

A DEEP WATER TRACE FOSSIL ASSEMBLAGE FROM THE
GERMAN RANCHO FORMATION, STUMP BEACH, SALT POINT STATE PARK

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ABSTRACT

Excellent exposures of sandstones, siltstones, and shales comprising the Paleocene-Eocene German Rancho Formation in sea cliffs at Salt Point State Park allow reconstruction of the depositional setting and documentation of the paleoenvironmental distribution of the biogenic structures. From sedimentological evidence the formation is interpreted to represent a progradational sequence of inner fan channel, levee, and interchannel submarine fan deposits formed at bathyal depths. Described sequences of channel levee and interchannel facies have a well-preserved ichnofauna that includes typically shallow sublittoral forms of *Thalassinoides* and *Ophiomorpha*. Successional relationships of traces implied by field observations in conjunction with the inferred mode of life of the trace-making organisms are presented as

a conceptual model that incorporates the dynamics of turbidite sedimentation. The cycle commenced following deposition of a turbidite sand. Early colonizers included producers of a large form of *Planolites*, *Chondrites*, and a small form of *Thalassinoides*, which in thinner bedded intervals occur only in mudstones and muddy siltstones. Following an interval of pelagic sedimentation the dominant burrowers in the muds were producers of a small form of *Planolites* (made by a vermiform deposit feeder?) and *Tasselia* (possibly the dwelling burrow of a pogonophoran); *Ophiomorpha* and *Thalassinoides* were produced by a deep burrowing organism, probably a thalassinid crustacean. Both are attributed to the activities of a single organism that constructed a thick-walled, peletally lined burrow in sand (*Ophiomorpha*) and an unlined burrow (*Thalassinoides*) in silt and mud. In addition, a back-filled form of *Thalassinoides* resembling *Teichichnus* may represent an escape or deposit-feeding trace of the same animal. The successional cycle was completed by renewed turbidite sedimentation which eroded surface muds, exhumed and transported *Tasselia*, and filled all open *Ophiomorpha* and *Thalassinoides*, possibly accounting for some of the back-filled (escape?) traces associated with these two forms. Recolonization by burrowing infauna started a new cycle and, in thinly bedded sequences, resulted in a complex overlap of trace generations.

The major conclusion of this and previous studies of deep sea fan ichnocoenoses is that many traces normally considered to be shallow water forms can be common at bathyal depths where the grain size of the substrate, rates of sedimentation, and organic content of the sediment converge on those typical of the shallow sublittoral environment. Therefore, bathymetric interpretations relying on trace fossil evidence must be used conservatively in conjunction with other sedimentological and paleontological evidence.

INTRODUCTION

Paleocene and Eocene marine sedimentary rocks of the German Rancho Formation (Wentworth, 1968) are exposed over a broad region west of the San Andreas fault between Fort Ross and Point Arena in the northern Coast Ranges of California (Fig. 1). The German Rancho rests unconformably on 5,000 feet of Upper Cretaceous marine sedimentary rocks designated informally as the Anchor Bay and Stewart's Point groups (Wentworth, 1966, 1968) and is conformably overlain by the Iversen Basalt of Miocene age (Weaver, 1944). In its northern exposures near Anchor Bay, the German Rancho section measures 3,000 m, but it thickens markedly to the south, reaching 6,000 m just north of Fort Ross (Wentworth, 1968).

The German Rancho Formation consists of predominantly thickly bedded sequences of medium to coarse grained gray, feldspathic sandstone, rhythmically in-

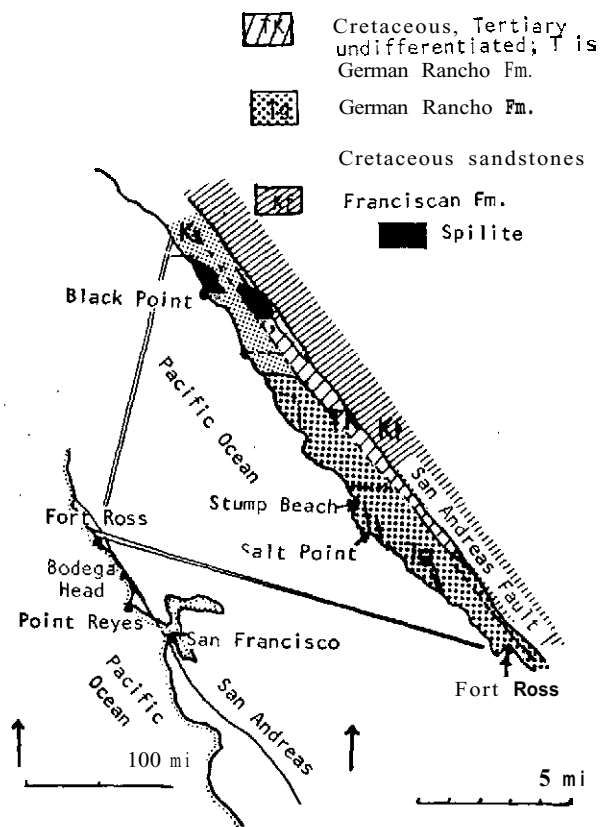


Figure 1. Location of Stump Beach at Salt Point State Park and generalized geologic map of the area (modified from Wentworth, 1968). Lines indicate faults; dashed where inferred.

terbedded medium to fine grained sandstone and dark mudstone, and subordinate amounts of conglomerate.

The German Rancho Formation has been assigned an age of Paleocene to Eocene based on a sparse fossil assemblage consisting of 3 gastropod species and several species of arenaceous foraminifera (Wentworth, 1968). Lack of distinctive lithologic units has inhibited subdivision of the formation into members, and local correlations are complicated by faulting and poor exposures in inland areas.

The depositional framework for the German Rancho Formation is not known in detail. Wentworth (1968) suggested that the Cretaceous and lower Tertiary sequences of this region were deposited by turbidity currents in a narrow, northwesterly-trending basin (the Gualala Basin) that was bounded on the east and west by granitic source terrains. The dominance of bathyal over abyssal foraminifera suggest water depths between 200 and 2000 m. Paleocurrent data indicate flow directions to the northwest, parallel to the long axis of the basin. More recently, Nilsen and Clarke (1975) and Graham and Berry (1979) suggested that the German Rancho sediments were deposited as a series of coalescing and prograding deep-sea fans.

North of Stewart's Point, a south-dipping section of several thousand feet of spilitic basalt is exposed in the core of the Black Point anticline (Fig. 1). This basalt lies in fault contact beneath the Upper Cretaceous strata of the Stewart's Point Group. The lowermost structural position of this basalt led Wentworth (1971) to suggest that the Gualala Basin may have been floored, at least in part, by oceanic crust.

The conglomerates of the Upper Cretaceous and lower Tertiary sediments are notably lacking in lithologies of the Franciscan complex which presently is exposed in the Coast Ranges east of the San Andreas fault. This has important implications for the regional tectonic history of the Gualala structural block in relation to San Andreas faulting (see Nilsen and Clarke, 1975; Graham and Berry, 1979). The most plausible source area for the conglomerates is the "Salinian" basement complex of the Sur Series exposed to the south, a dominantly granitic terrain with minor mafic, ultramafic, and metamorphic rocks.

Based on the interpretation of magnetic anomaly patterns on the Pacific Ocean floor and the inferred history of plate motions, Atwater (1970) suggested that the present San Andreas fault originated about 30 million years b.p., with the collision and subduction of the East Pacific Ridge in a trench lying offshore of western North America. The tectonic history for California as deduced from this model postulates: 1) Mesozoic subduction and underthrusting of the Franciscan complex beneath the Great Valley sequence, 2) late Cretaceous to early Tertiary right lateral transform faulting along a proto-San Andreas fault system (Suppe, 1970), 3) subduction of the Farallon Plate and the cessation of right lateral displacement from Paleocene to early Miocene, and 4) growth of the present San Andreas fault system from early Miocene to the present (Nilsen and Clarke, 1975, pp. 34-36).

Nilsen and Clarke (1975, p. 33) concluded that the Gualala Basin was one of several Cretaceous to early Tertiary deep marine basins that formed to the east and west of "Salinia", which at the time probably formed a long peninsula or island chain west of the

proto-San Andreas fault. This time interval coincided with a change in the tectonic regime from one of right-lateral faulting to subduction in a trench to the west of Salinia.

The amount of movement of the German Rancho Formation from its site of deposition to its present location due to slippage along the San Andreas and Hosgri-San Gregorio fault systems is a matter of debate. Differences are due to various interpretations of compositional similarities between sandstones on either side of the fault and to whether or not movement along the Hosgri-San Gregorio fault system is added to that of the San Andreas. Nilsen and Clarke's (1975) correlations require 200 miles (320 km) of post Miocene displacement along the San Andreas, whereas Graham and Berry's (1979) interpretations require at least 260 miles (415 km) of right lateral displacement since the Oligocene. Graham and Berry's (1979) paleogeographic reconstruction is illustrated in Fig. 2. Complete discussions of various aspects of the problem are available in Cummings et al. (1972), Nilsen and Clarke (1975), Graham and Dickenson (1978) and Graham and Berry (1979).

Few studies have focused on the depositional setting of the German Rancho Formation in one small area, and, except for brief reports by Marks (1977) and Clarke (1978) (on file in the Bodega Marine Laboratory Library), none have dealt in detail with the trace fossils. The purpose of this portion of the guidebook is to outline the facies and depositional environments of the German Rancho Formation at Stump Beach, briefly describe the trace fossils and their occurrences in these facies, and discuss the factors which might have controlled the distribution of the trace producers.

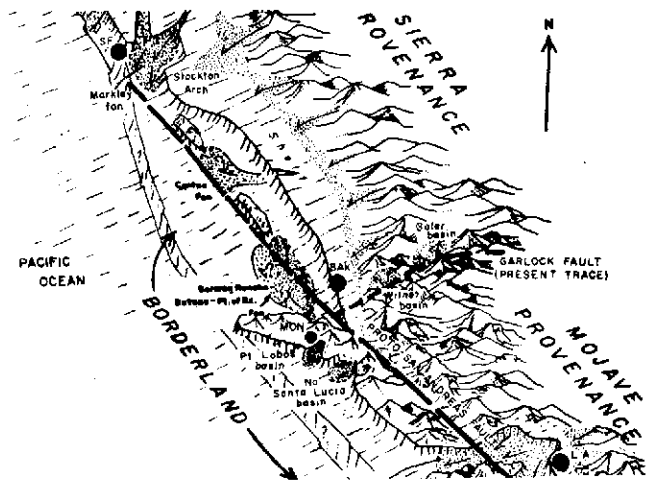


Figure 2. Paleogeographic reconstruction of a portion of California in the early Tertiary (from Graham and Berry, 1979, Figure 5C; they modified it from Nilsen and Clarke, 1975). SF = San Francisco; MON = Monterey, LA = Los Angeles, BAK = Bakersfield.

GERMAN RANCHO FORMATION AT STUMP BEACH

LOCATION

The sea-cliff exposures at Stump Beach on the northern boundary of Salt Point State Park along California State Highway 1 (Figs. 1, 3) provide easy access to an interval within the German Rancho Formation that is both well exposed and lithologically varied. The section is composed of four major lithofacies: 1) thickly bedded, coarse to pebbly arkosic sandstone, 2) interbedded sandstone and mudstone, 3) pebble to boulder conglomerate and breccia, and 4) interbedded mudstone and siltstone. Trace fossils are abundant in all facies except the conglomeratic facies in rocks exposed at the north end of Stump Beach Cove (Fig. 3, Location A) and at a second locality 500 m south of the cove (Fig. 3, Location B).

Facies

Pebbly Sandstone Facies

Comprising the basal part of the section to be seen on this trip (Fig. 3, Location A), this facies consists of thickly bedded, arkosic sandstone. Beds range from 2 to 3 m thick and show normal graded bedding and pebbly, channeled bases. Low angle cross-stratification is observable in the tops of some beds, some of which are overlain by an interval of thinly laminated fine-grained sandstone and interbedded mudstone. Some laminated horizons have load structures or ripple-cross-stratification; others are highly bioturbated. *Ophiomorpha* and *Thalassinoides* are abundant on extensive bedding plane surfaces of this facies.

Interbedded Sandstone and Mudstone Facies

This facies is characterized by relatively thick sandstone beds separated by intervals of alternating thinly bedded sandstone and mudstone. The thicker (10 to 30 cm) beds of fine to medium-grained sandstone are graded and parallel laminated in their upper portions (Bouma A B). The intervening intervals are comprised of siltstone and fine-grained sandstone beds 1 to 5 m thick showing ripple-drift-cross lamination (Bouma C) and interbedded dark mudstone (Bouma E). The thicker sandstone beds have sharper

upper and lower contacts (Fig. 4) in contrast to the thinner sandstones which have wavy bedding and are highly bioturbated. At the exposure of Location A (Fig. 3) this facies shows an upward thinning of sandstone beds and decrease in grain size; in the uppermost portion the average sandstone: shale ratio is 2.8 (n=24). At Location A this facies overlaps the pebbly sandstone facies. The contact between the two is not abrupt; the pebbly sandstone facies displays a fining upward trend which continues into the interbedded sandstone and mudstone facies.

Conglomeratic Facies

The upper part of the sandstone-mudstone facies is overlain at Location A (Fig. 3) by a thick sequence of pebble and boulder conglomerate that typically shows normal graded bedding and channeled bases. The conglomerates contain well-rounded clasts of granite, gneiss, biotite schist, amphibolite, quartzite, chert, marble, and intermediate to felsic porphyritic volcanic rocks. The thickest conglomerate is located about the middle of the section and is about 7 m thick. This conglomerate shows reverse grading, being pebbly at the base and bouldery near the top. A sparse molluscan fauna collected from this bed is presently under study for an age determination.

Interbedded with the conglomerates and coarse sandstones of this interval are beds and lenses of pebble and boulder breccia composed of rip-up clasts of thinly bedded, fine grained gray sandstone and siltstone, and dark gray to black shale. Most of the clasts are angular and many were deformed during transport. They range from tabular boulders up to 3 m long and 0.5 m thick down to more equant and rounded cobble-sized clasts.

In general, the conglomerate interval shows a fining and thinning upward sequence; the top of the section consists of thickly-bedded, coarse-grained sandstones with low angle cross-stratified tops, and channeled, pebbly bases. These beds in turn appear to be overlain by a sequence of medium to thin bedded medium grained sandstones and interbedded dark mud-

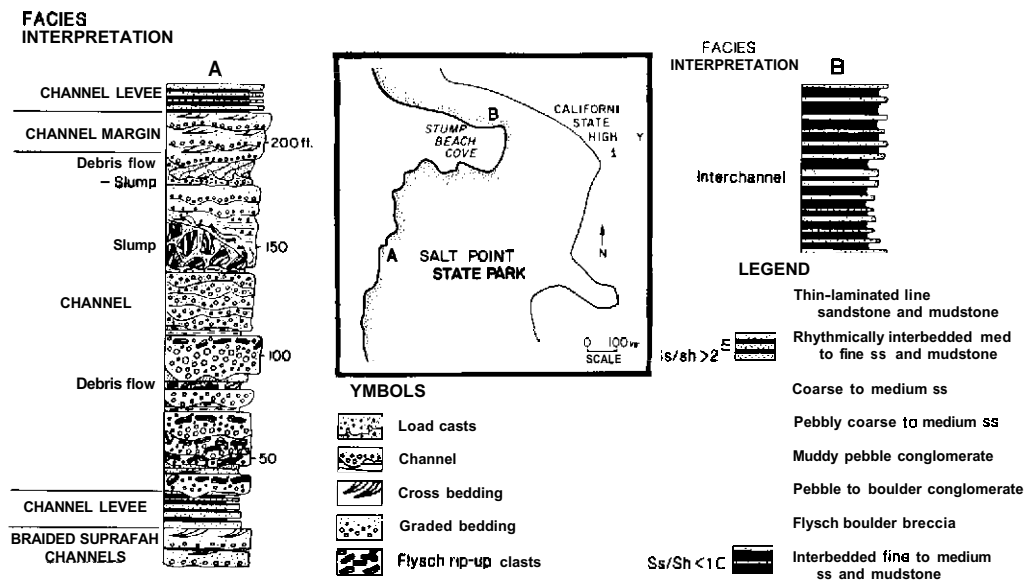


Figure 3. Location of outcrops at Stump Beach, with columnar section of each outcrop.

stone, showing rhythmic bedding, similar to the basal sequence exposed to the south. The top of this interval is in fault contact with the thinly bedded mudstone-sandstone facies exposed at the north end of the Stump Beach Cove (Location B, Fig. 3).

Approximately 15 m stratigraphically above the thickest conglomerate, a thick lense of boulder breccia occurs within a thickly bedded, coarse grained sandstone interval. The breccia consists of angular clasts up to 4 m long which are randomly oriented in a matrix of muddy sandstone. Most of the clasts show soft sediment folding, and the orientation of fold axes suggest northward transport. Some of the clasts have a poorly preserved ichnofauna dominated by *Planolites*. The basal and lateral contacts of the breccia are highly irregular; the upper contact is poorly exposed and truncated by an unconformity overlain by Pleistocene marine terrace deposits. Near its contacts with the breccia lense, the bedding of the enclosing sandstone is disrupted or lost. Numerous randomly oriented angular clasts of shale, and an occasional larger clast of pebbly conglomerate are scattered throughout the adjacent coarse sandstone matrix, along with irregular tensional fractures and dikes filled by finer grained sandstone.

Mudstone-Sandstone facies

At the north end of Stump Beach Cove (Location B, Fig. 3) a thick sequence (~ 100 m) of interbedded fine to medium grained, gray sandstone and dark gray mudstone forms steep cliffs above the beach (Fig. 5). The precise stratigraphic relationship of this sequence to the section exposed to the south (Location A, Fig. 3) is unclear, as it is bounded on both the north and south by faults. The sandstone to shale ratio averages 0.73 ($n=22$) significantly different ($t=3.04$, $P < .005$) from the interbedded sandstone and mudstone facies at the base of the section to the

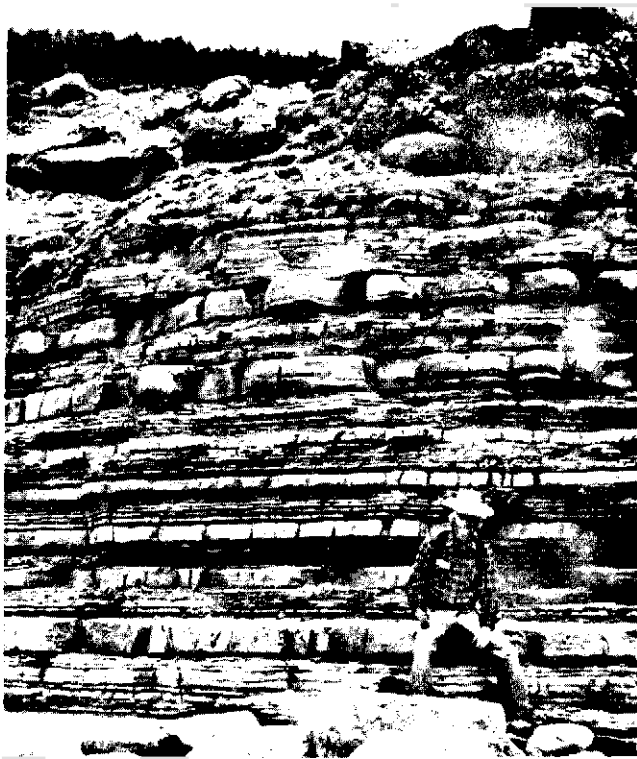


Figure 4. Interbedded sandstone and mudstone facies at Locality A (Fig. 3).

south. The sandstone **b** is range in thickness from 0.5 to 20 cm. The thinner sandstones show Bouma C E and B C E, and some of the thicker beds are normally graded.

Depositional Environment

Interest in modern and ancient submarine fan deposits has grown rapidly in the last decade and this work has been synthesized into generalized facies models by several authors (e.g. Walker and Mutti, 1973; Nelson and Nilsen, 1976; Walker, 1979). The rocks of the German Rancho Formation exhibit many of the typical characteristics of deep sea fan deposits and recently have been interpreted as such (Nilsen and Clarke, 1965; Graham and Berry, 1979). Applying the criteria in Tables 1 and 2 for the recognition of ancient submarine fan deposits from Nilsen and Nelson (1976), the section of the German Rancho Formation exposed south of Stump Beach Cove (Location A, Fig. 3) most closely resembles channel and associated levee deposits of the upper fan environment. This is reasonable in light of the association of boulder conglomerates (inferred channel deposits) and flysch clast breccias interpreted as debris flow and submarine slump deposits. The thickest conglomerate in the middle of the section shows reverse grading, typical of Walker's (1970, p. 96) upper fan-channel facies. The vertical changes in lithofacies up-section suggest the lateral migration and progradation of a major channel and its associated distributaries which eroded into and were eventually replaced by marginal levee deposits, now represented by the interbedded sandstone and mudstone facies sequences underlying and capping the conglomeratic facies (see Fig. 3). The relatively high sandstone to shale ratio (2.8) of the rhythmic turbidites at Locality A (Fig. 3), the predominance of Bouma B C E and C E sequences, and the bedding style support the contention that they represent levee facies (see Table 2).

Periodic overstepping of channel walls and rapid deposition may have produced localized debris flows and slumps into the channel which are now represented by monolithic breccias derived from poorly consolidated channel margin and interchannel turbidites.

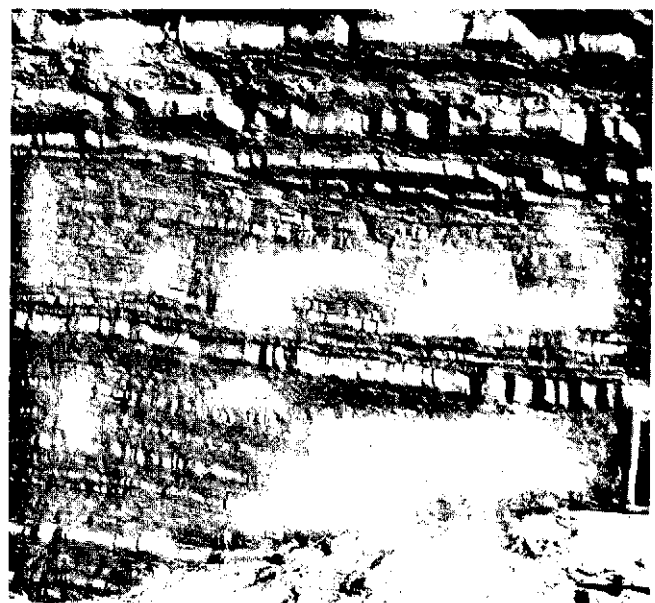


Figure 5. Mudstone-sandstone facies at Location B (Fig. 3). Hammer at bottom right for scale.

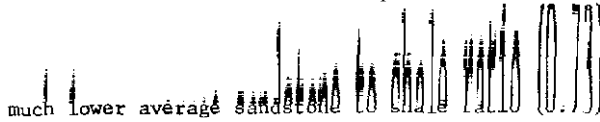
	Stratigraphy and Sedimentary Facies	Sediment Types	Sedimentary Structures
Upper Fan	Abrupt vertical and lateral changes between channel and interchannel facies; lenticular channel bodies enclosed within interchannel facies; isolated blocks of levee facies enclosed within channel facies.	Conglomerates and sandstones in channels flanked by fine sandstone and siltstone of levee or interchannel areas; silty mudstones limited in channel (except in fining upward sequence), but dominant in interchannel.	Bouma <u>A E</u> predominant. Some <u>A B</u> possible; coarsely-laminated beds having dish structure, mudstone rip-ups and clasts, very highly contorted beds and slump structures common; channel sands and gravels injected into interchannel beds; interchannel-like levee environment.
Middle Fan	Like upper fan region evolving to distinctly bedded and structured channel facies having thin well-developed mud interbeds associated with limited interchannel facies.	Sandstone in channels; interchannel having sandstone and siltstone.	Five Bouma <u>A B C D E</u> sequence common in channels; typically less complete Bouma sequences in interchannels; muds most bioturbated in interchannel.

Table 1: Characteristics of upper and middle fan deposits (after Nilsen and Nelson, 1976: 405-406, Table 4)

	Channel	Levee	Interchannel
Stratigraphy and Sedimentary Facies	Thick, coarse-grained beds having highly varied and poorly developed bedding; fining upward to fewer and thinner coarse-grained beds. Lenticular beds dominate; mud interbeds cut out, or incompletely developed, except in fining upward sequences.	Thin (<15 cm) well-bedded lenticular coarser sandstones alternating with equal amounts of fine-grained beds in rhythmic sequence.	Very thin and evenly bedded coarse grained layers alternating with greater amounts of interbedded mudstone.
Sediment Types	Dominantly sandstones and conglomerates, or muddy conglomerates and limited mudstones.	Fine grained sandstone, siltstone, and mudstone in equal proportions.	Very thin and evenly bedded coarse grained layers alternating with greater amounts of interbedded mudstone.
Sedimentary Structures	Bouma <u>C D E</u> poorly developed, if present. Beds display well-developed sole marks and channeled basal contacts.	Some Bouma <u>C D E</u> or <u>D E</u> units with convolute and ripple cross-laminated beds and starved ripples typically at tops of sandstone and siltstone beds.	Similar to levee but generally thinner bedded and laminated in upper fan.
Maximum Grain Size	Boulders	Coarse sand	Medium sand
Sandstone/Shale Ratio	> 1; High throughout, but may become lower in upper part of channel fill.	≥ 1; Intermediate and higher than in interchannel and distal areas.	< 1; Low, except in suprafan areas.
Conglomerate/Sandstone Ratio	High to zero	Generally zero	Generally zero
Depositional Processes	Slumps, slides, grain flow, fluidized sediment flow, debris flow, turbidity currents, and flow from bottom currents; and some hemipelagic sedimentation in periods of non-activity in channel.	Mainly turbidity-current suspension-load; normal hemipelagic deposition except near continental margin where turbid layer flow may dominate.	Mainly deposition by current suspension load separated by intervals of hemipelagic sedimentation.

Table 2: Characteristics for recognizing depositional environments in the upper fan facies (after Nelson and Nilsen, 1976: 405-406, Table 4)

The mudstone-sandstone facies at Location B (Fig. 3) is interpreted as a turbidite, yet it differs significantly from the interbedded sandstone and mudstone facies at the south end of Stump Beach in having a



much lower average sandstone to shale ratio (0.1) a more uniform bedding style, and a much greater total thickness than Locality A. These characteristics are compatible with the interpretation that they are interchannel deposits. On the upper fan, where flows are more channelized, interchannel deposits have low sandstone to shale ratios due to the predominance of pelagic sedimentation over overbank deposition. The lithologic similarity between the rocks exposed at Locality B and monolithic breccias of the channel facies at Locality A suggests that incised interchannel deposits may have provided much of the source material for the debris flows and slump deposits.

ICHNOCOENOSES FROM STUMP BEACH

Five trace fossil ichnogenera, representing dwelling and feeding burrows of an infaunal benthic community that occupied levee and interchannel environments on the Gualala submarine fan, have been identified from the turbidites at Stump Beach. The assemblage dominated by ichnogenera typically assigned to Seilacher's (1967) *Skolithos* and *Cruziana* ichnofacies of littoral to sublittoral depths (see Frey, 1975, p. 17, Table 2:1).

Trace Fossils

Ophiomorpha

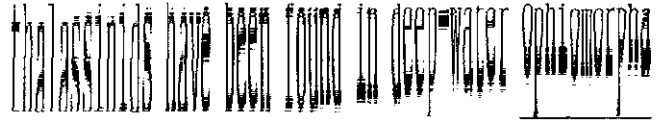
In the German Rancho Formation this trace consists of vertical shafts and horizontal branches 0.5 to 3 cm. in diameter characterized by a thick mammillate lining of pelletal mudstone (Plate 1A). Branching in the horizontal portions of burrows is common and complex, and bulbous swellings (turn around points?) often occur near points of branching.

At Stump Beach *Ophiomorpha* is abundant in the lower portion of the rhythmically-bedded sequence of the pebbly sandstone facies exposed at Location A, Fig. 3., especially in the thicker graded beds of medium to coarse grained sandstone. Burrow size is apparently related to bed thickness. In thinner bedded sequences burrower diameters range from 1.0 to 2.0 cm. As observed by Frey et al. (1978, p. 202) few branches occur in the upper and central portions of beds but tiered mazes occur near the bases of beds. Horizontal portions of the *Ophiomorpha* burrow system commonly are localized either: 1) at the bases of graded sandstone beds or 2) in the laminated sandstones and mudstones immediately subadjacent to these graded sandstone beds. This distribution of horizontal components of *Ophiomorpha* is in accord with that observed by Kern and Wame (1974, p. 896) in deep-water sediments of the (Eocene) Point Loma Formation of the San Diego area.

The density of burrows (including _____ and the very similar *Thalassinoides*, which lacks the knobby burrow wall shown in Plate 1A) varies laterally as well as vertically within beds. Within a 1 m thick sandstone bed the combined burrow densities for *Ophiomorpha* and *Thalassinoides* were estimated to be $100/m^2$ within a roughly circular area of $100 m^2$. Moving laterally away from this area, burrow density dropped abruptly to $10/m^2$. It is not clear whether this represents gregarious behavior, which might have environmental significance, or merely reflects

behaviorally insignificant patchiness.

Ophiomorpha is attributed to the burrowing of thalassinid crustacean and fossilized appendages of



(Hayward, 1976, p. 153). Thalassinids include both suspension feeders (e.g. *Callianassa major*, *Upogebia pugettensis*) and deposit feeders (e.g. *Callianassa californiensis*). *Ophiomorpha* ranges from the Jurassic to Recent. Although this trace traditionally has been considered to be a sensitive environmental indicator, Frey et al. (1978) have shown that the ichnogenus exhibits a broad range of burrow morphologies and environmental distributions.

Thalassinoides

Although lacking the characteristic mammillate burrow wall of *Ophiomorpha*, *Thalassinoides* resembles it in size and morphology (Plate 1C). Stump Beach specimens of *Thalassinoides* have a thin (0.5 mm) lining of mudstone. At Stump Beach, *Thalassinoides* passes laterally into *Ophiomorpha*. Kern and Wame (1974, p. 896) also observed this relationship and suggested that the transition in burrow morphology is governed by grain-size variations, the organism constructing *Ophiomorpha* in sand and *Thalassinoides* in finer-grained sediment. Our observations generally support the contention that a single species may have produced both traces. However, although *Ophiomorpha* is more abundant in sandstone, *Thalassinoides* occurs in sandstone as well as in the finer-grained sediments of the pebbly sandstone and interbedded sandstone and mudstone facies. Its maximum observed depth of penetration is 1 m in sandstone. "Rip-up" clasts of shale occur in the upper portions of some graded sandstone beds; where these are concentrated, *Thalassinoides* occurs preferentially within the clasts. Abundant, crescent-shaped laminae of mudstone are scattered over many bedding planes of sandstone beds and may represent the thin linings of *Thalassinoides* burrow walls which have been broken and disturbed by later burrowing.

A backfilled form of *Thalassinoides* (Plate 1F) is rare at the southern end of Stump Beach, occurring in the coarse-grained sandstone facies in association with the typical unbackfilled form (Plate 1C). Backfilled *Thalassinoides* were reported by Kern and Wame (1974, p. 897). However, the traces at Stump Beach lack the central double groove and strong bilateral symmetry of *Scolicia*, and are therefore tentatively included in *Thalassinoides*. The backfilling may have been a result of feeding activity or may reflect escape behavior, the animal stowing sediment in abandoned portions of the burrow system as it moved upward to maintain contact with the sediment-water interface after a sedimentation event.

Planolites

Two forms, differentiated on the basis of size, of the horizontal burrow *Planolites*, are present in the interbedded sandstone and mudstone facies and the mudstone-sandstone facies at Stump Beach. The larger ones are 0.3 mm to 1.0 cm in diameter, straight to gently curving cylindrical burrows that intersect but do not branch; they are most abundant as horizontal burrows, up to 30 cm long preserved along sandstone/mudstone interfaces, but they also have vertical components (Plate 1H). Maximum penetration depth observed is 20 cm. Burrow fill is typically sandstone, although some is mudstone. Most burrow boundaries are usually well defined, but some are indistinct, imply-

ing that the sediments may have been water saturated. This larger form of Planolites commonly is cut by larger Thalassinoides and Ophiomorpha. It resembles unbranched portions of Thalassinoides and in some cases the distinction between the two is not clear.

The small form of Planolites is a mud-filled burrow approximately 0.5 mm in diameter and 1.0 mm to 2.0 mm in length (Plate 1G). Although predominantly oriented parallel or oblique to bedding, it also has vertical components. Meanders and intersections are common. It occurs in mudstones where it is extremely abundant (30/cm² or more) when present. Commonly the trace is only faintly visible and its visibility is dependent upon a grain-size difference between the burrow fill and matrix. It is almost always cross-cut by the larger form of Planolites.

The small form of Planolites is interpreted as the burrow of a small, vermiform deposit feeder, possibly a polychaete worm, that was exploiting near-surface muds.

Planolites is a well known facies-breaking trace fossil (Seilacher, 1967). It has generally been attributed to the deposit-feeding activity of worm-like animals, although similar traces are reportedly produced by the bivalve Nucula (Piper and Marshall, 1969, p. 603).

Tasselia

Unbranched, cylindrical straight to gently curved cylindrical tubes approximately 1 mm in diameter are assigned to the ichnogenus Tasselia (Plate 1D). The tubes are jointed, with annulations at intervals of 2 to 3 mm; they also have fine transverse markings. In thin section (Plate 1E) three distinct regions are discernable: 1) a dark brown opaque outer wall which surrounds 2) an inner region of well indurated angular silt-sized grains of quartz and feldspar in a finely divided chlorite matrix, and 3) a central region where grains resembling the outer wall, large grains of chlorite, and occasional grains of pyrite are found. Microprobe analysis of the outer wall material and darker grains of the central region suggest that the material is organic.

According to Hantzschel (1975, p. 114), Tasselia normally is preserved in concretions. Because the concretion formation is caused by diagenesis rather than by original behavior, enclosure of the tubes in concretions is not a requisite for assignment of specimens to the ichnogenus. In the German Rancho Formation at Stump Beach the tubes are not in concretions, but rather occur as short segments usually 1 cm or less long (but up to 5 cm in length), oriented in diverse directions on mudstone-sandstone facies. The preservation of Tasselia suggests that the tubes were subjected to varying degrees of post-mortem breakage and transport. The tubes occur in some of the thinner sandstone beds lying along ripple cross-laminae, suggesting that they have been exhumed and transported by bottom currents. The effects of compaction and bioturbation were probably equally important. The tubes occur in the burrows of backfilled Thalassinoides, but not in the fillings of the other trace fossils.

Tasselia may represent the dwelling tubes of pogonopherans (Hantzschel, 1975, p. 114) or polychaete annelids. The case for a pogonopheran origin is compelling, as modern species in the Phylum Pogonophora secrete stiff, annulated chitinous tubes that

are usually oriented vertically in soft muds (Barnes, 1974, p. 679). The slender tubes are small (usually less than 2 mm) and constant in diameter, and much longer than the inhabitants who range from 10 to 85 cm in length. One of the longest species can be 35 cm long and live in a tube up to 1.5 m in length (Hyman, 1959, p. 211). Pogonopherans are unique in lacking a digestive tract. They may subsist on nutrients derived from external digestion of organic particles caught by tentacles extended from the tube (Barnes, 1974, p. 679); if so, they should be considered suspension feeders. Pogonopherans were unknown until the 20th century, due in part to their deep habitat. All live at depths greater than 100 m, and they are widespread, especially along continental slopes (Barnes, 1974, p. 679).

?Chondrites

At Stump Beach this trace consists of straight or gently curved cylindrical burrows 0.3 cm to 1 cm in diameter which branch at angles of 45° or less (Plate 1B). It commonly co-occurs with Planolites in laminated muddy siltstones and mudstones and along sandstone-mudstone interfaces at the bases of sandstone beds of the interbedded sandstone and mudstone facies.

Because the dendritic pattern of branching characteristic of Chondrites has not been found in specimens from Stump Beach, these forms are only tentatively included in the ichnogenus Chondrites. Like Planolites, it is a well known facies-crossing trace (Seilacher, 1964) and considered to have been produced by a vermiform deposit feeder.

Successional Relationships

The order relationships among the major trace makers have been reconstructed from field observations using the frequency of cross-cutting relationships, general patterns of co-occurrence and distribution, and inferred life-style of the organisms responsible for the traces. A relatively simple conceptual model, based on the periodic influx of new sediment by turbidity currents and the re-colonization by the infauna is summarized in Figure 6. The model is internally consistent, and accounts for most of the observed field relationships.

The model commences with passage of a turbidity current which erodes the underlying pelagic layer and deposits a layer of graded sand with a parallel laminated silty top (Bouma A B). Following this event, small Thalassinoides producers appear to have been among the first organisms to become established along with the producers of the large form of Planolites and ?Chondrites (Figure 6). All three of these ichnogenes show a preference for the thinly-laminated siltstone and mudstone at the top of the underlying sandstone and are especially abundant along sandstone-mudstone interfaces. The small Thalassinoides are attributed to burrowing juvenile thalassinid crustaceans, which excavated open burrow networks, and the Planolites and ?Chondrites possibly to burrowing polychaetes, or other worm-like animals that ingested the sediment. With continued pelagic sedimentation and the accumulation of a surface-mud layer, producers of Tasselia, probably tube-dwelling suspension feeders, and of the small form of Planolites became established (Figure 6). This appears to have been contemporaneous with the establishment of Ophiomorpha and the larger Thalassinoides, both forms attributed to thalassinacean crustaceans. The large open burrow systems generally cross-cut Planolites, ?Chondrites, and small

Thalassinoides and penetrate to the bases of most beds. Some backfilled Thalassinoides were also produced in this stage incorporating broken tubes of Tasselia, and were cut by the open burrow forms of Thalassinoides and Ophiomorpha. These ichnogenera were probably produced by the same organism which produced a thick mammillate burrow lining in coarser grained sediments and a thinly lined burrow in finer grained sediments.

With the passage of another turbidity current, the pelagic layer was eroded and the dwelling tubes of Tasselia exhumed, broken, and transported. (Figure 15c) The deposition of another sand layer would result in the filling of the open burrow systems of Thalassinoides and Ophiomorpha with sand from the overlying turbidite. In some cases this may have led to the creation of spreiten-filled Thalassinoides and Teichichnus as buried organisms escaped to the surface. The maximum escape depths for thalassinid shrimp are not specifically known. However, Miller (1977) found a 59% recovery of Callianassa californiensis burrow openings 75 hours after burial by 16 cm of sediment.

DISCUSSION

The trace fossil assemblage of the German Rancho Formation at Stump Beach shares many interesting similarities with ichnofaunas described from other deep water submarine fan deposits. Perhaps the most significant observation to emerge from previous studies is that several ichnogenera, traditionally considered important bathymetric indicators of littoral to sublittoral depths, are now known to be common bathyal depths in areas of active turbidite sedimentation.

Kern and Warme (1974) were the first to report Ophiomorpha and Thalassinoides from bathyal depths where they occur in the deep-sea fan deposits of the Upper Cretaceous Point Loma Formation. Significantly, in this and subsequent studies, to describe "shallow water" ichnofaunas from deep water environments, the paleoenvironmental framework was established independently using sedimentological criteria. Hayward (1976) reported an occurrence of mid-bathyal (100 to 3000 m.) Thalassinoides from lower Miocene deep sea fan deposits in New Zealand. Crimes (1978, p. 75) identified eight ichnogenera normally considered to be shallow water forms, from bathyal mid-fan lithofacies of an Eocene deep-sea fan succession in northern Spain. In the distal areas of the outer fan, the total number of shallow water traces declined progressively, being replaced by a more typically deep water assemblage. Ksiazkiewicz (1970) and Crimes (1970) also showed changes in the ethological character of trace fossil assemblages along proximal to distal gradients in deep water turbidites. In more proximal environments, spreiten traces dominated, whereas in progressively more distal areas, meandering, spiral, and patterned forms became most common. Crimes (1978, p. 78) suggested that there is preferential preservation of infaunal burrows in proximal and mid-fan environments, due to the loss of surface and near-surface traces by erosion. In conjunction with this, the buildup of organic rich muds in distal environments probably favors surface grazers and shallow deposit feeders, thus strengthening the trend.

Knowledge of the biology of modern deep sea fan environments is limited. However, Piper and Marshall (1969) described the biogenic structures produced by an infaunal community dominated by polychaete worms, bivalved molluscs, echinoids, and ophiuroids in the Holocene La Jolla deep-sea fan off southern California. They note that the highest population densities of burrowing organisms were attained on the marginal slopes of the channel valley (levee), and the lowest densities, within the channel and open fan (interchannel) areas. This provides an interesting parallel with trends observed in what are inferred to be the same facies in the German Rancho Formation. The greatest diversity of trace fossils is found in the interbedded sandstone and mudstone facies interpreted as levee deposits south of Stump Beach Cove (Location A, Fig. 3) whereas very few trace fossils occur in the associated channel deposits. The interchannel turbidites exposed at the north end of Stump Beach have a diversity lower than the levee turbidites, owing to the absence of Ophiomorpha and Thalassinoides which seem to prefer coarser, sandier substrates.

The major conclusion of this and previous studies of deep sea fan ichnocoenoses is that the bathymetric classification of Seilacher (1964, 1967) is a broad generalization and should be applied in conjunction with other sedimentological and paleontological criteria when determining depth. As Seilacher (1978, p. 194) has stated: "Water depth, by itself, is not a

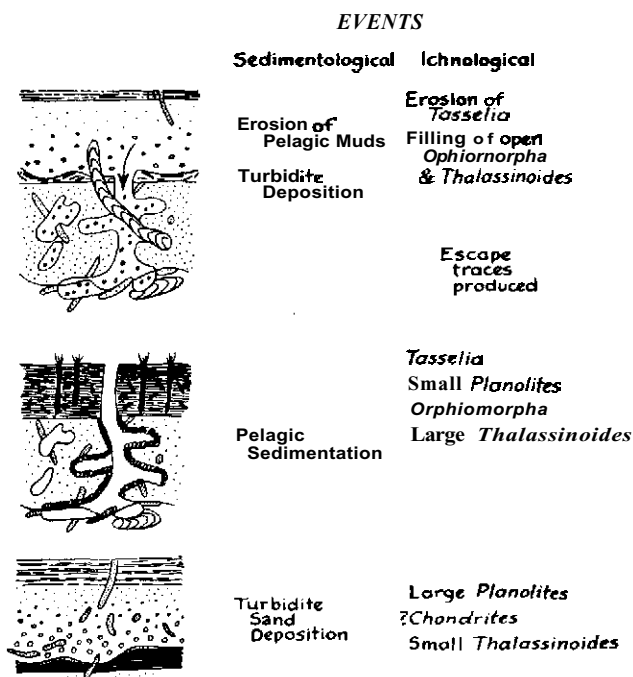


Figure 6. Successional relationships among major trace makers.

major ecological factor, but other more important parameters, such as turbulence, sedimentation rates and processes, diagenetic processes, productivity and evolutionary processes, are in one way or another depth related."

The distribution of deep sea fan and channel-margin faunas and the resulting ichnofaunas are closely related to substrate characteristics. In these environments where rates of sedimentation and grain size are locally increased and the organic content of the sediment is lower, substrate conditions converge on those more typical of shallow-water environments, resulting in a predominance of the traces of the shallow-water Skolithos and Cruziana ichnofacies.

The more detailed characteristics of the substrate, such as its mass properties, stability, microtopography, and nutrient content, also appear to be important in determining the diversity and behavior of the benthos (see Rhodes, 1974). When abundant, the organisms themselves may contribute significantly to conditioning the substrate in ways that affect all of the above. Neobiological studies have much to offer in improving our understanding of the importance of such factors in the stratigraphic record. The role of biological processes is vital to the interpretation of the post-depositional and diagenetic history of sediments, and qualifies as an important area for future research.

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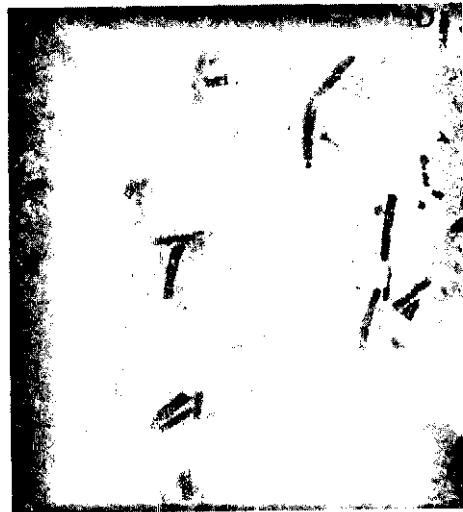
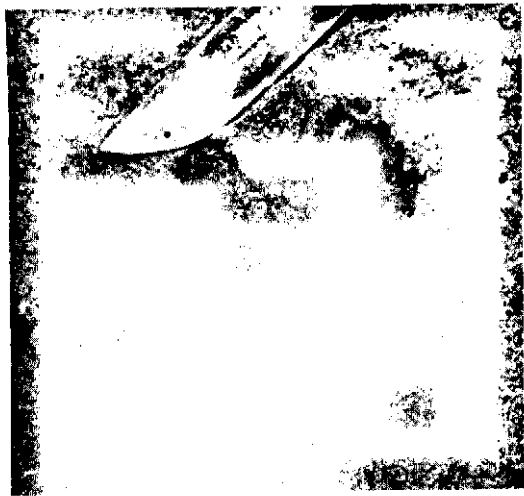
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Plate 1. All illustrated specimens are from interbedded sandstone and mudstone facies at Location A (Fig. 3).

- A. Ophiomorpha on top of sandstone bed. Note pustulose burrow wall.
- B. ?Chondrites at top of sandstone bed. Burrow diameter is approximately 1.5 cm.
- C. Knife blade is touching burrow lining of Thalassinoides on upper surface of sandstone bed.
- D. Fragments of Tasselia in mudstone. Tubes are approximately 1 mm in diameter.
- E. Transverse section of Tasselia as seen in thin section under plane polarized light. Tube is approximately 1 mm wide in long dimension.
- F. Back-filled Thalassinoides on upper surface of sandstone bed. Burrow is approximately 2 cm wide.
- G. Small form of Planolites in thin mudstone layer. Burrows 1 mm in diameter or less.
- H. Large form of Planolites at top of sandstone bed.

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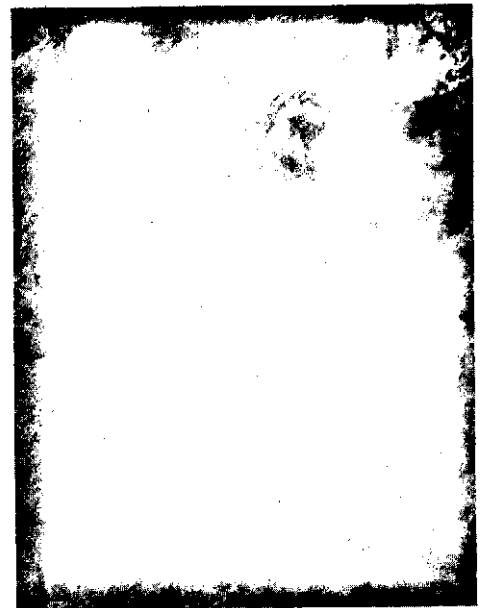
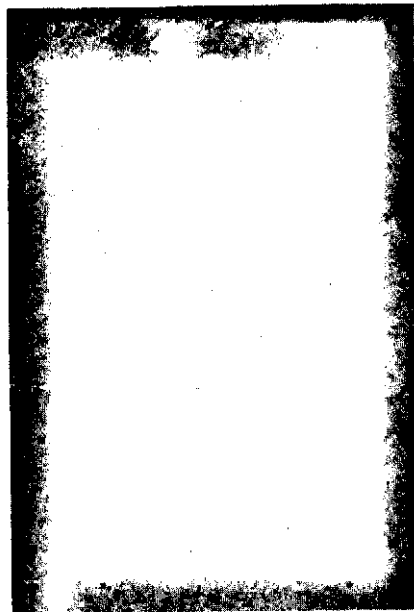
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