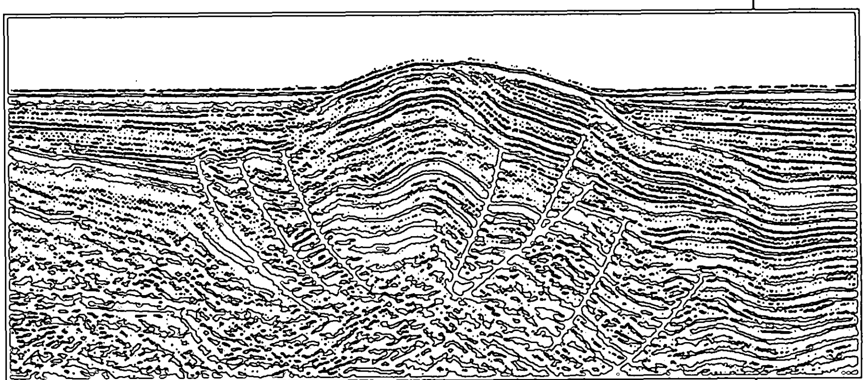
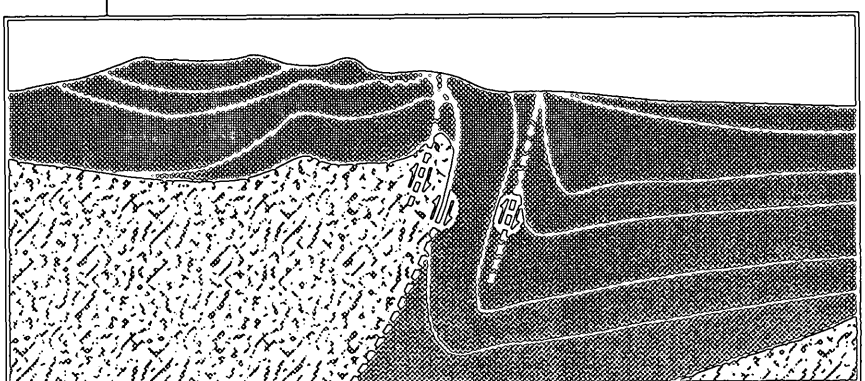
Sedimentology of the Conglomeratic Lower Member of the Lospe Formation (Lower Miocene), Santa Maria Basin, California

Provenance of Sandstone Clasts in the Lower Miocene Lospe Formation Near Point Sal, California



Geophysical section offshore Santa Maria basin



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By SAMUEL Y. JOHNSON and RICHARD G. STANLEY

Provenance of Sandstone Clasts in the Lower Miocene Lospe Formation Near Point Sal, California

By HUGH MCLEAN and RICHARD G. STANLEY

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SANTA MARIA PROVINCE

Edited by Margaret A. Keller

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

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Chapter D

Sedimentology of the Conglomeratic Lower Member of the Lospe Formation (Lower Miocene), Santa Maria Basin, California

By SAMUEL Y. JOHNSON and RICHARD G. STANLEY

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EVOLUTION OF SEDIMENTARY BASINS/ONSHORE OIL AND GAS INVESTIGATIONS—
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FIGURES

Sedimentology of the Conglomeratic Lower Member of the Lospe Formation (Lower Miocene), Santa Maria Basin, California

By Samuel Y. Johnson *and* Richard G. Stanley

Abstract

The lower Miocene Lospe Formation records the initial subsidence of the Santa Maria basin, a major petroleum province in central California. The lower member of the Lospe is best exposed in a 142-m-thick section at the North Beach (informal name) locality on Vandenberg Air Force Base. These North Beach exposures are divided into four units on the basis of distinctive sedimentary textures and structures. Unit 1 (0 to 47 m) consists mostly of crudely stratified lenticular and channel-form pebble to boulder conglomerate interpreted as mid-alluvial-fan streamflow and debris-flow deposits. Unit 2 (47 to 68 m) comprises mainly flat- to low-angle-bedded and channel-form pebble conglomerate interpreted as sheetflood and streamflow sediments deposited in a slightly more distal alluvial fan setting. Unit 3 (68 to 112 m) is a sedimentologically heterogeneous sequence of fine-grained to granular sandstone and pebble-cobble conglomerate. Flat-bedded sandstone and poorly sorted lenticular conglomerate beds are interpreted as the subaqueous sediment-gravity-flow deposits of a lacustrine fan delta. Interbedded channel-form conglomerate beds are interpreted as mainly subaerial streamflow and debris-flow sediments deposited during lacustrine regressions. Unit 4 (112 to 142 m) consists mostly of flat- and low-angle-bedded fine-grained to granular sandstone interpreted as high-density turbidity current deposits. Overall, the North Beach section is a fining-upward sequence that represents a long-term lacustrine transgression punctuated by many short-term lacustrine regressions. Paleocurrent data indicate that sediment transport was to the southeast. Sedimentologic data and interpretations are consistent with a rapidly evolving landscape and can provide important constraints on the paleogeography of the Santa Maria basin and the history of the San Simeon-Hosgri Fault.

INTRODUCTION

The onshore part of the Santa Maria basin of central California is a major petroleum province with cumulative production of more than 800 million barrels of oil and 800 billion ft^3 of associated gas (California Division of Oil and Gas, 1991a). Subsidence of the Santa Maria basin began in the early Miocene during an episode of local crustal extension driven by right-lateral shear along the boundary between the North American and Pacific plates (Hornafius, 1985; Luyendyk and Hornafius, 1987; Luyendyk, 1991; Stanley and others, 1992). The earliest phase of basin evolution is recorded by the lower Miocene Lospe Formation, an 800-m-thick sequence of nonmarine and shallow marine sedimentary rocks and interbedded tuffs. This paper describes the sedimentology of the lower member of the Lospe, composed of conglomerate and sandstone. These strata, interpreted herein as alluvial fan and lacustrine fan-delta deposits, provide important information for reconstructing paleogeography during the earliest phase of evolution of the Santa Maria basin and for understanding the depositional processes and facies that characterize the initial development of transtensional basins.

Acknowledgments

This research was supported by the Evolution of Sedimentary Basins Program and the Onshore Petroleum Investigations Program of the U.S. Geological Survey. We thank Vandenberg Air Force Base for permitting access to the outcrops that are the subject of this report. We benefited from stimulating discussions with R.B. Cole (University of Rochester), R.F. Dubiel (U.S. Geological Survey), Hugh McLean (U.S. Geological Survey), J.P. Smoot (U.S. Geological Survey), and D.R. Vork (UNOCAL). R.B. Cole and R.F. Dubiel also provided constructive reviews.

THE LOSPE FORMATION

The Lospe Formation (Wissler and Dreyer, 1943) consists of nonmarine and shallow marine sedimentary rocks and minor rhyolitic tuffs that crop out in the Casmalia Hills near Point Sal and that also occur in the subsurface of the

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Santa Maria basin (figs. 1, 2) (Woodring and Bramlette, 1950; Hall, 1978; McLean, 1991; California Division of Oil and Gas, 1991b). In its type area on the southwest flank of the Casmalia Hills (fig. 2), the Lospe Formation overlies the Jurassic Point Sal ophiolite of Hopson and Frano (1977) and is overlain by the lower Miocene (Saucesian and Relizian) Point Sal Formation (fig. 3). Woodring and Bramlette (1950) divided the Lospe into two mappable members: (1) a lower member consisting largely of reddish sandstone and conglomerate, and (2) an upper member consisting mainly of greenish sandstone, siltstone, and gypsiferous mudstone. The Lospe was determined to be of early Miocene age on the basis of microfossils and radiometric ages (Stanley and others, 1991). Palynomorphs suggest a temperate, "summer-wet" climate during Lospe deposition (D.R. Vork, oral commun., 1988).

The Lospe Formation crops out in several areas in the Casmalia Hills (fig. 2), including a 5-kilometer-wide outcrop belt extending east-southeast from the North Beach (informal name) locality on Vandenberg Air Force Base and smaller outcrops in the Corralitos Canyon-Point Sal Ridge area. The Corralitos Canyon-Point Sal Ridge outcrops are of poor quality and are involved in several small folds and are cut by several faults. A 413-m-thick section of the Lospe, extending from the basal unconformity (fig. 6) to the overlying Point Sal Formation, is well exposed along the sea cliff at North Beach. This section is cut by several faults, one of which juxtaposes disparate sedimentary facies at the top of the 142-m-thick lower member (fig. 6). The poorly exposed Lospe section inland from North Beach along the informally named Chute creek (fig. 2) is about 830 m thick and includes a poorly exposed 210-m-thick lower member. These thickness contrasts and the inferred facies juxtaposition suggest that part of the Lospe (including at least the upper part of the lower member) has been cut out by faulting in the North Beach section. The lower member of the Lospe Formation thins substantially to the southeast of Chute creek owing to post-depositional faulting (Dibble, 1989) and also possibly owing to original relief on an irregular basement surface (Woodring and Bramlette, 1950) and(or) a lateral facies change. Despite structural complexities, the North Beach outcrops of the lower member of the Lospe (fig. 2) are well exposed and pro-

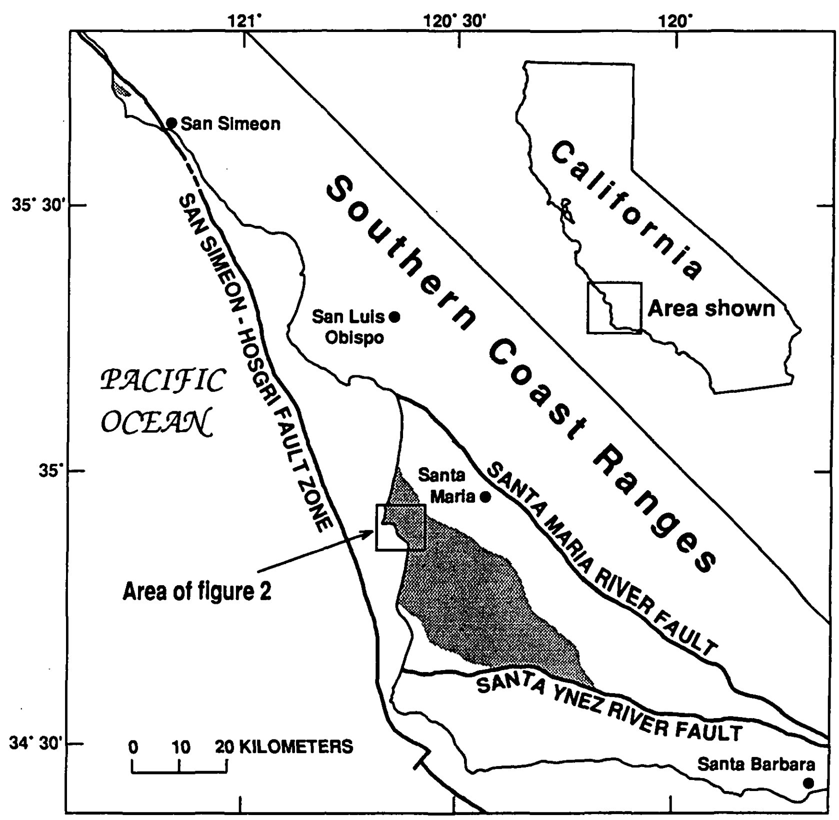


Figure 1. Index map of Santa Maria area. Onshore Santa Maria basin is triangular area bounded by Santa Maria River Fault, Santa Ynez River Fault, and present shoreline. Shaded areas show surface and subsurface distribution of Lospe Formation in the Santa Maria basin according to Hall (1978) and McLean (1991) and in the San Simeon area according to Hall (1976). Location of San Simeon-Hosgri Fault zone compiled and simplified from Hall (1975) and Steritz (1986).

vide the opportunity for detailed sedimentologic analysis. These outcrops are described and interpreted below.

SEDIMENTOLOGY OF THE LOWER MEMBER OF THE LOSPE FORMATION

The Lospe Formation unconformably overlies gabbros of the Jurassic Point Sal ophiolite (figs. 4, 6) at the base of the North Beach section. The overlying conglomerate and sandstone of the 142-m-thick lower member of the Lospe is here divided into four units based on distinctive sedimentary textures and structures. Beds in this section strike from about N. 70° W. to due west, nearly perpendicular to the north-south-trending shoreline; beds dip moderately to steeply (40° to 72°) to the north. This orientation permits a nearly complete description of the vertical distribution of sedimentary facies but only limited observation of the lateral distribution of facies. Paleocurrent measurements from the lower member (figs. 5, 6) suggest that paleoflow was to the east-southeast. Conglomerate clasts in the North Beach section consist of arkosic to lithic sandstone, gabbro, altered serpentinite, and chert, and minor carbonate nodules, blueschist, leucogabbro, altered volcanic rocks, unaltered green serpentinite, and tuff (Anderson, 1980; Hugh McLean, oral commun., 1992). These rocks are inferred to have been derived

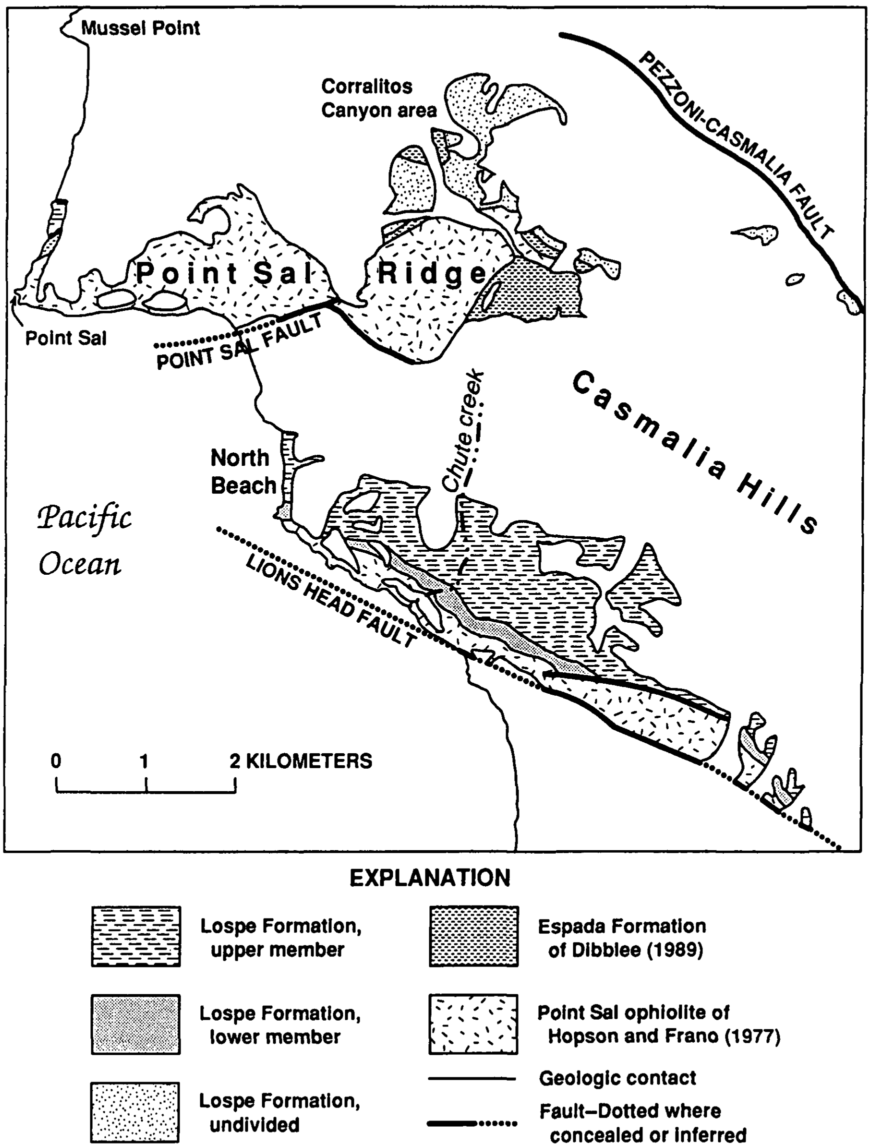


Figure 2. Location map of Point Sal area showing outcrop localities mentioned in text, important faults, and distribution of Point Sal ophiolite of Hopson and Frano (1977), Espada Formation of Dibblee (1989), and Lospe Formation. Blank areas are underlain by unconsolidated deposits and by non-Lospe rocks of Cenozoic age.

from regional basement rocks that include the Franciscan assemblage, the Point Sal ophiolite, and the Great Valley sequence (stratigraphic names used as in McLean, 1991). The Lospe sandstones are mainly lithic arenites (S.Y. Johnson, unpub. data, 1991).

Unit 1: 0 to 47 m

Unit 1 consists of interbedded reddish-brown pebble to boulder conglomerate and minor coarse-grained to granular sandstone and tuff (figs. 6, 7). Two types of conglomerate are recognized. The first type constitutes about 80 to 90 percent of the section and consists of crudely stratified (flat and low-angle bedded) to structureless pebble to cobble conglomerate. Beds range in thickness from 10 cm to several meters and are lenticular and irregular in shape (fig. 7*D*). Lower contacts of beds are typically low-angle (<20°) channel scours; upper contacts are typically convex upward. Relief on channel scours is generally less than about 20 cm; however, a steep channel margin at 3 m in the section (fig. 6) has 150 cm of relief. In massive intervals, subtle contrasts in pebble size, shape, and sorting define stratification. Pebbles and cobbles are typically moderately sorted, subangular to subrounded, and either clast supported or, less commonly, dispersed in a matrix of coarse-grained to granular sandstone. Clast diameter is generally less than 10 cm but ranges up to about 25 cm. Clast imbrication is common, particularly in thinner beds.

The second conglomerate type in unit 1 is much less common and consists of poorly sorted cobble to boulder conglomerate (figs. 6, 7). Typically, beds are internally structureless and fill narrow (50 to 500 cm wide), shallow (depth <100 cm) channels cut into crudely stratified, clast-supported conglomerate. Cobbles and boulders are typically poorly sorted, subangular to subrounded, and either matrix (medium-grained to granular sandstone) supported or clast supported. Some beds include both clast-supported and matrix-supported zones. Outsized boulders are as large as 80 cm in maximum dimension. Larger clasts are commonly concentrated at the tops of beds or on bed margins and in many cases project upward into overlying beds (fig. 7*B*, *C*, *D*). Conglomerate clasts commonly are randomly oriented (fig. 7*B*). Imbrication is uncommon.

Coarse-grained to granular sandstone forms uncommon lenses generally less than 30 cm thick (fig. 7*C*, *D*)

AGE (Ma)	PERIOD	EPOCH	SUBEPOCH	STAGE[1]	STRATIGRAPHY		THICKNESS, IN METERS
16	TERTIARY	Miocene	Middle	Luisian	Monterey Formation		490
17			Early	Relizian	Point Sal Formation		460
17.4				Saucesian	Lospe Formation	Upper member	620
17.7						Lower member	210
Hiatus (unconformity)							
96	CRETACEOUS	Late			Great Valley sequence	Upper petrofacies[2]	Unknown
138		Early				Lower petrofacies[2] (Espada Formation[3])	380
170	JURASSIC				Point Sal ophiolite[4]		Unknown
Tectonic contact							
TERTIARY(?) TO JURASSIC					Franciscan assemblage		Unknown

[1] Modified from Kleinpell (1938, 1980).
[2] Modified from McLean (1991).
[3] Espada Formation of Dibblee (1989).
[4] Point Sal ophiolite of Hopson and Frano (1977).

Figure 3. Stratigraphic chart showing Lospe Formation and bounding rock units.

that are internally structureless or have weakly defined low-angle stratification. These sandstone lenses generally overlie (sharply or gradationally) conglomerate beds; less commonly, they occur in the lower parts of channel fills. Tuff beds that are 20 cm thick occur at approximately 31 and 40 m in the section (figs. 6, 7*B*) and form laterally continuous (to the limits of the outcrop) sheets.

Sedimentologic textures (for example, coarse grain size, poor to moderate sorting, subangular clasts) and structures (dominantly intersecting low-angle channel fills) described above indicate deposition on an alluvial fan (for example, Bull, 1972; Nilsen, 1982) proximal to source. Crudely stratified conglomerate and less common moderately sorted clast-supported imbricate conglomerate were deposited in shallow fan channels by streamflow or possibly by hyperconcentrated flood flow (Smith, 1986). Uncommon sandstone lenses mainly reflect deposition during waning flood stages. The lack of crossbedding and other features representing deposition on migrating bedforms or on bars with more than minimal relief indicates that sand

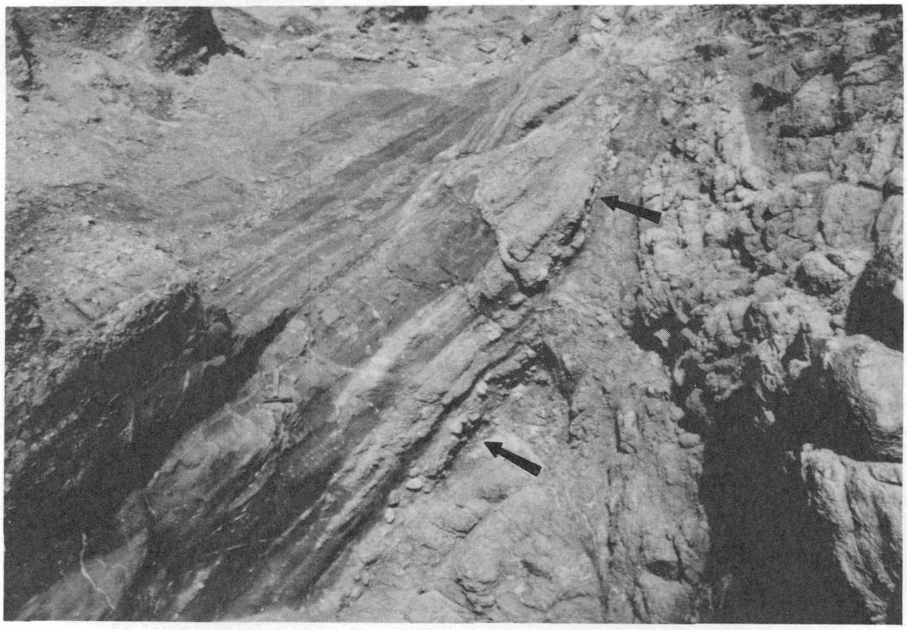


Figure 4. Unconformity (surface marked by arrows) between gabbros of the Point Sal ophiolite (right) and overlying conglomerate and sandstone of the lower member of the Lospe Formation (left). Hammer (center left) for scale.

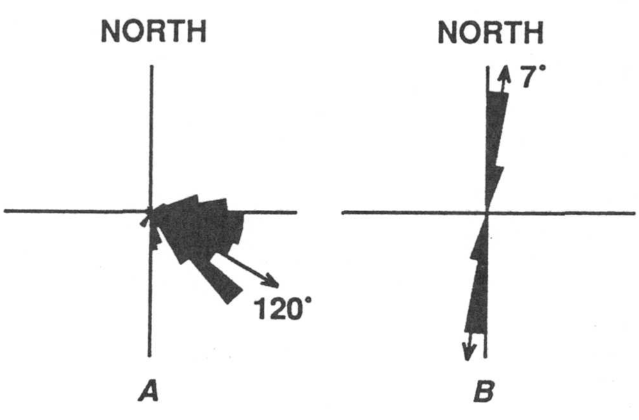


Figure 5. Rose diagrams showing paleocurrent data from Lospe Formation lower member in the outcrop belt between North Beach and Chute creek (fig. 2). Labelled arrows show vector means. ***A***, Clast imbrications (150 measurements). ***B***, Channel axes (7 measurements).

was similarly deposited by either shallow streamflow or by hyperconcentrated floodflow. Slow burial may have allowed the upper, more fine-grained parts of channel fills to be removed by erosion.

Poorly sorted cobble to boulder conglomerate beds are interpreted as debris-flow deposits, despite a general lack of clay matrix. The poor sorting and common random orientation of clasts, the presence of outsized clasts, the projection of clasts into overlying beds, and the mix of clast fabrics (both clast and matrix supported) within beds support this interpretation. These inferred debris-flow deposits generally fill channels (fig. 7), and the typical lack

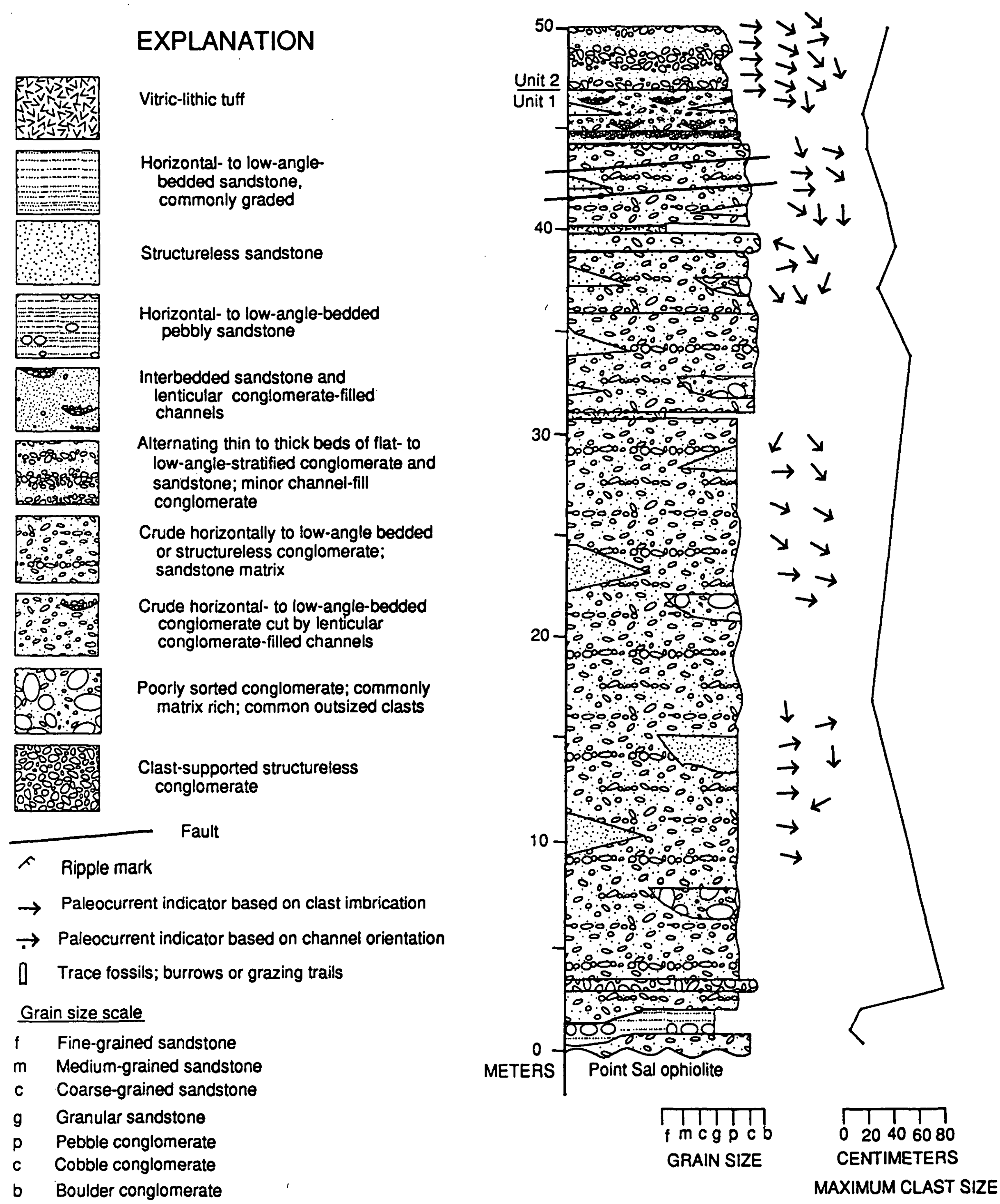
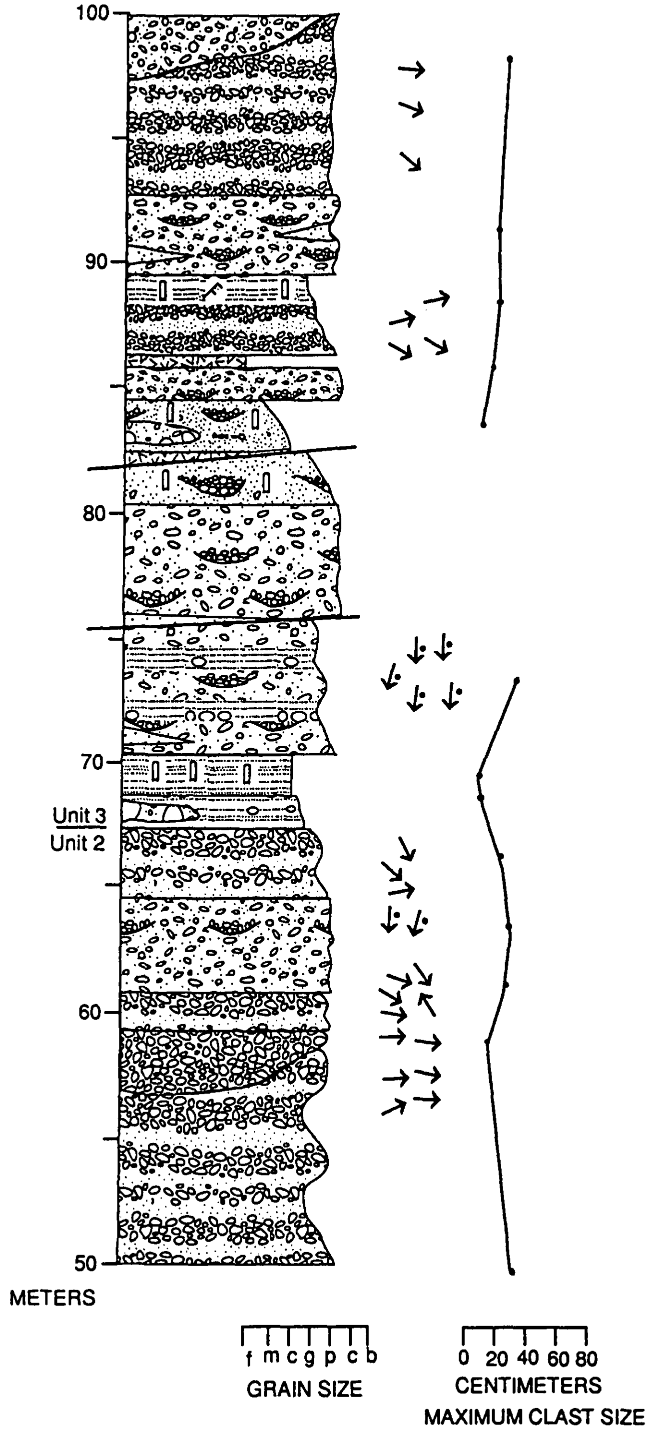


Figure 6. Schematic stratigraphic section of Lospe Formation lower member at North Beach.

of fine-grained matrix may in large part represent winnowing by subsequent streamflow through these channels. Comparable matrix-poor debris-flow deposits of alluvial fans have been described by Gloppen and Steel (1981) and Nemec and others (1984). The dominance of streamflow deposits relative to debris-flow deposits in unit 1 suggests deposition in a mid-alluvial-fan setting below the "intersection point" (Hooke, 1967).

Unit 2: 47 to 68 m

Unit 2 consists of reddish-brown interbedded pebble and cobble conglomerate and less common medium-grained to granular sandstone. Unit 2 is distinguished from unit 1 on the basis of finer grain size, generally more well-defined stratification, the occurrence of conglomerate-sandstone couplets, and the apparent paucity or absence of poorly sorted conglomerate of inferred debris-flow origin. Unit 2 consists largely of two sedimentary facies, present in relatively equal



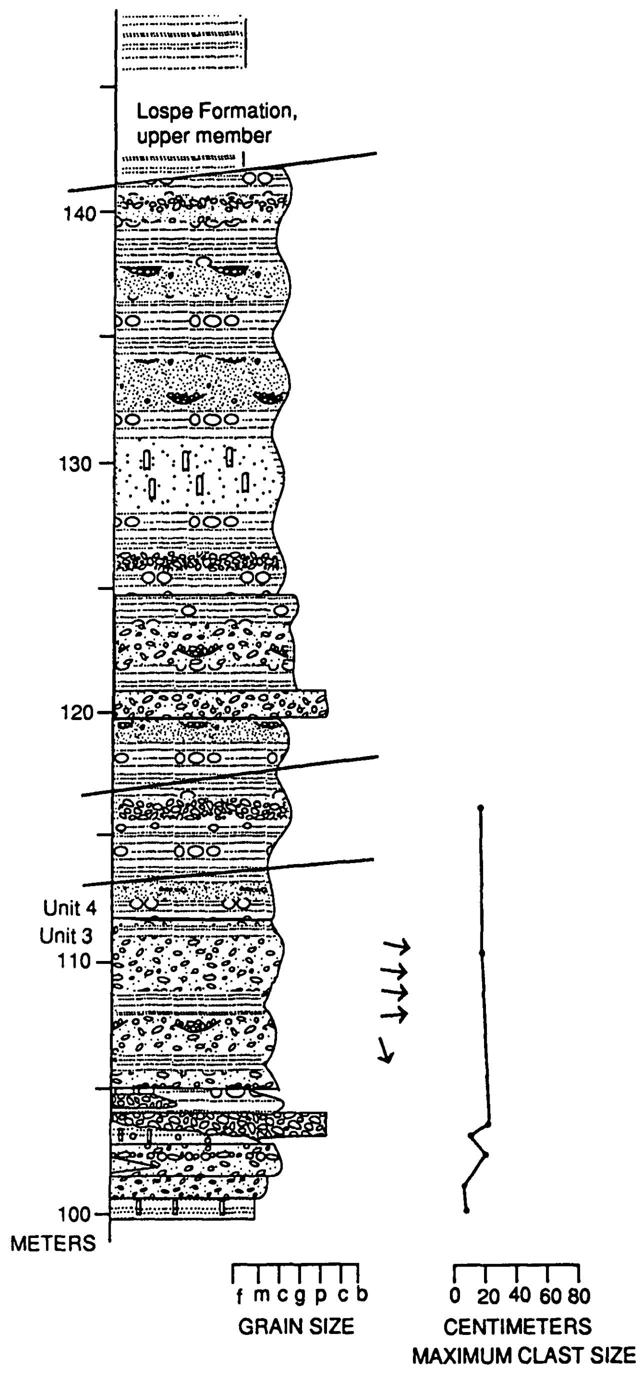
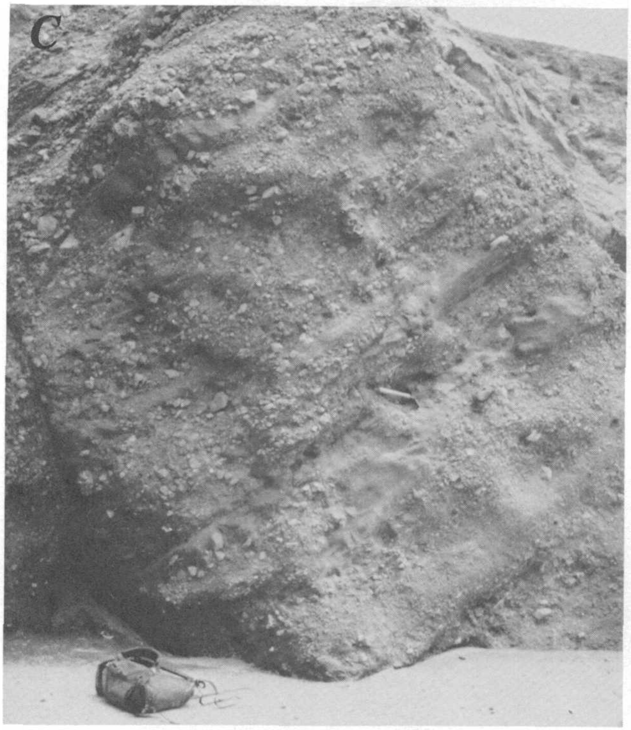


Figure 6.—Continued.

Figure 7. Selected outcrops of unit 1 of the Lospe Formation lower member (see fig. 6) illustrating stratification style. ***A***, Lenticular bed of poorly sorted pebble to cobble conglomerate (arrows show base and top of bed) of inferred debris-flow origin, overlain by flat-bedded clast-supported locally imbricate conglomerate of inferred streamflow origin. Approximately at 45 m in section shown in figure 6. ***B***, Section comprising (from lower right to upper left) lenticular channel-fill pebble conglomerate of inferred fluvial origin; tuff bed (approximately at 31 m in section shown in fig. 6); moderately sorted clast-supported pebble conglomerate of probable fluvial origin; and poorly sorted channel-filling (base of channel shown by arrows) cobble-boulder conglomerate of inferred debris-flow origin. Note variable orientation (vertical to horizontal) of clasts in inferred debris-flow bed, as well as concentration of large clasts at the top of the unit. ***C, D***, Photograph (*C*) and line drawing (*D*) showing bedding lenticularity and low-relief channels in interbedded conglomerate and sandstone. In *D*, stippled pattern represents sandstone; small gravel pattern shows well-sorted clast-supported conglomerate of inferred fluvial origin; pebble-sand pattern represents poorly sorted conglomerate of probable debris-flow origin. Light screen pattern represents areas of cover or poor exposure. Approximately at 46 m in section shown in figure 6.

amounts. The first facies resembles the crudely stratified streamflow conglomerate described in unit 1. Clast-supported pebble to cobble conglomerate forms irregular convex-upward lenticular beds bounded by low-angle (<20°) erosion surfaces (figs. 8*A*, *B*) defining broad (several meters wide) channels. Relief on channel scours is generally less than about 20 cm; however, at 57.5 m in the section (fig. 6) there is 140 cm of relief at the base of one channel. Conglomerate beds range up to about 150 cm in thickness. Pebbles and cobbles are typically moderately sorted, subangular to subrounded, clast supported, and commonly imbricate (fig. 8*C*). Clast diameter is generally less than 10 cm, but outsized clasts range up to 27 cm. These outsized clasts (fig. 8*C*) may represent redeposited debris-flow material. Many of these low-relief channel-filling units grade upward to structureless sandstone, and there is an increased proportion of sandstone in this facies relative to channel-fill fluvial deposits of unit 1. These sandstone beds are generally lenticular in shape and are erosionally truncated, indicating low preservation potential.



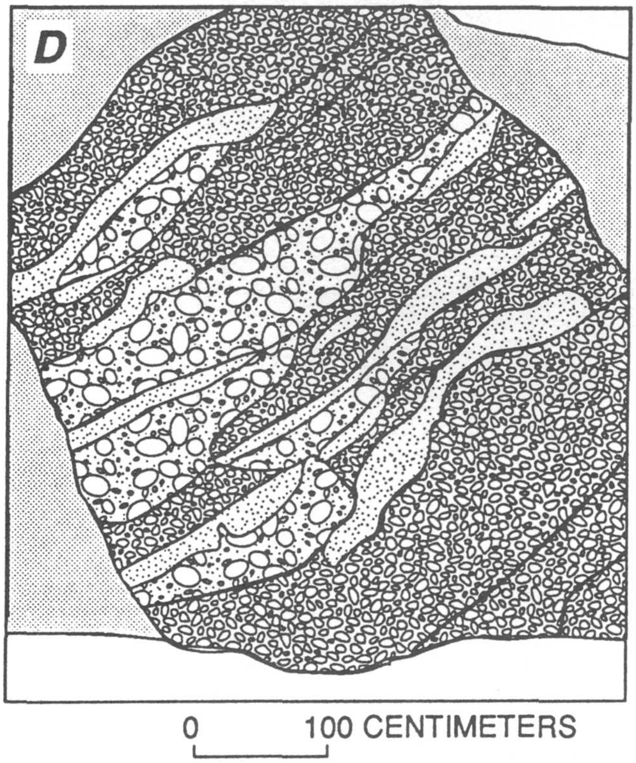


Figure 7.—Continued.

The second conglomerate facies in unit 2 consists of commonly graded couplets of pebble conglomerate and medium-grained to granular sandstone (fig. 8 *A*, *B*, *D*), interpreted as sheetflood deposits (Hogg, 1982). These couplets are typically 10 to 40 cm thick. The conglomerate-sandstone ratio in the couplets is roughly 5:1. Couplets typically have minor (<10 cm) low-angle (<10°) relief at their base and are laterally continuous for as much as 20 m. Pebbles are generally less than 10 cm in diameter, moderately to moderately well sorted, subrounded, clast supported, and commonly imbricated. Contacts within couplets between conglomerate and sandstone intervals are graded, or less commonly, sharp. The sandstone layer in couplets is typically thin and in many cases (as indicated by textural changes in amalgamated conglomerate layers) has been entirely removed by erosion. Comparable modern and ancient alluvial fan sheetflood deposits have been described by Blair (1987a, b) and many others.

Beds of inferred streamflow and sheetflood origin are complexly interbedded in unit 2 (fig. 8*A*, *B*). This architecture (Miall, 1985) suggests deposition in a slightly more distal alluvial fan setting than for unit 1, a setting where low-relief channels broadened so that streamflow became less confined and a mix of streamflow and sheetflood deposits accumulated.

Unit 3: 68 to 112 m

Unit 3 consists of reddish-brown to, less common, greenish-gray interbedded pebble and cobble conglomerate, fine-grained to granular sandstone, and minor tuff (fig. 6). It is distinguished from unit 2 on the basis of much finer grain size (conglomerate-sandstone ratio is about 1.2:1) and more diverse sedimentary textures and structures. Unit 3 consists of several depositional facies (figs. 9, 10, 11) and is the most heterogeneous of the four depositional units of the lower member of the Lospe Formation.

Fine-grained to granular sandstone is mainly flat bedded to very low angle bedded (fig. 11 *A*, *C*, *E*). Bed thickness

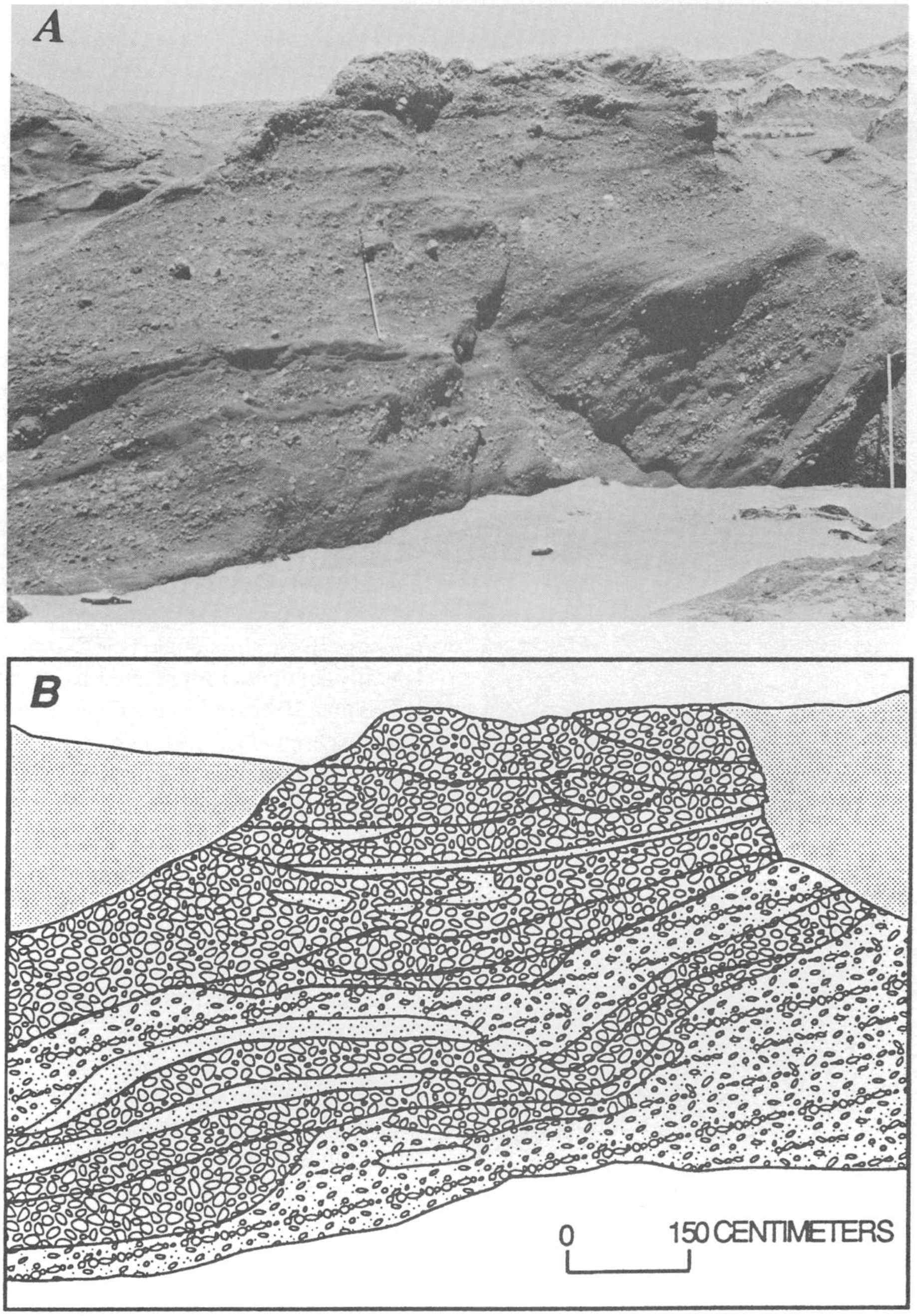


Figure 8. Selected outcrops of unit 2 of the Lospe Formation lower member (fig. 6) illustrating stratification style. ***A***, ***B***, Photograph (*A*) and line drawing (*B*) of flat-bedded conglomerate-sandstone couplets interpreted as sheetflood deposits (pebble-sand pattern), overlain by intersecting, low-angle channel-fill conglomerate (small gravel pattern). Lenticular sandstone interbeds represented by stippled pattern. View is slightly distorted because beds are dipping approximately 60° to the north, away from viewer. Jacob staff in center of photograph (150 cm long) rests between 50 and 55 m in section (fig. 6). Light screen pattern represents areas of cover or poor exposure. ***C***, Crudely stratified (beds dip from upper right to lower left) granule to cobble conglomerate, interpreted as streamflow deposits. ***D***, Three crudely graded couplets (arrows show upper couplet contacts) of flat- to low-angle-bedded imbricate conglomerate and coarse-grained to granular sandstone of inferred sheetflood origin. Couplets overlain by clast-supported conglomerate of inferred streamflow origin.

typically ranges from about 5 to 50 mm, and beds form intervals as thick as a few meters (fig. 6). Beds are sheetlike or are characterized by very low angle (<5°) contacts. Bed contacts are both sharp and diffuse. Sandstone is moderately sorted to well sorted, and grains are subrounded. Normal grading is common. Many flat-bedded sandstone intervals include thin (one or two clasts thick) sheets or lenses (20 to >200 cm wide) of pebble conglomerate. Conglomeratic channel fills incise into and thereby occur at the same stratigraphic level as many intervals of flat-bedded sandstone (fig. 10).

Primary stratification has been obscured to varying (generally small) degrees in sandstone beds at several horizons (at 70, 80 to 85, 88, 100, and 104 m, fig. 6) by bioturbation (fig. 11*D*). Trace-fossil forms include the following: (1) oblique to vertical burrows that are 5 to 20 mm wide, 50 to 110 mm deep, and internally structureless or, less commonly, have meniscate backfill; (2) irregular, bulbous-shaped, horizontal to subhorizontal, single and compound, sand-filled burrows (fig. 11 *D*) that are 10 to 30 mm wide and as much as 100 mm long; and (3) poorly preserved, discontinuous epichnial tracks less than 10 mm wide. Burrows are commonly calcite cemented, weather to a greenish-gray color, and are more resistant to erosion than enclosing reddish-brown sandstone.

Pebble and cobble conglomerate mainly occur as channel fills. There appears to be a continuum in the shapes and dimensions of conglomeratic channel fills from forms similar to those described in unit 2 (several tens of centimeters

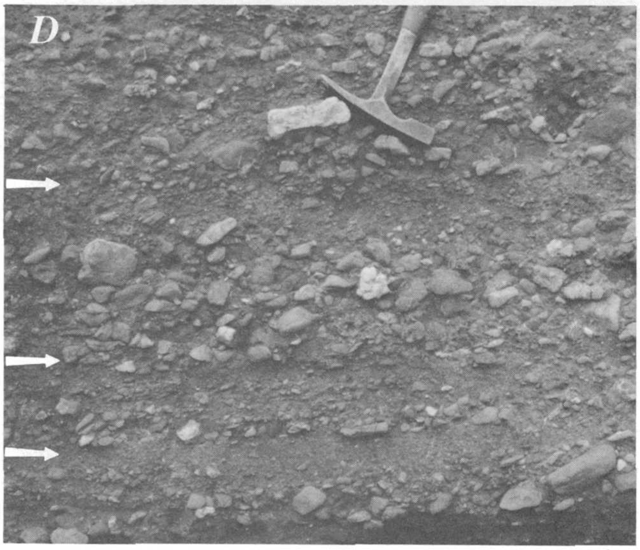


Figure 8.—Continued.

thick, several meters wide) to much narrower (tens of centimeters wide) forms that in some cases have steep (>60°) margins (figs. 9, 10, 11*A*, *C*, *F*). Contacts between conglomerate and overlying sandstone beds range from gradational to sharp. Pebbles and cobbles are typically moderately sorted, subangular to subrounded, and clast supported. Clast diameter is generally less than 10 cm but ranges up to 30 cm.

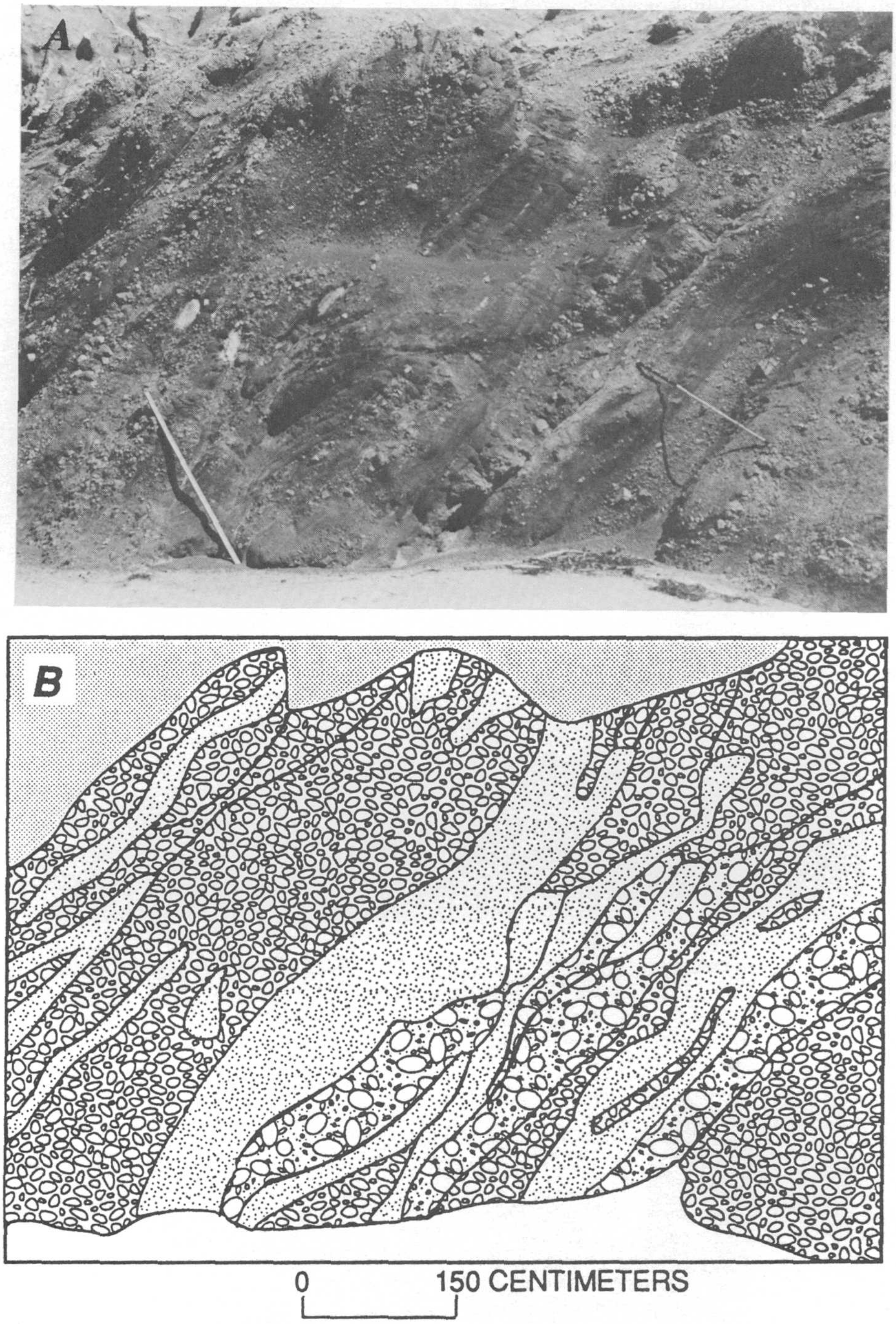


Figure 9. Photograph (*A*) and line drawing (*B*) of North Beach section at about 80 m (fig. 6) showing interbedded conglomerate and sandstone in unit 3 of the Lospe Formation lower member. *In line drawing, stippled pattern represents coarse-grained to granular* sandstone; small gravel pattern represents stratified moderately sorted conglomerate; pebble-sand pattern represents poorly sorted conglomerate of probable debris-flow origin. Jacob staffs in *A* are 150 cm long. Light screen pattern represents areas of cover or poor exposure.

Poorly sorted pebble and cobble conglomerate occurs as relatively flat-based lenses (~20 to 300 cm wide) and sheets and, less commonly, as channel fills (figs. 9, 11*B*). Bed thickness typically ranges from about 10 to 30 cm. Beds show no internal stratification and clast fabric is weak (parallel alignment of clast long axes) to random. Pebbles and cobbles are generally matrix (silt to granular sand) supported but are locally clast supported. Inverse to normal grading is present in a few beds (fig. 11*B*).

Finally, couplets of conglomerate and sandstone comparable to but more fine grained than those described for unit 2 occur between about 93 and 100 m in the North Beach section (fig. 6). These couplets are 20 to 60 cm thick, commonly have low-relief scours at their base, and have a conglomerate-sandstone ratio of about 1:1.

Sedimentary facies of unit 3 collectively indicate deposition in a fan-delta setting (Holmes, 1965; McPherson and others, 1987, 1988; Nemec and Steel, 1988). The alluvial fan deposits of units 1 and 2 were encroached by a standing body of water. Partial subaqueous deposition is indicated by (1) the abundance of well-sorted flat-bedded commonly graded sandstone, (2) evidence for a locally abundant burrowing infauna, and (3) the presence of uncommon inverse-to-normally graded, poorly sorted conglomerate (see discussion below). The paucity of evidence for significant wave activity indicates that the body of water occupied a restricted environment protected from wave energy. Cross-bedding is apparently absent, and conglomerate facies lack features (good sorting, well-defined stratification, common crossbedding, laterally continuous beds, well-defined clast fabrics) typical of marine fan-delta and shallow-marine environments (Clifton, 1973; Bourgeois and Leithold, 1984; Ethridge and Wescott, 1984; Nemec and Steel, 1984; Maejima, 1988; Marzo and Anadon, 1988). A lacustrine setting is favored because of the absence of marine macrofossils, which are generally abundant in deposits of restricted

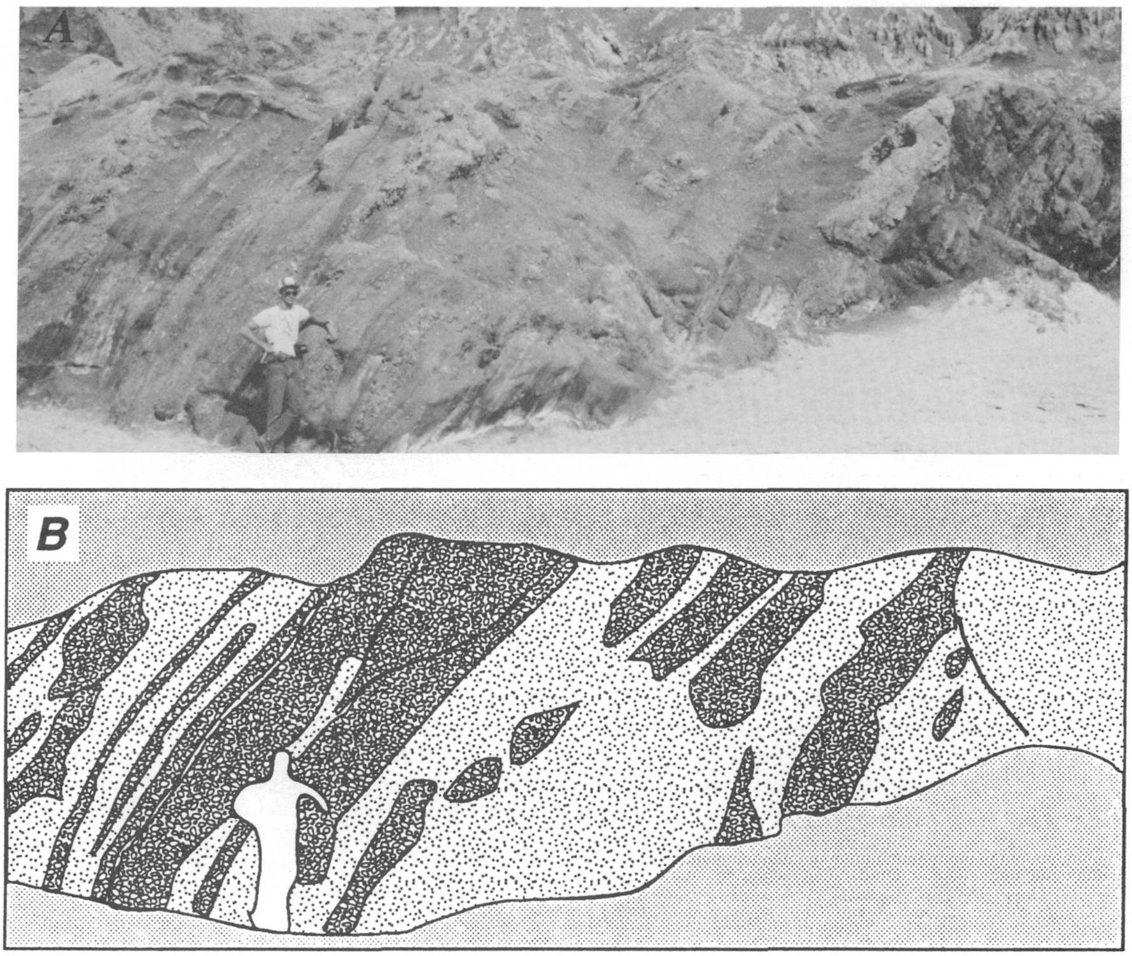


Figure 10. Photograph (*A*) and line drawing (*B*) of North Beach section at about 102 to 111 m (see fig. 6) in unit 3 of the Lospe Formation lower member showing geometry of conglomeratic channel fills (small gravel pattern) and flat-bedded sandstone (stippled pattern). Figures 11*E* and *F* show details of stratification. Note contrast with conglomerate bed geometry in unit 4 (fig. 12). Light screen pattern represents areas of cover or poor exposure.

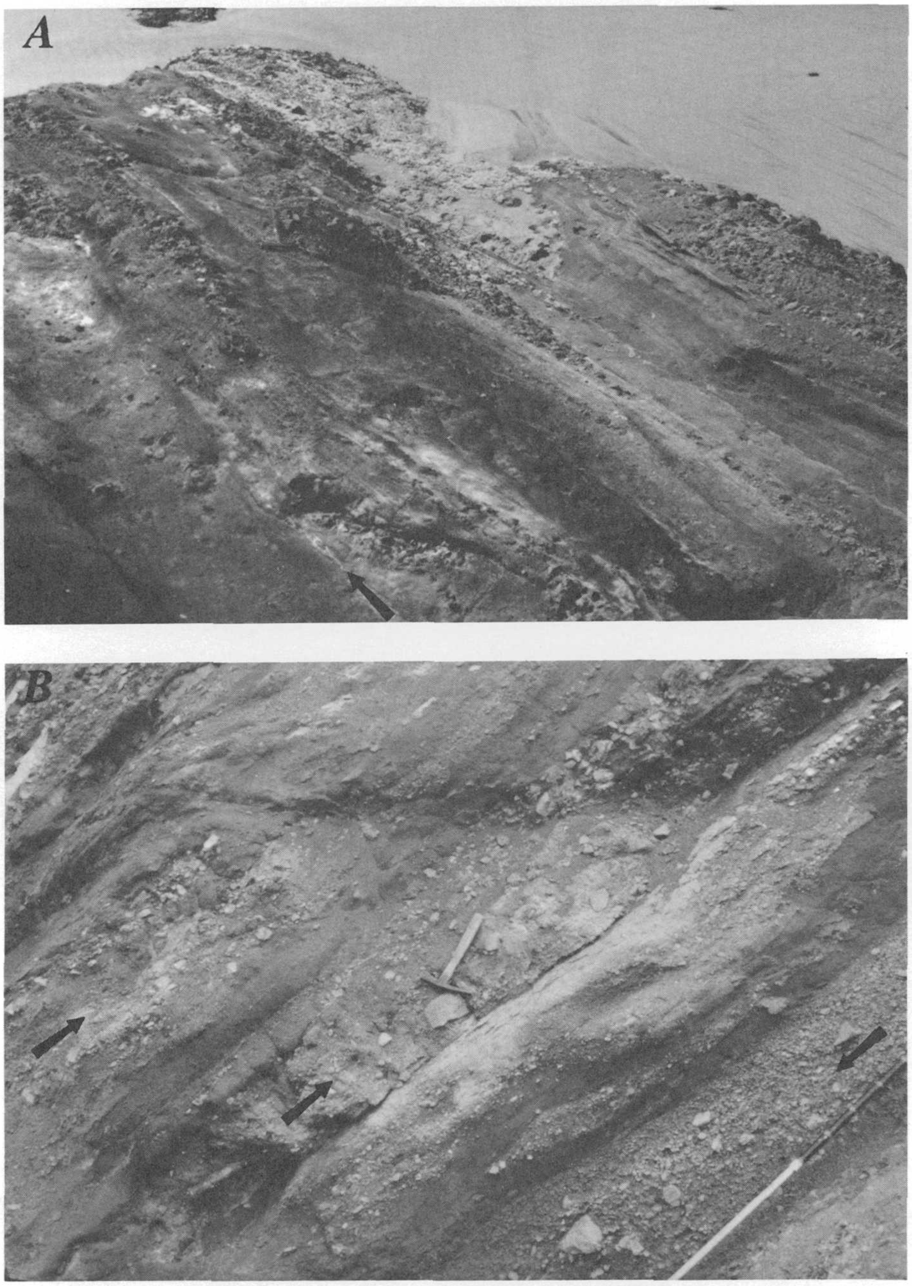
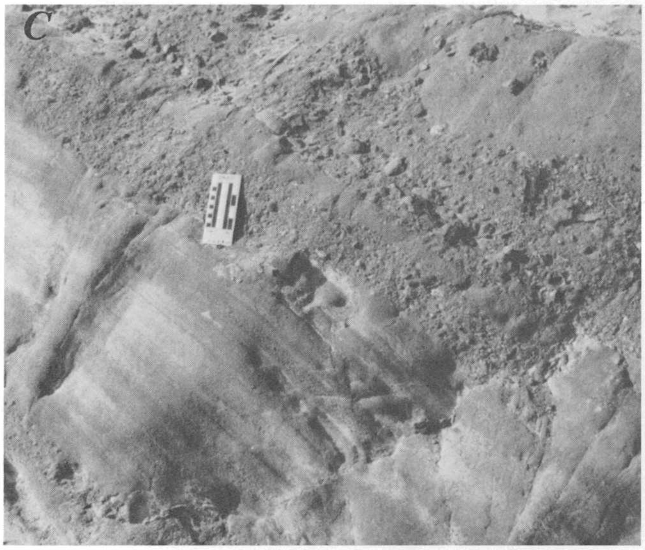


Figure 11. Details of stratification in unit 3 of the Lospe Formation lower member (see fig. 6). ***A***, Strata about 71 m in North Beach section of figure 6. Poorly sorted bed of probable debris-flow origin at base (arrow shows top of bed), overlain by interbedded channel-fill conglomerate and flat-bedded sandstone. Arrow indicates horizon of burrowed sandstone. Hammer (center left) for scale. ***B***, Detail of stratification in rocks of figure 9 showing lenticular conglomerate and flat- to low-angle-bedded fine-grained to granular sandstone. Poorly sorted beds (arrows) are of probable debris-flow origin. Lowest bed displays inverse to normal grading. ***C***, Graded flat beds of well-sorted fine-grained to granular sandstone overlain by lenticular channel-fill conglomerate and pebbly sandstone. At about 89 m in section shown in figure 6. ***D***, Bedding-plane view of top of intensely burrowed bed at 101 m in North Beach section (fig. 6). Burrows are calcite cemented, weather to a white color, and are more resistant to erosion than enclosing red sandstone. Scale bar (16.5 cm long) in lower right. ***E***, Detail of stratification in rocks of figure 10, showing well-sorted laterally continuous thin (1 to 5 cm) beds of fine-grained to granular sandstone. Pencil used for scale is 14 cm long. About 105 m in the section shown in figure 6. ***F***, Detail of stratification in rocks of unit 3, showing steeply dipping (top to left) beds of lenticular channel-fill conglomerate. At about 110 m in section shown in figure 6(top of section shown in fig. 10).

marine settings such as estuaries, and because sulfate isotopic data indicate that gypsum in mudstones of the overlying upper member of the Lospe Formation precipitated from a brine that could not have been in contact with marine waters (M.L. Tuttle, U.S. Geological Survey, oral commun., 1990; Stanley and others, 1992).

Moderately well sorted clast-supported conglomeratic channel fills and conglomerate-sandstone couplets are interpreted as subaerial (incised channel and sheetflood) deposits of this inferred fan delta. The subaerial (channel fill and sheetflood) deposits of the inferred fan delta are sedimentologically similar and only slightly more fine grained than those of underlying unit 2 and probably formed in a similar mid-alluvial-fan setting.

The increased proportion of sandstone in unit 3 (compared to underlying units) resulted from rapid sediment deposition associated with subaqueous flow expansion where sediment-laden streams entered the lake. Flat-bedded sandstone of unit 3 was probably deposited in part as sediment gravity underflows associated with major flood events. Nemec and others (1984) have suggested that sandstone beds in a similar lacustrine fan-delta sequence were deposited



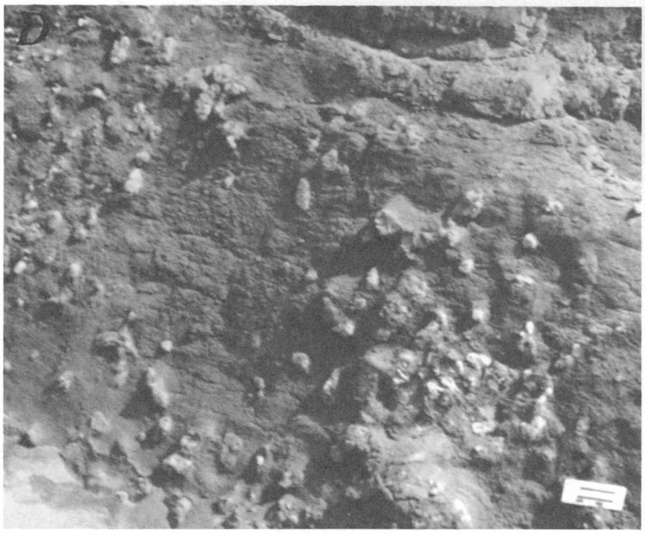


Figure 11.—Continued.

by flows transitional between grain flows and high-density turbidity currents. They suggested that deposition of these beds must have been rapid enough to prevent development of bedforms other than a diffuse plane bed but not so rapid that vertical segregation of grain sizes (grading) was entirely prevented. In some horizons, flat-stratified texturally mature sandstone beds may also reflect limited wave reworking and redeposition, some of which may have occurred during shoreline migrations driven by lake-level fluctuations. Horizons of abundant trace fossils reflect periods of nondeposition. Pollard and others (1982) have previously described shallow-lacustrine trace fossils from a similarly coarse-grained fan-delta sequence in Norway.

The poorly sorted partly matrix-supported pebble and cobble conglomerate beds (fig. 9, 11*B*) are interpreted as debris-flow deposits. The inverse to normal grading in some beds suggests a subaqueous origin (Nemec and Steel, 1984). The subaqueous debris flows probably originated in coarse material residing on unstable slopes (subaerial and subaqueous) near the alluvial fan/lake interface. Earthquake-induced shocks associated with basin-margin and regional tectonism could have provided a trigger for slope failure. Other poorly sorted conglomerate beds (most notably the uncommon channel fills) may have been deposited subaerially.

The channel-fill conglomerates of inferred subaerial origin represent significant breaks in lacustrine deposition. They commonly incise into inferred lacustrine sandstone (fig. 10), a fact which suggests fluctuating lake levels. The tendency toward narrower channel fills with steeper margins in unit 3 relative to units 1 and 2 probably reflects (1) the increased cohesion of the more fine-grained channel-bank material, and (2) the funneling effects of very low-relief lacustrine-shoreline bars and (or) dunes on streamflow (Smoot, 1991; Smoot and Lowenstein, 1991). Apart from the complex interfingering of inferred subaqueous and subaerial deposits, fluctuating lake levels are suggested by the presence of several thin (one or two clasts thick) pebble layers in sandstone-rich intervals, which might represent transgressive lags.

Unit 4: 112 to 142 m

Unit 4 consists of greenish-gray and minor reddish-brown fine-grained to granular sandstone and pebble to cobble conglomerate (fig. 6). It is largely distinguished from unit 3 on the basis of its finer grain size (conglomerate-sandstone ratio is about 1:3 to 4). Sandstone is mainly flat to low-angle bedded (figs. 12, 13). Sandstone beds are typically 1 to 15 cm thick and laterally continuous for several meters (to the limits of outcrops). Most beds are well sorted, but many contain dispersed granules and pebbles (fig. 13*A*). Bed contacts range from sharp to diffuse. Sharp contacts are planar or are characterized by low-relief scours (fig. 13*A*). Many beds are internally graded and plane laminated; ripple lamination and cross-bedding were not observed. Several beds are bioturbated and internally massive (fig. 13*B*). Burrows commonly form horizontal to inclined sand-filled tubes as much as 2 cm in diameter and 10 cm in length. These burrows are commonly calcite cemented, have a distinctive grayish color, and are more resistant to erosion than surrounding strata. Calcite cementation also characterizes many thin (<5 cm) planar beds (fig. 12, 13*A*, *B*). Some of these planar beds include calcite-cemented burrows and are inferred to represent relatively stable, extensively bioturbated surfaces.

Conglomerate beds are generally 5 to 50 cm thick, have sharp and planar lower contacts, and have sharp or diffuse upper contacts. Beds are internally massive or, less commonly, graded and form both laterally continuous sheets and discontinuous lenses (fig. 13). Some beds have convex-upward upper surfaces with as much as 20 cm of low-angle relief (fig. 12), a fact which suggests deposition as lobes or bars. As in unit 3, there are many one- to two-clast thick pebbly layers (fig. 12, 13*A*). Conglomerate-filled channels (figs. 12, 13*A*) are also present but are smaller and less common than in unit 3. Pebbles and cobbles in unit 4 conglomerate beds are typically moderately sorted and mainly clast supported; less commonly, pebbles are dispersed in a matrix of coarse-grained to granular sandstone. Clast diameter is generally less than 5 cm but ranges up to 18 cm.

Unit 4 mainly represents shallow subaqueous lacustrine deposition along the front of a fan delta. Strata were originally deposited by sediment gravity flows, including high-density turbidity currents (see unit 3 discussion above) and possibly uncommon debris flows. Significant reworking by waves and fluctuating shorelines is suggested by the laterally continuous well-sorted sandstone beds and by the one- to two-clast thick conglomerate beds interpreted as lag deposits. The uncommon conglomeratic channel fills (figs. 12, 13*A*) were probably incised and filled on the lower alluvial fan surface during lacustrine regressions. The greenish-gray color of the predominantly subaqueous deposits of unit 4 contrasts markedly with the reddish-brown color of underlying alluvial fan deposits; the color difference probably reflects distinctly different oxidizing/reducing conditions in the early diagenetic environment.

Rocks Overlying Unit 4 in the North Beach Section

A fault in the North Beach section (fig. 6) juxtaposes north-dipping unit 4 with south-dipping strata (on the south limb of a small fold) in the lower part of the upper member of the Lospe Formation. These north-dipping strata consist of gray and brown interbedded fine- and medium-grained sandstone and mudstone (sandstone-mudstone ratio is about 3:1). Coarse-grained sandstone occurs as uncommon beds and lenses, and conglomerate is rare. Sandstone beds are generally 5 to 30 cm thick, have sharp bases, are laterally continuous (for about 10 m, the limits of outcrop), and commonly are internally graded. Incomplete Bouma sequences characterize most graded beds. The Bouma

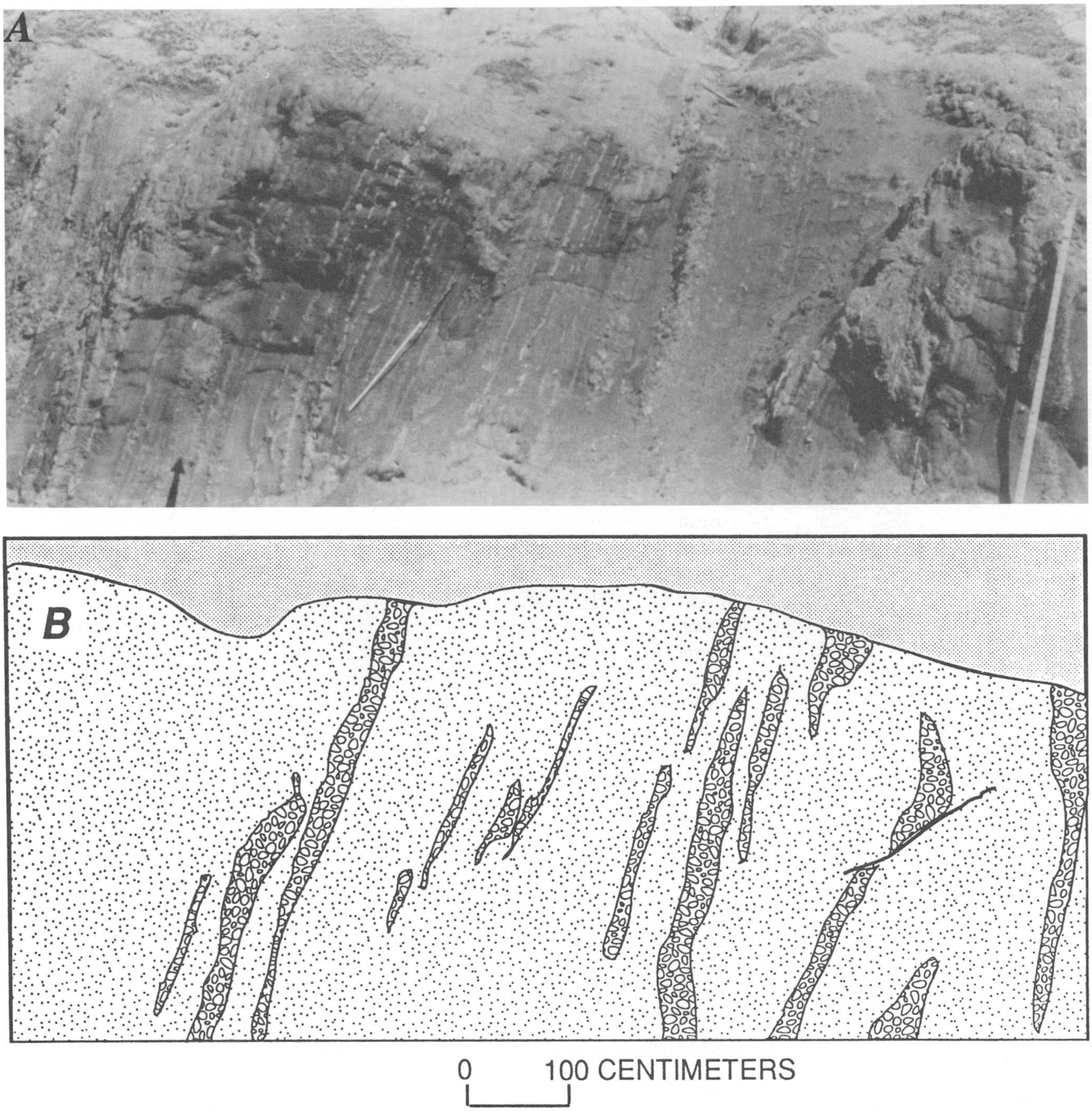


Figure 12. Photograph (*A*) and line drawing (*B*) of unit 4 of the Lospe Formation lower member at about 125 to 130 m in North Beach section (fig. 6) showing geometry of conglomeratic lenses (small gravel pattern) interbedded with flat-bedded sandstone (stippled pattern). See figure 13*A* for close-up of one- to two-clast-thick conglomerate lens and bounding strata at level of jacob staff in left center of figure 12*A*. Arrow (at lower left) in figure 12*A* shows conglomerate bed with convex-upward relief, suggesting deposition as a lobe or bar. Note contrast with conglomerate bed geometry in unit 3 (fig. 10). Light screen pattern represents areas of cover or poor exposure.

sequences indicate deposition by turbidity currents (Bouma, 1962) of lower density than those inferred for the more coarse-grained beds of units 3 and 4.

Sedimentary textures and structures in these overlying beds and their stratigraphic position between fan-delta deposits and more fine-grained lacustrine rocks suggest deposition in a lacustrine prodelta setting. This setting is consistent with the fining-upward transgressive trend in the lower member of the Lospe. However, the abrupt facies change at the contact between the two members strongly suggests that a part of the overall transgressive sequence has been cut out by faulting.

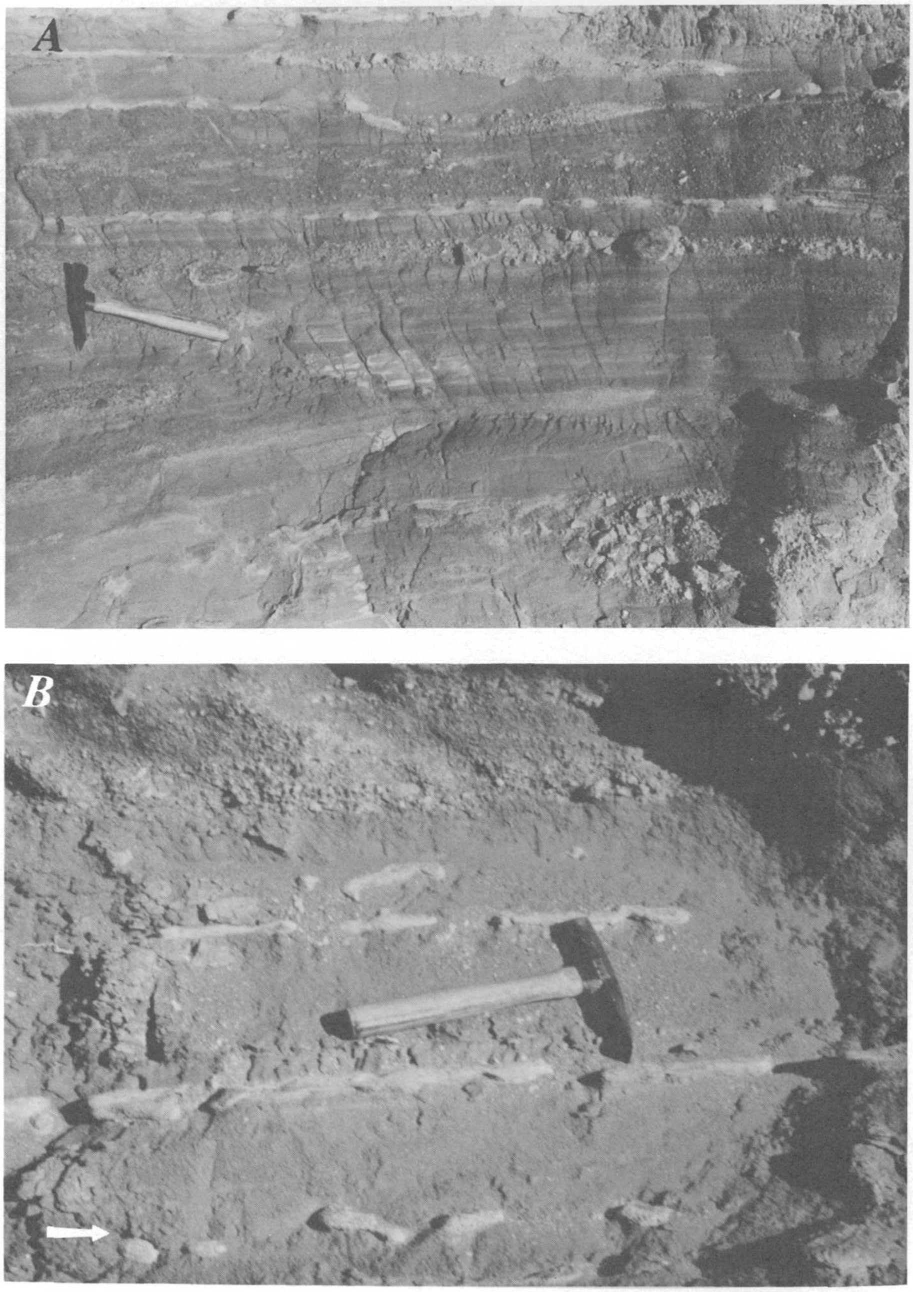


Figure 13. *A*, Close-up view of stratification in unit 4 of the Lospe Formation lower member shown in figure 12 (rotated to horizontal) showing one- to two-clast-thick conglomerate lens and bounding sandstone. Channel-fill conglomerate is at base of photograph, and granule-lined scour surface and thin conglomeratic lens are at top of view. *B*, Detail of stratification at approximately 125 m in North Beach section (fig. 6) showing light-colored calcite-cemented layers (above and below hammer) and trace fossils in lowermost cemented horizon (marked with arrow).

DISCUSSION

The lower member of the Lospe Formation in the Casmalia Hills area is a fining-upward sequence that records alluvial fan (units 1 and 2) and lacustrine fan-delta (units 3 and 4) sedimentation during initial subsidence of the Santa Maria basin. The limited outcrop does not allow reconstruction of the morphology of this fan and fan delta; however it apparently lacks the steep foresets of Gilbert-type fan deltas (Fisher and others, 1969), which are characteristic of sequences deposited along steep basin margins in many extensional basins (Leeder and others, 1988). The Lospe fan delta apparently had lesser relief and may resemble the "shelf-type" fan deltas described by Ethridge and Wescott (1984) and Colella (1988). Relatively slow initial subsidence of the Santa Maria basin and (or) high rates of sediment supply could have inhibited development of steeper depositional surfaces.

The pattern of sedimentation in the lower member of the Lospe indicates a long-term transgression punctuated by short-term regressions. There are many factors that could have contributed partly or wholly to the relative rise in lake level needed for transgression:

(1) Increased run-off into the lake, either owing to a climate change or to enlargement of the area of the drainage basin feeding the lake. There is no direct sedimentologic evidence (such as an upward increase in channel dimensions or changes in suites of sedimentary structures indicating greater depth of flow) for an increase in runoff during deposition of the North Beach fan. However, the lake was probably fed by more than one source; therefore, the limited data from the North Beach section are inadequate to test the climate-change hypothesis. There is similarly no data to test the enlarging-drainage-basin hypothesis; however, because the central coast of California was very active tectonically during the early Miocene (Hall, 1978; Anderson, 1980; Luyendyk and Hornafius, 1987; Luyendyk, 1991), significant reorganization of drainage patterns would have been expected.

(2) Progressive tectonic tilting of the basin floor in the direction of the North Beach alluvial fan. Tilting is required because (all other factors being equal) uniform subsidence would result in equal lowering of the alluvial fan, lake level, and any lake outflows. Basin tilting is common in extensional basins (Leeder and others, 1988).

(3) Given the conditions outlined in either 1 or 2 above, a decrease in sediment supply would contribute to the magnitude of the transgression.

Rocks of the North Beach section described above provide constraints on reconstructions of local paleogeography. The very coarse texturally immature sediments of units 1 and 2 suggest an alluvial fan depositional environment and a nearby source. Fan deposition, characterized mainly by shallow streamflow, sheetflood, and debris-flow deposits, was clearly ephemeral; thus the drainage basin feeding the fan was probably small. Clast compositions (Anderson, 1980; Hugh McLean, oral commun., 1992) indicate that rocks exposed and eroding in the source drainage basin included the Franciscan assemblage, the Point Sal ophiolite, and the Great Valley sequence. These rocks occur over a large range of structural and stratigraphic levels (fig. 3). The drainage-basin source for the alluvial fan was therefore probably cut by high-angle faults along which diverse basement rocks were juxtaposed.

Because most of the local area is draped by post-Lospe strata, the exact location of the above-described structurally complex source area and other inferences about source-drainage-basin geometry during Lospe time are problematic. We recognize three possible configurations for the source of the North Beach alluvial fan sediments.

(1) The nearby source could have been an uplifted block on the west flank of an unmapped north-northwest-trending offshore fault, parallel to the San Simeon-Hosgri Fault. This hypothetical structure would need to have been located more than about 2 km from the North Beach section and west of Point Sal, because basement rocks at Point Sal are apparently not cut by such a fault (Dibblee, 1989). In this scenario, the paleoslope indicated by paleocurrent directions (figs. 5, 6; vector mean = 120°) would have been oriented about 45° to the basin margin. The San Simeon-Hosgri Fault is located about 10 km offshore (fig. 1), too far away to feed an alluvial fan characterized to such a degree by the coarse immature sediments of the North Beach section.

(2) The nearby source could have been an uplifted block on the southwest side of the southeast-trending (~130°) Lions Head Fault, located approximately 500 m southwest of the Lospe outcrop belt (fig. 2). In this scenario, sediment transport (figs. 5, 6) was nearly parallel to the basin-bounding fault. If this inferred block were the source of the North Beach alluvial fan sediments, then streams on the fan surface must have been diverted in a short distance to nearly follow a basin-axial trend. This diversion would presumably be a response to asymmetric basin subsidence.

(3) The nearby source could have been an uplifted block of Mesozoic basement on the north side of the Point Sal fault, located 1 to 2 km north of the North Beach section in the present area of Point Sal Ridge (fig. 2). Preliminary data (R.G. Stanley and others, unpub. data, 1991) indicate that this block was uplifted and eroding during Lospe time; however, the basement rocks that are presently exposed along Point Sal Ridge do not include the structurally low Franciscan assemblage, a requirement for any possible source. Franciscan rocks could have been exposed and completely eroded north of the present Point Sal Ridge outcrops but only if the base of the Lospe Formation exposed in the Corralitos Canyon area is younger than the lower member of the Lospe at North Beach. At this time none of our three hypotheses can be ruled out, but 1 or 2 seem more likely because of the highly speculative assumptions required for 3.

Documentation of the sedimentology of the lower member of the Lospe Formation is potentially an important element in understanding the amount and timing of right-lateral displacement along the San Simeon-Hosgri Fault. Hall (1975, 1978) and Graham and Dickinson (1978a, b) noted similarities between the lower member of the Lospe Formation in the Casmalia Hills area and coarse-grained ophiolite-derived conglomerate in the San Simeon area (fig.1). They inferred that these units were contiguous at the time of deposition and used this inference as an important factor in proposing 80 to 115 km of right-lateral displacement on the San Simeon-Hosgri Fault. These inferences were made without the benefit of detailed sedimentologic analysis of the relevant strata in either area. The data provided here on the sedimentology and vertical sequence of the lower member of the Lospe should, in combination with similar information collected from the San Simeon outcrops, allow more rigorous testing of displacement models on this fault system.

CONCLUSIONS

The conglomeratic lower member of the Lospe Formation records initial subsidence of the Santa Maria basin of central California. The lower member is best exposed in a 140-m-thick section along North Beach on Vandenberg Air Force Base. Four depositional units are recognized in this section on the basis of distinctive sedimentary textures and structures. These four units comprise a fining-upward sequence that records deposition by mostly streamflow, debris-flow, and sheetflood mechanisms in an alluvial fan setting (units 1 and 2) and by subaerial streamflow and subaqueous sediment-gravity-flow mechanisms in a lacustrine fan-delta setting (units 3 and 4). Vertical facies trends suggest a long-term lacustrine transgression punctuated by many short-term regressions. Sedimentologic data and interpretations reported here are consistent with a rapidly evolving landscape and should ultimately provide important constraints on regional paleogeographic reconstructions, most notably the offset history of the San Simeon-Hosgri Fault.

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Chapter E

Provenance of Sandstone Clasts in the Lower Miocene Lospe Formation Near Point Sal, California

By HUGH MCLEAN and RICHARD G. STANLEY

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EVOLUTION OF SEDIMENTARY BASINS/ONSHORE OIL AND GAS INVESTIGATIONS—
SANTA MARIA PROVINCE

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Provenance of Sandstone Clasts in the Lower Miocene Lospe Formation Near Point Sal, California

By Hugh McLean *and* Richard G. Stanley

Abstract

Conglomeratic alluvial fan and fan-delta facies of the lower Miocene Lospe Formation exposed in seacliffs at North Beach (informal name), southeast of Point Sal along the central California coast, contain an assemblage of clasts chiefly derived from Mesozoic basement rocks. Paleocurrent data suggest that these Lospe deposits were derived from sources located in the modern offshore.

Although the Lospe Formation at North Beach unconformably overlies ultramafic rocks of the Point Sal ophiolite and the Lospe conglomerate beds contain numerous ophiolitic clasts, the beds also contain many nonophiolitic clasts including an assortment of quartzofeldspathic and lithic sandstones and various colors of chert including red radiolarian chert. Rare clasts include blueschist, nodular lime clasts, and felsic volcanic rocks.

Detrital modes, textures, lithic fragment populations, and accessory minerals of many of the sandstone clasts suggest a petrologic affinity with rocks of the upper part of the Great Valley sequence. Some clasts have the same petrographic characteristics as sandstone (so-called graywacke) knockers in melange of the Franciscan assemblage. Clasts that resemble the lower part of the Great Valley sequence are rare. The assortment of sandstone clasts in the Lospe Formation suggests that in early Miocene time Franciscan melange, the Point Sal ophiolite, and Great Valley sequence rocks were uplifted and subaerially eroded. Angular clasts of blueschist and red radiolarian chert also suggest a provenance that includes melange of the Franciscan assemblage.

INTRODUCTION

The Lospe Formation is an 830-m-thick sequence of sedimentary and associated tuffaceous rocks that unconformably overlie basement rocks of Mesozoic age. Recent radiometric ages of tuffs reported by Stanley and others (1990 a, b, and 1991) indicate an early Miocene age. The type section of the Lospe Formation is located in the Casmalia Hills, an area in west-central California first mapped in detail by Woodring and Bramlette (1950) (fig. 1). Approximately 140 m of conglomeratic alluvial fan and fan-delta facies of the Lospe are well exposed in seacliffs along a north-trending section of coast southeast of nearby Point Sal where the Lospe Formation unconformably overlies the Point Sal ophiolite. The seacliff outcrops are informally called North Beach in our report. North Beach is located approximately 10 km southwest of the Santa Maria Valley oil field (fig. 1) and is located within the perimeter of Vandenberg Air Force Base (VAFB).

Previous Work

Anderson (1980) studied the sedimentology and composition of the Lospe Formation at several localities in the area of the Santa Maria basin, including North Beach, which she called "VAFB" section in her report. Her work focused on the provenance of Lospe clasts and the tectonic implications of clast assemblages. Anderson's pebble counts from the basal part of the North Beach section indicated an abundance of ophiolitic debris. Ophiolitic clasts included gabbro and red serpentinite (a silica carbonate rock that is an alteration product associated with the ophiolitic rocks). Anderson also reported chert, leucogabbro, carbonate nodules (called nodular lime clasts in our report), metavolcanic rocks, claystone, and rare blueschist. In contrast to the local abundance of ophiolitic debris, however, some of the North Beach conglomerate beds contain as much as 80 percent sandstone clasts (Anderson, 1980, p. 185).

Anderson (1980) reported detrital modes of four sandstone clasts from the North Beach section. Two of the clasts contained detrital potassium (K) feldspar; the other two clasts contained no K-feldspar. The assemblage of sandstone clasts in the basal part of the North Beach section was interpreted by her to have been derived from a source other than the Franciscan assemblage (Anderson, 1980, p. 136). The sedimentary source for clasts from the lower and upper parts of the Lospe Formation in the Point Sal area was interpreted by Anderson (1980, p. 136) to be "Upper Cretaceous Great Valley sequence-equivalent and (or) Paleogene

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sedimentary rocks." North-northwest to south-southeast oriented trough axes at North Beach were reported by Anderson (1980, p. 74, 75). Anderson (1980, p. 69) also reported north-northeast to south-southwest oriented cut-and-fill channel axes in conglomeratic alluvial fan facies of the Lospe on VAFB. Anderson's (1980) paleogeographic reconstruction for the Lospe Formation at Point Sal portrayed an eastward-directed alluvial fan system that incorporated sandstone clasts derived from a source located no more than 50 km to the southwest (southwest according to modern coordinates) at the time of deposition.

Subsequent work by Stanley and others (1990 a, b, and 1991) on the age and sedimentology of the Lospe Formation in the Casmalia Hills identified two discrete alluvial fan systems each with a different paleoflow and clast assemblage. At the North Beach section they reported southeast flow and a mixed-clast assemblage, whereas in the Corralitos Canyon (fig. 1) section they reported northeast flow and mainly ophiolitic clasts. The ophiolitic clast assemblage at Corralitos Canyon was also noted by Anderson (1980), but no paleocurrent data were cited. Clast assemblages at North Beach suggested to Anderson (1980) that the conglomerates of the Lospe Formation were derived by subaerial erosion from at least three Mesozoic lithotectonic elements: (1) ophiolitic rocks that lithologically resemble parts of the Point Sal ophiolite of Hopson and others (1975), Hopson and Frano (1977), and Hopson and others (1981); (2) sandstones that are lithologically similar to those of the upper and lower Great Valley sequence of the Santa Maria basin; and (3) a variety of lithologies that occur as knockers in melange of the Franciscan assemblage such as blueschist and red radiolarian chert. Rare felsic volcanic clasts were interpreted by Anderson (1980, p. 134) as being derived from a fourth provenance composed of middle Tertiary rocks.

Woodring and Bramlette (1950) mapped the geology of the Casmalia Hills, where some Upper Jurassic sedimentary rocks were called the Knoxville Formation. Lithologically similar (and tentatively age-equivalent) rocks along the southern margin of the Santa Maria basin were called the Espada and Honda Formations by Dibblee (1950). Gray (1980), Hall (1982), and McLean (1991) reported the presence of correlative rock units in the subsurface of the Santa Maria basin.

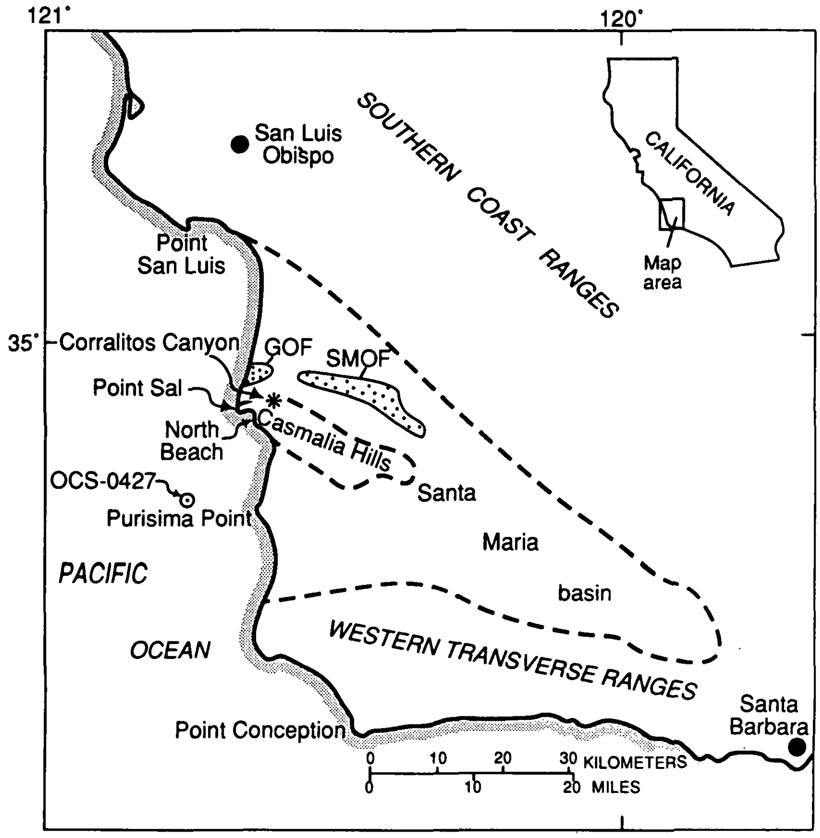


Figure 1. Index map showing location of North Beach section of the Lospe Formation and other relevant geographic features. GOF, Guadalupe oil field; SMOF, Santa Maria Valley oil field; OCS-0427, offshore location of Pennzoil test well.

This report expands on the reconnaissance sedimentary petrology of sandstone clasts reported by Anderson (1980) and addresses the petrologic diversity and provenance of such clasts in the Lospe Formation at North Beach. Provenance of the Lospe sandstone clasts was determined by comparing the detrital modes and other petrographic characteristics of different clast types with outcrops of the lower and upper parts of the Great Valley sequence, sandstone knockers in melange of the Franciscan assemblage, Upper Cretaceous rocks in the subsurface of the nearby Santa Maria basin, and outcrops of lithologically similar rocks at Point San Luis. Comparisons were made using petrographic information on outcrops and core material that were published by McLean (1991).

Methods

Pebble- and cobble-size sandstone clasts were collected from the Lospe Formation in the North Beach section between 3 m and 82.1 m stratigraphically above its basal contact with the Point Sal ophiolite. Samples were selected to represent as many different textures and compositions as could be determined from the study of hand specimens. Twenty-seven clasts were selected for thin section study and point counting; table 1 lists the raw point count data. Detrital modes that are tabulated in table 2 are also illustrated in ternary diagrams in figure 2. In most cases, the detrital modes were determined by counting between 300 and 400 framework grains of quartz, feldspar, and rock fragments in standard thin sections that had been stained for K-feldspar. Point counting followed the methods outlined by Dickinson (1970). The Gazzi-Dickinson method of Ingersoll and others (1987) was used to minimize the effects of grain size differences. Unfortunately, the Gazzi-Dickinson method requires that polycrystalline grains with individual crystals larger than 0.0625 mm be counted as a separate component mineral rather than as a rock fragment. Consequently, percentages of polycrystalline rock fragments such as those of granitic and (or) metamorphic origin in medium and coarser grained sandstones tend to be underrepresented.

PETROGRAPHIC DATA

Comparison of Sandstone Clasts from the Lospe Formation with Mesozoic Sandstones in and Adjacent to the Santa Maria Basin

Figure 2 compares the detrital modes of Lospe Formation sandstone clasts at North Beach with outcrops of the upper and lower parts of the Great Valley sequence and sandstones of the Franciscan assemblage. Plots of Qt-F-L and Qm-F-Lt in this study (fig. 2) differ only slightly for most rocks because of low percentages of polycrystalline quartz and chert (note that Qt and Lt both include chert and polycrystalline quartz). Ternary plots of volcanic, sedimentary, and metamorphic rock fragments were omitted in this study because their sum rarely exceeded 60 or 70 points per thin section (table 1); only values greater than 100 were considered to be statistically significant.

Upper Jurassic and Lower Cretaceous Sandstones of the Lower Part of the Great Valley Sequence

Rocks of the lower part of the Great Valley sequence that crop out around the perimeter of the Santa Maria basin consist of sandstone, shale, mudstone, and chert-pebble conglomerate and range in age from Late Jurassic (Tithonian) to Early Cretaceous. Partly coeval rocks were mapped in the Casmalia Hills as the Upper Jurassic Knoxville Formation by Woodring and Bramlette (1950), whereas rocks of an overall similar age exposed on the south and east flanks of the Santa Maria basin were called the Espada Formation (Late Jurassic and Early Cretaceous) and the Honda Formation (Late Jurassic) by Dibblee (1950). The Knoxville and Espada Formations in the Santa Maria basin comprise petrofacies of the lower part of the Great Valley sequence. These rocks conformably overlie radiolarian cherty mudstones that form the upper part of the Point Sal ophiolite. The Knoxville and Espada sandstones around the Santa Maria basin are characterized by high percentages of spilitic volcanic rock fragments and chert and by low percentages of quartz and feldspar (fig. 2). K-feldspar abundance rarely exceeds trace amounts in these rocks. Plagioclase grains and volcanic rock fragments are relatively unaltered, especially when compared to sandstones with similar Q-F-L ratios in the Franciscan assemblage.

The Qt-F-L and Qm-F-Lt diagrams in figure 2 illustrate that the detrital modes of only two clasts of the Lospe Formation are lithic rich, which is a characteristic of rocks of the lower part of the Great Valley sequence (the undivided Espada Formation of Dibblee (1950) and Knoxville Formation). Table 1 includes data for three outcrop samples (L87-2B, 89C-444, and 89C-430) of lower Great Valley rocks. The suites of lithic rock fragments and accessory minerals indicate that only two Lospe sandstone clasts (L-10 and L-14) might have been derived from the Knoxville or Espada Formation. In addition, a clast of chert-pebble conglomerate was also collected but not point counted; chert-pebble conglomerate is a common constituent of the lower part of the Great Valley sequence. Accessory grains of clinopyroxene (augite) in clast L-10 (table 1, see Cpx) are noteworthy because such grains are rare in the rocks of the lower part of the Great Valley sequence but were report-

Table 1. Point count data for sandstone clasts of the Lospe Formation

[Inferred provenance based on petrographic data: Ku, upper part of the Great Valley sequence (Upper Cretaceous); Kl, lower part of the Great Valley sequence (the undivided Espada Formation of Dibblee (1950) and Knoxville Formation) (Upper Jurassic and Lower Cretaceous); OC, outcrop sample of Lower Cretaceous sandstone; KJf, knockers in melange of the Franciscan assemblage (Jurassic and Cretaceous). Qm, monocrystalline quartz; Qp, polycrystalline quartz; plag., plagioclase; K-spar, potassium feldspar; biot., biotite; musc., muscovite; L-unid., unidentified lithic (rock) fragments; L-meta., metamorphic rock fragments; L-sed., sedimentary rock fragments; L-volc., volcanic rock fragments; epid., epidote; opq., opaque grains; lc, lime clasts; cpx, clinopyroxene; sph, sphene; cmt., intergranular cement and (or) matrix; NC, not counted]

Sample no.	Infer. prov.	Qm	Qp	Chert	Plag.	K-spar	Biot.	Musc.	L-unid.	L-meta.	L-sed.	L-volc.	Epid.	Opq.	Other	Cmt./matrix	Total count
89C-409A	Ku	123	5	0	155	34	21	2	24	12	7	0	1	2	0	35	421
89C-409B	Ku	126	12	0	172	23	5	3	16	10	0	3	3	2	0	54	429
89C-409C	Ku	97	3	0	161	34	7	0	35	11	2	4	5	1	0	63	423
89C-409D	Ku	114	11	0	136	29	10	0	19	19	2	0	6	0	0	71	417
89C-410C	Ku	100	4	0	144	35	14	4	28	0	10	6	2	1	0	74	422
L-5	Ku	116	5	2	138	35	19	12	37	8	14	0	3	0	0	162	551
L-6	Ku	132	20	0	159	30	32	4	31	17	0	4	4	3	0	44	480
L-7	Ku	172	14	0	99	29	31	7	52	10	1	0	11	4	0	NC	430
L-9	Ku	100	13	0	173	18	30	6	44	17	1	5	11	0	0	83	501
L-11	Ku	134	13	3	180	24	10	11	51	25	0	5	7	1	0	73	537
L-12	Ku	117	7	3	212	49	19	2	27	22	0	3	5	0	0	64	530
L-15	Ku	129	7	1	107	21	16	1	19	25	3	12	2	4	lc,5	71	423
L-16	Ku	127	3	2	165	23	32	3	21	15	1	6	4	0	lc,2	33	437
L-18	Ku	115	12	0	162	21	20	7	35	7	1	3	2	0	sph,2	40	427
L-21	Ku	116	10	0	176	30	34	3	40	8	4	0	0	3	lc,4	85	513
L-22	Ku	89	7	0	110	7	19	5	35	17	3	9	4	2	0	105	412
L-10	Kl	14	9	0	64	0	0	0	186	41	0	80	12	4	cpx,3	111	524
L-14	Kl	19	11	2	23	1	0	0	65	29	0	78	7	0	0	108	343
L87-2B	Kl, OC	4	3	0	51	0	0	0	125	6	0	111	8	0	cpx,2	56	366
89C-444	Kl, OC	70	31	0	48	7	3	2	169	36	4	11	0	3	lc,7	89	480
89C-430	Kl, OC	50	31	18	21	6	0	0	73	67	20	58	0	0	lc,3	59	406
89C-410A	KJf	172	36	2	109	0	15	2	59	51	19	2	0	0	0	37	504
89C-410B	KJf	99	114	0	60	0	0	0	65	15	5	46	0	6	lc,11	48	469
L-1	KJf	45	0	0	21	0	7	3	7	0	3	0	0	4	0	42	132
L-3	KJf	135	21	1	129	0	5	26	51	8	0	0	5	3	0	53	437
L-4	KJf	55	19	1	67	0	1	4	56	17	0	2	8	1	0	43	274
L-8	KJf	153	10	0	174	0	44	9	43	4	2	0	3	0	0	73	515
L-17	KJf	124	10	3	148	0	18	4	30	10	0	2	3	5	hbl,1	58	416
L-19	KJf	82	26	12	90	0	5	0	93	2	0	19	6	2	lc,2	80	419
L-20	KJf	50	21	6	49	0	4	0	82	6	0	19	4	2	0	49	292

ed locally in the Espada Formation along the southern flank of the Santa Maria basin by McLean (1991).

Upper Cretaceous Sandstones in the Basement of Santa Maria Basin and at Point San Luis

K-feldspar-bearing, quartzofeldspathic (arkosic) sandstones in core material from exploratory wells in parts of the Santa Maria basin basement were reported by Gray (1980). Palynomorphs associated with the sandstones in some wells were reported to be of Late Cretaceous age by Gray (1980). McLean (1991) reported that Upper Cretaceous sandstones were penetrated by several wells in the Santa Maria Valley and Guadalupe oil fields (fig. 1). The Upper Cretaceous sandstones in and around the Santa Maria basin are characterized petrographically by abundant quartz and plagioclase (McLean, 1991). McLean (1991, p. 6) reported that 21 Upper Cretaceous subsurface rocks averaged $Q_{30}F_{40}L_{30}$, whereas 27 outcrop sandstones averaged approximately $Q_{36}F_{44}L_{20}$. K-feldspar (mainly orthoclase and microcline) ranges from 5 to 10 percent, biotite ranges from 2 to 5 percent, and detrital epidote from 1 to 2 percent. Lithic rock fragments typically include intermediate volcanic rocks, quartz mica schist, and granitoid rocks. Texturally, the rocks are characterized by subangular to subrounded grains that are moderately sorted and framework supported. The rocks contain little primary argillaceous intergranular matrix, although pseudomatrix formed from lithic rock fragment alteration is abundant in some rocks.

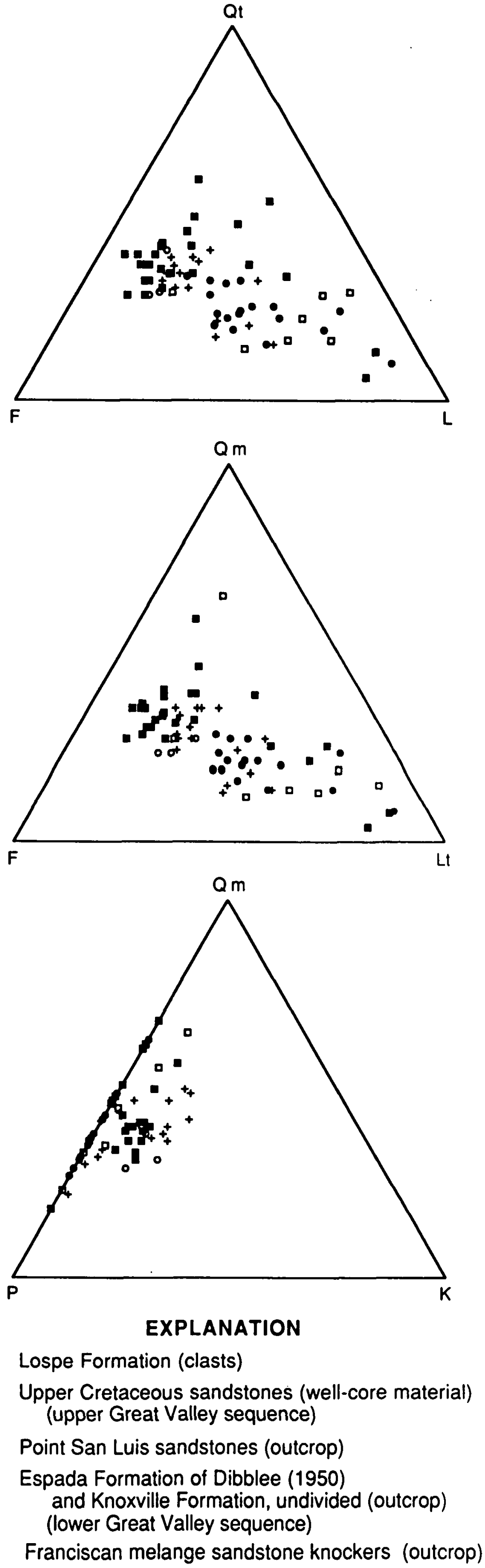
Surface rocks that are almost identical petrographically to the Upper Cretaceous subsurface sandstones in the Santa Maria basin crop out at Point San Luis (fig. 1). Although fossils have not been reported in the isoclinally folded strata at Point San Luis, previous workers such as Lee-Wong and Howell (1977), Smith (1978), and Gray (1980) have interpreted these rocks as being compositionally consistent with sandstones of the Great Valley sequence of Late Cretaceous age.

Detrital modes shown in figure 2 illustrate that Qt-F-L and Qm-F-Lt for 16 Lospe clasts either overlap or are

Table 2. Detrital modes, in volume percent, of sandstone clasts in the Lospe Formation

[Qt, monocrystalline and polycrystalline quartz and chert; F, feldspar--plagioclase (P) and K-feldspar (K); L, aphanitic lithic rock fragments excluding polycrystalline quartz and chert; Qm, monocrystalline quartz; Lt, aphanitic lithic rock fragments including polycrystalline quartz and chert. Ku, upper part of the Great Valley sequence (Upper Cretaceous); Kl, lower part of the Great Valley sequence (the undivided Espada Formation of Dibblee (1950) and Knoxville Formation) (Upper Jurassic and Lower Cretaceous); KJf, Franciscan assemblage (Jurassic and Cretaceous). ND, not determined]

Sample No.	Qt,F,L	Qm,F,Lt	Qm,P,K	Inferred provenance
89C-409A	36,53,11	35,53,12	39,50,11	Ku
89C-409B	39,55,06	39,54,07	39,54,07	Ku
89C-409C	28,56,16	28,56,16	33,55,12	Ku
89C-409D	39,52,09	36,52,12	41,49,10	Ku
89C-410C	32,54,14	30,54,16	36,52,12	Ku
L-5	35,49,16	33,49,18	40,48,12	Ku
L-6	39,48,13	34,48,18	41,50,09	Ku
L-7	49,34,17	46,34,20	57,33,10	Ku
L-9	30,51,19	27,51,22	34,59,07	Ku
L-11	34,47,19	31,47,22	40,53,07	Ku
L-12	28,60,12	27,60,13	31,56,13	Ku
L-15	41,39,20	39,39,22	50,42,8	Ku
L-16	36,52,12	35,52,13	40,52,8	Ku
L-18	36,51,13	32,51,17	39,54,7	Ku
L-22	34,42,24	32,42,26	43,53,4	Ku
L-21	32,53,15	30,53,17	36,55,9	Ku
Ku mean----	34,51,15	33,50,17	40,51,9	
89C-410A	47,25,28	39,25,36	61,39,0	KJf
89C-410B	53,15,32	25,15,60	62,38,0	KJf
L-1	59,28,13	59,28,13	68,32,0	KJf
L-3	45,38,17	39,38,23	51,49,0	KJf
L-4	N D	N D	N D	KJf
L-8	42,45,13	40,45,15	47,53,0	KJf
L-17	41,46,13	38,46,16	46,54,0	KJf
L-19	36,28,36	25,28,47	48,52,0	KJf
L-20	33,21,46	21,21,58	51,49,0	KJf
KJf mean---	44,31,25	36,31,33	54,46,0	
L-10	06,16,78	04,16,80	18,82,0	Kl
L-14	13,10,76	08,10,88	N D	Kl



▶ **Figure 2.** Comparison of detrital modes of sandstone clasts in the Lospe Formation with other in-place sandstones of Mesozoic age in and adjacent to the Santa Maria basin. Qt, monocrystalline quartz, polycrystalline quartz, and chert; F, plagioclase and potassium feldspar; L, lithic rock fragments; Qm, monocrystalline quartz; Lt, lithic rock fragments including polycrystalline quartz and chert; P, plagioclase feldspar; K, potassium feldspar.

contiguous with the more quartzofeldspathic samples of Upper Cretaceous sandstones and the Point San Luis rocks. Features common to both clasts and in-place Upper Cretaceous rocks include grain shapes and grain compaction, degrees of plagioclase alteration, types of lithic fragments, and accessory minerals (notably epidote). Grains range from angular to subrounded and are moderately to poorly sorted with tight and often interpenetrating grain boundaries. Twinned and untwinned plagioclase vary from clear grains with no visible alteration to moderately and heavily mottled grains that are almost entirely replaced by either sericite, calcite, or, in rare cases, epidote. The variation in plagioclase alteration and the presence of detrital K-feldspar and detrital epidote suggest that much of the plagioclase alteration might be inherited from altered (granitic?) source rocks rather than being products of post-burial diagenesis. K-feldspars often are partly albitized, a fact which suggests that both clasts and in-place rocks shared a common burial history. Lithic fragments common to both Lospe clasts and in-place Upper Cretaceous sandstones are characterized by abundant aphanitic grains of unidentifiable origin; granitic grains composed of various combinations of quartz, plagioclase and K-feldspar; quartz-mica schist; weakly foliated polycrystalline quartz tectonite; and rare felsic and spilitic volcanic rocks.

Sandstone Knockers in Melange of the Franciscan Assemblage

Detrital modes of sandstone and metasandstone knockers (tectonic phacoids) in melange of the Franciscan assemblage from outcrops along the eastern and northern margins of the Santa Maria basin were reported by McLean (1991); their detrital modes are illustrated in figure 2. The Franciscan sandstone (so-called graywacke) knockers studied by McLean (1991) vary widely in composition from rocks composed mainly of altered mafic volcanic fragments to rocks that contain abundant quartz and plagioclase; none of the Franciscan sandstone knockers contained K-feldspar, regardless of their quartz and feldspar content. McLean (1991) reported textural evidence that suggested some of the Franciscan sandstones had originally contained K-feldspar, which had altered to albite (probably during subduction). The Franciscan melange sandstone knockers are typically crisscrossed by veinlets of quartz and (or) calcite, contain albitized feldspar, and have a matrix composed of a mix of chlorite and quartz. Lithic rock fragments have a bleached or washed-out appearance in plane light, which may be the result of pervasive chloritization. Clasts in the Lospe Formation that share the aforementioned petrographic characteristics are interpreted as being probably derived from Franciscan melange sandstones (table 1).

DISCUSSION

Overlapping and (or) gradational detrital modes that are illustrated in figure 2, as well as similar textures and common accessory minerals, indicate that most of the sandstone clasts in the Lospe Formation at North Beach were derived from either the upper part of the Great Valley sequence or from knockers in melange of the Franciscan assemblage. A few clasts were derived from the lower part of the Great Valley sequence.

McLean (1991) noted that the Q-F-L modes of sandstones in melange of the Franciscan assemblage overlapped those of most of the lower part of the Great Valley sequence and the more lithic-rich part of the upper Great Valley sequence. Compositional and textural similarities suggested to McLean (1991) that the Franciscan rocks might be composed of subducted and accreted lower Great Valley sequence and subducted and accreted lower parts of the upper Great Valley sequence. The age of the subducted sandstones in the Franciscan assemblage of the Santa Maria basin area is inferred to range from Late Jurassic to early Late Cretaceous (pre-Cenomanian?). Geographically, most of the Franciscan melange sandstones sampled by McLean (1991) were from outcrops located near the eastern and northern margins of the Santa Maria basin and possibly represent an older (landward) part of the accretionary complex than that part which lies seaward of the modern coastline. Relatively high percentages of quartz and feldspar in Lospe clasts that are interpreted to have a Franciscan provenance were possibly derived from younger melange that contained subducted Campanian and younger Great Valley sequence rocks.

CONCLUSIONS

As was noted by Anderson (1980), clasts in the Lospe Formation at North Beach reflect erosion of at least three Mesozoic lithotectonic elements as well as pre-Lospe felsic volcanic rocks of probable middle Tertiary age (Cambria Felsite or correlatives?). Radiometric ages of tuff reported by Stanley and others (1991) indicate an early Miocene age for the Lospe Formation. Much of the coarse Lospe conglomeratic detritus was derived from nearby masses of ophiolitic rocks. Some material, however, such as blueschist, red radiolarian chert, and altered sandstone (so-called graywacke) was most likely derived from Franciscan melange. Many of the sedimentary clasts in the Lospe Formation at North Beach near Point Sal were derived from the upper part of the Great Valley sequence and from melange of the Franciscan assemblage. Anderson (1980) reported that some of the sandstone clasts might have been derived from a Paleogene source, and this remains as a possibility because Paleocene and Eocene sandstones in the southern Coast Ranges and in the Western Transverse Range are indistinguishable petrographically from those of Upper Cretaceous age. Paleogene sandstones, however, are unknown in areas that have been penetrated by drilling in the basement of both the onshore and offshore parts of the Santa Maria basin (McCulloch, 1987), except for Eocene strata that were reported by Vedder and others (1991) in the Pennzoil OCS 0427 test well, which is located about 11 km west of Purisima Point and 15 km south-southwest of Point Sal. Vedder and others (1991, p. 947) cited an unpublished paleontologic report that indicated the Pennzoil well had penetrated a 27-m section of white micaceous sandstone and microfossil-rich mudstone and shale, which was "possibly equivalent to part of the Anita Shale."

Southeast-oriented paleocurrent indicators (as determined by modern coordinates) in the North Beach section suggest that Mesozoic basement now located offshore probably consists of ophiolite, Franciscan melange, and rocks of the lower and upper parts of the Great Valley sequence. The Pennzoil well data suggest that at least remnants of Paleogene rocks exist in the offshore Santa Maria basin.

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