 and 879 meters came from either north (Vancouver Island-British Columbia) or south (Klamath Mountains) of the site (Figure 1). Although the Columbia River is presently closer to Site 174 than either of the other two sources and is known to have existed at this time (Snavely and Wagner, 1963), it apparently did not contribute coarse material to this section. Further detailed work on the sand-silt mineralogy of Site 174 deposits is required to determine which source (northern or southern) contributed the largest share of Pliocene sediment.

The lithostratigraphy of Site 174 indicates a geologic history increasingly dominated by terrigenous sediment. One interpretation is that sedimentation throughout the region increased as a result of continental glaciation, uplift of the Coast Ranges, and volcanism in the Cascade Range; another is that convergence of the oceanic and continental crust brought Site 174 progressively closer to the continental margin, where sedimentation rates are higher. Both probably occurred, although the effects of each mechanism are difficult to separate. Pleistocene increases in sedimentation are well known, for instance, at Site 173 on the northern California margin, rates of sedimentation increased beginning 3.5 m.y. ago, and by 2 m.y. they were about eight times the previous rates, as shown further on. Convergence is suggested by the abundance of a type of clay that accumulates in environments far from shore (Hayes, Chapter 28).

Columbia River sediment began to reach Site 174 about 1.5 m.y. ago (Scheidegger et al., Chapter 25). This change in provenance occurred before Astoria Fan formed and the discontinuity at its base developed. If a previous trench existed, it must have been filled, at least in the vicinity of the Columbia River, to allow the turbidity currents access onto the abyssal plain. The absence of a Columbia River heavy mineral suite before 1.5 m.y. ago suggests that most of its coarse sediment may have been trapped in structural basins on the shelf and slope (Kulm and Fowler, 1971; Braislin et al., 1971). Perhaps the increased sedimentation in Pleistocene time caused overflow of the basins and transport of sand down submarine canyons. Otherwise it is difficult to account for the absence of Columbia River heavy mineral suites before Pleistocene time.

In middle and late Pleistocene time the abyssal plain sediments now along the eastern margin of Cascadia Basin were downwarped to form the trench-like depression. The timing of this event is not well known because the microfossil control at Site 174 is relatively poor. Astoria Fan may have transgressed the site shortly after the first major glacial eipsode, either 0.8 or 1.2 m.y. ago (kent et al., 1971). The age of Astoria Fan is discussed more completely in the summary of results.

Oregon Lower Continental Slope, Site 175

The northern lower continental slope of northern Oregon and Washington is formed by a sequence of relatively broad anticlines and intervening troughs (Kulm et al., Appendix 1; Silver, 1972). Site 175 is in a narrow trough between the two lowermost anticlines on the Oregon continental slope (Figures 1 and 2). Greenish gray silty clay of Pleistocene age forms most of the cored section. Sand turbidites like those of Astoria Fan are absent. Interbeds of sand and silt abyssal turbidites begin to occur at about 100 meters, and they are similar in lithology to the turbidites found at Site 174, just below the sediments of Astoria Fan (Figure 2, Unit 2). At both sites these sequences of sediment have a similar clay mineral composition (Hayes, Chapter 28) and the same Columbia River heavy mineral suite (Scheidegger et al., Chapter 25), and they accumulated at similar rates, suggesting that sediment from the same source reached both sites.

A significant change in benthic foraminiferal assemblages at 80 meters indicates a change in paleodepth at Site 175. Above 80 meters the indicated paleodepth is close to the present depth of water at Site 175 (2000 m), whereas below 80 meters the assemblages are typical of water depths greater than 2200 meters (Ingle, Chapter 14). The change in depth occurred 0.3 to 0.4 m.y. ago, according to the radiolarian and diatom stratigraphy at Site 175 (Schrader, Chapter 17; Kling, Chapter 16). This implies that the depth at this site was greater than 2200 meters, and during its upward migration to 2000 meters it passed 2200 meters 0.3 to 0.4 m.y. ago.

This implied uplift, and the abyssal plain-like lithology, suggest that part of the abyssal plain is incorporated into the slope. Seismic reflection records support this interpretation. Although some records show a sequence of complex and obscure acoustic events at the continental slope-Cascadia Basin juncture, a few records show continuity of reflectors that indicates upwarping of Astoria Fan sediment to form the first fold of the slope (Kulm et al., Appendix I; Silver, 1972).

Northern Oregon Continental Shelf, Site 176

Unconformities, ranging in age from late Eocene to Pleistocene, are present in the sedimentary section on the Oregon continental shelf (Fowler and Kulm, 1971; Kulm and Fowler, 1971; Braislin et al., 1971). Most unconformities display an angular discordance like that observed in the vicinity of Nehalem Bank (Kulm et al., Appendix I) and indicate major periods of uplift and erosion.

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[2] All rates of sedimentation are corrected for compaction using the porosity-depth curve in Chapter 26. Although rates of sedimentation in turbidites vary greatly, the thicknesses of the sequences used here are great enough to ensure a good average estimate of rate. The rates are calculated from the following data: 911 meters deep, estimated age = 8 m.y.; 750 meters deep, estimated age = 4 to 5 m.y.; 294 meters deep, estimated age = 0.4 to 1.0 m.y.

Site 176 is located in 193 meters of water on the western flank of Nehalem Bank, where one of the youngest angular discordances is clearly identified. A Pleistocene transgressive and regressive sequence of silty clays and abundant coarse sediment discordantly overlies a Pliocene fissile shale. A paleodepth for the shale of at least 500 meters deeper than the present depth at the site is indicated by foraminiferal assemblages (Ingle, Chapter 19). The age of the unconformity is difficult to determine. The oldest sediments overlying the shale are inferred to be 0.92 to 1.3 m.y. old, on the basis of the diatom assemblage (Schrader, Chapter 17); the unconformity must therefore be more than 1 m.y. old.

Summary of Results and Discussion

Briefly summarized, our interpretations of the lithologic sequences and seismic records are consistent with incorporation of eastern Cascadia Basin sediment into the continental slope. Migration of Site 174 toward the continent since Miocene time is suggested by the pelagic sedimentation followed by increasingly greater amounts of terrigenous sediment, although the effects of more widely dispersed sedimentation with time cannot be separated from those of increasing proximity. Depression of the trench-like feature, upwarping and folding of the abyssal plain adjacent to the continental slope, and initial development of Astoria Fan were essentially simultaneous. Tectonism appears to have been concentrated at the base of the slope in the last 1 m.y. because the youngest unconformity on the continental shelf developed from tectonism older than 1 m.y., whereas the slope was tectonically active at least 0.3 to 0.4 m.y. ago.

Others have suggested that a segment of eastern Cascadia Basin was uplifted and incorporated into the continental slope by folding (Byrne et al., 1966; Kulm et al., Appendix I; Silver, 1972). The folds could have been produced by compression or by vertical uplift through block faulting of the basement. A full discussion of alternative tectonic mechanisms is not attempted here but the arguments are summarized.

Although vertical uplift through block faulting of the basement seems less likely than compression, it cannot be dismissed as a mechanism. Block faulting is a less attractive interpretation because the limbs of several folds do not appear stretched or pulled apart (see seismic records in Kulm et al., Appendix I; Silver, 1972) and there is no evidence for a basement relief commensurate with surface topography. Major vertical faults in the basement would probably disrupt the linear magnetic anomalies that cross the lower slope (Silver, 1972). Therefore, a series of anticlines and synclines formed in a sedimentary blanket draped over a block-faulted basement relief is less likely than compressional structures over a landward-dipping basement.

Compressional folding at continental margins has been considered to originate from underthrusting of oceanic crust beneath the continent. Scholl and Marlow (in press) suggest that off the Aleutian Arc similar folding may also develop from detachment or large gravity slides on the continental slope, with development of folds at the foot of the large slides. The greatest objection to gravity sliding is that all paleodepth indicators on the upper slope and shelf (Byrne et al., 1966; Chapter 7) show uplift rather than the subsidence required by slides. On the other hand, the idea that part of Cascadia Basin was incorporated into the continental slope by underthrusting is consistent with the present evidence.

A maximum limiting rate of underthrusting can be estimated for the region off Oregon by comparing cross sectional areas of deformed sediments with the corresponding projections of the original undeformed areas. This technique, which was applied by Silver (1972) to folded belts off Washington, is shown diagrammatically in Figure 3.

The estimate of maximum underthrusting depends on the time of initial uplift at Site 175. During uplift the site apparently passed through 2200 meters water depth at 0.3 to 0.4 m.y. However, if the site was on the floor of Cascadia Basin in Pleistocene time, then uplift must have begun before deposition of Astoria Fan because no fan sediment was drilled at Site 174[3]

The age of Astoria Fan is poorly known because of insufficient microfossils. Foraminifera in the section below Astoria Fan indicate that at least one major climatic fluctuation preceded deposition of the fan. This suggests an age younger than the 1.0 to 1.2 m.y. continental glacial period or possibly the more intense 0.8 m.y. glaciation (Kent et al., 1971). It seems unusual that the base of Astoria Fan does not correspond to the first continental glaciation. The fan may not have extended to the site (275 km south of Astoria Canyon) during the first major glaciation because of the rate at which sediment was supplied or because the site was farther from the mouth of Astoria Canyon at that time. Perhaps Astoria Fan reached Site 174 as a result of a shift in the center of deposition as well as climatic change.

An indication of initial uplift at Site 175 is the sediment color change at 120 meters and the last interbedded turbidite at 100 meters. These lithologic changes are dated at 0.59 m.y. and 0.75 m.y. by extrapolating linearly between the 0.3 radiolarian and the 0.92 diatom boundary. With an apparent compression of 16 km (Figure 3), the 0.59 m.y. age implies a 2.7 cm/yr maximum rate of subduction, and the 0.7 m.y. and 1.0 m.y. ages imply rates of 2.3 and 1.6 cm/yr, respectively. These maximum rates are based on the assumption that Site 175 was once part of the abyssal plain, and although much uncertainty is involved, they compare favorably with the 2 cm/yr estimate made by Silver (1972).

A LATE CENOZOIC HISTORY OF THE GULF OF ALASKA OFF KODIAK ISLAND

The Broad Historical Framework From Site 178

The continental margin off Kodiak Alaska was sampled on Leg 18 of study its geologic history and the tectonic

[3]The assumption that sediments penetrated at Site 175 were deposited on the lower continental slope is permissible. This assumption gives lower rates of underthrusting than the maximum limit developed because it increases the assumed age of initial uplift.

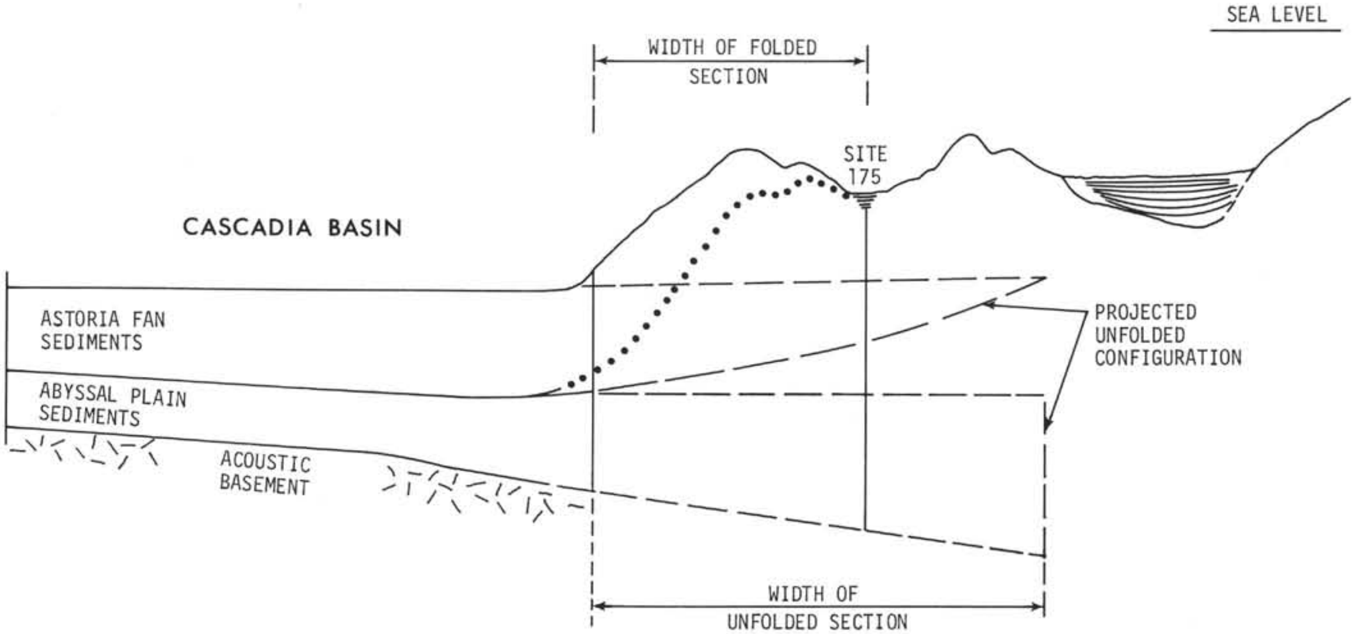

Figure 3. *Diagram of the method used in estimating the amount of compression seaward of Site 175. The cross-sectional area of the first fold is outlined by vertical lines at the foot of the slope and directly below the site. The original configurations of Astoria Fan and the abyssal plain sediments were projected as shown by dashed lines from the known section until their combined cross-sectional area equaled that of the folded section. The difference between the folded and unfolded widths, or the apparent compression, is 16 km. Another approximation in which the sea floor profile of the first fold is straightened out gives 11 km apparent compression. The maximum extent of Astoria Fan in the first fold is suggested by the dotted line.*

mechanisms operating across the Aleutian Trench (Figure 4). A geophysical study prior to Leg 18 (von Huene, 1972) provided the basis for selecting drill sites and the structural framework for interpreting core data. The interpretation of Site 178 and its associated seismic records sets the broad framework of geologic history for the area. It indicates a general transition from lowlands in early Miocene time to high mountains with extensive glaciers in Pliocene and Pleistocene time, and upon this broad record other tectonic events are superimposed. These events have been described in geologic studies on land (Burk, 1965; Plafker, 1971; Kirschner and Lyon, in press), and Site 178 records with continuity the timing of major events and provides some indication of their relative intensity.

Site 178 Lithostratigraphy

The lithology at Site 178 varies from a deep-ocean pelagic section to thick glacial marine turbidites in the following sequence. Overlying basalt basement is 30 meters of pelagic clay shale, overlain in turn by 7 meters of varicolored claystone-chalk, and then by a 110-meter sequence of hard olive gray mudstones with increasing interbeds of silt and sand turbidites. In the next higher section, buried turbidity current channels are large enough to be seen in the seismic records. This transition from dominantly pelagic to dominantly turbidite sedimentation probably began in early or middle Miocene time on the basis of foraminiferal and nannofossil stratigraphy, although diatom stratigraphy suggests a late Miocene time of transition. Then the lithology changes to gray silts and clays of middle Pliocene through Pleistocene age containing ice-rafted debris, and this lithology dominates the upper 280 meters of the 777-meter sediment section cored. Thus, lithology indicates an early Miocene deep-ocean pelagic environment, a transition to a deep-ocean terrigenous sedimentary environment beginning in early or middle Miocene time, and abundant glacial material in Pliocene and Pleistocene time (Figure 5). This sequence is consistent with rates of sedimentation, textural characteristics, and clay mineralogy.

Rates of sedimentation between the top and bottom of this hole differ by almost two orders of magnitude. At the top, late Pleistocene rates range from 215 to 135 m/m.y. Rates drop to 105 m/m.y. in the early Pleistocene. In the preceding 18.2 m.y. since early Miocene the rates average 41 m/m.y., and prior to the Miocene they are from 3 to 9 m/m.y.[4] (Figure 6). The long Miocene to Pleistocene average caused by lack of reliable dates is unfortunate

[4]The pre-Miocene rates were estimated using a thickness from a seismic record by tracing the lower Miocene reflection to an area where anomaly 20 has been determined. Using the pre-Miocene sediment thickness and 47 m.y. basement age (Heirtzler et al., 1968), a rate was calculated. The 9 m&m.y. rate estimated in this way compare well with the 3 m/m.y. rate in sediments at Site 183 that are of equivalent age (Creager, Scholl et al., in press).

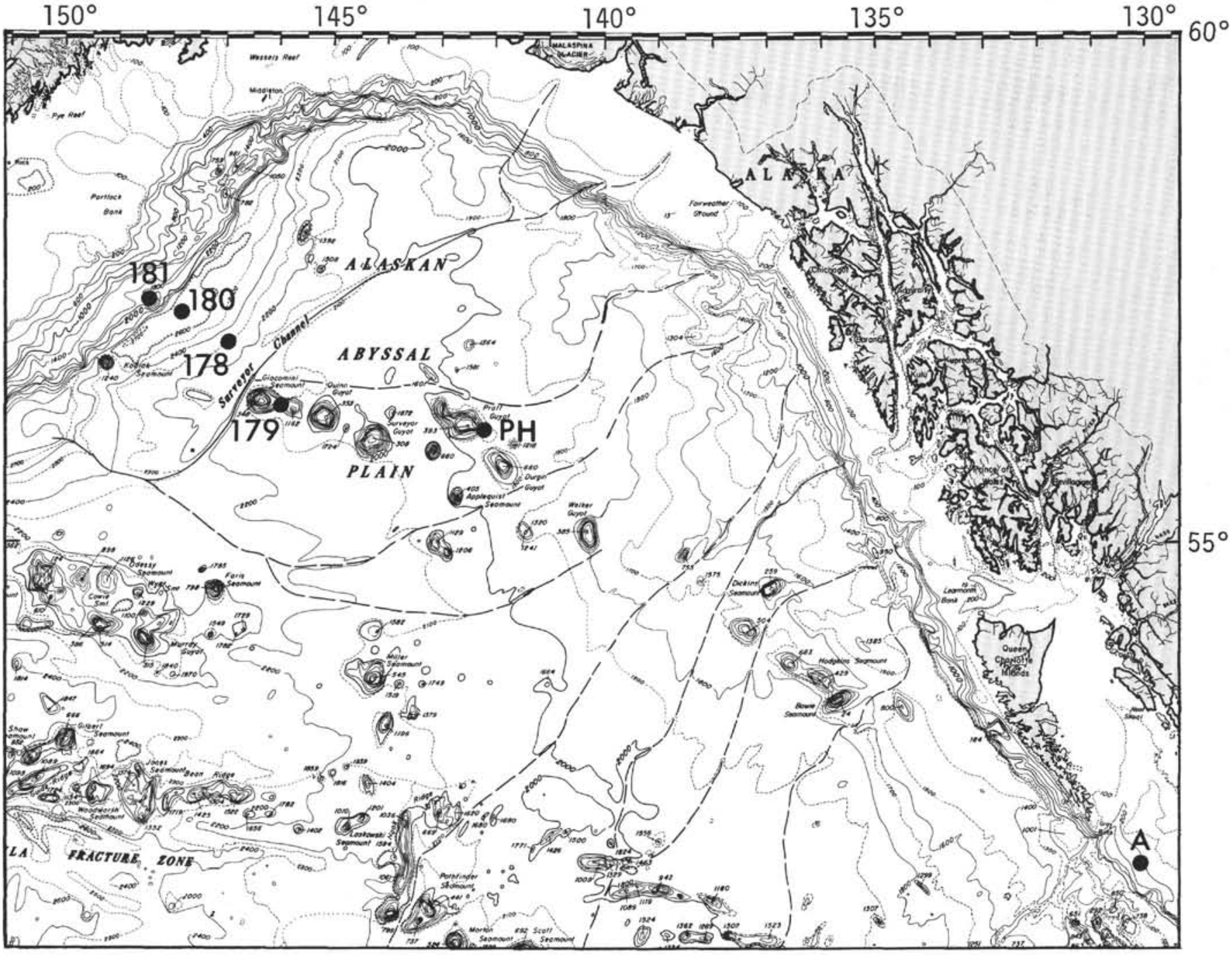

Figure 4. *Map of the Gulf of Alaska showing positions of Sites 178, 179, 180, and 181. Sites A and HP are localities at which the sediments now found at Site 178 may have been deposited, assuming that the oceanic plate was moving at rates proposed by Atwater (1970) (A) and by Hayes and Pitman (1971) (HP).*

because large changes in rate during this interval are indicated by the rates found at Sites 173 and 183 (Figure 6). The changes in rate since early Miocene reflect a large influx of terrigenous sediment, which probably increased rapidly in middle Pliocene time (about 4 m.y. ago).

Clay mineralogy studies by Hayes (Chapter 28) also indicate an influx of terrigenous sediment. Mixed-layer clays which are characteristic of slowly deposited deep-sea pelagic sediments make up 90 percent of the early Miocene samples but only 30 percent of the middle Miocene samples. Terrigenous montmorillonite, chlorite, and mica increase greatly in Pliocene samples.

The particle size distribution of the early Miocene sediment is consistent with the implications from clay mineralogy (Figure 6). The very fine particle size is below the size of aeolian dust (Arrhenius, 1963), suggesting that little terrigenous material is present. The extreme pelagic character of this sediment cannot be used to fix the distance of Site 178 from shore in Miocene time. However, these textures must have originated in an environment hundreds of kilometers from shore. Pliocene sediments 550 km off California contain abundant terrigenous material (Wesser, 1970).

Another significant lithostratigraphic change is the great increase in ash falls during Pliocene and Pleistocene time (Pratt et al., Chapter 20). The number of ash falls per million years is 2 in the Miocene, 8 in the Pliocene, and 14 in the Pleistocene.[5]

These are the major lithostratigraphic data from which a geologic history can be deduced, and they are consistent with the geologic history already known from studies on land.

[5] For this computation the depth of the Miocene-Pliocene boundary was estimated from the curve in Figure 5.

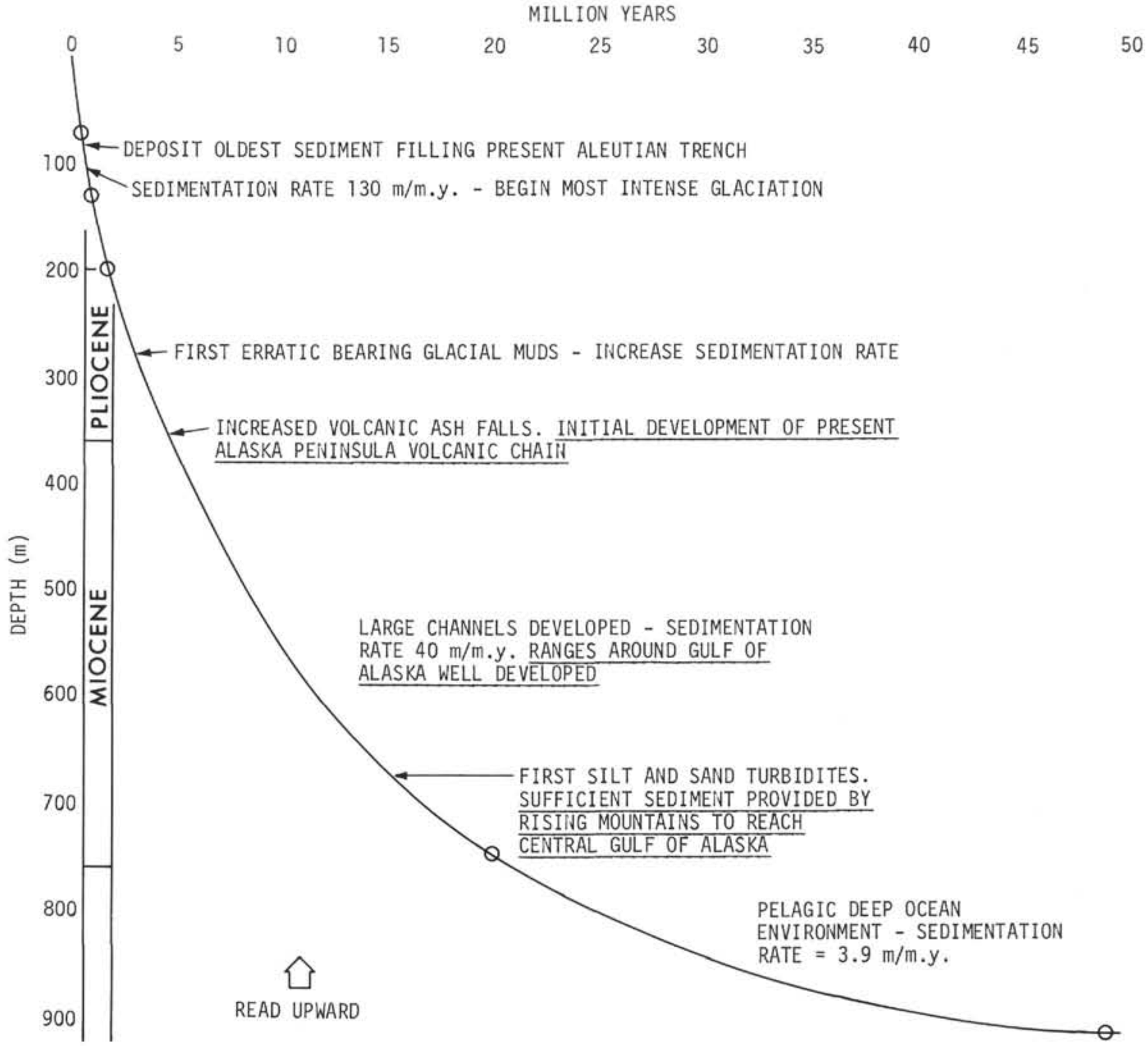

Figure 5. *Changes in lithology with time. The curve of depth versus time is controlled at the circles using biostratigraphic correlations with the absolute time scale (after Berggren, 1972; Hays, 1970; and Schrader, Chapter 17). Other observations are entered at appropriate depths, and interpretations are underlined.*

On-land History

Uplift of the Chugach-St Elias Mountains is indicated by the late Tertiary transition from sediment deposited in a warm and temperate low-energy marine environment (Poul Creek Formation) to sediments deposited in a cold and temperate higher energy marine environment (Yakataga Formation) (Plafker, 1971). The transition begins in early middle Miocene or possibly late Miocene and is indicated by alternating cold- and temperate-water megafaunas. Large conglomerate lenses and the marine tillites from Miocene tidal glaciers suggest mountains of great height, and, the thick sections that locally contain 55 percent sandstone indicate rapid erosion.

A similar uplift of the Kenai Mountains is indicated by the sediments of Cook Inlet (Kirschner and Lyon, in press). In late Miocene time, uplift of the central Alaska Range blocked an earlier source of sediment from the north, and a simultaneous uplift of the Chugach-Kenai Mountains is represented by thick conglomerate, sandstone, and siltstone in the Cook Inlet Basin. In Pliocene time a major source from the west marks increasing uplift of the Alaska Range, and the composition of these sediments indicates increasing volcanism. The Alaska Peninsula, a continuation of the Alaska Range, also developed during the Pliocene (Burk, 1965). Uplift and volcanism have continued there to the present time. The onshore history thus indicates development of high mountains with mountain valley glaciers along the central part of the gulf in middle or late Miocene time and development of the present Alaska Peninsula and Alaska Range in early Pliocene time.

Proposed Pacific Plate Movement and Landward Migration of Site 178

Two plate models of the north Pacific which best explain present observations were proposed by Hayes and Pitman (1970) and Atwater (1970). Relative movements between the Pacific and North American plates are the same in both models since about 5 m.y. ago. A 6 cm/yr

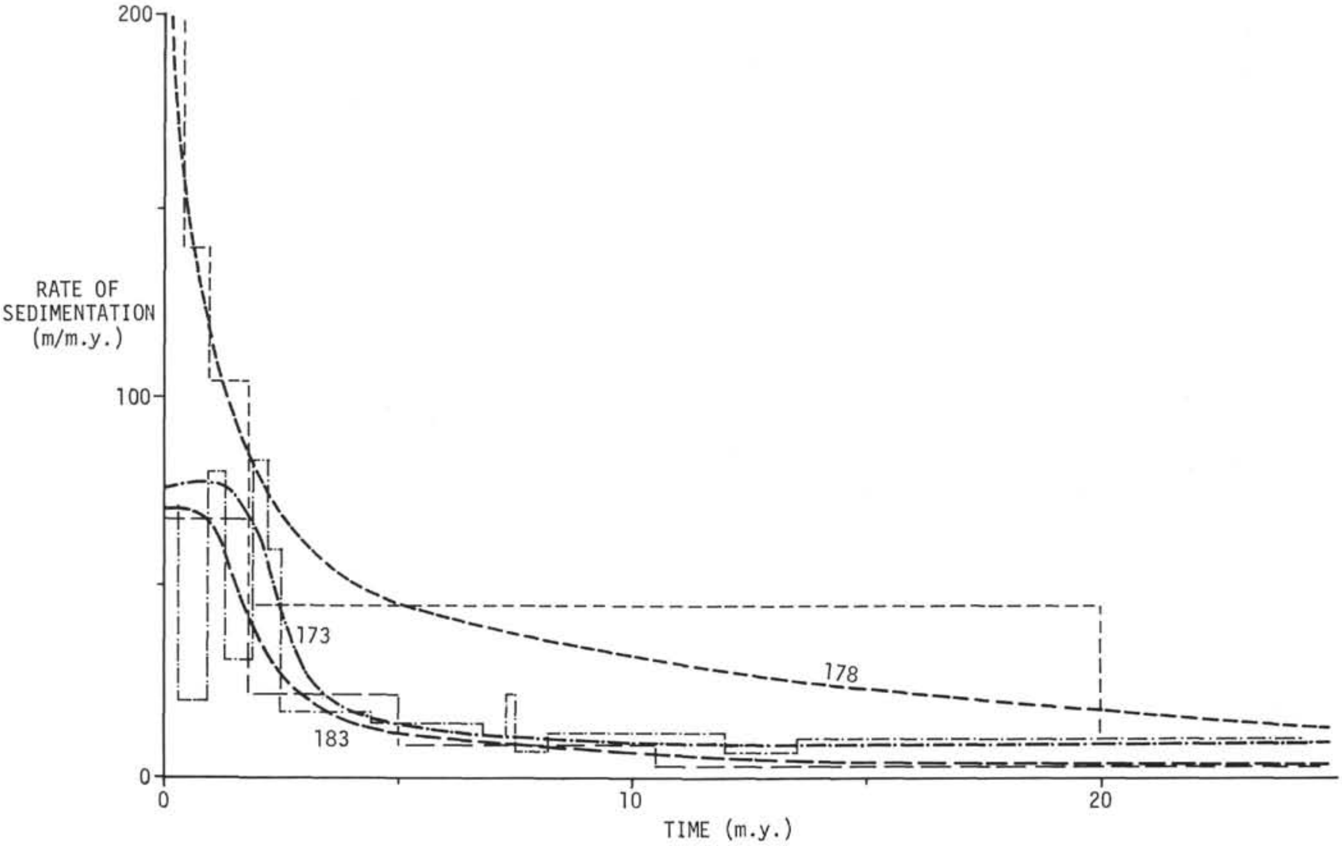

Figure 6. *Rates of sedimentation for Sites 173, 178, 183. The stepped curves are observed data through which the smoothed curves are drawn.*

constant rate of Pacific plate migration occurs simultaneously with the opening of the Gulf of California about 5 m.y. ago (Larson, 1972). From 5 m.y. to 20 m.y., the Hayes-Pitman model indicates that the Pacific plate was more or less stationary with respect to the North American plate, whereas the constant-motion Atwater model indicates a 6 cm/yr northwest migration.

According to Atwater's model, the position of Site 178 in the lower Miocene (20 m.y.) is next to the present continental slope between Vancouver and the Queen Charlotte Islands (Figure 4). At this position much terrigenous material would have been deposited, because much was found at Site 177, which is slightly less than 100 km south of the Site 178 Miocene position. However, a deep-ocean pelagic environment (Figures 5 and 6) is indicated by the lower Miocene sediments at Site 178. According to the Hayes-Pitman model the lower Miocene position is almost in the center of the Gulf of Alaska, a position much more in agreement with the lithology at Site 178.

Plate motion probably contributed to the change from pelagic to turbidite sediments at Site 178 by gradually bringing the site closer to Kodiak Island. The terrigenous sediment could have resulted from uplift and increased erosion of mountains around the Gulf of Alaska alone, however, as was previously pointed out, the early Miocene deep-sea pelagic clays (Figure 7) could not have accumulated at the present location of Site 178. This conclusion is consistent with an apparent change in sediment source since Miocene time. The lower part of the Miocene section thickens eastward in seismic records, implying an eastern source, whereas the upper part of the Pleistocene age thickens westward, consistent with the present western source despite trapping of sediment by the Aleutian Trench (von Huene, 1972).

Major Events of Miocene to Pleistocene Age

About 20 m.y. ago, the central Gulf of Alaska had a deep-ocean pelagic environment which soon began to receive increasing amounts of terrigenous debris (Figure 5). Approximately 13 to 14 m.y. ago, a turbidite environment with large channels existed throughout the gulf. This change in environment must correspond to uplift of the mountains around the Gulf of Alaska, which may have begun in early Miocene time. The mountains were high enough by the middle and late Miocene to produce the large quantities of sediment that flooded the Gulf of Alaska out to its central part. Then in early Pliocene time (ca. 5 m.y. ago), volcanic activity on the Alaska Peninsula (Pratt et al., Chapter 20) marked the development of the present Alaska Peninsula. Soon thereafter, periods of abundant icebergs provided rafted debris beyong the continental shelf

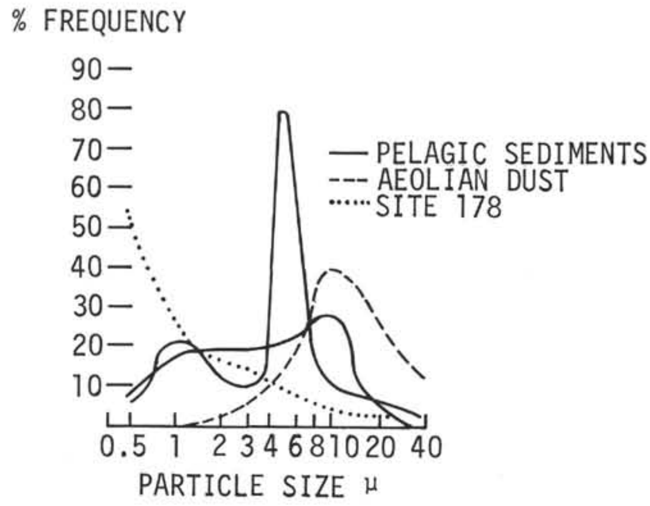

Figure 7. *Comparison of north Pacific particle size and aeolian partial size. (Arrhenius, 1963) with early Miocene (Core 57, 145-147 cm) of Site 178.*

(von Huene et al., Chapter 21; Kent, et al., 1971). Volcanism and ice rafting became especially intense about 1 m.y. ago.

Existing Aleutian Trench, Site 180

Two objectives at Site 180 were to find the age of sediments filling the Aleutian Trench and to study their lithofacies. Poor recovery in the silt and sand turbidites, interval coring, and the great quantities of glacial debris that diluted the microfossil content resulted in a fragmentary lithostratigraphy and cast doubt on whether the complete trench-fill section had been penetrated. Since no biostratigraphic zone boundary was recognized, only a maximum age was available for Site 180.

After Site 180 was summarized, a more refined Gulf of Alaska glacial chronology (von Huene et al., Chapter 20) provided a good framework into which the fragmentary Site 180 lithostratigraphy could be fit. There is only one fit in which all ages and rates of sedimentation are consistent with those obtained by tracing reflectors of known age from Site 179 to Site 180 (Figure 8). The interpretation in Figure 8 is based on the assumption that sediments from the 100,000-year interglacial were not recovered. This is likely since only 0.5 meters of core was recovered in the 64 meters drilled at the depths where this interglacial should occur. The consistency of the proposed glacial chronology with age data is shown in Figure 9. Biostratigraphically, the sediments at the bottom of Hole 180 are younger than 0.26 m.y. (based on rare and poorly preserved diatoms below 415 m) or 0.3 m.y. (based on sporadic Radiolaria). This is consistent with a correlation with Site 178 that has been made by tracing a seismic reflector between the two holes (Figure 9). The reflector at the bottom of Hole 180 intercepts Hole 178 at a point 8 meters below where the 0.3 m.y. age determination was made. The 0.3 m.y. age is consistent with the glacial chronology in Figure 8. It is concluded that sediments at the bottom of Hole 180 are 0.3 (±0.05) m.y. old.

The reflector just below the deepest trench fill intercepts Hole 178 between the first change from normal to reversed paleomagnetism, or about 0.69 m.y. A precision for the age of the trench fill is obtained by applying the average rate of sedimentation for Hole 180 to the remaining section below the level of the hole, giving 0.26 m.y. or a total age of 0.56 m.y. Therefore, the oldest sediments in the trench are presumed to be 0.6 ±0.1 m.y. old. This age is basically tied to the biostratigraphy and paleomagnetic stratigraphy at Site 178.

The average rate of sedimentation at the deepest part of the trench is 1780 m/m.y. The possible glacial maximum rate is greater than 2845 m/m.y., and the interglacial minimum is 350 m/m.y. The average rate in the trench is about 10 times greater than the average rate of sedimentation on the Alaskan Abyssal Plain at Site 178.

Sedimentation in the Aleutian Trench has been summarized by Piper et al. (in press). It is much like that in any other elongate basin where the facies patterns and rates of sedimentation are controlled by the abundance and character of the landward source. Turbidity currents, slides, and creep down the continental slope supply about 90 percent of the trench fill. Sediment from the slope is redistributed along a broad axial channel at the base of the slope that has formed from turbidity currents. Sands are thought to be confined to the channel, and the graded silts in Hole 180 probably represent overbank deposits.

The material filling the trench may be much younger than the trench itself. If the trench had formed only 0.6 m.y. ago, the section that was depressed to form it should contain a former continental-rise type of sedimentary wedge. However, no such feature appears in seismic records in the depressed section below the trench fill (von Huene, 1972), and any previous rise or trench must now be incorporated into the continental slope. Since the Aleutian Trench is one component of a tectonic system that includes the Kenai and Chugach mountains, the trench may have begun to form at the same time as these mountains, in the early or middle Miocene. It is even more likely that the trench had formed by the time the Aleutian volcanoes had begun forming, in the Pliocene. Thus, although the trench may have existed since the Pliocene, and perhaps even as early as the middle Miocene, the oldest sediment it contains is 0.6 m.y. old. It is tempting to speculate about the amount of sediment incorporated into the slope. If the width of the trench fill now is any indication of the previous width, then about 40 km of the trench might be incorporated each million years. However, rates of sedimentation at Site 178 were lower prior to 0.6 m.y. ago (Figure 6) and rates of sedimentation were probably lower in the trench also, so the previous width of trench fill would be correspondingly less. Nonethless, the likelihood that the Aleutian Trench is much older than the sediment filling it supports the concept of subduction.

Deformation of the Lower Continental Slope, Site 181

A core from Site 181 shows a deformation of the lower continental slope sediment that was undetected in the seismic records. This core consists of two distinctly different lithologies (Figure 10) that are separated by a fault or some other discontinuity. Above the discontinuity

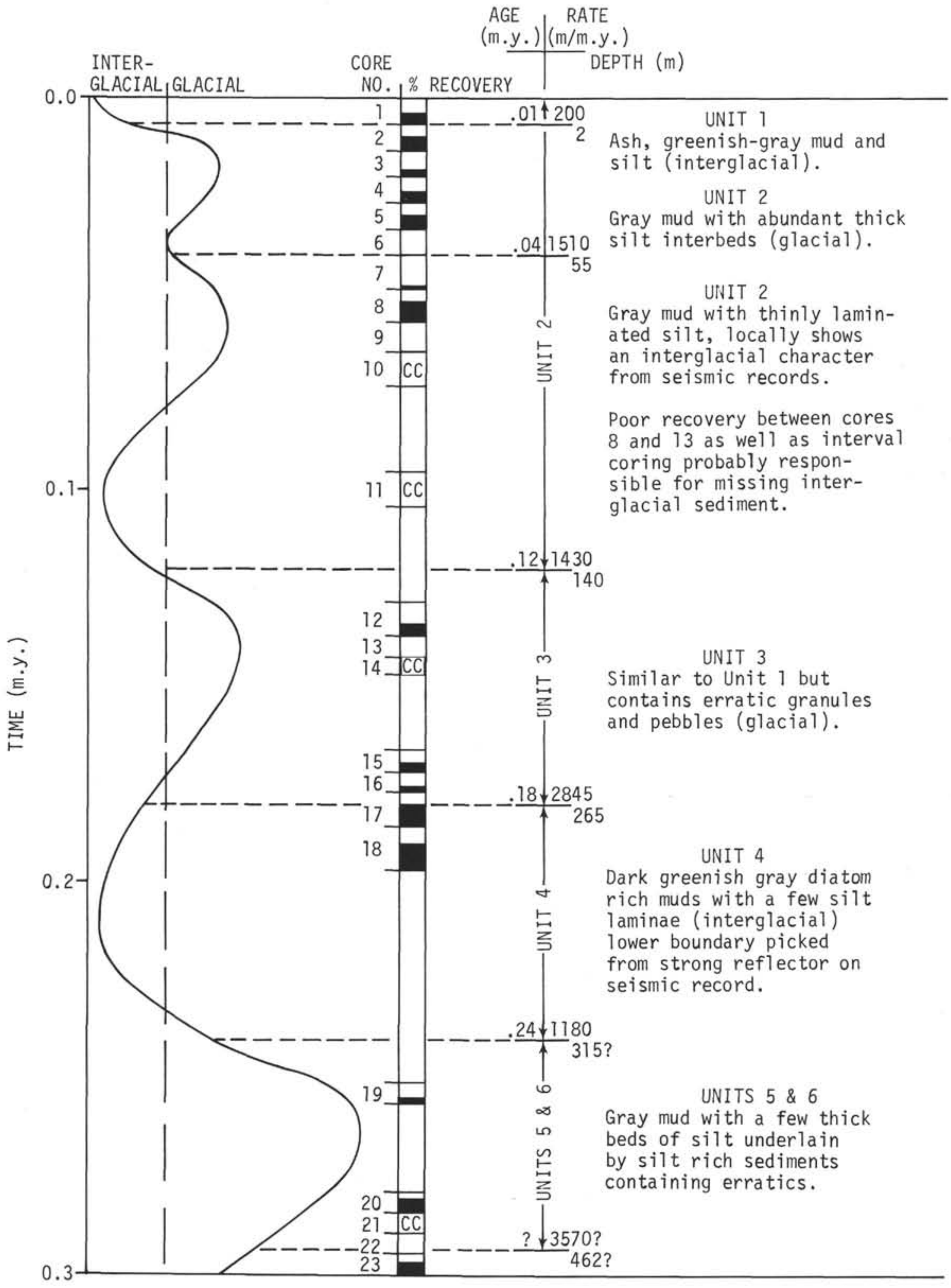

Figure 8. *Interpretation of glacial events in the core from Site 180 using the glacial chronology developed in Chapter 21. CC = core catcher.*

are lower continental slope sediments that appear tilted and mildly deformed on seismic records (Figure 10). Below it are highly deformed sediments of an unknown provenance that correspond to acoustic basement in seismic records.

The upper sequence consists mainly of muds with interbedded clean graded sands that indicate continuity of the site with the main source of turbidity currents on the continental slope. Only the upper 70 cm of the core

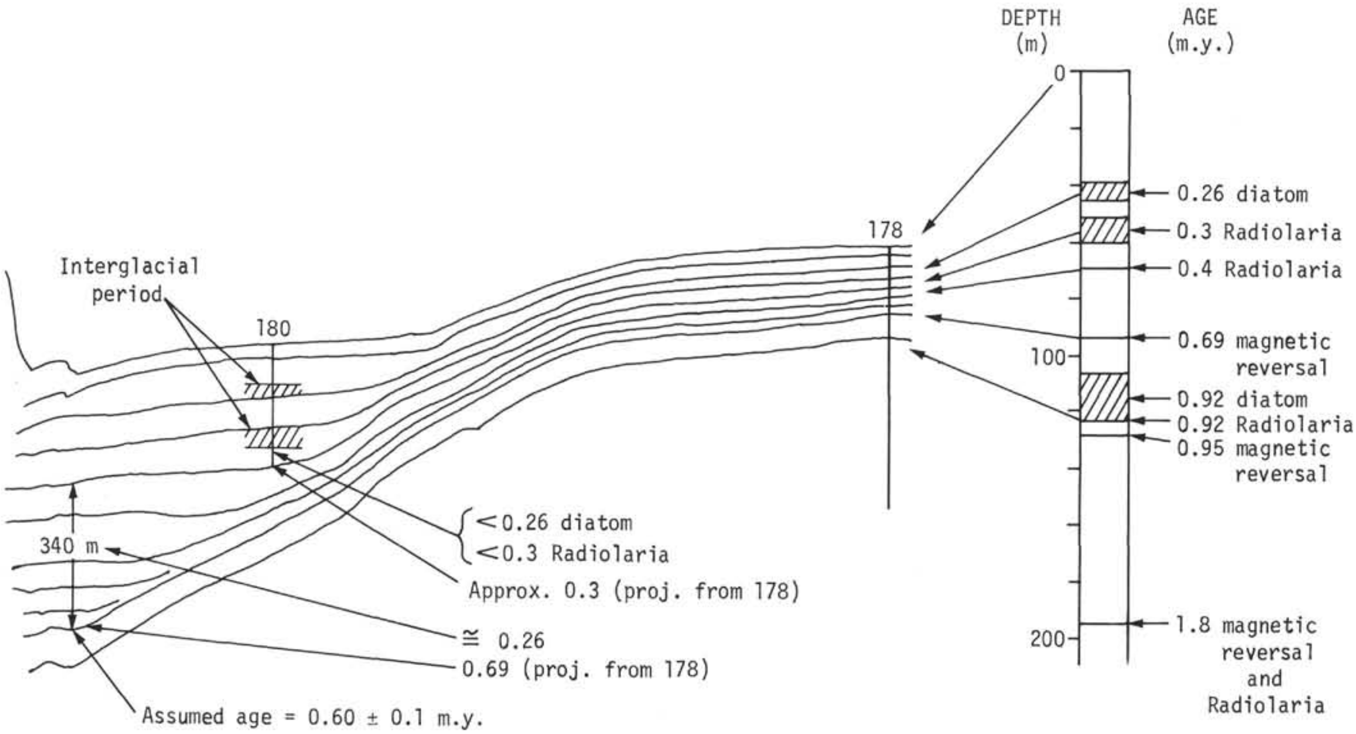

Figure 9. *Diagram showing control of age in sediments filling the Aleutian Trench.*

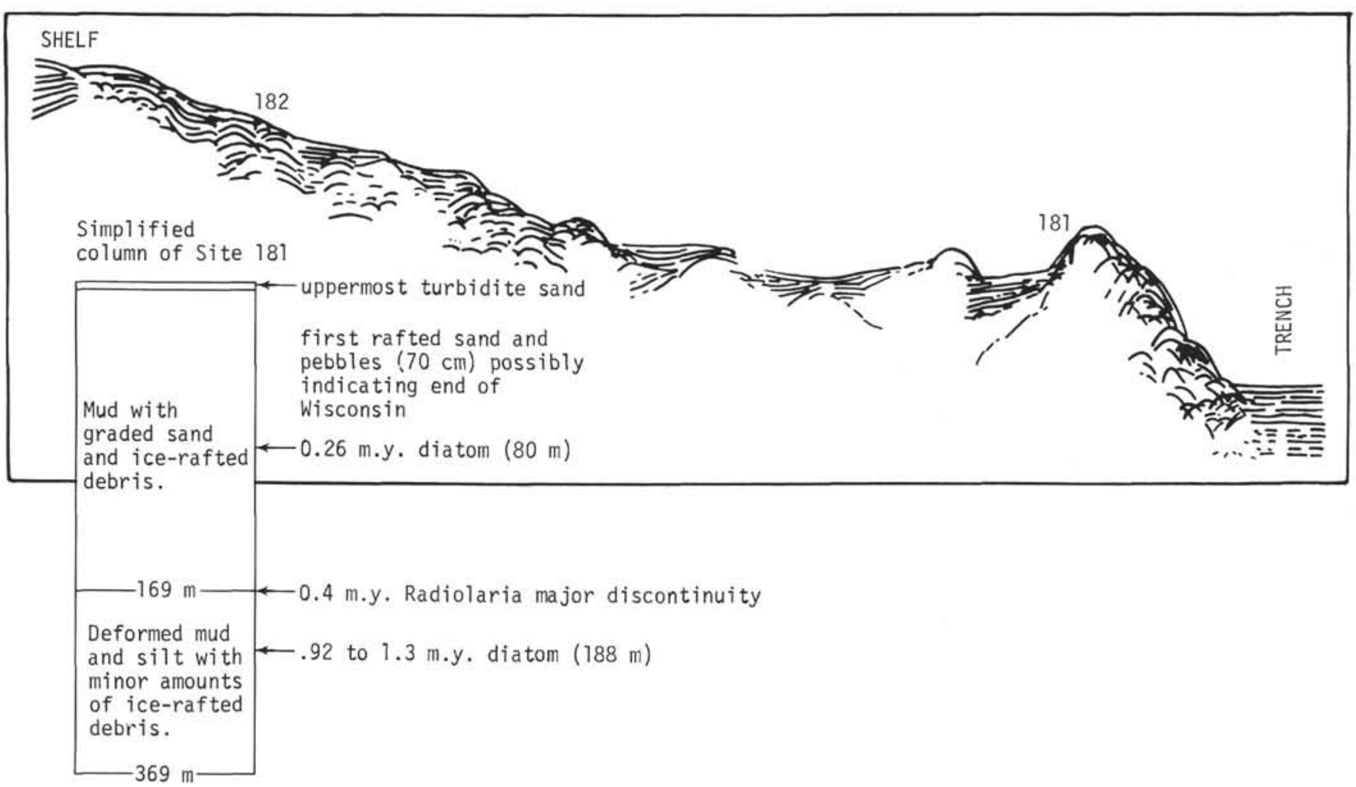

Figure 10. *Simplified column of Site 181 and tracing of seismic record showing the position of Site 181 on the lower continental slope.*

consists of hemipelagic sediments, in keeping with the present position of the site on an isolated knoll (Figure 10). This implies that Site 181 was uplifted 465 meters, and since the 0.26 m.y. diatom boundary occurs at 104 meters, uplift must have been rapid. The minimum rate of uplift, 0.2 cm/yr (2200 m/m.y.), is conservative; a maximum limit could be as high as 2.1 cm/yr (21,000 m/m.y.) if the uppermost ice-rafted erratics found at this site correspond to 11,000 yrs, the end of the Wisconsin Glaciation.

Sediments of the lower unit (Figure 10) probably owe their unusual character to tectonic rather than syn-sedimentary processes; they are separated from the upper unit by a fault or unconformity that leaves a hiatus at least 0.5 m.y. long. The contact was first noticed aboard ship by the sudden increase in drill bit pressure, pump pressure, and drilling time required to cut a core. Deformation was apparent in the core from the small silt layers that outlined irregular folds and microfaults.

Laboratory studies onshore amplify and confirm the shipboard observations. The porosity of the lower sediments (20% to 32%) is one-half or less than that of sediment at equivalent depths in the other cores (Lee et al., Chapter 27; von Huene et al., Chapter 26). Consequently, bulk densities are also higher than usual (2.12 to 2.14 g/cc). The degree of over-consolidation (Lee et al., Chapter 27) suggests past overburden pressures equivalent to those found at about 1.5 km beneath the sea floor, rather than the 170- to 370-meter depth where the sediments were drilled. Electron microscopic examination shows deformation of quartz grains and breaking of sand grains by movement within the sediment after deposition (Krinsley, Chapter 30). Clay mineralogy indicates that temperatures were not great enough to cause thermal diagenetic changes (Hayes, Chapter 28), but an analysis of organic constituents (Appendix VI) indicates temperatures greater than those normally found at the recovery depth and a greater depth of burial. Therefore, laboratory studies and shipboard observations indicate deformation in a deeper environment than those from which the samples were recovered.

The upper part of unit 2 contains a diatom assemblage between 0.92 and 1.3 m.y. old, but otherwise the sediments contain no microfossils. The clay-sized minerals at lower levels are different from other Pleistocene clays, and they might indicate a Pliocene age (Hayes, Chapter 28). Pliocene and Pleistocene sediments may have been mixed together during deformation. In any event, the 0.92 to 1.3 m.y. diatom age dates a time of intense deformation.

The original provenance of the lower sequence has not yet been determined. Its general lithology varies little from that of the abyssal plain, the trench, or the lower slope, but it differs from the lithology at Site 182 on the middle continental slope. The concentration of ice-rafted erratic material is higher than that found in the present trench sediment at Site 180 but roughly the same as that of the abyssal plain or lower slope. Displaced benthic foraminifera from shallower water are common in the upper unit, whereas in situ lower bathyal species predominate in the lower unit. These data suggest that the original provenance of the lower unit was at an equivalent or greater depth of water than the present depth.

Without knowledge of original provenance it is difficult to work out a mechanism by which the slope and deformed sediments developed. An obvious explanation might be the decoupling of an oceanic sediment sequence from the subducting oceanic plate and deformation as it impinged against the continental slope. However, soft undeformed trench sediments cannot push against the slope to form a 2000-meter high fold with limbs that locally dip 40 degrees, nor do they have the strength to exert the pressure that dewatered and deformed the sediment at Site 181. Simple uplift and gravity sliding are equally inadequate to explain the high-pressure environment, the lithology, and the sequence of microfossil assemblages. In seismic records, there is a suggestion of piercement structures along the lower continental slope (von Huene, 1972), a concept that might fit the evidence. Piercement is suggested by the lower slope topography, which consists of ridges slightly elongate parallel to the margin or nearly equidimensional. With rates of tectonism as rapid as those indicated by the upper section of the core at Site 181, the topography should reflect mainly tectonism with little masking by sedimentation. However, if piercement occurs, it is probably a secondary process and not the predominant continental slope tectonic mechanism.

A significant contribution of Site 181 is the evidence of deformed young sediments along the lower continental slope and the fact that this deformation was unresolved on seismic records.

Summary of Results and Discussion

One objective of Leg 18 was to study the tectonic mechanisms operating at the eastern Aleutian Trench. We think the evidence favors subduction. More than the usual amount of data is now available for the eastern Aleutian Trench area, which makes it possible to develop some arguments for tectonic mechanisms in addition to those based on seismology or magnetic anomalies.

The study of Leg 18 cores gives a temporal continuity to the geologic events of southern Alaska. The three most obvious events recorded on land in the ocean are: (1) uplift of mountains now surrounding the Gulf of Alaska, probably beginning in the early or middle Miocene; (2) a great increase in volcanism 5 m.y. ago, which probably signifies initial development of the present Alaska Peninsula; and (3) glaciation that is evident on shore in the Miocene and became strong enough 3 to 4 m.y. ago to contribute extensive ice-rafted debris to abyssal marine sediments.

Evidence Related to Subduction

The trench may have first developed as part of the Miocene tectonic event that resulted in uplift of the Chugach-St. Elias Mountains. The present trench probably existed 5 m.y. ago when the Alaska Peninsula volcanic arc first formed, and the 0.6 m.y. old sediment filling the trench probably represents only a part of the total trench-filling material. The quantity of material that must now be incorporated into the continental slope is emphasized by the width of trench fill, 25 km, that accumulated in 0.6 m.y.

Seismic records across the continental margin off Kodiak Island (von Huene, 1972) show that oceanic basement dips landward beneath the continental slope, rather than conforming to slope topography, as would a basement cut by vertical faults and covered by a conforming blanket of sediment. Nevertheless, the existing evidence precludes neither vertical faulting nor subduction because the most convincing type of evidence, folding and faulting, is obscured owing to the rarity of coherent reflectors below steep lower continental slopes. The usual internal pattern of overlapping hyperbolic reflections (artifacts of the seismic method) is the same from a hard rock as it is from highly deformed soft rock. At Site 181 the lack of internal structure in seismic records was probably caused by the intensity of deformation, because sediments as deformed as those recovered would not reflect well, especially when much of the seismic energy has been scattered by a rough, tilted ocean floor. However, where the lower slopes dip less than 10 degrees, some seismic records show continuation of trench fill 12 to 14 km beneath the slope (von Huene, 1972). Here the trench fill appears to be covered by slumps, and the locus of deformation has been elusively shifted landward out of sight under the slope. What this suggests is that folds and faults that convincingly show sense of tectonic movement may be too deep and too complex to be delineated by the geophysical techniques (single channel seismic) that have been used in published studies.

There is support for subduction from the results of Leg 18 in the evidence for westward movement of Site 178, and the indication that a great deal of oceanic sediment has been incorporated into the continental slope. Subduction followed by upward migration of mobile sediments is a possible explanation for deep past burial of the deformed sediments at Site 181. A weakness of the subduction hypothesis is the difficulty in explaining steep lower continental slopes against undeformed trench deposits in the presence of constant subduction.

Estimated Rates of Subduction (games of subduction)

If subduction is the driving tectonic mechanism in the Aleutian Trench area, then it is important to find the rate of plate convergence. Despite the many uncertainties in the estimates that follow, they are presented here because convergence between the American and Pacific plates has not been established beyond qualification in any type of study.

Two ways of estimating subduction rates are diagrammed in Figure 11. In the first, the seaward limit of the trench fill is assumed to mark a time line that moves landward (with respect to a fixed point) during subduction (Figure 11, C_2-C_0). This slope migration causes the center seaward because of sedimentation as well as the incorporation of trench fill and abyssal sediment into the slope (Figure 11, C_0-C_2). This slope migration causes the center of trench deposition to shift seaward by at least an equivalent amount. Therefore the rate of subduction is equivalent to the apparent landward movement of the time line, minus the seaward migration of the continental slope. This assumes, of course, that all rates of sedimentation have been constant during the time covered. As was shown previously, sedimentation is not constant; however, it has been greater in the past 0.6 m.y. than during any equivalent Neogene period. Therefore the maximum possible rate of subduction can be estimated by this method from the Leg 18 data at the Aleutian Trench.

The apparent landward movement of the time line in the past 0.6 ±0.1 m.y. is 25 km, the width of the trench fill (t_0 to C_0). The amount of slope migration caused by sediment deposition can be measured from rates of deposition on the continental slope (Chapters 12 and 13, Sites 181 and 182). These rates have been less than 450 m/m.y. in the past 1 m.y. and were usually between 100 m/m.y. and 200 m/m.y. Despite this range of uncertainty a conceivable maximum rate of sedimentation on the slope would be the rate in the adjacent trench of 1780 m/m.y. Since this maximum is only 3 percent or 4 percent of the apparent rate of landward movement, the uncertainty is insignificant.[6] The amount of slope migration caused by incorporation of trench material cannot be determined without knowledge of the lower slope internal structure. Since this effect is not accounted for, the maximum rate is biased to a higher value. With these qualifications, the maximum rate of subduction for the past 0.6 ±0.1 m.y. is 3.6 to 4.8 cm/yr.

An alternate method of equivalent cross sections used in estimating subduction off Oregon gives rates from 2.1 cm/yr to 3.0 cm/yr (Figure 11B). It is assumed that in 0.6 ±0.1 m.y. the trench area (A) changed its configuration to that of the lower contienental slope and lost 20 percent of its volume through dewatering. Perhaps this value is biased toward a minimum rate because compaction of area C (Figure 11) cannot be measured.

There are many uncertainties in these estimates; however, all are lower than Pleistocene rates proposed in the north Pacific models (Atwater, 1970; Hayes and Pitman, 1970). The results of Leg 19 (Creager, Scholl et al., in press) and a study by Hamilton (in press) also suggest slower convergence of the Pacific and American plates in Neogene time.

CONCLUSIONS

The study of cores recovered on Leg 18 has strengthened the evidence for rapid tectonism, underthrusting, and incorporation of abyssal sediment at continental margins off Oregon and Alaska. Since rates of sedimentation are more rapid than expected, buried structures are younger than was previously thought and rapid rates of tectonism are possible. This is seen in the 0.6 m.y. age of the present Aleutian Trench fill and the folding of young abyssal sediments that are being incorporated into the Oregon continental slope. The most likely tectonic mechanism is underthrusting, although vertical uplift by block faulting cannot be completely ruled out. Evidence for underthrusting is largely indirect. Folds and faults that indicate underthrusting will probably not be detected until better

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[6]This quantitatively rules out the possibility that all apparent landward movement of the time line is caused by sedimentary outbuilding alone because the apparent rate of landward movement is 25 to 50 times greater than sedimentary outbuilding.

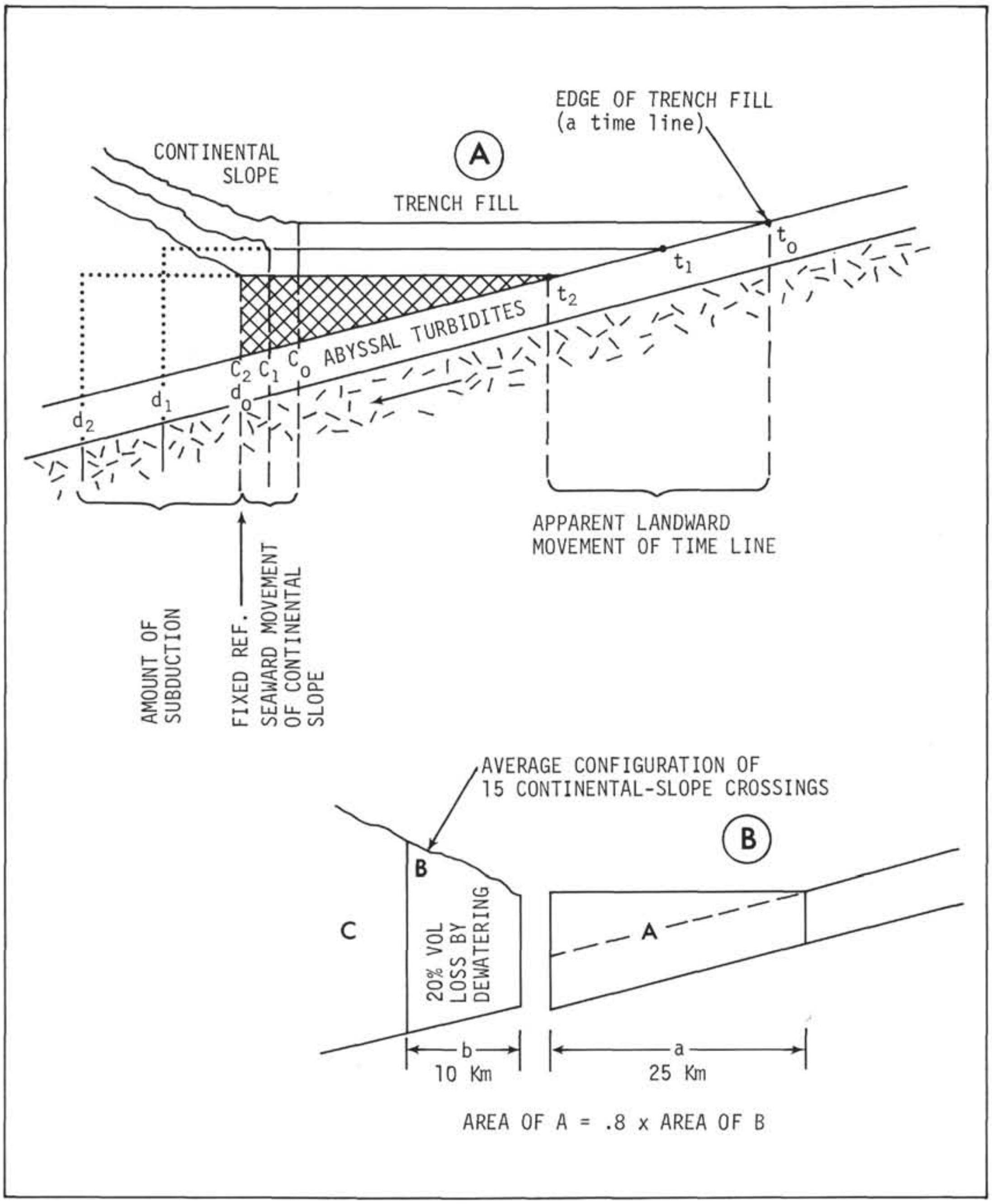

Figure 11. *Models used to estimate rates of subduction. Model A shows three stages in time at* t_0, t_1, t_2, *as marked by the seaward edge of trench fill. The apparent landward migration of the time line is greater than subduction because the continental slope builds seaward. Therefore, the rate of subduction,* d_0, d_1, d_2, *is equivalent to the apparent landward migration of the time line, minus the seaward migration of the slope. Model B shows the method of equivalent cross section in which cross section A is equal to B plus the 20 percent by volume of water assumed to be lost by tectonism and greater depth of burial. The lower continental slope configuration was determined by averaging fifteen profiles across the slope in this area. The basement configuration is based on seismic reflection and refraction data (von Huene, 1972). The present width of the trench fill was used and therefore the subductions are probably high.*

techniques are developed; even the better than average single-channel seismic records do not reveal them. However, the knowledge of tectonic mechanisms at continental margins can be significantly advanced by combining detailed seismic surveying and drilling, even though continental margins are very complex. This is shown by the rates of underthrusting within significantly narrow limits that were estimated with the Leg 18 data. Off Oregon the estimates agree with the rates from the models proposed by Silver (1969, 1971, and 1972) and Atwater (1970); however, across the Aleutian Trench, estimated rates are consistently less. Since this has also been suggested in other recent studies (Creager, Scholl et al., in press; Hamilton, in press), the north Pacific models may be questioned.

Structural similarities and differences of the two margins drilled might be the result of similar tectonic mechanisms operating at different rates. The higher rates of underthrusting and the well-developed Benioff zone off Alaska contrast with the lesser rates and the absence of a Benioff zone off Oregon. This parallels the pronounced trench off Alaska in contrast to the very subdued and filled trench-like feature off Oregon. Such a comparison may extend to the mainly unresolvable deformation off Alaska and the more orderly folds of the lower continental slope off Oregon.

If intense underthrusting is the principal tectonic mechanism under the continental shelf, there must be a high degree of decoupling across a relatively narrow zone, with very little transmission of the compressional stress to the upper crust. The near-surface geology in the continental shelves off Oregon and Kodiak Island is not dominated by Neogene thrust faults and overturned folds (Kulm et al., Appendix I; Braislin et al., 1971; von Huene et al., 1972). Most Neogene faults dip steeply on either side of the vertical, the asymmetry of folds is mild, and nothing has been found that suggests a zone of intense thrusting deeper in the crust.

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