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DESCRIPTION OF BEDS EXPOSED AT FORT FUNSTON, GOLDEN GATE NATIONAL RECREATION AREA, NORTHWESTERN SAN FRANCISCO PENINSULA, CALIFORNIA

By

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INTRODUCTION

A thick section of Pleistocene beds is excellently exposed in wave-cut bluffs on the northwestern San Francisco Peninsula, California. These exposures extend from near Fleishhacker Zoo on the north to near Mussel Rock, where the San Andreas fault intersects the shoreline, on the south. The most detailed previous investigation of these beds was by Hall (1965a, 1965b, 1966). The present investigation focuses on the upper part of the section described by Hall; this part of the section is exposed in the bluffs from Fleishhacker Zoo south to Fort Funston, which is now part of Golden Gate National Recreation area. Specifically, this investigation focuses on the section from the uppermost Pleistocene stratigraphic unit, the Colma Formation, to slightly below a prominent white tuff bed that has been dated as 450,000 years old (Meyers and others, 1980). The Colma Formation is probably no younger than the last major interglacial stage (Hall, 1965b, 1966), which occurred about 73,000 to 127,000 years ago (Shackleton and Opdyke, 1973; Pisias and Moore, 1981).

No consensus has been reached on the stratigraphic terminology of most of the beds discussed in this report. We follow the terminology of Hall (1965b, 1966), who divides the sequence, from the base upward, into the Merced Formation, the unnamed beds, and the Colma Formation. We agree with Hall (1965a) that the unnamed beds should eventually be assigned to the Merced, but formal assignment should await a more widely available publication. The reasons for assigning the unnamed beds to the Merced are that the two units are lithologically similar and that the unconformity separating the two units has little more significance than other unconformities within each of the units, whereas the unconformity separating the unnamed beds from the Colma Formation is definitely more angular than the others.

Because our study focuses on stratigraphic units that are generally much thinner than the named formations, we use an informal lettering and numbering system for the units we describe. Each recognized unconformity-bounded sequence is designated by a letter; the uppermost sequence is designated Z, and underlying sequences are lettered in reverse alphabetic order (Fig. 1). A future report will extend the numbering system further downward stratigraphically. Within each uncomformity-bounded sequence, each relatively homogeneous lithologic unit is designated by a subscript number following the letter that designates the sequence. The units in each sequence are numbered 1, 2, 3,... from the lowermost unit upward.

Geographic features referred to in this report are: (1) <u>the ramp</u>, which leads from Great Highway to the beach at the northern end of the bluffs; (2) <u>the northern gully</u>, at the north end of Hall's (1965b, 1966) cross section showing relationships from Fleishhacker Zoo to Thornton Beach; (3) the southern gully, at the 1300-ft mark of Hall's cross section; and (4) the artificial fill, from the 2900-ft to the 3300-ft marks of Hall's cross section.

The lithologic descriptions in this report are based on field observations. Color symbols in this report are based on the Munsell system. Sand grain sizes were determined by visual comparison with sieved samples. Thicknesses of beds and sets of crossbeds are classified as small-scale (less than 0.04 m), medium-scale (0.04-1.0 m), and large-scale (more than 1 m). Dip angles of crossbeds are classified as low-angle (less than 15°), medium-angle (15°-25°), and high-angle (greater than 25°).

COLMA FORMATION

(SEQUENCE Z)

The Colma Formation is interpreted to be a single progradational sequence, designated sequence Z. The sequence is relatively uniform in character and is here classified as a single lithologic unit, designated unit Z_1.

Unit Z_1

Lithology: Sand, in part pebbly.

Thickness and distribution: The Colma caps the wave-cut bluffs along most of the Fort Funston area. Locally missing by erosion. Thickness as much as 4.0 m (13 ft).

Color: Everywhere more or less oxidized to yellowish or brownish colors.

Texture: Fine- to medium-grained sand and medium to very coarse grained pebbly sand.

Composition: The sand contains numerous laminae rich in black opaque heavy minerals. The pebbles are lithologically heterogeneous, including well-rounded pebbles of resistant rock types from distant sources, angular pebbles of chert and graywacke probably from nearby outcrops of Franciscan rocks, and pebbles and cobbles of partially indurated sandstone from underlying beds.

Sedimentary structures: Well defined to obscured by modern weathering. The most common structures are flat lamination, gently inclined lenticular bedding, and small- to medium-scale intermediate- to high-angle crossbedding.

Vertical variations: Upward fining.

Lower contact: Sharp, erosional, with local relief of as much as 2 m. Where pebbles are sparse and sedimentary structures are obscured by weathering, the lower contact may be very difficult or impossible to identify.

The lower contact rises in elevation from near beach level at the north (the ramp) to nearly 100 m at the south (south of Thornton Beach State Beach). The Colma oversteps all the other units described here and rests on progressively older units to the south.

Weathering and diagenesis: The Colma has probably been exposed to weathering from the time of its deposition to the present, except where it has been covered by Holocene dune sand. As a result, it is highly oxidized and has a soil developed at its top. The soil has a thick (up to 1 m), brownish gray (10YR 3/1 when wet), sandy A horizon, in part accretionary.

Interpreted depositional environment: Largely a beach. The lowermost part probably in part nearshore, and the uppermost part possibly in part eolian. Probably a progradational sequence.

UNNAMED BEDS OF HALL (1965B, 1966)

The unnamed beds are 162 m (530 ft) thick where most fully preserved. They are overlain unconformably by the Colma Formation and underlain unconformably by the upper member of the Merced Formation of Hall (1965b, 1966). The unnamed beds are here divided into five unconformity-bounded sequences designated, from the top downward, Y, X, W, V, and U (Fig. 1). Three of these (Y, X, and V) are interpreted to have formed by progradation, whereas the other two have an uncertain relationship to changing water depth or land elevation. The uppermost sequence (Y) was included in the Colma Formation by Hockstetler (1978) but was included in the unnamed beds by Hall (1965a). Hall's usage is followed here because the unconformity at the top of sequence Y is demonstrably a major angular unconformity, whereas the unconformity at the base of sequence Y does not have an easily demonstrated angularity.

The basal contact of the unnamed beds has been variously interpreted; Hall (1965b, 1966) refers to the contact as "an apparent angular unconformity" but then states that "the angular discordance may be in part the result of subaqueous sliding and have no great time significance." The confusion about the nature of the contact is based partly on Hall's (1965b, 1966) opinion, which we consider mistaken, that the beds above the unconformity dip more steeply than those below. Although the surface of unconformity itself does locally dip more steeply than the underlying beds, the overlying beds do not have the same orientation as the steeply dipping part of the surface of unconformity but rather have the same orientation as the beds beneath the unconformity. Moreover, the surface of unconformity is only locally more steeply dipping than the adjacent beds; to both the north and the south of its steeply dipping section, the surface of unconformity flattens out and has the same orientation as the underlying and overlying beds (Fig. 2). These features indicate that the unconformity is not angular but was formed as a surface with considerable topographic relief; in other words, the steeply dipping part of the unconformity is a fossil hillside. Minor slumping down this hillside occurred, but this slumping only modified the character of the contact. There is no evidence that the slumping was subaqueous.

SEQUENCE Y

Interpreted as an open-coast progradational sequence consisting of, from the top down, a backshore sand (unit Y_3), a beach foreshore sand (unit Y_2), and a nearshore sand and gravel (unit Y_1). Thickness 17.4 m (57 ft) where sequence is most fully preserved.

Unit Y_3

Lithology: Sand.

Thickness: 9.1 m (30 ft) where unit is most fully preserved (in vicinity of northern gully). Gradually thins northward to 4.6-5.2 m (15-17 ft) at base of ramp due to truncation of uppermost beds by Colma Formation. Local relief of upper contact as much as 2 m.

Color: Yellowish gray (5Y 7/2) where weathering is least, but with numerous rusty oxidized bands.

Texture: Almost all the sand fine grained. Rare lenses of medium to coarse, slightly pebbly sand less than 1 m below undoubted Colma beds may belong to the Colma Formation, in which case the contact is locally cryptic.

Composition: Nonmicaceous; a few laminae rich in black opaque heavy minerals.

Sedimentary structures: The most visible structure is flat to gently lenticular bedding of medium scale. Lamination and other minor structures are generally absent or indistinct, in part because of weathering, but are visible locally, especially under overhangs. Lamination types include (1) flat to gently dipping lamination, mostly of undetermined origin but in part formed by climbing wind ripples, (2) small-scale crosslamination formed by current ripples, (3) rare medium-scale crosslamination, in part subaqueous and in part eolian, and (4) climbing-adhesion-ripple structures (only one example identified). The lamination in many beds was penecontemporaneously deformed on a small to medium scale, producing wavy to contorted lamination; most of the deformation was probably caused by loading or liquefaction under load, and the load may have been applied by overlying sediment or by animals walking over the sediment; burrowing may also have contributed to the deformation. Many beds contain small (1-2 mm in diameter) steeply inclined to vertical tubes outlined by iron oxide or clay minerals; the tubes are interpreted as probably root tubes but possibly burrows. Where such tubes are common, lamination is indistinct or absent.

Minor rock types: Rare laminae of sandy clayey silt, olive gray (5Y 6/2) where least weathered but commonly rusty. The thickest (as much as 5 mm) such lamina occurs in one of the most intensely deformed beds.

Vertical variations: The largest deformational structures occur in the basal 2 m. Undoubted eolian beds occur no lower than 4 m above the base. In general, however, the unit is remarkably uniform from top to base.

Lower contact: Placed at a change from indistinctly laminated sand with root(?) tubes to underlying sand that is distinctly laminated; gradational through a zone a few centimeters thick.

Diagenesis and weathering: Many beds contain interstitial weathering products (iron oxides and clay minerals), which make the unit resistant to erosion and which obscure the primary sedimentary structures. Secondary structures include Liesegang banding and rare concretions of iron and (or) manganese oxides. Steeply inclined to overhanging sides of scours at upper contact suggest that some of the weathering preceded deposition of the Colma Formation.

Interpreted depositional environment: Backshore sand flat above the level of normal high tides, at times lightly vegetated but not forested, at times partly covered by small eolian dunes. Deposition was in part eolian, on both dry and wet surfaces, and in part subaqueous, in flowing water and in shallow, ephemeral ponds. Submergence may have resulted from storm surges, stream flooding, or rainfall directly on the flats.

Unit Y_2

Lithology: Sand.

Thickness: 3.4-3.7 m (11-12 ft).

Color: Yellowish gray (5Y 7/2) where least weathered; some beds oxidized to grayish yellow (5Y 7/4) or rarely to more intense rusty colors.

Texture: Most of the sand fine grained; some in lower part medium grained and containing rare, scattered pebbles. Locally, a few centimeters of medium-grained sand at the top.

Composition: Nonmicaceous except a few laminae. Some laminae, especially in the upper part, rich in black opaque heavy minerals.

Sedimentary structures: Well defined. Dominant structure is flat to very gently inclined lamination. Some small-scale crosslamination (formed by current ripples) in upper part. Some gently inclined scour-and-fill structures of medium scale. A few large scours (as deep as 2 m, probably channels) filled largely by sand similar to that in adjacent beds but locally floored by pebbles. Some V-shaped trace fossils in the lower few tens of centimeters.

Fossils: Very rare probable molds of pelecypods; no shell material preserved, and molds visible only as strongly curved seams a few centimeters in length.

Vertical variations: Fining upward; upper part richer in heavy minerals and with more cross-lamination.

Lower contact: Gradational lithologically. Placed at top of uppermost medium-scale high-angle crossbedding, which is commonly the top of the uppermost highly pebbly sand.

Diagenesis and weathering: Weathering slight; sand unconsolidated.

Interpreted depositional environment: Beach, largely foreshore, ranging from near normal high tide level at the top to near low tide level at the base. Large scours probably formed by streams or runnels carrying rain runoff or wave overwash, and small-scale crosslamination formed by flow through such channels.

Unit Y_1

Lithology: Sand and gravel.

Thickness: 6.1 m (20 ft) at base of cliff, thinning southward to 3.0 m (10 ft) at top of cliff.

Color: The sand beds yellowish gray (5Y 7/2) where least weathered; some beds oxidized to grayish yellow (5Y 7/4) or rarely to more intense rusty colors. The gravel composed mostly of relatively dark pebbles.

Texture: The sand partly nonpebbly, fine to medium grained, and partly pebbly, medium to very coarse grained. The gravel beds composed of pebbles, mostly with a sandy matrix. Mean grain size of most gravel less than 10 mm; maximum pebble size less than 50 mm in most beds. Pebbles mostly well rounded.

Composition: Much of the sand slightly micaceous, and some laminae highly micaceous (the mica is biotite). Pebbles lithologically heterogeneous, mostly of resistant rock types. A few larger clasts of partly indurated sand derived from the underlying beds. White quartz pebbles conspicuous.

Sedimentary structures: Well defined. The dominant structure is medium-scale, medium- to high-angle trough crossbedding. Some sand beds have flat or gently dipping lamination, and some of the gravel is flat bedded. Lower contacts of gravel beds are commonly irregular, with step-sided depressions generally 5-20 cm wide. Some of these depressions are probably scours, but some are probably pebble-filled burrows modified by scour. One sand bed near the top locally bioturbated, containing the trace fossil *Macaronichnus segregatis*.

Minor rock type: Several thin beds (as much as 10 cm thick) of silt, with associated highly micaceous sand. The thickest such bed characterized by climbing current ripples. Commonly highly oxidized.

Vertical variations: Fining upward; the gravel is most abundant and the pebbles coarsest near the base of the unit.

Lower contact: Sharp, erosional, with local relief of as much as 15 cm. Beds above this unconformity overlap to the south. Unconformity is perhaps slightly angular at top of bluff, but angularity cannot be confirmed because the original horizontal cannot be definitely identified in the underlying sand, which is characterized by large-scale crossbedding.

Diagenesis and weathering: Weathering slight in most of unit, but the highly micaceous and silty beds tend to be strongly oxidized. Unconsolidated.

Interpreted depositional environment: Nearshore marine, probably along an open coast, though the silt and micaceous sand suggest either some degree of protection from waves or a nearby major source of suspended sediment. Large clasts at base of sequence represent a transgressive lag deposit.

SEQUENCE X

Interpreted as an open-coast progradational sequence consisting of, from the top down, a discontinuous, transitional unit of uncertain relationship to adjacent units (unit X_5), an eolian sand (unit X_4), a beach sand (unit X_3), a nearshore sand (unit X_2), and an offshore (inner shelf) sand (unit X_1). Thickness 45.7 m (150 ft).

Unit X_5

Lithology: Sand, in part pebbly.

Thickness: 0-1 m (0-3 ft); present in isolated ledge on beach between ramp and northern gully. The ledge is generally covered in summer. Probably fills a depression in the underlying eolian sand (unit X_4).

Color: Grayish yellow (5Y 7/4) to light brown (5 YR 5/6); nowhere unoxidized.

Texture: Fine- to medium-grained sand. The upper 45 cm of sand contains numerous pebbles scattered through the sand and concentrated in pockets.

Composition: The pebbles are similar to those in the overlying unit (unit Y_1).

Sedimentary structures: Bedding obscure except in the lower 30-60 cm. Structures in that part of unit include flat to gently inclined lamination, at least part of which was formed by subcritically climbing wind ripples, and climbing adhesion ripples. The pebbly sand at the top contains small vertical tubes interpreted by Clyde Wahrhaftig (written communication) to be root tubes, but which could possibly be burrows. The pebbly pockets are probably burrow fills.

Lower contact: Sharp and erosional.

Diagenesis and weathering: Upper part of the unit contains interstitial weathering products (iron oxides and clay minerals), which make the unit resistant to erosion and which obscure the primary sedimentary structures.

Interpreted depositional environment: Probably diverse, but the well-stratified lower part is definitely eolian. The upper part of the unit may be a paleosol (Wahrhaftig, written communication), but, if so, the presence of pebbles similar to those in the overlying nearshore sand and gravel (unit Y_1) is puzzling. The pebbles may have been carried down into this unit by marine burrowing animals after the sea in which unit Y_1 was deposited covered the area.

Unit X_4

Lithology: Sand.

Thickness: 27.4 m (90 ft).

Color: Yellowish gray (5Y 7/2) where least weathered; some beds oxidized to grayish yellow (5Y 7/4) or to more intense rusty colors.

Texture: Most of the sand fine grained, but some medium grained. Pebbles absent.

Composition: Nonmicaceous. Some laminae rich in black opaque heavy minerals

Sedimentary structures: Well defined, but locally obscured by weathering, especially near the top. Dominant structure is medium- to large-scale, medium- to high-angle crossbedding. Flat to gently inclined lamination is fairly common. Some of the flat to moderately inclined lamination was formed by climbing wind ripples. Climbing adhesion ripples are recognizable in several beds in the lower few meters. One bedding surface near the base of the unit has symmetrical, straight-crested ripples interpreted to be wave ripples. No trace fossils. Structureless weathered zones within the unit have sharp tops and gradational bases and are less than 0.5 m thick.

Vertical variations: No significant variations.

Lower contact: Placed at change from unconsolidated sand to underlying relatively consolidated sand; contact is gradational through a zone a few centimeters thick.

Diagenesis and weathering: Sand only slightly weathered and unconsolidated except in the upper few meters and in a few other zones within the unit, where interstitial weathering products (iron oxides and clay minerals) give the sand resistance to erosion and obscure the stratification. The structureless weathered zones are interpreted as paleosols.

Interpreted depositional environment: Unvegetated eolian dunes and interdune flats. The flats were at times ponded, at times subaerially exposed but wet, and at times dry. At times the dunes became lightly vegetated, and soils developed. The dunes were planed off before deposition of the overlying sequence.

Unit X_3

Lithology: Sand.

Thickness: 3.0 m (10 ft).

Color: Yellowish gray (5Y 7/2) to grayish yellow (5Y 7/4).

Texture: Most of the sand fine grained, but some medium grained. No pebbles.

Composition: Nonmicaceous. Some laminae rich in black opaque heavy minerals.

Sedimentary structures: Mostly planar lamination. Some gently lenticular lamination, the lenses of medium scale. Some of the lamination in the upper 1 m was formed by climbing wind ripples.

Vertical variations: Eolian sand identified only in upper 1 m.

Lower Contact: Placed at top of uppermost bed intensely bioturbated by Macaronichnus segregatis; gradational through a zone a few centimeters thick.

Diagenesis and weathering: Only slightly oxidized but very resistant to erosion, presumably because of interstitial clay-mineral weathering products. Primary lamination greatly obscured by Liesegang banding that is nearly parallel to the lamination.

Interpreted depositional environment: Beach, ranging from backshore at the top to near low tide level at the base. The interstitial clay is secondary, but why it occurs in this beach sand but in none of the others is unexplained; the position of the water table may have been important in some way.

Unit X_2

Lithology: Sand.

Thickness: 7.6 m (25 ft).

Color: Yellowish gray (5Y 7/2).

Texture: Fine- to medium-grained sand in upper part; mostly fine-grained sand in lower part, but some medium- to coarse-grained sand. Some of the medium to coarse sand slightly pebbly, the pebbles as much as 1 cm in diameter.

Composition: Some of the sand micaceous, a few laminae highly so.

Sedimentary structures: Flat to gently lenticular bedding of medium scale and medium-scale, medium- to high-angle trough crossbedding. Many beds in upper part intensely bioturbated, containing the trace fossil *Macaronichnus segregatis*; bioturbation may be common in lower part also, but distinct trace fossils uncommon.

Vertical variations: Largest pebbles and coarsest average grain size near top; greater tendency to bimodality near base. Variations not pronounced, however. *Macaronichnus* most common in upper part.

Lower contact: Placed at horizon below which very fine grained sand becomes common; gradational over several meters.

Diagenesis and weathering: Lower part only slightly weathered and nearly unconsolidated. Becomes more resistant to erosion upward because of increased interstitial clay weathering products. No significant oxidation.

Interpreted depositional environment: Nearshore marine, probably along an open coast; rarity of pebbles may be due either to some degree of protection from large waves or to unavailability of pebbles.

Unit X_1

Lithology: Dominantly sand.

Thickness: 7.6 m (25 ft).

Color: Yellowish gray (5Y 7/2), in part very light (5Y 8/1).

Texture: Mostly fine- to very fine-grained sand, but some sand in upper part of unit medium to coarse grained and slightly pebbly. In lower part of unit, pebbles derived from underlying unit are common; these pebbles were originally concentrated in thin beds and in burrow fillings, but were later scattered by bioturbation and incorporated into burrow walls.

Composition: Much of the sand slightly micaceous. Rare laminae of silt and associated highly micaceous sand occur as partings between sand beds.

Sedimentary structures: Bedding mostly flat, of medium to large scale. Some medium-scale, low- to high-angle crossbedding, especially near top. Lamination absent or indistinct in many beds, due at least in part to bioturbation. Several types of trace fossils are evident, the most striking of which are large vertical burrows with pebbles incorporated into the walls and filled by sand or gravel.

Vertical variations: Pebbles derived from underlying unit become less abundant upward. Medium- to coarse-grained sand becomes more common upward.

Lower contact: Sharp, but somewhat obscured by incorporation of pebbles from underlying unit into lower part of unit. Presumably erosional, but flat.

Diagenesis and weathering: Only slightly weathered, nearly unconsolidated. The palest sand beds may have been bleached of their iron content.

Interpreted depositional environment: Marine inner shelf, probably at water depths less than 20 or 30 m. No other unit in the unnamed beds contains as much very fine sand or was as intensely bioturbated by a variety of organisms. The occurrence of pebbles reflects a local source (the underlying unit) but at the same time implies episodically strong currents.

Sequence W

Interpretation questionable. Certainly estuarine in part, and perhaps a transgressive sequence. On the other hand, perhaps not a sequence of related beds formed during a single progressive change in water depth. Consists of an estuarine-channel or open-coast nearshore sand and gravel (unit W_2) at the top and an estuarine mud (Unit W_1) below. Thickness is 16.8 m (55 ft).

Unit W_2

Lithology: Sand and gravel.

Thickness: 9.1 m (30 ft).

Color: The sand yellowish gray (5Y 7/2) where least weathered, but commonly oxidized to grayish yellow (5Y 7/4) or to more intense rusty colors, especially in lower part. The pebbles mostly dark.

Texture: The sand dominantly medium grained, but ranging from very fine (where rich in black opaque heavy minerals) to very coarse (where pebbly). The gravel beds composed of pebbles having a mean size less than 10 mm; maximum pebble size less than 50 mm in most beds. Sand matrix generally present in gravel beds. Pebbles mostly well rounded.

Composition: The sand mostly nonmicaceous, but slightly micaceous in upper part. Some laminae and thin beds of sand composed mostly of black opaque heavy minerals. The pebbles lithologically heterogeneous, mostly of resistant rock types.

Sedimentary structures: Well defined. Dominant structure is medium-scale, medium- to high-angle tabular and trough crossbedding. Some sand beds have flat or gently dipping lamination, especially in lower part of unit. Some of the black sand beds were penecontemporaneously folded on a small scale. Trace fossils common in lower 0.6 m.

Vertical Variations: Coarsening upward. No pebbles in the lower 0.6 m, and no gravel beds in the lower 5 m. Trace fossils common in lower 0.6 m., rare or absent above. Crossbedding more abundant in upper part.

Lower contact: Placed between sand and underlying mud. Gradational through a zone of a few centimeters.

Diagenesis and weathering: Only slightly weathered in upper part, but becoming strongly oxidized toward base. Unconsolidated or nearly so. Oxidation probably occurred long after burial.

Interpreted depositional environment: Most probably an estuarine tidal channel, less probably open-coast nearshore marine. The estuarine interpretation is favored because of absence of trace fossils except near the base, consistency of crossbed dip directions, tabular nature of most sets of crossbeds, and conformable relation to underlying estuarine mud (unit W_1).

Unit W_1

Lithology: Mud.

Thickness: 7.6 m (25 ft).

Color: Light gray (N7) when dry, medium-dark gray (N4) when wet. Dark gray (N 3) in basal 0.3 m.

Texture: Silty clay, sandy in part, especially near contacts.

Composition: Not highly organic except in basal 0.3 cm. Contains gypsum veinlets and calcite shell material, especially in lower part.

Sedimentary structures: Bedding flat, generally indistinct. Upper 2-3 m and basal 0.5 m nearly structureless, probably because of intense bioturbation. Rest of unit thin bedded and in part laminated, moderately bioturbated and with trace fossils.

Fossils: Molds, casts, and some preserved shells of invertebrates, mostly mollusks (Hall, 1965b, 1966).

Vertical variations: Organic-rich mud only near base. Shells most abundant immediately above organic-rich mud. Bioturbation probably most intense near base and in upper part.

Lower contact: Sharp. Relief uncertain because of poor exposure and disturbance by small faults.

Diagenesis and weathering: Sufficiently compacted to be more resistant to erosion than adjacent sands. Gypsum in lower part fills fractures. Carbonate shell material dissolved except near beach level. Contains yellowish alteration product, probably jarosite, in upper 0.5 m.

Interpreted depositional environment: According to Hall (1965b, 1966), the fauna suggests an estuarine tidal-flat environment. The physical structures suggest a shoaling from a subtidal environment at the base to an intertidal environment at the top, but there is no evidence of high intertidal or supratidal salt marsh at the top. Possibly formed by lateral accretion on the side of an estuarine tidal channel.

Sequence V

Interpreted as an open-coast progradational sequence consisting of, from the top down, a diamictite interpreted as a paleosol (unit V_5), an alluvial sand (unit V_4), an eolian and backshore sand (unit V_3), a beach sand (unit V_2), and a nearshore sand and gravel (unit V_1). Thickness 25.9 m (85 ft). The upper two units could conceivably be more closely related to sequence W than to sequence V, in which case they would be considered the basal parts of a transgressive sequence.

Unit V_5

Lithology: Clayey pebbly sand (because neither the clay nor the pebbles are segregated in beds, the rock is a diamictite).

Thickness: 2.4-3.7 m (8-12 ft).

Color: Dark greenish gray (5GY 3/1) in upper 30 cm where freshly exposed during winter erosion of beach; this upper part is oxidized to grayish brown (5YR 4/2) where exposed for longer periods. Color grades downward to moderate brown (5YR 4/6) about 2 m below top and grades into less intense and lighter brownish colors below this.

Texture: Upper part is sand with interstitial clayey matrix and with randomly scattered angular pebbles. The interstitial matrix becomes less abundant toward base of unit, and the pebbles show an increasing tendency to be concentrated in lenses.

Composition: The pebbles mostly Franciscan graywacke and chert.

Sedimentary structures: Upper part of unit structureless, lower part with indistinct lenticular bedding.

Minor rock type: Locally, a 5-cm-thick bed of grayish brown silty clay occurs near the base of the unit.

Vertical variations: Distinct; see under color, texture, and sedimentary structures.

Lower contact: Placed at top of distinctly bedded sand; gradational through a zone of a few decimeters.

Diagenesis and weathering: The interstitial clayey matrix probably originated by weathering. Nature of rapidly oxidizable greenish material near top of unit is unknown. Resistant to erosion because of interstitial weathering products.

Interpreted depositional environment: Probably a paleosol developed on pebbly, sandy alluvium. The alluvium was probably stratified throughout, but the pebbles became scattered by bioturbation accompanying soil formation. The alluvium was similar to that forming the underlying unit (unit V_4) except for being more pebbly. Source of pebbles was an area of Franciscan rocks.

Unit V_4

Lithology: Sand, in part pebbly.

Thickness: 1.8-3.0 m (6-10 ft).

Color: Grayish yellow (5Y 7/4) in lower part, oxidized to more intense brownish colors in upper part.

Texture: Medium- to fine-grained sand, slightly pebbly in part. The pebbles are poorly rounded.

Composition: Nonmicaceous. Many laminae of fine-grained sand rich in black opaque heavy minerals. The pebbles similar to those in the overlying unit.

Sedimentary structures: Well defined; the dominant structure is gently lenticular bedding of small to medium scale. Some small- and medium-scale high-angle crossbedding.

Vertical variations: Pebbles are more common toward top of unit.

Lower contact: Sharp, apparently erosional but with little relief.

Diagenesis and weathering: Only slightly weathered in lower part, becoming more oxidized upward. Nearly unconsolidated in lower part; interstitial weathering products become more common upward.

Interpreted depositional environment: Alluvial; shallow braided streams or sheet flow across an alluvial fan or flat.

Unit V_3

Lithology: Sand.

Thickness: 10.1 m (33 ft).

Color: Yellowish gray (5Y 7/2).

Texture: Mostly fine-grained sand, some medium-grained sand. A few pebbly sand beds; the pebbles poorly rounded.

Composition: Nonmicaceous. The pebbles mostly Franciscan chert and graywacke.

Sedimentary structures: Well defined under suitable conditions of exposure, but easily obscured. Variable, including flat bedding and subordinate small- to large-scale, low- to high-angle crossbedding. Some beds with small-scale penecontemporaneous deformation, probably due to bioturbation (burrowing or footprints).

Minor rock type: A few thin (less than 2 cm thick) beds of brownish gray (5YR 5/1) sandy silty clay associated with the few beds of pebbly sand.

Vertical variations: No significant variations noted.

Lower contact: Placed at horizon below which flat lamination is the dominant structure; gradational over several decimeters.

Diagenesis and weathering: Only slightly weathered, unconsolidated.

Interpreted depositional environment: Backshore flat and unvegetated eolian dunes, above level of normal high tides. Occasionally washed by small streams or sheet flow draining an area of Franciscan rocks.

Unit V_2

Lithology: Sand

Thickness: 2.4-3.0 m (8-10 ft).

Color: Mostly yellowish gray (5Y 7/2), but with some black sand beds.

Texture: Mostly fine-grained sand, some medium-grained sand. Locally a few centimeters of coarse, slightly pebbly sand at the top.

Composition: Nonmicaceous. Several beds, as much as 5 cm thick, of fine to very fine grained sand composed almost entirely of black opaque heavy minerals.

Sedimentary structures; Well defined; dominantly flat to very gently dipping (westward, at angles of as much as 5°) lamination. Several thin beds near the top are characterized by climbing-adhesion-ripple structure.

Vertical variations: In general, slightly finer toward the top. Climbing adhesion ripples found only near the top.

Lower contact: Placed at top of uppermost highly pebbly sand; gradational through a zone a few decimeters thick.

Diagenesis and weathering: Only slightly weathered, unconsolidated.

Interpreted depositional environment: Beach, ranging from backshore at the top to foreshore at the base.

Unit V_1

Lithology: Sand and gravel.

Thickness: 6.1-7.6 m (20-25 ft).

Color: The sand yellowish gray (5Y 7/2), the gravel composed mostly of relatively dark pebbles.

Texture: Fine- to medium-grained nonpebbly sand, medium to very coarse grained pebbly sand, and pebble gravel, mostly with a sandy matrix. Mean grain size of most gravel beds less than 10 mm; maximum pebble size less than 50 mm in most beds. Pebbles mostly well rounded.

Composition: The sand mostly nonmicaceous, but slightly micaceous near the base. Upper part contains several thin beds composed largely of black opaque heavy minerals. Pebbles lithologically heterogeneous, mostly of resistant rock types.

Sedimentary structures: Well defined. The dominant structure is medium-scale, medium- to high-angle trough crossbedding. Some sand beds have flat or gently dipping lamination, and some beds of fine sand are intensely bioturbated by *Macaronichnus segregatis*. Some gravel beds, especially in upper part of unit, are flat bedded.

Vertical variations: Gravel is coarsest and most abundant near base of unit. *Macaronichnus*, black sand, and flat-bedded gravel are most common in upper part.

Lower contact: Sharp, erosional.

Diagenesis and weathering: Only slightly weathered, unconsolidated.

Interpreted depositional environment: Largely nearshore marine, probably open-coast. Upper part may be a gravelly beach foreshore, as suggested by black sand and flat-bedded gravel. Large clasts at base represent a transgressive lag deposit.

Sequence U

Largely or entirely nonmarine, consisting of, from the top down, largely eolian sand (unit U_3), freshwater mud and peat (unit U_2), and alluvial gravel and sand (unit U_1). Change in relative sea level during deposition of these beds is unknown, but ponding near beginning of deposition suggests transgression. Total thickness of sequence ranges from 59.4 m (195 ft) where the sequence fills a former valley to 47.2 m (155 ft) farther south where the sequence rests on a former high area.

Unit U_3

Lithology: Sand.

Thickness: 47.2 m (155 ft).

Color: Yellowish gray (5Y 7/2) where least weathered; in part oxidized to more intense yellowish or brownish colors. Zones interpreted as paleosols are pale yellowish brown (10 YR 5/2) in their upper parts, moderate brown (5 YR 4/6) in their lower parts.

Texture: Mostly fine-grained sand, but some medium-grained sand. No pebbles. Zones interpreted as paleosols are slightly clayey.

Composition: Nonmicaceous. Many laminae rich in black opaque heavy minerals, especially near base of unit.

Sedimentary structures: Well defined. Dominant structure is medium- to large-scale (sets as thick as 6 m), medium- to high-angle crossbedding. Some flat to gently dipping planar lamination. Some of the less steeply dipping lamination was formed by climbing wind ripples. Much of the more steeply dipping crossbedding is of sandflow type. Much of the crossbedding in the lower 10 to 20 m is contorted on a large scale. Several massive intervals with root structures (steeply inclined to vertical tubes 1-10 mm in diameter outlined by iron oxides or clay minerals), sharp tops, and bases gradational into stratified sand are interpreted as paleosols. A few of the paleosols have laminae of clay, silt, or carbonaceous matter at their tops. Vertical tubes in basal part of unit may be burrows rather than root tubes.

Vertical variations: Paleosols most common in upper part. Black opaque heavy minerals and penecontemporaneous deformation most common in lower part.

Lower contact: Sharply overlies valley-filling mud of unit U_3. Tongues of unit U_2 extend obliquely upward and southward into sand of unit U_3 (Fig. 2). Farther south, unit U_2 pinches out against former valley side, and unit U_3 rests unconformably on the upper member of the Merced Formation of Hall (1965b, 1966).

Diagenesis and weathering: For the most part only slightly weathered, unconsolidated. Several paleosols, especially in the upper part (as many as four anastomosing paleosols in the upper 10-15 m). The paleosols are resistant to erosion because of interstitial weathering products (iron oxides and clay minerals).

Interpreted depositional environment: Mostly unvegetated eolian dunes and interdune flats. Lower few tens of meters may be partly or entirely subaqueous, formed by lateral infilling of freshwater lakes or brackish lagoons, as suggested by intertonguing with mudbeds of unit U_2. High concentration of heavy minerals in these basal sands suggests derivation from beach. Large-scale convolute bedding in basal part due largely to loading of underlying mud, perhaps aided by slumping down foreset slopes and by earthquake-induced liquefaction. At times the dunes became stabilized by low vegetation and soils developed.

Unit U_2

Lithology: Mud and peat.

Thickness: Main body as much as 9.1 m (30 ft) thick; pinches out to south against sand that mantles north-dipping buttress unconformity (former valley side). Several tongues as much as 2 m thick extend obliquely upward and southward from top of main body and pinch out between sand beds of unit U_3 (Fig. 2). Thinner tongues form mud drapes on sand foreset beds.

Color: Ranging from very light gray (N8) where diatomaceous to grayish black (N2) where peaty. Mostly light olive gray (5Y 7/1) when dry, medium-dark olive gray (5Y 4/1) when wet.

Texture: Mostly silty clay, in part sandy. Peat beds contain wood fragments as much as 6 cm in diameter.

Composition: Darker beds are peaty, lighter beds are diatomaceous.

Sedimentary structures: Flat-bedded, thin to thick bedded. Some distinct trace fossils and root tubes. The thick unlaminated beds may be intensely bioturbated. Upper part of main body is intensely deformed into giant flame structures, probably by loading while the mud was only slightly compacted.

Fossils: Listed by Hall (1965b, 1966). Diatoms are of fresh-water type. Rare bones and teeth of land mammals. Wood fragments in peat beds.

Vertical variations: Most organic-rich peat beds in middle of main body. Only the upper part of the main body has undergone severe penecontemporaneous deformation.

Lower contact: Conformable on gravel of unit U_1.

Diagenesis and weathering: Sufficiently compacted to be more resistant to erosion than adjacent sand and gravel. Largely unweathered.

Interpreted depositional environment: Freshwater marsh, swamp, and pond. The intertonguing of units U_3 and U_2 suggests that pond waters at times extended at least several meters up the foreset slopes of laterally infilling sand bodies. Occasionally brackish conditions cannot be ruled out. Ponding was restricted to valley area of former land surface.

Unit U_1

Lithology: Gravel and sand.

Thickness: As thick as 3.0 m (10 ft). Main gravel body pinches out to south against buttress unconformity (Fig. 2). Lower part of buttress unconformity mantled by slumped sand. Higher parts of unconformity locally mantled by as much as 30 cm of gravel or pebbly sand. The main gravel body is exposed only on the beach during winter low tides; during summer, it is buried by modern beach sand.

Color: Composed of a mixture of light and dark clasts.

Texture: Mainly poorly sorted gravel consisting mostly of pebbles but partly of cobbles and even boulders. Most of the clasts are poorly rounded.

Composition: The gravel clasts are heterogeneous. Most of the larger clasts are derived from relatively indurated (weathered or concretionary) beds of the underlying Merced Formation. The smaller clasts are mainly Franciscan chert and graywacke.

Sedimentary structures: Indistinctly bedded.

Vertical variations: Fining upward.

Lower contact: Sharp, erosional, with many meters of relief over a distance of many tens of meters, and as much as 2 m of local relief.

Diagenesis and weathering: Nearly unweathered.

Interpreted depositional environment: The gravel is alluvial. The main gravel body as restricted to a valley floor. The sand that mantles the former valley side is a slump mass derived from the underlying rocks.

UPPER MEMBER OF MERCED FORMATION OF HALL (1965b, 1966)

Only the upper part of the upper member of the Merced Formation of Hall (1965b, 1966) is considered here. The beds considered are those down to a level slightly below the prominent white tuff dated at 450,000 years by Meyer et al. (1980). These beds are divided into two unconformity-bounded progradational sequences, designated, from the top down, T, and S.

The upper member of the Merced Formation differs from the unnamed beds in being somewhat more indurated and in having a larger proportion of estuarine or lagoonal beds. The average degree of induration of sands in this unit is similar to that of unit X_3, the most indurated sand of the unnamed beds. No sands of this member are as unconsolidated as some of those in the unnamed beds. The unconformity separating the lower and upper members differs from those within the lower and upper members in having much greater original topographic relief, at least in the exposures along the coastal bluff.

Sequence T

Interpreted as an open-coast progradational sequence consisting of, from the top down, a series of paleosols and interbedded largely nonmarine deposits (unit T_4, of uncertain relationship to adjacent units), an eolian sand (unit T_3), a backshore (and locally foreshore) sand (unit T_2), and a foreshore and nearshore sand and gravel (unit T_1). Thickness 32.6-37.2 m (107-122 ft).

Unit T_4

Lithology: Clayey sand and clayey pebbly sand (diamictite) interbedded with sand.

Thickness: 3.0-4.3 m (10-14 ft). Absent to the north, where the unconformity above this unit cuts deeper into the section (Fig. 2).

Color: The clayey pebbly sand is a distinctive grayish orange pink (5YR 6/2). The clayey sand is light olive gray (5Y 6/1).

Texture: The clayey pebbly sand is sand with interstitial clayey matrix and with randomly scattered angular pebbles. The clayey sand beds are similar but without the pebbles. The interstitial matrix becomes less abundant toward the base of each of these beds, and the clayey sand or clayey pebbly sand grades downward into relatively well sorted sand.

Composition: The pebbles in the clayey pebbly sand are mostly Franciscan chert and graywacke. The sand that locally fills depressions cut into this clayey pebbly sand is rich in black opaque heavy minerals and is locally a black sand.

Sedimentary structures: The clayey sand and clayey pebbly sand beds are structureless. Each of these structureless beds has a sharp top and grades downward into stratified sand. The most common structures in the stratified beds are flat and gently inclined lamination and small-scale cross-lamination. Stratified sand locally fills a steep-sided depression cut as deeply as 1 m into the clayey pebbly sand.

Minor rock types: Locally, a silt lamina as thick as 1 cm overlies the clayey pebbly sand.

Vertical variations: A clayey pebbly sand bed 1-2 m thick forms the base of the unit. Interbedded clayey sand (locally pebbly) and sand in couplets 0.5-1 m thick form the upper 2-3 m.

Lower contact: Placed between structureless clayey pebbly sand and underlying stratified, relatively well sorted sand. Gradational through a zone a few decimeters thick.

Diagenesis and weathering: The interstitial clayey matrix of the clayey sand and clayey pebbly sand probably originated by weathering before burial. Early formation of clayey matrix facilitated formation of the steep side of the depression cut into the clayey pebbly sand. High on the bluff, the clayey beds have been bleached to light gray by modern weathering.

Interpreted depositional environment: The clayey sand and clayey pebbly sand beds are interpreted as paleosols developed on sand and on pebbly sand, respectively. The sand between the paleosols and on which the clayey sand paleosols were developed may been deposited either by water or by wind, whereas the pebbly sand must have been alluvial. The pebbles became randomly scattered in the clayey pebbly sand because of bioturbation (burrowing and root growth and decay) accompanying soil formation. The black sand filling the depression cut into the clayey pebbly sand may be a beach deposit.

The paleosols are restricted to the upland-flat part of the unconformity at the top of the unit and are absent from the valley-floor and valley-side parts of this unconformity. The pebbly alluvium on which the lowest paleosol was developed was almost certainly deposited before the valley was cut. Deposition of the overlying nonpebbly part of the unit and soil formation may have preceded, accompanied, or followed valley cutting.

Unit T_3

Lithology: Dominantly sand.

Thickness: 10.7-13.7 m (35-45 ft).

Color: Yellowish gray (5Y 7/1) where least weathered. Upper 2 m everywhere oxidized to rusty colors, moderate brown (5YR 4/6) where most intense. Where the unit occurs high on the bluff, other beds are oxidized.

Texture: The sand largely fine grained, in part medium grained. A few thin beds of pebbly sand, the pebbles in which are angular to subangular and mostly less than 50 mm in diameter.

Composition: Nonmicaceous. A few laminae rich in black opaque heavy minerals. The pebbles mostly Franciscan graywacke and chert.

Sedimentary structures: Generally well defined except within a few decimeters of the top. Dominant structure is medium- to high-angle crossbedding, mostly of medium scale but in part of large scale. Flat to gently inclined lamination is fairly common. Some of the flat to gently inclined lamination was formed by climbing wind ripples. Climbing-adhesion-ripple structures present locally. No trace fossils. Pebbly sand beds are gently lenticular.

Minor rock types: A few laminae of light gray silt and silty clay as thick as 1 cm associated with flat-laminated sand.

Vertical variations: No significant variations noted except for (1) the occurrence of highly oxidized sand near the top even in places where adjacent beds are not highly oxidized and (2) an abundance of pebbly sand in the lower 4 m south of the area of artificial fill, above the Daly City sewer outlets.

Lower contact: Placed at change from largely crossbedded sand to underlying largely flat-bedded sand. Locally sharp, but a few medium-scale sets of crossbeds occur several meters below the contact.

Diagenesis and weathering: Partially indurated and fairly resistant to erosion. The oxidation of the sand where exposed near the top of the bluff represents modern weathering. The oxidation of the upper 1-2 m where it is exposed at lower elevations, on the other hand, is interpreted as having occurred during the formation of the overlying paleosols.

Interpreted depositional environment: Unvegetated eolian dunes and interdune flats. Pebble-carrying streams occasionally entered the dune field. The silt and clay beds were deposited in ephemeral interdune ponds.

Unit T_2

Lithology: Sand.

Thickness: 9.1-12.2 m (30-40 ft).

Color: Yellowish gray (5Y 7/1) where dry and unoxidized in bluffs; darker and more intensely colored (5Y 6/2) where freshly exposed and wet at beach level. Some beds oxidized to yellowish and brownish colors.

Texture: The sand largely fine grained, in part medium grained.

Composition: Nonmicaceous. Some laminae rich in black opaque heavy minerals. No pebbles.

Sedimentary structures: Well defined. The dominant structure is flat to gently lenticular bedding of medium to small scale. Lamination is generally present within the beds. Lamination types include: (1) flat to gently dipping lamination, mostly of undetermined origin but in part formed by climbing wind ripples; (2) small-scale crosslamination formed by current ripples, (3) rare medium-scale crosslamination, at least in part eolian, and (4) climbing-adhesion-ripple structures. The lamination in many beds was penecontemporaneously deformed on a small to medium scale, producing wavy to contorted lamination; most of the deformation was probably caused by loading or by liquefaction under load, and the load may have been applied by overlying sediment or by animals (including very large mammals such as mammoths or mastodons) walking over the sediment; burrowing may also have contributed to the deformation. Many beds contain small (1-10 mm in diameter) steeply inclined to vertical tubes outlined by iron oxide or clay minerals; the tubes are interpreted as probably root tubes but possibly burrows. Where such tubes are common, lamination is indistinct or absent.

Minor rock type: Rare laminae of sandy clayey silt or clayey silty sand, olive gray (5Y 6/1) where least weathered but commonly rusty, as thick as 1 cm. These laminae occur in two beds, each about 30 cm thick, that have been penecontemporaneously deformed on a medium scale.

Fossils: A few land-mammal fossils have been found in one bed (Hall, 1965b, 1966).

Vertical variations: The tubes interpreted as root tubes are most common in the upper 1-2 m. In general, the unit is remarkably uniform from top to bottom.

Lower contact: Placed at the top of the uppermost gravel bed. Gradational in the sense that gravel beds become more common downward.

Diagenesis and weathering: Partially indurated and fairly resistant to erosion. Most beds unweathered or nearly so where exposed at beach level. The two penecontemporaneously deformed beds that contain clayey laminae are strongly oxidized except where they are exposed during winter at low elevations, where they are covered by modern beach sand during summer. Several of the zones with abundant root tubes are probably paleosols.

Interpreted depositional environment: Backshore sand flat above the level of normal high tides. At times lightly vegetated but not forested, at times containing small unvegetated eolian dunes. Deposition was in part eolian, on both dry and wet surfaces, and in part subaqueous, both in flowing water and in shallow, ephemeral ponds. Submergence may have resulted from storm surges, stream flooding, or rainfall directly on the flats. The lower 2 m may locally be beach foreshore deposits.

Unit T_1

Lithology: Sand and gravel.

Thickness: 6.7-10.1 m (22-33 ft).

Color: The sand beds yellowish gray (5Y 7/1) where least weathered. The gravel composed mostly of relatively dark pebbles.

Texture: The sand partly nonpebbly, fine to medium grained, and partly pebbly, medium to very coarse grained. The gravel beds composed of pebbles, mostly with a sandy matrix. Mean grain size of most gravel beds less than 10 mm; maximum pebble size less than 50 mm in most beds. Cobbles occur locally at the base. Pebbles mostly well rounded.

Composition: Nonmicaceous. Some sand laminae rich in black opaque heavy minerals. Pebbles lithologically heterogeneous, mostly of resistant rock types. Some pebbles and cobbles of partially indurated sand derived from underlying beds occur near the base.

Sedimentary structures: Well defined. The dominant structure is medium-scale, medium- to high-angle trough crossbedding. Some sand beds have flat or gently dipping lamination, and some of the gravel is flat bedded. Some sand beds intensely bioturbated, containing the trace fossil *Macaronichnus segregatis*.

Vertical variations: Fining upward. Flat-bedded sand and gravel more common toward the top. Sand rich in heavy minerals common only near top.

Lower contact: Sharp, erosional, with as much as 0.7 m local relief.

Diagenesis and weathering: Partly indurated. Unweathered or nearly so at beach level.

Interpreted depositional environment: Nearshore marine in large part, probably along an open coast. Upper part probably beach foreshore, as suggested by flat bedding and concentrations of heavy minerals.

Sequence S

Interpreted as a shallowing-upward estuarine sequence consisting of, from the top down, a supratidal- and intertidal-flat sand (unit S_2) and an intertidal and subtidal sand and silt (unit S_1). A distinctive white tuff bed occurs near the top of unit S_2). Thickness 8.5 m (28 ft). Described only from exposure at Daly City sewer outlets, the northernmost exposure of this unit.

Unit S_2

Lithology: Sand, with tuff (described under Minor rock type) near the top.

Thickness: 4.3-4.9 m (14-16 ft).

Color: Yellowish gray (5Y 7/1) where dry and unoxidized in bluffs; darker and more intensely colored (5Y 6/2) where freshly exposed and wet at beach level. Some beds oxidized to yellowish and brownish colors. Tuffaceous sand very light gray.

Texture: The sand largely fine grained, in part medium grained.

Composition: Nonmicaceous in upper part, slightly micaceous in lower part. The sand above the tuff bed tuffaceous in part. Some laminae rich in black opaque heavy minerals.

Sedimentary structures: Well defined. The dominant structure is flat to gently lenticular bedding of medium to small scale. Lamination is generally present within the beds. Lamination types include: (1) flat to gently dipping lamination, mostly of undetermined origin but in part formed by climbing wind ripples; (2) medium-scale crosslamination of eolian origin; and (3) climbing-adhesion-ripple structures. The lamination in some beds was penecontemporaneously deformed on a small to medium scale, producing wavy to contorted lamination; this deformation was caused by animals, including split-hoofed ungulates (perhaps elk or deer), that walked over the sediment. Some beds, including the one most intensely deformed by footprints, contain small (3-6 mm in diameter) vertical tubes that are either root tubes or, more probably, burrows.

Minor rock type: Where the unit is most fully preserved, a white (N 9) tuff bed occurs 0.7 m below the top; the sand overlying the tuff was locally eroded before deposition of the overlying unit (unit T_1). The tuff is composed mostly of volcanic glass fragments but contains a small fraction of volcanic mineral grains. The tuff forms a bed averaging 0.3 m thick, overlain by as much as 0.2 m of tuffaceous sand. The tuffaceous sand has climbing adhesion ripples at one or two horizons, but the tuff itself is internally structureless or indistinctly stratified. Sand-filled burrows or root tubes locally penetrate the tuff.

Fossils: A broken but nearly entire valve of a large (approximately 10 cm long) pelecypod was found immediately above or immediately below the tuff by Brian Atwater in 1977 (Atwater, written communication, 1982).

Vertical variations: Beds of undoubted eolian origin occur only in the upper part, both above and below the tuff bed. Footprint structures occur only in the lower part. The uppermost preserved bed is riddled with burrows or root tubes.

Lower contact: Placed at top of sand with abundant trace fossils other than footprints. Gradational over several decimeters.

Diagenesis and weathering: Partially indurated. Most beds at beach level unweathered or nearly so, but a few beds strongly oxidized.

Interpreted depositional environment: Estuarine supratidal (at top) to intertidal (at base) sand flat; similar to an open-coast beach backshore environment, but not interpreted as such because the underlying beds are of estuarine intertidal to subtidal origin.

Age: The tuff bed has been dated by various methods. The latest and most reliable estimate of its age is 450,000 years (Meyer and others, 1980).

Unit S_1

Lithology: Sand and mud.

Thickness: 3.0-3.7 m (10-12 ft).

Color: The sand yellowish gray (5Y 7/1) where dry and unoxidized; darker and more intensely colored (5Y 6/2) where freshly exposed and wet at beach level. The mud light gray (N 7) where dry and unoxidized in bluffs; olive gray (5Y 5/1) where freshly exposed and wet at beach level.

Texture: The sand fine grained, silty in part. The mud ranging from silt to silty clay.

Composition: The sand micaceous. The mud not rich in organic matter.

Sedimentary structures: Well defined in upper part, indistinct in lower part. The sand beds average 0.2-0.3 m thick, the mud beds 0.1 m thick. Bedding most flat, but locally medium-scale crossbedding in basal 0.5 m. Bioturbated throughout, with distinct trace fossils, especially steeply inclined burrows 1-2 cm in diameter filled largely by stratified sand even where they penetrate mud beds. Intensity of bioturbation is greatest in lower part, where original bedding has been largely destroyed. Large burrows at base penetrate underlying unit.

Fossils: Large burrows at base contain casts of pelecypods in growth position.

Vertical variations: Intensity of bioturbation decreases upward.

Lower contact: Sharp, marked by large, steeply inclined burrows (5-15 cm in diameter, as deep as 30 cm). Underlying bed is a clayey pebbly sand similar to unit V_5 and to the lower part of unit T_4, interpreted as a paleosol developed on pebbly sand alluvium.

Diagenesis and weathering: Partially indurated. Unweathered or nearly so at beach level. Basal burrowed zone strongly oxidized in exposures in bluff.

Interpreted depositional environment: Estuarine intertidal (at top) to subtidal (at base). Possibly formed by lateral accretion on the side of an estuarine tidal channel.

CONCLUSIONS

The beds described here were deposited in coastal environments ranging from the inner shelf to eolian dunes. Both open-coast and estuarine environments are represented. The beds are grouped into unconformity-bounded sequences, within most of which the sediment surface gradually rose with respect to sea level throughout deposition of the sequence. In other words, most of the sequences are progradational or regressive. A few of the sequences may be transgressive in whole or in part, but most of the transgressions that must have alternated with the regressions are represented only by unconformities and thin lag deposits resting on the unconformities.

The marine and littoral parts of the progradational sequences are interpreted to have been deposited at times when relative sea level was at a high stand or was beginning to fall. The overlying eolian and alluvial parts of the progradational sequences may have formed in the same part of the sea-level cycle or may have formed later, when sea level was at a low stand (compare to Atwater, Hedel, and Helley, 1977). The unconformities separating the progradational sequences from one another are interpreted to have formed by subaerial erosion when sea level was at or near a low stand or by marine erosion when sea level was rising. If any of the sequences are transgressive, they were probably deposited as sea level was rising (compare to Dupre, Clifton, and Hunter, 1980). Although local tectonic events cannot be ruled out as a cause of at least some of the changes in relative sea level, glacio-eustatic sea-level changes must have been a major contributing factor and may have been the sole cause of the depositional-erosional cycles.

The average time involved in a cycle of sea-level change can be roughly calculated from the number of cycles between the Colma Formation and the dated tuff bed. The Colma Formation is almost certainly no younger than oxygen-isotopic stage 5 of Shackleton and Opdyke (1973), a period of glacio-eustatic sea-level high stands that occurred 73,000 to 127,000 years ago according to Pisias and Moore (1981). Although an older age cannot be ruled out, the Colma is provisionally regarded to have formed sometime during oxygen-isotopic stage 5. The Colma (Sequence Z) is at least the fifth progradational sequence above Sequence S, which contains the tuff bed dated at 450,000 years ago (Meyer and others, 1980). If no other sea-level cycles other than those represented by the five definitely progradational sequences (Sequences T, V, X, Y, and Z) occurred during this 323,000- to 382,000-year time span, the average periodicity of sea-level cycles was 65,000-76,000 years. Given the substantial probability that other sea-level cycles did occur but did not leave preserved deposits or left deposits that were not identified as progradational sequences, the average periodicity of sea-level cycles could easily have been less.

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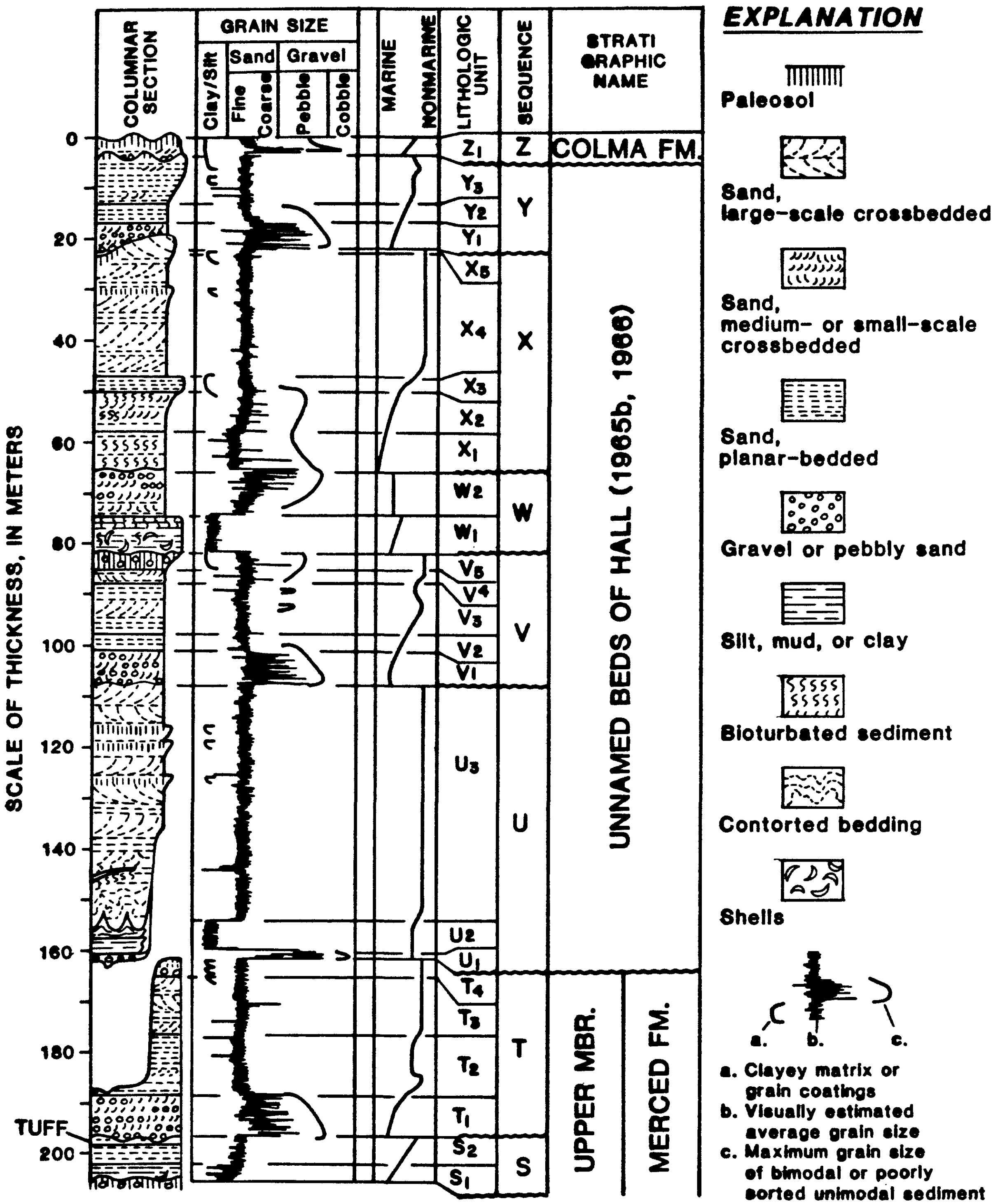

Figure 1. Stratigraphic column of beds described in this report. Except on the columnar section, the uppermost beds preserved beneath the unconformity separating sequences U and T are dropped so that they fall below the lowermost beds preserved above the unconformity. Details of grain-size curve are schematic.

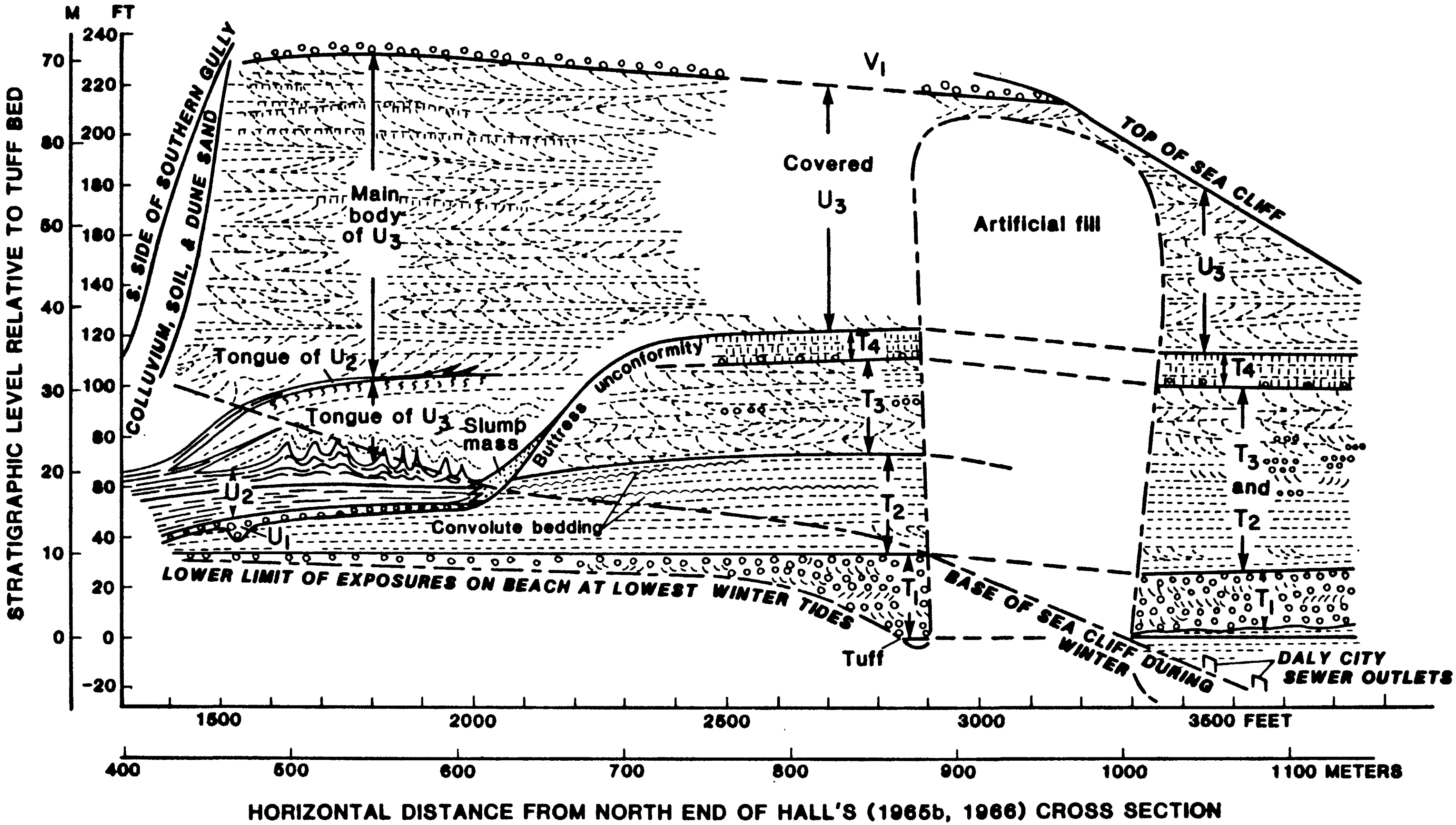

Figure 2. Stratigraphic cross section of beds exposed between the southern gully and the Daly City sewer outlets. Most of the beds below the base of the sea cliff are exposed only during winters, when the beach is partially stripped of its sand. Symbols for lithologic and bedding types are the same as in Figure 1.