

Composition of modern deep-sea sands from arc-related basins

J. Barry Maynard, Renzo Valloni & Ho-Shing Yu

SUMMARY: Petrographic and chemical examination of modern deep-sea sands shows a clear distinction between active and passive plate-tectonic settings. Among active settings, sands from forearc basins of island arcs and basins from strike-slip continental margins can be distinguished, but those from other arc-related settings overlap considerably in composition. In particular, sands from continental margin subduction zones and those from the backarc of island arcs appear to be indistinguishable.

Chemically, arc-related sands are very close in composition to ancient greywacke sandstones. For instance, sodium almost always exceeds potassium. Thus it is not necessary for sodium to be added to sands diagenetically to make greywackes, as has been suggested.

The influence of tectonics on the composition of sandstones has long been a central feature of sandstone petrology. The geosynclinal model of global tectonics stimulated much thought on this subject. Probably the best-known ideas are those of Krynyne (e.g. 1942). Subsequently such research declined, but the plate model for global tectonics has produced a new wave of interest (e.g. Crook 1974; Schwab 1975; Potter 1978; Dickinson & Suczek 1979). Much of this work has relied on data from ancient sediments, where diagenetic changes and difficulty in deciphering the tectonic setting limit the usefulness of the conclusions. Much more work is needed on recent sediments to establish a baseline against which ancient sediments can be compared.

We have previously reported (Valloni & Maynard 1981) the results of our work on the petrography of a set of recent deep-sea sands from piston cores. In this paper we shall compare this petrographic information with bulk chemistry, and attempt to relate these to tectonics in arc-related settings.

Plate tectonic models of depositional basins

First, it is necessary to define the terms used. The classification of sedimentary environments using plate tectonics has been extensively discussed by Dickinson (1974), Dickinson & Seely (1979) and Reading (1978, chapter 14). These ideas are summarized in Table 1. The most important subdivision is into passive and active settings, as originally pointed out by Inman & Nordstrom (1971). In the classification used here, passive settings are synonymous with their 'trailing-edge coast'. We have subdivided

their 'collision coasts' and 'marginal sea categories'. The petrography of sands from the passive settings and the collision-related settings has been described in some detail by Dickinson & Valloni (1980). In this paper, therefore, we concentrate more on the arc-related settings, and introduce the chemical properties of the sediments.

Deep-sea sands are found in most of the environments listed in Table 1, but are most common in strike-slip and subduction settings and the later stages of intercontinental rifting. Of the subduction settings, the continent side of a subducting continental margin (the backarc of continental margin arcs) does not contain deep-sea sands. Instead, many of the world's big rivers derive their sediments from these areas (e.g. the Amazon), so that the sands described by Potter (1978) may largely fill this category. Thus the important environments from the standpoint of this paper are basins of island arcs and basins lying seaward of continental margin volcanic arcs or strike-slip plate boundaries.

Petrography

About 80 samples of deep-sea sands, mostly from Lamont-Doherty piston cores supplemented by some DSDP material, were studied petrographically (Fig. 1). The details of the methods used and the depository for all of the original data are given in Valloni & Maynard (1981). For petrography, the sands were sieved to isolate the fine sand fraction, because of the strong effect of grain size on feldspar content (e.g. Field & Pilkey 1969, fig. 3). The results are summarized in Table 2 and Fig. 2.

The samples separate well into passive (trailing edge) and active settings on the basis of the

TABLE 1. *Plate tectonic classification of sedimentary environments (after Reading 1979, chapter 14; Dickinson & Valloni 1980, fig. 2)*

I Spreading-related or passive settings

(A) *Intracratonic rifts* (East Africa). Mostly filled by alluvial fans and lakes

(B) *Failed rifts* or aulacogens (Benue Trough). Thick sequence of deposits ranging from deep-sea fan to fluvial

(C) *Intercontinental rifts*

- 1 Early (Red Sea). Evaporites and some clastics
- 2 Late (Atlantic). Early stage sediments along margins overlain by continental shelf or deltaic deposits, passing seaward into oceanic crust overlain by turbidites and finally pelagics. Often termed *trailing-edge*

II Active settings

(A) Continental collision-related

- 1 *Remnant ocean basins* (Bay of Bengal). Thick turbidite fan deposits eventually piled into imbricate thrust sheets
- 2 *Late orogenic basins* (sub-Himalayas). Variety of terrestrial and shallow marine deposits, but dominantly fluvial. Termed *peripheral foreland basins* if on the subducting plate

(B) *Strike-slip fault-related settings* (California). Thick sequences of deep-marine to fluvial sediments in small basins, mostly derived from adjacent uplifts

(C) Subduction-related settings

- 1 *Continental margin magmatic arcs* (Andes)
 - (a) Forearc. Thin to thick deposits ranging from turbidites to fluvial. Termed *leading-edge* in some classifications
 - (b) Backarc. Very thick, mostly terrestrial, accumulations. Forms much of the molasse facies of older models. Sometimes termed *ensialic backarc* or *retroarc*
- 2 *Intra-oceanic arcs* (Japan, Aleutians)
 - (a) Forearc. Thin turbidite deposits plus pelagics
 - (b) Backarc. Thin to thick accumulations of clastics near the arc, passing into pelagics and possibly into terrigenous clastics again at the continental margin

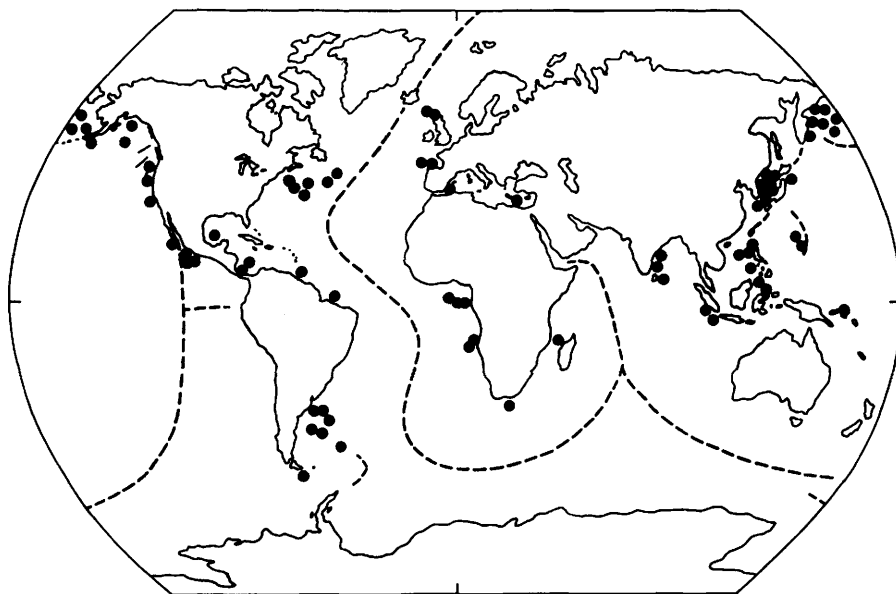


FIG. 1. Sample location map.

primary petrographic variables quartz (Q), feldspar (F), and fine-grained rock fragments (L). Samples with more than 40% quartz are almost exclusively from basins adjacent to passive continental margins (Fig. 2). In addition,

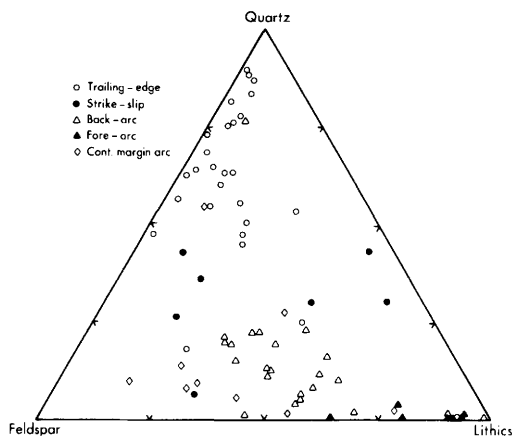


FIG. 2. Framework constituents of modern deep-sea sands from various tectonic settings.

samples from intraoceanic forearc basins are easily distinguished: they are composed almost entirely of volcanic rock fragments. Samples from the other three settings have extensive areas of overlap on triangular plots (Fig. 3).

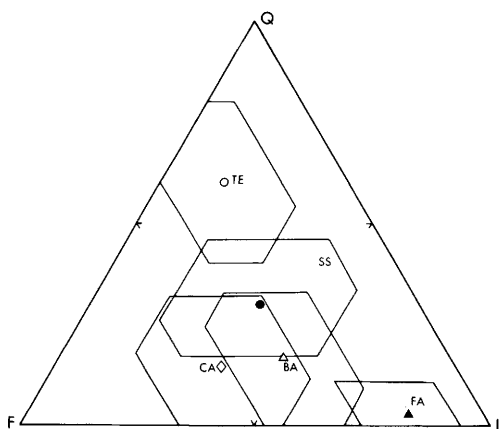


FIG. 3. Range of variation in framework petrography of deep-sea sands. The polygons show one standard deviation about the mean. (See Ingersoll 1978 for a discussion of this representation.) TE = trailing-edge; SS = strike-slip; CA = continental margin arc; BA = backarc of island arc; FA = forearc of island arc.

Supplementary variables such as the type of feldspar or rock fragments have often been used as further discriminants. Fig. 4 shows that

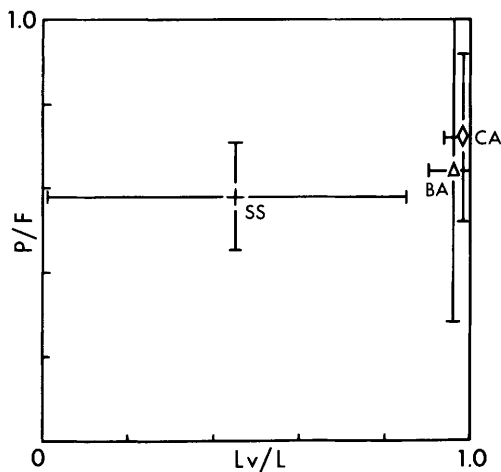


FIG. 4. Petrography of deep-sea sands from tectonic settings that overlap on Fig. 3. Note the very close similarity of samples from the backarc of island arcs (BA) to those from the forearc of continental margin arcs (CA). P/F is the ratio of plagioclase to total feldspar; Lv/L the ratio of volcanics to total lithics.

all three of these settings have about the same proportion of plagioclase in the feldspar, but that the strike-slip related settings have a significantly lower proportion of volcanic grains in the rock fragments. In ancient rocks, this difference may translate to less matrix. Thus, of the five settings considered, three have a reasonably distinct petrography, but basins lying on the ocean side of magmatic arcs on continental margins seem to contain sands almost identical in composition to those found in the backarc basins of island-arcs.

All of the arc-related sands share the characteristics of low quartz content and a high proportion of volcanic lithic fragments. Valloni & Maynard (1981) suggested several subdivisions of this petrographic type. They identified:

Volcanic-vitric sands (Vv). These sands have virtually no quartz, and are made up almost entirely of volcanic grains having a vitric texture or glass shards. They are almost entirely confined to forearc basins of island arcs (Fig. 5). *Volcanic-lithic sands* (Vp and Vk). These sands contain about equal amounts of feldspars and lithic fragments, with volcanic grains again making up almost all of the lithic fragments.

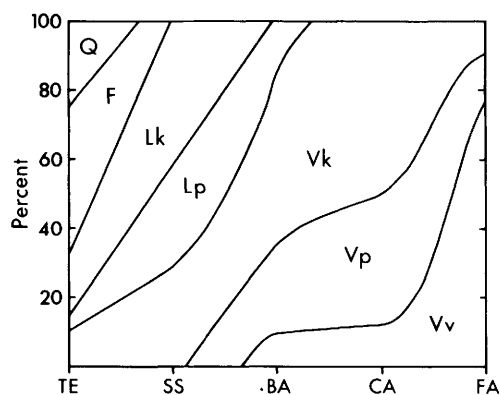


FIG. 5. Distribution of petrographic types by tectonic setting. See text for abbreviations.

ity: the forearc and backarc basins contain very different sands for a given arc-type. To what extent this difference between backarc and forearc sands also applies to continental margin arcs we cannot say, having no backarc sands of this type. Studies of shelf sands of Indonesia would provide the appropriate contrast. This result suggests that in general more elaborate tectonic subdivisions will not be reflected in petrography, although within a given basin such variations may be detectable (e.g. Moore 1979).

Another limitation is the surprising similarity in composition of sands from the backarc of island arcs and the forearc of continental margin arcs. These two settings are likely to be preponderant in ancient arc-related terranes, and their close similarity is discouraging for the use of petrography to distinguish them. Why this pattern occurs is not clear to us.

TABLE 2. Petrology of modern deep-sea sands

Tectonic setting	No. of samples	Q	F	L	C/Q	P/F	Lv/L
Trailing-edge (TE)	29	61	26	13	0.10	0.13	0.13
Strike-slip (SS)	7	31	36	33	0.31	0.58	0.45
Continent margin-arc (CA)	8	16	53	31	-	0.72	0.98
Oceanic arc							
(1) Backarc (BA)	27	16	34	50	0.19	0.64	0.89
(2) Forearc (FA)	9	3	16	81	-	0.90	0.99

Heavy minerals are particularly abundant (3–6%). Vp refers to a sub-variety with almost all plagioclase feldspar, Vk to one with appreciable (>20%) K-feldspar. These sands are characteristic of both the backarc basins of island arcs and the forearc basins of continental margin arcs.

Lithofeldspathic sands (Lp and Lk). These sands are significantly richer in quartz than the preceding varieties. Feldspar and lithic fragments are again present in subequal amounts, but volcanic grains no longer predominate. Two sub-types are distinguished based on the predominance of plagioclase (Lp) or K-feldspar (Lk). Among the quartz grains, polycrystalline varieties are abundant (20–30%). These sands are most common in strike-slip settings, although they are also found off passive continental margins. Two quartz-rich types (Q and F) can also be distinguished, but they are confined to passive settings (Fig. 5).

The distribution of sand types is somewhat curious, because there is apparently no relationship to the type of island arc. That is 'mature' island arcs like Japan and 'primitive' arcs like the Marianas, seem to be producing the same sands. The big difference is in polar-

How do these results compare with ancient sediments? Dickinson & Suzcek (1979) found similar compositions in ancient sandstones. Their arc-related samples fall into the same part of the QFL triangle as ours (Fig. 6), except for our samples from intra-oceanic forearc basins. Probably such sands are rarely preserved in sandstones on the continents. Their 'continental block provenance' corresponds to our passive settings. We have few samples from the area they designate 'recycled orogen provenances' but sands of this composition make up the bulk of the samples reported from modern big rivers by Potter (1978). Crook (1974) has presented data from analysis of over 300 ancient turbidites that differ in some respects from our modern sands (Fig. 7). He divided these rocks into quartz-rich, quartz-intermediate, and quartz-poor varieties, as shown. He suggested that these divisions correspond to trailing-edge continental margins, leading-edge continental margins (both strike-slip and subduction), and island arcs. Our modern sands show both the passive margin sands and the arc-related sands crossing these divisions. Instead, a division at about 40% quartz separates the passive and active settings, with

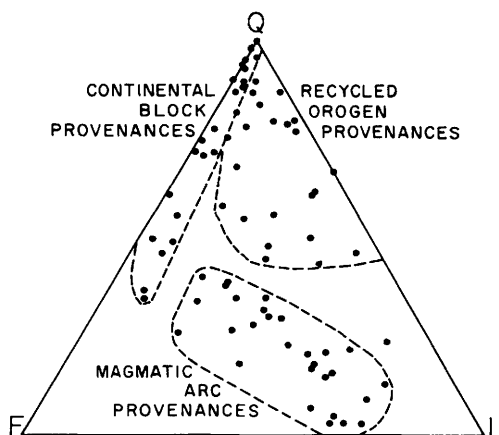


FIG. 6. Petrography of sands as related to tectonic setting of the source area, largely from ancient samples, from Dickinson & Suczek (1979, fig. 9). The distribution matches closely that of Fig. 2, except compositions assigned to recycled orogen provenances are rare in our samples.

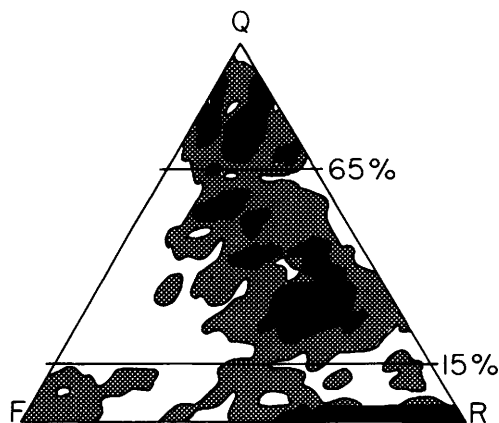


FIG. 7. Petrography of ancient turbidite sandstones, after Crook (1974). The QFR triangle differs from the QFL triangle used in the other figures in shifting the values somewhat towards the R corner (all polyminerals grains counted as rock fragments), as discussed in Valloni & Maynard (1981).

no possible further subdivision of the active settings based on quartz. Some of the difference between our results and his are probably attributable to our use of only fine sands, which might give higher feldspar. It seems unlikely that all of the difference can be explained by such analytical variables, however. This con-

trast between recent and ancient sands needs further study, especially considering the similarity of Potter's (1978) river sands to Crook's pattern.

Bulk chemistry

Most of these samples were also analysed for bulk chemistry. The object was to make a comparison between the composition of beds of turbidite sand and the immediately overlying mud. These can then be compared with ancient turbidite sand-shale pairs to see whether there is exchange of components between the sand and shale beds during diagenesis. Also we wished to see if the tectonic subdivisions previously described are associated with distinctive chemical compositions. During diagenesis, and low-grade metamorphism, much of the type of petrographic information described earlier becomes obscured. This is particularly true of the types of rock fragments, many of which are converted to matrix. Therefore it would be particularly helpful if chemical analyses could be used, because these processes seem to produce little change in bulk chemistry, except for water and CO_2 . In addition to the modern sands and associated muds, 129 samples of ancient turbidite sandstones and shales were analysed. Age, location, and chemical analyses for these samples are presented in the appendix. Determinations were made using atomic absorption following fusion of the sample with LiBO_2 and dissolution in HNO_3 (Yu 1979).

The set of ancient turbidite sands and shales that we used is unfortunately rather limited. The sampling is biased towards Cambro-Ordovician rocks of the Appalachian Basin. Also, virtually all of the samples we collected turned out to be from active tectonic settings, based on our interpretation of the literature, probably either forearc to a continental margin (e.g. Southern Uplands of Scotland) or from backarc basins of island arcs (Cambrian of Appalachian Basin?). Usually, this kind of assignment to subvarieties of active settings is very tentative, so we have not attempted it. On the other hand, the average sandstone composition from these samples is close to that reported by Pettijohn (1963, table 12) for a similar sampling of greywackes, so we feel that our samples are representative. There is no comparable data set for the shales: ours appears to be the first compilation of chemical data on shales of this type.

As with petrography, the results show that passive settings are quite distinct (Table 3, Figs

TABLE 3. Bulk chemistry of modern deep-sea sands and associated muds

Tectonic setting	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	K ₂ O	Na ₂ O
1 Sands							
Trailing-edge	77.9	9.8	2.9	1.3	4.1	2.0	1.9
Strike-slip	67.8	15.6	3.7	2.3	3.6	2.9	3.9
Continental margin arc	69.5	14.1	3.9	1.9	4.4	2.6	3.6
Backarc	68.8	14.4	4.5	2.4	4.4	2.0	3.6
Forearc	61.5	15.2	7.7	3.8	6.7	1.4	3.8
2 Muds							
Trailing-edge	65.9	13.7	5.3	2.8	8.2	2.6	1.5
Strike-slip	65.8	14.4	6.8	3.4	4.9	2.0	2.7
Continental margin arc	66.1	16.9	6.4	3.2	3.0	2.5	2.4
Backarc	68.0	14.9	6.5	3.1	2.8	2.3	2.5
Forearc	68.9	12.1	7.2	3.0	4.9	1.5	2.6

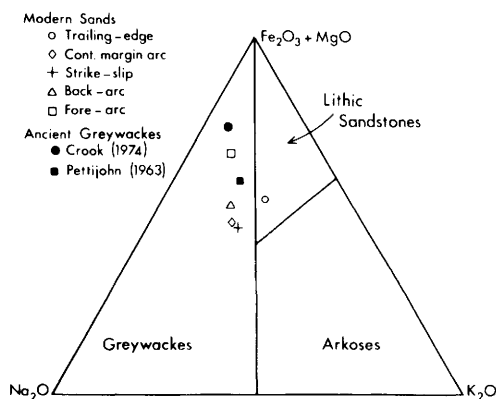


FIG. 8. Comparison of the chemical composition of modern deep-sea sands with ancient greywackes. Sands from trailing-edge continental margins fall outside the compositional range for greywackes, but the arc-related samples all have compositions typical of greywackes. Fields from Blatt *et al.* (1972, fig. 9–2).

8 & 9). The sands are particularly rich in SiO₂ and the K₂O/Na₂O ratio is almost always greater than one. The muds are even more enriched in K₂O (Fig. 10), but have SiO₂ values similar to the other muds. Sands and muds from forearc basins of island-arcs are also distinctive, having extremely low K₂O/Na₂O ratios and very high Fe₂O₃ + MgO (Table 3). The other three settings, however, have sands and muds of very similar composition. Samples from strike-slip basins and continental margin-arc basins are chemically identical, and intra-oceanic backarc basins are distinguished only by slightly lower K₂O/Na₂O and slightly higher Fe₂O₃ + MgO (Table 3). Figs 9 and 10 show, however, that

there is a large amount of overlap. Thus it seems unlikely that bulk chemistry can be used to distinguish among types of arc-related sandstones in ancient rocks.

Greywackes, the typical sandstone type of turbidites, are exceptionally rich in Na₂O compared with other sandstone types (e.g. Pettijohn *et al.* 1972, p. 211). It is not known, however, whether this high Na₂O reflects Na-rich source rocks or is a diagenetic feature. For instance, both primary and secondary sources of Na₂O have been proposed for the albite-rich Charny greywackes of Quebec (Middleton 1972; Lajoie 1973; Lajoie *et al.* 1974). Diagenetic addition of Na₂O could be either a local process, caused by exchange of K⁺ in sands for Na⁺ in interbedded shales, or could involve introduction of Na⁺ by migrating pore fluids. A comparison of the chemistry of modern and ancient turbidite sands should show whether the high Na₂O can reasonably be interpreted as a primary feature or whether diagenetic additions seem to be called for.

Fig. 9 shows that sands from the four active settings are similar in chemical composition to ancient greywacke sandstones, particularly in the K₂O/Na₂O ratio. The shales, however, show a pronounced enrichment in K₂O compared with their modern counterparts (Table 4). Does this reflect diagenetic changes? Fig. 11 shows a comparison between the compositions of the sands and their associated muds or shales. This diagram shows that the increase in K₂O/Na₂O in the ancient shales is not matched by a corresponding decrease in the sands. Thus the sands could not have acted as a source of K⁺ during diagenesis. In fact, the close similarity in composition of the recent and ancient turbidites

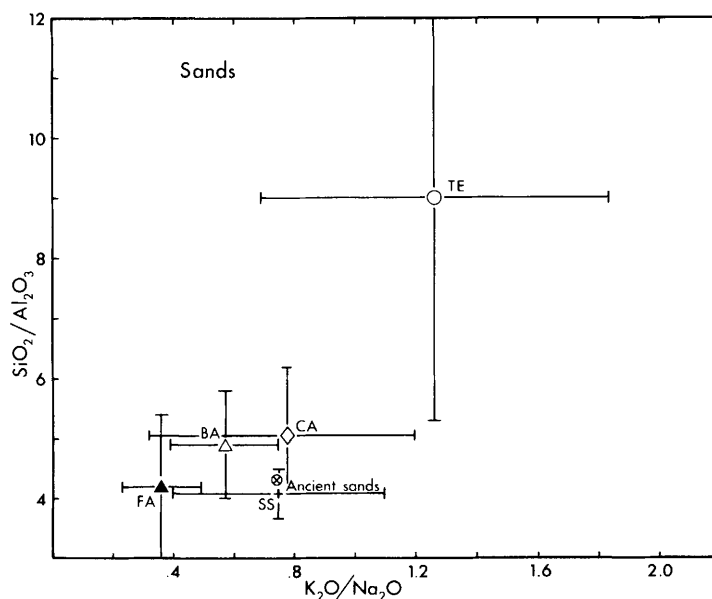


FIG. 9. Chemistry of deep-sea sands. Note the extensive overlap of the active tectonic settings. The coincidence of arc-related sands and ancient greywackes suggests that diagenetic additions are not necessary to explain the composition of these sandstones. Error bars are one standard deviation each side of the mean.

TABLE 4. Comparison between modern deep-sea sands and ancient turbidites

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	K ₂ O	Na ₂ O	K ₂ O/Na ₂ O
1 Sands								
Modern*	68.8	14.5	4.4	2.2	4.3	2.2	3.7	0.60
Ancient†	70.4	14.2	5.4	2.2	2.6	2.1	3.1	0.68
Ancient‡	66.9	14.4	4.6	2.1	7.7	2.0	2.5	0.78
2 Shales								
Modern*	67.3	15.3	6.5	3.2	3.1	2.3	2.5	0.92
Ancient‡	61.3	18.3	6.5	3.1	5.1	4.0	1.4	2.9

* Average of SS, BA and CA samples.

† Data of Pettijohn (1963).

‡ One hundred and twenty-nine samples of sand and shale from ancient turbidites (Appendix).

suggests that no diagenetic additions are necessary to explain the chemistry of these sandstones.

How then can the chemistry of the shales be explained? Note the much higher K₂O content of the older shales. This pattern is not confined to this type of shale, but seems to be a worldwide secular trend in shale composition (Weaver 1967; Ronov & Migdisov 1971; Van Moort 1972). Some preliminary work in our laboratory suggests that this high K₂O in Lower Palaeozoic shales is due to detrital K-feldspar, and so is a primary rather than a diagenetic effect. A similar conclusion probably also applies to the older

sandstones. Note in Fig. 11 that the Lower Palaeozoic sandstones have a higher K₂O/Na₂O ratio than younger ones. This trend again argues against diagenetic addition of Na₂O, but it also suggests that Lower Palaeozoic clastics have an anomalously large K₂O content. There are many reports (Bowie *et al.* 1966; Odom 1975; Stablein & Dapples 1977; Swett & Smit 1972) of highly feldspathic sands of this age from environments not normally associated with arkoses (e.g. beaches and tidal flats). Interpretations of their origin vary, but the abundance of this type of occurrence suggests some non-uniform event in the Earth's history.

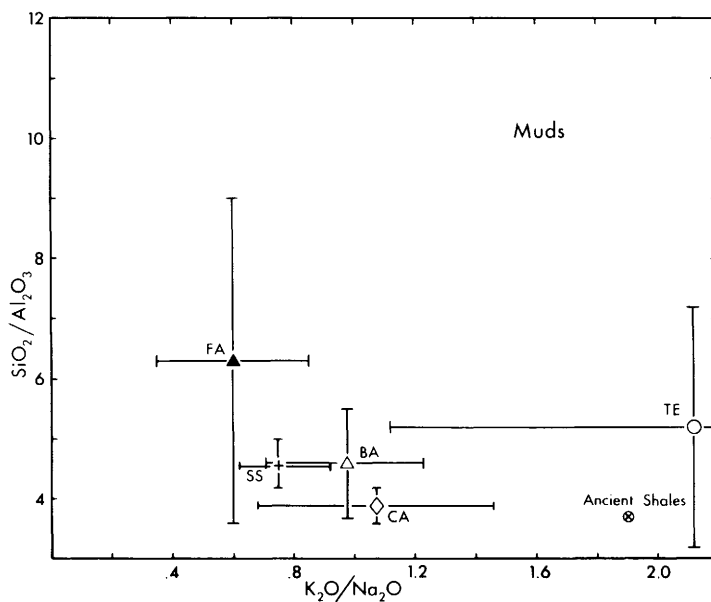


FIG. 10. Chemistry of muds interbedded with deep-sea sands. As with the sands, the arc-related settings show extensive overlap. Note the strong enrichment of ancient shales in K_2O .

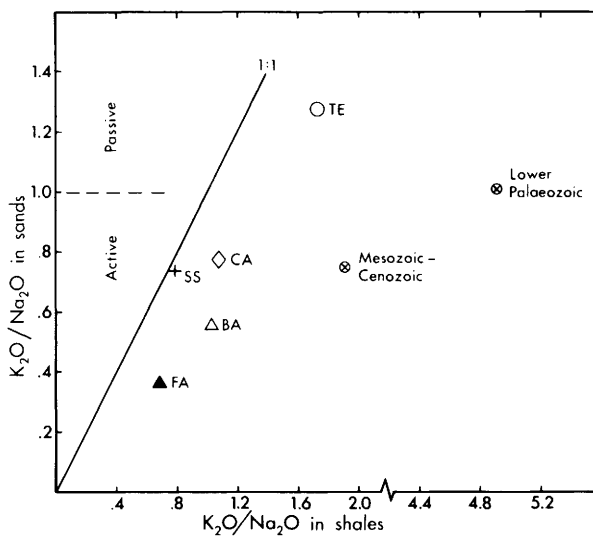


FIG. 11. Comparison of the compositions of turbidite sands and associated muds or shales shows that older sands do not become depleted in K_2O relative to the shales. The very high K_2O/Na_2O in Palaeozoic shales is due to detrital K-feldspar, and so is a depositional rather than a diagenetic effect.

Conclusions

Tectonics was found to exert a strong influence on the composition of modern deep-sea sands, but only broad categories are distinguishable.

For example, active and passive settings are quite distinct in both petrography and bulk chemistry. Quartz contents higher than 40%

and K_2O/Na_2O greater than 1.0 indicate sands from passive (trailing-edge) continental margins. Subdivisions of active settings are much less distinct, with the forearc of continental margin arcs (leading-edge margins) having almost identical sands to those from the backarc of island arcs.

The bulk chemistry of sands from active settings is quite similar to the reported composition of average greywacke. From this we infer that it is not necessary to have post-depositional changes in composition to make greywackes. Comparison of some ancient turbidite shales with modern turbidite muds supports this con-

clusion. High K_2O in Lower Palaeozoic shales of this type appears to be a primary rather than a diagenetic effect.

ACKNOWLEDGMENTS: We thank our many colleagues who have discussed these ideas with us, particularly Paul Potter, Bill Dickinson, and Chris Suczek. Maynard wishes to express grateful appreciation to the staff of Grant Institute of Geology, University of Edinburgh, for help with preparation of the manuscript. Research supported in part by NSF Grant EAR79-03919. The Lamont-Doherty Core Collection is maintained through NSF Grants OCE76-18049 and ONR contract CN14-75-C-0210.

References

- BLATT, H., MIDDLETON, G. V. & MURRAY, R. 1972. *Origin of Sedimentary Rocks*, Prentice-Hall, New Jersey, 634 pp.
- BOWIE, S. H. U., DAWSON, J., GALLAGHER, M. J. & OSTLE, D. 1966. Potassium-rich sediments in the Cambrian of northwest Scotland. *Trans. Instn Ming Metall.* **78**, B125-45; **79**, B60-9.
- CROOK, K. A. W. 1974. Lithogenesis and tectonics: the significance of compositional variation in flysch arenites (greywackes). *Spec. Publ. Soc. econ. Paleontol. Mineral. Tulsa*, **19**, 304-10.
- DICKINSON, W. R. 1974. Plate tectonics and sedimentation. *Spec. Publ. Soc. econ. Paleontol. Mineral. Tulsa*, **22**, 1-27.
- DICKINSON, W. R. & SEELY, D. R. 1979. Structure and stratigraphy of forearc regions. *Bull. Am. Assoc. Petrol. Geol.* **63**, 2-31.
- & SUCZEK, C. A. 1979. Plate tectonics and sandstone composition. *Bull. Am. Assoc. Petrol. Geol.* **63**, 2164-72.
- & VALLONI, R. 1980. Plate settings and provenance of sands in modern ocean basins. *Geology*, **8**, 82-6.
- FIELD, M. E. & PILKEY, O. H. 1969. Feldspars in Atlantic continental margin sand off the south-eastern U.S. *Bull. geol. Soc. Am.* **80**, 2097-102.
- INGERSOLL, R. V. 1978. Petro-facies and petrologic evolution of the late Cretaceous forearc basin, northern and central California. *J. Geol.* **86**, 335-52.
- INMAN, D. L. & NORDSTROM, C. E. 1971. On the tectonic and morphologic classification of coasts. *J. Geol.* **79**, 1-21.
- KRYNINE, P. D. 1942. Differential sedimentation and its products during one complete geosynclinal cycle. *Ann. Primero congresso Panamericano de Ingeniera de Minas y Geologia (Santiago, Chile) Geologia 1st Pt.* **2**, 537-61.
- LAJOIE, J. 1973. Albite of secondary origin in Charny Sandstones, Quebec: discussion. *J. sediment. Petrol.* **43**, 575-6.
- HEROUX, Y. & MATHEY, B. 1974. The Precambrian shield and Lower Paleozoic shelf: the unstable provenance of the Lower Paleozoic flysch sandstones and conglomerates between Beaumont and Bic, Quebec. *Can. J. Earth Sci.* **11**, 951-63.
- MIDDLETON, G. V. 1972. Albite of secondary origin in Charny Sandstones, Quebec. *J. sediment. Petrol.* **42**, 341-9.
- MOORE, G. F. 1979. Petrography of subduction zone sandstones from Nias Island, Indonesia. *J. sediment. Petrol.* **49**, 71-84.
- ODOM, I. E., 1975. Feldspar grain-size relations in Cambrian arenites, upper Mississippi Valley. *J. sediment. Petrol.* **45**, 636-51.
- PETTIOHNS, F. J. 1963. Chemical composition of sandstones. *Prof. Pap. U.S. geol. Surv.* **440-S**, 21 pp.
- POTTER, P. E. & SIEVER, R. 1972. *Sand and Sandstone*. Springer-Verlag, New York, 628 pp.
- POTTER, P. E. 1978. Petrology and composition of modern big river sands. *J. Geol.* **86**, 423-49.
- READING, H. G. (ed). 1978. *Sedimentary Environments and Facies*. Blackwell Scientific Publications, Oxford, 576 pp.
- RONOV, A. B. & MIGDISOV, A. A. 1971. Geochemical history of the crystalline basement and the sedimentary cover of the Russian and North American platforms. *Sedimentology*, **16**, 137-87.
- SCHWAB, F. L. 1975. Framework mineralogy and chemical composition of continental margin-type sandstone. *Geology*, **3**, 487-90.
- STABLEIN, N. K. & DAPPLES, E. C. 1977. Feldspars of the Tunnel City Group (Cambrian), western Wisconsin. *J. sediment. Petrol.* **47**, 1512-38.
- SWEIT, K. & SMIT, D. E. 1972. Paleogeography and depositional environments of the Cambro-Ordovician shallow marine facies of the North Atlantic. *Bull. geol. Soc. Am.* **83**, 3223-48.
- VALLONI, R. & MAYNARD, J. B. 1981. Detrital modes of modern deep-sea sands as related to plate tectonics: a first approximation. *Sedimentology*, **28**, 75-83.
- VAN MOORT, J. C. 1972. The K_2O , CaO , MgO and CO_2 contents of shales and related rocks and their implications for sedimentary evolution since the Proterozoic. *24th Int. geol. Congr., Sect.* **10**, 427-39.

WEAVER, C. E. 1967. Potassium, illite and the ocean.
Geochim. cosmochim. Acta, **31**, 2182–96.

YU, H. 1979. *Three aspects of sandstone diagenesis:*

compaction and cementation of quartz arenites and chemical changes in graywackes. Dissertation, PhD, Univ. Cincinnati (unpubl.).

J. BARRY MAYNARD, Department of Geology, University of Cincinnati, Cincinnati, Ohio 45221, U.S.A.

RENZO VALLONI, Istituto Petrografia, Università di Parma, 43100 Parma, Italy.

HO-SHING YU*, Department of Geology, University of Cincinnati, Cincinnati, Ohio 45221, U.S.A.

* Present address: Pennzoil International, P.O. Box 2967, Houston, Texas 77001, U.S.A.

Appendix

Bulk chemistry of some ancient turbidite sands (sd) and Shales (sh)

		# of samples	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	K ₂ O	Na ₂ O	SiO ₂ /Al ₂ O ₃	K ₂ O/Na ₂ O	Inferred tectonic setting
Pico, Repetto Fmns. Pliocene	Sd	3	66.6	15.0	2.62	0.88	8.84	3.14	2.94	4.44	1.07	Active
Ventura Basin, Cal.	Sh	4	67.5	15.9	5.47	2.51	3.11	2.92	2.54	4.25	1.15	
Marnoso Arenacea Lower Miocene	Sd	1	60.5	13.9	2.61	2.60	16.5	1.89	2.07	4.35	0.91	Active
Muraglione Pass, Toscana, Italy	Sh	3	49.2	16.7	5.27	5.85	18.9	2.88	1.14	2.95	2.53	
Macigno Oligocene	Sd	2	66.8	14.5	3.48	2.32	8.20	2.21	2.56	4.61	0.86	Active
Pieve pelago, Italy	Sh	4	66.4	15.0	5.33	3.28	4.37	3.11	1.97	4.43	1.58	
Loreto Fmn Oligocene	Sd	1	58.4	16.6	4.76	2.43	15.4	0.88	2.19	3.52	0.40	Active
Magallenes Prov., Chile												
Prealpine Flysch Oligocene	Sd	4	62.4	13.7	3.21	2.92	14.8	1.32	1.67	4.55	0.79	Active
Val d'Illicez Switzerland	Sh	7	58.7	16.4	5.61	3.34	12.5	2.46	1.09	3.59	2.26	
Cretaceous sands of Tierra del Fuego Magallenes Prov., Chile	Sd	13	66.8	16.4	6.60	2.72	2.26	1.80	3.49	4.07	0.52	Active
Lewes River Group Laberge Grp. Triassic-Jurassic Whitehorse Yukon	Sd	4	63.9	15.5	5.75	2.67	6.28	2.00	3.79	4.14	0.53	Active
Escuminac Fmn. Devonian	Sd	1	68.3	10.5	4.13	2.00	12.3	1.98	0.77	6.50	2.57	Passive
Miguasha, Quebec	Sh	2	66.7	16.0	6.72	3.00	3.64	3.00	0.94	4.18	3.19	
Gala Greywacke Silurian	Sd	3	67.3	15.0	5.35	2.18	1.67	3.61	4.91	4.49	0.73	Active
Innerliethen, Scot.	Sh	2	67.7	15.7	5.43	3.23	1.20	3.97	2.65	4.31	1.50	
Aberystwyth Grit Silurian	Sd	3	71.8	15.0	6.70	1.80	2.03	1.35	1.41	4.78	0.96	Active
Aberystwyth, Wales	Sh	7	66.7	17.4	7.22	2.02	1.25	4.19	1.29	3.83	3.25	
Frenchville Fmn Silurian	Sd	1	57.1	11.9	2.70	1.15	19.3	3.57	4.39	4.82	0.81	Active
Stockholm, Maine	Sh	3	65.7	12.5	5.80	3.12	8.01	3.07	1.77	5.26	1.73	
Martinsburg Fmn Ordovician	Sd	16	83.0	11.4	3.93	0.63	0.29	0.48	0.30	7.25	1.60	Active
Lehigh Gap, Penn.	Sh	17	58.7	25.9	6.26	1.66	0.36	6.51	0.53	2.27	12.3	
Martinsburg Fmn Ordovician	Sd	4	73.5	11.3	5.80	1.71	4.11	2.06	1.51	6.50	1.36	Active

Composition of modern deep-sea sands

561

Williamsport, Md.	Sh	4	61.9	21.8	7.53	2.07	0.66	5.22	0.82	2.84	6.36	
Utica Fmn. Ordovician	Sd	4	69.1	15.0	4.51	2.15	5.72	1.84	1.70	4.62	1.08	Active
St Antoine de Tilley, Quebec	Sh	3	63.3	16.8	6.41	4.37	3.31	4.72	1.06	3.77	4.45	
Normanskill Fmn Ordovician	Sd											
Hudson Valley, N. Y.	Sh	4	56.9	19.6	8.00	3.66	7.14	4.09	0.71	2.90	5.76	Active
Sillery Grp. Cambrian	Sd	5	69.1	15.2	6.38	2.48	2.84	1.43	2.63	4.55	0.54	Active
St Lawrence Valley, Quebec	Sh	4	54.6	25.8	9.74	2.44	0.64	5.42	1.37	2.12	3.95	
Average sand		15	66.9	14.4	4.6	2.1	7.7	2.0	2.5	4.65	0.78	
Average shale		13	61.3	18.3	6.5	3.1	5.1	4.0	1.4	3.35	2.86	
Pettijohn's average greywacke (volatile-free basis)		61	70.4	14.2	5.4	2.2	2.6	2.1	3.1	4.96	0.68	