UPLIFT HISTORY AND EARTHQUAKE RECURRENCE AS DEDUCED FROM MARINE TERRACES ON MIDDLETON ISLAND, ALASKA

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ABSTRACT

Middleton Island, near the margin of the continental shelf in the northern Gulf of Alaska, has emerged from the sea during six major episodes of coseismic uplift from oldest to youngest of about 7 m, 8 m, 6 m, 9 m, 7.5 m, and 3.5 m which are recorded by marine terraces. All but the youngest uplift have been dated by radiocarbon methods at roughly 4,300, 3,800, 3,100, 2,390, and 1,350 radiocarbon years before present, reapectively, and the most recent uplift occurred during the March 27, 1964 Alaska earthquake. Recurrence time for these movements is on the order of 500 to 1,350 years. Average uplift rate is approximately 1 cm/yr since the island first emerged from the sea 4,300 years ago and there appears to be an abrupt decrease in the rate of upli£t to 0.6 cm/yr in the interval preceding uplift of the 1964 terrace. Uplift of the terraces is believed to result from local imbrication along thrust faults within the upper plate during major earthquakes related to slip on the Aleutian megathrust. Available data from the Middleton Island terraces and 1964 coseismic displacements suggest that much of the interseismic strain accumulated in the eastern part of the 1964 Alaska earthquake focal region has yet to be released. Together with historic seismicity, the data suggest that the accumulated strain is most likely to be released during one or more future earthquakes along the 100- to 200-km-long segment of plate boundary extending eastward from the vicinity of Middleton Island to Icy Bay.

INTRODUCTION

Middleton Island is located near the edge of the continental shelf in the northern Gulf of Alaska. Structurally, it is situated near the leading edge of the North American plate where it is being relatively. underthrust by the Pacific plate along the Aleutian Trench. The island, which trends northeast-southwest, is about 8 km long, 1.6 km wide, and has a maximum elevation of 47.6 m (fig 1).

During the March 27, 1964 Alaska earthquake the island was abruptly uplifted several meters with resultant exposure of a marine terrace. This terrace, together with five higher and older radiometrically dated marine terraces on the island provide an exceptionally clear record of intermittent earthquake-related tectonic movements during the past four millenia. It is the purpose of this paper to briefly outline data relevant to the nature and age of these terraces and to speculate on the tectonic history recorded by them.

Previous work

The marine terraces at Middleton Island were first described, on the basis of a brief air reconnaissance, by Capps (1933) who correctly inferred that the terraces recorded pulsating uplifts relative to sea level. In 1949, Don J. Miller visited the island for about 1 week during which time he carried out a remarkably thorough examination of both the bedrock geology and marine terraces (Miller, 1953). Despite the fact that he had no adequate topographic maps and radiocarbon dating of the terrace materials was not yet feasible, Miller succeeded in delineating the pre-1964 terraces and he speculated that they were probably of latest Pleistocene or Holocene age and tectonic in origin.

Present investigation

Our study of the Middleton Island terrace sequence was carried out by one or both of the authors during brief visits to the island in 1963, 1965, 1967, and 1970. The objectives were to date the terraces with radiocarbon methods, obtain precise data on the terrace elevations with particular emphasis on the heights of beach angles, and determine how much information on the terrace history could be deduced from the unconsolidated deposits on them. As part of this study a special base map at scale 1:10,000 with 5-ft contour intervals was prepared by photogrammetric methods by the Topographic Division of the U.S. Geological Survey from high-quality airphotos taken by the U.S. Coast and Geodetic Survey after the 1964 earthquake. Additional control on the elevation and configuration of the terraces is provided by three lines of levels surveyed across the island in 1963 by the senior author.

DESCRIPTION OF THE TERRACES

The most striking feature of Middleton Island is the steplike character of its surface which consists of a series of six terraces with average beach angle elevations above MLLW of about 6.4, 14, 23, 29, 37 and 44 m (figs. 1-3). Beach angle elevations for terraces I-V are estimated to be accurate within 11 m and the terrace heights are thus indicated as 3-m-wide bands on figure 4. This uncertainty is due to a combination of the possibility of slight tilting of the island which gives different beach angle elevations for the higher terraces across the island, mantling of the beach angles by talus, slope wash, and peat which conceal it in most places, and initial variations in the elevation of the beach angles. Steep sea cliffs, cut into moderately well indurated early Pleistocene marine strata that dip northwest as much as 30°, are developed around much of the island as a result of rapid erosion by the prevailing southeasterly and southwesterly storm waves. The northwestern end of the island is largely constructional, being made up of sand and gravel derived by longshore drift from erosion of outcrop on the southern part of the island. In this area the lower terraces slope off gradually to merge with the present beach and an area of irregular dunes.

Terrace uplift history

Long-continued late Quaternary emergence and tilting of Middleton Island is indicated by the exposure on the island of a beveled early Pleistocene marine section roughly 1,000 m thick that dips 22-30° northwest (Plafker and others, 1975; Miller, 1953). In addition, marine seismic reflection data on the adjacent shelf indicate that even the youngest Quaternary strata are deformed in a complex of structural highs and lows (Plafker and others, 1975). The marine terraces of Middleton Island, as interpreted on figures 2 and 3, record pulsating emergence of the Middleton platform in seven stages. Each terrace consists of a wave-cut bedrock surface overlain by stratified deposits of gravel, sand, and mud formed in the associated beach, lagoon, and shallow marine environments, and of peat formed in a freshwater or subaerial environment after emergence. Following the convention established by Miller (1953), the stages of emergence and the resulting terraces and associated features are designated by the Roman numerals I-VI with I representing the highest terrace and the earliest recorded stage of uplift, and VI representing the terrace formed in 1964. The following description of the sequence of terrace development is modified after MIller (1953). The major differences are in the elevations. Miller's were from relatively inaccurate altimeter readings whereas ours are based on the large-scale topographic map, level lines, and altimeter readings. In addition, we recognize a narrow stage V terrace on the southeast coast of the island that was not delineated by the previous reconnaissance work.

Preservation of so many strikingly developed terraces in the small area of Middleton Island is the result of a fortuitous balance between uplift and rate of marine erosion. The marginal slope of steeper gradient below a depth of 27 m around the present Middleton platform may represent part of the surface of the ancestral island or submarine bank initially exposed to marine planation. Projection of this slope to the present level of the stage I terrace indicates that the island or submarine bank exposed to marine planation at the outset of stage I may have been as much as 4.8 km wide and 16 km long. Other stages of uplift may have intervened between any two successive stages represented by the terraces now preserved on Middleton Island, but, if so, they are not recorded. Evidence to indicate emergence of the Middleton platform above the present stand also is lacking.

At the outset of stage I, partly indurated bedrock forming the Middleton platform was placed within the limit of wave action, either by (1) differential upwarping accompanied by tilting of the bedrock; (2) regional uplift of the sea bottom on which the platform already stood as a topographic high; or (3) eustatic lowering of sea level. The platform did not necessarily emerge as an island at this stage but, instead, may have formed a submarine bank. The marine terrace formed during stage I is preserved on the highest part of Middleton Island. The average altitude of the terrace surface ranges from about 44 m near the middle to about 40 m at either end. In the southern, broader part of the terrace (fig. 3) the wave-cut bedrock surface lies for the most part at an altitude of 40-41 m but rises abruptly to altitudes of up to 48 m in many conical to ellipsoidal mounds. These mounds, which are grouped in several rows that parallel the strike of the bedrock, represent erosional remnants formed along layers of more resistant bedrock. The unconsolidated deposits resting on the bedrock surface in the southern part of the stage I terrace range in thickness from about 30 cm (atop some of the mounds) to about 3 m. Auger holes, pits, and natural sections in the present sea cliff at the margin of the southern part of the terrace show as much as 1-1.3 m of interbedded sand and mud, locally gravelly, overlain by 0.3-2 m of peat. At many places the peat rests on the surface of the bedrock.

After stage I the ancestral Middleton Island, including the preserved part of the stage I terrace and an adjacent, probably much larger, area, emerged in pulses to the present stand. The remaining parts of the terraces and adjacent wave-cut cliffs of stages II, III, and IV form roughly concentric bands around the south and east margins of the stage I terrace. The stage V terrace, in contrast, is preserved only in two narrow bands on the northwest and northeast sides of Middleton Island. The wave-cut cliffs formed during stages V and VI cut all the higher terraces.

The beach angle of the stage II terrace (toe of the adjacent wave-cut cliff) is at an average altitude of 37 m, indicating vertical movement of the land with respect to sea level of at least 7 m between stages I and II. The inner margins of the lower uplifted terraces are at altitudes of about 29 m, 23 m, and 14 m, indicating additional uplift of at least 8 m between stages II and III, 6 m between stages III and IV, 9 m between stages IV and V, and 7.6 m between stages V and VI. The most recent pulae of emergence relative to sea level at Middleton Island occurret at the time of the great earthquake of March 27, 1964. During this seismic event the island was tectonically uplifted 3.4 m (Plafker and Rubin, 1967). As a result, a terrace surface was permanently exposed above high tide level around the perimeter of the island. This terrace, labeled VI on figures 2 and 3, varies in width from about 20 m to 150 m and is the narrowest of the six terraces on the island. Below this terrace the littoral zone between the low tide and high tide shorelines (0 and 10-ft contours, fig. 1) is a broad platform that has an average width of about 200 m and a maximum width of 700 m near the southwest and northeast ends of the island.

Terrace Deposits

In the northern, narrower part of the stage I terrace the altitude of the bedrock surface decreases northward, but the general level of the terrace surface is maintained by a corresponding increase in the thickness of.the unconsolidated deposits. This part of the terrace is, therefore, a constructional feature.

The unconsolidated deposits of the stage II and stage III terraces, as exposed in natural sections and in a few pits and auger holes, are similar to the previously described deposits of the stage I terrace.

Near the north end of the stage IV terrace the bedrock surface falls from an altitude of 12 m to sea level within about 100 m. Here, as at the north end of the stage I terrace, the general level of the terrace is maintained for some distance north of the point where the bedrock surface begins to fall off, by a corresponding increase in thickness of the unconsolidated deposits.

The hooked projection at the north end of the stage III terrace, which is entirely composed of gravel in a ridge that rises to 6 m above the level of the stage IV terrace, probably formed as a spit that merges at its south end with the stage III beach deposits.

The stage IV terrace, lying along the southeast side of Middleton Island, is mantled by thick deposits of predominantly sand and gravel with ridges of stratified sand and gravel that rise as much as 2 m above the general level of the terrace. These ridges are believed to have been a series of either spits or offshore bars behind which finer grained sediment was trapped.

The stage V terrace at the northwestern end of the island and along the northeastern side of the island is mantled with a sequence of lagoonal deposits that accumulated behind offshore gravel bars. The lagoonal deposits are especially well exposed along the northeastern shore of the island where they are incised by the stage VI sea cliff. A section of these deposits, which are up to 4 m thick, is shown on figure 4.

Around most of the shore of Middleton Island the wave-cut bedrock surface being formed at the present stage either is exposed or is covered by not more than a few tens of centimeters of unconsolidated deposits that are constantly being reworked and redistributed by wave and current action. These deposits consist of sand and pebble gravel that form the narrow beach and well-rounded cobbles and boulders that form spits or cobble-boulder pavements or are scattered at random on the bedrock surface. The bedrock surface probably slopes off at the north end of the island in the vicinity of the sand-gravel spit, for it is not exposed there even at the lowest tide stage. Notations on U.S. Coast and Geodetic Survey hydrographic chart 5422 show predominantly rock bottom, with scattered patches of sand and gravel, out to and at some places beyond, the 27 m depth contour around the island.

RADIOCARBON DATA

The ages of the pre-1964 terraces have been determined by radiocarbon dating of 24 samples of fossil driftwood in the deposits on the terraces or peat from within or on the terrace deposits. Sample localities are shown on figure 3 and the analytical data are given in table 1.

All dates used in this paper are in radiocarbon years. Application, of tree ring corrections will increase the ages of the four older terraces to about 4,900, 4,300, 3,400, and 2,500 years and result in slightly reduced average uplift rates and longer uplift recurrence intervals. As these differences are within the limits of error of the data and do not affect the conclusions of this paper no attempt has been made to correct the radiocarbon dates.

Although Middleton Island is almost treeless, driftwood is abundant on the present beaches and has been found on all terraces except for stage II. Radiocarbon dates on driftwood are believed to provide the most reliable times for terrace emergence where they are incorporated into beach deposits or lag gravels immediately above the bedrock surface.

Peat deposits develop readily in the cool, moist climate that prevails at Middleton Island. The peat, however, may begin to accumulate at any time after terrace emergence so that the basal peat can be considered to provide only a minimum age for the surface on which it occurs. Furthermore, because the basal peat is always subject to contamination with roots from above, the radiocarbon ages may be younger than the initial time of peat formation.

Figure 4 shows the ages of radiometrically dated wood and peat samples plotted against the average shore angle elevation of the five older terraces. Also shown is the height of the 1964 terrace and a eustatic sea level curve after Coleman and Smith (1964) for the past 5,000 years.

The data suggest the following ages for the older terraces: I- 4,300±250 b.p., II- approximately 3,800 b.p., III- 3,100±250 b.p., IV- 2,390±200 b.p., and V- 1,350±200. The lowest terrace, VI, formed in 1964 and the lower part of this surface is approximately at the mean higher high tide level (10-foot contour on figs. 1 and 3).

Terrace I is well dated by two wood samples (3, 5) and peat from the base of a section 238 cm thick (4). Samples 1 and 2 from this same surface yield ages that are as much as 1,000 years younger than terrace emergence.

The age of terrace II is poorly constrained as no driftwood was found in the deposits on its surface. Sample 7 provides a minimum age of 3,590 years and the second peat sample (6) formed long after emergence of the terrace. We have inferred a linear uplift rate on the basis of the better data obtained from the adjacent terraces (fig. 4) which yields an extrapolated age of about 3,800 years for this surface.

The age of terrace III is based on the two oldest peat samples (12 and 13). A driftwood sample (14) from this terrace is anomalous in that it is roughly 1,000 years older than the deposits in which it occurs. Because the age of the sample £alls in the age range of dated driftwood from the stage I terrace, we believe that it was eroded out of the highest terrace and subsequently incorporated into the stage III beach deposits. This is analogous to the present process whereby abundant driftwood from the older terraces--especially stages I and V--has been deposited on the modern beaches.

The age of the stage IV terrace is closely controlled by two dates on driftwood (15, 16) that are essentially the same within the limits of the dating method.

The stage V terrace is very well dated by three wood samples (21, 23, 24) and one peat sample (22) that yield reasonably concordant ages. This terrace is unique in that it has a sequence approximately 4 m thick of unconsolidated deposits containing abundant driftwood and some peat on it along the northeast side of the island. These deposits are believed to represent beach and lagoonal deposits that were deposited after emergence of the terrace approximately 1,350 years ago as indicated by the columnar section on figure 4. Sample 24, in lag gravel on the terrace surface, dates initial uplift as do samples of comparable age from this terrace on the opposite side of the island (22, 23, 24). Subsequently, a lagoon developed that was gradually filled in with sediment; the age of some of these deposits is given by samples 18 (660±250 b.p.) and 17 (460±250 b.p.).

COSEISMIC MOVEMENTS AND POSSIBLE INTERSEISMIC MOVEMENTS

The Middleton Island terraces were cut during long periods of stability or slight submergence relative to sea level and were elevated during brief intervals of coseismic uplift. Two curves depicting the most probable uplift histories are depicted on figure 5. For the pre-1964. stages, it is not known whether the indicated uplifts represent single events or more than one event that are relatively closely spaced in time. Because sea level was at or near its present stand during the period in which the terraces were formed (fig. 4), eustatic sea level changes did not play a significant part in their formation. Minimum coseismic uplifts are 7 m for stage I, 8 m for stage II, 6 m for stage III, 9 m for stage IV, 7.5 m for stage V, and 3.5 m for stage VI.

The solid curve on figure 5 assumes no interseismic recovery, and the dashed line shows a more probable situation in which there is a significant, but unknown, component of interseismic submergence. Interseismic submergence has been observed over an extensive region of Prince William Sound, the mainland coast, and at Kayak and Wingham Islands where as much as 4.7 m submergence occurred in the interval between uplift of the stage V and VI terraces at Middleton Island (Plafker and Rubin, 1967; Plafker, 1969). It is uncertain whether the submergence extended as far out on the continental shelf as Middleton Island although submergence may be indicated by two lines of evidence. One is that the pre-earthquake high sea levels reached to the base of the prominent sea cliff that encircles much of the island, which could be due to either a very long period of relative stability and erosion or to some submergence since the stage V uplift of the island. The second is that unconsolidated deposits, such as those on the stage V terrace (fig. 4), were deposited in a lagoon on the lower part of the terrace long after emergence. It is not known whether the observed relationships are indicative of interseismic submergence or normal marine processes that resulted in accumulation of these lagoonal deposits. However, the time lag between coseismic uplift and accumulation of the lagoonal deposits, the high sedimentation rate of 2 m/200 years indicated by the ages and stratigraphic positions of samples 17 and 18, and the evidence for widespread coastal submergence elsewhere in the region are all suggestive of interseismic submergence. From figure 5, it should be apparent that if interseismic submergence did occur, the true coseismic uplift for the pre-1964 terraces is equal to the indicated uplift plus the amount of interseismic subsidence.

RECURRENCE INTERVALS AND UPLIFT RATES

The 1964 coseismic uplift, together with available radiometrically dated samples from the five higher terraces indicate recurrence intervals on the order of 500 years between stages I and II, 700 years between II and III, and III and IV, 1,040 years between IV and V, and 1,350 years between V and VI (fig. 5). As noted earlier, it should be emphasized that the indicated coseismic uplift could represent either a single earthquake or more than one earthquake that are relatively closely spaced in time.

The average uplift rate for the Middleton Island terrace sequence, which is slightly more than 1 cm/yr (1.05 cm/yr), is among the highest documented rates of tectonic uplift in the world. In detail, however, the rate of uplift appears to show significant and systematic changes with time as indicated by the light solid line on figure 5. Within the limitations of the data, the uplift rates averaged about 1.25 cm/yr for the 1,200 years between stages I to III, 0.87 cm/yr for 1,650 years between stages III to V, and O.59 cm/yr for 1,350 years between the stage V and VI uplifts.

FUTURE EARTHQUAKES

The likelihood of another great earthquake and related uplift at Middleton Island cannot be predicted from the available data. It is clear that the 1964 uplift of 3.5 m, which followed the longest lnterseismic interval recorded in the marine terraces at Middleton Island, is significantly less than the steps between the older terraces which range from 6 to 9 m and average 7.5 m (fig. 5). As a consequence, the resulting 1964 terrace is less than half the width of the older ones (fig. 2).

If the uplift rate at Middleton Island was constant over the last few thousand years, it would be possible to predict that more than half of the accumulated strain is not represented by the 3.5 m of uplift in 1964. This could be taken to imply that the region may be overdue for another tectonic earthquake involving additional uplift of the island of about 3.5 m (Plafker, 1972). These data, together with the historic seismic record (Sykes, 1971) have been used to identify the segment of the Gulf of Alaska continental margin extending east of Middleton Island as a region where one or more major earthquakes are highly probable (Plafker and others, 1975). The causative plate boundary fault for the postulated event could overlap the Middleton Island area and result in enough uplift to bring it up to the apparent long-term trend.

On the other hand, one could argue that the rate of uplift, as shown on figure 4, has been decreasing progressively over the last 4,000 years and that the 3.5 m of uplift in 1964 has relieved most of the accumulated strain. If so, the uplift rate must have abruptly diminished by about 0.25 cm/yr during the last 1,350 years. Although such a change is possible, it does not appear to be likely in view of the long history of active uplift, tilting, and truncation that is recorded in the bedrock and marine terrace sequence at Middleton Island.

Another alternative possibility is that part of the accumulated strain not released during the 1964 earthquake will be released by postseismic creep deformation during a time interval that will be short relative to the earthquake recurrence time. The combined coseismic and postseismic uplift could be comparable to the amount of uplift that has affected the older terraces. Northwestward postseismic tilt of Middleton Island from 1966 to 1975 suggests that at least local adjustments to the coseismic deformation have apparently persisted for a period of 10 years (Prescott and Lisowski, 1977). The measured northwestward tilt, which is in the same sense as the long term tilt recorded in the dipping Pleistocene strata that underlie the island, has been tentatively interpreted by Prescott and Lisowski (1977) as indicative of either 2.5 m/yr slip on the flat-dipping Aleutlan megathrust or 1 m/yr slip on the more steeply dipping thrust fault that is inferred to bound the Middleton Shelf on the southeast (fig. 8C). No data on post-1964 elevation changes relative to sea level are available for Middleton Island to corroborate the observed tilting. However, the closest permanent tide gage, located at Cordova 100 km north of Middleton Island on the mainland, has shown a 6 percent decrease in the 2 m coseismic uplift during the decade following the earthquake (table 2). Unfortunately, no other tide gage data are available within the area that was uplifted during the 1964 earthquake. However, observations by one of us (George Plafker) along the mainland coast since the earthquake indicate that there have been no measurable postseismic vertical movements on the scale of those required by Prescott and Lisowski (1977) to account for the tilting at Middleton Island.

An independent check on the recurrence intervals indicated by the terrace data is from the measured horizontal strains associated with the 1964 earthquake and the relative plate motion in the region as deduced from oceanic paleomagnetic data. Assuming that convergence in the eastern Aleutian Trench is uniform at a rate of 5.5 cm/yr (Minster and others, 1974) and that the surface component of horizontal displacement measured by triangulation surveys is at least 20 m (Plafker, 1969), the strain released could have accumulated in only 360 years if the strain were purely elastic. Thus, even if we assume significant amounts of aseismic creep and permanent deformation, it is clear that the 1964 event could not have released all the horizontal strain accumulated during the period of 1,350 years preceding the earthquake. Gradual postseismic horizontal extension in the area of the triangulation survey should presumably result in elastic thinning and further subsidence relative to sea level. In fact, however, all four permanent tide gages in the region that subsided have shown the opposite effect during the decade after the earthquake, with recoveries on the order of 12 to 34 percent of the amount of earthquake-related subsidence (table 2).

In summary, the accumulated Middleton Island terrace data suggest recurrence intervals of 500 to 1,350 years for large arc-related events of the 1964 type. The data from terrace uplift steps and rates at Middleton Island, together with the results of triangulation resurveys in the earthquake-affected region suggest that at least half of the strain accumulated during the 1,350 years that preceded the 1964 earthquake has yet to be released, assuming no significant aseismic prequake creep. The accumulated strain could be released either by aseismic creep or in one or more large earthquakes over a time interval that is short, relative to the interval between successive terrace uplifts. Because the tide gage data indicate recovery rather than continued gradual strain release in the decade following the 1964 earthquake, it appears more likely that any residual accumulated strain will be released during future earthquakes along the Pacific-North American plate boundary.

A SEISMIC GAP IN THE NORTHERN GULF OF ALASKA?

The general tectonic setting of Middleton Island is on the upper plate above a low-angle thrust fault along which the Pacific plate is relatively underthrusting the North American plate in a northwesterly direction (fig. 7). As a consequence of this relative motion, nearly orthogonal convergence is presently occurring along the eastern part of the Aleutian megathrust and Pamplona fault zone, whereas dextral slip characterizes the Fairweather and Queen Charlotte transform faults. The structurally complex area between the transform and underthrust zones in the vicinity of Malaspina Glacier is the focal region of the series of great earthquakes and tectonic displacements that occurred in the vicinity of Yakutat Bay in 1899 (Tarr and Martin, 1912; Thatcher and Plafker, 1972). Marine geophysical data indicate that an oblique underthrust fault system, the Transition fault, lies along the base of the continental slope between the eastern end of the Aleutian Trench and the northern end of the Queen Charlotte fault. This is a zone along which late Cenozoic deformation has occurred locally and which may still be weakly active seismically. It can be considered as a subhorizontal zone of oblique subduction between the Pacific plate and North American continental crust. The present shift of the plate boundary to the Fairweather-Pamplona system is interpreted as an evolutionary process in which a complicated oblique arc juncture is being converted into a much simpler right-angle junction (Plafker and others, 1978).

According to the present interpretation, there should be no major seismic gap in the area east of Icy Bay because the transform segment of the plate boundary has been largely relieved of accumulated elastic strain energy by the 1958 Lituya Bay earthquake on the Fairweather fault (Sykes, 1971) and by the 1972 Sitia earthquakes on its presumed offshore extension to the southeast (Page, 1974). Furthermore, the 1899 Yakutat Bay earthquakes relieved strain in the complex zone near Malaspina Glacler and possibly on the northern part of the Fairweather fault (Thatcher and Plafker, 1977). Thus, the mayor remaining seismic gap along the Gulf of Alaska margin appears to be the segment, about 100-200 km long, between the offshore Pamplona zone and the eastern part of the 1964 earthquake focal region to the west (fig. 7).

MECHANISM OF TERRACE UPLIFTS

A major unresolved question is how are terraces uplifted ln steps during major tectonic earthquakes? Clearly, the worldwide historical record shows that this phenomenon is primarily related to thrust-type earthquakes in arc environments. In the Gulf of Alaska, geochronologic studies of terrace sequences on the mainland west of Icy Bay and near Lituya Bay (Hudson and others, 1976) together with the Middleton Island data indicate that local diastrophic structural growth, rather than regional tectonic deformation, is probably the dominant mechanism of terrace formation. This conclusion is based on the differences in tectonic setting between the three areas of terraces, the general lack of correlation of terrace ages and heights along the Gulf of Alaska margin, and the occurrence of all three terrace sequences on the flanks of growing anticlinal structures (Hudson and others, 1976).

Figure 8 illustrates three general cases of coseismic deformation across the area affected by tectonic deformation durlag the 1964 earthquake and the resultant inferred or observed vertical surface displacements. The section line is oriented in a northwest-southeast direction through Middleton Island (line A-A', fig. 6).

In figure 8A deformation within the upper plate ls considered to be entirely elastic and the coseismic slip is along the megathrust and equal in amount to the preseismic horizontal strain. The resultant coseismic surface displacements would be primarily subsidence due to elastic extension and attenuation of the upper plate with a small component of uplift at the leading edge of the upper plate due to updip thrusting. Such movement clearly could not result in uplift of terraces such as those at Middleton Island.

In figure 8B part of the stored elastic strain is dissipated by imbrication on the thrust faults that broke the surface at Montague Island (Plafker, 1967) and the remainder results in warping of the leading edge of the upper plate due to a "hang-up" on the megathrust. In this model the upper plate is tectonically shortened by approximately the amount of the preseismic horizontal strain. The 1964 coseismic vertical surface displacements are compatible with this model, but the high rate of uplift and tilting locally in the Middleton Island area are not satisfactorily explained by regional warping.

The preferred model, shown in figure 8C, attributes the observed uplift to the Montague Island faults and two or more submarine thruat faults within the upper plate. According to thia model most, if not all, of the preseismic horizontal strain is taken up by imbricate thrust faulting within the upper plate. Such a model can adequately account for the observed coseismic uplift as well as the long-term deformation at Middleton Island. It is also compatible with marine geophysical data indicating that the continental margin in the region of near-orthogonal convergence is characterized by a series of fault-bounded asymmetrical anticlinal folds and broad intervening aynclines that involve deformation of late Cenozoic strata (Bruns and Plafker, 1975; Plafker and others; 1975).

In conclusion, the combined data on structure, terraces, and 1964 coseismic displacements suggest that terrace formation is related to growth of local anticlinal structures within the upper plate and that the positions of theae structures change with time. A consequence of this conclusion is that terraces are not likely to be correlatable from place to place in this type of tectonic environment and it is unwarranted to assume constant uplift (or subsidence) rates over long periods of time.

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FIGURE CAPTIONS

1. Location and topography of Middleton Island.

2. Profiles across Middleton Island ahowing marine terraces (Roman numerals I-VI). Arrows indicate the beach angle location for the 1964 terrace; datum is mean lower low water.

3. Map of marine terraces on Middleton Island, and locations of radiometrically dated samples listed in table 1.

4. Diagram of terrace height versus age. Locations of numbered samples are shown on figure 3 and date information is presented in table 1. The inset at right is a stratigraphic column for the sequence of unconsolidated deposits on the stage V terrace. Eustatic sea level curve is after Coleman and Smith (1964).

5. Generalized diagram showing average terrace height and minimum tectonic uplift per event(s), versus terrace age and approximate recurrence interval. The solid curve shows an inferred uplift sequence assuming no interseismic vertical movement; the dashed line assumes some interseismic subsidence. The light solid line indicates the average uplift rate between terraces.

6. Map showing the distribution of tectonic uplift and aubsidence in south-central Alaska related to the March 27, 1964 Alaska earthquake (Plafker, 1969). Isobase contours in meters.

7. Map showing locations of earthquake epicenters and late Cenozoic faults in the northern Gulf of Alaska region. Large arrow indicates the inferred movement direction of the Paciflc crustal plate relative to North America. From Plafker and others, 1975.

8. Diagrammatic vertical displacement profiles (above) and structure sections through the crust and mantle (below) across the northern part of the region affected by the 1964 earthquake (line A-A', fig. 6). Figure A assumes all slip occurs along the underthrust plate boundary (Aleutian megathrust) at time of earthquake and the profile above shows the predicted vertical displacements at the surface which would be associated with such movement. Figure B shows the vertical displacements resulting from a combination of imbricate fautling within the upper plate and warping of the upper plate due to a "hang-up" on the megathrust. Figure C shows the step-like displacement pattern that would result from multiple imbrication on thrust faults within the upper plate.

Table 1. Radiocarbon-dated samples from the marine terraces on Middleton Island.

Map 1/ No.	Field No. 2/	Lab No. 3/	Location Latitude	Location Longitude	Material Dated	C-14 Age 4/ (BP)	Calendar Age 5/ (BP)	Sample Depth 6/ (cm)	Comments
				TERRACE I					
1	67APR14	W-2190	59° 25.03'N	146° 21.56'W	Peat	3340±250	3899 (3592) 3349	137	Drill hole
2	67APR13	W-2191	59° 25.10'N	146° 21.44'W	Peat	4300±250	5289 (4864) 4529	182	Drill hole
3	67APR7A	W-2185	59° 25.37'N	146° 21.42'W	Wood	4100±250	4962 (4804, 4773, 4606, 4589, 4568) 4279	35	
3	67APR7B	W-2058	59° 25.37'N	146° 21.42'W	Peat	3760±250	4518 (4144, 4105, 4096) 3829	37	Same section as W-2185
4	63APR32	W-1405	59° 25.37'N	146° 21.42'W	Wood	4470±250	5459 (5212, 5195, 5051) 4735	200	
				TERRACE II					
5	65APR86C	W-1728	59° 26.03'N	146° 19.53'W	Peat	940±350	1260 (911) 558	105	
6	67APR15	W-2062	59° 24.76'N	146° 21.98'W	Peat	3590±250	4269 (3896) 3589	152	Drill hole
				TERRACE III					
7	65APR73A	W-1732	59° 26.05'N	146° 19.36'W	Peat	550±200	680 (546) 440	30	
8	Willimovsky 2A	W-1205	59° 27.37'N	146° 18.34'W	Peat	600±250	740 (633, 603, 561) 440	150-210	
9	67APR11	W-2187	59° 24.55'N	146° 20.77'W	Peat	2370±250	2759 (2352) 2119	46	
10	67APR12	W-2060	59° 24.56'N	146° 20.84'W	Peat	2480±250	2849 (2709, 2633, 2605, 2587, 2541, 2535, 2499) 1930	107	
11	70APR3B	W-2546	59° 24.53'N	146° 22.08'W	Peat	3020±250	3479 (3248, 3225, 3218) 2859	143	Collected from talus block
12	70APR3A	W-2548	59° 24.46'N	146° 21.97'W	Peat	3260±250	3829 (3472) 3219	152	
13	65APR81B	W-1797	59° 26.02'N	146° 19.39'W	Wood	4185±250	5041 (4825, 4750, 4728, 4663, 4656) 4409	50	Probably recycled from Terrace I
				TERRACE IV					
14	67APR9	W-2059	59° 24.88'N	146° 20.28'W	Wood	2220±250	2706 (2311, 2231, 2207) 1930	200	
15	63APR31	W-1404	59° 24.78'N	146° 20.45'W	Wood	2390±200	2749 (2356) 2159	131	
				TERRACE V					
16	62AKA2E	W-1261	59° 26.19'N	146° 18.74'W	Wood	460±250	670 (515) 290	90-120	
17	62AKA2B	W-1259	59° 26.19'N	146° 18.74'W	Wood	660±250	881 (666) 500	150-180	
18	Willimovsky 4	W-1202	59° 26.33'N	146° 19.66'W	Peat	700±250	920 (671) 510	~180	
19	67APR6	W-2057	59° 27.05'N	146° 17.73'W	Wood	1020±350	1290 (938) 660	198	
20	65APR73B	W-1796	59° 25.55'N	146° 21.04'W	Wood	1150±500	1550 (1061) 660	60	
20	65APR73B	W-1837	59° 25.55'N	146° 21.04'W	Wood	1120±200	1280 (1053) 797	60	Re-run of W-1796
21	67APR17	W-2064	59° 26.29'N	146° 19.68'W	Peat	1250±250	1390 (1178) 930	~140	
21	67APR16	W-2063	59° 26.29'N	146° 19.68'W	Wood	1380±250	1530 (1296) 1060	~210	Same section as W-2064
22	65APR67B	W-1724	59° 26.29'N	146° 19.68'W	Wood	1350±200	1420 (1287) 1060	30-60	

1/ Figure 3.
2/ Samples collected by George Plafker (APR), Thor Karlstrom (AKA), and N.J. Willimovsky (Willimovsky).
3/ Run at USGS laboratory in Reston, Virginia by proportional gas counting.
4/ The error quoted is one standard deviation of the counting statistics times an error multiplier of two to allow for all laboratory uncertainties.
5/ Calendar age calculated from Stuiver and Reimer (1986). Error listed is the width of intersection of radiocarbon age plus its error with the calibration curve with its one sigma error band.
6/ Depths given are below ground surface at sample site.

Table 2. Postseismic elevation changes between 1964 and 1974 at tide gages in the region affected by vertical tectonic movements during the March 27, 1964 Alaska earthquake. Locations of gages shown on figure 6.

Tide gage	1964 coseismic displacement (cm)	Postseismic displacement (cm)	Postseismic recovery (percent)
Cordova	+189	-12	6
Kodiak	-171	+58	34
Seldovia	-119	+14	12
Anchorage	-79	+14	18
Seward	-110	+15	14

28

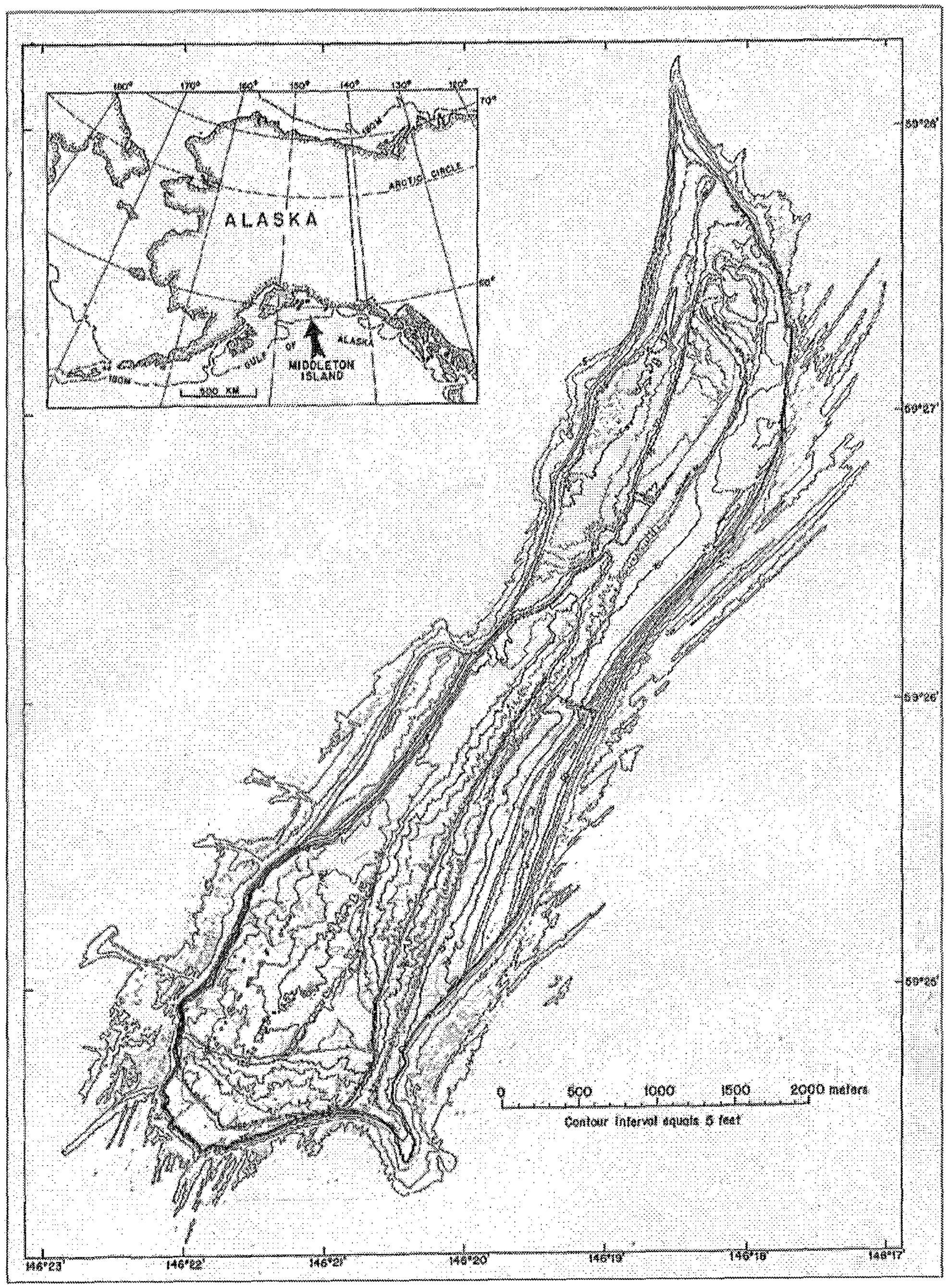


Figure 1

714

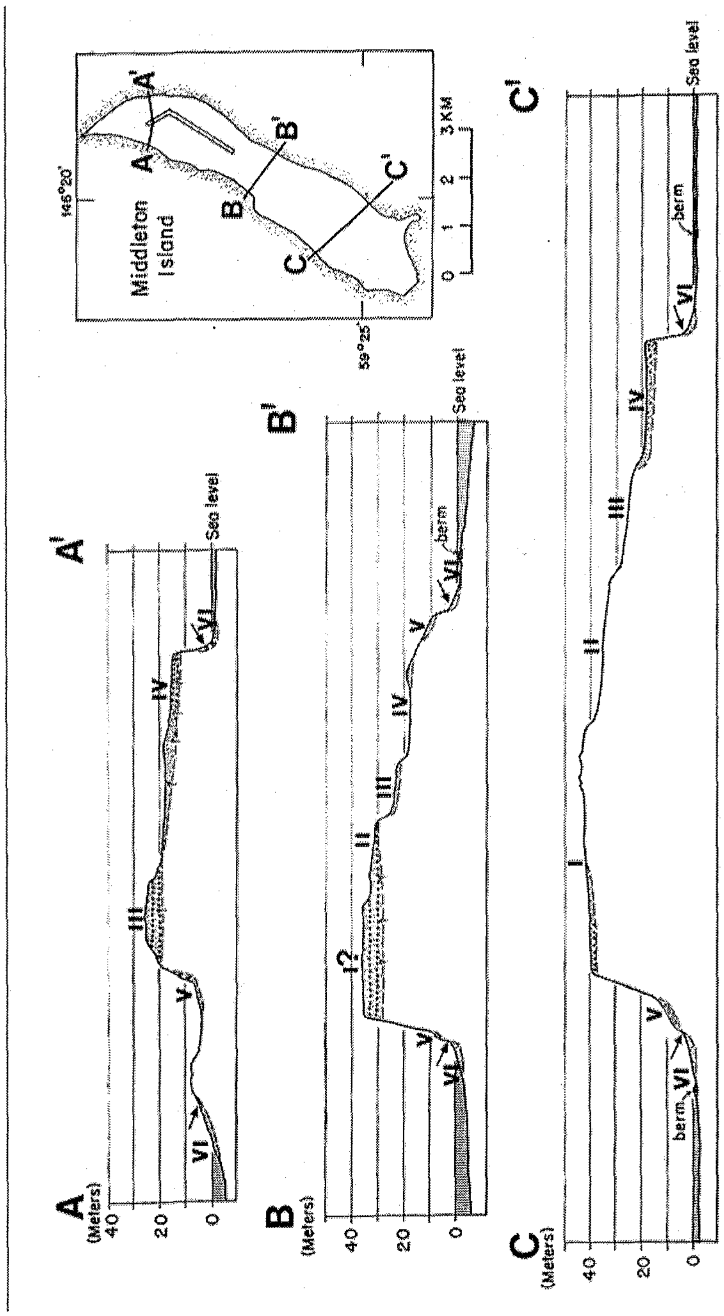

Middleton Island
146°20'
59°25'
0 1 2 3 KM
A
A'
B
B'
C
C'
(Meters)
40
20
0
I
I?
II
III
IV
V
VI
berm
Sea level
0
500
1000 M

Figure 2.

30

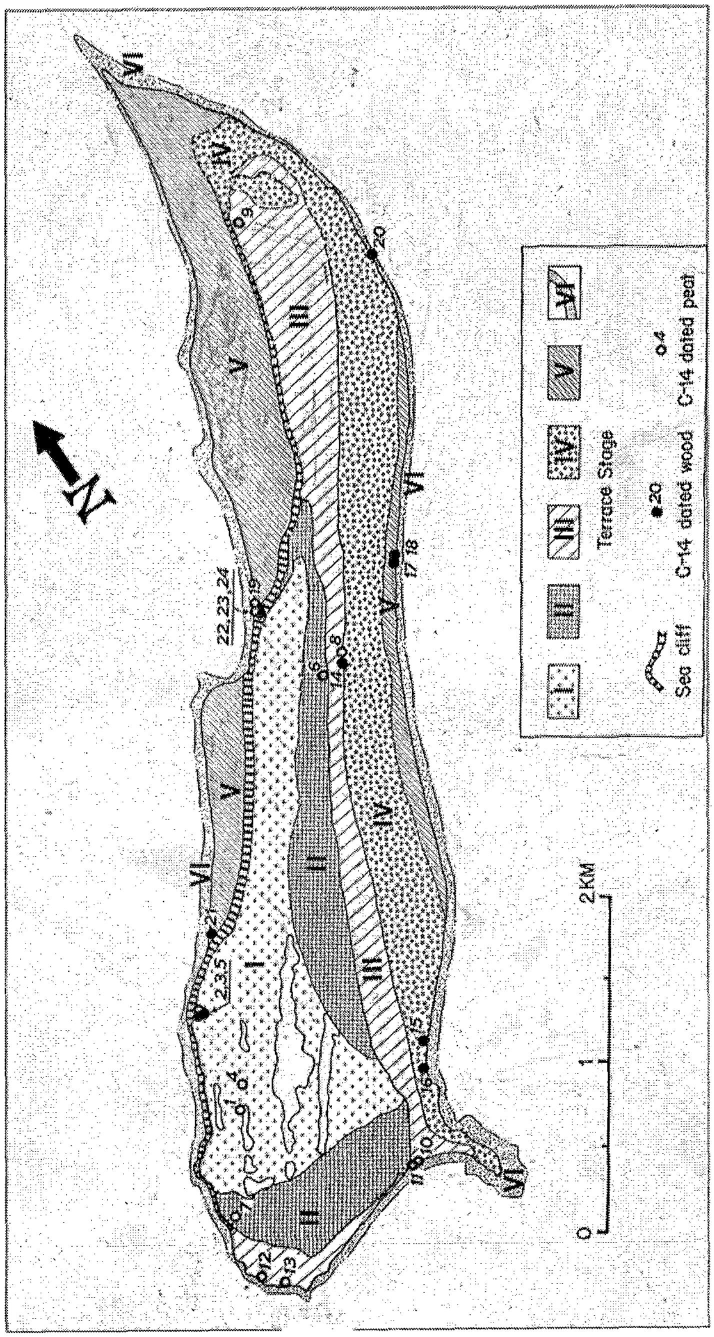


Figure 3.

716

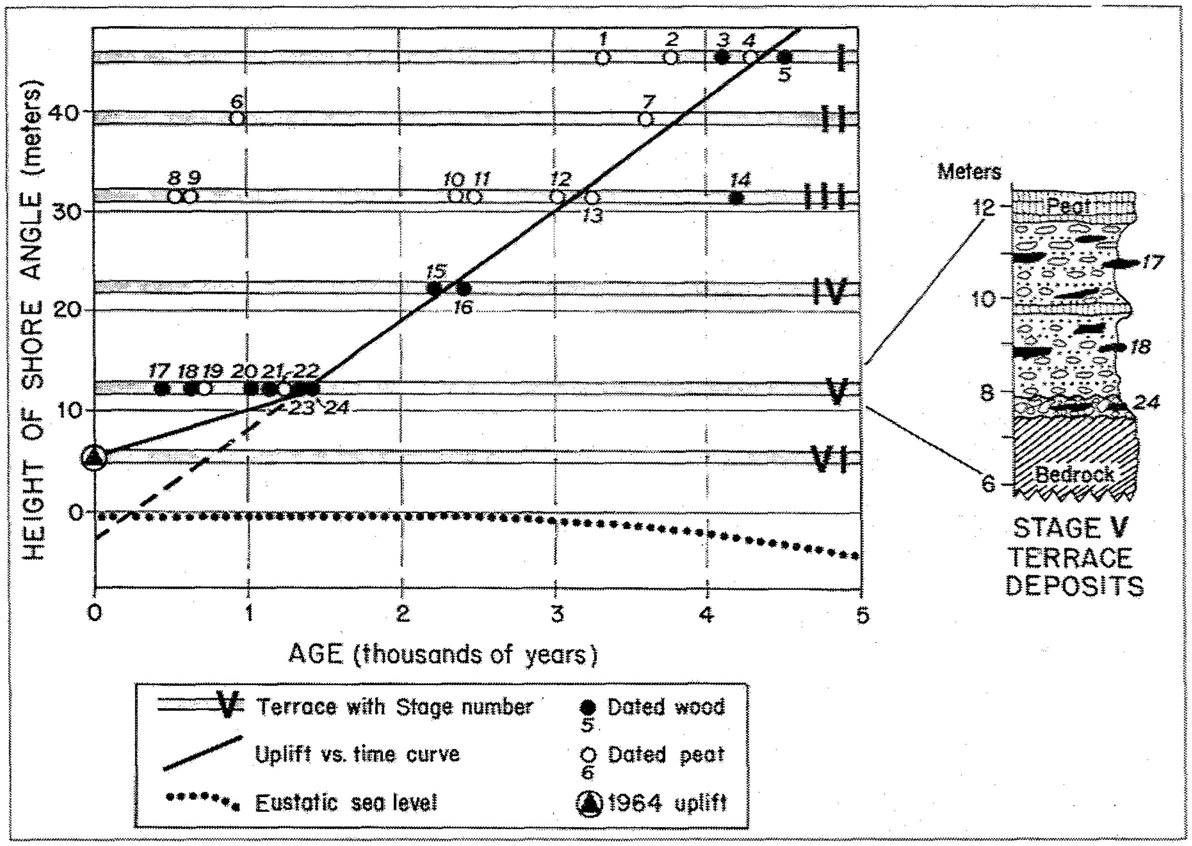

HEIGHT OF SHORE ANGLE (meters)
AGE (thousands of years)
I
II
III
IV
V
VI
Meters
Peat
Bedrock
STAGE V TERRACE DEPOSITS
Terrace with Stage number
Uplift vs. time curve
Eustatic sea level
Dated wood
Dated peat
1964 uplift

Figure 4.

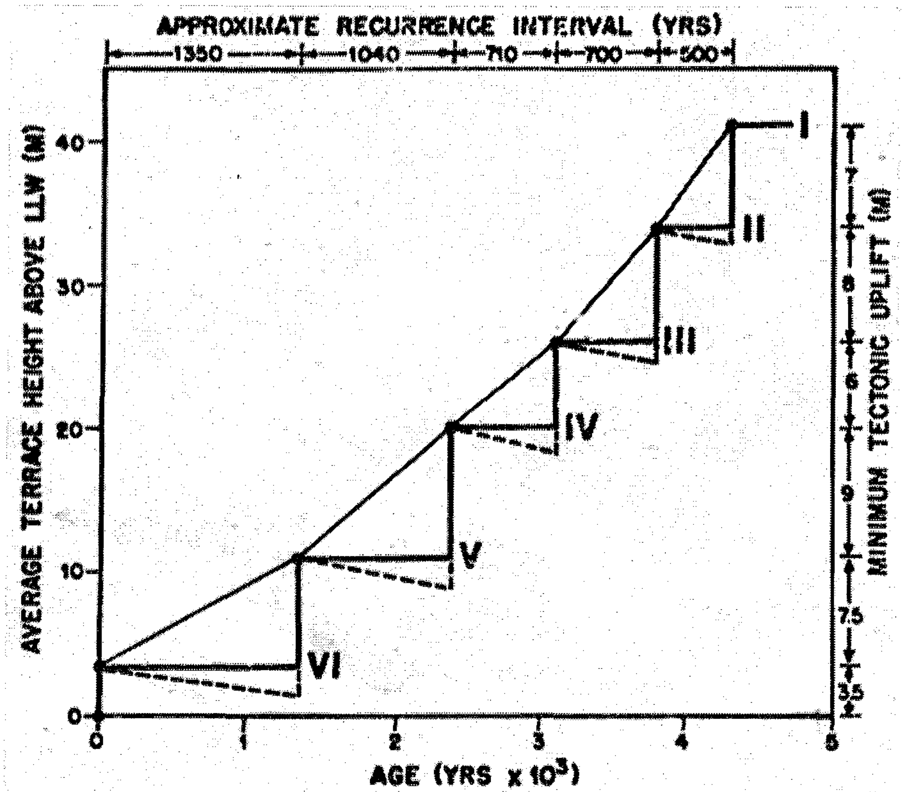

APPROXIMATE RECURRENCE INTERVAL (YRS)
1350
1040
710
700
500
AVERAGE TERRACE HEIGHT ABOVE LLW (M)
MINIMUM TECTONIC UPLIFT (M)
AGE (YRS x 10^3)
I
II
III
IV
V
VI
7
8
6
9
7.5
3.5
0
1
2
3
4
5
10
20
30
40

Figure 5.

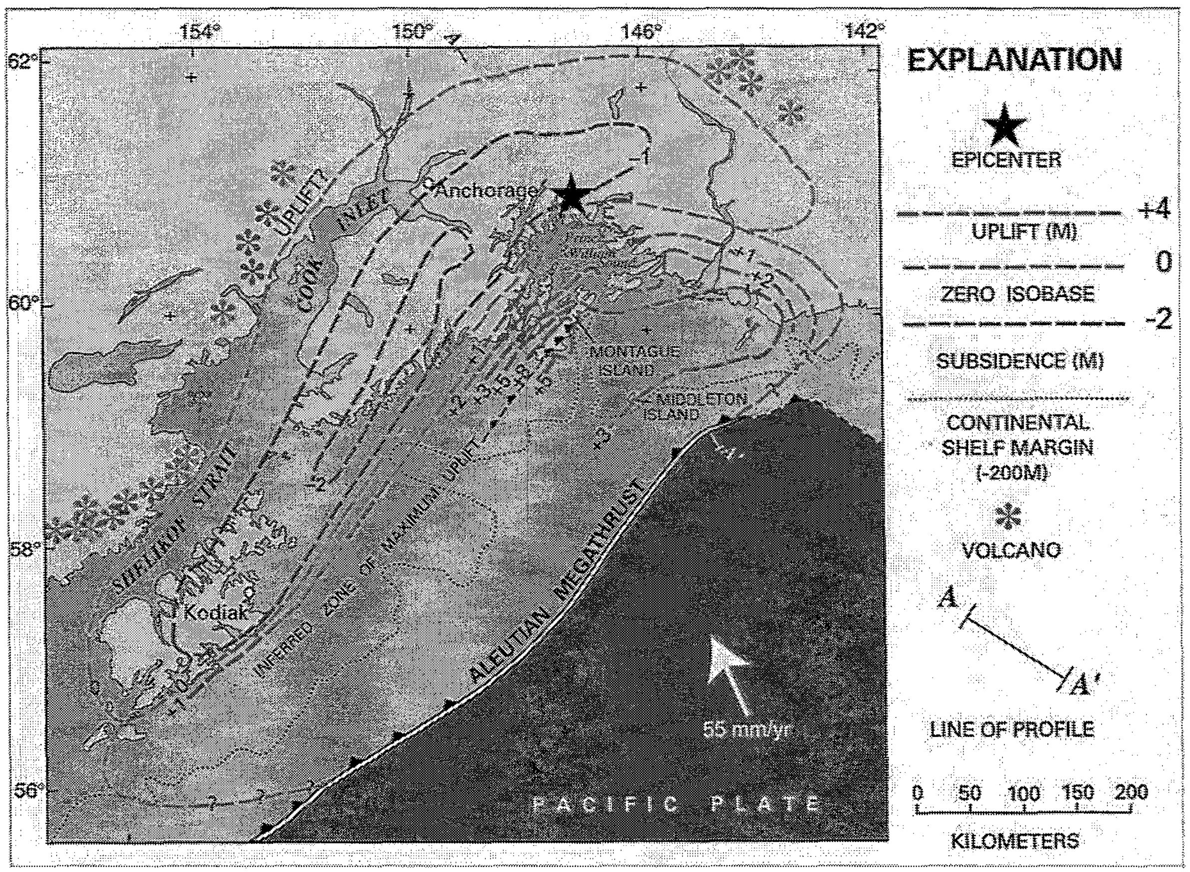
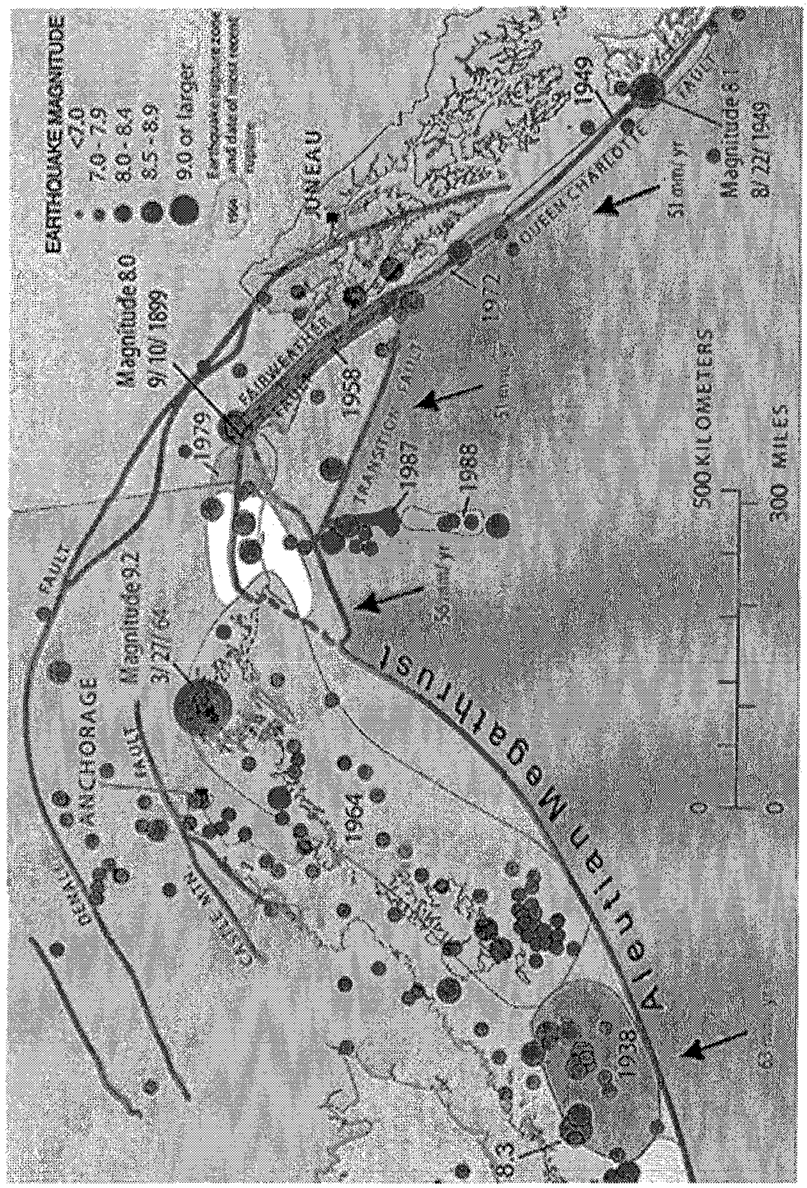

154°
150°
146°
142°
62°
60°
58°
56°
UPLIFT?
COOK INLET
Anchorage
SHELIKOF STRAIT
Kodiak
MONTAGUE ISLAND
MIDDLETON ISLAND
INFERRED ZONE OF MAXIMUM UPLIFT
ALEUTIAN MEGATHRUST
55 mm/yr
PACIFIC PLATE
EXPLANATION
EPICENTER
+4
UPLIFT (M)
0
ZERO ISOBASE
-2
SUBSIDENCE (M)
CONTINENTAL SHELF MARGIN (-200M)
VOLCANO
A
A'
LINE OF PROFILE
0 50 100 150 200
KILOMETERS

Figure 6.

34



720

Figure 7.

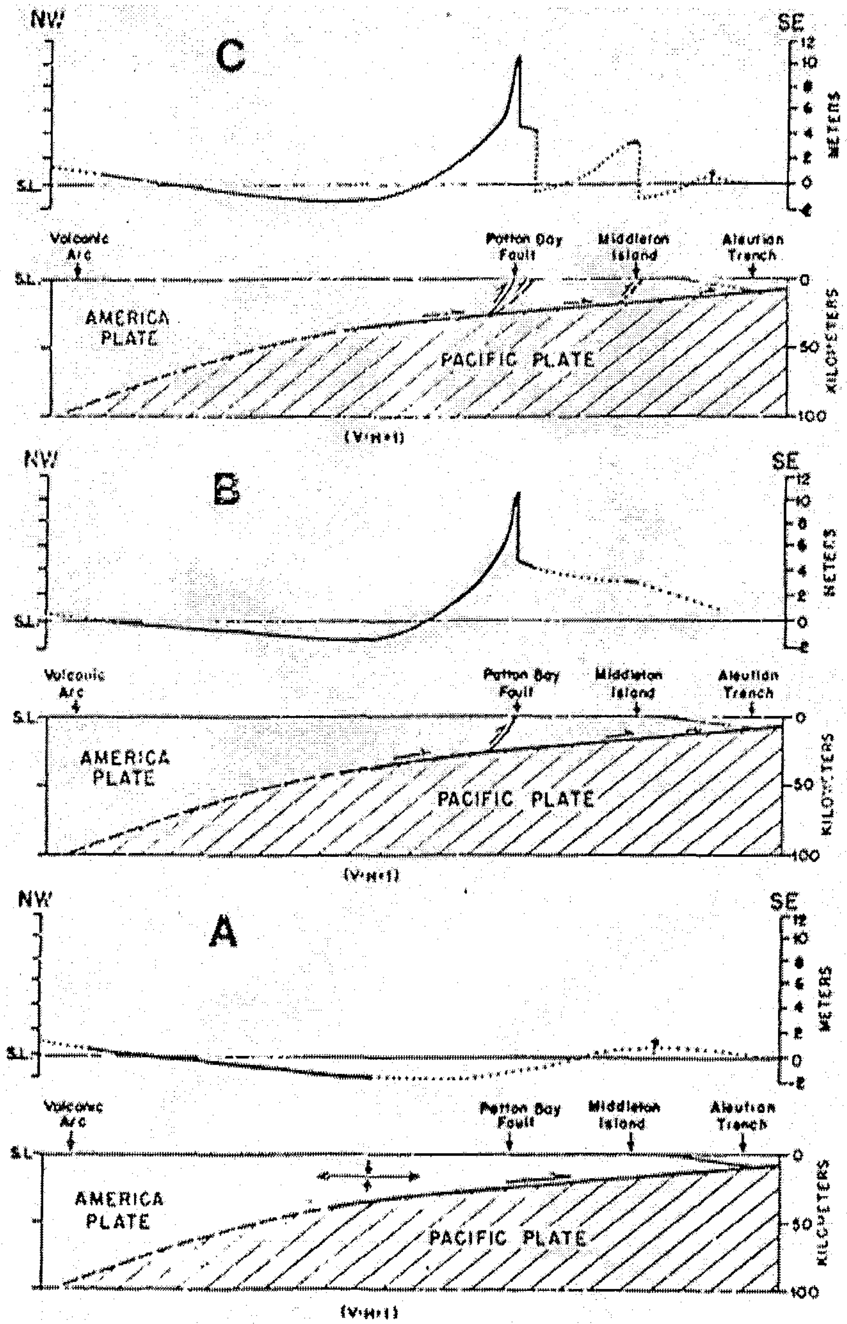

NW
SE
C
B
A
S.L.
METERS
KILOMETERS
Volcanic Arc
Patton Bay Fault
Middleton Island
Aleutian Trench
AMERICA PLATE
PACIFIC PLATE
(V=H=1)

Figure 8.