INGERSOLL & SUCZEK 1979

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 49, NO. 4. P. 1217–1228
FIGS. 1–6, DECEMBER, 1979

0022-4472/79/0049-1217/$03.00

PETROLOGY AND PROVENANCE OF NEOGENE SAND FROM NICOBAR AND BENGAL FANS, DSDP SITES 211 AND 218[1]

RAYMOND V. INGERSOLL
Department of Geology
University of New Mexico
Albuquerque, New Mexico 87131
AND
CHRISTOPHER A. SUCZEK
Department of Geology
Western Washington University
Bellingham, Washington 98225

ABSTRACT: The Bengal-Nicobar submarine fan complex is part of a linked sedimentary chain consisting of molasse, deltaic, and flysch deposits resulting from the sequential closing of a remnant ocean basin. Ultimate sources for turbidite sand from this fan complex are the uplifted gneissic, sedimentary, and metasedimentary terranes of the Himalayas.

Detailed point-counts of lithic grains, as well as standard QFL percentages, of 22 Neogene sand samples from DSDP sites 211 and 218 reveal very uniform compositions. Typical QFL percentages are: 55-30-15. Plagioclase/total feldspar is typically near 0.7. Lithic types are dominated by quartz-mica tectonite, quartz-mica aggregate, polycrystalline mica, and other sedimentary and metasedimentary varieties. Andesitic volcanic lithic grains are absent. The indicated provenance ("tectonic highlands") for Bengal-Nicobar sands contrasts markedly with that of sand and sandstone derived from magmatic arcs and rifted continental margins. Lithic populations of magmatic arc sand and sandstone are dominated by volcanic grains, whereas lithic populations of rifted continental margin sand and sandstone are dominated by polycrystalline quartz and sedimentary grains. Two triangular plots of lithic grains distinguish the provenance of sandstone derived from major tectonic settings. Detailed point-counts of lithic grains from thick sedimentary accumulations of unknown tectonic setting are a powerful paleogeographic tool when used in the manner outlined here.

INTRODUCTION

The Bengal-Nicobar submarine fan complex represents the largest single accumulation of sediment in the world today. This fan complex has a total length exceeding 3000 kilometers, a width exceeding 1000 kilometers and a thickness that is locally in excess of 16 kilometers (Curray and Moore, 1971, 1974). The Bengal Fan is separated from the Nicobar Fan by the Ninety-East Ridge, but both are part of the same sediment dispersal system (Fig. 1). Sediment within this fan complex is derived predominantly from the greatest uplifted area on earth (the Himalayas), and is fed through the world's largest deltaic complex (the Ganges-Brahmaputra Delta). The Ganges River drains the south side of the Himalayas and the Brahmaputra River drains the north side. Together, these rivers have the highest amount of suspended load of any modern river system (Curray and Moore, 1971).

Much of the sediment derived from the Himalayas has not reached the Ganges-Brahmaputra Delta or the Bengal-Nicobar Fan. In Pleistocene and Recent times, considerable detritus has been retained in the floodplains of the Ganges and Brahmaputra rivers in front of the Himalayan uplifts. In late Tertiary time, the Siwalik and related formations were deposited in similar floodplain and alluvial fan settings, and subsequently uplifted and deformed in the Himalayan foothills. All of these thick sedimentary units accumulated in a rapidly subsiding peripheral basin (Dickinson, 1974) whose genesis is linked intimately to the deformation and uplift of the Himalayas. Thus, the Himalayan-Bengal system illustrates how linked sedimentary components of molasse (Siwaliks), deltaic

---

[1] Manuscript received March 6, 1979; revised June 25, 1979.

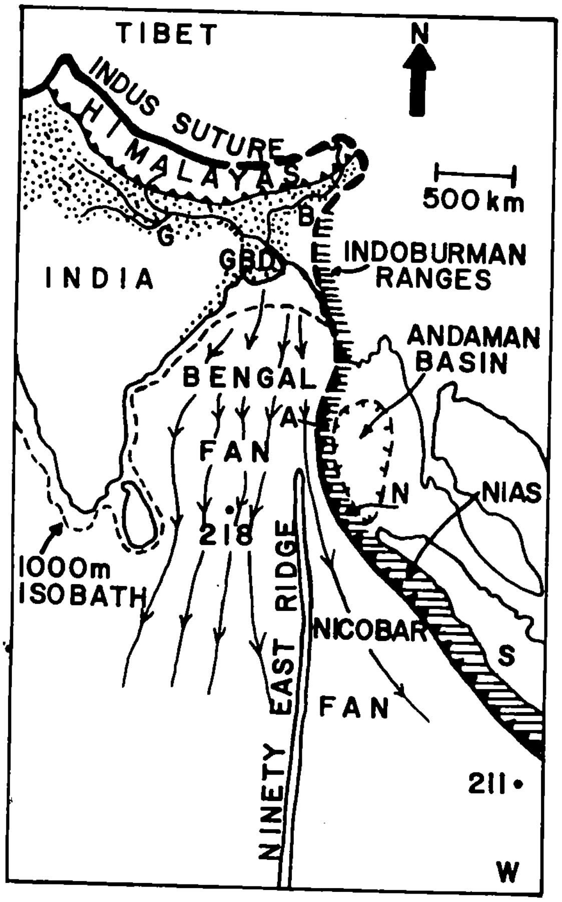

FIG. 1.—Map showing location of DSDP sites 211 and 218, as well as important geologic and geographic features. Stippled pattern denotes Quaternary alluvium of Ganges (G) and Brahmaputra (B) river systems, and the Ganges-Brahmaputra Delta (GBD). The Siwalik and related formations were deposited in a similar tectonic-geographic setting south of the fold-thrust belt (barbed symbols) on the south side of the Himalayas. The heavy solid line denotes the Indus suture belt. The solid barbed symbol east of the Nicobar and Bengal fans denotes the Sunda trench, behind which are forearc basin deposits, and accreted material (horizontal lines) that is exposed on land in the Indoburman Ranges, on the Andaman (A)-Nicobar (N) islands and on Nias Island, among others. Sumatra (S) and the Wharton Basin (W) also are shown. See Graham et al. (1975) for a thorough discussion of tectonics of the area.

(Ganges-Brahmaputra) and flysch (Bengal-Nicobar) deposits form as a result of sequential closing of remnant ocean basins (Graham et al., 1975).

Many workers (e.g., Curray and Moore, 1971, 1974; McKenzie and Sclater, 1971; Powell and Conaghan, 1973) have discussed the plate tectonic evolution of the Indian Ocean and the collision of the Indian subcontinent with the Eurasian continent that resulted in the formation of the Himalayas. Graham et al. (1975) discussed these events from the points of view of basin evolution, sedimentation and sediment dispersal patterns. Figure 1 contains the important components of the modern dispersal systems, but the reader is referred to Curray and Moore (1971, 1974) and Graham et al. (1975) for a thorough discussion.

To test the hypothesis that turbidite sand at the outer edges of the Bengal-Nicobar fan system was derived ultimately from the Himalayas, and in order to determine its petrologic characteristics, we point-counted Neogene sand from two Deep Sea Drilling Project (DSDP) holes. The results are compared to petrologic data from other components of the Himalayan-Bengal dispersal system as well as from sand and sandstone derived from other suture belts, magmatic arcs, rifted continental margins and other tectonic settings. The results are in agreement with those of Graham et al. (1975, 1976) regarding the dominant tectonic control of petrologic characteristics of turbidite sand and sandstone derived from single sources.

PREVIOUS PETROLOGIC WORK

Diverse petrologic studies of the Siwalik and related formations of the Himalayan foothills (e.g., Chaudhri, 1969, 1970, 1971, 1972; Krynine, 1937; Sinha and Sastri, 1973; Tandon, 1976) indicate uplifted crystalline basement terranes as the predominant provenance. Less work has been completed on the petrology of sediments of the Ganges-Brahmaputra Delta area, but the available literature also indicates an uplifted crystalline basement provenance (e.g., Mallik, 1976). Mallik (1978) and Thompson (1974) have published the only data concerning the petrology and provenance of Bengal-Nicobar sand (as well as other Indian Ocean sand), with the exception of our own results (Ingersoll and Suczek, 1976).

Sandstone from Nias Island (uplifted subduction complex of the Sunda magmatic arc) has petrologic characteristics somewhat similar to those of the Bengal-Nicobar fan even though much of the Nias sediment was derived from the Sunda arc (Moore, 1979). These similarities can be explained by noting that extensive sedimentary and crystalline terranes on the west coast of Sumatra contributed non-volcanic detritus to the trench-slope basins of Nias (Moore, 1979). Melanges on Nias have petrologic characteristics more similar to Bengal-Nicobar sand than do trench slope deposits and thus might be derived ultimately from the Himalayas, at least in part. More work on sandstone from the Sunda subduction complex is needed to resolve this uncertainty.

Graham et al. (1976) presented detailed petrologic data from the Ouachita Mountains and Black Warrior Basin, and discussed the tectonic setting and provenance of these sandstones. These data, along with those of Gazzi et al. (1973) and those presented here, detail the lithic populations of sandstone deposited within non-marine, deltaic and submarine fan settings formed within sequentially closing suture belts (Graham et al., 1975). Provenance for Ouachita-Black Warrior Basin sandstones was a mixed sedimentary-metasedimentary terrane devoid of volcanics. According to the tectonic analogy between the Appalachian-Ouachita system and the Himalayan-Bengal system (Graham et al., 1975), lithic sand-grain populations from the Bengal-Nicobar fan system should be similar to those from the Ouachita-Black Warrior Basin system since both suites of sandstone were deposited within remnant ocean basins formed between converging continental margins. Results presented here confirm this hypothesis.

Graham et al. (1976) also discussed how sandstone derived from magmatic arcs usually is clearly distinguishable from suture-derived sandstone based on lithic populations. Extensive petrologic data exist for arc-derived sandstone (e.g., Dickinson, 1971; Dickinson and Rich, 1972; Ingersoll, 1976, 1978; Stewart, 1978), and these previous investigations form the basis for comparison with our results.

Petrologic data on lithic populations of turbidite sand derived from rifted continental margins are scarce, but the few available results (Bartolini et al., 1975; Campbell and Clark, 1977; Hubert and Neal, 1967) show marked contrasts with lithic populations from suture- and arc-derived sand and sandstone. Details of lithic populations from these various tectonic settings are discussed below.

SAMPLE LOCATIONS AND SEDIMENT SOURCES

DSDP sites 211 and 218 are the only ones drilled into the Bengal-Nicobar fan system that contain turbidite sand (Von der Borch, Sclater et al., 1974). DSDP site 218 is located near the center of the Bengal Fan, east of the southern tip of India (Fig. 1). Site 211 is at the southern end of the Nicobar Fan (Fig. 1). Site 211 is separated from the Sunda arc by the Sunda trench, along which the east edge of the Nicobar Fan is being consumed by subduction (Bowles et al., 1978). The Wharton Basin separates Site 211 from the rifted continental margin of Australia. Derivation of turbidite sand at Site 211 from the Sunda arc in the vicinity of the Andaman-Nicobar islands cannot be ruled out, but the absolutely indistinguishable nature of the sand from Sites 211 and 218 suggests that all sand studied was derived from the same source (Himalayas). In addition, even sand derived from the area of the Andaman-Nicobar islands may have ultimate sources in the Himalayas because these islands consist of a subduction complex formed by deformation of the east side of the Bengal-Nicobar fan (Moore et al., 1976). Thus, even if recycled by the processes of subduction-accretion and subsequent gravity-induced sliding, all sand studied from Sites 211 and 218 probably has ultimate sources in the Himalayas.

SAMPLE PREPARATION

Twenty-two samples of sandy sediment from thin turbidite layers were selected from sites 211 and 218. Sampled sediment ranges in age from Miocene through Pleistocene.

Samples were dried in a warm oven, and their dry weights were recorded. They were then covered with water and soaked for three hours to allow them to disaggregate. The six samples that were not disaggregated after that time were further treated with a 30% peroxide solution to dissolve organic material. All samples were wet-sieved through a 250-mesh screen to remove the clay-sized fraction; they then were dried and reweighed. All samples were rich in mica, but mica is difficult to interpret for provenance studies. Therefore, a portion of the mica present in each sample was removed by shaking the sand gently down a piece of filter paper. The more spherical grains consisting of other minerals rolled off the paper, while many of the mica flakes remained behind. Samples were reweighed and the weight percent of mica removed was calculated. In every case, some mica remained in the sample. The prepared sand samples were mixed with epoxy and allowed to harden, forming artificial sandstone. From these, thin sections were prepared and stained for both plagioclase and potassium feldspar.

PETROGRAPHIC TECHNIQUES

In order to increase the accuracy and reproducibility of our work, we used a multi-operator method of point-counting (as utilized by Graham et al., 1976). Each of the authors counted on a separate half of each section; the results were compared and recounts were made in cases where there were significant differences in results between operators. Generally, our original counts were in good agreement. The results for both operators were summed together; modes and lithic percentages were calculated from these sums.

Two point counts were made on each sample, one for QFL mode and a second for lithic types. For the first count each operator counted 300 points (for a combined total of 600) at a spacing of 0.5 mm. The main categories are Qm, P, K and L$_t$ (Table 1), with the first three distinguished on the basis of presence or absence of stains and twinning. Heavy minerals, carbonate grains, mica and miscellaneous grains were included in this count.

For the second count, each operator counted 150 lithic points (for a combined total of 300) at a spacing of 0.5 mm. Categories included are volcanic-hypabyssal, polycrystalline mica, quartz-mica tectonite, quartz-mica aggregate, quartz-mica-feldspar aggregate, polycrystalline quartz, argillite-shale and indeterminate-miscellaneous. Descriptions of these lithic types are given below.

Since these "sandstones" were made artificially by gluing together sand and silt grains, no counts were made of interstitial material. Points that did not fall on grains were not counted, so that totals are total numbers of grains counted. One difficulty encountered in the counting was caused by the presence in some samples of incompletely disaggregated material (generally small clumps of fine-grained carbonate and clay), with some clumps including foram tests or terrigenous silt or sand. Such material was not counted. Foram tests also were omitted from our counts. Our petrographic techniques follow those of Dickinson (1970), Graham et al. (1976) and Ingersoll (1978), unless otherwise noted.

TABLE 1.—*Grain Parameters (modified from Graham et al., 1976)*

(a) Q = Qm + Qp	where	Q	=	total quartzose grains
		Qm	=	monocrystalline quartz grains
		Qp	=	polycrystalline aphanitic quartz grains
(b) F = P + K	where	F	=	total feldspar grains
		P	=	plagioclase feldspar grains
		K	=	potassium feldspar grains
(c) Lt = L + Qp	where	Lt	=	total aphanitic lithic grains
		L	=	unstable aphanitic lithic grains
(d) L = Lm + Lv + Ls	where	Lm	=	metamorphic aphanitic lithic grains
		Lv	=	volcanic-hypabyssal aphanitic lithic grains
		Ls	=	sedimentary aphanitic lithic grains
(e) L = Lvm + Lsm	where	Lvm	=	volcanic-hypabyssal and metavolcanic aphanitic lithic grains
		Lsm	=	sedimentary and metasedimentary aphanitic lithic grains

LITHIC TYPES

A brief description of each of the eight categories of lithic grains used in this study follows:

1) Volcanic-hypabyssal: fine-grained lithic grains recognized as volcanic by the presence

of felsitic, microlitic or lathwork textures;

2) Polycrystalline mica: mica aggregates, all of which have schistose fabric (Fig. 2);

3) Quartz-mica tectonite: metamorphic lithic grains composed of quartz and mica, and having a preferred planar fabric (Fig. 2, 3C and 3D);

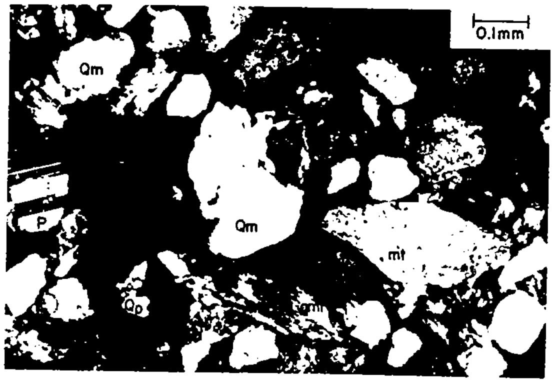

FIG. 2.—Photomicrograph showing typical field of view of Neogene sand. Selected grains are labelled as follows: Qm: Monocrystalline quartz, Qp: polycrystalline quartz, P: plagioclase feldspar, mt: mica tectonite (polycrystalline mica), qmt: quartz-mica tectonite.

4) Quartz-mica aggregate: lithic grains composed of quartz and mica, but without a preferred planar fabric;

5) Quartz-mica-feldspar aggregate: lithic grains composed of quartz, mica and feldspar, and generally without planar fabric;

6) Polycrystalline quartz: microcrystalline aggregates of mono-mineralic quartz with most domains smaller than the thickness of a thin section (including chert) (Fig. 3B);

7) Argillite-shale: dark, semi-opaque, fine-grained detrital aggregates (Fig. 3A);

8) Indeterminate-miscellaneous: lithic grains not clearly fitting into any of the above categories.

The categories of quartz-mica tectonite and quartz-mica aggregate were differentiated on the basis of presence or absence of a planar fabric. Most grains clearly have or lack this fabric, but for some grains the distinction

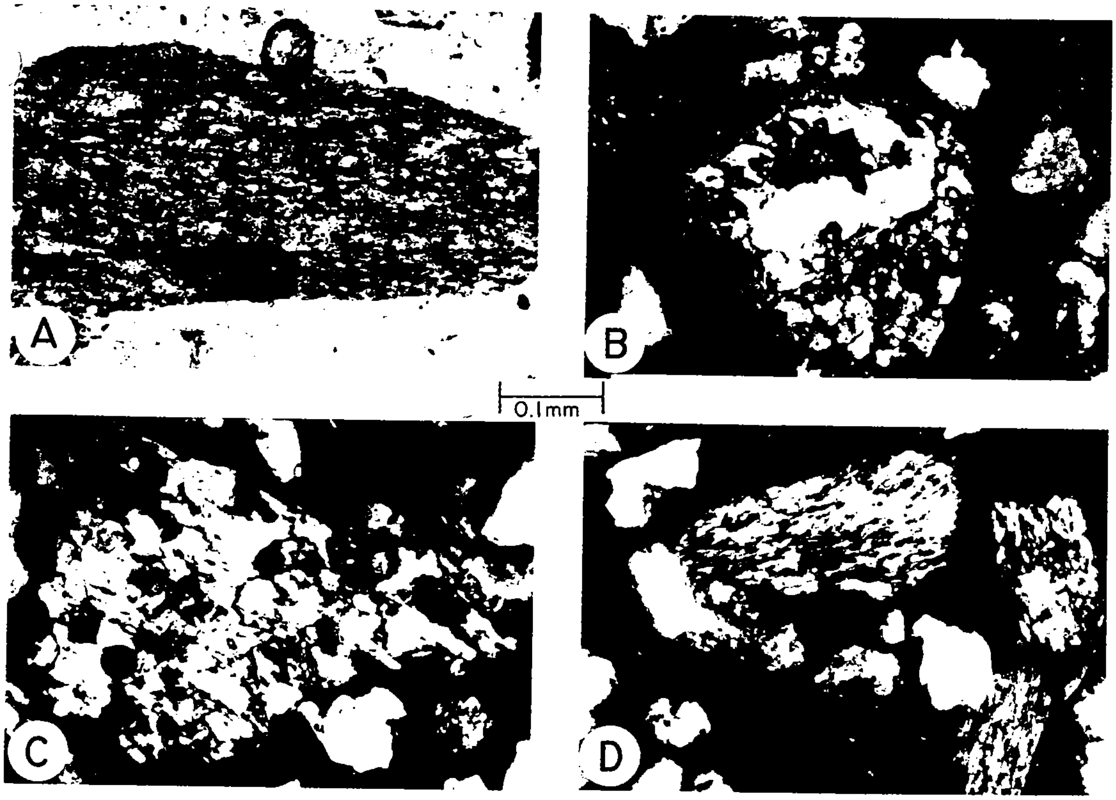

FIG. 3.—Photomicrographs of typical lithic grains. A) Argillite-shale, ordinary light. B) Polycrystalline quartz, rossed nicols. C) Quartz-mica tectonite, crossed nicols. D) Quartz-mica tectonites and monocrystalline quartz, ossed nicols.

is difficult. The largest discrepancy between operators occurred here, with RVI favoring quartz-mica tectonite and CAS favoring quartz-mica aggregate; we believe that our respective biases cancel each other in the final results. The category argillite-shale, which may grade into quartz-mica tectonite, was distinguished easily by both fine grainsize and dark color. Grains were counted as polycrystalline quartz only if they contain no mica; otherwise they were called quartz-mica aggregate or tectonite. Volcanic-hypabyssal grains are rare in these samples, but we included in that category all grains with any indication of volcanic texture.

PETROGRAPHIC RESULTS

Point-count data were recalculated as indicated in Table 1, and resulting modes and lithic percentages appear in Table 2. Three types of triangular plots were constructed from these data. Figure 4 is a standard QFL plot that illustrates the quartzofeldspathic nature of the Bengal-Nicobar sand. The QFL plot does not clearly differentiate provenance, as the compositions of the studied sand plot in an area transitional from typical plutonic provenance to more quartzose "tectonic" provenance (Dickinson, 1970; Graham et al., 1976). Uplifted crystalline (plutonic and gneissic) as well as reworked sedimentary and metasedimentary terranes are the indicated sources.

Two other types of triangular plots of lithic components (Fig. 5) are more indicative of provenance and tectonic setting. The QpLvLm plot was introduced by Graham et al. (1976) as a useful indicator of provenance. The same plot is hereby designated the QpLvmLsm plot to avoid confusion of terminology with the other lithic plot (LmLvLs). Graham et al. (1976) clearly intended their Lv category to include volcanic and metavolcanic lithic grains and their Ls category to include sedimentary and metasedimentary lithic grains. We feel the modification of notation clarifies their intent. The LmLvLs triangular plot (Fig. 5B) is suggested here as another useful provenance indicator. Both the QpLvmLsm and LmLvLs triangular plots are useful in differentiating sand

TABLE 2.—*Modal Point Count Data. Values shown are based on 600 total grain points and 300 total lithic points. See Table 1 for explanation of symbols*

Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Mean and One Standard Deviation
% QFL																							
Q	54	56	71	49	63	51	61	49	56	55	54	59	58	64	58	56	56	66	51	52	61	63	57 ± 6
F	28	26	22	24	23	35	25	38	35	33	33	27	24	18	19	29	31	25	40	26	23	30	28 ± 6
L	18	18	7	27	13	14	14	13	9	12	12	14	17	17	23	15	13	9	9	21	16	7	14 ± 5
P/F	.59	.63	.61	.72	.56	.65	.74	.69	.63	.78	.57	.60	.61	.96	.72	.76	.62	.64	.68	.69	.92	.66	.68 ± .10
% L_t																							
1. volcanic-hypabyssal	4	2	1	4	4	3	4	4	4	4	4	2	2	1	1	3	6	3	3	6	6	7	4 ±2
2. polycyrstalline mica	14	10	8	11	4	8	8	14	8	14	11	10	7	9	8	10	14	11	8	8	12	11	10 ± 3
3. quartz-mica tectonite	31	38	27	35	24	30	28	36	23	30	32	27	28	22	34	37	27	32	35	26	33	35	30 ± 5
4. quartz-mica aggregate	25	25	38	27	37	18	29	20	18	25	23	38	32	48	27	26	28	28	27	33	27	24	28 ± 7
5. quartz-mica-feldspar aggregate	5	6	7	4	13	14	9	6	10	7	6	13	9	4	7	6	9	9	12	7	2	6	8 ± 3
6. polycrystalline quartz	5	6	6	3	5	14	11	7	9	8	7	2	3	2	2	4	5	5	4	4	3	4	5 ± 3
7. argillite-shale	9	9	5	8	5	7	6	7	8	6	10	2	10	5	11	11	8	8	4	9	13	9	8 ± 3
8. indeterminate-miscellaneous	7	4	7	8	7	6	4	6	20	6	6	7	10	8	10	5	4	4	6	7	4	6	7 ± 3
% (L_t−8)																							
Qp(6)	5	6	6	3	5	15	12	7	11	8	8	2	4	3	2	4	5	6	5	4	3	4	6 ± 3
Lvm(1)	5	2	1	5	4	3	5	4	5	4	4	3	3	1	1	3	6	3	3	6	6	7	4 ± 2
Lsm(2+3+4+5+7)	90	92	93	92	91	82	84	89	84	88	88	95	94	96	97	93	89	91	92	90	91	89	90 ± 4
% (L_t−8−6)																							
Lm(2+3+4+5)	85	88	93	86	89	88	88	87	83	88	84	96	86	93	87	85	85	88	92	83	80	83	87 ± 4
Lv(1)	5	2	1	5	5	4	5	4	6	5	4	3	3	1	1	3	6	4	3	7	6	7	4 ± 2
Ls(7)	10	10	6	9	6	9	7	8	11	7	12	2	11	5	12	12	8	9	5	10	14	10	9 ± 3

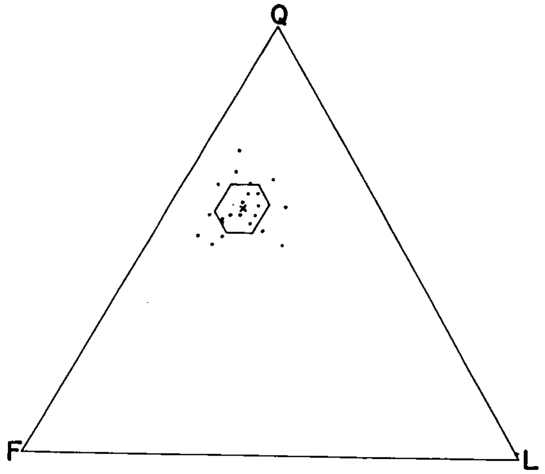

FIG. 4.—QFL diagram showing compositions of Neogene sand from DSDP sites 211 and 218. "X" denotes mean of 22 samples, and the outlined area is a measure of the dispersion of the data, as determined by standard deviations (see text for discussion of meaning of this field of variation).

derived from suture belts, magmatic arcs and rifted continental margins, as discussed more fully below.

Plagioclase-to-total-feldspar ratios of the twenty-two samples studied have a mean of less than 0.7 (Table 2). This value is lower than that for most sand derived exclusively from volcanic terranes and is fairly typical for sand derived from mixed plutonic and metamorphic terranes of granitic composition (Dickinson, 1970; Dickinson and Rich, 1972; Ingersoll, 1978). Scarce data from sandstone derived from other suture belts have similar values (Graham et al., 1976).

The means and standard deviations tabulated in Table 2 and plotted on Figures 4, 5, and 6 are not statistically rigorous values because the data sets are constant-sum and constrained (see Ingersoll (1978) for discussion). The exact meaning of the standard deviation fields as plotted on Figures 4, 5, and 6 is statistically ambiguous. Nonetheless, the fields are measures of the dispersion of the data and are useful in illustrating visually the contrasts in populations. Using standard deviation calculations in this manner seems justifiable as long as no quantitatively rigorous statistical meaning is attached to the calculations.

Lithic populations of Bengal-Nicobar sand are dominated by metasedimentary types (Table 2, Fig. 5). QFL percentages are dominated by monocrystalline quartz, plagioclase feldspar and potassium feldspar, in that order (Table 2, Fig. 4). In addition, micas (predominantly muscovite and biotite) were abundant in the original samples (see above). These characteristics suggest that the provenance for the sand consists of uplifted crystalline basement terranes of granitic to granodioritic composition, as well as extensive low- to high-grade metasedimentary terranes. These conclusions are in excellent agreement with hypothesized provenance for coeval non-marine sediments of the Hima-

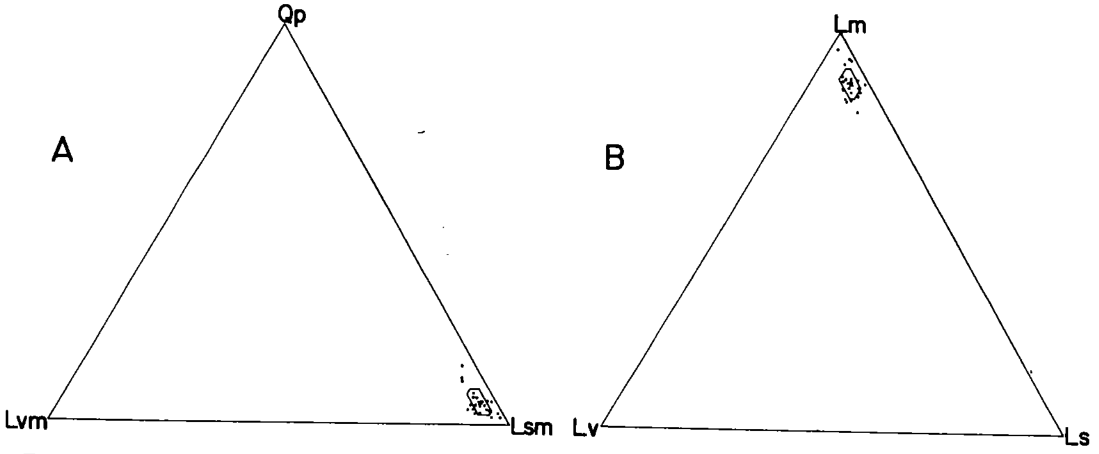

FIG. 5.—Triangular plots showing compositions of Neogene sand from DSDP sites 211 and 218. "X" denotes mean of 22 samples, and the outlined area is a measure of the dispersion of the data, as determined by standard deviations (see text for discussion of meaning of these fields of variation). Parameters defined in Table 1. A) QpLvmLsm diagram. B) LmLvLs diagram.

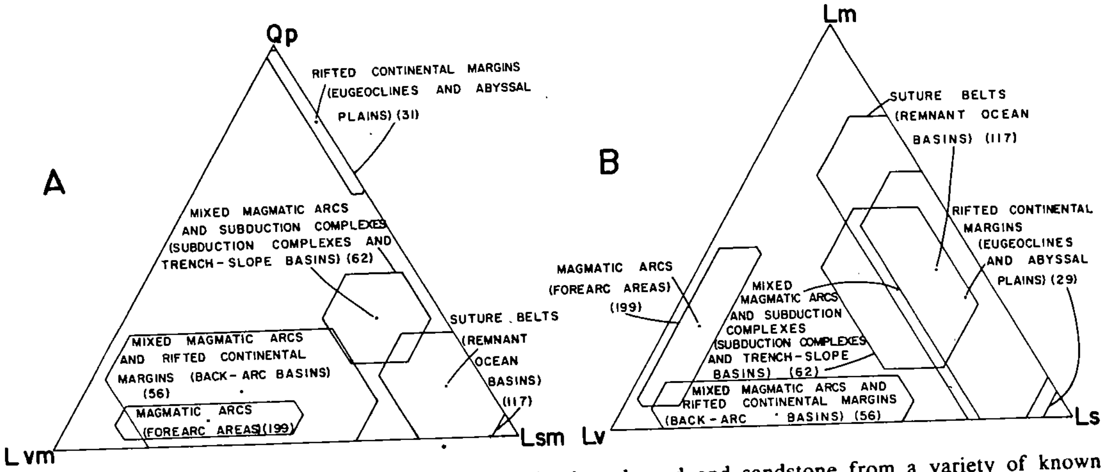

FIG. 6.—Triangular plots showing compositions of selected sand and sandstone from a variety of known tectonic settings. For each group, the provenance, depositional setting (in parentheses) and number of data sets (in parentheses) are labelled, and the mean and field of dispersion (see text) are shown. See text for meaning and use of these plots as well as data sources. A) QpLvmLsm diagram. B) LmLvLs diagram.

COMPARE OUCH-BK WAR

layan foothills (Siwaliks and related formations) (Chaudhri, 1969, 1970, 1971, 1972; Krynine, 1937; Sinha and Sastri, 1973; Tandon, 1976). They also are in agreement with possible provenance for sediment in the Ganges-Brahmaputra Delta area (Mallik, 1976). Thus, the data presented here support the concept of linked dispersal systems within non-marine, shallow marine and deep marine settings as suggested by Graham et al. (1975, 1976). Lithic populations remain proportionately constant through this entire dispersal network, and are reliable guides to provenance.

The virtually complete lack of andesitic volcanic lithic fragments within the studied samples is noteworthy. Out of approximately 6600 lithic grains that we counted, only one grain was clearly identifiable as an andesitic fragment with microlitic texture. In contrast, lithic populations of sand and sandstone derived from magmatic arcs usually are dominated by microlitic lithic grains (Dickinson, 1970, 1971; Dickinson and Rich, 1972; Ingersoll, 1978). Samples from carboniferous sandstones of the Ouachita-Black Warrior basin system similarly contain mostly metasedimentary lithic grains (Graham et al., 1976).

The following characteristics of Bengal-Nicobar sand contrast with those of the Carboniferous sandstones of the Ouachita-Black Warrior basin system despite the similarities of provenance and tectonic setting: 1) higher QFL% feldspar, 2) lower QFL% quartz, 3) higher QpLvmLsm% sedimentary-metasedimentary lithic grains, and 4) lower QpLvmLsm% polycrystalline quartz. These characteristics may be explained by two possible differences between the Himalayan and Appalachian suture belts. The Himalayas have been uplifted to an extreme degree due to renewed underthrusting following initial continental collision (Powell and Conaghan, 1973). Thus, Neogene sand derived from the Himalayas is richer in high-grade metamorphic (including gneissic) detritus than are sandstones derived from either the Appalachians during the Carboniferous or, possibly, the Himalayas during the Paleogene. The latter two sandstone groups likely were derived from lower-grade metasedimentary and sedimentary terranes that have since been eroded. This explains the higher feldspar, higher metasedimentary lithics and lower polycrystalline quartz of the Bengal-Nicobar samples. The other differences can be explained by the fact that significant quantities of both monocrystalline and polycrystalline quartz were contributed to the Carboniferous Ouachita sandstones from the extensive North American craton (Graham et al., 1976). In contrast, the Indian sub-continent is relatively small and probably has not contributed significant detritus to the Bengal-Nicobar fan system.

IMPLICATIONS AND CONCLUSIONS

Graham et al. (1976) proposed the QpLvmLsm triangle (originally the QpLvLs triangle) as a useful plot for distinguishing provenance of rapidly deposited sand-sized sediment derived from single sources. We agree with their findings and refine the meaning of the plot with the aid of new data from the present study as well as data available from the literature (Fig. 6A, Table 3). In addition, we plot data from the same sources on an LmLvLs triangular plot (Fig. 6B, Table 3) with equally interesting results. We emphasize that this type of approach is valid only for sand-sized sediments that have been rapidly deposited and have been derived from regionally homogeneous source areas with definitive tectonic settings. Many factors determine sand and sandstone compositions (Suttner, 1974), and our approach applies only where transportation, depositional environment and diagenesis are subordinate to provenance in determining composition. Thick sequences of flysch and molasse from different tectonic settings are most successfully studied using this approach.

Sand and sandstone derived from three primary tectonic settings can be differentiated readily using lithic populations: magmatic arcs, suture belts and rifted continental margins. Figures 6A and 6B demonstrate that the fields constructed from the means and standard deviations (see discussion above) do not overlap for these three primary tectonic settings, with one exception (Fig. 6B). Naturally, some sand and sandstone would plot outside these primary fields and still belong to one of the groups (e.g., Bengal-Nicobar sand, Figs. 5B, 6B). However, it is unlikely that sediment derived from one of the above tectonic settings would plot within the field of another setting. As Graham et al. (1976) point out, the contrasts in lithic populations (Fig. 6) are quite fundamental, as each field represents several determinations by different operators working on separate sediment accumulations which in many cases are in excess of ten kilometers in thickness. As more data become available, the various fields will shift somewhat, but we feel that the basic distinctions shown will stand the test of time.

The fundamental differences expressed by the QpLvmLsm and LmLvLs triangular plots are that: 1) magmatic arcs consist of fine-grained volcanics with subordinate amounts of fine-grained metasedimentary material (coarse-grained plutonics produce few, if any, lithic fragments as defined by the petrographic techniques of Dickinson (1970)); 2) suture belts lack significant volcanics, but primarily consist of uplifted sedimentary and metasedimentary terranes as well as high-grade gneiss terranes (the latter produce mainly quartz and feldspar, as do plutonic terranes); and 3) rifted continental margins

TABLE 3.—*Means and standard deviations of six parameters for different provenances. Number of data sets shown in parentheses*

Provenance	Qp	Lvm	Lsm	Lm	Lv	Ls
Magmatic Arcs	6.4 ±4.1 (199)	63.3 ±20.5 (199)	30.4 ±19.8 (199)	25.2 ±19.5 (199)	67.6 ±22.7 (199)	7.3 ±4.9 (199)
Suture Belts	13.0 ±13.6 (117)	8.7 ±12.9 (117)	78.4 ±16.1 (117)	37.9 ±38.7 (117)	9.5 ±13.1 (117)	52.6 ±37.5 (117)
Rifted Continental Margins	80.4 ±18.4 (31)	1.0 ±2.1 (31)	18.7 ±18.6 (31)	30.7 ±32.1 (29)	7.0 ±14.1 (29)	62.3 ±31.6 (29)
Mixed Magmatic Arcs and Subduction Complexes	30.8 ±11.2 (62)	14.4 ±11.5 (62)	55.0 ±12.0 (62)	33.4 ±20.3 (62)	20.1 ±14.8 (62)	46.5 ±19.4 (62)
Mixed Magmatic Arcs and Rifted Continental Margins	13.7 ±14.7 (56)	52.3 ±27.3 (56)	34.0 ±31.0 (56)	2.6 ±8.9 (56)	62.6 ±30.8 (56)	34.8 ±28.3 (56)

are dominated by shallow-marine quartzose sediments (miogeocline) and older, slightly uplifted sedimentary and coarse-grained crystalline terranes. The usual result of these heterogeneous sources for sediment shed off rifted continental margins is a predominance of quartz-rich detritus that is transported through submarine canyons to accumulate within the continental rise (eugeocline) or on abyssal plains. Thus, the factors controlling lithic populations of sand and sandstone derived from rifted continental margins include subdued tectonism and, therefore, subdued subaerial relief, which, in turn, allows intense weathering in source areas and favors the preservation of only the most chemically stable lithic grains (Qp and Ls) (e.g., Cleary and Conolly, 1971, 1974).

Tectonic settings containing sediments of mixed provenance are, naturally, more difficult to deal with. Trench-slope basins (Moore and Karig, 1976) with mixed provenance of magmatic-arc and reworked subduction complex material are an example of such complexity. The best available data from such settings are those of Moore (1979) from Indonesia, and Jacobson (1976, 1978) and Smith (1978) (also Smith et al., 1979) from California. In Moore's area an additional complication exists in that older sediments adjacent to the magmatic arc also contributed detritus. Sand and sandstone deposited in trench-slope basins have lithic populations intermediate among those of the three primary tectonic settings (Fig. 6). The QpLvmLsm plot appears to better differentiate trench-slope basin deposits from eugeoclinal or forearc basin sediments, whereas the LmLvLs plot appears to better differentiate trench-slope basin deposits from forearc basin deposits.

The provenance of Moore's (1979) melange sandstone on Nias is not definitively established in our minds. We agree with him that the Nias trench-slope basin deposits are composed of sediments derived from the magmatic arc along with reworked sediments from the frontal arc and, possibly, from the subduction complex itself. However, we think it is possible that his melange sandstone may be deformed Bengal-Nicobar fan material ultimately derived from the Himalayas, at least in part. The similarities in lithic populations of our data with the melange data of Moore lead us to this conclusion. However, it must be remembered that the melanges in question are older (Oligocene-Miocene) than our Bengal-Nicobar samples (Miocene-Pleistocene) and are coarser-grained. Also, paleogeography during the Oligocene was significantly different (see Curray and Moore, 1974; Graham et al., 1975), so that sources for these coarse-grained melanges might be sought in numerous places. We feel that a likely source might be the ancestral Ganges-Brahmaputra delta area. This area was south of its present location relative to Nias during the past. In any case, we feel that the ultimate sources for the melanges on Nias Island remain unresolved (see Moore (1979) for another viewpoint).

Also plotted on Figure 6 are point-count data from turbidite sand deposited in marginal seas (back-arc basins) (Harrold and Moore, 1975; Stewart, 1977). As expected, these data plot near the magmatic arc provenance field, but they are displaced toward the Qp and Ls corners of the two triangular plots. This displacement is the result of mixing of detritus derived from both magmatic arc sources and rifted continental margin sources. In fact, Harrold and Moore (1975) demonstrate the transitional nature of the petrology of turbidite sand within back-arc basins, depending on proximity to the magmatic arc.

Data from sand derived from unknown or mixed sources (e.g., Bartolini et al., 1975; Stewart, 1976) were plotted on the two triangular plots to test the plots' usefulness. As expected, the resulting fields usually plotted between or partly overlapping the three primary fields. Data of Bartolini et al. (1975) for sand derived from the Nile Delta were included in the plots for rifted continental margins, but their other data were plotted as unknowns with nondefinitive results. Stewart's (1976) data plotted overlapping or between the primary fields on both triangular plots, suggesting that provenance for these sediments was a mixed assemblage of terranes, a conclusion similar to Stewart's.

In conclusion, we think that the data presented here along with the compilation of others' data indicate that lithic populations of sand and sandstone deposited rapidly and derived from tectonically homogeneous sources are the key to paleogeographic and paleotectonic reconstructions based on provenance studies. Care must be taken in sampling, petrographic techniques and interpretation, and the complexity of possible paleotectonic reconstructions must be considered carefully. The techniques outlined here should prove useful in many situations in which differentiation of possible sources for sand and sandstone is a key to unravelling geologic history. Dickinson and Suczek (1978, in press) have reached a similar conclusion based on additional data treated in a somewhat different manner.

ACKNOWLEDGMENTS

We especially thank W. R. Dickinson and S. A. Graham who were coworkers during the early stages of this study. G. F. Moore kindly supplied us with a preprint of his paper and additional data from Nias Island. J. R. Curray, Dickinson, Graham, V. Kolla, and Moore reviewed the manuscript. We also thank Ruperto Laniz for masterful preparation of thin sections.

The departments of geology of Stanford University, The University of New Mexico, and Western Washington University provided logistical and financial support.

This work was supported by the National Science Foundation through the Deep Sea Drilling Project which provided samples.

REFERENCES

Bartolini, C., Malesani, P. G., Manetti, P., and Wezel, F. C., 1975, Sedimentology and petrology of Quaternary sediments from the Hellenic Trench, Mediterranean Ridge and the Nile Cone from D.S.D.P., Leg 13, cores: Sedimentology, v. 22, p. 205–236.

Bowles, F. A., Ruddiman, W. F., and Jahn, W. H., 1978, Acoustic stratigraphy, structure, and depositional history of the Nicobar Fan, eastern Indian Ocean: Marine Geology, v. 26, p. 269–288.

Campbell, J. S., and Clark, D. L., 1977, Pleistocene turbidites of the Canada Abyssal Plain of the Arctic Ocean: Jour. Sed. Petrology, v. 47, p. 657–670.

Chaudhri, R. S., 1969, Provenance of the Lower Tertiary sediments of the northwestern Himalayas: Indian Geol. Assoc. Bull., v. 2, p. 51–56.

———, 1970, Petrology of the Siwalik formations of the northwestern Himalayas: Indian Geol. Assoc. Bull., v. 3, p. 19–25.

———, 1971, Petrogenesis of Cenozoic sediments of the northwestern Himalayas: Geol. Mag., v. 108, p. 43–48.

———, 1972, Heavy minerals from the Siwalik formations of the northwestern Himalayas: Sed. Geology, v. 8, p. 77–82.

Cleary, W. J., and Conolly, J. R., 1971, Distribution and genesis of quartz in a piedmont-coastal plain environment: Geol. Soc. America Bull., v. 82, p. 2755–2766.

———, 1974, Hatteras deep-sea fan: Jour. Sed. Petrology, v. 44, p. 1140–1154.

Curray, J. R., and Moore, D. G., 1971, Growth of the Bengal deep-sea fan and denudation of the Himalayas: Geol. Soc. America Bull., v. 82, p. 563–572.

———, and ———, 1974, Sedimentary and tectonic processes in the Bengal deep-sea fan and geosyncline, *in* Burk, C. A., and Drake, C. L., eds., The Geology of Continental Margins: New York, Springer-Verlag, p. 617–627.

Dickinson, W. R., 1970, Interpreting detrital modes of graywacke and arkose: Jour. Sed. Petrology, v. 40, p. 695–707.

———, 1971, Detrital modes of New Zealand graywackes: Sed. Geology, v. 5, p. 37–56.

———, 1974, Plate tectonics and sedimentation, *in* Dickinson, W. R., ed., Tectonics and Sedimentation: Soc. Econ. Paleontologists Mineralogists Spec. Pub. No. 22, p. 1–27.

———, and Rich, E. I., 1972, Petrologic intervals and petrofacies in the Great Valley Sequence, Sacramento Valley, California: Geol. Soc. America Bull., v. 83, p. 3007–3024.

———, and Suczek, C. A., 1978, Plate tectonic influences on sandstone compositions: Geol. Soc. America Abs. with Programs, v. 10, p. 389.

———, and ———, in press, Plate tectonics and sandstone compositions: Am. Assoc. Petroleum Geologists Bull.

Gazzi, P., Zuffa, G. G., Gandolfi, G., and Paganelli, L., 1973, Provenienza e dispersione litoranea delle sabbie delle spiagge adriatiche fra le foci dell'Isonzo e del Foglia: inquadramento regionale: Memorie della Societa Geologica Italiana, v. 12, p. 1–37.

Graham, S. A., Dickinson, W. R., and Ingersoll, R. V., 1975, Himalayan-Bengal model for flysch dispersal in the Appalachian-Ouachita system: Geol. Soc. America Bull., v. 86, p. 273–286.

———, Ingersoll, R. V., and Dickinson, W. R., 1976, Common provenance for lithic grains in Carboniferous sandstones from Ouachita Mountains and Black Warrior Basin: Jour. Sed. Petrology, v. 46, p. 620–632.

Harrold, P. J., and Moore, J. C., 1975, Composition of deep-sea sands from marginal basins of the northwestern Pacific, *in* Initial Reports of the Deep Sea Drilling Project: Washington, D.C., U.S. Government Printing Office, v. 31, p. 507–514.

Hubert, J. F., and Neal, W. J., 1967, Mineral composition and dispersal patterns of deep-sea sands in the western North Atlantic petrologic province: Geol. Soc. America Bull., v. 78, p. 749–772.

Ingersoll, R. V., 1976, Evolution of the Late Cretaceous fore-arc basin of northern and central California [unpub. Ph.D. thesis]: Stanford, Stanford Univ., 200 p.

———, 1978, Petrofacies and petrologic evolution of the Late Cretaceous fore-arc basin, northern and central California: Jour. Geology, v. 86, p. 335–352.

———, and Suczek, C. A., 1976, Petrology and provenance of Neogene sand from the Nicobar and Bengal fans, DSDP sites 211 and 218: Geol. Soc. America Abs. with Programs, v. 8, p. 934.

JACOBSON, M. I., 1976, Petrologic variations in Franciscan sandstones from the Diablo Range, California [unpub. Masters thesis]: Berkeley, Univ. California, 173 p.

———, 1978, Petrologic variations in Franciscan sandstone from the Diablo Range, California, *in* Howell, D. G., and McDougall, K., eds., Mesozoic paleogeography of the western United States: Soc. Econ. Paleontologists Mineralogists, Pacific Section, Pacific Coast Paleogeography Symp. 2, p. 401–417.

KRYNINE, P. D., 1937, Petrography and genesis of the Siwalik series: Am. Jour. Sci., v. 34, p. 422–446.

MALLIK, T. K., 1976, Shelf sediments of the Ganges delta with special emphasis on the mineralogy of the western part, Bay of Bengal, Indian Ocean: Marine Geology, v. 22, p. 1–32.

———, 1978, Mineralogy of deep-sea sands of the Indian Ocean: Marine Geology, v. 27, p. 161–176.

MCKENZIE, D., AND SCLATER, J. G., 1971, The evolution of the Indian Ocean since the Late Cretaceous: Geophysical Jour. Royal Astronomical Soc., v. 24, p. 437–528.

MOORE, D. G., CURRAY, J. R., AND EMMEL, F. J., 1976, Large submarine slide (olistrostrome) associated with Sunda arc subduction zone, northeast Indian Ocean: Marine Geology, v. 21, p. 211–226.

MOORE, G. F., 1979, Petrography of subduction zone sandstones from Nias Island, Indonesia: Jour. Sed. Petrology, v. 49, p. 71–84.

———, AND KARIG, D. E., 1976, Development of sedimentary basins on the lower trench slope: Geology, v. 4, p. 693–697.

POWELL, C. MCA., AND CONAGHAN, P. J., 1973, Plate tectonics and the Himalayas: Earth Planet. Sci. Letters, v. 20, p. 1–12.

SINHA, R. N., AND SASTRI, V. V., 1973, Correlation of the Tertiary Geosynclinal sediments of the Surma Valley, Assam and Tripura State (India): Sed. Geology, v. 10, p. 107–134.

SMITH, G. W., 1978, Stratigraphy, sedimentology and petrology of the Cambria Slab, San Luis Obispo County, California [unpub. Masters thesis]: Albuquerque, Univ. New Mexico, 123 p.

———, HOWELL, D. G., AND INGERSOLL, R. V., 1979, Late Cretaceous trench-slope basins of central California: Geology, v. 7, p. 303–306.

STEWART, R. J., 1976, Turbidites of the Aleutian abyssal plain: mineralogy, provenance, and constraints for Cenozoic motion of the Pacific plate: Geol. Soc. America Bull., v. 87, p. 793–808.

———, 1977, Neogene turbidite sedimentation in Komandorskiy Basin, western Bering Sea: Am. Assoc. Petroleum Geologists Bull., v. 61, p. 192–206.

———, 1978, Neogene volcaniclastic sediments from Atka Basin, Aleutian Ridge: Am. Assoc. Petroleum Geologists Bull., v. 62, p. 87–97.

SUTTNER, L. J., 1974, Sedimentary petrographic provinces: an evaluation, *in* Ross, C. A., ed., Paleogeographic provinces and provinciality: Soc. Econ. Paleontologists Mineralogists Spec. Pub. No. 21, p. 75–84.

TANDON, S. K., 1976, Siwalik sedimentation in a part of the Kumaun Himalaya, India: Sed. Geology, v. 16, p. 131–154.

THOMPSON, R. W., 1974, Mineralogy of sands from the Bengal and Nicobar fans, sites 218 and 211, eastern Indian Ocean, *in* Initial Reports of the Deep Sea Drilling Project: Washington, D.C., U.S. Government Printing Office, v. 22 p. 711–713.

VON DER BORCH, C. C., SCLATER, J. G., ET AL., 1974, Initial reports of the Deep Sea Drilling Project, U.S. Government Printing Office, Washington, D.C., v. 22, 890 p.