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Nested Submarine-Fan Channels in the Capistrano Formation, San Clemente, California

ROGER G. WALKER *Department of Geology, McMaster University, Hamilton, Ontario L8S 4M1, Canada*

ABSTRACT

At San Clemente State Beach, eight turbidite-filled channels are exposed in a 550-m-long, 30-m-high sea cliff. The channel margins show a progressive northwestward lateral shift in position and thus are nested one alongside another. Three adjacent channels trend between 270° and 300°, with west-northwest turbidity-current flow. Four other adjacent channels trend between 230° and 240°, with southwest flow. Seven of the eight channels received mud and silt deposits in the form of a drape over the channel walls before deposition of graded sand beds took place. In some channels, these graded beds belong to the "classical" turbidite facies, but in others, the sandstone deposits are pebbly, beds are thick, and interbeds of shale are thin to absent. In three of the channels, there is an overall upward fining and thinning of beds, implying progressive channel abandonment. By contrast, the beds filling one channel become coarser and thicker upward, implying a prograding turbidite lobe. The channels are assigned to the braided suprafan part of the submarine-fan model. *Key words: turbidite, Miocene.*

INTRODUCTION AND OBJECTIVES

At San Clemente State Beach, there is a series of nested channels cutting into bioturbated and diatomaceous mudstone and filled by "classical" turbidites, massive sandstone, and pebbly sandstone. The locality is well known because many field excursions have stopped there, yet there is no detailed published description of the cliff face illustrating each channel, nor is there any published interpretation of the channels in light of recent advances in the development of submarine-fan models of turbidite deposition (Normark, 1970, 1974; Mutti and Ghibaudo, 1972; Walker and Mutti, 1973; Mutti, 1974; Nelson and Nilsen, 1974; Walker, 1975). This paper examines the geometry of the channels and relates it to the type of turbidites that fill the channels. This can best be done by illustrating the cliff face in detail (Fig. 1), producing as a by-product a field guide to the area that is more detailed than that published by Weser (1971). A guide is particularly useful at San Clemente, because much of the interest lies in the multiple nested channels, and it is difficult to appreciate the mutual relationships of these channels on a first visit without a guide.

The sedimentary deposits at San Clemente are assigned to the lower part of the Capistrano Formation and are late Miocene (late Mohnian) in age. The Capistrano Formation is about 525 m thick, of which only 15 m is exposed at San Clemente State Beach (Bergen, 1971, p. 11). The upper part of the cliffs is composed of Pleistocene terrace deposits, consisting of cross-bedded and imbricated gravels at the base which grade up through sandstone into bioturbated mudstone at the cliff top.

The part of the section with nested channels trends southeastward from the car park (Fig. 2), taken as zero datum on my measured section (Fig. 1). The reference line, both horizontally and vertically, is the Santa Fe Railroad track (Fig. 1). Northwest of the car park, the cliff lacks deep nested channels, although much local scouring is present. About 300 m to the northwest, the cliff becomes much lower, and the presence of houses ruins the outcrop for detailed sedimentology. Consequently, my description applies to the 600-m section southeast of the car park. Distances refer to meters southeast of the car park (Fig. 1).

For a more general guide to the Newport Lagoon–San Clemente area, see the guidebook by Bergen and others (1971). It contains a guide to the San Clemente area by Weser (1971), a paper on deep-sea fan minitopography by Normark (1971), and papers on the adjacent Dana Point outcrop by Piper (1971), Bartow (1971), White (1971), and Ingle (1971).

DESCRIPTION OF NESTED CHANNELS

The first channel in the sequence of eight nested channels is about 500 m southeast of the car park. From the 500-m point, the channels shift progressively laterally toward the northwest, with no preserved evidence of switching back toward the southeast. Most are fairly obvious in the cliff, although the quality of outcrop has been deteriorating during the past five years. Individually numbered channels are shown in Figure 1.

Prechannel Sedimentation

From the 500-m point southeastward, prechannel sedimentary deposits are exposed in the cliff. They consist dominantly of highly bioturbated mudstone but contain one prominent zone 5 to 6 m above datum (Fig. 1) in which there are five or six thin, graded sandstone beds interpreted as turbidites. In the gully at 700 m, ripple crests can be seen in plan view, indicating paleoflow directions of 230°, 245°, and 265° (Table 1) for these turbidity currents. The most prominent bed in this group is calcareous and deformed into small folds (at 500 m) that die out southeastward in the direction of thinning of the bed.

Channel 1

This channel is very poorly exposed because of an extensive wash of mud over the cliff face (Fig. 3). No strike could be measured on the channel wall, and it is the only channel wall that does not have a mudstone-siltstone drape. The average inclination of the wall as seen in outcrop is about 18°. The fill of the channel is also poorly exposed, but it appears to consist mainly of classical turbidites (as defined in the facies scheme of Walker and Mutti, 1973, p. 132) in graded beds some 10 to 60 cm thick. Individual beds thin out against the channel wall. In the thinner beds, the maximum grain size is about 1 mm, but the thicker beds contain pebbles as much as 1 cm in diameter. The mudstones between individual sandstones are extensively bioturbated.

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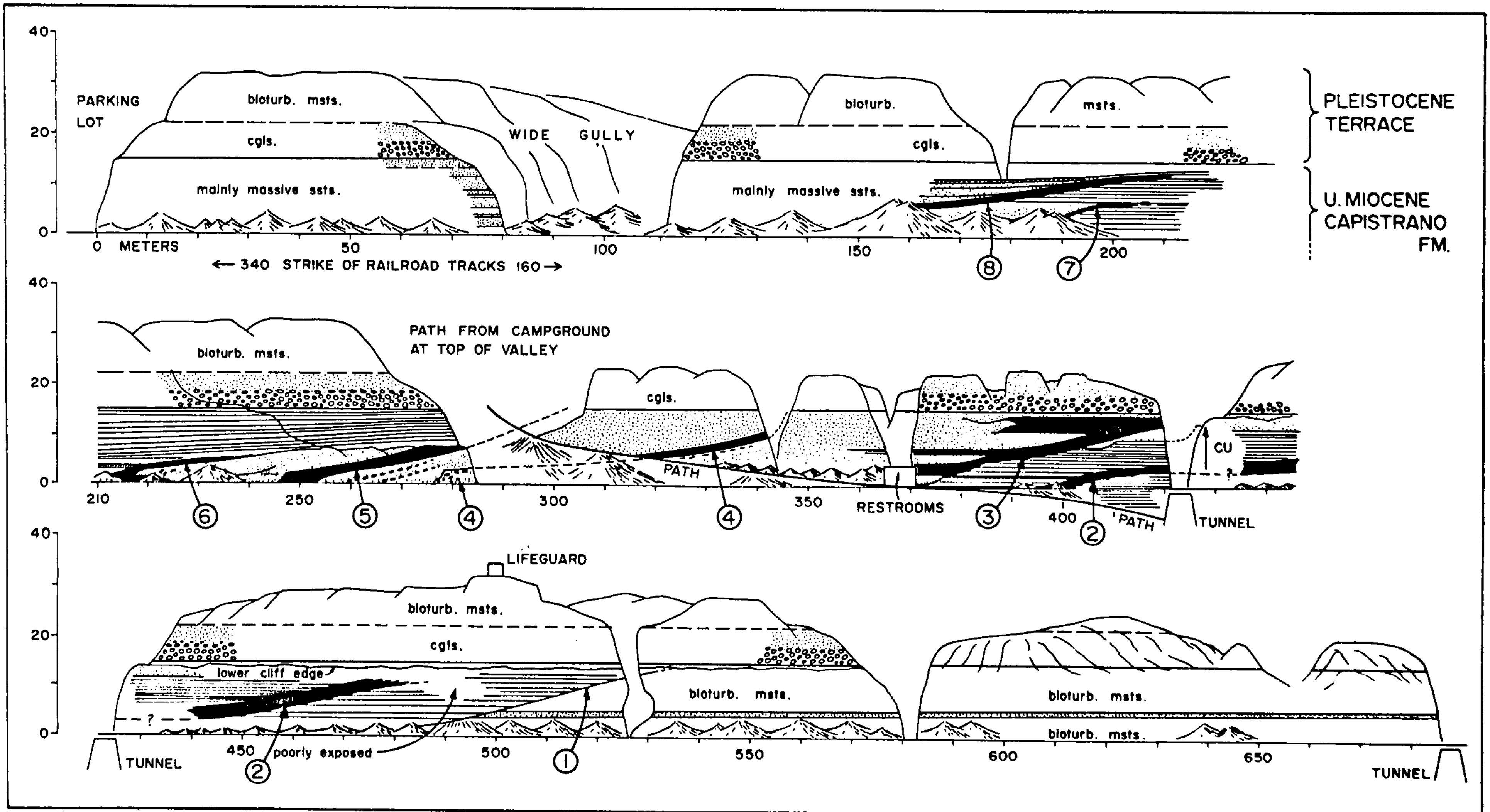

Figure 1. Cliff section at San Clemente, southeast of car park. Reference level is railroad track, which strikes 340° to 160°. Circled numbers indicate individual channels (discussed in text).

Some of the best exposures of the turbidites in channel 1 can be seen at 420 m, in the cliff face. Well-developed ripple-drift cross-lamination indicates a flow direction toward 300° (northwest).

Channel 2

This channel (Fig. 4) cuts out the fill of channel 1 and represents a northwestward shift of channel position of about 40 to 100 m, the distance depending on where the wall of channel 2 is measured. The main part of the cut can be seen between 400 and 470 m (Fig. 1); at 440 m it seems to flatten out into bedding, and what I interpret as the same cut reappears at 420 m and cuts downward to the 400-m point, where the exposure of the channel wall ends. At both places, the channel wall has a thick (1.20- to 2.0-m) drape of dark-gray to black clay and irregularly bedded silty mudstone. Bedding in the drape is parallel to the channel wall (Fig. 5), which has a maximum apparent dip of 18° and averages between 12° and 15°.

The strikes of the channel walls shown in Table 1 were obtained by carefully digging away some of the sandstone layers that had been truncated by the channels, creating a small "cave" below the overhanging mudstone-siltstone drape. A notebook was pressed against this overhang to even out the irregularities, and the dip and strike of the notebook were recorded. This procedure is admittedly not very accurate, but one fact that gives a little confidence in the results is the grouping of readings apparent in Table 1: channels 2, 3, and 4 trend between 270° and 300°, and channels 5 through 8 trend between 230° and 240°.

Channel 2 strikes 270° at 450 m in the section, and two readings at 420 m indicated strikes of 270° and somewhere between 275° and 300°. Below the lifeguard station at 500 m, the channel wall begins to flatten out and approach bedding, but poor exposure in November 1973 and February 1974 made the upper margin of the channel uncertain.

The fill of channel 2 consists of mudstone and thin turbidites at the base, but passes upward into thicker and coarser grained beds.

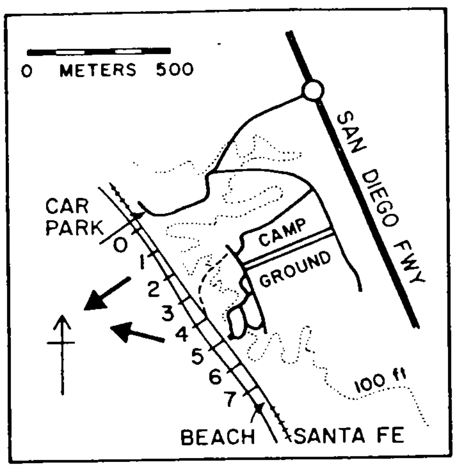

Figure 2. San Clemente State Beach and campground can be reached from San Diego Freeway, south of town of San Clemente, using exits marked "San Clemente State Beach." Numbers along coast are in hundreds of meters southeast of car park and correspond to numbering in Figure 1. Dashed line from campground to coast at 370 m above railroad track is footpath; black square at 500 m is cliff-top lifeguard station. Heavy arrows indicate generalized paleocurrent directions for channels 2, 3, and 4 (southern arrow) and 5, 6, 7, and 8 (northern arrow).

Figure 3. Channel 1 (arrow) cutting into bioturbated mudstone. Horizontal deformed bed is limestone, together with a few thin, graded sandstones (see Fig. 1 and text).

TABLE 1. SUMMARY OF CHANNELS AT SAN CLEMENTE

Channel	Trend of wall (°)	Other paleocurrent indicators (°)	Wall inclination (°)	Drape, thickness (m) and nature	Nature of fill	Shift in position (m)
Prechannel beds		230* 245* 265*				
1	?	300 (ripples within fill)	18	None	Turbidites, 10- to 60-cm beds	40 to 100
2	270 275 to 300		18 (max) 12 to 15	1.20 to 2.00; dark-gray, black clay; silty mudstone	Coarsening-upward turbidites, beds 5 to 10 cm (base) to 20+ cm (top)	20 to 60
3	285		12	1.80; laminated siltstone, tough brown clay	Massive sandstone, pebbly sandstone (see Fig. 9)	60
4	295	295 (strike of conglomerates)	16	1.20; laminated siltstone, lumpy and bedded clay	Very massive sandstone and pebbly sandstone	20 to 50
5	240		5	1.00 siltstone, thin, very fine sandstone	Thinning- and fining-upward, massive sandstone to classical turbidites	40
6	240		<5 (max 20)	0.30; brown and black silty mudstone	Classical turbidites, 20-cm beds thinning upward	40
7	235		15 max	0.75; mudstone, lenticular sandstone	Massive sandstone, thinning up into classical turbidites	20
8	230, 235		18	1.40; black and brown clay	Massive sandstone and classical turbidites (see Fig. 9)	

Note: Channels 2, 3, and 4 have similar trends (270° to 300°). Channels 5, 6, 7, and 8 have similar trends (230° to 240°).

* Ripple crests on turbidites within bioturbated mudstones (see Fig. 1).

This sequence of thickening and coarsening upward (Fig. 6) has been recognized in many other turbidite formations (see especially Mutti and Ghibaudo, 1972) and will be discussed again later. The sequence is 10 to 12 m thick and begins within the mudstone-siltstone drape; the first graded beds are 5 to 10 cm thick, thickening to 20+ cm in the upper part of the sequence. The top is cut out by a pebbly sandstone bed that rests within a small scour of 2- to 3-m total depth. In the northwest-facing wall of the gully at 420 m, where the coarsening-upward sequence is best seen (Fig. 6) the scour is about 1 m deep.

Channel 3

The thickening- and coarsening-upward sequence filling channel 2 is abruptly truncated by channel 3 (Fig. 7). Channel position shifted 20 to 60 m northwestward, depending upon where the wall of channel 2 is measured. Neither the top nor the bottom of the cut is exposed; the top was apparently truncated by the Pleistocene terrace. The inclination of the channel wall is about 12°, and the strike at 380 m is 285°. The channel margin can also be seen in the upper part of the gully at 420 m, and a rough sighting across the gully gave a channel-wall strike of 255°.

The mudstone-siltstone drape covering the channel wall averages about 1.80 m thick and consists of laminated siltstone and clay bedded parallel to the channel wall, together with very fine grained tough brown clay (Fig. 8). As well as lining the channel wall, the drape appears within the channel at at least two higher levels, indicating pauses in sand filling. The uppermost mudstone-siltstone drape can be seen to be truncated by massive sandstone (just below the Pleistocene terrace at 390 m), and the lower drape also dies out northwestward.

A complete sequence was measured through the fill of channel 3, beginning immediately southeast of the restrooms (at 370 m) and continuing up the steep gully behind the restrooms (Fig. 9). The lowermost beds are sandy (1.0 to 2.80 m; Fig. 9) and cut into the fill of channel 2 (which is just visible at path level; Fig. 1). The drape of channel 3 appears between 2.80 and 4.60 m (Fig. 9). Sandstones above the drape range from 20 cm to 1.75 m thick (Fig. 10); the second drape (6.65 to 7.25 m; Fig. 9) consists of thin graded sandstone passing up into mudstone, with thinning of sandstone

Figure 4. Channel 2, arrows showing base of mudstone-siltstone drape. Lower part of fill consists mainly of siltstone that climbs wall above drape (above notebook). Siltstone forms lower part of coarsening-upward fill of channel 2 (see Fig. 6). Upper sandier turbidites thin out against channel wall.

Figure 5. Mudstone-siltstone drape of channel 2 cutting erosively across laminated fine sandstone and clay of channel 1 fill. Many of these clay layers now consist of isolated clasts; they were probably deposited that way, although disruption in situ (bioturbation) is possible. Dark bars on notebook each 5 cm long.

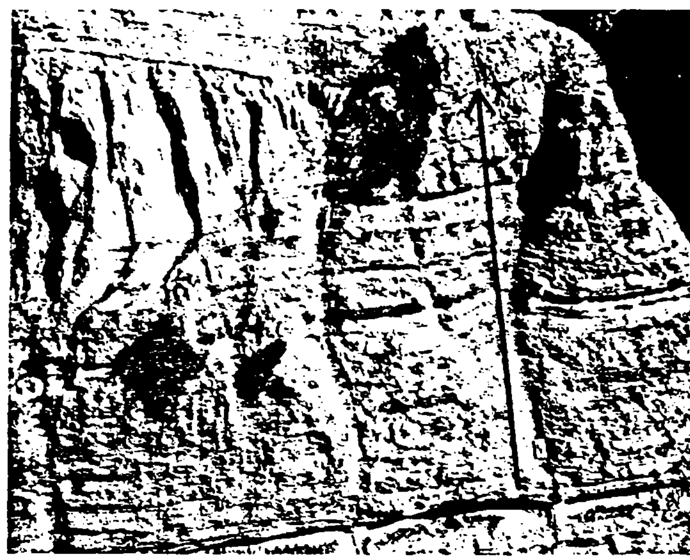

Figure 6. Thickening- and coarsening-upward sequence (arrow) as part of channel 2 fill, in gully at 425 m (Fig. 1). Sequence begins at level of notebook and ends about at level of dark vegetation, top center. Sequence is partly eroded by massive sandstone in scour to left of arrowhead.

Figure 7. Channel 3, with arrow showing base of mudstone-siltstone drape. Note truncation of sandstone (channel 2 fill, to right) by drape, and pinching-out of channel 3 sandstone against drape.

and thickening of mudstone southeastward toward the channel margin. The upper part of the fill is dominantly sandstone and pebbly sandstone in beds roughly 50 cm to 1.10 m thick. Grading is prominent, with pebbles as much as 2 cm in diameter in the lower parts of the beds. Within this sequence, channeling (Figs. 9, 11) is present, with a depth of scouring of at least 2 m.

Channel 4

The fill of channel 3 is truncated by channel 4, representing a northwestward shift in channel position of about 60 m. Neither the top nor the bottom of channel 4 is exposed; the top is truncated by the Pleistocene terrace. At 330 m, the channel is well exposed adjacent to the path down from the campground, and the wall is inclined at about 16°. It steepens to subvertical around the corner in a small gully at 345 m and flattens out northwestward before cutting down sharply again at 280 m. The strike of the channel wall is about 295°.

The nature of the fill of channel 4 is different from that of any of the other channels. In the small gully at 345 m, the lowermost fill consists of a jumble of large (as long as 50 cm) mud clasts. The clasts can also be seen between 320 and 340 m, along the path, below the prominent mudstone-siltstone drape in a zone about 1.30 m thick. It may be necessary to clean off the face below the mudstone drape to see the clasts; the lower contact between the jumbled clasts in a sandy matrix and the massive sand fill of channel 3 is rather vague (shown by a dotted line in Fig. 1). At 280 m, the same type of contact is seen (Fig. 11), with large clasts of laminated gray silty clay up to 1 m long jumbled in a matrix of very coarse sandstone and gravel (clasts as much as 3 cm in diameter). The large silty clay clasts are unlike any part of the fill of channel 3 and must have more than an immediately local derivation.

Above the clasts along the path (320 to 340 m), there is a prominent mudstone-siltstone drape (Fig. 12) about 1.20 m thick, consisting of gray clay partly broken into small (2- to 10-cm) lumps in a sandy matrix and partly bedded parallel to the channel wall. In this drape, the clay and siltstone layers are roughly in equal proportion with sandier layers, making this drape the sandiest at San Clemente.

The fill of channel 4 above the path consists of thickly bedded graded pebbly sandstone with amalgamation and loading between beds and no interbedded fines. As indicated in Figure 1, this pebbly sandstone must be cut out by channel 5 somewhere in the wide gully that runs up to the campground. The fill of channel 4 between 260 and 280 m consists of two beds that grade from conglomeratic bases to sandy tops (Fig. 13). The lower bed has a maximum clast size of about 20 cm; the mean of the 10 largest clasts is 15 cm. It grades both vertically (Fig. 14) and laterally (southeastward) into pebbly sandstone and massive sandstone, and the strike of the base is 295°, parallel to the wall of channel 4. Both conglomerate beds

Figure 8. Detail of drape of channel 3, showing laminated siltstone grading up into clay; graded units shown by arrows. Some of silty layers are slightly burrowed (top center). Dark bars on notebook each 5 cm long.

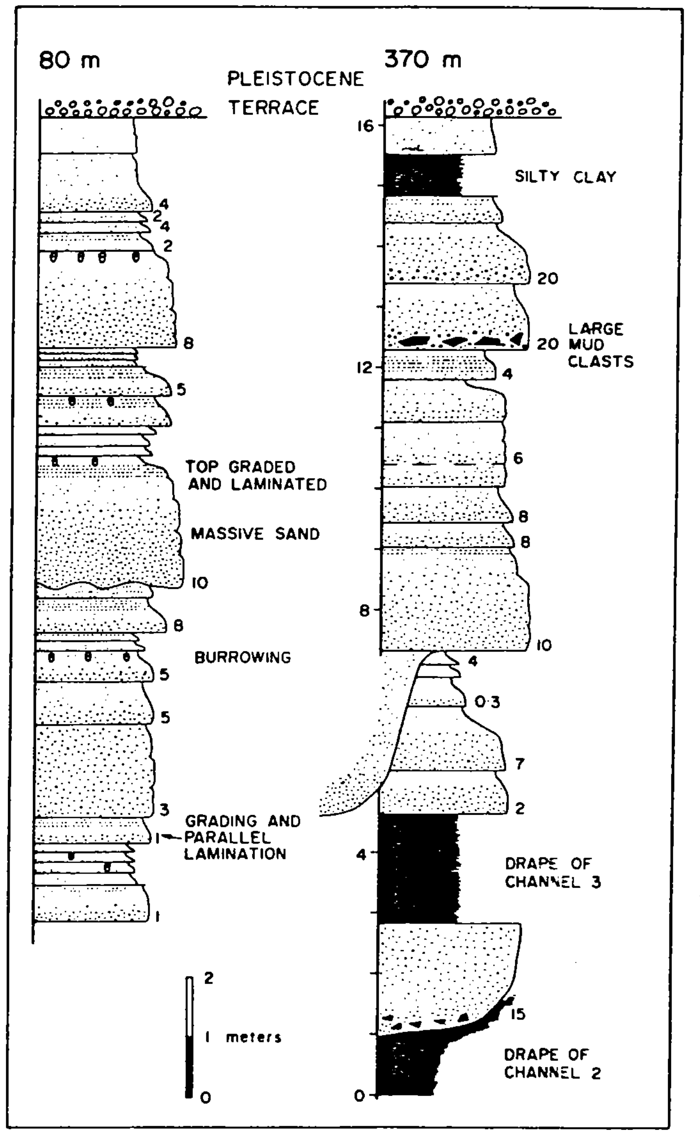

Figure 9. Two typical measured sections through fills of channels 3 (at 370 m, gully behind restrooms) and 8 (steep gully at 80 m). Numbers by bases of beds indicate approximate maximum grain sizes in millimeters. Lowest silty clay below restrooms appears to be continuation of drape of channel 2.

have an initial dip of 9° to the north — they are the only beds in the whole section that show an initial dip, other than the mudstone-siltstone drapes.

Channel 5

The erosion surface of channel 5 slightly truncates the upper of the two dipping conglomerates that fill channel 4 (Fig. 13). This erosion surface must continue as shown by the dotted line in Figure 1, truncating the massive sandstone that fills channel 4, and thus accounting for the change from classical turbidites below the Pleistocene terrace at 270 m to massive pebbly sandstone at 310 m.

Neither the top nor the bottom of channel 5 is seen. The inclination of the channel wall is about 5°, and the strike is 240°. This strike represents a change from that of channels 2, 3, and 4 (270° to 300°). The shift in channel position, 4 to 5, is about 20 to 50 m northwestward, depending on where the wall of channel 4 is measured.

The drape covering channel 5 is about 1 m thick. The lower silty layers are bedded parallel to the channel wall, as are the thin sandy layers that appear in the upper part of the drape. At about 8 to 9 m above the railroad tracks, there is a low cliff, and the drape appears to flatten out into regional bedding at this cliff edge. Above the clif edge, the classical turbidites that fill channel 6 sweep across th massive sandstone and drape of channel 5 (Fig. 13). This massiv sandstone, which forms most of the fill of channel 5, dies ou against the drape, except at the base of the cliff (245 m), where i channels into the drape. This sandstone is only 8 m thick and i overlain by the drape of channel 6, implying that channel 5 was no completely filled (to Pleistocene terrace level, 15 m above the railroad tracks) before channel shifting took place, covering the lowe 8 m of fill with another drape.

Figure 10. Internal scouring between massive and pebbly sandstones; part of fill of channel 3 in gully behind restrooms (at 370 m; see Fig. 9). Dark bars on notebook each 5 cm. Cobbles at lower left have been washed down gully from Pleistocene terrace.

Figure 11. Margin (arrow) of channel 4 at 280 m (Fig. 1). Note large mud clasts irregularly bedded within coarse and pebbly sandstone within channel. Dark bars on notebook each 5 cm long.

Channel 6

Channel 6 (Fig. 15) represents a 40-m shift in position northwestward from the position of channel 5. The bottom of the channel is not visible, but the top represents a gradual flattening of the channel wall until it merges with regional bedding. The maximum inclination of the wall is about 20°, but it is mostly less than 5°. The strike is 240°, the same as channel 5.

The lowermost drape of channel 6 is 30 cm thick, comprising unstratified brown and black silty mudstone. The drape thickens higher up the channel wall as additional layers of siltstone from within the channel fill amalgamate onto the drape (Fig. 15).

The main fill consists of classical turbidites — graded beds of coarse sandstone passing upward into siltstone. The sandstone pinches out spectacularly against the drape in the lower part of the channel, filling it to its banks (Fig. 15). Higher, the turbidites pass across the channel wall and across the drape of channel 5, indicating a temporarily nonchanneled depositional environment. These are some of the thinnest bedded turbidites in the section, with indi-

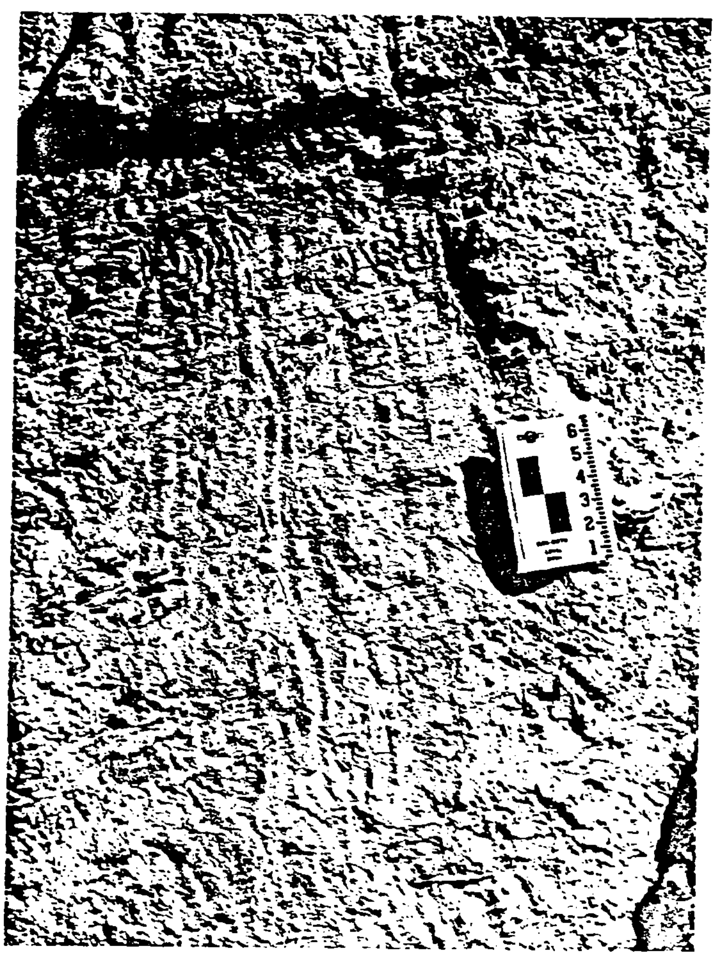

Figure 12. Drape of channel 4, above path at 330 m (Fig. 1). Note crude alternations of sandy and clayey layers, with much of clay existing as irregular lumps rather than continuous layers. Dark bars on notebook each 5 cm long.

vidual sandstone-siltstone couplets rarely exceeding 20 cm. In the highest part of the cliff, at 220 m, the turbidites are even thinner and appear to be related to the filling of channel 7 (Figs. 1, 15).

Channel 7

This channel (Fig. 16) represents a northwestward shift in position of about 40 m from channel 6. The bottom of the channel is not seen; upward, the inclination of the channel dies out from a maximum of 15° to 0° as the channel margin approaches bedding. The strike of the channel wall is 235°, very close to the 240° strikes of channels 5 and 6.

The drape of channel 7 is about 75 cm thick, consisting of interbedded mud and lenticular sandstone. Bedding in the drape is parallel to the channel wall, flattening upward and passing into regional bedding. Unlike any of the other channel margins, the sandstone immediately underlying the drape of channel 7 has been reworked to a depth of about 15 cm to conform to the dip of the channel wall. In all other channels, the underlying sandstones are abruptly truncated.

The lower part of the fill consists of massive sandstone beds as much as 1 m thick, with maximum basal grain size of 4 to 6 mm. Bouma sequences are present, particularly in one 1-m bed that shows divisions A, B, and C (in the form of ripple-drift cross-lamination). These massive beds are truncated by channel 8, but farther to the southeast, the upper part of the fill of channel 7 high in the cliff appears to consist of much thinner bedded turbidites with thicker interbedded mudstone. Thus the fill of channel 7 is a thinning-upward (and probably fining-upward) sequence, and the uppermost turbidity currents flowed across the tops of channels 7 and 6, finally dying out against channel 5 (Figs. 1, 13, 16). This suggests that channels 6 and 7 are relatively minor cuts within an overall deeper channel (5) that was finally filled only after channels 6 and 7 had been obliterated.

Channel 8

This channel (Fig. 17) represents a shift in position of about 20 m northwestward from channel 7, or a shift of about 100 m from the position of channel 5. The base of the channel is not seen, and the drape, although beginning to flatten out at the cliff top, is apparently cut off by the Pleistocene terrace. Maximum channel-wall inclination is about 18°, and the strike is between 230° and 235°.

The drape is prominent, as much as 1.40 m thick, and consists of black and brown tough clays interbedded with silty clay. Bedding is parallel to the channel margin (Fig. 18).

At 170 m, the fill appears to become thicker bedded upward. The lower beds are turbidites ranging in thickness from 10 to 20 cm. They climb up the channel margin for a vertical height of 1 m or so before becoming finer grained and finally merging with the drape (Fig. 17). As these beds climb toward the channel margin, the interbedded mudstones tend to thin out. The upper part of the fill is a much thicker bedded sequence of sandstones with fewer and thinner interbedded mudstones. These beds pinch out against the drape, without climbing up the margin as far as the lower beds. At the cliff top, just below the Pleistocene terrace, the turbidites become thinner bedded again (Fig. 17).

Nonchanneled Beds, 0 to 150 M

The section from the car park to 150 m shows mostly parallel-bedded thick sandstone and interbedded siltstone. The section can be seen easily in the wide gully at 100 m, where more bedding irregularity is apparent than in the main cliff face. A typical section measured up the steep gully at 80 m is shown in Figure 9.

Irregularly Bedded Sandstone Northwest of Car Park

The section northwest of the car park consists of a high cliff about 300 m long, exposing irregularly bedded pebbly sandstone. Scouring to a depth of several meters is common, as is amalgama-

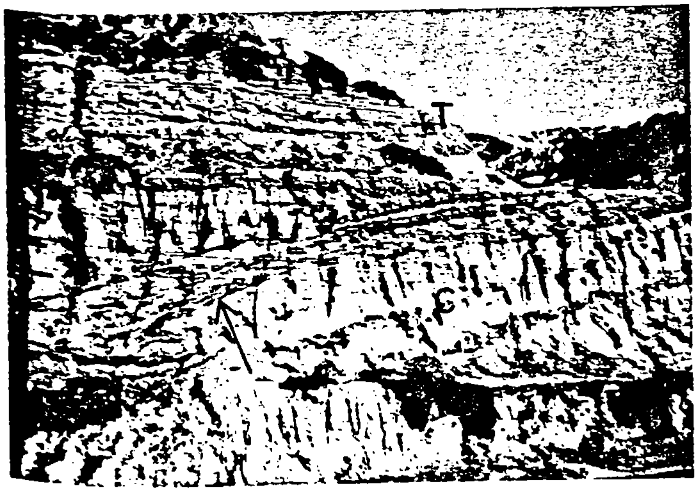

Figure 13. Channel 5, arrow showing base of drape. Below channel, fill of channel 4 consists of graded conglomerates with an initial northward dip (C). Lower massive sandstone of channel 5 dies out against drape (level of top of telephone pole), but higher in cliff, classical turbidites (T) are evenly bedded and probably represent beds belonging to fills of channels 6 and 7 (...

Figure 14. Detail of grading in two conglomerates shown in Figure 13. Contact between upper conglomerate and mudstone-siltstone drape of channel 5 appears gradational in this photograph, although it can be seen to be erosional in Figure 13. Dark bars on notebook each 5 cm long. Northward dip of conglomerates is original depositional dip; camera was held horizontal in regional bedding.

tion of successive pebbly sandstone beds to form thick composite beds. Interbedded siltstone tends to be thin and laterally impersistent. Bouma sequences are rare, and well-developed graded bedding is much less common than southeast of the car park. In the bases of some of the coarser units, clast sizes are estimated to reach 20 to 30 cm; the cliff is mostly inaccessible for detailed measurements. Northwest of this high cliff, houses come down almost to beach level, and the section becomes unsuitable for detailed sedimentology. The coarse sandstone and gravel are truncated northwestward by a channel (Weser, 1971, Pl. XI–A), and the beds exposed along the coastal highway between San Clemente and Dana Point consist predominantly of diatomaceous mudstone.

DISCUSSION

The detailed descriptions highlight four general problems: (1) Are the channels unrelated, or do they fall into distinct groups? What controls the apparent northwestward shift in position? (2) Do the mudstone-siltstone drapes represent channel abandonme after cutting? (3) What relationship is there between chann geometry, nature of the fill, and development of fining- (thinning upward and coarsening- (thickening-) upward sequences? (4) Ho can the channel system be fitted into the submarine-fan model as is now understood?

Figure 15. Channel 6, arrow showing base of drape. Note that lower sandstone thins toward drape and passes laterally into mudstone and siltstone of the drape (to right of A). Behind uppermost telephone wires, turbidites can be seen to pass across top of drape, and most of turbidites (T) in photograph were probably deposited on a smooth, nonchanneled surface.

Channel Grouping and Shifting

The San Clemente channels fall into two groups with respect t paleocurrent trend: channels 2 through 4 trend between 270° an 300°, and channels 5 through 8 trend between 230° and 240°.

Channels 1 through 4 show other similarities that suggest the are genetically related. The walls all have a similar dip (12° to 18' Table 1), and the mudstone-siltstone drapes are relatively thic (1.20 to 2.0 m; Table 1). The channel fills appear to become pro gressively more massive, from the poorly exposed but relativel silty fill of channel 1 through the sandier classical turbidite fill o channel 2 to the massive sandstone fills of channels 3 and 4 (witl channel 3 having more silty interbeds between the sandstones tha channel 4). Channel shifting has thus resulted in progressivel sandier fills, and it is also noticeable that the largest intraclasts ar associated with the most massive sandstone fill in channel (Fig. 11).

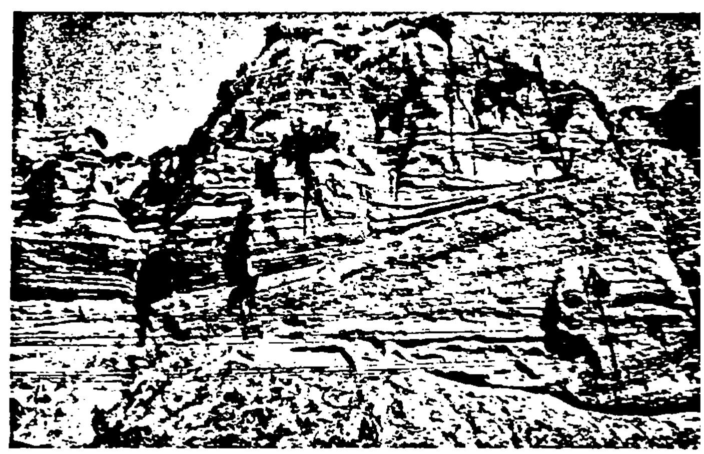

Figure 17. Channel 8, arrows showing drape. Note horizontal bed within channel (left) and slight tendency for them to climb up channel wall thinning and passing into drape.

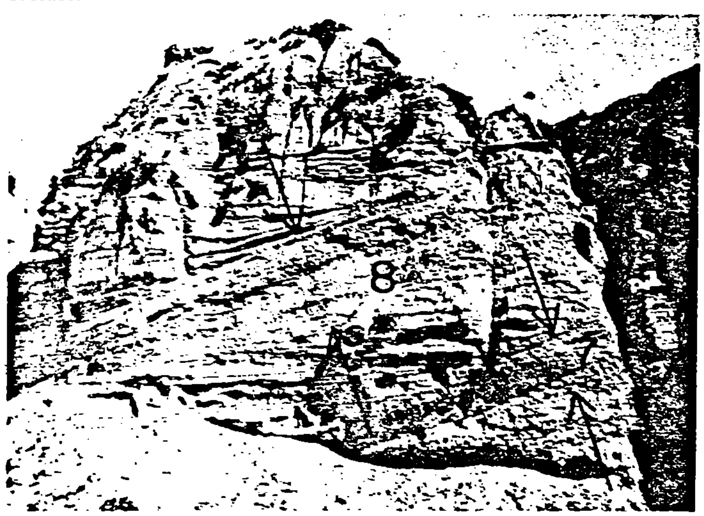

Figure 16. View of channels 7 and 8, with arrows showing tops and bottoms of drapes of both channels. Fill of channel 7 is mostly eroded away by channel 8, but it consists of massive sandstone toward base, becoming thinner upward.

Figure 18. Detail of drape of channel 8, showing abrupt truncation of graded sandstone (fill of channel 7) and crude bedding parallel to truncation surface within mudstone-siltstone drape. Dark bars on notebook each 5 cm long.

The possibility that the channels are genetically related does not explain the apparent progressive northwestward shift, nor why the fills became progressively sandier. The term "apparent progressive shifting" is used because one cannot be sure that the preserved sequence of channels is the original sequence. For example, between channels 1 and 2, several channels may have been cut and filled farther to the northwest; channel 2 would represent simply the final southestward shift in position. However, in the case of channels 1 through 4, a reasonable argument can be made for progressive shifting (rather than many random shifts in position) because of the similar channel-wall trends and the progressive change in the nature of the fill.

A similar progressive shifting can be proposed for channels 5 through 8, with trends between 230° and 240°. Channels 6 and 7 have similar classical turbidite fills that pass over the top of the lower part of the fill of channel 5 and must die out against the upper part of the wall of channel 5 (not exposed — see Fig. 1). Therefore, channels 6 and 7 may represent smaller scours within the lower part of channel 5 — this is reinforced by the fact that the drapes are thin (0.30 and 0.75 m) and that the overall dip of the walls is low. Within the channel 5-6-7 complex, the preserved pattern of shifting is progressively northwestward, and this pattern continues to the position of the final channel, channel 8. Channel 8 truncates the entire 5-6-7 complex; the wall is steeper, the mudstone-siltstone drape thicker, and the fill sandier than the 5-6-7 complex (Fig. 9). The beds filling channel 8 crop out between 0 and 170 m — over this distance, they are mostly continuous and parallel, although many examples of minor channeling between beds can be seen in the gully at 100 m.

Mudstone-Siltstone Drapes and Implications of Channel Depth

Channels 2 through 8 have mudstone-siltstone drapes ranging in thickness from 30 cm to 2 m. All of the drapes are laminated parallel to the channel walls (Figs. 5, 8, 12, 18), indicating a significant period of time between channel cutting and sandy channel filling in this part of the channel. This raises two other questions: To what extent are channels cut and then abandoned before deposition?, and What controls the balance between cutting and filling?

The fill of channel 8 (Fig. 17) indicates that some sandy turbidite within the main channel can grade into laminated siltstone-clay couplets up the channel wall and into the drape. This suggests that many of the San Clemente channels are deeper than now seen in the cliffs. After cutting, sandy plugging may have begun immediately, but the sand would have been restricted to the channel floor. Higher on the channel walls (as seen in the cliffs at San Clemente), alternating deposition of siltstone and clay in layers parallel to the channel walls would represent deposition of materials from the suspended load high in the turbidity currents. There is abundant evidence that sand remained close to the channel floor, as can be seen from the way that many sandy beds pinch out rather than climb up the channel walls (Figs. 7, 13, 15). After several, or many, currents have flowed through the channel, the lower part would be sand plugged, and the upper walls would be draped. Continued filling would produce sandy beds that pinch out against the drape (Figs. 7, 13, 15).

In channels 4 and 8, it is particularly easy to count the number of silt-clay alternations in the drape (Figs. 12, 18). Some alternations are destroyed by bioturbation, and some siltstone layers may represent more than one current. Nevertheless, I estimate that the drape of channel 4 involves about 10 distinct flows that deposited alternating silt (and fine sand) layers and clay layers. The drape of channel 8 contains less siltstone and sandstone and may represent 8 to 10 flows. If we now estimate the average thickness of individual beds seen in channels 4 and 8, we can use these figures to estimate a thickness for the 8 to 10 beds suggested to be in the channel below outcrop level. For channel 4, this thickness may be about 10 m (representing 10 beds about 1 m thick), and for channel 8, it may be about 4 to 5 m (beds averaging about 50 cm; see Fig. 9). If these figures are accepted as minima (that is, the lower beds might be thicker than average), the minimum channel depths for the San Clemente cliff section could be 20 to 25 m.

The possibility remains, however, that cutting and filling were not closely associated. Cutting may have been related to avulsion on the suprafan, catastrophic shifting in position of the inner-fan channel, or long-term changes in the sizes and velocities of turbidity currents generated. The new channels may have been abandoned for a long time, receiving only deposition of fines from suspension. Reoccupation of the channels by turbidity currents would lead to final plugging and channel switching to yet another location. However, the close relationship of channels 1 through 4 with respect to cutting, filling, switching, and paleocurrent trend does not fit very well with the randomness implied by the above hypothesis.

Channel Geometry and Nature of Fill

I have noted that in the first group of channels, the fill becomes progressively sandier from channel 1 to channel 4. The fill of channels 5, 6, and 7 is dominantly classical turbidite, and the fill of channel 8 is mainly thick massive and graded sandstones.

The San Clemente area is one of the best exposed areas in North America in which to examine the suggestion of many workers that gradual abandonment of a submarine-fan channel may lead to a sequence in which individual turbidites become thinner and more fine grained upward (Mutti and Ghibaudo, 1972; Mutti and Ricci Lucchi, 1972; Mutti, 1974). Such a sequence is developed in the channel 5-6-7 complex, both in terms of overall fill (at 260 m) and in terms of the fill of channels 6 (at 210 m) and 7 (at 190 m) (see Figs. 15, 16). The thinning- and fining-upward sequence is not seen in channels 1 through 4. Indeed, there is a trend from channels 1 to 4 of increasing grain size in the fill, and within channel 2 there is a thickening- and coarsening-upward sequence exposed in the gully at 425 m (Fig. 6). The coarsening-upward sequence probably represents progradation of a lobe of turbidites (Mutti and Ghibaudo, 1972), in this case down a channel, with scouring at the top of the sequence and development of smaller channels (as seen at 410 to 420 m, and in the gully at 425 m).

It is unfortunate that the northwestern margins of the channels are never exposed at San Clemente (except for a small, poorly exposed margin beneath the houses north of the car park; Weser, 1971, Pl. XI–A). Consequently, the overall depth and width of the channels are unknown.

San Clemente Channels and the Submarine-Fan Model

A model for the development of modern submarine fans was first presented by Normark (1970); the model has recently been elaborated (Normark, 1974). In the model, submarine fans are divided into an inner fan with usually one major leveed channel, a midfan characterized by a suprafan bulge, and an outer fan of rather smooth topography. The suprafan bulge forms at the end of the inner-fan leveed channel and consists of an inner area of shallow braided channels and an outer depositional lobe.

The channels at San Clemente fit reasonably well with the braided suprafan part of the model. There is clear evidence that the channels have shifted in position, yet there is no evidence of constructional levees (which are characteristic of the inner-fan channel but rather discontinuous and poorly formed in the braided suprafan; Normark 1970). The minimum postulated depths are about 20 to 25 m; the maximum depths may not be much greater than this because channels 6 and 7, and probably 2 and 8, die out before erosion by the Pleistocene terrace, and therefore the tops, if not the bottoms, can be seen. Nonleveed channels a few tens of meters deep would fit well with the braided-suprafan part of the model, because the inner-fan valley tends to be much deeper and wider, without so much tendency to lateral shifting.

A second feature indicating channel formation on the braided suprafan is the nature of the channel fills. In ancient fans, the inner-fan valley tends to be an area of conglomerate and pebbly sandstone deposition, without much evidence of classical turbidites (see Mutti and Ricci Lucchi, 1972; Walker and Mutti, 1973; Mutti, 1974). By contrast, the braided-suprafan area tends to be the locus of deposition of pebbly and massive sandstones, and perhaps some classical turbidites, although these would seem to be better developed beyond the channeled area, on the suprafan depositional lobe (Walker, 1975). Therefore, the facies within the channels at San Clemente is more characteristic of the braided suprafan, or suprafan depositional lobe, than of the inner-fan channel.

The extent to which shifting suprafan lobes result in a coalesced sandstone sheet will depend upon how rapidly the lobes shift. If they shift infrequently, older abandoned lobes will tend to be covered by fines, and the shifting lobes will tend to be separated by fines. This might be the case at San Clemente, where the first channel cuts into bioturbated mudstone rather than a pre-existing suprafan lobe of sandstone.

Because of the difficulty of tracing channel patterns in recent sediments, particularly abandoned and filled channels, advances in understanding of channeled fans will probably come mainly from ancient sedimentary rocks. The degree to which the San Clemente channels typify fan behavior will only become apparent as more and more channels are studied in detail.

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