Stop 6

PLIOCENE SHALLOW-WATER SEDIMENT GRAVITY FLOWS AT MOSS BEACH, SAN MATEO COUNTY, CALIFORNIA

Thomas J. Wiley
Stanford University
Stanford, CA 94305

Ellen J. Moore
U.S. Geological Survey
Menlo Park, CA 94025

ABSTRACT

Two sections of Pliocene rocks from the upper part of the Purisima Formation are exposed northeast of the Seal Cove fault in the James Fitzgerald Marine Preserve at Moss Beach, San Mateo County, California. These sections contain fine to very coarse grained clastic rocks that were deposited in a shallow-marine environment. They overlie the Cretaceous Montara granodiorite of Darrow (1963), and are a part of the Salinian tectonic block.

The succession consists of three facies:
Facies 1. Repeated units in which shell/pebble conglomerate alternates with massive, hummocky cross-stratified, or parallel-laminated sandstone beds, interpreted as shelf sediments deposited and reworked by wave-generated currents.
Facies 2. Conglomerate and pebbly sandstone, commonly massive, inversely graded, or inverse-to-normally graded but in places cross-stratified or tightly packed, which alternate with cross-stratified and ripple-laminated fine sandstone; this facies is interpreted as sediment gravity flows deposited in a background of shelf sediment and reworked to varying degrees by shelf waves and tides.
Facies 3. Boulder and granule conglomerate, either disorganized, inverse-to-normally graded, or stratified, interpreted as subaqueous sediment gravity flows with only minor signs of reworking.

These three facies, occuring vertically in the same order, form several coarsening-upward sequences in a crude coarsening-upward overall succession. The beds were deposited adjacent to, and pinch out against, a granitic highland that was probably subaerially exposed to the north. The depositional setting is interpreted as a fan delta building into a south-facing bay or partly protected west-trending coastal segment. The distal reaches (Facies 1) were on the inner shelf and dominated by storm-wave processes. The middle reaches (Facies 2) contain in situ pelecypods that suggest water depths were shallower than 45 m and received sediment gravity flows that were reworked to varying degrees by waves. The proximal reaches (Facies 3) contain coarse-grained sediment gravity flows that show few signs of reworking, probably because of protection from waves at the head of the subaqueous part of the fan delta.

INTRODUCTION

At Moss Beach, California, an intriguing section is exposed in which fine-grained fossiliferous sandstone beds are interstratified with gravel and boulder beds. The coarser-grained components seem to have been deposited by sediment gravity flows, the fine-grained by traction currents in a shallow-marine setting. This study attempts to explain the apparent dichotomy indicated by the major facies types.

LOCAL GEOLOGY

The strata considered in this study are from the upper (Pliocene) part of the Purisima Formation. They overlie the Cretaceous Montara granodiorite of Darrow (1963) and are themselves unconformably overlain by Pleistocene terrace deposits. The Pliocene rocks crop out in two northwest-trending synclines on the northeast side of the Seal Cove fault (Figure 1).

The Seal Cove fault is continuous with the San Gregorio-Hosgri fault, a major northwest-trending right-lateral strike-slip fault (Graham and Dickinson, 1978). The San Andreas fault lies 12 kilometers to the east of the study area. It joins the Seal Cove fault under the Pacific Ocean northwest of San Francisco, 40 kilometers to the north.

The Purisima Formation, named by Haehl and Arnold (1904), occurs on both sides of the San Gregorio-Hosgri fault trend from San Francisco to Carmel (Branner and others, 1909; Touring, 1959; Cummings and others, 1962; Clark, 1966; Greene and Clark, 1979). Rock types present in the Purisima Formation include mudstone, tuff, diatomite, siltstone, sandstone, and conglomerate. Touring (1959) provides a detailed description of the Purisima of the northern Santa Cruz Mountains, which he divides into five mappable units. Glen (1959) correlated the coarse clastic rocks at Moss Beach with the upper part of the Purisima Formation, on the basis of mollusks.

As summarized by Clark and Brabb (1978), the Neogene strata of the northern Santa Cruz Mountains exhibit dramatic stratigraphic changes across the San Gregorio fault. To the northeast of the fault, the Purisima Formation comprises up to 1720 meters of shallow-marine siltstone, sandstone, and mudstone, resting conformably upon the Santa Cruz Mudstone of Clark (1966) and unconformably overlain by Pleistocene marine-terrace deposits. Southwest of the San Gregorio fault, a thinner section of the Purisima Formation lies unconformably on the Cretaceous Pigeon Point Formation, on the Miocene Monterey Formation, and on porphyritic rhyolitic volcanic rocks.

The Seal Cove fault juxtaposes the shallow-water deposits of the southern Moss Beach syncline against a deeper-water facies of the Purisima Formation. Whereas the rocks to the northeast of the Seal Cove fault have not been assigned to one of Touring's members, Glen (1959) notes that the coarse Moss Beach strata are younger than the strata southwest of the Seal Cove fault.

Paleobathymetry, based on published sources, on reinterpretation of published faunal lists, and on new paleontologic data, suggests that the Purisima Formation was deposited in a sea which varied in depth by 500 m or more. This points to local

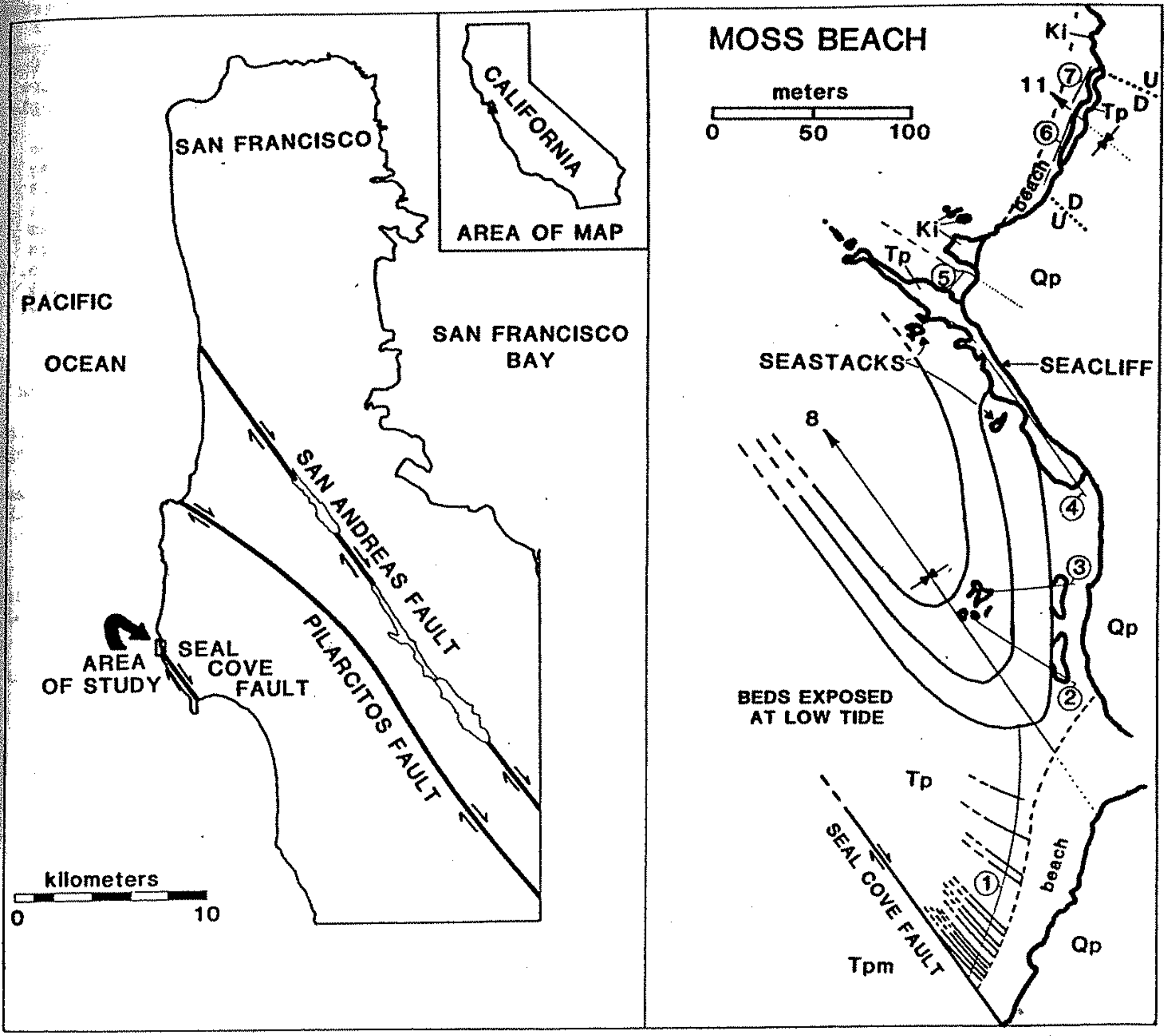


Figure 1: Location Map. Ki is Cretaceous intrusive basement (Montara granodiorite), Tp is Tertiary Pliocene Purisima Formation described in this study, Tpm is Tertiary Pliocene Purisima Formation mudstones exposed southwest of the Seal Cove fault, Qp is Pleistocene terrace deposits. Circled numbers refer to stratigraphic columns in Figure 7.

tectonics as a main control of bathymetry.

PALEOMAGNETISM

A study of paleomagnetism was undertaken to determine if the rocks have been rotated since they were deposited. A rotation would affect the paleocurrent directions and structures and their interpretation.

Moss Beach is located at longitude 122 degrees west, latitude 37 degrees north. Recent measurements of the magnetic field at Moss Beach give a declination (epoch 1965) of 62 degrees. The axial geocentric dipole model predicts that the present field has a declination of 0 degrees and an inclination of 57 degrees.

7 ?

inclination

declination: 16°?

7

Oriented samples were taken from the southern section at Moss Beach; no samples from the northern section were measured because fine-grained beds were not available for sampling. After measuring the natural remanant magnetization (NRM) of each specimen, the alternating-field (AF) technique of magnetic cleaning was applied. Most samples were subjected to peak alternating fields of 5, 10, 15, 25, 35, and 45 mT. Weak specimens were not subjected to the stronger demagnetization fields.

NRM intensities were very weak, they ranged from

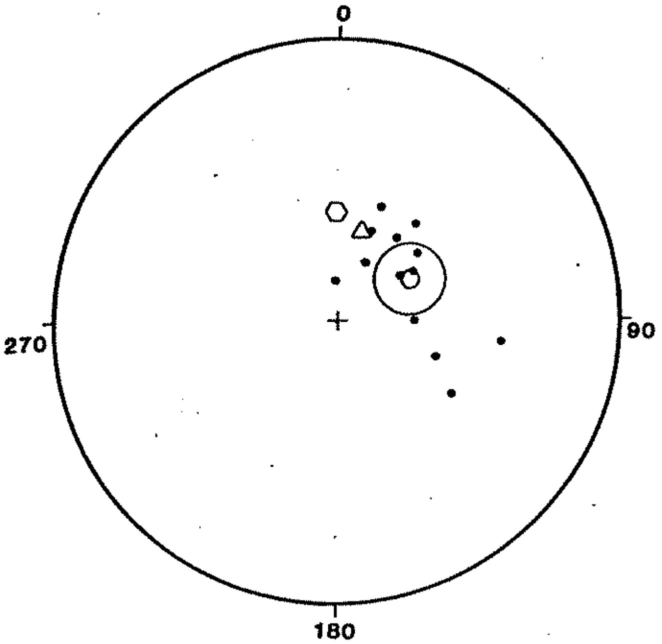


Figure 2: Magnetic directions. Solid dots are magnetic directions from demagnetization vectors for 13 sites at Moss Beach. Small circle is the mean direction; large circle is the circle of 95% confidence about the mean. Hexagon is magnetic direction predicted by the axial geocentric dipole model. Triangle is the present (1965) field direction at Moss Beach. (Lower hemisphere, equal area plot)

8.16×10^{-5} to 2.08×10^{-3} Amp/meter and averaged 7.39×10^{-4} Amp/meter. Intensities after maximum AF demagnetization ranged from 3.77×10^{-5} to 4.89×10^{-4} Amp/meter and averaged 2.04×10^{-4} Amp/meter.

Zijderveld (1967) plots of demagnetization curves were made and demagnetization vectors calculated where magnetization directions remained stable and intensity decreased with increasing strength of the AF demagnetization field.

Comparison of the mean for tectonically corrected versus uncorrected original NRM directions and Zijderveld (1967) vectors--the fold test--was accomplished by the use of the "F" test (see McElhinny, 1970, p. 77-89 for a discussion of the statistical methods and tests). This test showed that the precision of the mean for the corrected field directions was significantly worse than that of the uncorrected directions. This means that the rocks have been remagnetized since they were folded. Authigenic opaque grains observed in thin sections of the magnetic specimens may be the source of the secondary magnetization.

An average declination of 60 degrees and inclination of 65 degrees (Figure 2), with a circle of 95% confidence (alpha 95) of radius 10 degrees, was calculated for the rocks of the southern section. The average declination of 60 degrees is significantly different from the 16-degree declination of the present field and from the 0-degree declination predicted by the axial geocentric dipole model for the present field. The average inclination of 65 degrees is not significantly different from either that of the present field--62 degrees--or from the 57 degrees predicted by the axial geocentric dipole model. The declination directions for individual specimens are widely scattered, even among specimens from a single site, and appear to reflect varying amounts of present-field contamination. If this is true, the actual rotation could be more than the 60 degrees calculated.

The paleomagnetic data suggest that the rocks have been rotated clockwise 50 to 70 degrees since they were folded. To compensate for this rotation, paleocurrent directions and appropriate structural data have been rotated 60 degrees counterclockwise.

STRUCTURAL GEOLOGY

Pliocene strata at Moss Beach have been folded into two synclines separated by granitic basement. Stereographic analysis of bedding attitudes shows that the axis of the southern fold trends N36°W and plunges 8 degrees to the northwest, and the axis of the northern syncline trends N51°W and plunges 11 degrees to the northwest (Figure 3), roughly coaxial with the southern fold. These fold axes are parallel to the N36°W trend of the right-lateral Seal Cove fault which bounds the southern syncline on the southwest. They are also parallel to the trends of the Pilarcitos and San Andreas right-lateral faults located several kilometers to the east (Figure 1).

Several sets of faults with small displacements cut the Pliocene rocks. The limbs of the northern

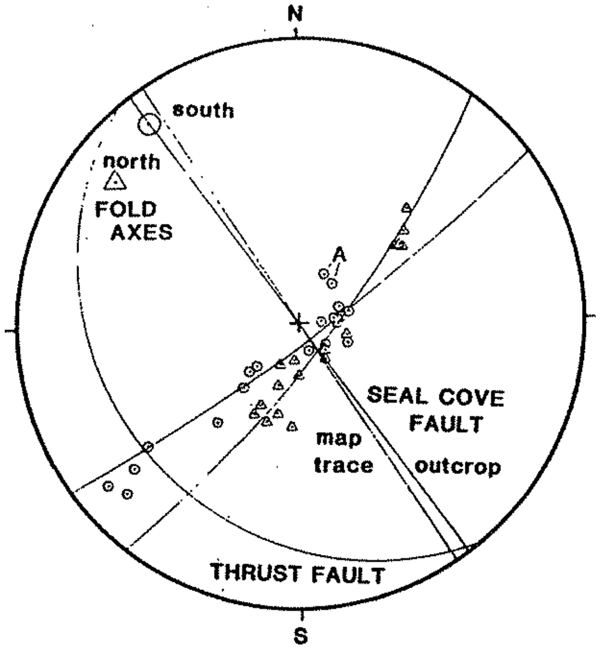


Figure 3: Structural geology of Moss Beach. Triangles and circles are bedding attitudes from the north and south sections respectively. Thrust fault is located in the hinge of the southern syncline. Group "A" from beds near contact with granodiorite. (Lower hemisphere, stereographic plot)

syncline are truncated by high-angle faults that juxtapose the Pliocene deposits against the Cretateous granodiorite. Minor thrust faults intersect bedding planes in lines subparallel to the fold axes (Figure 3), evidence for faulting.synkinematic with the folding episode.

The structural grain of the Moss Beach area is parallel to the trend of the throughgoing regional faults. This makes the folds difficult to explain in terms of classic wrench folding (Dibblee, 1976; Harding, 1976). Instead, these folds probably belong to Page's (1981, p. 403) group of "unexplained anticlines and synclines" that parallel the trend of the San Andreas fault.

When the fold axes are rotated 60 degrees counterclockwise to compensate for the postfolding clockwise rotation, both the folds and the thrust faults are placed in an orientation compatible with classic wrench-folding models. In this orientation, the folds are consistent with wrench folding associated with Seal Cove faulting (Figure 4) and with the regional strain produced by the San Andreas system.

A 60-degree rotation is large for such young rocks. This, and the fact that the section is directly adjacent to a large strike-slip fault, suggests that the Pliocene rocks may have been rotated independently of the older, better indurated rocks east of the fault.

PALEONTOLOGY

Previous Work

Glen (1959) correlated the coarse-grained clastic rocks at Moss Beach with the finer-grained rocks more typical of the upper part of the Purisima Formation. This correlation is based on 26 species of mollusks. He interpreted the fauna of the stratigraphically lowest beds at Moss Beach as representative of shallow depths, below tide level but probably not deeper than 20 to 40 m. Glen interpreted the upper part of the section as "deposited in a small shallow embayment which probably became increasingly restricted and disconnected from the ocean, culminating in a brackish water environment at the time of deposition of the uppermost bed."

Benthic Foraminifers

Two species of benthic foraminifers have been identified from the Moss Beach syncline. Ingle (1981) listed the Neogene benthic foraminifers of the Southern California Continental Borderland and assigned the species to microfaunal zones or biofacies. One of the foraminifers present at Moss Beach, *Nonionella miocenica* (Cushman), is listed in the inner-shelf biofacies, where water depth ranges from 0 to 50 m. The other species, *Uvigerina juncea* (Cushman and Todd), lives in water depths of 50 to 150 m--Ingle's outer-shelf biofacies. Both species were found together in a single sample from Facies 1, suggesting that the water depth was near 50 m.

Pelecypods In Living Position

A search was made for any Pliocene marine mollusks preserved in living position, to help determine the depth of deposition of the containing sediment by recognizing fossils that had not been transported. This search proved successful, and numerous specimens of *Tresus nuttallii* (Conrad) were found in life position. Most of the specimens are exposed in cross section (Figure 5a) as a result of erosion, with the exposed section on the horizontal wave-cut surface almost perpendicular to the dorsal ventral margins of the shells. A few almost complete double-valved specimens also were found, and these were in living position.

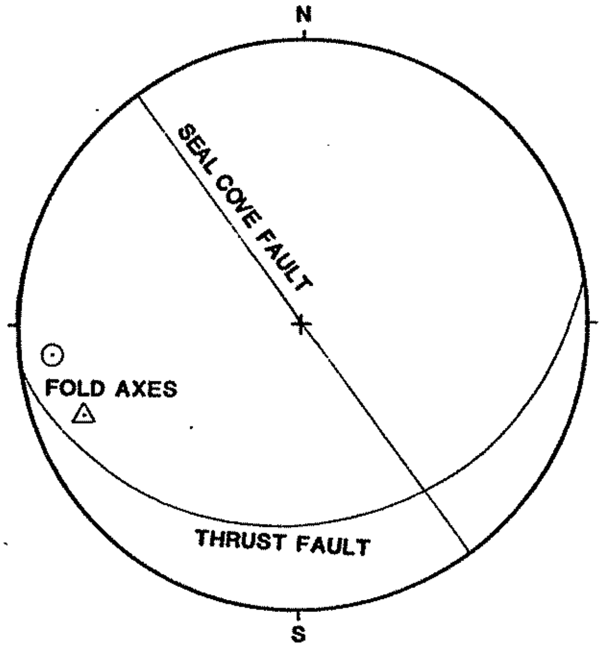


Figure 4: Structural geology corrected for post-deformation rotation. Fold axes and minor faults rotated 60 degrees counterclockwise in accordance with paleomagnetic data. Note that a single horizontal compressive stress oriented at about 175-355 degrees could produce all these structures. (Lower hemisphere, stereographic plot)

Pohlo (1964) studied 14 live specimens of *Tresus nuttallii* and noted that the larger specimens (those over 60 mm in length) may burrow to a depth of 1 meter and that the long axis of the shell lies at about 60 degrees to the water-sediment interface (Figure 6). Except during burrowing, the siphon is always perpendicular to the water-sediment interface. The specimens of *T. nuttallii* collected in this study are mainly 100 mm or more in length. The exposure and preservation of the specimens is such that it is difficult to ascertain the exact orientation of the shells, but they seem to have been at the 60 degree angle to the water-sediment interface appropriate to a living position.

Most of the shells of *T. nuttallii* in the main layer of upright articulated specimens, are about 1 m below a graded granule-conglomerate bed. Between the shells and the graded bed are numerous concretionary vertical burrows (Figure 5b). These burrows contain layers concentric around single or double vertical centers about 5 mm apart, a spacing which matches that of the juxtaposed inhalent and exhalent siphons of *T. nuttallii*. The ghost shrimp, *Callianassa californiensis* (Dana), is found living in modern habitats with *Tresus* and it also burrows in the mud,

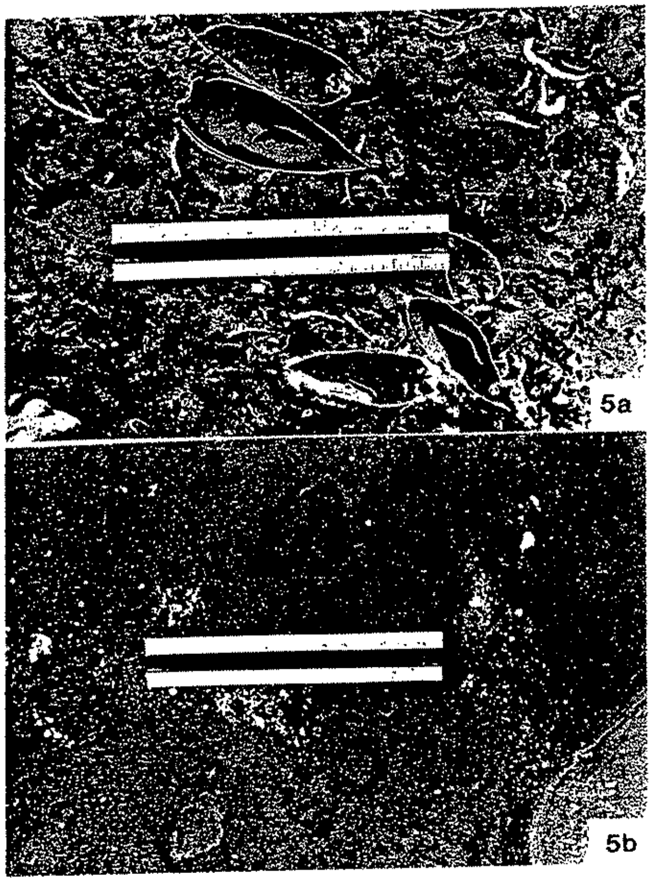


Figure 5: 5a, life-position shells of the pelecypod *Tresus nutallii* (Conrad) exposed on bedding plane, these are large individuals; 5b, concentricly laminated trace fossils exposed on bedding plane, some with double centers, associated with life-position pelecypods.

but the burrows are much branched and complicated (Ricketts and Calvin, 1952, p. 265) rather than simple and vertical. Although some of the burrows have single centers, we believe that at least those with double centers are probably the burrows of the clam *Tresus*. Perhaps the bed of mollusks was smothered by deposition of the overlying granule-conglomerate bed. Subsequent decay preserved the double center of the siphons in the concretions.

Tresus nuttallii lives today from Alaska to Baja California Sur in bays, estuaries, and sheltered areas on the outer coast, from the high-tide line to a depth of 45 m (Hertlein and Grant, 1972, p. 318).

One specimen of *Spisula* (*Mactromeris*) sp. cf. *S.* (*M.*) *catilliformis* (Conrad) also was found in life position. *Spisula catilliformis* lives today from Washington to Baja California Sur at depths of 20 to 75 m and rarely in shallower places (but seldom so shallow as to be exposed at average low tides), in fine sand or firm sandy mud in bays, sloughs, and estuaries, as well as in more quiet and protected areas along the outer coast (Fitch, 1953, p. 88).

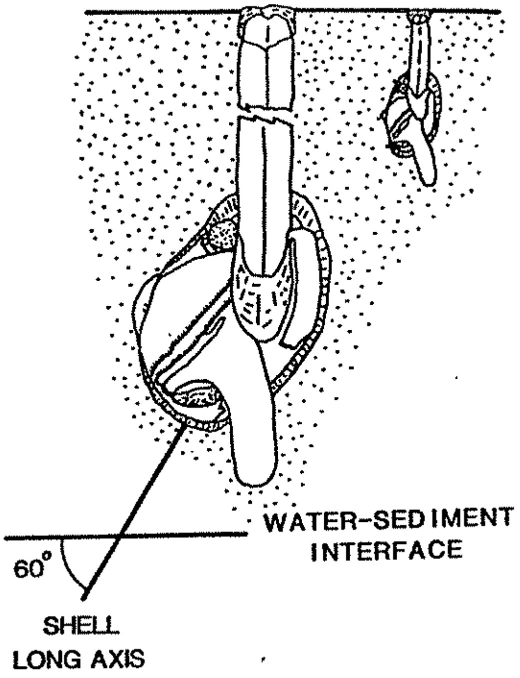


Figure 6: Growth position of the pelecypod *Tresus nuttallii* showing large (85 mm) and small (25 mm) individuals (after Pohlo, 1964).

On the basis of the present distribution of *T. nuttallii* and *S. catilliformis*, the fossil fauna exposed at Moss Beach probably lived at a depth between 20 and 45 m in a bay, estuary, or other protected area along the outer coast.

SEDIMENTOLOGY

The sedimentary rocks at Moss Beach can be divided into three facies which combine to form several coarsening-upward sequences.

Facies 1: Laminated, Cross-bedded, and Massive Sandstone Beds Alternating with Shell/Pebble Conglomerate Beds

Description

This facies occurs at three stratigraphic positions (Figure 7) and consists mainly of repeated fining-upward units in which shell/pebble conglomerate grades abruptly into sandstone (Figure 8).

In the Moss Beach section, 92 sandstone beds range in thickness from 5 to 150 cm and average 37 cm. Some of the thicker beds seem to be amalgamated. The grains are moderately-well sorted medium sand with rare granules, pebbles, and shell fragments. Sandstone beds are parallel laminated, low-angle (swaley and hummocky) cross-bedded, and massive. Lateral change from laminated or cross-bedded sand to massive sand is common. Individual beds can usually be followed the length of an outcrop.

In the section, 86 beds of shell/pebble conglomerate are from 5 to 100 cm thick (mean 25 cm). The average grain size is 0.6 cm with clasts as large as 6 cm in most beds and rare larger clasts with long diameters up to 20 cm. The large clasts are

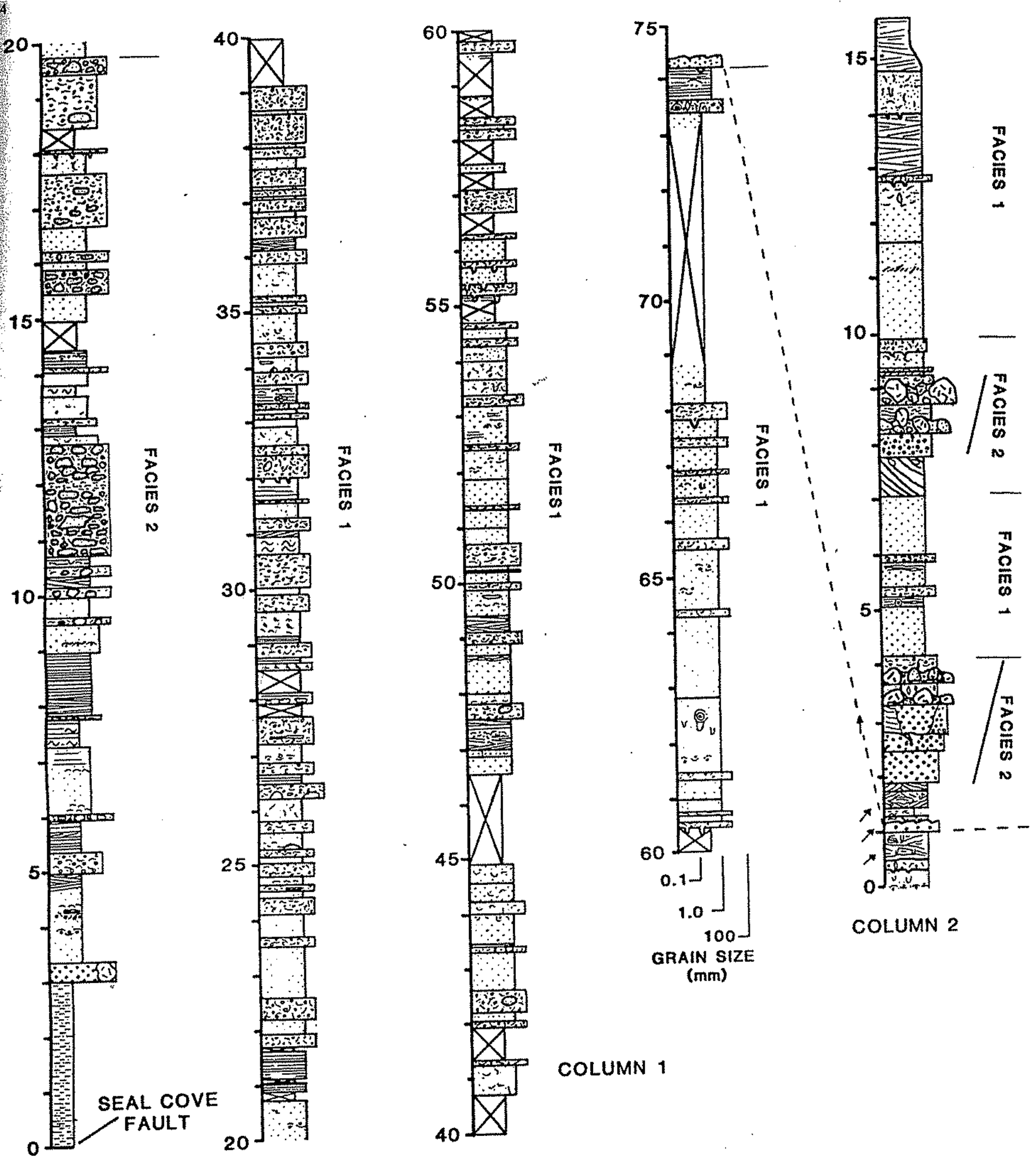
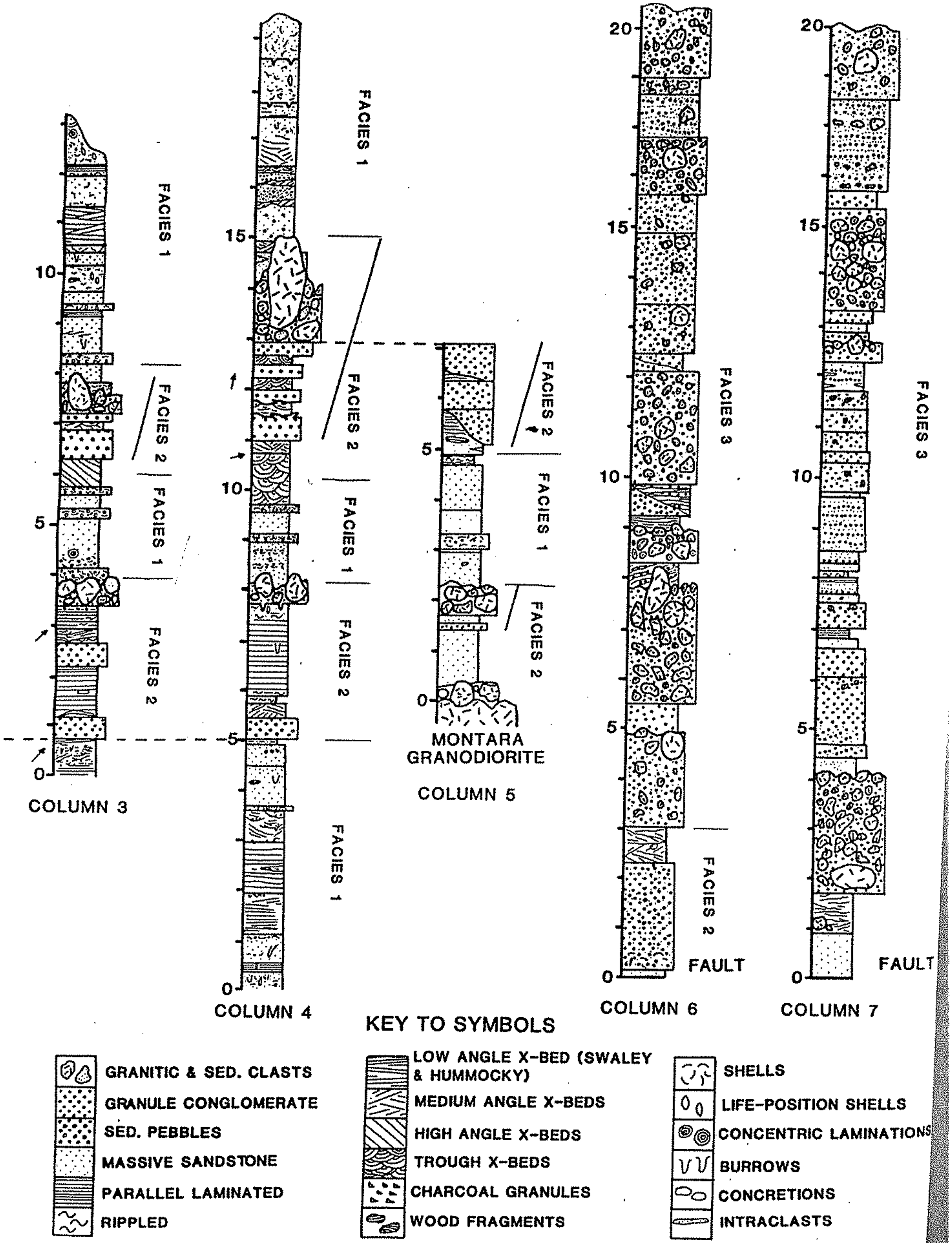


Figure 7: Stratigraphic columns from Moss Beach. Column locations are shown on Figure 1. Arrows are paleocurrent directions. Solid diagonal lines are next to Facies 2 coarsening-upward sequences. Dashed lines tie equivalent beds. Thicknesses in meters.


0
5
10
FACIES 1
FACIES 2
FACIES 1
FACIES 2
COLUMN 3
0
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15
FACIES 1
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FACIES 1
FACIES 2
FACIES 1
COLUMN 4
0
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FACIES 2
FACIES 1
FACIES 2
MONTARA
GRANODIORITE
COLUMN 5
0
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20
FACIES 3
FACIES 2
FAULT
COLUMN 6
0
5
10
15
20
FACIES 3
FAULT
COLUMN 7
KEY TO SYMBOLS
GRANITIC & SED. CLASTS
GRANULE CONGLOMERATE
SED. PEBBLES
MASSIVE SANDSTONE
PARALLEL LAMINATED
RIPPLED
LOW ANGLE X-BED (SWALEY & HUMMOCKY)
MEDIUM ANGLE X-BEDS
HIGH ANGLE X-BEDS
TROUGH X-BEDS
CHARCOAL GRANULES
WOOD FRAGMENTS
SHELLS
LIFE-POSITION SHELLS
CONCENTRIC LAMINATIONS
BURROWS
CONCRETIONS
INTRACLASTS

Figure 8: Facies 1—alternating beds of shell/pebble conglomerate and sandstone. Tops to right.

typically disc or blade shaped. Shell and clast long axes usually parallel bedding. In many beds, individual pelecypod valves are preferentially oriented with the convex side up. Both normal and inverse coarse-tail grading have been recognized in shell/pebble beds, normal grading is the more common. Elongate clasts exposed in bedding planes have a preferred northwest orientation (Figure 9).

Poorly exposed beds of rippled fine sand, silt, and clay make up about 1% of the facies. Bioturbation is common in Facies 1 sandstone beds and in the finer-grained shell/pebble beds.

Where sandstone underlies shell/pebble conglomerate, 60% of the contacts are sharp and the remainder are sharply gradational. Where sandstone overlies shell/pebble conglomerate, 75% of the contacts are gradational and 25% are sharp. Very thin shell/pebble conglomerate beds often pinch out laterally leaving amalgamated sandstone beds.

Interpretation

The succession consists of repeated sedimentation units in which normally graded shell/pebble beds with sharp, scoured bases grade abruptly into hummocky cross-stratified or parallel-laminated sandstone beds. This is not always well developed but nevertheless dominates the succession. Alternating sandstone and shell/pebble conglomerate beds similar to these have been interpreted as storm deposits by Kreisha (1981).

The observed fining-upward trend in each unit can be interpreted in terms of decreasing energy produced by a waning storm on a shallow shelf. Consistent with this idea is the hummocky cross-stratification, as several authors (Leckie and Walker, 1982; Hunter and Clifton, 1982; Hamblin and Walker, 1979) have interpreted hummocky cross-stratification as being produced by storm waves. Leckie and Walker (1982) define swaley cross-stratification as consisting "of a series of superimposed concave-upward shallow scours about 0.5 to 2 m wide and a few tens of centimeters deep." They attribute it to bottom currents generated by storm waves shoreward of, and in shallower water than, the hummocky cross-beds. Several parallel-laminated sandstone beds contain small concave-up pelecypod shells suggesting the laminations are produced by ripple migration rather than sheet flow (Clifton and Boggs, 1971). The small percentage of fine-grained beds in this facies (and throughout the Moss Beach section) suggests that the water was shallow enough that small frequent storms could rework the bottom with enough energy to prevent the preservation of most of the fair-weather siltstone and mudstone beds. Clast long axes in shell/pebble beds were probably oriented parallel to wave crests (Figure 9).

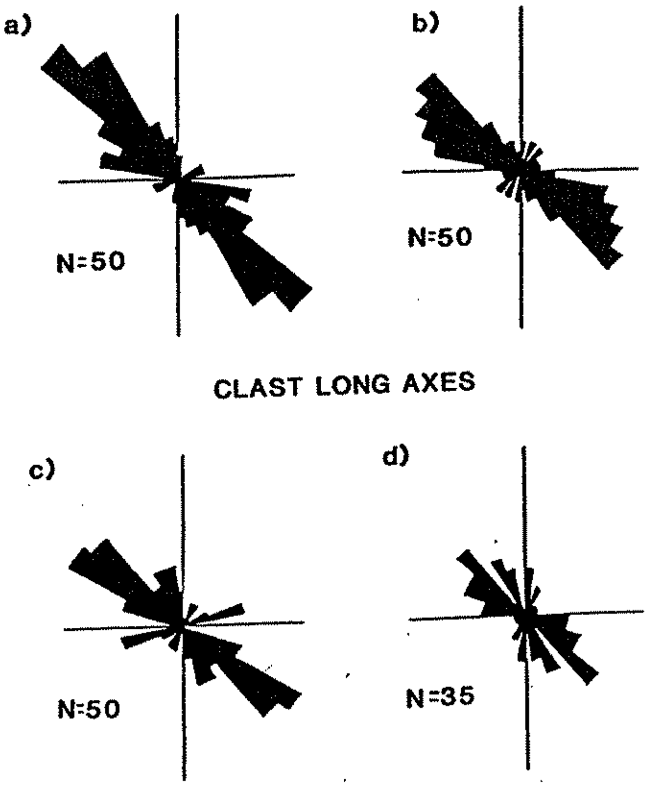

Figure 9: Facies-1 paleocurrents. Long axes of clasts in shell/pebble conglomerate. Clasts with long axis (x) and short axis (y) where x/y is greater than 3. Oscillatory currents perpendicular to long axes. Not corrected for rotation.

Many of the differences between ideal fining-upward units and beds in the measured sections seem to be due to bioturbation.

Facies 2: Clast-supported Boulder Conglomerate, Granule Conglomerate, and Massive or Cross-Bedded Sandstone

Description

Coarse-grained sandstone beds of Facies 2 are from 10 to 90 cm thick (average 45 cm). Most beds contain a few pebbles up to 1 or 2 cm in diameter and rarely a lone 5 cm clast. These beds are usually trough, tabular, or hummocky cross-bedded but some have been bioturbated and are massive. Bed geometry ranges from lenticular to broad tabular sheets. Contacts are usually sharp.

Granule-conglomerate beds have an average thickness of 40 cm, but vary from "granule thick" to 2 m.

The average grain size is 0.5 cm, maximum 10 cm. Angular quartz, biotite, feldspar, and granitic rock fragments make up most of the grains, with small amounts of shell fragments, wood fragments, and metamorphic and sedimentary rock fragments. Asymmetrical and symmetrical megaripples with long straight crests (Figure 10a) are developed on the tops of two granule conglomerate beds (Figure 7, column 4 at 11.5 m and column 2 at 1 m). While cross-bedding is obvious in several places, most granule-conglomerate beds seem massive or show indistinct inverse or inverse-to-normal coarse-tail grading (Figure 10b). Repetitions of these graded sequences indicate that some of the thicker beds are amalgamated. Like that in the coarse-grained sandstone beds, bed geometry ranges from lenticular to tabular. Lower contacts are sharp, the granule conglomerate often fills burrows in underlying coarse sandstone beds. Upper contacts may be gradational with boulder and cobble conglomerate and coarse-grained sandstone; upper contacts are sometimes rippled.

Facies 2 boulder and cobble conglomerate beds range from 10 to 250 cm thick (average 60 cm). Clasts average 15 cm in diameter and are angular to moderately well rounded. Granitic clasts with diameters of more than 1 m occur in most beds (maximum 2.5 m). Sedimentary clasts range up to 35 cm in diameter. Bed thickness is usually defined by the diameter of the largest clasts, in most places the beds consist of a layer a single clast thick (Figure 10c). But in those places where the beds are several clasts thick, they show coarse-tail inverse grading with a base of smaller clasts supported in a matrix of pebbly sandstone overlain by larger clasts (often the largest in the section) supported by each other (Figure 10d). Clasts have a random orientation. Sandstone clasts predominate at the base of the section, adjacent to the Seal Cove fault. Granitic clasts are far more common higher in the section and farther to the north. Boulder-conglomerate beds may have amalgamated contacts. Upper contacts are usually sharp, with finer sediment filling in between the boulders. Lower contacts are usually sharp, but may be gradational above granule-conglomerate beds. The gastropod Nucella sp. cf. N. lima (Martyn) is the most common fossil preserved in the boulder conglomerate.

Lenticular beds of interlaminated rippled fine sand, silt, and clay make up about 2% of Facies 2.

Within Facies 2, the beds and bed types commonly associate in such a manner as to coarsen and thicken upward. Alternating sandstone, pebbly sandstone, and rippled fine sand, silt, and clay are the most common bed types at the base of the facies, but give way to amalgamated granule conglomerate that is capped by boulder conglomerate at the top of the facies (Figure 7, column 4, 11-15 m). Similar lateral variations in this facies can be seen by comparing equivalent parts of different sections.

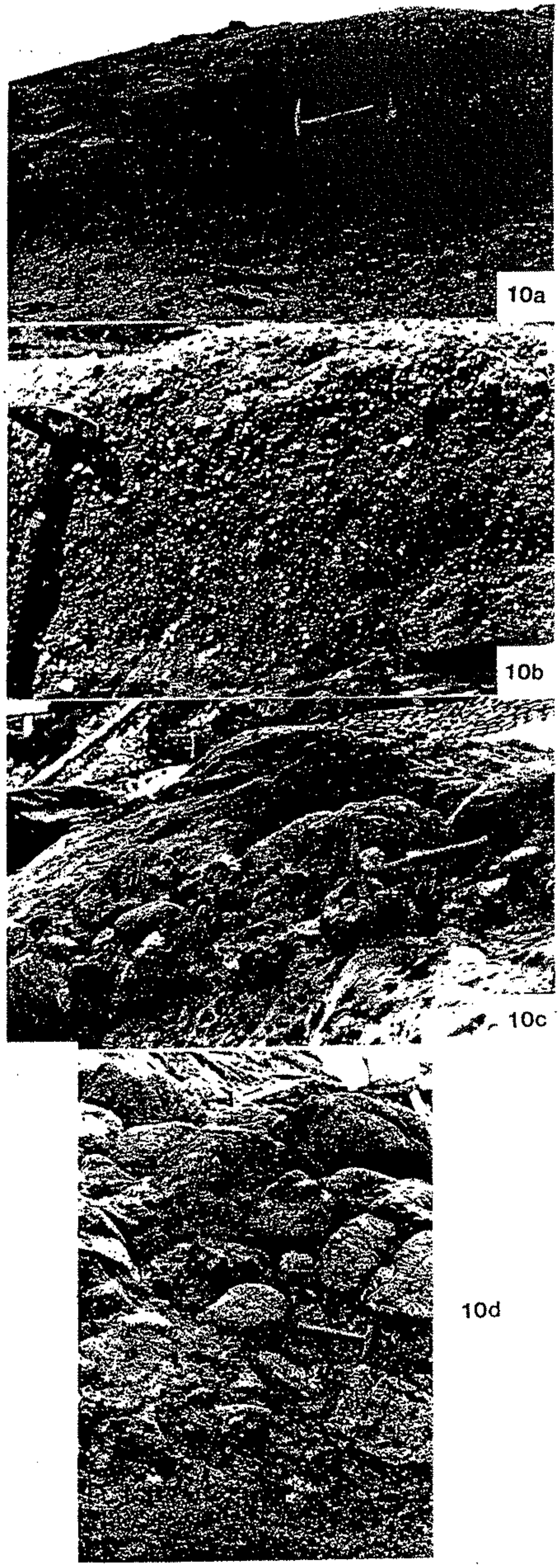

Figure 10: 10a, Facies-2 granule conglomerate with symmetrical ripples; 10b, granule conglomerate showing coarse-tail inverse grading; 10c, boulder conglomerate, single clast thick; 10d, boulder conglomerate, inverse graded and matrix supported at the base—these are some of the largest clasts in the section.

Interpretation

Facies 2 is interpreted as sediment gravity flows which were deposited and subsequently reworked to varying degrees in an environment otherwise dominated by wave processes similar to those which produced Facies 1.

Many of the beds in this facies are similar to those in Facies 1. In some places Facies 2 beds seem similar to Facies 1 shell/pebble conglomerate; hummocky cross-stratified, parallel laminated, and massive sandstone; and rippled fine sandstone, siltstone, and mudstone. Structures in all but the fine-grained beds are interpreted as having been formed by wave-generated currents, like they were in Facies 1. Several of the rippled fine sandstone and siltstone beds in Facies 2, however, show bidirectional paleocurrents (Figure 11) and are interpreted as having been deposited by weak tidal currents. These beds formed the background in which granule- and boulder-conglomerate beds were deposited.

Similarities in the internal structure, bed geometry, and distribution of Facies 2 granule- and boulder-conglomerate beds suggests that both were originally deposited by similar or closely related processes. Both may show inverse or inverse-to-normal coarse-tail grading, poor sorting, and random orientation of clasts. The most common bed geometry in both cases is lenticular. The thickest parts of lenticular granule-conglomerate beds are usually overlain by the thickest parts of the boulder-conglomerate beds. Facies 2 granule- and boulder-conglomerate beds in the upper part of the section have a predominantly granitic composition with very few mollusk shells, distinctly different from associated shell/pebble conglomerate beds that contain only rare granitic clasts. The granule- and boulder-conglomerate beds are interpreted as originally having been deposited by sediment gravity flows. Where they were not reworked, they appear similar to resedimented conglomerate beds described by Walker (1975, 1977), Nemec, Porebski, and Steel (1980), and Gloppen and Steel (1981).

Many granule- and boulder-conglomerate beds seem to have been reworked to form cross-stratified granule conglomerate, cross-stratified sandstone, and one-clast-thick boulder and cobble conglomerate. Asymmetric and symmetric megaripples are preserved on the tops of several of the granule-conglomerate beds. One set of asymmetric megaripples (Figure 7, column 2, 1.2 m, and Figure 11) has long straight crests that trend northwest, with the lee side to the northeast. Clifton, Hunter, and Phillips (1971) describe similar ripples from an "asymmetric rippled zone" in the inner part of the offshore. Working on the Oregon coast, with the highest of every ten waves averaging 1.5 to 2 m, they found that this zone occurred in depths of 4 to 10 m (Clifton, Hunter, and Phillips, 1971; Clifton, 1976). This zone would presumably occur in deeper water under larger storm waves. Symmetrical megaripples on an amalgamated contact between granule-conglomerate beds (Figure 10a, and Figure 7, column 4, 11.4 m) are similar in form to those Clifton, Hunter, and Phillips (1971) describe in their "symmetric rippled zone" at depths of 10 to 20 meters. The grain size at Moss Beach, however, is somewhat coarser. The structures also resemble those from their "inner rough zone" which formed at depths of about 1 m off steep beaches on the Oregon coast; but the tops of "inner rough zone" beds are probably not preserved in ancient deposits (H. Edward Clifton, pers. comm., 1983). Wave reworking of granule conglomerate is not always limited to the tops of the beds, several are cross-stratified throughout.

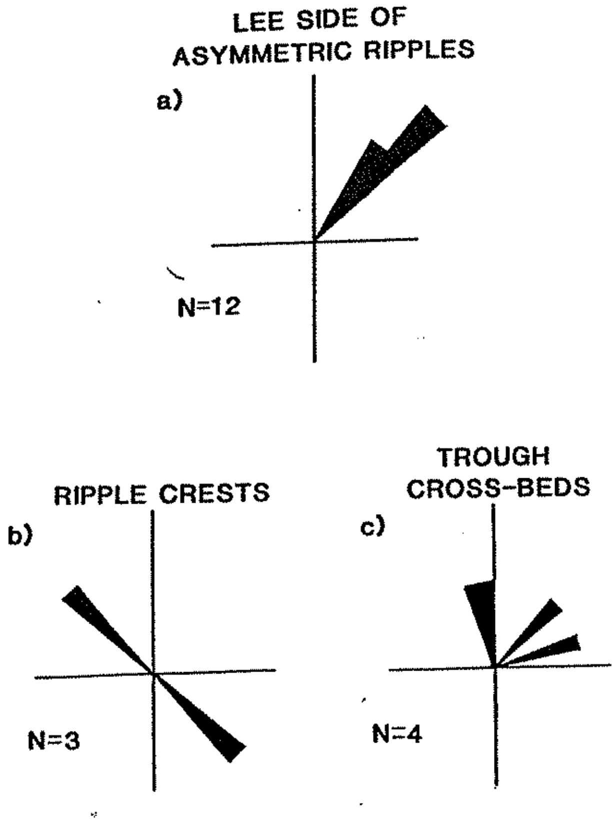

Figure 11: Facies-2 paleocurrents. 11a, lee side (right angle to crest) for asymmetric wave ripples developed on the top of granule-conglomerate beds 1 m above the base of column 2 (Figure 7); 11b, ripple crests in rippled fine sand and silt, foresets were observed dipping in both directions perpendicular to the crests; 11c, down-trough direction in trough cross-bedded sandstones.

The smaller and rounder clasts in the boulder conglomerate make up most of the widely distributed one-clast-thick parts of the beds. The largest clasts are concentrated at the tops of the thickest parts of the beds, usually where they are more than one clast thick. This suggests that wave-generated currents like those that formed megaripples in the granule conglomerates may have modified boulder-conglomerate beds by redistributing the smaller clasts and any pebbly sandstone matrix originally present in the top of the conglomerate bed.

Life-position specimens of *Tresus nuttallii* and *Spisula catilliformis* are abundant in-between the lower two boulder-conglomerate beds in column 2 (Figure 7), suggesting that the water depth was 20 to 45 m or possibly shallower where Facies 2 was deposited. Macaroni-like trace fossils similar to *Macaronichnus segregatis* (Clifton and Thompson, 1978) have been observed in discreet layers in Facies 2 sandstone beds. *M. segregatis* traces are much like the burrows made by a polycheate worm which lives in modern shallow subtidal and intertidal zones (Clifton and Thompson, 1978)

The distribution and internal structures of Facies 2 boulder- and granule-conglomerate beds suggests that these rocks were originally deposited as sediment gravity flows from several sources. They were subsequently reworked and redistributed to varying degrees by wave-generated currents. Wave-generated structures and the fossil fauna indicate a water depth of less than 45 m when Facies 2 was deposited.

Facies 3: Stratified Granule Conglomerate and Boulder Gravel

Description

Sixteen beds of stratified granule conglomerate range in thickness from 10 to 100 cm and average 40 cm. The average pebble size is 1 cm with isolated individual clasts of 10 to 20 cm in most beds (maximum 50 cm). Granules sometimes alternate with very coarse sand to form 2 to 4 cm layers which give these beds a stratified appearance.

Six beds of boulder gravel in which clasts are supported by a matrix of pebbly sand range from 0.2 to 4 m thick and average 1.3 m. Clasts average 12 cm with the maximum diameter in most beds being 50 cm, and several are 1 m in diameter. The percentage of matrix varies; in a few places the clasts support each other and look like Facies 2 boulder conglomerate. Preferred orientation is absent, and in places the long axes of clasts are oriented perpendicular to bedding (Figure 12) and may extend above the top of a bed. Upper and lower contacts are usually sharp, but may be gradational.

No shells have been found in beds of Facies 3, and sandstone clasts are very rare. Differences between Facies 3 beds in measured columns 6 and 7, on opposite limbs of the northern syncline, indicate the predominant bed form is lenticular.

Biotite and amphibole derived from the granodiorite give the beds a blue-green color.

Interpretation

The overall coarse-grained nature of these rocks, the angular shape of many of the larger clasts, and the lack of shells in the beds suggests Facies 3 is a more proximal facies than either Facies 1 or Facies 2.

The sedimentary structrues and textures—horizontal stratification, random clast orientation, poor sorting, inverse or inverse-to-normal grading—suggest sediment gravity flows were the dominate process by which these beds were deposited.

Because no fossils are preserved, some doubt remains as to whether or not these are subaqueous flows. Several facts support a subaqueous origin. The color change due to a lack of oxidation of these sediments indicates that they were probably deposited in a marine environment. The Facies 3 beds conformably overlie shell-bearing beds of Facies 2. The presence of granule conglomerate with relatively well developed inverse and inverse-to-normal grading suggests a degree of mobility within the flows probably more typical of subaqueous than subaerial sediment gravity flows. In a comparison of subaqueous and subaerial sediment gravity flows of this type, Gloppen and Steel (1981) found the ratio of bed thickness (BT) to maximum clast diameter (MCD = mean diameter of 10 largest clasts) to be a useful discriminator of the depositional environment. Their average BT/MCD for subaerial sediment gravity flows ranges from 1.8 to 3.1, and for subaqueous flows from 5.1 to 6.2. In Facies 3 the BT/MCD ranges from 4.5 to 12.5 and averages 6.8, nearly equal to values Gloppen and Steel measured for subaqueous sediment gravity flows.

Figure 12; Facies 3 boulder conglomerate, clasts supported in a matrix of pebbly sandstone. Board in center is about 1 m long and is approximately parallel to bedding.

The grain size distribution and internal structure of these beds resembles that of conglomerate beds found in submarine canyons and the inner parts of submarine fans described by Walker (1975, 1977). Walker (1975) proposed three facies models for resedimented conglomerate. Beds of Facies 3 at Moss Beach have characteristics of each of Walker's models but are not sufficiently like any particular one to be assigned as a group. However, the similarity to deep-marine resedimented conglomerate also implies that Facies 3 was deposited by submarine sediment gravity flows.

These subaqueous sediment gravity flows were probably initiated by large floods in small coastal streams with very steep gradients, or by landslides or avalanches off nearby seacliffs. Modern fan deltas have been described from freshwater lakes (Nelson, 1967) where flooding streams cause sediment gravity flows. Nemec, Porebski, and Steel (1980) describe ancient marine fan delta deposits from southwestern Poland which contain matrix- and clast-supported conglomerate, pebbly sandstone, and sandstone similar to those exposed at Moss Beach.

The lack of fine-grained material in Facies 3 is probably a reflection of its coarse-grained granitic source. The small fine-grained fraction that was initially present would have been held in suspension and transported offshore by wave-generated currents. Some cross-bedded granule conglomerate and that part of the boulder gravel which is clast-supported was probably modified by wave-generated currents between storm/flood events.

It is interesting to compare Facies-3 beds in the northern section with Facies-2 boulder conglomerate in the southern section. The smaller maximum grain diameters in the northern section must reflect a change in the gradient or nature of the source rocks (jointing, etc.), or perhaps the thickest, coarsest parts of Facies-2 boulder-conglomerate beds should be considered to represent Facies 3 in the southern section, or both.

VERTICAL SEQUENCES AND TRENDS

Vertical sequences have been divided into minor sequences and major sequences. Minor sequences are units of two or three related beds, usually less than a meter thick overall, that commonly fine upward. Major sequences are more than a meter thick, contain at least three beds, and commonly coarsen and thicken upward.

Minor Sequences

Description

Facies 1 consists almost entirely of minor sequences of shell/pebble conglomerate-to-sandstone and has already been described above.

In Facies 2, three types of minor sequence were recognized: (1) granule conglomerate overlain by trough cross-bedded coarse-grained sandstone, (2) granule conglomerate overlain by hummocky cross-bedded sandstone, and (3) granule conglomerate overlain by ripple-laminated fine-grained sandstone. In each of these units the contact between the granule conglomerate and the bed above is gradational or sharply gradational. The top of the granule-conglomerate bed is commonly wavy, with granule layers extending into the overlying bed.

Interpretation

Each change in bed type within a minor sequence represents a change in the dominant depositional process (for example, sediment gravity flow versus tractive transport) or in the intensity or level of energy of a process (for example, upper versus lower flow regime).

Facies 1 shell/pebble conglomerate-to-sandstone units have been interpreted as resulting from a decrease in wave energy.

Minor sequences described from Facies 2 may be interpreted in two ways. First, they may represent a change from deposition by sediment gravity flows to deposition by wave-generated currents (possibly tide-generated currents in the case of the ripple-laminated fine-grained sandstone beds); the wave-generated currents reworked the tops of the granule-conglomerate beds and subsequently deposited the overlying bed. Second, where granule-conglomerate beds have been completely reworked, the resulting sequences are interpreted as being caused by a decrease in wave energy (or a change from wave-generated currents to tidal currents for ripple-laminated fine-grained sandstone beds).

Major Sequences

Description

Facies 1 and 2 alternate in the southern section to form at least two 3 to 10 meter coarsening-upward sequences (Figure 7). Overall, the southern section records an upward increase in grain size and bed thickness. A sandstone dominated source also changes to a granitic source.

The northern section is coarser in its upper part, with Facies 2 overlain by Facies 3, and it is coarser overall than the southern section.

Interpretation

Coarsening-upward sequences in both sections represent decreasing water depth, increasing energy, progradation of depositional lobes, or reduced distance to the sediment source. At Moss Beach local tectonism may have exerted a primary control over the progradation. The coarsening and thickening upward sequences are remarkably similar to those described by Nemec, Porebski, and Steel (1980) from fan-delta deposits they studied in Poland: "The studied succession . . . is organized into large (110-150 m) and small-scale (5 to 30 m) sequences, both of which show (1) upward coarsening and thickening, (2) upward trend of sandstones and pebbly sandstones to matrix-rich conglomerates to clast-supported conglomerates, and (3) a less clear upward tendency of massive and normally graded beds to inversely graded beds."

The change from a sandstone to a granite source up through the section could reflect local uncovering of the granite, deposition from two adjacent sources, or a wrench tectonic effect.

LATERAL TRENDS

Description

The southern section thins to the north. Close to the Seal Cove fault (Figure 7, column 1) the section is at least 70 meters thicker than it is at its northwestern end (Figure 7, section 5), where it is in depositional contact with the Cretaceous Montara granodiorite of Darrow (1963). This thinning is accompanied by an increase in the grain size and bed thickness to the north and east in the beds of Facies 2.

In two places the boulder-conglomerate beds of Facies 2 change character laterally to become more like the boulder beds of Facies 3. At 13 meters in column 4, and at 3 meters in column 2 the maximum size of the boulders increases, the bed thickness increases, and the proportion of pebbly sandstone matrix increases. Steep-walled channels occur at these two spots but nowhere else in Facies 2. Accompanying the change in the boulder-conglomerate beds is an increase in the thickness and number of the granule-conglomerate beds.

Within individual beds, more sedimentary clasts occur farther to the south. A comparison of the northern and southern sections shows more sedimentary clasts in the southern section.

Interpretation

After rotating the trends outlined above in accordance with the paleomagnetic data, we find that the rocks were deposited in a basin which was probably deeper to the south and shallower to the north. Much of the coarsest-grained sediment was supplied from point sources to depositional lobes of a prograding fan delta and partly redistributed by wave-generated currents.

Lateral variation in the proportion of granitic

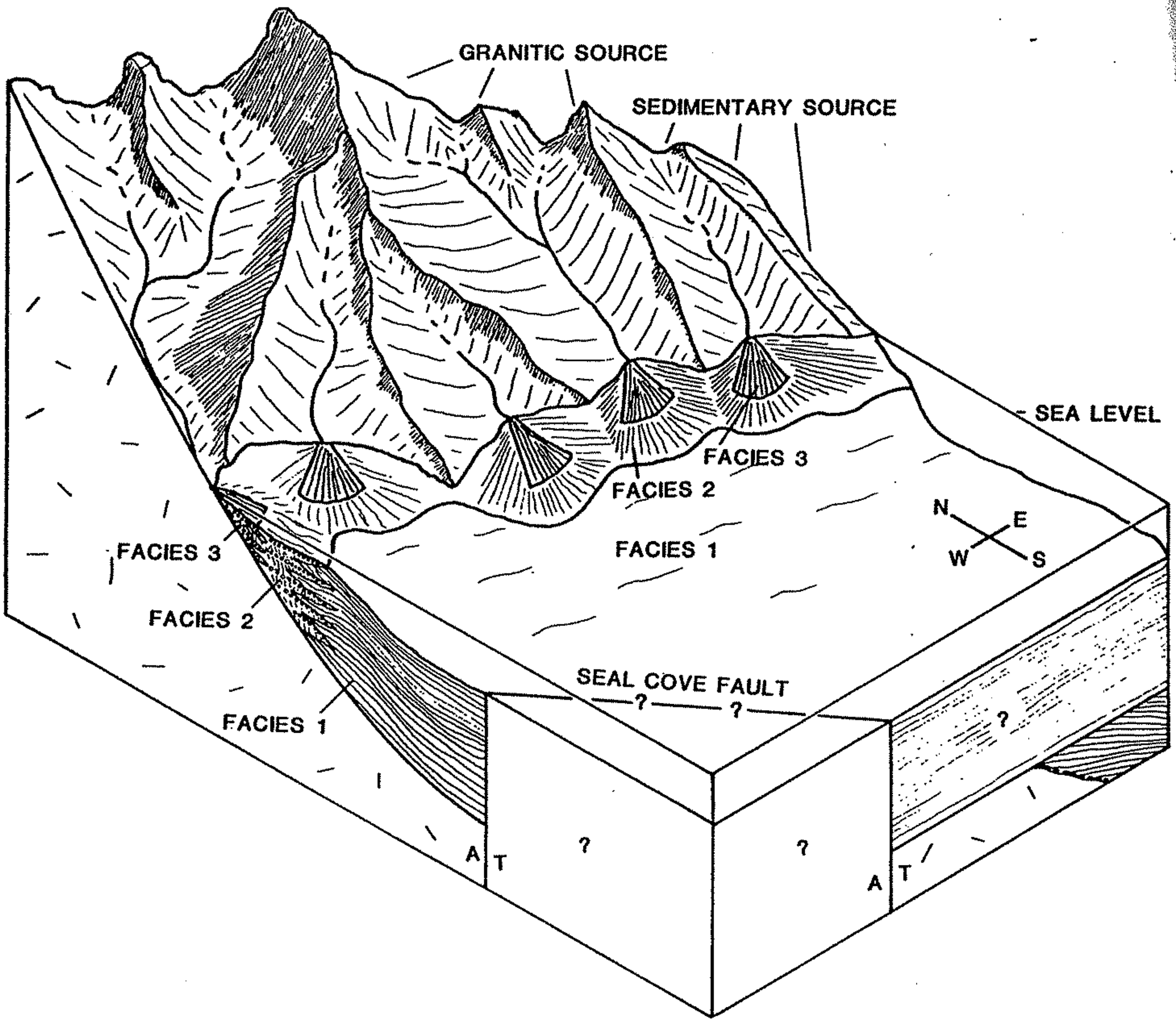

Figure 13: Reconstruction of the depositional environment for Pliocene sediment deposited at Moss Beach.

and sedimentary detritus suggests that the two principle sources were separated by distance, not time, with a sedimentary source to the east and south of a granitic source--much like it is today.

DEPOSITIONAL ENVIRONMENT

The depositional environment was probably offshore from a steep coast or cliff along a west-trending protected part of the coast or in a south-facing deep-water bay. Short west-trending segments of coast and south-facing bays are formed on the modern California coast in association with strike-slip faults. Whereas the main trend of the modern coast is parallel to the San Andreas fault system, at many places--Point Reyes on the San Andreas fault, Monterey Bay on the San Gregorio/Palo Colorado fault, Half Moon Bay on the Seal Cove fault--a right-lateral strike-slip fault intersects the shoreline to form a bay, reentrant, or short west-trending segment of the coast. The rocks at Moss Beach seem to have been deposited in a similar environment, where the Seal Cove fault intersected the Pliocene shoreline and formed a bay which paralleled the fault or created a protected section of west-trending coastline (Figure 13).

Paleocurrents corrected for postdepositional rotation imply that waves approached the coast from the south. These waves reworked the bottom; they had enough energy to move pebbles 1+ cm in diameter offshore in Facies 1 and closer to shore probably moved clasts up to 20 or 30 cm in diameter. Stratigraphic columns suggest more than 70 meters of relief on the granitic basement over a distance of only 400 meters, implying a paleoslope on the order of 10 degrees. Depths adjacent to the shore were probably 5 to 10+ meters with the bottom steeply dropping to 20 to 50+ meters. Short streams with steep gradients or landslides supplied coarse-grained sediment, in the form of sediment gravity flows, to wave-modified fan deltas adjacent to the steep shoreline (Figure 13). Some of this resedimented conglomerate was deposited farther offshore, or in protected areas, or was armored by clast-supported coarse conglomerate so that its internal structure (or lack of structure) was not modified by wave-generated currents (Facies 3). That resedimented conglomerate which was subsequently reworked in varying amounts by wave-generated currents formed Facies 2. In the intervals between storms, deposition was more like that on a typical inner shelf (Facies 1), so that Facies 1 and 2 are interbedded.

Other submarine features common at the intersection of the coastline and large faults include the head reaches of submarine canyons. Several occur along the California coast today in depths as shallow as 10 meters. A wave-modified canyon head can be considered as another environment in which the beds at Moss Beach might have formed. A combined fan delta and submarine canyon would provide a system by which pebbles, cobbles, and boulders could be transported directly from the land all the way to the base of the continental slope. The lateral continuity of the beds in Facies 1, the likely presence of depositional lobes in Facies 2 and 3, the lack of shells in Facies 3, the abundance of large wood fragments in Facies 2 and 3, and the angular shapes of many of the clasts are factors which favor the fan-delta model over the submarine-canyon-head model.

SUMMARY AND CONCLUSIONS

There are five phases in the history of the Pliocene rocks exposed northeast of the Seal Cove fault at Moss Beach. In the earliest phase, movement along the Seal Cove fault caused a steep or cliffed west-trending segment of coast or south-facing deep-water bay to form. Later, shelf-type sediment accumulated offshore while gravity flows deposited coarse-grained sediment nearshore. Renewed activity on the Seal Cove fault folded the rocks, forming the two synclines. Subsequently, the rocks were remagnetized and then rotated clockwise 60 degrees ± 10 degrees. Finally, the area was uplifted and eroded, resulting in an unconformity over which the Pleistocene sediment was deposited.

The significance of this study is three fold: first, it describes an ancient wave-modified fan delta, a sedimentary environment which has not previously been well documented; second, it reports on the occurrence of resedimented conglomerate in a very shallow-marine setting; and third, it shows that the Seal Cove fault has probably been active since at least the early late Pliocene.

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