DAVID BLOOM

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KEN McMILLEN

Deep-Water Sandstone Facies and Ancient Submarine Fans: Models for Exploration for Stratigraphic Traps[1]

ROGER G. WALKER[2]

Abstract Five main facies of deep-water clastic rocks can be defined: classic turbidites, massive sandstones, pebbly sandstones, conglomerates, and debris flows (with slumps and slides). The classic turbidites consist of monotonously parallel-interbedded sandstones and shales without channeling; internal sedimentary structures include grading, parallel lamination, and cross-lamination. Massive sandstones are thicker, coarser, and commonly channelized. They lack the sedimentary structures of classic turbidites, but do contain evidence of dewatering during deposition. Pebbly sandstones tend to be well graded, and can contain parallel stratification and large-scale cross-stratification. Conglomerates are characterized by inverse and normal grading, parallel and cross-stratification, and commonly have a preferred clast fabric (imbrication). Both the pebbly sandstones and conglomerates commonly are channelized.

The facies can be fitted into a model of submarine-fan deposition. Modern fans are subdivided into an upper fan (suprafan), characterized by (1) a single deep channel with levees, (2) a middle fan, built up from suprafan lobes that periodically switch in position, and (3) a topographically smooth lower fan. The suprafan lobes have shallow, braided channels on their inner parts, but the outer suprafan lobes are smooth, and grade basinward into the smooth lower fan and basin plain.

The smooth suprafan lobes and lower fan are characterized by deposition of the classic turbidite facies, and the braided part of the suprafan lobes by massive and pebbly sandstones. When one lobe is abandoned and another starts to prograde elsewhere, the first lobe is blanketed by mud, forming a potential stratigraphic trap. The upper-fan channel is an area of coarse sediment deposition, or conglomerates where gravel and boulders are supplied to the basin. During fan progradation, thickening- and coarsening-upward facies sequences can be formed in a manner analogous to those of deltas. Fan channels also can be abandoned progressively, forming thinning- and fining-upward sequences similar to those of fluvial or distributary channels. These sequences can be identified on electric logs.

Where basin shales act as hydrocarbon-source areas, the classic turbidites can act as conduits, leading the hydrocarbons to the thicker, laterally coalesced massive and pebbly sandstones of the braided suprafan lobes. These bodies can be of the order of 25 km in diameter, and up to 100 m thick. The coarse deposits of the upper-fan channel also might form good reservoirs, being bounded by shales (levee deposits) on either side, and possibly by shales above if the fan-channel system is abandoned. Such channels can be tens of kilometers long, several kilometers wide, and a few hundred meters deep. Reservoirs may be present in all of these environments.

INTRODUCTION

Prolific reservoirs in the Los Angeles and Ventura basins, the Great Valley of California, and parts of the Texas and Louisiana Coastal Plain, among others, are producing from deep-water sandstones. The family of deep-water sandstones includes classic turbidites together with other coarser grained facies such as pebbly sandstones and conglomerates. The feature that they all share in common is that of depositional setting, because they all accumulated at one time as unstable piles of loose sediment in shallow (wave agitated) water, and all subsequently were resedimented by gravity into deeper water (consistently below storm wave base). The term "resedimented" implies no specific transportation process, but embraces everything from fully turbulent turbidity currents to debris flows moving as semirigid plugs.

This paper will review the various sandstones and conglomerates that geologists recognize as deep-water deposits. The entire suite of rocks belongs to the "resedimented coarse-clastic family," but excludes oceanic mudstones, oozes, and related fine-grained deposits. The various members of the family will be related to depositional environments known in modern submarine fans (Normark, this issue of AAPG *Bull.*), and near the end of this paper, I will suggest how the submarine-fan model may be used in petroleum exploration.

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[1] Manuscript received, May 16, 1977; accepted, November 16, 1977.

[2] Department of Geology, McMaster University, Hamilton, Ontario, Canada.

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As well as the basins mentioned, turbidite reservoirs have been recognized in the southern fringes of the Hackberry wedge (Louisiana), and prospecting for more turbidite reservoirs is currently important in offshore southern California, and in the North Sea (Thomas et al, 1974; Fowler, 1975; Parker, 1975) where the giant Forties and Montrose fields are producing from turbidites with good reservoir qualities associated with upper and middle submarine-fan environments (Skipper, 1977).

With so much oil and gas in turbidites, it is unfortunate that so few producing fields have been described in detail. Important studies of areas involving turbidites and deep-water channels associated with hydrocarbon production include the Los Angeles basin (Barbat, 1958; Yerkes et al, 1965; Mayuga, 1970; Gardett, 1971), the Ventura basin (Nagle and Parker, 1971; Hsü, 1977), the Great Valley of California (Sullwold, 1961; Martin, 1963), Sacramento Valley (Edmondson, 1965; Dickas and Payne, 1967; Weagant, 1972), southern and offshore Louisiana (Paine, 1966; Sabate, 1968; Benson, 1971), Texas (Hoyt, 1959), and Pennsylvania (Dixon, 1972). Some of these basins will be examined in more detail later, after a discussion of the facies in the resedimented coarse-clastic family and their relation to submarine-fan depositional systems.

RESEDIMENTED COARSE-CLASTIC FAMILY

The purpose of this section of the paper is to introduce the members of the family, as presently conceived. There have been various classification schemes and jargon terms used (turbidites, fluxoturbidites, grain flow deposits, neptunites, etc.), but I now believe that quite a simple scheme will suffice as a framework for understanding the relations between members of the family. The scheme presented is a simplification of that given by Walker and Mutti (1973), which in turn was based on the excellent synthesis of a large amount of information by Mutti and his Italian colleagues (Mutti and Ricci Lucchi, 1972). The scheme also has the advantage of an increasingly sound experimental and theoretical basis (Middleton and Hampton, 1976).

The most important members of the family are: (1) classic turbidites, (2) massive sandstones, (3) pebbly sandstones, (4) clast-supported conglomerates, and (5) matrix-supported beds (debris flows, pebbly mudstones, slumps).

The first four members are believed now to have been deposited from flows in which fluid turbulence was important as a grain- and clast-supportive mechanism. During the final stages of deposition from the flow, other mechanisms may take over and develop a characteristic suite of sedimentary structures in each facies. The fifth facies includes all the matrix-supported beds (debris flow deposits, pebbly mudstones, and the like): during transport, fluid turbulence was a much less important mechanism.

Classic Turbidites

The features that distinguish classic turbidites (Figs. 1, 2) from other members of the resedimented family are: (1) very parallel bedding, with consistent alternations of sandstone and shale (normally without channeling or major changes in bed thickness laterally); and (2) a consistent set of internal sedimentary structures that can be described using the Bouma (1962) model (Fig. 3).

The term "classic" turbidite is applied because there has been very extensive study of such beds since the concept of turbidites and turbidity currents first was introduced (Kuenen and Migliorini, 1950; Natland and Kuenen, 1951). As a result, there is extensive general agreement among sedimentologists as to characteristics that define such beds—they have become "classic." These features include: (1) a suite of erosional markings associated with the sharp base of each sandstone bed (sole marks); (2) a suite of internal sedimentary structures within each sandstone bed (including overall graded bedding, with horizontal lamination and ripple cross-lamination); (3) a covering pelitic layer on top of each sandstone that, in outcrop, gives the characteristic monotonous alternation of sand-shale-sand-shale-sand-shale (Figs. 1, 2); (4) a bedding regularity such that individual beds can be traced for hundreds or thousands of meters laterally without appreciable thickness changes (Figs. 1, 2).

Sole marks are prominent in outcrops of classic turbidites, but rarely would be visible in cores. They are grouped into two types, tool marks, carved into the underlying substrate by tools (sticks, larger clasts, etc.) in the current, and scour marks, cut into the substrate by fluid scour alone. Both types of markings are vitally important in determining local and regional paleoflow patterns in basins. In oriented cores, grain orientation can be used equally successfully in determining flow directions (Hsü, 1977), and this technique will be discussed later. The sharp sandstone bases with scour and/or tool marks indicate the sudden and erosive appearance of a turbidity current in an area of former mud deposition in very quiet water.

Within the sandstone layer, classic turbidites contain a dazzling array of sedimentary structures (Dzulynski and Walton, 1965). The most important of these were grouped into a sequence

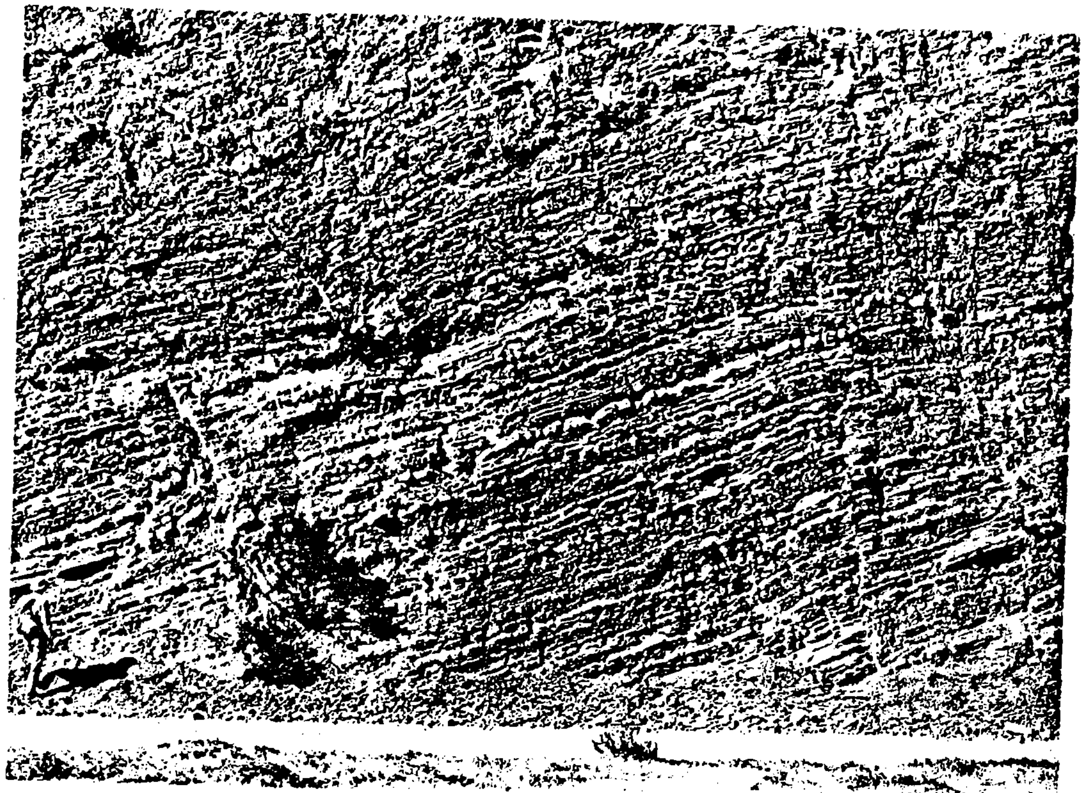

FIG. 1—Thin-bedded turbidite facies, Cretaceous rocks at Buellton, California.

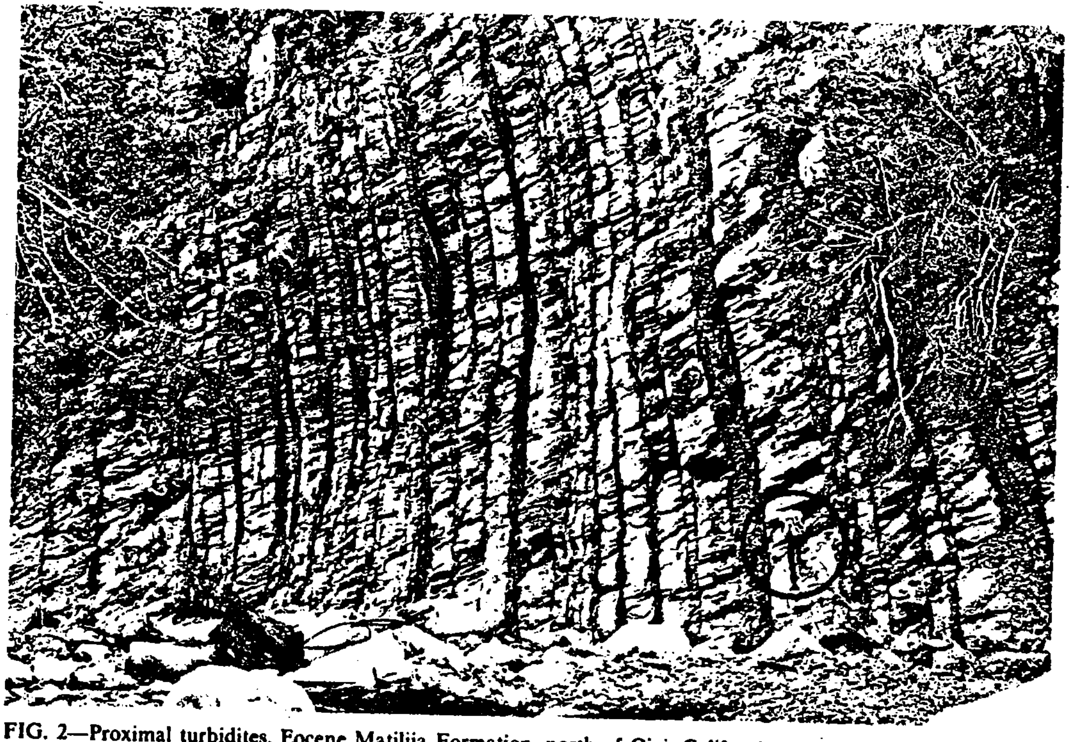

FIG. 2—Proximal turbidites, Eocene Matilija Formation, north of Ojai, California. As compared with Figure 1, much higher sand/shale ratio, and much thicker individual sandstone beds. Stratigraphic top on left; figure circled for scale.

by Bouma (1962; Fig. 3), and they form the basis for the classic turbidite predictive model (Walker, 1976a, b). Bouma's division A consists of massive (structureless) or graded sandstone. Several studies have shown that within division A there is a preferred grain orientation (Spotts and Weser, 1964; Colburn, 1968; Onions and Middleton, 1968; Parkash and Middleton, 1970) with grains commonly oriented at some angle to the flow directions independantly determined from sole marks. Spotts and Weser (1964, p. 218) found a grain orientation that diverged from the sole-mark orientation by an average of about 45° counterclockwise, but Onions and Middleton (1968) found no consistent relation between grain orientation and sole marks; in fact, grain orientation varied as much as 90° on either side of the sole-mark directions. However, Colburn's (1968) data show a much closer agreement between grain orientations and sole marks, and Parkash and Middleton (1970) demonstrated that the grain orientations measured near the base of the bed deviated least from the sole-mark directions. They also showed increasing divergence upward through a bed. Onions and Middleton (1968) gave a useful summary of techniques, statistical procedures, and test for operator errors.

Grain orientation has been used as a paleoflow indicator in several producing fields. One of the best examples is from the Ventura field, California, where Hsü (1977, p. 149) demonstrated an east-west preferred grain fabric in oriented cores, with a presumed westerly flow for the Repetto turbidites. The flow direction agreed closely with that indicated by ripple cross-lamination in the same cores.

Bouma's division B is characterized by horizontal lamination, normally in medium- to fine-sand sizes. If the bed can be split along lamination planes, parting lineation commonly can be seen, reflecting the excellent grain orientation associated with this type of horizontal lamination (Allen, 1964). There is no extensive report in the literature of the relation between grain orientation in division B and sole-mark directions; where division B parting lineation can be compared with sole marks in the field, the directions commonly are very similar. In oriented cores, I tentatively would recommend a grain-orientation study of division B rather than division A, simply because the standard deviation about the vector mean-grain orientation is normally less in division B (i.e., the grain orientation is "better developed").

Division C is characterized by ripple cross-lamination, which in some beds may be convoluted. The cross-lamination can consist either of a single row of ripples on top of division A or B, or of a multiple set of climbing ripples. The single row probably indicates reworking of underlying sediment by the tail of the turbidity current (or possibly a semipermanent ocean current), whereas a set of climbing ripples indicates active deposition of sediment from the turbidity current during rippling (Walker, 1969). If the rate of deposition is too high, fluid is trapped between the grains, and the ripple cross-lamination becomes convoluted as the fluid escapes. Paleoflow directions measured from ripple cross-lamination are notoriously variable, and division C should be used as a paleocurrent indicator only if all else fails. It is possible to measure cross-lamination in oriented cores (see Hsü, 1977, p. 149-151), but it may be difficult to interpret the results in terms of paleoslope.

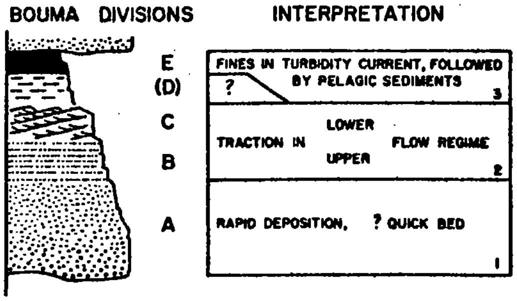

FIG. 3—Bouma model for classic turbidites. Division *A* is massive or graded, *B* is parallel laminated, *C* is rippled, *D* consists of faint laminations of silt and mud, and *E* is pelitic.

In Bouma's original definition, division C was overlain by division D, an upper division of horizontal lamination in silt and clay. This division cannot be seen in weathered or tectonized outcrops, and I prefer to describe it as (D) and include it with division E, the pelitic division. The pelitic material is normally a structureless gray silty clay, or darker gray clay. In many Tertiary basins where forams are abundant, fauna of most of division E consists of transported shallow-water benthonic forams. This implies that most of the sediment in division E was introduced into the basin by the turbidity current. However, the uppermost part of E may consist of a brown foraminiferal lutite with benthonic bathyal or abyssal forams—this represents the normal fine-grained deposition in the basin between turbidity currents (Natland, 1963).

The Bouma sequence now can be considered as a model for classic turbidites. It performs the four main functions of a model very well (a model should be a norm for purposes of comparison, a guide for future observations, a predictor in new situations, and a basis for interpretation; Walker, 1976a, b).

Hydrodynamic interpretation of classic turbidites—The Bouma sequence is an excellent basis for hydrodynamic interpretation (Walker, 1965; Harms and Fahnestock, 1965; Middleton and Hampton, 1976). Deposition can be envisaged in three phrases (Fig. 3).

The first stage involves the rapid deposition of grains from suspension. Continued shear of these grains by the flow, together with the escape of trapped pore water, tends to make the deposit (division A) massive and structureless, and it is perhaps surprising that there can be a preferred grain fabric. Details of this proposed mechanism were given by Middleton and Hampton (1976).

The second phase of deposition is characterized by traction of grains on the bed (Fig. 4). By comparison with experimental work, division B represents the plane bed with sediment movement of the upper flow regime. Divisions B and C can be formed either by reworking previously deposited sediment, or by continued deposition from the turbidity current at lower and lower flow velocities.

The third phase of deposition, divisions (D) and E, represents the quiet accumulation of fine sediments from the tail of the current, with possibly some hemipelagic deposition after the current has died away completely.

Predictive implications of Bouma model—In the preceding interpretation, each division of the Bouma sequence represents a progressively waning current, upward through the bed (Figs. 3, 5). Individual turbidity currents also wane progressively in their journey across the basin floor, and it follows from the model that near the point where deposition begins, turbidites will tend to begin with division A (Fig. 5). Progressively farther from this area, as the currents wane, beds will tend to begin with division B and, in the most distant areas, velocities will have fallen to the point where deposition begins with division C (Fig. 5).

Together with the change in sedimentary structures at the bases of beds, other systematic changes in turbidite characteristics take place from the point where deposition begins to distal depositional environments. Specifically, turbidites in the area of initial deposition tend to be thicker bedded (sandstones >about 20 to 30 cm) and coarser grained (division A typically medium sand or coarser). They also have a higher sand/shale ratio and individual beds tend to begin with Bouma's division A (Figs. 2, 3, 5).

These characteristics define a classic turbidite facies now termed "proximal" (the area of initial deposition). Until now, the term "distal" was used for the contrasting finer, thinner bedded, low sand/shale ratio, Bouma B and C type turbidites. It is now important to term this facies "thin-bedded turbidites" (Fig. 1) rather than distal, because the thin-bedded facies can be deposited in several depositional environments, not all of which are distal (Mutti, 1977). This problem is discussed later, and is illustrated in Figure 13.

The first three criteria—sandstone thickness, grain size, and sand/shale ratio—are particularly important because they may be interpreted from electric logs. The distinction between proximal and distal depositional environments is important in general basin analysis. In the case of hydrocarbon reservoirs, this distinction may be indicative of directions of hydrocarbon migration. For example, of the many reasons given by Barbat (1958) for the abundance of hydrocarbons in the Los Angeles basin, we may note specifically the interfingering of carrier and reservoir sands, and the lateral persistence of fine-grained rocks. Thus, the basin shales interbedded with the thin-bedded turbidite facies may make good source rocks. Oil and gas expelled from these source rocks may be stored in the thin-bedded turbidites, and if these sandstones have good permeability, it may migrate toward the basin margin. Here, the thicker and more extensive sands (proximal classic turbidites, massive and pebbly sandstones) may form good stratigraphic traps, as will be discussed later.

Massive Sandstones

The classic turbidite facies passes gradationally into the massive sandstone facies by a decrease in abundance of interbedded shales, by an increase in channeling and irregularity of bedding, by an increase in overall grain size, and by an increase in sandstone-bed thickness. Thus, the massive sandstone facies consists essentially of massive sandstones, without shaly interbeds (Fig. 6). In the Bouma terminology, a stratigraphic sequence of beds would be described as AAAAA, etc., because horizontal lamination (B), ripple cross-lamination (C), and interbedded fines (D and E) are typically absent. I suggest that the Bouma model is inappropriate with respect to this facies, particularly as it does not describe the one sedimentary structure that is present in some massive sandstones—*dish structure* (Fig. 7).

Typically, massive sandstones are 0.5 to 5 m thick, and may be composite (several flows welded or amalgamated together). Tool marks and scour marks are present on the bases of beds, but internally the beds are not only massive, but com-

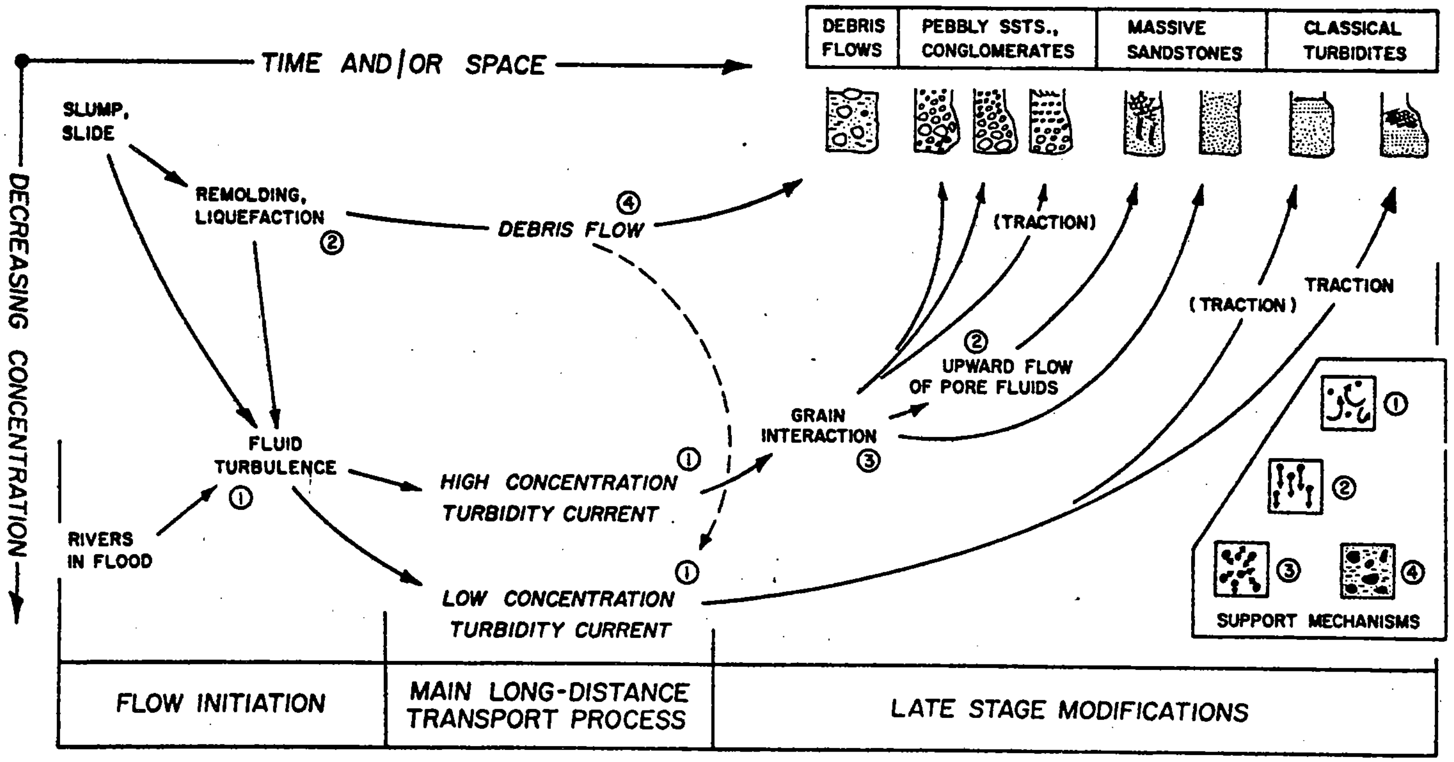

FIG. 4—Processes of initiation, long-distance transport, and deposition for currents transporting sediment into deep water. Framework is one of time and/or space, and concentration of flows. Grain-supporting mechanisms (insert, lower right) include: 1, fluid turbulence; 2, liquefaction; 3, collision between individual grains (dispersive pressure in grain flow); and 4, matrix strength (as in debris flow). Modified in discussion with Middleton (personal commun.) from Middleton and Hampton (1976), to show possibility of debris flows becoming turbulent, and to eliminate grain flows as long-distance transport processes.

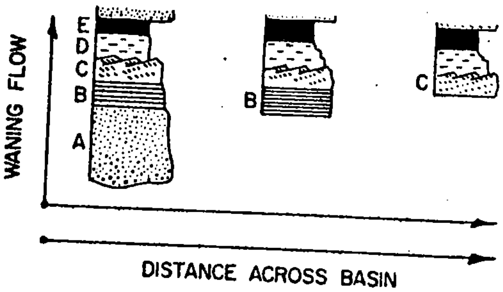

FIG. 5—Interpretation of *ABCDE* Bouma sequence in terms of waning flow suggests that groups of turbidites beginning with divisions *B* and *C* represent deposition from progressively slower flows. This can be related to increasing distance across basin, although it is emphasized in text that some *CDE* thin-bedded turbidites can be present on levees in proximal environments, and hence *CDE* turbidites are not necessarily distal.

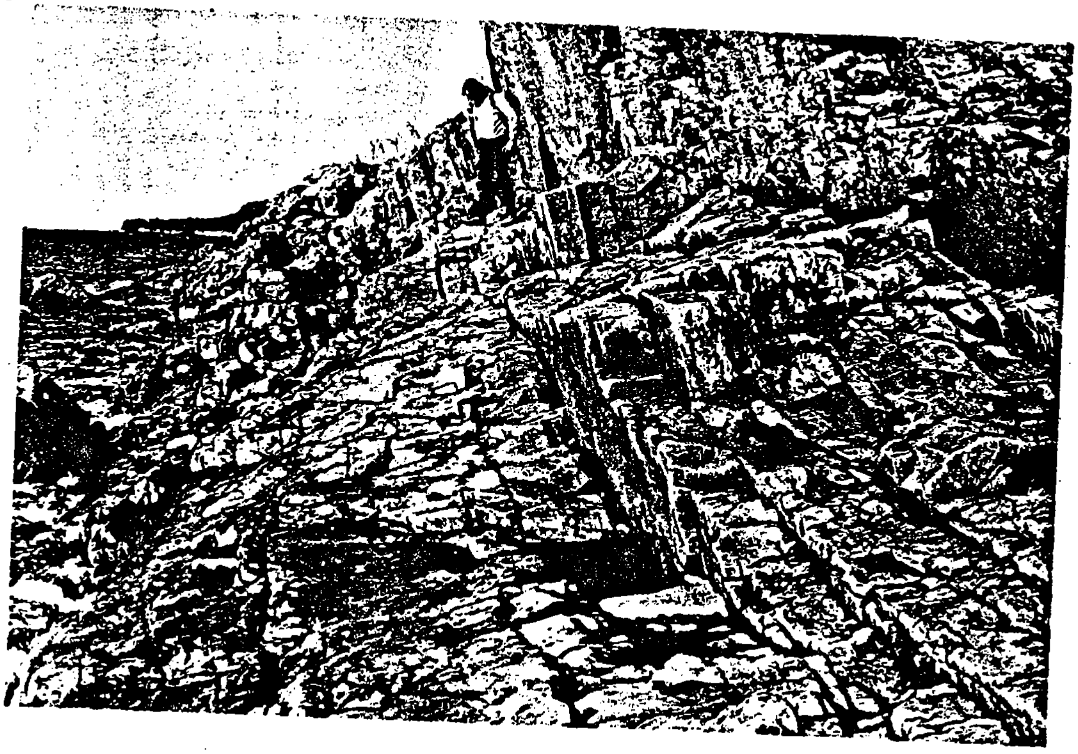

FIG. 6—Massive sandstone facies, with no interbedded shales. Cambrian-Ordovician Cap Enragé Formation, Quebec Appalachians. Stratigraphic top on left. Compare with Figure 2.

FIG. 7—Dish structures and vertical fluid-escape pipes (pale). Within circle, fluid from below two adjacent dishes breaks through between dishes to form vertical pipe.

monly are ungraded. The only sedimentary structures reflect vertical intergranular fluid escape during deposition—vertical fluid-escape tubes, and dish structures (defined as thin, subhorizontal, flat-to-concave upward argillaceous laminations in sandstones; Fig. 7). Details of the origin of dish structures have been discussed by Lowe and LoPiccolo (1974) and Lowe (1975). The various fluid-escape features suggest deposition from a flow in which the final grain-support mechanism before deposition is the upward flow of pore fluid (fluidized flow; Lowe, 1976). It seems probable that the currents that transported the sediment most of the way into the basin were turbidity currents maintaining the sand in suspension. During late stages of transport and initial stages of deposition, grains became highly concentrated toward the base of the flow. The fluid trapped between those accumulating grains finally escaped upward, fluidizing the sand and developing the characteristic sedimentary structures (support mechanism 2 of Fig. 4). The massive sandstones without dish structure bear a final imprint that reflects grain collisions and a less forceful escape of pore water, resulting in massive beds without fluid-escape features (Fig. 6).

Pebbly Sandstones

The pebbly sandstone facies (Figs. 8, 9) is distinct from the massive sandstone facies, and it has not yet been established whether or not the facies grade into each other. In the Los Angeles and Ventura basins, pebbly sandstones are abundant

FIG. 8—Pebbly sandstone facies, Cambrian St. Damase Formation, Quebec Appalachians, shows irregular, probably loaded, base; excellent graded bedding; and crudely developed horizontal stratification in upper part of bed.

in outcrop, and form some of the major reservoirs.

Beds range from about 0.5 to over 5 m in thickness, and are characterized by sharp bases and absence of shaly interbeds. The Bouma model is not applicable. Sole marks tend to be large, with flute casts up to 1 m long on some beds. Internally, the beds commonly are well graded, from basal pebbly sandstone (clasts up to about 2 cm) up into medium (and rarely fine) sandstone. The most characteristic internal sedimentary structures are stratification and cross-stratification—dish structures and dewatering pipes are present but less common. The stratification commonly consists of alternating pebble-rich and pebble-poor layers, the layers having gradational bases and tops. Average layer thickness is in the range of 5 to 10 cm. The cross-stratification consists of medium-scale (sets 20 to 30 cm) trough or planar-tabular cross-beds of pebbly sandstone (Fig. 9). It must be emphasized that any form of cross-stratification larger than ripple cross-lamination (sets up to about 5 cm thick) is extremely rare in the resedimented coarse-clastic family, yet when medium-scale cross-stratification is present, it is normally in the pebbly-sandstone facies.

There is no model that attempts to organize the internal features of pebbly sandstones into a Bouma-like sequence, and it is not known whether there is a consistent relation between the various sedimentary structures (grading, horizontal stratification, cross-stratification, dish, and dewatering structures). Although imbrication of the coarser clasts commonly can be seen with the naked eye

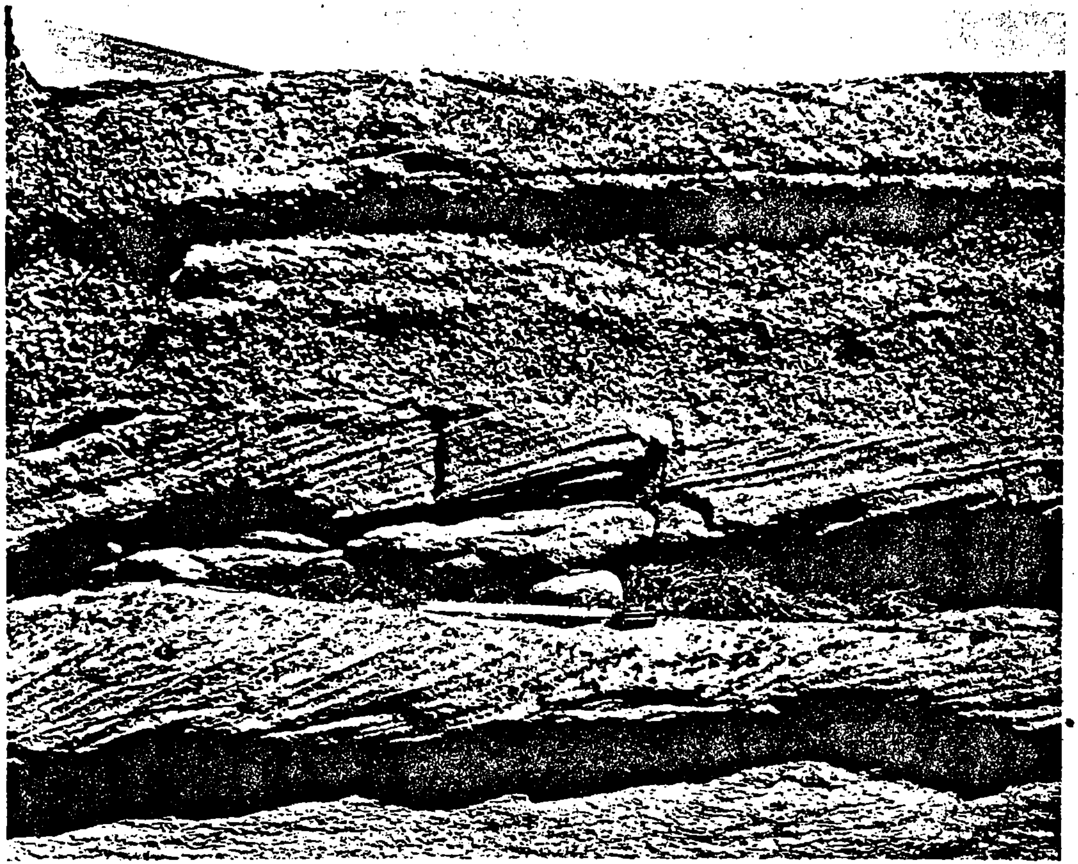

FIG. 9—Pebbly sandstone facies, Cambrian-Ordovician Cap Enragé Formation, Quebec Appalachians. Two sets of cross-bedding below main pebbly horizon probably represent separate depositional event from main pebbly sandstone.

in the field, there has not been a comprehensive study of pebbly-sandstone fabrics. Field observations of many pebbly-sandstone formations in the Cambrian-Ordovician Appalachian flysch belt of Quebec, and in Cretaceous and Tertiary pebbly sandstones in California, suggest that the long axes of the grains parallel the flow (as in classic turbidites). In the Miocene pebbly sandstones at Dana Point, California, not only are the long axes mostly parallel with flow, but the long axes dip upstream to define the imbrication (Walker, 1975a). This is a very uncommon fabric, and has been discussed in detail by Davies and Walker (1974) and Walker (1975a, 1977).

In outcrop, the pebbly sandstones commonly are lenticular, and have irregular and scoured bases. Interbedded shales are uncommon. Many pebbly-sandstone formations are rather thick (tens or hundreds of meters) sheet sands, built up by lateral and vertical coalescing of a large number of individual graded beds. In places where this facies fingers out downcurrent into classic turbidites (as appears to happen in the Los Angeles basin), a perfect potential source-carrier-reservoir situation is established.

The transport mechanisms for the pebbly sandstones are probably similar to those for the massive sandstones, namely, a major phase of suspension by fluid turbulence as the sediment is swept into the basin, and late-stage modifications during deposition (mainly clast collisions) that give rise to the structureless graded base (Figs. 4, 8). For reasons not yet understood, traction of clasts on the bed was important in many pebbly sandstones, giving rise to stratification and cross-stratification.

Clast-Supported Conglomerates

There is probably a gradation between the coarser grained pebbly-sandstone facies, and the finer grained and stratified conglomerates. Conglomerates are prominent members of the resedimented family in many areas (Appalachians of Quebec, California, Oregon), and may act as reservoir rocks in the Los Angeles and Ventura basins.

As a result of recent work on conglomerates there is some agreement on the important features to observe in the field. These include the type of grading (normal or inverse), the presence or absence of stratification (if present, its type, layer thickness, and fabric; Walker, 1975a), and the presence or absence of imbrication (Harms et al, 1975). The combination of these features has led to the proposal of three intergradational models for clast-supported conglomerates (Walker, 1975a, 1976b, 1977; Fig. 10).

Individual beds of conglomerate can range from a little under a meter to over 50 m (as in the Jurassic Otter Point conglomerates in southwestern Oregon). They have sharp, commonly channeled bases, and tend to be laterally unpersistent. Shale layers rarely are preserved between beds, if indeed they ever were deposited.

In the inverse to normally graded conglomerates (Figs. 10, 11), the inverse grading is rarely thicker than 20 to 30 cm, and passes up into normal grading or massive bedding. There tends to be a well-developed preferred fabric in the form of an imbrication in which the long axes of the clasts are parallel with flow and dip upstream. The hydrodynamic implications of this form of imbrication have been discussed by Walker (1975a, 1977).

In the downcurrent direction, although not necessarily in the same beds, the inverse grading dies out, and graded-bed conglomerates are developed (Fig. 10). These lack inverse grading and stratification, but commonly have a well-developed imbrication. Even farther downstream, but not necessarily in the same beds, are the graded-stratified conglomerates (Fig. 10). Above the graded part of the bed, stratification can consist either of horizontal alternations of coarse and fine layers, or of cross-stratified gravels very similar to those shown in Figure 9. The cross-stratification is discussed in the following section.

In the field, it is very difficult to trace individual conglomerate beds in the downcurrent direction, and the downstream relations suggested in Figure 10 are based upon theoretical considerations of the formation of inverse grading and stratification (Davies and Walker, 1974; Walker, 1975a, 1977). It is not intended to imply in Figure 10 that any one current deposits a single bed that changes in character downstream. It *is* intended

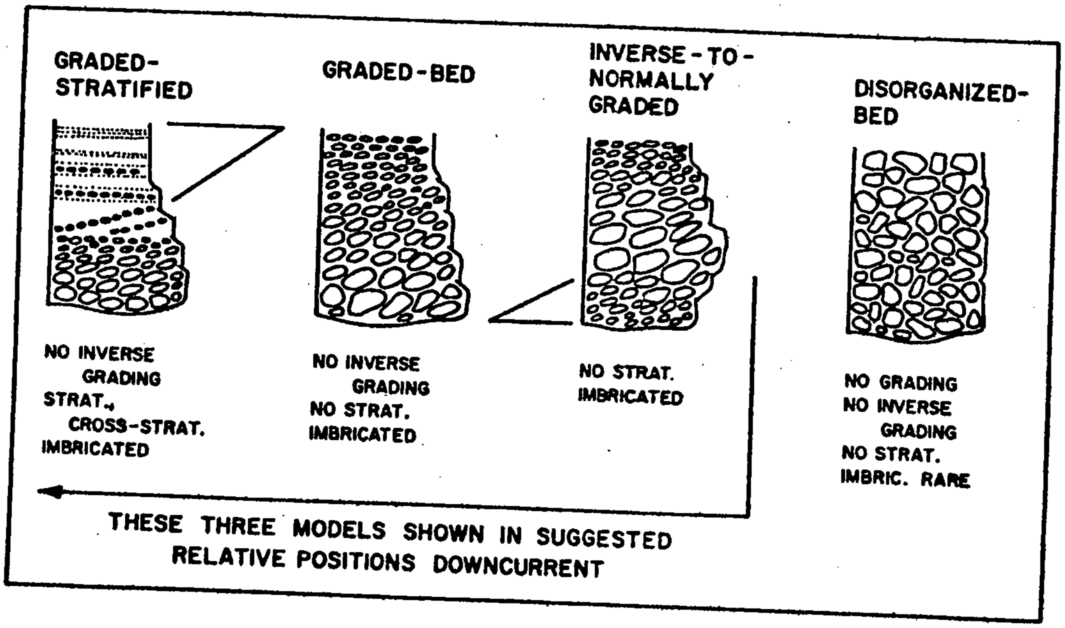

FIG. 10—Four models for resedimented conglomerates. Inversely to normally graded, graded-bed, and graded-stratified models are shown in relative downcurrent position, but this relation is suggested on theoretical grounds only.

FIG. 11—Inverse to normally graded conglomerate, also showing imbrication in both larger and smaller clasts. Clasts dip upstream, hence flow is to left. Cambrian-Ordovician Cap Enragé Formation, Quebec Appalachians.

to imply that currents which deposit sediment in the most proximal areas tend to produce inverse to normally graded beds, and that other currents might bypass the proximal areas, and begin deposition farther downstream, producing graded-stratified beds (Walker, 1975a).

Pebbly sandstones and conglomerates—fluvial or resedimented?—In some situations, there is a real possibility of confusion between pebbly sandstones and conglomerates in fluvial and deep-water environments. The basis for confusion lies in the features common to both environments—the abundance of channeling, abundance of massive and poorly stratified gravels, presence of large-scale cross-stratification, presence of graded (or "fining upward") gravels, and presence of imbrication.

In most situations, the distinction between the two environments can be based upon the associated facies. Fluvial sandstones and conglomerates may be associated with other flood-plain features, such as rootlets, calichelike concretions, and desiccation cracks, whereas in deep water there is an association with other members of the resedimented family, of which classic turbidites might be the most easily recognized.

The presence of a marine fauna also would favor a resedimented interpretation. Shallow (transported) or deep (in situ) faunal elements can be present in the resedimented conglomerates and associated fine-grained beds, but would not be present in fluvial conglomerates.

As a final criterion, the type of imbrication also may be used to distinguish fluvial and resedimented conglomerates. In fluvial situations, pebbles roll on the bed around their long axis, and the normal imbrication is long axis transverse to flow, with intermediate axis dipping upstream. In many resedimented conglomerates, the imbrication is long axis parallel with flow, with long axis dipping upstream. These different imbrications can be identified in unoriented cores, even if the regional paleocurrent directions were not known, and hence can be very important in areas where the only information is subsurface. Details of conglomerate fabrics were discussed by Davies and Walker (1974), Harms et al (1975, p. 136-137), and Walker (1975a, 1977), and an important discussion of very large-scale cross-stratification in resedimented conglomerates was given by Winn and Dott (1977).

Matrix-Supported Beds

This group of beds includes those that were transported into the basin in such a manner that the deposit consists of matrix-supported sand, pebbles, cobbles, and boulders (mainly subaqueous debris flows), and those that attained their texture by shorter distance movements within the depositional part of the basin (slumps).

Slumps (Fig. 12) can be on a small scale, involving a few beds that become broken and folded together, or can range up to thicknesses of tens of meters. In the latter case, tens or perhaps hundreds of beds can be involved, and the style of dislocation can range from immense open folds (Gregory, 1969) to complete disruption, mixing, and brecciation of the strata. In many published basin reconstructions, the orientation of the slump-fold axes has been used to establish the dip of the paleoslope. The assumptions behind this method can be very misleading, and the general

FIG. 12—Slumped facies, Cretaceous at Point Fermin, California. Laminated shales are slumped and contorted, and sandstone blocks (presumably torn from originally interbedded turbidites) are incorporated into slump.

problem of slump-fold orientation has been reviewed by Walker (1970, p. 223-226). A useful and illuminating case history has been documented by Lajoie (1972), and the method of plotting slump folds on stereonets was discussed by Hansen (1967, 1971).

The sedimentary features of subaqueous debris flows are relatively poorly documented, although the process has been discussed in detail by Hampton (1972). Bases of beds tend to be irregular, and they lack the normal suite of tool and scour marks. However, if some large blocks are in contact with the bed, broad "slide" marks can be produced. Internally, the beds are chaotic, and easily can be confused with tillites (again, the overall stratigraphic context and facies relations may be the determining factor in correct identification). Consistent preferred fabrics seem to be absent, although some debris flows locally may show some imbrication. Normal and inverse graded bedding are not developed consistently, although locally there may be some inverse grading at the base of some beds. It is well established that the clast-support mechanism in debris flows is matrix strength (Fig. 4). Because of this, large clasts can "float" in the upper part of the flow, and upon deposition, these clasts can project upward above the top of the bed. In the field, upward-projecting clasts are the most characteristic and diagnostic features of debris flows. The Haymond boulder beds (Marathon basin, Texas; McBride, 1966) are a classic example.

GRADATIONS BETWEEN FACIES IN RESEDIMENTED FAMILY

The five facies described represent a simplification of a scheme first published by Mutti and Ricci Lucchi (1972) and Walker and Mutti (1973). We are concerned here not with subdivisions of the basic facies scheme, but the general extent to which the facies grade into each other. Most of the data concerning these gradations consist of casual observations rather than rigorously defined associations, and more information on the relations, particularly from an economic viewpoint, is urgently required.

It seems well established that within the classic turbidites there is a complete facies transition from thin bedded (Bouma C[D]E types, Figs. 1, 3,

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5) to proximal (Bouma ABC[D]E or AE types, Figs. 2, 3, 5).

From limited published data, it also appears that there is a gradation in facies from classic proximal turbidites into massive sandstones. The gradation is characterized by a thickening of the sandstone beds, and loss of the monotonously regular sand/shale interbedded appearance of the outcrop (Fig. 2). The loss of bedding regularity is due to increasing amounts of scouring and channelling associated with the massive sandstone, resulting in composite sandstones without interbedded shales (Fig. 6).

The extent of a gradation between massive sandstones and pebbly sandstones, if any, is not known. It remains an important research topic, because it is difficult to construct a predictive basin model if the extent of facies transitions is not known. Although there are some formations in which both pebbly and massive sandstones are present, the differences (especially in the development of graded bedding, horizontal and cross-stratification in pebbly sandstones) between the facies suggest rather different depositional mechanisms. This may indicate in turn two distinct facies, rather than two types with a gradation between them.

However, there does appear to be a gradation between the pebbly sandstone and clast-supported conglomerate facies. In particular, the style of horizontal stratification in the pebbly sandstones is very similar to that of the graded-stratified conglomerates, and the gradation between the two facies is dominantly one of bed thickness and clast size. Similarly, the gradation among the various conglomerate facies is by loss of stratification (graded stratified → graded bed) and then appearance of inverse grading (graded bed → inverse to normally graded).

The suggested gradations between facies describe general relations among rock types, rather than changes that could be predicted within individual beds. A more detailed discussion of lateral and vertical facies relations—the basis of a predictive basin model—can be given only within the context of a submarine-fan model. Such a model, in a general way, expresses many of the detailed relations from a large number of individual studies.

SUBMARINE FANS

A detailed review of modern submarine fans has been given by Normark (this issue). There has been an important interplay between recent and ancient sediment studies in deriving the present fan model. The first studies directly applicable to geology were of the smaller California borderland fans (Gorsline and Emery, 1959). At about the same time, the first submarine-fan interpretation of ancient rocks was suggested, by Sullwold (1960, 1961), with reference to the late Miocene Tarzana fan in the Santa Monica Mountains. He emphasized in his interpretation the lenticularity of the sandstones (0 to 4,000 ft in 16 mi or 0 to 1,200 m in 26 km), and the radial paleocurrent directions fanning from a point source (? foot of canyon) north of the outcrop area.

As work continued in offshore southern California (Shepard and Einsele, 1962), definite sedimentary facies began to be associated with particular topographic parts of the fans and, in 1964, Hand and Emery recognized slope, canyon or channel, levee, and apron environments. They discussed the sediments from a geologic point of view, and even published an inferred map of current directions for the adjacent Newport, Oceanside, and Carlsbad fan systems. This work stimulated the first very detailed interpretation of an ancient fan, with descriptions of different turbidite facies, drawings and photographs of fan channels, and an overall fan stratigraphy (Walker, 1966a, b). This Late Carboniferous fan from northern England will be discussed in detail later.

Work on recent and ancient fans continued in the late 1960s, but increasing sophistication in seismic profiling led to important new insights into modern fan morphology and evolution (Normark, 1970). Shortly afterward important summaries of Italian fans were published (Mutti and Ghibaudo, 1972; Mutti and Ricci Lucchi, 1972) and these papers presented fan models very similar to that which Normark (1970) had suggested from recent-sediment studies. Since then, many recent and ancient-sediment studies have emphasized one fan model, which will be used in this paper as the basis for facies relations, fan stratigraphy, and sand-body prediction. Important recently published fan interpretations of ancient rocks include those of Nilsen and Simoni, 1973 (Butano Sandstone, Eocene, California); Mutti, 1974 (various Italian fans); Stanley, 1975 (guidebook to the Annot Sandstone, southern France); Kruit et al, 1975 (guidebook and discussion of the superbly exposed San Sebastian fan, northern coast of Spain); and Mutti, 1977 (Hecho Group, Eocene, Spain).

Relation of Facies to Fan Morphology

The proposed facies distributions suggested here (Fig. 13) are based on the morphologic subdivisions suggested by Normark (this issue). The upper fan is characterized by a single leveed channel that may have within it a sinuous, meandering thalweg channel flanked by relatively flat

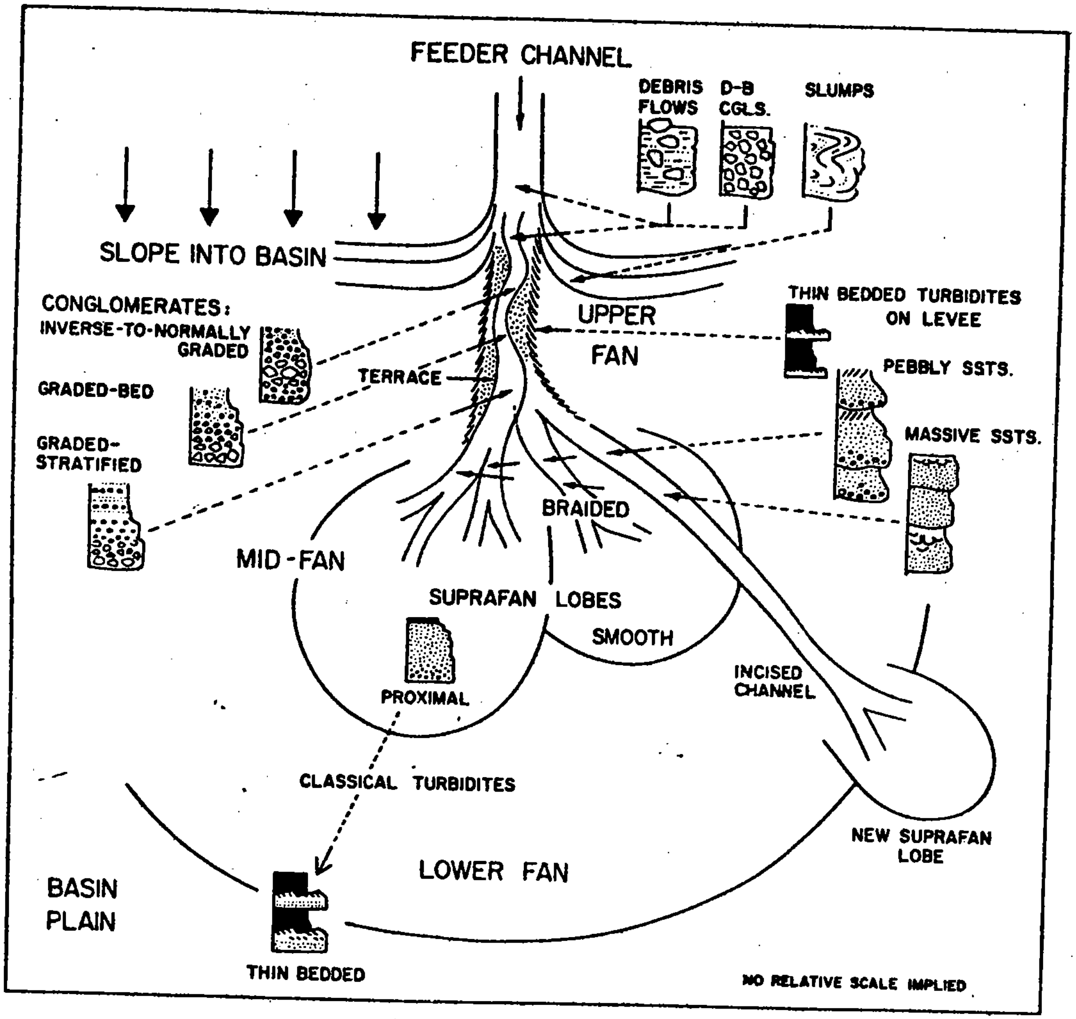

FIG. 13—Model of submarine-fan deposition, relating facies, fan morphology, and depositional environment. *D-B* indicates disorganized-bed conglomerates.

terraces (Buffington, 1964, p. 50-52; Shepard et al, 1969, Fig. 2). The middle fan is built up by deposition on suprafan lobes, which shift in position from time to time in the manner of switching delta lobes. The inner part of the suprafan lobes is characterized by shallow, nonleveed braided channels, whereas the outer part is smooth and merges imperceptibly with the smooth lower fan. This area is indistinguishable from the basin plain in most cases.

In Figure 13, the various facies of the resedimented family are shown in their interpreted positions. This interpretation is based on the detailed morphology described by Normark, the known relations among facies in ancient rocks, the abundance and depth of channeling associated with the various facies, and an unfortunately small number of recent sediment cores on modern fans.

Basin plain and lower fan—These topographically smooth, low-gradient areas (Fig. 13) are characterized by slow hemipelagic deposition, interrupted periodically by turbidity currents. Deposition on the smooth, featureless bed results in very regularly and parallel-bedded classic turbidites, which are thin bedded on the basin plain, but become thicker bedded toward the middle fan. Proximal turbidites, retaining the monotonous sand/shale interbedding of Figure 2, also suggest a smooth seafloor, probably the smooth outer part of the suprafan lobes (Fig. 13).

Suprafan lobes—Deposition in the braided-channel parts of the suprafan lobes will not result in such continuous parallel bedding as on the smooth lobe farther downslope. The most likely facies to be deposited in the channels are the massive and pebbly sandstones, both characterized in outcrop by lenticular bedding and shallow channels. As the channels braid and switch position, sand bodies will tend to coalesce, and any fine material that was deposited between channels will tend to be scoured away and not preserved. Relatively fine-grained, small-scale turbidity currents using these channels may deposit classic turbidites within them, and turbidites displaying Bouma sequences (Figs. 3, 5) are known from cores of several modern fan channels (Haner, 1971, on Redondo fan; Cleary and Conolly, 1974, on Hatteras fan). Conversely, unusually large and coarse-grained flows may transport gravel and boulders into the braided suprafan channels, dumping the coarse material as a conglomeratic lag on the channel floor. In general, however, the braided suprafan probably is dominated by massive and pebbly sandstones.

Upper fan—The main upper-fan channel (Fig. 13) is probably the area of deposition of the conglomeratic facies, if such coarse material is being supplied to the basin. The conglomerate first will be deposited in the thalweg channel, and perhaps also on the terraces when large flows spill out of the thalweg. Alternatively, conglomerates might be restricted to the thalweg channel, and sandstones could be deposited on the terraces (from finer material originally suspended higher in the flows). Relations in the upper-fan channel are conjectural because of extremely limited coring in modern examples, and because interpretations of ancient upper-fan channels have not, until very recently, been concerned with distinguishing thalweg and terrace deposits. The levees of the upper-fan channel tend to consist of fine-grained alternations of thin sandstone beds and mudstones. These belong to the thin-bedded turbidite facies, and in ancient examples easily could be confused with the similar facies on the basin plain. This problem will be considered again later.

Feeder channels—The feeder channels, or submarine canyons, act mainly as conduits for the sand and gravel moving out toward the fan. They may be plugged either by coarse materials (slumps, debris flows, conglomeratic or other coarse material as availalbe at source), or by very fine material (clays, mudstones). The latter commonly results from a relative rise of sea level, cutting the fan off from its original source of sediment; a good example of this is the abandoned, mud-filled, Mississippi feeder channel (Sabate, 1968).

STRATIGRAPHIC EVOLUTION OF FANS

The lateral facies relations already discussed and shown in Figure 13 now can serve to predict vertical stratigraphic sequences under conditions of active fan progradation. The concept of a specific stratigraphic sequence arising from fan progradation first was suggested by Walker (1966a), and a direct, explicit comparison of submarine fans with deltas was made by Mutti and Ghibaudo (1972) and Mutti and Ricci Lucchi (1972). By developing this comparison, they suggested that fan progradation would result in a coarsening-upward sequence very similar to that of a delta. They also compared the upper fan and suprafan channels to deltaic distributary channels.

It is now possible to relate specific facies to specific parts of prograding-fan systems. Progradation of the lower fan onto the basin plain should result in a sequence of classic turbidites in which the sandstone beds become slightly coarser grained and slightly thicker upsection. This is termed a thickening- and coarsening-upward sequence (C-U on Fig. 14). All of the turbidites in such a sequence would tend to be of the thin-bedded facies (sequence 1 of Fig. 14), similar to the "outer fan thin bedded turbidites" of Mutti (1977, p. 119).

Above the lower-fan sequence one would predict a sedimentary record of the middle fan. The smooth parts of the suprafan lobes would prograde in much the same way as the lower fan, and give rise to a thickening- and coarsening-upward sequence that would begin with classic turbidites, but would terminate upward in massive or pebbly sandstones (Fig. 14, sequences 3, 4; Fig. 15). Again, bed thickness, grain size, and sand/shale ratio would all increase upward. The middle fan area is gradually built up by lateral switching, coalescing, and superimposition of the suprafan lobes. Consequently, one lobe can become abandoned, and a different one become the main locus of deposition. The first lobe might receive a veneer of mudstone while the second lobe was being built, but eventual reestablishment of another lobe in the same position as the first would lead to superimposed thickening- and fining-upward sequences, perhaps separated by a veneer of mudstone.

Within the suprafan channels themselves, Mutti and Ghibaudo (1972, Table 2) suggested that a fining-upward sequence would be developed during channel filling and abandonment. The se-

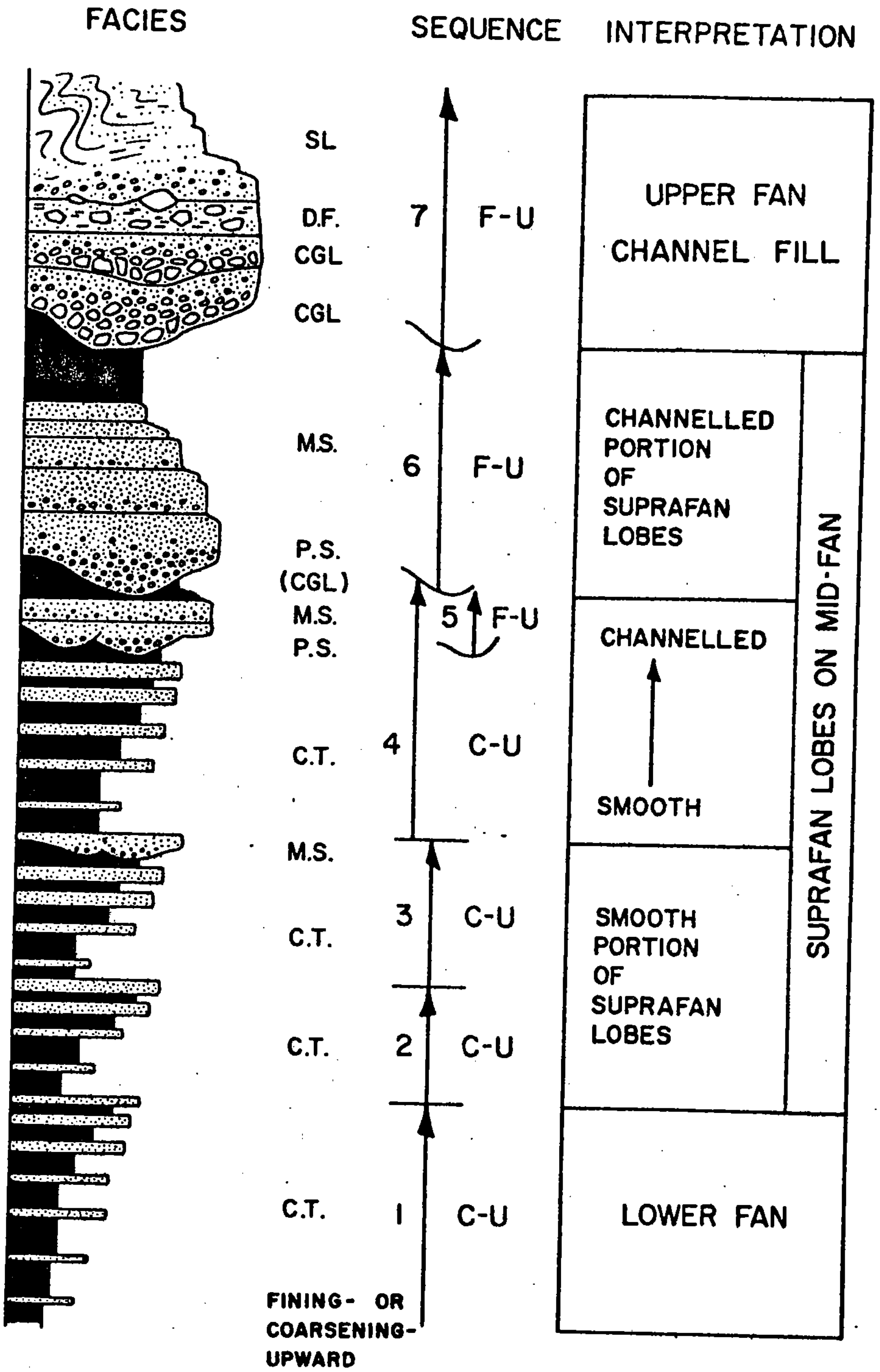

FIG. 14—Hypothetical stratigraphic sequence that could be developed during fan progradation. *C-U* represents thickening- and coarsening-upward sequence; *F-U* represents thinning- and fining-upward sequence; *C.T.*, classic turbidites; *M.S.*, massive sandstones; *P.S.*, pebbly sandstones; *CGL*, conglomerate; *D.F.*, debris flows; *SL*, slumps. Numbered sequences discussed in text.

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FIG. 15—Thickening- and coarsening-upward sequence in Jurassic turbidites, southwestern Oregon. Beds are overturned, and base of sequence (right) is shown by white line. Offset by fault runs down cliff. Lower part of sequence consists dominantly of thin-bedded turbidites, center of sequence consists of proximal classic turbidites, and upper part of sequence (from circled figure to left edge of photo where beds disappear into beach) consists of massive sandstones. Similar to sequence 3 in Figure 14.

quence would be comparable in principle (but not in details of stratification) to the filling and abandonment of a fluvial or delta-top distributary channel. Thus, in Figure 14, sequence 5 represents a fining- and thinning-upward sequence (F-U represents fining upward) from pebbly to massive sandstones, and thence to mudstones after complete channel abandonment. Similarly, sequence 6 represents the abandonment of a deeper suprafan channel, and sequence 7 represents the filling and abandonment of the main upper-fan channel. Facies in this channel could include conglomerates, debris flows, and slumps.

Thus, the overall stratigraphy developed during continuous fan progradation would consist of one major coarsening-upward sequence (Fig. 14), on which would be superimposed smaller coarsening-upward sequences in the lower part (1-4 of Fig. 14; Fig. 15), and fining-upward sequences in the upper part (5-7 of Fig. 14). Under normal circumstances, these trends in bed thickness and grain size should be readily identified on electric logs but, without any other information, they would be extremely difficult or impossible to distinguish from trends within a prograding deltaic sequence.

Several modifications of this overall model are possible, and are based upon (1) fan abandonment and (2) accelerated progradation and channel entrenchment. Fans can be abandoned by cutting off their source of sediment, most commonly by a relative rise of sea level. The shoreline and shallow subtidal areas of maximum sand supply and longshore transport shift away from the basin center, thus cutting off supply from the canyon or feeder channel heads. The end result is that only fine suspended sediment can be deposited in the feeder channel, and as a veneer on the fan. Several of the large modern fans (Mississippi, Amazon, Astoria) have been starved since the post-Pleistocene rise of sea level; in the case of the Mississippi, the abundance of supply of fine sediments from the river has led to the filling of the old feeder channel (Sabate, 1968).

In cases of accelerated progradation (possibly related to a relative lowering of sea level, or accelerated supply of sediment, or both), the upper-fan channel begins to cut downward and outward across the fan. Much of the area of the old fan can be bypassed, and a new depositional lobe constructed seaward of the old fan. The channel cutting across the present La Jolla fan is a possible example of such a system. Normark and Piper (1969) related channel incision to the last rise in sea level but, importantly, the canyon head cut landward and remained in the surf zone, assuring a continuous supply of sediment during channel entrenchment.

This type of behavior in an ancient system perhaps could be detected by unusual facies relations, for example, a channel filled with conglomeratic facies cutting into a sequence of distal turbidites believed to have come from the same source. An incised channel of this type is sketched in Figure 13, and possible examples will be discussed in the following.

EXAMPLES OF ANCIENT SUBMARINE FANS

The discussion so far in this paper has centered on resedimented facies, their relation to a fan model, and facies sequences that would be predicted if the fan prograded. In this section, I propose to examine ancient submarine fans in the light of the model, to discuss details of facies relations and, where possible, give examples from hydrocarbon reservoirs. The various morphologic parts of the fan will be discussed first, and then one complete fan will be reviewed.

Feeder Channels

The term feeder channel is preferred over submarine canyon because of the immense scale suggested by the term canyon. Feeder channels have been reviewed recently by Whitaker (1974), who tabulated channel characteristics, and gave a full bibliography. There are only a few known cases of preservation of long feeder channels, but some of them are important hydrocarbon traps. These include the Meganos (Dickas and Payne, 1967), Yoakum (Hoyt, 1959), Mississippi (Sabate, 1968), Hackberry (Paine, 1966; Benson, 1971), Gevaram (Cohen, 1976), Rosedale (Martin, 1963), and Cook (Bloomer, 1977) channels; their major dimensions are shown in Table 1.

One surprising feature of the Meganos, Yoakum, Mississippi, and Gevaram channels is their monotonous, very fine-grained fill. In the case of the Mississippi, this is known to be due to a relative rise of sea level, trapping any coarse sediment at the new shoreline and supplying only fines to the abandoned channel. These fine sediments act as an updip seal to hydrocarbons in the sediments outside the Meganos, Yoakum, and Mississippi channels. These channels all appear to have been cut by turbidity currents, and the deposits of these currents may well have formed fans spreading from the ends of the feeder channels. The coalesced suprafan sands of these and similar fans should make attractive drilling targets if they can be located, and other geologic conditions are suitable. The Meganos and Yoakum "fans," with their fine-grained channel fills, might be particularly attractive because the fill initially would have acted as an updip trap for any hydrocarbons that might have been present in the fan sediments. The survival of these stratigraphic traps obviously would depend on the subsequent structural histories of the areas.

The Gevaram Canyon, with its gray-black shaly fill (plus a few very porous sand lenses up to 10 m thick), is neither a reservoir itself, nor an updip seal. Cohen (1976) interpreted the canyon fill as the source of hydrocarbons that have accumulated in an immediately overlying reservoir (Helez formation). One would predict a fan lying at the end of the canyon, which now would be offshore, in the Mediterranean.

The Hackberry turbidite sandstones are prolific producers (Benson, 1971), and apparently were deposited in a structurally controlled trough rather than a feeder channel initially cut by turbidity currents. Under these conditions, the present submarine-fan model cannot predict whether a fan might be present downslope, or whether all turbidity-current deposition took place within the trough.

The Cook channel (lower Permian of west-central Texas, Bloomer, 1977, p. 355-357) is the smallest feeder channel listed in Table 1. Bloomer interpreted the sandstone fill of the channel as a bundle of turbidites, and the SP curves suggest a fining-upward sequence within the channel (Bloomer, 1977, Figs. 20, 21). The channel itself appears to be cut into the lower-slope environment. The North Bloodworth field is a stratigraphic trap producing from the channel-fill sandstones.

Upper Fan

The upper fan is characterized by one relatively deep, leveed channel that only rarely shifts in position. The coarse deposits within the channel tend to be surrounded by the finer levee deposits on either side. Because of the scale of these channels, tens or hundreds of meters deep, and hundreds of meters to kilometers wide, very few have been identified in outcrop. One possible example from the Quebec Appalachians is discussed here,

Table 1. Characteristics of some Feeder Channels

Channel	Age, Location	Length (km)	Width (km)	Depth (m)	Fill
Meganos	Late Paleocene, Sacramento Valley	80+	3.2 to 9.7	600	Silty shales
Yoakum	Mid-Eocene, Texas	80	16	900	Silty shales, more sand up channel
Mississippi	Pleistocene, Coastal La.	about 80	3.3	600	Clay
Hackberry	Oligocene, S.W. Louisiana	24	14	200+	Turbidites and shales
Rosedale	Late Miocene Bakersfield, Cal.	about 10	2.6	400	Turbidites and shales
Gevaram	Early Cretaceous, Israel	16+	up to 15	938	Gray-black silty shale
Cook	Early Permian, West-central Texas	5+	1.7	30+	Turbidites and shales, fining-upward sequence

and others will be discussed in the section on the Shale Grit (and see Walker, 1966a, b).

The Grosses Roches conglomerate in Quebec shows a channelized thinning- and fining-upward sequence; a diagrammatic section compiled from Hendry (1973) and from my own field notes is shown in Figure 16. The main channel contact itself (Fig. 17) is fairly steep, and cuts into bedded and massive silty mudstones without any evidence of interbedded turbidites. The observed depth of erosion is about 20 m. The lowest observed part of the fill consists of very lenticular sandstone and conglomerate beds that fit well with the disorganized-bed model (Fig. 10). A preferred fabric was observed in only one bed, and there was little evidence of grading or stratification. Above the channelized conglomerates and lenticular sandstones there is a unit of massive sandstones, followed by poorly exposed classic turbidites (Fig. 16). These in turn are cut by a second conglomerate-filled channel.

The Grosses Roches conglomerate is assigned tentatively to the upper fan (or possibly upstream part of the braided suprafan) because of the monotonous silty mudstone outside the channel, and the disorganized-bed conglomerates within the lower part of the channel fill. It is also a good example of a channelized thinning- and fining-upward sequence. The Grosses Roches conglomerates now outcrop only on one thrust slice, and no predictions as to the facies upstream and downstream can be checked.

The channel is relatively shallow compared with modern upper-fan channels (Normark, this issue). However, the 20-m (minimum) Grosses Roches channel and the 20 to 50-m channels in the Shale Grit (Walker, 1966b, discussed later) are among the deepest observed in outcrop. It is also possible that the observed channels are thalweg channels, incised into the deposits on the floor of a much deeper inner-fan channel. This suggestion has been made for deposits in the Cambrian-Ordovician Cap Enragé Formation (Quebec Appalachians; Johnson, 1974), where the larger channels themselves, if they exist, are not observed. In recent sediments, the best example of a meandering thalweg channel cutting through sediments on an essentially flat main-channel floor is in the La Jolla fan (Shepard et al, 1969, p. 392). The thalweg channel here is roughly 30 to 40 m deep and about 250 m wide (within a main valley 1.5 km wide and 100 to 120 m deep; these measurements are close to those of the Shale Grit channels discussed later; Fig. 22).

Upper-fan channel deposits, flanked by fine-grained levee sediments, are potential reservoirs. This is particularly so if the system is abandoned because of sea level rise, and a fine grained mud-

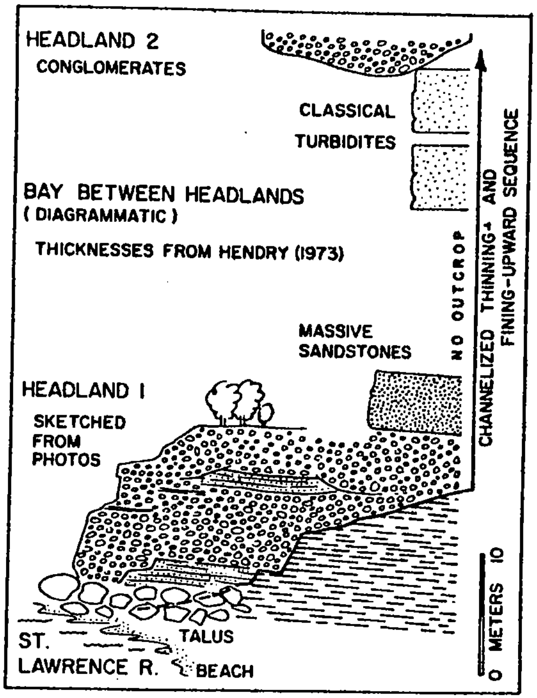

FIG. 16—Thinning- and fining-upward sequence within channel in Ordovician Grosses Roches conglomerate, Quebec Appalachians. *Headland 1* is sketched from photos (see Fig. 17); rest of sequence has been added in correct stratigraphic position from exposures of massive sandstones and classic turbidites in bay west of headland 1.

stone drape is laid down over the upper-fan channel deposits, and updip, in the feeder channel. The preservation of such a reservoir obviously depends on the subsequent structural history of the area.

Mid-Fan: Braided Channels on Suprafan Lobe

This part of the fan is potentially one of the best petroleum reservoirs; the sediments are fairly coarse grained, and lateral and vertical coalescing of channels gives rise to extensive reservoir sands that can be sealed by shale beds. The shale beds are not deposited one by one on top of each turbidite; rather, a thick shale bed (several meters) blankets one suprafan lobe when it is abandoned completely by channel switching (Fig. 18). Upcurrent, conglomerates may become more conspicuous if coarse material were available, and downcurrent, the massive and pebbly sandstones will tend to pass into classic proximal turbidites.

The first example of rocks interpreted as a braided suprafan-lobe deposit is the Capistrano Formation (upper Miocene) at San Clemente, California (Walker, 1975c). This classic area contains a series of eight channels nested within each other, and filled variously with pebbly and massive sandstones, some classic turbidites, and two conglomeratic beds. A map of the cliff face is shown in Figure 19. Only one wall of the channels (numbered in Fig. 19) can be seen, and the dip of the wall is between 5 and 20°. The estimated depths of the channels are 20 to 25 m (Walker, 1975c, p. 923). Channels 2 to 4 trend about 270 to 295°, and a second (and distinct) group of channels (5 to 8) trend about 235 to 240°. The entire channel complex is cut into bioturbated mudstones with rare, thin silty turbidites.

The channel fills are uncommon in that seven out of eight begin with a claystone or silty mudstone drape on the channel walls, 30 cm to 2.0 m thick. There is some evidence to suggest that these drapes were deposited by turbidity currents because, in one channel, sandy turbidites near the base can be seen to pass up the wall into silty mudstones. Presumably the sand load of the current moved close to the bed, and the finer suspended load was deposited higher on the channel wall. Most of the fill consists either of graded pebbly sandstones (lamination and cross-stratification very uncommon) or of classic turbidites. According to the model established earlier in this paper, the association of pebbly sandstones and classic turbidites would suggest deposition on the outer part of the braided part of the suprafan lobe, at the point where the channels are dying out and the topography is becoming smoother.

Thinning- and fining-upward sequences are not present in all the channels, but can be identified in the channel 5-6-7 complex (Walker, 1975c, p. 923).

The Capistrano Formation also crops out at Dana Point, a few miles north of San Clemente (Bartow, 1966; Normark and Piper, 1969; Piper and Normark, 1971). The dominant facies are conglomerates, graded pebbly sandstones and massive sandstones, with some slumping and extensive channeling (including the Doheny channel). In their reinterpretation, Piper and Normark (1971) specifically referred their "lower sands and conglomerates" (not part of the Doheny channel) to a suprafan depositional environment. Again, the main criterion for such an interpretation is the presence of channeling, in particular association with the massive and pebbly sandstone facies.

Because the fan model discussed in this paper dates from the work of Normark (1970), there are relatively few ancient fans that have been inter-

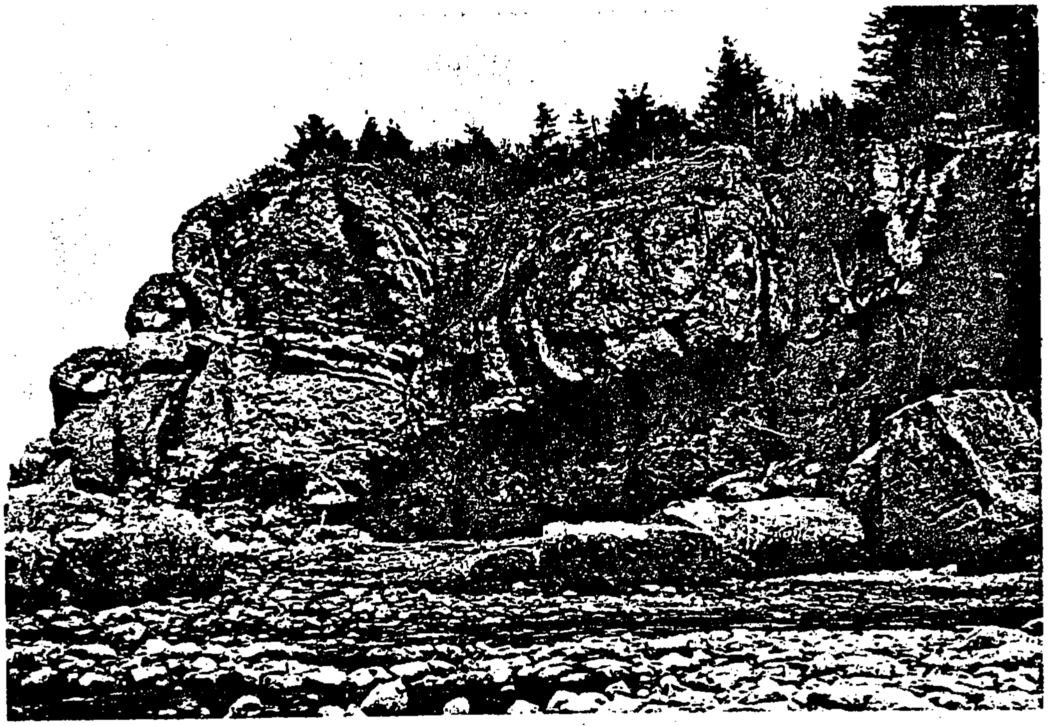

FIG. 17—Ordovician Grosses Roches conglomerate, Quebec Appalachians, in headland 1 (Fig. 16). Channel cuts into silty shales without turbidites (cliff and wave-cut platform), and is filled mostly by disorganized conglomerates and very lenticular sandstones. Lenticularity is caused mostly by erosion by overlying conglomerates. Channel base about 18 m above wave-cut platform at right edge of photo.

preted using Normark's terminology. Nevertheless, the conglomerate, pebbly sandstone, and massive sandstone facies of the braided suprafan are distributed abundantly in California, and I suggest that such units as the Cabrillo and La Jolla formations (San Diego–La Jolla area), the Cretaceous rocks of the Simi Hills (Colburn and Fritsche, 1973), the Matilija Sandstone (Link, 1975), and the Repetto Formation of the Los Angeles basin could all be reinterpreted, at least in part, with reference to the braided suprafan. In the Ventura basin, parts of the Repetto also may represent braided suprafans, an interpretation based upon isopach maps recently published by Hsü (1977). In Hsü's Figure 18, the producing AO_1 sand of the Ventura field is shown over an area 5 km long, 2.5 km wide. Isopachs show the sand in branching and rejoining elongate stringers, a pattern that essentially is braided. Individual sand stringers (? channels) are roughly 250 to 450 m wide, and up to 13 m thick. The sands pinch out into shales to the north and west, and the stringers are oriented ESE to WNW, suggesting turbidity-current flow toward the west-northwest (Hsü, 1977, p. 143-150). There is little or no evidence in the electric logs published by Hsü (1977, Fig. 4) that the sands in these possible braided channels are in thinning- and fining-upward sequences.

Implications of Thinning- and Fining-Upward Sequences: Fan-Channel Deposits?

It has been suggested in the foregoing that thinning- and fining-upward sequences form by the progressive abandonment of channels in upper-fan or braided-suprafan areas. The first interpretations along these lines were suggested by Mutti and Ghibaudo (1972) and Mutti and Ricci Lucchi (1972). The sequences recently have been emphasized by Ricci Lucchi (1975), but he did not discuss their origin in much detail.

Thinning- and fining-upward sequences, of the order of 10 to 50 m (and possibly to 100 m) thick, should be identified readily on electric logs. In a submarine-fan context, the problem is whether or not the sequences are always (or mostly) related

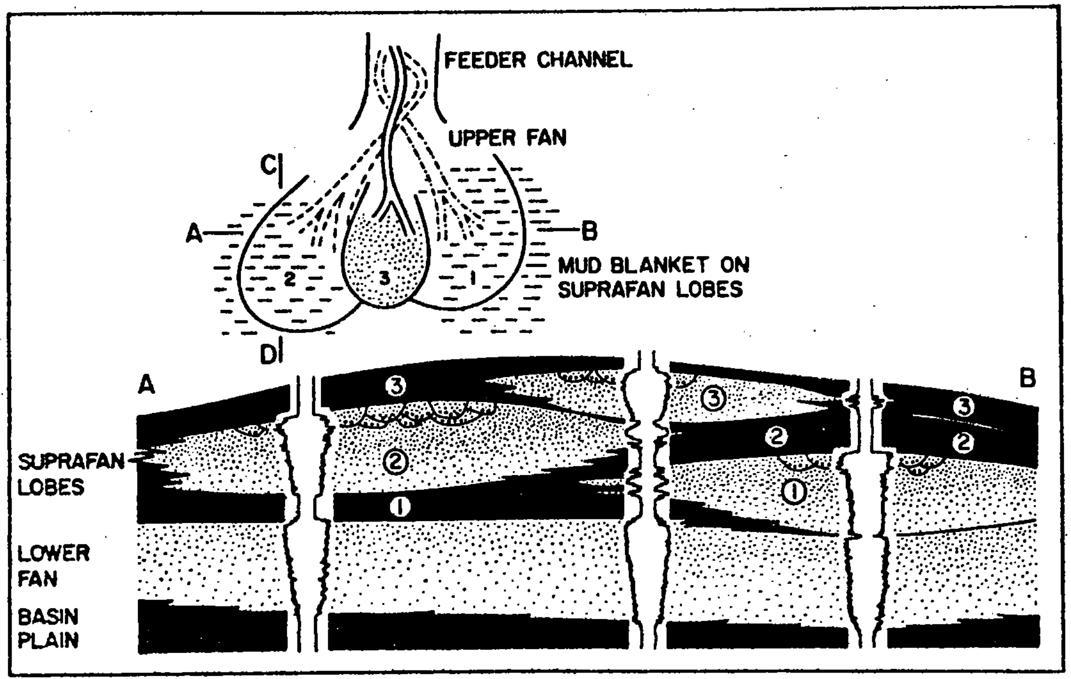

FIG. 18—Hypothetical vertical cross section across prograding lower-and middle-fan system. Lower-fan sequence is coarsening-upward, and each suprafan lobe has coarsening-upward sequence, from thin-bedded turbidites to channelized massive and pebbly sandstones. Each suprafan-lobe sequence also shales out laterally into mudstone drape that covers adjacent parts of fan. Sequence shown in cross section is result of suprafan-lobe switching, from position 1, to 2, to 3 (see plan view, upper part of diagram). Lobe switching may be related to changing meander patterns in upper-fan channel. Hypothetic electric logs illustrate coarsening-upward prograding-lobe sequences, fining-upward channel-fill sequences, and highlight problems of correlation in such a system. Compare with Figure 21, which is interpreted to represent cross section *C-D* of plan view of Figure 18.

to channel filling. The channel-fill interpretation suggests that a channel can be used as a funnel for turbidity currents, perhaps for a long time, until one particularly large, coarse flow partly plugs the base of the channel. During this time, the channel may have been nondepositional, or the channel floor may have been aggrading at about the same rate as the levee, thus maintaining the channel topography. However, after deposition of a large plug in the base, the channel may not be deep enough for subsequent flows which would overtop the banks and lead to eventual channel diversion. Thus the old channel gradually would be abandoned, most of the flows going elsewhere, and would be plugged up gradually with thinner and finer grained beds. These in fact may be overbank deposits from other more active channels.

This interpretation of thinning- and fining-upward sequences is perhaps the most plausible, unless one appeals to progressive changes of volume and grain size of material supplied at the basin margin (perhaps related to long-term tectonic controls).

The relation of thinning- and fining-upward sequences to channels has important implications in basin analysis and the prediction of facies distributions. The Cretaceous conglomerates at Wheeler gorge, California (Walker, 1975b), and the Jurassic Otter Point Formation of southwestern Oregon (Walker, 1977) both contain spectacular thinning- and fining-upward sequences which pass from conglomerates into massive sandstones, classic turbidites, and dark mudstones. In neither example is there any field evidence of channeling. The problem is easy to state but hard to answer. Do the sequences necessarily imply channeling? If so, one would predict a sandy fan system a little farther downcurrent (as was predicted earlier for the Meganos and Yoa-

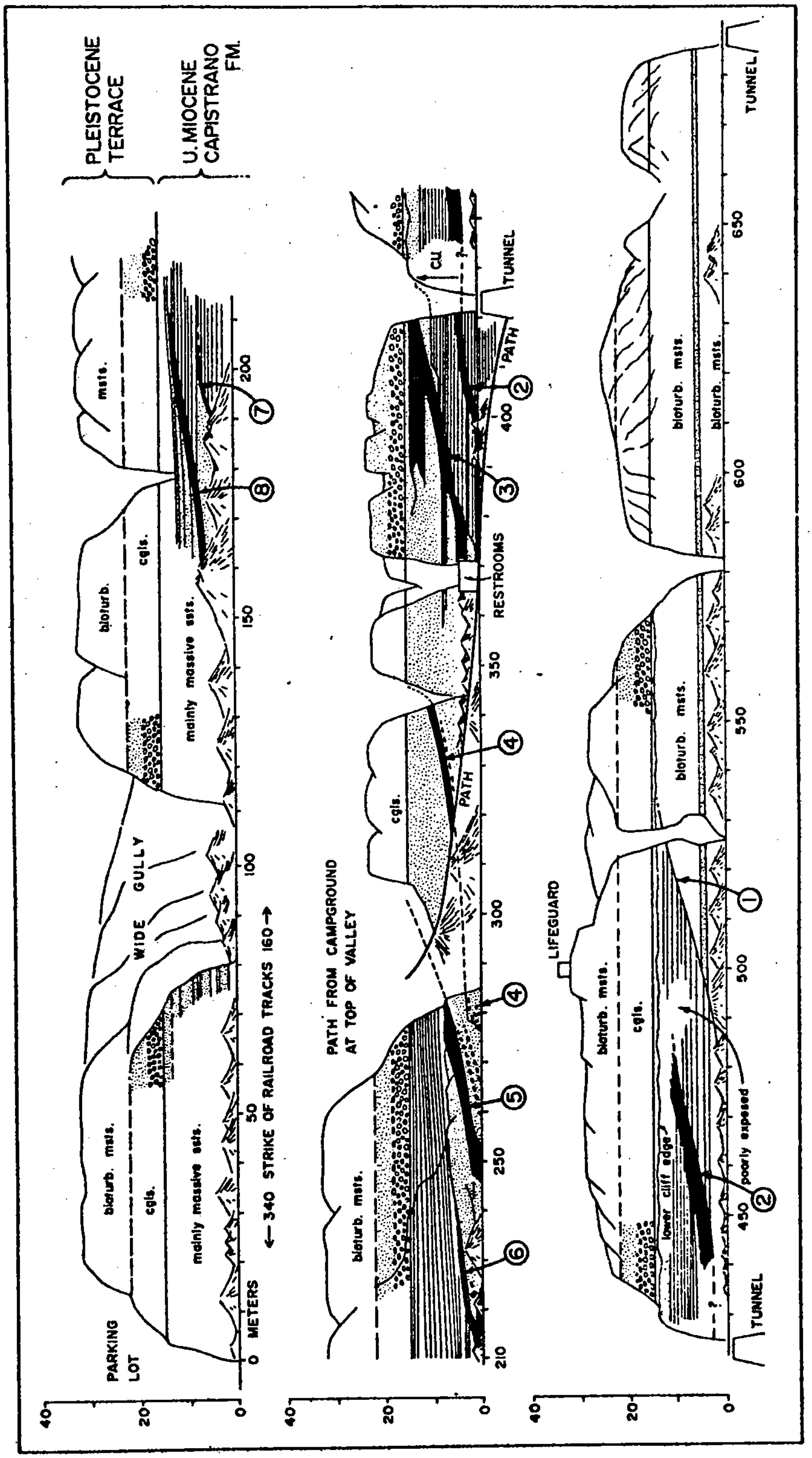

FIG. 19—Measured profile of cliff face at San Clemente, California. Individual channels are numbered, and black layers represent mudstone drapes on channel walls. Within Capistrano Formation, stippling represents massive and pebbly sandstones; horizontal ruling represents classic turbidites. Upper conglomerates and bioturbated mudstones form part of Pleistocene terrace. Vertical = horizontal scale, in meters.

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kum channels). If the major conglomeratic thinning- and fining-upward sequences do not imply channeling, there is no model for predicting the facies downcurrent or for explaining the sequences themselves.

Incised-Fan Channels

It was emphasized earlier that the basic fan model describes the facies developed during steady progradation. However, under some circumstances, fan channels can become incised. If this happens, turbidity currents will bypass the fan, and the channels will tend to lengthen as they become more and more incised. As a result of lengthening, the channels will cut into previously deposited classic turbidites of the smooth suprafan lobe (Fig. 13). Such channels would not be predicted by the model to cut into classic turbidites unless they were to some extent incised.

A good example of this is the Cambrian St. Roch Formation at L'Islet Wharf, Quebec Appalachians (Hubert et al, 1970; Rocheleau and Lajoie, 1974). Here, a channel (Fig. 20) with depth of erosion exceeding 50 m cuts into a thickening- and coarsening-upward sequence of classic turbidites. The turbidites are neither truly proximal nor truly distal—they are somewhere in between. The flow direction for the turbidites averages 170° (my measurements, 19 readings); erosional markings on the channel base average 210° (flutes, grooves, scours; my measurements, 6 readings). It is therefore reasonable to assume

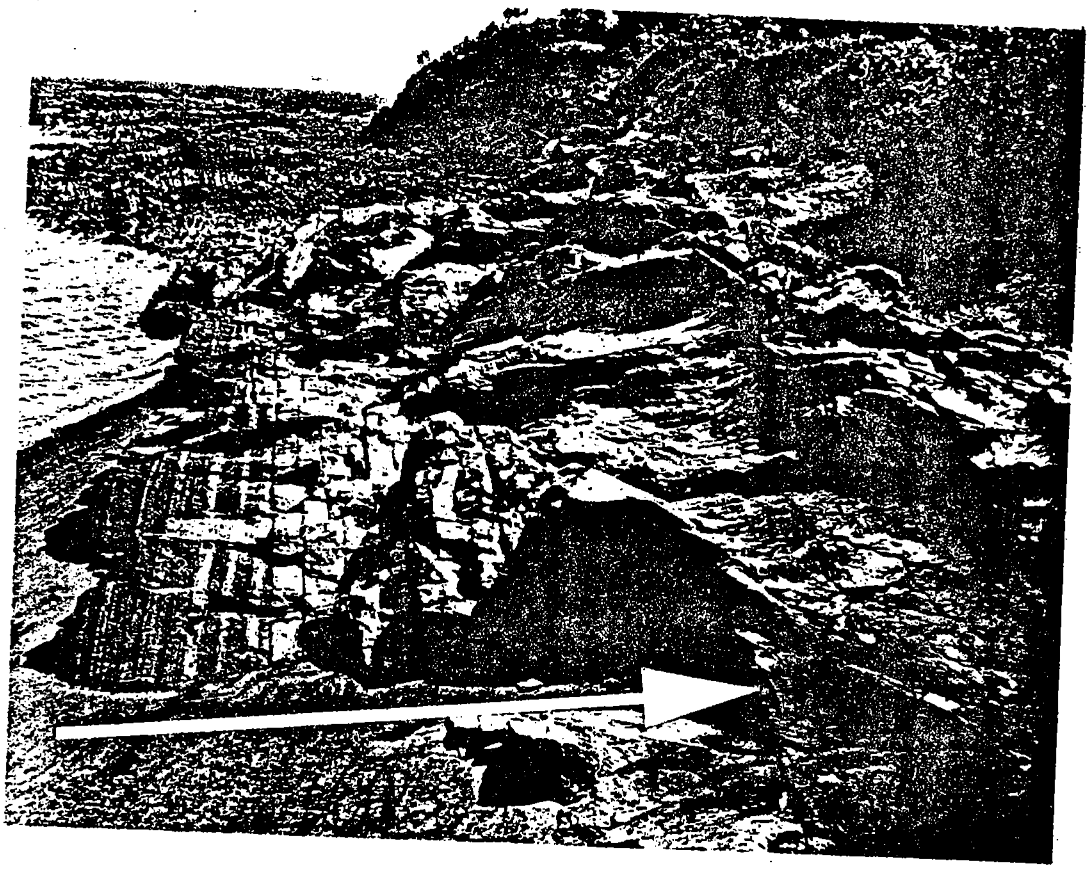

FIG. 20—Channel complex in Cambrian St. Roch Formation, Quebec Appalachians. Stratigraphic top on right. Channel (foreground and cliff in background) cuts into coarsening-upward sequence of classic turbidites (upper left). Channel fill consists of graded-bed and graded-stratified conglomerates, and massive sandstones. Arrow (foreground) shows basal, 7-m thick, graded-stratified conglomerate grading into massive sandstone.

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that the turbidites were supplied from the same source as the channel fill, and that both are related parts of the same fan complex.

The channel itself has been filled in two or three stages. The lowermost 7 m (Fig. 20) consists of a graded-stratified conglomerate (3 m) that passes upward into massive sandstones (4 m). Higher in the channel, there are more alternations of conglomerate and massive sandstone that imply stages of filling and partial abandonment, followed by renewed scouring, and renewed filling. It is significant that the conglomerate facies is graded stratified (Fig. 20), because it was predicted in Figure 10 that this facies would be farthest downcurrent of any of the conglomerate facies. Hence of the various conglomerate facies, the graded-stratified would be the most likely in an extended, incised channel juxtaposed with classic turbidites. This is exactly the situation at L'Islet Wharf.

A second possible example of an incised channel is the Doheny channel at Dana Point, California. This channel has an exposed depth of about 20 m, and has been illustrated excellently by Bartow (1966) and Piper and Normark (1971). The basal channel fill consists of chaotic coarse massive sandstones. Individual beds are irregular, in places deeply channelled, and have gravelly or pebbly bases. The upper part of the channel fill is bedded, consisting of turbidites tens of centimeters thick, and extending laterally for over 100 m. Thus the fill is generally thinning- and fining-upward. The channel cuts into silts with interbedded fine sands 10 to 50 cm thick, interpreted as turbidites. The juxtaposition of a deep channel with coarse and pebbly sandstones at its base, cutting into a unit composed dominantly of siltstones, suggests that the channel is incised into the fan surface (Normark, personal commun., 1977).

Interpretation of channels incised into classic turbidites leads to the prediction of a new suprafan lobe beyond the incised channel (Fig. 13). Prediction of such lobes would be of possible importance in hydrocarbon exploration. A prediction of this type has been made by Normark (1974, p. 66) for the La Jolla and Monterey systems. The present La Jolla fan valley is incised into the fan as a result of headward erosion during the last rise in sea level. The head of the canyon remained in the shore zone, resulting in continuous sediment supply rather than abandonment and blanketing by mud. Beyond the foot of the present fan valley, about 15 km southeast and in water about 100 m deeper, there is an area of "hummocky suprafan morphology" (Normark, 1974, p. 66), but "further study, preferably with the deep tow, would be necessary to substantiate this observation."

Smooth Suprafan Depositional Lobes and Outer Fan

These two areas are very difficult to distinguish, both physiographically and sedimentologically. They lack two of the major features attributed to submarine fans, channels, and the massive and pebbly sandstone facies, and their recognition may depend upon an outward fanning of paleocurrent directions, and evidence of coarsening-upward facies sequences. Even this latter criterion may not be diagnostic, because thickening- and coarsening-upward sequences could develop in any prograding wedge of turbidites, not necessarily associated with submarine fans (Walker and Sutton, 1967). Nevertheless, a fan situation appears to be the most likely for the thickening- and coarsening-upward sequences, and exploration in an upcurrent direction may locate a coarse, coalesced sand body representing the braided suprafan.

There are probably a large number of thickening- and coarsening-upward sequences of classic turbidites in North America (Fig. 15), and particularly in California but, unfortunately, very few have been described. The best known examples are from the Mediterranean area, particularly the Messanagros Sandstone (Oligocene–lower Miocene, Island of Rhodes, Greece; Mutti, 1969) and the San Salvatore Sandstone (lower Miocene, Appennines, Italy; Mutti and Ghibaudo, 1972). The sequences vary from about 5 to 45 m (Ricci Lucchi, 1975, Tables 1, 2), and may include a few, to as many as 37 individual coarse layers.

Obviously it would be of predictive importance if the thickness of these sequences, and number of coarse beds within them, were related to features on the braided suprafan (for example, channel depth, bed thickness, and grain size). Perhaps a thickening- and coarsening-upward sequence that itself is rather thin (<5 m) implies only a minor progradation, possibly related to rather shallow suprafan channels and very rapid channel switching. Conversely, a thicker (20 m +) thickening- and coarsening-upward sequence would imply more stable, and probably deeper, suprafan channels. Unfortunately, there are no data to substantiate these hypotheses.

Suprafan Lobe Switching: Reservoir Implications

Normark (1970, 1974, this issue) has emphasized that suprafan lobes tend to switch in position periodically. The control may be either a switch in position of the upper-fan channel, or a switch in position of the meandering thalweg channel (Fig. 18). The result is the relatively abrupt abandonment of one lobe, and the beginning of progradation of another. After abandonment, the only sediment reaching the old lobe will consist of suspended fine sediments and gradually, during progradation of the new lobe, the old one will be smothered by a mud blanket. These mud blankets are potentially excellent sealing layers for hydrocarbons that may be trapped in marine and pebbly sandstones of the suprafan lobe.

Neither the thicknesses of the suprafan lobes, nor of the mud blankets, are known from recent sediment studies. Few ancient studies refer specifically to suprafan lobes and blanketing mudstones. Reinterpretation of some examples described in the literature, together with my own observations, suggests that average suprafan-lobe mudstone blankets range from 5 to 50 m (Cretaceous of Simi Hills, California; Upper Carboniferous of northern England, Walker, 1966a; Ventura basin, Hsü, 1977). This thickness of mudstone would form a very effective barrier to vertical hydrocarbon migration, and each individual suprafan lobe could be sealed off as an individual reservoir (Fig. 18). Similar shale layers overlie sands, some of them gas producers, in the Forbes Formation (Grimes gas field, California; Weagant, 1972, and personal commun., 1977). The sands are from about 10 to 60 m thick, but the blanketing shales are more variable, ranging "from a few tens to several hundred feet" (Weagant, personal commun., 1977).

In lateral extent, suprafan lobes on modern fans are roughly equidimensional and from 10 to 15 km across (up to 50 km on Monterey fan). Their thickness can be estimated only from interpretations of ancient rocks but, for individual lobes, the range may be of the order of 20 to 120 m.

The relations between suprafan-lobe sandstone bodies and blanketing shales, particularly the shaling out of the sands at the margin of the lobe, are well displayed in electric logs of the Ventura field recently published by Hsü (1977, Fig. 4). A simplification of some of these logs from the middle producing zone is shown in Figure 21. Between markers DA and DC in well 6 there appears to be a thinning- and fining-upward sequence about 40 m thick. It grades laterally into siltstones and mudstones about 30 m thick in well 1; these mudstones appear to blanket the underlying sand body (DC to DF, Fig. 21). The sand body between markers DC and DF appears to contain a thickening- and coarsening-upward sequence in well 1 about 65 m thick, which also partly shales out laterally toward well 6. The generalized paleoflow is approximately westerly (Hsü, 1977), roughly from well 6 toward well 1. The shaling out therefore is seen parallel with the paleoflow direction, and this is illustrated diagrammatically by the line CD in Figure 18. The shaling out takes place over a distance of about 8 km, but this does not necessarily define the size of the suggested suprafan lobes. If the submarine-fan model is used in more detail to interpret these

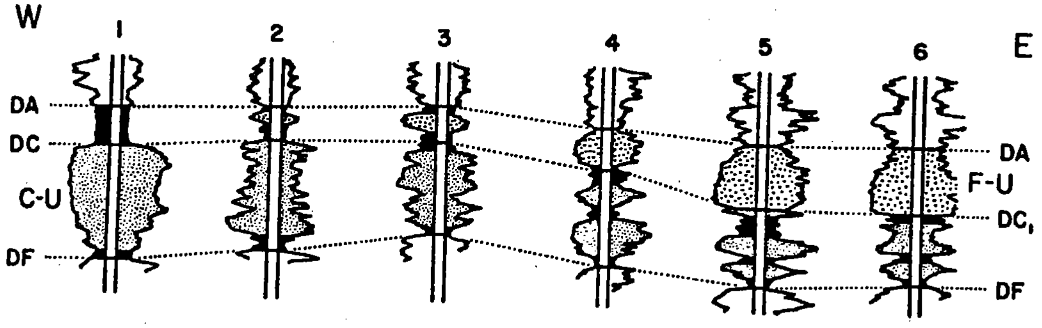

FIG. 21—Simplification of Hsü's (1977, Fig. 4) electric-log correlations of middle producing zones, lower Pliocene Repetto Formation, Ventura field, California. Correlations between E-log markers *DA*, *DC*, and *DF* are shown, and fining-upward (*F-U*) sequence in well 6, and coarsening-upward (*C-U*) sequence in well 1 are identified. Sandstones shale out, *DA* toward west (downcurrent) and *DC* toward east (upcurrent). This east to west downcurrent trend could be representative of cross section along *CD* of Figure 18. In order 1 through 6, the wells illustrated are Shell Taylor 505, Shell Taylor 349, TWA Hartman 44, TWA Lloyd 161, TWA Lloyd 165, and TWA V.L. & W. 84.

electric logs, it might be suggested that the thinning- and fining-upward DA-DC sands in wells 5 and 6 (Fig. 21) represent channel-fill sands. The thickening- and coarsening-upward DC-DF sand in well 1 is more suggestive of the unchanneled part of a prograding suprafan lobe. Thus the sandstone-mudstone packages between the electric-log markers appear to fit the switching suprafan-lobe model rather well.

THE SHALE GRIT: A COMPLETE ANCIENT SUBMARINE FAN

Several formations, or parts of formations, have been assigned to various depositional environments on submarine fans, and examples have been given earlier. However, there are very few descriptions of complete ancient submarine fans. By complete, I imply a prograding sequence from basin-plain turbidites, upward through fan deposits into silty mudstones deposited on a prograding slope. The fan deposits themselves must show evidence of channeling, and of the various facies sequences discussed earlier.

One of the best examples is the Shale Grit fan of northern England (Walker, 1966a, b). The term "Shale Grit" is a formal stratigraphic unit (dating from 1811) of formation status, and the fan is of Namurian (*Reticuloceras* R_{1c} zone) age (late Carboniferous; Namurian is roughly equivalent to Morrowan plus Atokan).

The fan was deposited in a deep basin between two older limestone "highs" (Fig. 22). Supply of coarse-clastic material was consistently from the north or northeast, and the entire fan sequence, plus associated facies, represents the filling of the basin. The stratigraphic sequence is shown in Table 2. The original slope into the basin was created by block faulting at the southern margin on the northern limestone "high," and the stratigraphic sequence from the Edale Shales up into the Kinderscout Grit represents the southward progradation of facies down the basin, building up the observed stratigraphic sequence.

The initial clastic material being supplied to the southern (distal) end of the basin was black mud (up to 250 m thick), followed by classic turbidites of the Mam Tor Sandstones (100 to 130 m). According to Allen (1960, p. 194), sandstones increase in abundance upward and, by further thickening and coarsening, pass up into the Shale Grit. Thus the Mam Tor Sandstones would appear to constitute one overall thickening- and coarsening-upward sequence, and probably can be assigned to the basin-plain and lower-fan areas of the present submarine-fan model. The base of the Shale Grit was defined by the incoming of massive sandstones—beds consistently thicker than 60 cm, with many composite amalgamated sandstone beds without interbedded shales (Fig. 22). The sandstones are coarse (maximum grain size 3 to 4 mm), and commonly pebbly (up to 1 cm), and clearly belong to the massive and pebbly sandstone facies defined earlier in this paper (they originally were termed "facies C" by Walker, 1966a). As well as these facies, the Shale Grit also contains classic turbidites and thinly laminated dark mudstones. In the lower part of the Shale Grit (informally designated), classic turbidites are more abundant than the massive sandstones, and there are several thickening- and coarsening-upward sequences that begin with dark mudstones, and pass upward into classic turbidites and finally into massive sandstones (Fig. 22). I did not recognize these sequences as such in 1966, although several can be discerned in my original published stratigraphic sections (Walker, 1966a, Fig. 4, redrawn as Fig. 22 of this paper). Many more can be recognized in my unpublished sections (Walker, 1964), and they vary in thickness from a few meters to nearly 60 m. Only one major channel (> 2 m deep) is known in the lower Shale Grit and hence, with the evidence of the facies, facies sequence, and general absence of channels, I now assign this part of the Shale Grit to the smooth outer parts of suprafan lobes. The thinly laminated dark mudstones in the Shale Grit probably represent quiet blanket deposition on top of an abandoned lobe, while a new lobe was forming elsewhere (Figs. 22, 23). They vary in thickness from 3 to 30 m, averaging about 10 m, and can be mapped continuously in the field for up to 10 km. The sequences of turbidites and massive sandstones between dark mudstones average about 30 m in thickness. It follows that an "average" prograding outer suprafan lobe is approximately 30 m thick and 4 to 10 km wide perpendicular to flow direction (Walker, 1966a, Table 3); this "average" lobe then was abandoned and draped with 10 m of dark mudstone.

The upper part of the Shale Grit differs from the lower part in two important ways; (1) the massive and pebbly sandstones are much more abundant than in the lower part and (2) there are nine major channels with observed depths up to 20 m (Fig. 22). The association of these particular facies with channels strongly suggests a braided-suprafan depositional environment. Thickening- and coarsening-upward sequences are present, up to 120 m thick, but contain coarser grained facies than the sequences in the lower part of the Shale Grit. The sequences contain nothing but massive and pebbly sandstones in their upper parts, and scouring and bed amalgamation is common. The major channels in the upper Shale Grit were de-

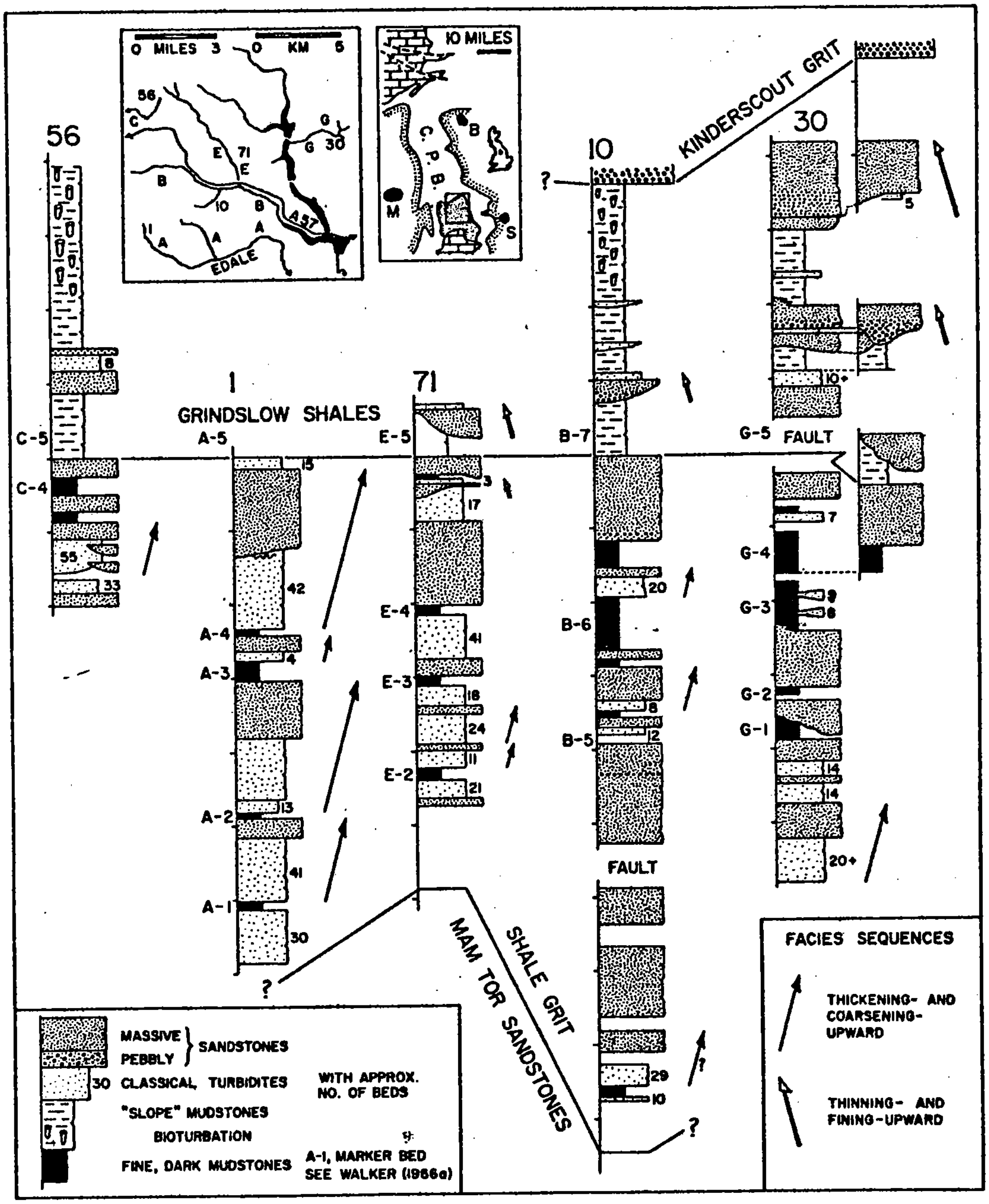

FIG. 22—Measured sections of Shale Grit and Grindslow Shales. Datum is at base of Grindslow Shales; thickness marks on left of columns are 25 m apart. Small inset map shows location of area at southern end of central Pennine basin, *C.P.B.*, between Sheffield, *S*, and Manchester, *M*. Larger inset map shows subdivision of area into smaller areas, *A*, *B* etc., in which mudstone marker beds can be mapped continuously. Numbers indicate location of measured sections. Highway A-57 links Sheffield and Manchester.

Table 2. Stratigraphy of Shale Grit Fan and Associated Rocks*

Formation	Approximate Thickness (m)	Lithology and Interpretation
Kinderscout Grit	150	Mainly coarse sandstones, some shales. Shallow water deltaic complex. (Collinson, 1969)
Grindslow Shales	100-120	Massive and laminated mudstones and shales. Mainly prograding slope deposits (Walker, 1966a, b; Collinson, 1969). Upper fan channels at base.
Shale Grit	130-240	Sandstones and shales. The upper part was mainly deposited on the braided suprafan; the lower part was deposited on smooth suprafan lobes.
Mam Tor Sandstones	100-130	Classical turbidites deposited on lower fan or basin plain (Allen, 1960).
Edale Shales	250	Black basinal mudstones.

* All formations are Late Carboniferous (Namurian) in age. Most Edale Shales belong to zones E, H, R_{1a} and R_{1b}. Uppermost Edale Shales, and all other formations, belong to zone R_{1c}.

scribed by Walker (1966b). Channel directions, interpreted from the strike of the channel walls, are toward south and southeast; this is in agreement with sole marks on the associated turbidites and massive sandstones. The fill is commonly fining upward (Fig. 22; Walker, 1966b, p. 1902), and there is evidence within the channel fills of slight channel shifting and minor periods of renewed scouring during channel filling. Again, this is very consistent with a braided-suprafan interpretation.

The upper fan, characterized by major channels stratigraphically surrounded by mudstones (Mutti and Ghibaudo, 1972), probably is represented by the lowermost part of the Grindslow Shales (Fig. 22). Here, there are seven major channels filled with fining-upward sequences of pebbly and massive sandstones. These channels probably merge imperceptably upslope into feeder channels, and the separate identification of the two is not possible. These channels have observed depths of up to 50 m, and mapping suggests widths of at least 1 km (Walker, 1966b). Many of them appear to be complex, multiple cuts. The silty mudstones outside the channels represent the bottom of the prograding slope and most of the sediment probably was deposited rapidly by spill-over from turbidity currents flowing down the feeder, and upper-fan channels.

The overall interpretation is shown in Figure 23. It is clear that the stratigraphic sequence (Table 2) represents an overall coarsening-upward prograding submarine fan. The system appears to have been fed by a very actively prograding, major delta (Pennine delta), and the slope and upper-fan environments, commonly not preserved, here have been buried rapidly by the delta.

The Shale Grit fan is particularly important because the mud blankets between individual suprafan lobes can be mapped in the field (Walker, 1964), and hence a quantitative reconstruction of the lobes can be attempted. It highlights the type of information that must be obtained from other ancient fans if a "general fan model" is to be used quantitatively in hydrocarbon exploration.

CLASSIC TURBIDITES WITHOUT SUBMARINE FANS

It is clear from the foregoing discussion that submarine fans are characterized by relatively coarse-grained facies associated with channels. In the absence of massive and pebbly sandstones, and in the absence of channels meters or tens of

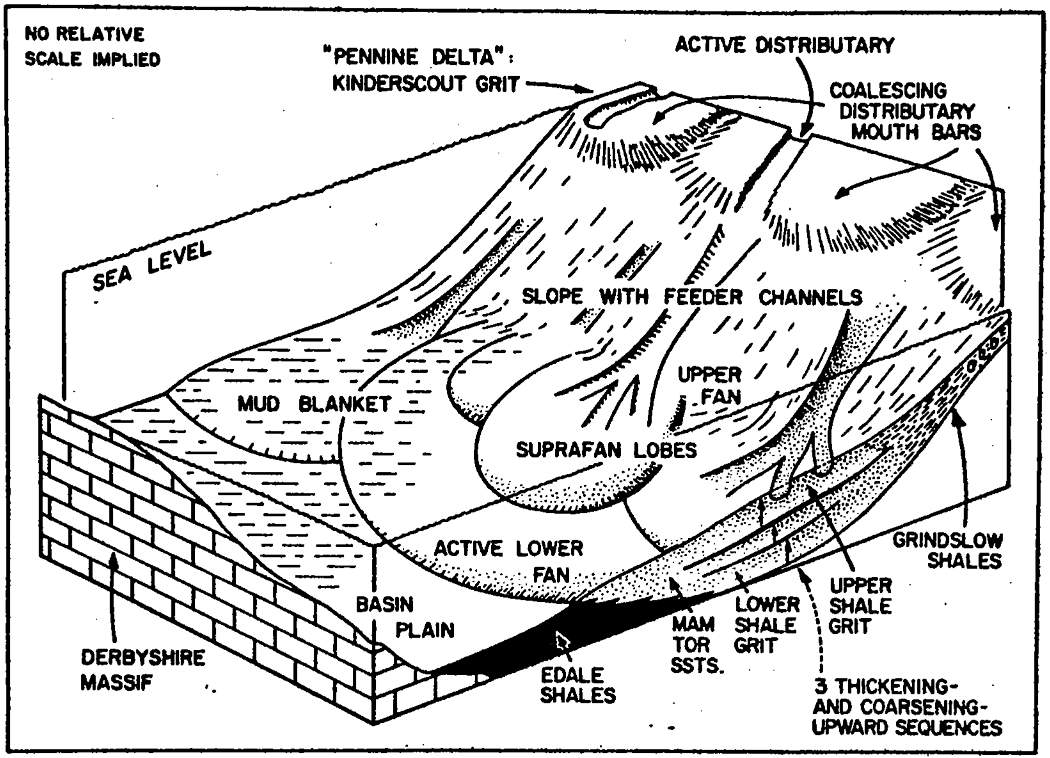

FIG. 23—Block diagram restoration of Shale Grit and associated formations. Modified from Walker (1966a). Compare with Figures 13 and 18.

meters deep, the fan model may be inappropriate or incorrect to use.

There are at least two situations in which classic turbidites are present in thick extensive sequences without evidence of associated coarse, channelized fans. The first is the exogeosynclinal situation, typified by the Middle Ordovician turbidites in Quebec (Enos, 1969) and the central Appalachians (McBride, 1962), and by the Mississippian and Pennsylvanian Stanley and Jackfork turbidites of the Ouachita Mountains (Morris, 1974). In these systems, paleocurrent flow is dominantly parallel with the basin axis, and hence parallel with tectonic strike. It generally is assumed that supply is from many points along the margins of these elongate troughs, and that turbidity currents flow downslope toward the basin axis, and then swing around to flow consistently parallel with the basin axis (see, for example, Morris, 1974, Figs. 14, 19). If fans of the type discussed in this paper are formed, they would be at the foot of the marginal slope into the basin. However, this environment normally is destroyed during continued uplift in the source area and thrusting of the turbidite sequences toward the craton, as typified in the Appalachian and Ouachita systems. Even within the axial turbidite systems prediction is difficult. It must be remembered that all of the prediction of facies relations implied by Figure 13 is based upon the spreading of turbidity currents from a single feeder channel. Within the long exogeosynclinal troughs, the turbidites in any one vertical stratigraphic sequence may have come from several different sources. Vertical trends (thickening or thinning upward) may be meaningless or absent, unless individual beds can be assigned to their own source, and it never has been demonstrated that this is possible.

A second situation of abundant classic turbidites without associated coarser facies (massive and pebbly sandstones), and without deep channels, is in prodeltaic areas on the craton. One of

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the best examples is the Upper Devonian turbidite sequence of the central Appalachians, in the lower part of the Catskill clastic wedge. In New York State, the only evidence of submarine fans consists of two superimposed thickening-upward sequences of classic turbidites (Walker and Sutton, 1967); these Upper Devonian units remain flat into northern Pennsylvania and form one of the reservoirs in the Bradford field (Dixon, 1972).

In the Susquehanna Valley area of Pennsylvania, there appear to be no bed thickness or grain-size trends within the 450-m thick sequences of classic turbidites (Walker, 1971). Where the Susquehanna Valley sequences are traced eastward for about 200 km toward the Lehigh Valley area (toward source), the classic turbidite sequences thicken upward into massive sandstones. However, apart from this facies change, there is no other indication that the submarine-fan model as discussed in this paper is applicable to the Upper Devonian "prodeltaic" turbidites.

Prodeltaic turbidites are present in other parts of the Upper Devonian and Mississippian clastic wedges of the Appalachians, and there is a thin turbidite sequence in the lower part of the Cretaceous Mesaverde clastic wedge in the Price, Utah, area (lower part of the Panther tongue). However, models have not been worked out for prodeltaic classic turbidites on the craton. Differences from the submarine-fan model discussed in this paper may arise from differences in grain size and turbidity-current generating mechanisms at the deltaic source, differences in length and angle of the prodelta slope on which the currents accelerate, the possible absence of a single main feeder channel on the delta slope, and relatively rapid switching of delta lobes resulting in changing points of supply of turbidity currents to their depositional areas.

EXPLORATION PREDICTIONS FROM FAN MODEL

As a conclusion to this review, I will summarize some important ways in which the fan model might be used in the prediction of stratigraphic traps. In emphasizing the general points, it will be necessary to ignore local problems of source and migration of the petroleum, diagenesis of the reservoir sands, and tectonic disruptions.

1. The study of the thickness, distribution, and grain size of the various facies suggests that a principal target would be the inner part of a suprafan lobe. Here, the massive and pebbly sandstones would be relatively coarse and thick, with fewer and thinner shales between individual beds. Also, each suprafan lobe may be sealed off by a mud blanket during lobe abandonment (Figs. 18, 21). Suprafan lobes may be identified from their coarsening-upward appearance on electric logs, together with associated fining-upward sequences due to channel filling on the suprafan lobes (Fig. 18). However, in the absence of any other information about the turbidite or deep-water aspect of the system, channelized suprafan lobes would be indistinguishable on electric logs from delta lobes with distributaries.

2. Suprafan lobes might be predicted at the downstream end of feeder channels and upper-fan channels. If they have not been displaced too much by subsequent tectonics, suprafan lobes might be found as downstream continuations of the Rosedale, Meganos, Yoakum, and Gevaram channels. If a positive identification of an upper-fan channel (as opposed to a slope feeder channel) could be made, the channel width or channel cross-sectional area may predict the fan radius, as suggested by Normark (this issue, Figs. 6A, B).

3. Unusual facies relations have important predictive value, particularly the discovery of incised channels in which the channel fill is uncommonly coarse, and cuts into facies that normally would be expected much farther downfan (Fig. 13). Such channels may well have new suprafan lobes at their downstream end. These would suggest potential drilling targets much farther out into the basin than would be expected without the evidence of channel incision. In this context, it must be remembered that the channels themselves might not be visible, but could be predicted by the presence of thinning- and fining-upward sequences. If such sequences are found beginning with massive and pebbly sandstones, or even conglomerates, and associated outside the sequences with dark mudstones and classic turbidites, the assemblage also might represent an incised-channel situation with a possible fan at the downstream end. The sandy Doheny channel (Piper and Normark, 1971) cutting into silts with classic turbidites, and the Wheeler gorge (California) conglomeratic thinning- and fining-upward sequences that rest on dark mudstones (Walker, 1975b) might be two examples where fans could be predicted downstream.

4. Several feeder channels are known from subsurface studies to be filled with fine-grained silts and clays. These can act as updip sealing layers for hydrocarbons in rocks outside the channels. The fine-grained fill appears to be related to channel abandonment, probably because of a relative rise of sea level (as is known for the Mississippi channel, Sabate, 1968). However, relative rise of sea level is a widespread phenomenon, and it is probable that adjacent canyons and channels also were abandoned and filled with fine-grained

materials. Thus the discovery of one major mud-filled feeder channel (Yoakum, Meganos, Mississippi, Gevaram) predicts that if adjacent feeders were present, they also probably will be mud filled, and perhaps act as updip sealing layers.

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