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V. 63, No. 12 (December 1979), P. 2164-2182, 7 Figs., 1 Table

# Plate Tectonics and Sandstone Compositions[1]

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**Abstract** Detrital framework modes of sandstone suites from different kinds of basins are a function of provenance types governed by plate tectonics. Quartzose sands from continental cratons are widespread within interior basins, platform successions, miogeoclinal wedges, and opening ocean basins. Arkosic sands from uplifted basement blocks are present locally in rift troughs and in wrench basins related to transform ruptures. Volcaniclastic lithic sands and more complex volcano-plutonic sands derived from magmatic arcs are present in trenches, forearc basins, and marginal seas. Recycled orogenic sands, rich in quartz or chert plus other lithic fragments and derived from subduction complexes, collision orogens, and foreland uplifts, are present in closing ocean basins, diverse successor basins, and foreland basins. Triangular diagrams showing framework proportions of quartz, the two feldspars, polycrystalline quartzose lithics, and unstable lithics of volcanic and sedimentary parentage successfully distinguish the key provenance types. Relations between provenance and basin are important for hydrocarbon exploration because sand frameworks of contrasting detrital compositions respond differently to diagenesis, and thus display different trends of porosity reduction with depth of burial.

## INTRODUCTION

Sandstone compositions are influenced by the character of the sedimentary provenance, the nature of the sedimentary processes within the depositional basin, and the kind of dispersal paths that link provenance to basin. The key relations between provenance and basin are governed by plate tectonics, which thus ultimately controls the distribution of different types of sandstones. Data for modern marine and terrestrial sands from known tectonic settings provide standards to evaluate the effect of tectonic setting on sandstone composition. By direct analogy with such modern sands and by inference for older sandstone suites, broad categories of sandstone can be correlated with specific types of source terranes and basins associated with diverse plate tectonic regimes. Crook (1974) and Schwab (1975) have shown previously that quartz-rich rocks are associated typically with passive continental margins, that quartz-poor rocks are mostly of volcanogenic derivation from magmatic island arcs, and that rocks of intermediate quartz content are associated mainly with active continental margins or other orogenic belts. Our conclusions here are extensions and amplifications of their views (see also Krynine, 1948).

## FRAMEWORK MODES

As the character and amount of interstitial cement and matrix are largely a function of diagenesis, provenance studies focus on proportions of detrital framework grains (Dickinson, 1970). For comparative analysis of sandstone suites, varied framework modes must be cast in common terms that reflect key factors of sand genesis (Table 1). For this study, we recalculated all modal compositions as volumetric proportions of the following categories of grains (Graham et al, 1976): (1) stable quartzose grains, Q, including both monocrystalline quartz grains, Qm, and polycrystalline quartzose lithic fragments, Qp, which are chiefly chert grains; (2) monocrystalline feldspar grains, F, including plagioclase, P, and K-feldspar, K; and (3) unstable polycrystalline lithic fragments, L, of two kinds: (a) Lv, volcanic and metavolcanic types, and (b) Ls, sedimentary and metasedimentary types. The total lithic fragments, Lt, then equal the sum of unstable lithic fragments, L, plus stable quartzose lithic fragments, Qp. Extraneous constituents, such as heavy minerals and calcareous grains, are disregarded in this scheme.

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Table 1. Mean Framework Modes of Selected Suites of Sandstones and Modern Sands (*)

| | Suites | N | Q | F | L | Qm | F | Lt | Qp | Lv | Ls | Qm | P | K | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I. | CONTINENTAL BLOCK PROVENANCES | | | | | | | | | | | | | | |
| | A. Craton Interior Provenance | | | | | | | | | | | | | | |
| 1.* | Western subprovince, western North Atlantic Quaternary | 92 | 87 | 11 | 2 | 79 | 11 | 10 | 78 | 11 | 11 | 88 | 2 | 10 | Hubert and Neal, 1967 |
| 2.* | Pleistocene Turbidites, Canada basin, Arctic Ocean | 19 | 89 | 8 | 3 | 69 | 8 | 23 | 87 | 9 | 4 | 90 | 1 | 9 | Campbell and Clark, 1977 |
| 3. | Cretaceous-Tertiary deposits, middle Mississippi Valley | 12 | 98 | 2 | 0 | 95 | 2 | 3 | -- | -- | -- | 98 | ? | ? | Potter and Pryor, 1961 |
| 4. | Carboniferous units, Eastern Interior Coal Basin | 307 | 96 | 2 | 2 | 95 | 2 | 3 | -- | -- | -- | 98 | 1 | 1 | Potter and Pryor, 1961;<br>Siever, 1957 |
| 5. | Mid-Paleozoic formations, Illinois-Michigan basins | 40 | 99 | 1 | 0 | 99 | 1 | 0 | -- | -- | -- | 99 | ? | ? | Potter and Pryor, 1961 |
| 6. | Southwestern Montana Paleozoic, platform-miogeocline hinge | 27 | 100 | 0 | 0 | 100 | 0 | 0 | -- | -- | -- | 100 | 0 | 0 | McLane, 1971, 1972 |
| 7. | Pre-Carboniferous Paleozoic units, Ouachita Mountains | 24 | 88 | 8 | 4 | 88 | 8 | 4 | -- | -- | -- | 92 | ? | ? | Morris, 1974 |
| 8. | Cambrian units, Upper Mississippi Valley region | 40 | 90 | 10 | 0 | 89 | 10 | 1 | -- | -- | -- | 90 | ? | ? | Potter and Pryor, 1961 |
| 9. | Mojave Desert Precambiran and Cambrian, southern California | 494 | 94 | 6 | 0 | 89 | 6 | 5 | -- | -- | -- | 94 | 1 | 5 | Lobo and Osborne, 1976 |
| 10. | Precambrian or Cambrian Harpers Formation, central Virginia | 35 | 93 | 6 | 1 | 88 | 6 | 6 | -- | -- | -- | 93 | 1 | 6 | Schwab, 1971 |
| 11. | Precambrian or Cambrian Antietam Formation, central Virginia | 46 | 94 | 6 | 0 | 90 | 6 | 4 | -- | -- | -- | 94 | 1 | 5 | Schwab, 1970 |
| | Transitional between suites A & B | | | | | | | | | | | | | | |
| 12.* | Deep-sea turbidite sands, Hatteras abyssal plain | 23 | 76 | 18 | 6 | 73 | 18 | 9 | 33 | ? | ? | 81 | ? | ? | Cleary and Conolly, 1974 |
| 13.* | Eastern subprovince, western North Atlantic Quaternary | 10 | 78 | 20 | 2 | 68 | 20 | 12 | 84 | 8 | 8 | 78 | 4 | 18 | Hubert and Neal, 1967 |
| 14. | Mesozoic-Cenozoic sediments, Labrador-Greenland margins | 42 | 72 | 23 | 5 | 71 | 23 | 6 | -- | -- | -- | 76 | 2 | 22 | Higgs, 1978 |
| 15. | Middle Triassic Moenkopi Formation, Colorado Plateau | 131 | 72 | 23 | 5 | 67 | 23 | 10 | 48 | 34 | 18 | 75 | 10 | 15 | Cadigan, 1971 |

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Table 1. Continued

| | Suites | N | Q | F | L | Qm | F | Lt | Qp | Lv | Ls | Qm | P | K | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 16. | Cambrian Harmony Formation, north-central Nevada | 79 | 75 | 24 | 1 | 75 | 24 | 1 | -- | -- | -- | 76 | 17 | 7 | Suczek, 1977 |
| 17. | Southeastern Idaho Paleozoic | 13 | 72 | 27 | 1 | 71 | 27 | 2 | -- | -- | -- | 73 | ? | ? | Suczek, 1977 |
| | B. Uplifted Basement Provenance | | | | | | | | | | | | | | |
| 18.* | Salton Basin, Holocene alluvium, southern California | 7 | 46 | 47 | 7 | 45 | 47 | 8 | -- | -- | -- | 49 | 30 | 21 | Van de Kamp et al, 1976 |
| 19.* | Indurated Neogene turbidites, Gulf of Alaska seafloor | 8 | 37 | 55 | 8 | 29 | 55 | 16 | 50 | 32 | 18 | 35 | 53 | 12 | Hayes, 1973 |
| 20. | Salinian Block Tertiary, California Coast Ranges | 36 | 56 | 39 | 5 | 55 | 39 | 6 | -- | -- | -- | 59 | 21 | 20 | Graham, 1976 |
| 21. | Santa Ynez Range Paleogene, California Transverse Ranges | 24 | 50 | 47 | 3 | 47 | 47 | 6 | -- | -- | -- | 50 | 28 | 22 | Van de Kamp et al, 1976 |
| 22. | Santa Ynez Range Paleogene, California Transverse Ranges | 25 | 35 | 56 | 9 | 33 | 56 | 11 | 24 | 46 | 30 | 39 | 40 | 21 | Helmold, 1979 |
| 23. | Salinian Block Cretaceous, California Coast Ranges | 64 | 49 | 43 | 8 | 41 | 43 | 16 | 50 | 19 | 31 | 49 | 27 | 24 | Lee-Wong and Howell, 1977 |
| 24. | Pennsylvanian Minturn Formation, central Colorado | 68 | 61 | 38 | 1 | 55 | 38 | 7 | -- | -- | -- | 60 | 22 | 18 | Boggs, 1966 |
| 25. | Precambrian Mechum River Formation, Virginia Blue Ridge | 34 | 71 | 26 | 3 | 48 | 26 | 26 | ~90 | ? | ? | 65 | 10 | 25 | Schwab, 1974 |
| II. | MAGMATIC ARC PROVENANCES | | | | | | | | | | | | | | |
| | C. Undissected Arc Provenance | | | | | | | | | | | | | | |
| 26.* | Volcaniclastic trench sands, Guatemala, Central America | 26 | 1 | 43 | 56 | 1 | 43 | 56 | 0 | 99 | 1 | 2 | 97 | 1 | Enkeboll, 1979 |
| 27.* | Marginal seafloor Neogene, Philippine and Japan Seas | 22 | 13 | 15 | 72 | 12 | 15 | 73 | 2 | 46 | 52 | 43 | 47 | 10 | Harrold and Moore, 1973 |
| 28.* | Atka Basin Neogene, Aleutian Ridge, Alaska | 27 | 7 | 34 | 59 | 3 | 34 | 63 | 6 | 92 | 2 | 8 | 89 | 3 | Stewart, 1978 |
| 29. | Mesozoic Moehau Formation Coromandel Peninsula, N.Z. No. Is. | 12 | 9 | 21 | 70 | 9 | 21 | 70 | ~0 | ~100 | ~0 | 30 | 63 | 7 | Skinner, 1972 |
| 30. | Jurassic Methow-Pasayten sequence, Washington-Canada | 14 | 5 | 30 | 65 | 5 | 30 | 65 | ~0 | 98 | 2 | 15 | 85 | ~0 | Tennyson and Cole, 1978; Cole, 1973 |

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Table 1. Continued

| | Suites | N | Q | F | L | Qm | F | Lt | Qp | Lv | Ls | Qm | P | K | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 31. | Lower-Middle Jurassic units, central Oregon | 9 | 3 | 32 | 65 | 1 | 32 | 67 | 2 | 94 | 4 | 3 | 95 | 2 | Dickinson et al, 1979 |
| 32. | Triassic North Range Beds, Southland, N.Z. So. Is. | 9 | 3 | 25 | 72 | 3 | 25 | 72 | ~0 | 96 | 4 | 11 | 89 | ~0 | Boles, 1974 |
| 33. | Upper Paleozoic units of New South Wales | 62 | 3 | 29 | 68 | 3 | 29 | 68 | ~0 | ~100 | ~0 | 7 | 93 | ~0 | Crook, 1960; Chappell, 1968; Raam, 1968 |
| | Tranistional between suites C & D | | | | | | | | | | | | | | |
| 34.* | Insular sands, northern Puerto Rico shelf | 27 | 21 | 31 | 48 | 14 | 31 | 55 | 13 | 56 | 31 | 40 | 51 | 9 | Breyer and Ehlmann, 1979 |
| 35.* | Neogene turbidites, Komardorskiy basin, Bering Sea | 28 | 21 | 28 | 51 | 9 | 28 | 63 | 19 | 64 | 17 | 24 | 68 | 8 | Stewart, 1977 |
| 36. | Neogene "blue-sand" units, California Coast Ranges | 13 | 16 | 25 | 59 | 16 | 25 | 59 | ~0 | 82 | 18 | 39 | 41 | 20 | Lerbekmo, 1961 |
| 37. | Bristol Basin, Cenozoic Alaska Peninsula, Alaska | 52 | 18 | 28 | 54 | 18 | 28 | 54 | 0 | 63 | 37 | 36 | 48 | 16 | Galloway, 1974 |
| 38. | Jamaican Paleogene units | 5 | 22 | 18 | 60 | 20 | 18 | 62 | 2 | 94 | 4 | 53 | 43 | 4 | Wright and Dickinson, 1972 |
| 39. | Shumagin-Sanak Islands Cretaceous, southern Alaska | 47 | 16 | 29 | 54 | 14 | 29 | 57 | 4 | 92 | 4 | 32 | 65 | 3 | Moore, 1973 |
| 40. | Jurassic-Cretaceous Stony Creek petrofacies, Great Valley sequence, California | 33 | 21 | 24 | 55 | 20 | 24 | 56 | 2 | 89 | 9 | 46 | 52 | 2 | Dickinson and Rich, 1972 |
| 41. | Upper Jurassic and middle Cretaceous, central Oregon | 14 | 15 | 27 | 58 | 7 | 27 | 66 | 11 | 66 | 23 | 20 | 70 | 10 | Dickinson et al, 1979 |
| 42. | Triassic-Jurassic units, Southland, N.Z. So. Is. | 5 | 18 | 44 | 38 | 14 | 44 | 42 | 9 | 67 | 24 | 24 | 59 | 17 | Dickinson, 1971 |
| (II) | D. DISSECTED ARC PROVENANCE | | | | | | | | | | | | | | |
| 43.* | Fine-grained trench sands, Oaxaca, Mexico | 13 | 31 | 50 | 19 | 29 | 50 | 21 | 10 | 40? | 50? | 37 | 38 | 25 | Enkeboll, 1979 |
| 44.* | Japan Basin Neogene, Sea of Japan | 4 | 34 | 45 | 21 | 33 | 45 | 22 | 6 | 59 | 35 | 42 | 42 | 16 | Harrold and Moore, 1973 |
| 45. | Gray's Harbor–Chehalis Basins Cenozoic, Washington | 26 | 30 | 29 | 41 | 30 | 29 | 41 | ~0 | 46 | 54 | 51 | 41 | 8 | Galloway, 1974 |
| 46. | Middle Tertiary sandstones, Olympic Peninsula, Washington | 127 | 38 | 32 | 30 | 28 | 32 | 40 | 24 | 52 | 24 | 47 | 46 | 7 | Stewart, 1970 |

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| | Suites | N | Q | F | L | Qm | F | Lt | Qp | Lv | Ls | Qm | P | K | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 47. | Paleogene turbidites of Aleutian abyssal plain | 23 | 38 | 37 | 25 | 29 | 37 | 34 | 26 | 38 | 36 | 44 | 42 | 14 | Stewart, 1976 |
| 48. | Eocene sandstones, Klamath Mountains, southwest Oregon | 38 | 35 | 30 | 35 | 29 | 30 | 41 | 14 | 72 | 14 | 49 | 27 | 24 | Dott, 1965 |
| 49. | Upper Cretaceous, Median Zone, southwest Japan | 116 | 32 | 32 | 36 | 32 | 32 | 36 | ~0 | 72 | 28 | 50 | 34 | 16 | Teraoka, 1977 |
| 50. | Upper Cretaceous Methow-Pasayten sequence, Washington | 35 | 26 | 53 | 21 | 26 | 53 | 21 | ~0 | 54 | 46 | 33 | 54? | 13? | Tennyson and Cole, 1978; Cole, 1973 |
| 51. | Upper Cretaceous Rumsey petrofacies, Great Valley | 53 | 40 | 41 | 19 | 39 | 41 | 20 | 5 | 65 | 30 | 48 | 28 | 24 | Ingersoll, 1976, 1978; Dickinson and Rich, 1972 |
| 52. | Upper Cretaceous petrofacies, Great Valley sequence, San Joaquin Valley, California | 81 | 30 | 32 | 38 | 27 | 32 | 41 | 6 | 39 | 55 | 46 | 42 | 12 | Ingersoll, 1976, 1978 |
| 53. | Mid-Cretaceous Boxer and Cortina "lo-lithic" petrofacies, Sacramento Valley, California | 81 | 35 | 36 | 29 | 33 | 36 | 31 | 7 | 67 | 26 | 48 | 38 | 14 | Ingersoll, 1976, 1978; Dicksinson and Rich, 1972 |
| 54. | Mid-Cretaceous Boxer and Cortina "hi-lithic" petrofacies, Sacramento Valley, California | 34 | 23 | 31 | 46 | 21 | 31 | 48 | 4 | 77 | 19 | 40 | 39 | 21 | Ingersoll, 1976, 1978; Dickinson and Rich, 1972 |
| 55. | Lower Cretaceous Lodoga petrofacies, Great Valley sequence, northern California | 32 | 48 | 23 | 29 | 46 | 23 | 31 | 6 | 68 | 26 | 67 | 29 | 4 | Dickinson and Rich, 1972 |
| 56. | Cretaceous Shimanto terrane, Kyushu-Shikoku, Japan | 583 | 27 | 41 | 32 | 27 | 41 | 32 | ~0 | 89 | 11 | 40 | 46 | 14 | Teraoka, 1977 |
| 57. | Mesozoic Torlesse Group, eastern New Zealand | 7 | 39 | 36 | 25 | 34 | 36 | 30 | 16 | 37 | 47 | 49 | 34 | 17 | Dickinson, 1971 |
| 58. | Permian-Jurassic Waipapa Group, New Zealand | 9 | 28 | 36 | 36 | 28 | 36 | 36 | ~0 | 45 | 55 | 44 | 38 | 18 | Mayer, 1969 |
| III. | RECYCLED OROGEN PROVENANCES | | | | | | | | | | | | | | |
| | E. Subduction Complex Provenance | | | | | | | | | | | | | | |
| 59. | Mid-Cretaceous Virginian Ridge Formation, Methow-Pasayten sequence, Washington | 18 | 45 | 25 | 30 | 5 | 25 | 70 | 57 | 27 | 16 | 75 | 25 | 0 | Tennyson and Cole, 1978; Cole, 1973 |

(Continued on next page)

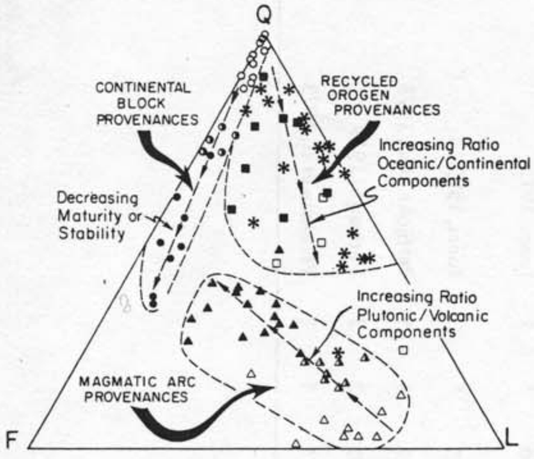
Table 1. Continued

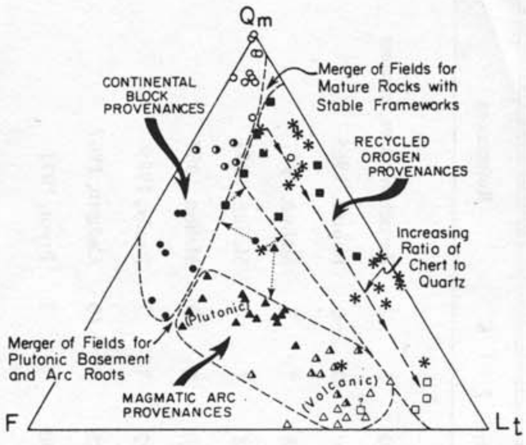
| | Suites | N | Q | F | L | Qm | F | Lt | Qp | Lv | Ls | Qm | P | K | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 60. | Upper Jurassic epiclastic units, Sierra Nevada foothills belt, California | 50 | 24 | 9 | 67 | 8 | 9 | 83 | ~20? | 20? | 60? | -- | -- | -- | Behrman and Parkison, 1978;<br>Parison, 1976;<br>Behrman, 1978 |
| 61. | Upper Triassic Vester Formation, central Oregon | 11 | 50 | 13 | 37 | 5 | 13 | 82 | 54 | 33 | 13 | 28 | 67 | 5 | Dickinson et al, 1978 |
| 62. | Silurian-Devonian Gazelle Formation, northern California | 5 | 61 | 7 | 32 | 12 | 7 | 81 | 60 | 20 | 20 | 63 | ? | ? | Condie and Snansieng, 1971 |
| | F. Collision Orogen Provenance | | | | | | | | | | | | | | |
| 63. | Bengal-Nicobar Fans Neogene, Indian Ocean | 22 | 58 | 28 | 14 | 57 | 28 | 15 | 6 | 4 | 90 | 67 | 22 | 11 | Ingersoll and Suczek, 1979 |
| 64. | Apennine Oligocene, Italy | ? | 56 | 18 | 26 | 54 | 18 | 28 | 13 | 9 | 78 | 75 | ? | ? | Sestini, 1970 |
| 65. | Apennine Eocene, Italy | ? | 90 | 5 | 5 | 83 | 5 | 12 | 58 | ~0 | 42 | 94 | ? | ? | Sestini, 1970 |
| 66. | Apennine Cretaceous, Italy | ? | 80 | 6 | 14 | 60 | 6 | 34 | 60 | 10 | 30 | 91 | ? | ? | Sestini, 1970 |
| 67. | Carboniferous lithic sandstones, Black Warrior basin, Alabama | 12 | 62 | 6 | 32 | 44 | 6 | 50 | 36 | 5 | 59 | 88 | 8 | 4 | Graham et al, 1976 |
| 68. | Carboniferous lithic sandstones, Ouachita Mountains, Arkansas | 12 | 79 | 3 | 18 | 67 | 3 | 30 | 39 | 3 | 58 | 96 | 3 | 1 | Graham et al, 1976 |
| 69. | Carboniferous Haymond Formation, Marathon Mountains, Texas | 45 | 68 | 20 | 12 | 65 | 20 | 15 | 20 | 0 | 80 | 76 | 19 | 5 | McBride, 1966 |
| 70. | Ordovician Plynlimon Group, west-central Wales | 10 | 78 | 13 | 9 | 70 | 13 | 17 | 47 | 6 | 47 | 84 | ? | ? | James, 1971 |
| 71. | Ordovician Tourelle Formation, Gaspe Peninsula, Quebec | 19 | 68 | 12 | 20 | 62 | 12 | 26 | 30 | 12 | 58 | 85 | 6 | 9 | Hiscott, 1978 |
| | G. Foreland Uplift Provenance | | | | | | | | | | | | | | |
| 72.* | Feldspathic petrofacies, High Plains Cenozoic, Wyoming | 147 | 55 | 25 | 20 | 46 | 25 | 29 | 31 | 2 | 67 | 65 | 17 | 18 | Stanley, 1976 |
| 73. | Oligocene Duchesne River Formation, Uinta Basin | 46 | 87 | 2 | 11 | 73 | 2 | 25 | 56 | ~0 | 44 | 97 | 1 | 2 | Andersen and Picard, 1974 |
| 74. | Paleocene Paskapoo Formation, Alberta foothills-plains | 46 | 44 | 12 | 44 | 33 | 12 | 55 | 20 | 18 | 62 | 73 | ? | ? | Carrigy, 1971 |
| 75. | Paleocene Paskapoo Formation, Alberta foothills-plains | 40 | 70 | 3 | 27 | 42 | 3 | 55 | 50 | 1 | 49 | 93 | ? | ? | Carrigy, 1971 |

(Continued on next page)

Table 1. Continued

| | Suites | N | Q | F | L | Qm | F | Lt | Qp | Lv | Ls | Qm | P | K | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 76. | Cretaceous Nanushuk Group, Alaskan North Slope | 66 | 52 | 6 | 42 | 36 | 6 | 58 | 30 | 10 | 60 | 90 | 8 | 2 | Bartsch-Winkler, in press |
| 77. | Upper Mesozoic clastics, Canadian Rocky Mountains | 16 | 67 | ~0 | 33 | 37 | ~0 | 63 | 48 | 11 | 41 | 100 | ~0 | ~0 | Rapson, 1965 |
| 78. | Upper Blairmore Group, Lower Cretaceous Alberta | 16 | 46 | 6 | 48 | 32 | 6 | 62 | 23 | 18 | 49 | 88 | ? | ? | Mellon, 1967 |
| 79. | Middle Blairmore Group, Lower Cretaceous, Alberta | 58 | 22 | 24 | 54 | 16 | 24 | 60 | 8 | 59 | 33 | 48 | ? | ? | Mellon, 1967 |
| 80. | Lower Blairmore Group, Lower Cretaceous, Alberta | 8 | 74 | 0 | 26 | 38 | 0 | 62 | 55 | 0 | 45 | 100 | 0 | 0 | Mellon, 1967 |
| 81. | Upper Jurassic Morrison Formation, central Colorado | 18 | 89 | 7 | 4 | 85 | 7 | 8 | -- | -- | -- | 92 | ? | ? | Brady, 1969 |
| 82. | Upper Jurassic Morrison Formation, Colorado Plateau | 124 | 82 | 13 | 5 | 76 | 13 | 11 | 55 | 45 | 0 | 85 | 5 | 10 | Cadigan, 1967 |
| 83. | Permian Yellow Sands, North Sea region | 15 | 85 | 7 | 8 | 66 | 7 | 27 | 73 | ~0 | 27 | 90 | ? | ? | Pryor, 1971 |
| 84. | Quartzarenite facies, Carboniferous Trenchard Group, England | 5 | 87 | 8 | 5 | 65 | 8 | 27 | 82 | ~0 | 18 | 90 | ? | ? | Jones, 1972 |
| 85. | Litharenite facies, Carboniferous Trenchard Group, England | 5 | 46 | 5 | 49 | 17 | 5 | 78 | 36 | ~0 | 64 | 75 | ? | ? | Jones, 1972 |
| 86. | Upper Paleozoic Alleghenian molasse, Appalachian basin | ? | 79 | 3 | 18 | 76 | 3 | 21 | ? | ? | ? | ? | ? | ? | Pettijohn et al, 1973 |
| 87. | Mississippian Antler trough, east-central Nevada | 11 | 73 | 2 | 25 | 43 | 2 | 55 | 54 | 1 | 45 | 95 | 2 | 3 | Harbaugh, 1979 |
| 88. | Lower Paleozoic Taconic molasse, Appalachian basin | ? | 78 | 3 | 19 | 77 | 3 | 20 | ? | ? | ? | ? | ? | ? | Pettijohn et al, 1973 |





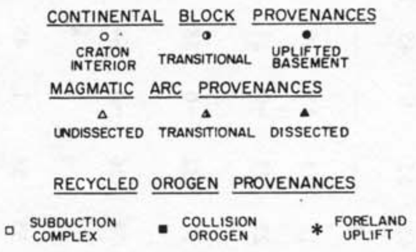


FIG. 1—Triangular *QFL* plot showing mean framework modes for selected sandstone suites derived from different types of provenances (data from Table 1): *Q* is total quartzose grains, including monocrystalline *Qm* and polycrystalline *Qp* varieties; *F* is total feldspar grains (all are monocrystalline); *L* is total unstable lithic fragments (all are polycrystalline).

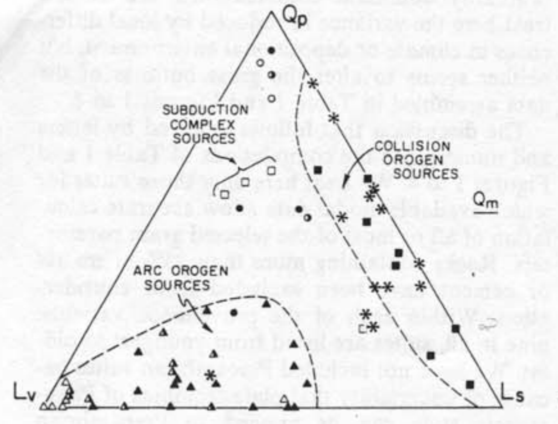
FIG. 2—Triangular *QmFLt* plot showing mean framework modes for selected sandstone suites derived from different types of provenances (data from Table 1): *Qm* is monocrystalline quartz grains; *F* is total feldspar grains (all are monocrystalline); *Lt* is total polycrystalline lithic fragments, including stable quartzose *Qp* as well as unstable *L* varieties.

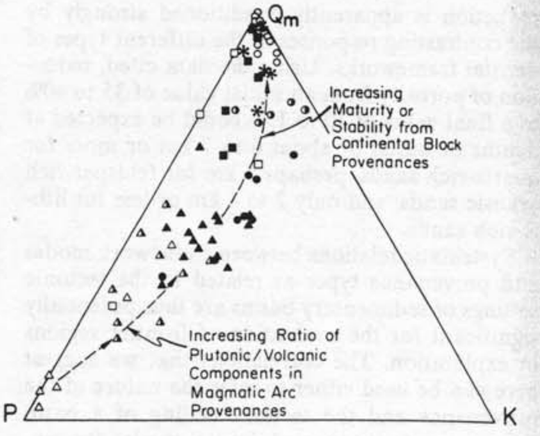
To display the data, we use four complementary triangular diagrams (Figs. 1-4), each of which involves a different set of grain populations. The QFL and QmFLt plots (Figs. 1, 2) both show full grain populations, but with different emphasis: (a) where all quartzose grains are plotted together (QFL), the emphasis is on grain stability, and thus on weathering, provenance relief, and transport mechanism as well as source rock; (b) where all lithic fragments are plotted together (QmFLt), the emphasis is shifted toward the grain size of the source rocks, because finer grained rocks yield more lithic fragments in the sand-size range. The QpLvLs and QmPK plots (Figs. 3, 4) show only partial grain populations, but reveal the character of the polycrystalline and monocrystalline components of the framework, respectively. Each of the four plots serves to discriminate critically between certain pairs of provenance and basin types.

## SANDSTONE POROSITY

The performance of sandstone reservoirs for hydrocarbons depends mainly upon the texture of the aggregate of framework grains, and not upon their composition. Moreover, the initial porosity of sand deposits is controlled primarily by the nature of the sedimentary processes active during dispersal and sedimentation. Thus, the mode and distance of transport and the local depositional environment influence initial porosity much more than does the nature of the provenance or the tectonic setting of the depositional basin. Consequently, detrital frameworks of widely varying composition can be deposited as aggregates having quite similar grain shapes, degrees of sorting, and initial porosities.

However, frameworks of contrasting compositions behave quite differently during diagenesis, and display various rates of porosity reduction





CONTINENTAL BLOCK PROVENANCES

○ CRATON INTERIOR ◐ TRANSITIONAL ● UPLIFTED BASEMENT

MAGMATIC ARC PROVENANCES

△ UNDISSECTED ◭ TRANSITIONAL ▲ DISSECTED

RECYCLED OROGEN PROVENANCES

□ SUBDUCTION COMPLEX ■ COLLISION OROGEN * FORELAND UPLIFT

FIG. 3—Triangular *QpLvLs* plot showing mean proportions of polycrystalline lithic fragments for selected sandstone suites derived from different types of provenances (data from Table 1): *Qp* is polycrystalline quartzose grains, mainly chert; *Lv* is total volcanic-metavolcanic rock fragments; *Ls* is unstable sedimentary-metasedimentary rock fragments.

FIG. 4—Triangular *QmPK* plot showing mean proportions of monocrystalline mineral grains for selected sandstone suites derived from different provenances (data from Table 1): *Qm* is quartz grains; *P* is plagioclase feldspar grains; *K* is K-feldspar grains.

with depth of burial. Being chemically more reactive than quartz, feldspar grains and nonquartzose lithic fragments readily undergo mineralogic alteration and experience enhanced intrastratal solution at comparatively shallow depths. These effects tend to promote cementation or growth of authigenic matrix that inhibits retention of porosity during progressive burial. In addition, lithic fragments tend more readily to be deformed or crushed by increasing overburden. This effect accelerates the reduction of sandstone porosity by simple compaction as the depth of burial increases.

The diagenetic behavior of a particular sandstone during progressive burial is a specific response to a complex set of boundary conditions. For example, the nature of interbedded strata, the local geothermal gradient, the rate of burial, the chemistry of pore fluids, and the hydrodynamic setting of the stratigraphic horizon in question all exert influence on diagenetic processes. The evolution of sandstone porosity through time thus cannot be predicted for a given basin from a knowledge of framework composition alone.

Nevertheless, it is clear that striking contrasts in the rate of porosity reduction with depth of burial are typical for sandstones having generally quartzose, feldspathic, and lithic frameworks. For example, the rate of reduction in bulk porosity is substantially less than 5% net per kilometer of burial for quartzose sandstones of the Gulf Coast region, yet is about 5% net per kilometer of burial for arkosic (quartz-feldspar) sandstones in California (Zieglar and Spotts, 1978). In more lithic sandstones, the comparable figure is commonly well in excess of 5% net per kilometer of burial (Galloway, 1974). Although the exact constraints that control the progress of diagenesis vary in each example, the net integrated effect of prevalent diagenetic processes that pertain to porosity reduction is apparently conditioned strongly by the contrasting responses of the different types of detrital frameworks. Using the data cited, reduction of porosity from an initial value of 35 to 40% to a final value of 10 to 15% could be expected at depths of burial of about 6 to 7 km or more for quartz-rich sands, perhaps 5 km for feldspar-rich arkosic sands, and only 2 to 4 km or less for lithic-rich sands.

Systematic relations between framework modes and provenance types as related to the tectonic settings of sedimentary basins are thus potentially significant for the evaluation of frontier regions in exploration. The correlations that we suggest here can be used either to infer the nature of the provenance and the tectonic setting of a basin from a reconnaissance of detrital modes for representative sandstones, or to predict the probable nature of sandstone frameworks from an understanding of the overall tectonic setting. In general, evolving porosities of potential sandstone reservoirs depend as much upon diagenetic processes controlled largely by framework composition as upon the original depositional textures of unconsolidated parent sands.

## PROVENANCE TYPES

The detritus in most sandstones can be ascribed to sources within a restricted catalog of provenance types. In each example, several types of basins may commonly receive sediment from a particular type of provenance. Table 1 and Figures 1 to 4 are thus both arranged to place prime emphasis on provenance, but typical relations between provenance and associated basins are highlighted in the following discussion.

We classify all provenances and derivative sandstone suites into three general groups: (1) continental block, for which sediment sources are on shields and platforms or in faulted basement blocks; (2) magmatic arc, for which the sources are within active arc orogens of island arcs or active continental margins; and (3) recycled orogen, for which sources are deformed and uplifted stratal sequences in subduction zones, along collision orogens, or within foreland fold-thrust belts. We further subdivide each of these broad categories into several variants. In certain cases, we also indicate the nature of common kinds of transitional sandstone suites that form compositional bridges between the key variants. However, no scheme with the scope that we attempt here can allow for every special circumstance of sediment origin and dispersal (e.g., van Andel, 1958). In rare cases, local vagaries of geologic history can mix sediment drawn from any arbitrary combination of source rocks. We believe, nevertheless, that our scheme serves as a valid practical catalog of the ordinarily dominant combinations. We do not treat here the variance introduced by local differences in climate or depositional environment, but neither seems to alter the gross outlines of the data assembled in Table 1 and Figures 1 to 4.

The discussion that follows is keyed by letters and numerals to the compilations of Table 1 and Figures 1 to 4. We treat here only those suites for which available modal data allow accurate calculation of all or most of the selected grain parameters. Rocks containing more than 25% of matrix or cement have been excluded from consideration. Within each of the provenance variants, nine in all, suites are listed from youngest to oldest. We have not included Precambrian suites because of uncertainty that plate tectonics of Phanerozoic style can be applied to Precambrian terranes. Others may wish to compare modal data for Precambrian suites with our Phanerozoic data set. We have also excluded suites of hybrid sandstones that contain a significant proportion of carbonate sand grains, whether of intrabasinal or extrabasinal origin. This deliberate omission is an inherent limitation of our data set, but avoids questionable interpretations. Such hybrid suites have been studied too little to support firm conclusions.

We have tabulated and plotted mean values of selected grain parameters for 88 sand and sandstone suites. Altogether, the data represent thousands of separate point counts performed by scores of operators. However, individual sets of means were calculated from fewer than 5 to more than 500 counts. Because sampling procedures and counting routines were different for the various suites, we have not calculated standard deviations for the means cited here. In general experience, however, the counting errors (Van der Plas and Tobi, 1965) for the grain parameters selected are probably less than 5% of the whole rock for individual counts. Standard deviations of means for multiple samples are commonly 5 to 10%, but rarely 10 to 15%, of whole rock. Fields delineated by clusters of points in Figure 1 must be interpreted with allowance for appropriate halos of variance about each plotted point. Comparative data in one example (suites 21, 22), where methodologies of the respective operators contrasted strongly, may well represent the limits of discrepancy to be expected in the data presented.

## CONTINENTAL BLOCK PROVENANCES

Detritus from nonorogenic continental blocks forms a spectrum of sand types derived from the broad positive areas of stable cratons at one extreme and from locally uplifted, commonly fault-bounded basement blocks at the other extreme (Fig. 5).

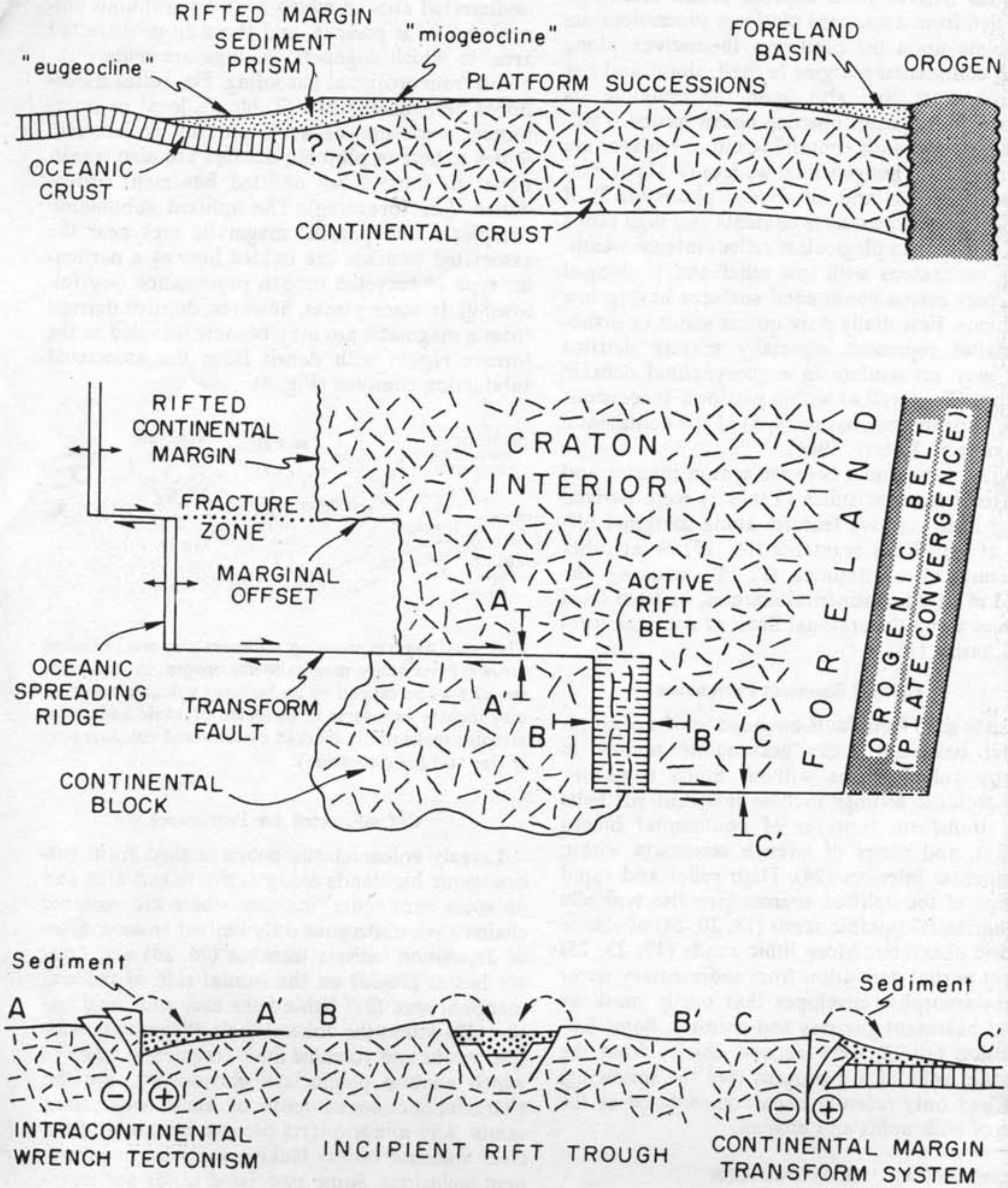


FIG. 5—Diagram showing key continental block provenances and selected types of associated basins. Craton interior provenance shown in plan (center) and profile (top) view contributes sediment to adjacent rifted margin sediment prism along passive continental margin (left), to local platform successions within continental block, and to cratonal flank of foreland basin (right) beside orogenic belt. Uplifted basement provenances (bottom) contribute sediment to local basins associated with incipient rupture or wrench deformation of continental block at *AA'*, *BB'*, and *CC'*.

### A. Craton Interior Provenance

Sands derived from exposed shield areas and recycled from associated platform successions accumulate upon the platforms themselves, along rifted continental margins in shelf, slope, and rise environments, and also upon the ophiolite sequences of adjacent opening ocean basins. Typical quartzose sands containing minor feldspar are present within miogeoclinal wedges (9-11) at continental margins and on abyssal plains (1, 2) of the seafloor. High quartz contents and high ratios of K-feldspar to plagioclase reflect intense weathering on cratons with low relief and prolonged transport across continental surfaces having low gradients. Essentially pure quartz sands or orthoquartzites represent especially mature detritus that may accumulate in eugeosynclinal oceanic settings (7) as well as within platform successions (3, 6, 8) or interior basins (4, 5) of the continental blocks (e.g., Ketner, 1966).

Suites transitional between craton interior and uplifted basement suites (Table 1) were derived either from positive features along marginal offsets at transform segments (16, 17) or at other structural discontinuities (12-14) breaking the trend of rifted continental margins, or from local sources along the cratonal flank of complex foreland basins (15).

### B. Uplifted Basement Provenance

Sands shed from fault-bounded uplifts of continental basement rocks accumulate mainly in nearby yoked basins without much transport. Key tectonic settings include incipient rift belts (25), transform ruptures of continental blocks (18-23), and zones of wrench tectonism within continental interiors (24). High relief and rapid erosion of the uplifted sources give rise typically to quartzo-feldspathic sands (18, 20, 24) of classic arkosic character. More lithic sands (19, 23, 25) reflect partial derivation from sedimentary cover or metamorphic envelopes that partly mask or shield basement gneisses and granites. Some listed suites (19-23) were derived chiefly from the plutonic belts of arc orogens (see the following) that had only recently been consolidated at the time of bulk uplift and erosion.

## MAGMATIC ARC PROVENANCES

Detritus eroded from arc orogens (Fig. 6) forms a spectrum of sand types including lithic-rich volcaniclastic debris at one extreme and more quartzo-feldspathic detritus of largely plutonic origin at the other extreme. The range of modern sands present in the Cascadia basin on the Juan de Fuca plate west of the Cascades volcanic chain displays the variability of arc-derived detritus well (Duncan and Kulm, 1970, Fig. 3). We here divide arc-derived suites into those eroded from undissected arcs, in which nearly continuous volcanic cover is present, and those from dissected arcs, in which cogenetic plutons are widely exposed from erosional unroofing. For suites transitional between the two (Table 1), local or intermittent exposure of such plutons is inferred. Suites richest in plutonic detritus are also transitional to those from uplifted basement provenances (see foregoing). The uplifted subduction complexes that parallel magmatic arcs near the associated trenches are treated here as a particular type of recycled orogen provenance (see following). In some places, however, detritus derived from a magmatic arc may become mingled in the forearc region with debris from the associated subduction complex (Fig. 6).

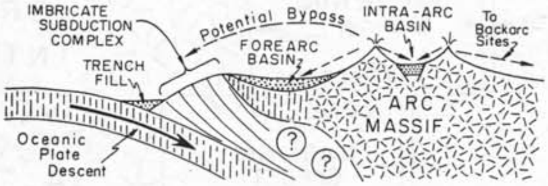


FIG. 6—Diagram showing sediment dispersal (dashed arrows) from active magmatic arc orogen, in which arc massif may be capped by undissected volcanic cover, or may include exposures of dissected plutonic and metamorphic rocks partly masked by scattered volcanic cover (see text for discussion).

### C. Undissected Arc Provenance

Largely volcaniclastic debris is shed from volcanogenic highlands along active island arcs and on some continental margins where arc volcanic chains have undergone only limited erosion. Sites of deposition include trenches (26, 29) and forearc basins (30-33) on the frontal side of the arc, marginal seas (27) behind the arc, and local basins (28) within the volcanic belt. Plagioclase feldspar grains and volcanic lithic fragments, many of which contain plagioclase phenocrysts, are the characteristic constituents of such arc-derived sands. Any minor quartz present is mainly of the clear volcanic variety lacking vacuoles or prominent inclusions. Some associated sands not represented in the table show strong concentration of plagioclase grains relative to lithic fragments from intense reworking of the volcaniclastic debris.

Suites listed as transitional between undissected and dissected arc provenances (Table 1) also include examples from trench (39), forearc (36, 40-42), intra-arc (34, 38), and backarc (35,37) depositional settings. In each example, minor admixtures of plutonic detritus are demonstrable, even though the main sources were still volcanic. Contributions from the subvolcanic roots of the arc massifs are reflected in higher contents of quartzose grains.

### D. Dissected Arc Provenance

More mature and eroded magmatic arcs, especially those along continental margins, shed detritus of mixed plutonic and volcanic origin into both forearc (45-55) and backarc (44) basins. Some of these sands reach trench settings (43, 46, 56-58). Sand compositions are complex but less lithic than volcaniclastic debris; typical framework modes plot near the middle of the QFL diagram (Fig. 1). Both feldspars are commonly present in significant proportions, and nonvolcanic lithic fragments are prominent in varying degrees. Common plutonic quartz with trains of vacuoles and inclusions far exceeds clear volcanic quartz in abundance. Arc volcanism commonly continues in mature magmatic arcs even as dissection is exposing older plutonic roots of the arc terrane to erosion. The volcanic cover and the batholithic core of the volcano-plutonic arc orogen thus serve jointly and simultaneously as sediment sources. This relation is best documented (Dickinson and Rich, 1972) for the Great Valley sequence (51-55), deposited within a late Mesozoic forearc basin in California (Dickinson and Seely, 1979). Several suites from other forearc basins (45, 48-50) are of similar character. Analogous sands may be transported into the trench (43) or beyond (47), and later incorporated into deformed subduction complexes (46, 56-58) by continued plate consumption. Because of controversy about the sediment sources, however, we have omitted modal data (e.g., Jacobson, 1978) for the Franciscan assemblage, which is the subduction complex coeval with the Great Valley sequence in California, and will treat its provenance elsewhere.

## RECYCLED OROGEN PROVENANCES

The key source rocks in several kinds of orogenic provenances are uplifted terranes of folded and faulted strata from which recycled detritus of sedimentary or metasedimentary origin is especially prominent. We provisionally divide these orogen provenances into subduction complexes of deformed oceanic sediments and lavas, collision orogens formed along crustal sutures between once-separate continental blocks, and foreland uplifts associated with foreland fold-thrust belts (Fig. 7). The latter develop either adjacent to suture belts or between magmatic arcs and retroarc basins located within continental blocks behind the arcs. Complex orogenic belts may include all three kinds of provenance in subparallel linear belts which may jointly contribute mixed detritus to varied successor basins. Arc-derived detritus may also be incorporated into such mixed suites in ways detailed in the following.

### E. Subduction Complex Provenance

Tectonically uplifted subduction complexes composed of deformed ophiolitic and other oceanic materials form a structural high along the trench-slope break between the trench axis and the volcanic chain within arc-trench systems. In some places, this structural high is emergent as an isolated sediment source along the so-called outer sedimentary arc where varying proportions of greenstone, chert, argillite, graywacke, and some limestone are exposed as constituents of melanges, thrust sheets, and isoclines formed by deformation within the subduction zone. Sediment derived from such uplifted terranes can be shed either toward the arc into forearc basins (59, 61) or into the trench, where it again becomes incorporated into the subduction complex (60, 62). The key signal of sand having such a derivation is an abundance of chert grains, which exceed combined quartz and feldspar grains in our examples by a factor of as much as two or three. However, all the subduction complexes in our examples are composed mainly of chert, argillite, and greenstone evidently drawn into subduction zones that were starved for clastic sediment. Presumably, the chert signal would be more subdued for subduction complexes from which the sandy components of trench-fill or abyssal-plain turbidites were recycled in quantity. Moreover, local thrust slices or protrusions of serpentinite form special sources of serpentine-grain sandstones not represented among our examples.

Admixtures of debris from subduction complexes may be expected in sands shed from both arc and collision orogens. Arc-derived detritus that is transported into or beyond the trench may systematically acquire a chert-rich component in crossing the structural high of the subduction complex. This effect may explain the elevated short chert content of some magmatic arc suites (e.g., 47, 57) deposited in the trench or beyond. Collision-derived detritus from suture belts that contain remnants of the intervening seafloor in the form of ophiolitic melanges will also systematically include a component of sand derived from such residual subduction complexes.

### F. Collision Orogen Provenances

Orogens formed by crustal collision are composed largely of nappes and thrust sheets of sedi-

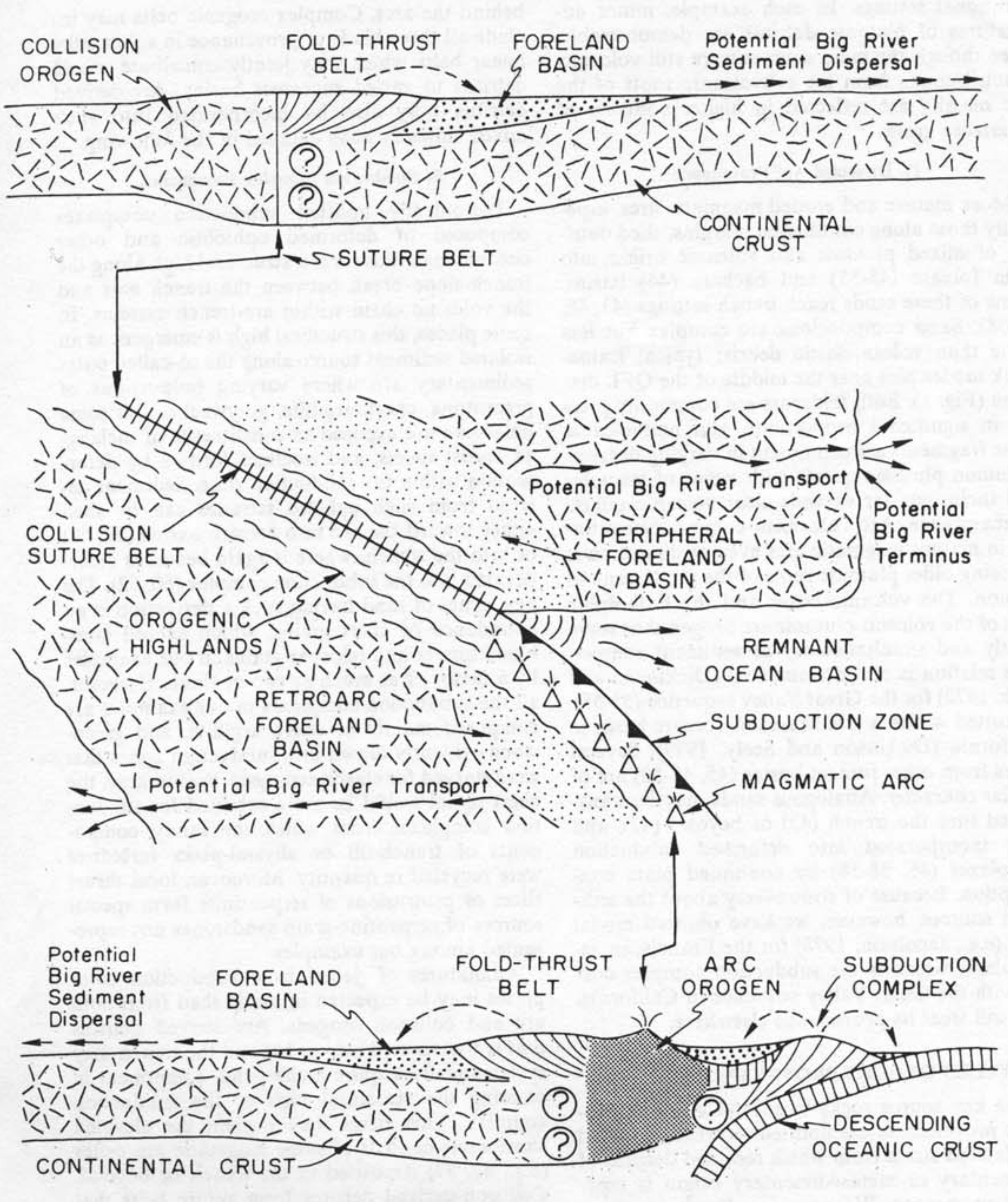


**FIG. 7**—Diagram showing key recycled orogen provenances and selected types of associated basins. Plan view (center) shows evolving continent-continent collision (analogous features result also from arc-continent collision). Concentric arcs and wavy arrows within remnant ocean basin show delta-lobe and turbidite-fan progradation, respectively. These deposystems reflect longitudinal sediment dispersal from developing collision orogen into closing ocean basin, along flank of which subduction zone of arc orogen is still active (Graham et al, 1975). Profile at top shows foreland uplift and basin flanking collision orogen. Profile at bottom shows foreland uplift and basin flanking arc orogen, as well as trench and forearc basin within active arc-trench system. Dashed arrows on profiles denote dispersal of recycled sediment from foreland fold-thrust belts (top and bottom), and from subduction complex (bottom only).

mentary and metasedimentary rock that represent sequences present along and near the preceding continental margins prior to their juxtaposition along a suture belt. Subordinate sources that are associated with these terranes include the ophiolitic melanges along the suture belt and structurally dislocated plutonic terranes of basement blocks or magmatic arcs involved in the crustal collision. Collision-derived sediment is mainly shed longitudinally from the evolving orogen into closing remnant ocean basins as turbidites (63, 68-70), but also enters foreland basins flanking the orogen (67, 71) and complex successor basins developed along the suture belt (64-66). Typical sands (67, 68), composed largely of recycled sedimentary materials, have intermediate quartz contents, a high ratio of quartz to feldspar, and an abundance of sedimentary-metasedimentary lithic fragments. Some quartzose sandstones (65) apparently represent recycled cratonic debris. Sandstones with high feldspar contents (63, 64; 69-71) probably contain significant contributions from igneous terranes uplifted adjacent to the crustal sutures. Sandstones with high chert contents (65-68; 70, 71) may include significant contributions from melange terranes caught along the suture belts, although chert nodules from carbonate successions may also be important sources. Debris from sand-rich subduction complexes may well be nearly indistinguishable from chert-rich collision-derived debris, although a higher Lv/Ls ratio may prove to be diagnostic of the former (see Table 1 and Fig. 3).

### G. Foreland Uplift Provenance

Foreland fold-thrust belts form highlands from which sediment is shed directly into adjacent foreland basins, which also receive sediment from positive areas on the craton beyond. Although foreland basins may flank either arc or collision orogens, the fold-thrust uplands generally shield the basins from sediment sources in the magmatic arcs or along the suture belts. Consequently, sands are typically recycled from sedimentary successions within the fold-thrust belts. Some quartzose sands (81, 82) thus resemble suites from continental blocks (Table 1), whereas other chert-rich sands (75, 77, 80, 83, 84, 87) are essentially indistinguishable from similar recycled sands from collision orogens. One especially chert-rich suite (85) resembles subduction complex suites. Some suites (74, 76, 78) couple high chert contents with even more abundant sedimentary lithic fragments of less stable varieties. The feldspathic suite (72) from the Cenozoic of the High Plains incorporates detritus from exposed basement blocks uplifted within the broken foreland of the Laramide belt of the central Rockies. In the Mesozoic of the Alberta foreland, some sandstones (79) contain abundant volcaniclastic detritus derived from the arc terrane that lay within the adjacent orogen beyond the foreland fold-thrust belt. Our data thus imply varied provenance for different foreland settings, but do not define the variants well. Perhaps the most characteristic rocks (e.g., 73, 86, 88) couple moderately high quartz contents with strikingly low feldspar contents. Some sandstones in foreland suites (e.g., 74-80) contain high proportions of recycled detrital carbonate grains eroded from exposed limestone and dolostone units, but these rocks are not included in our compilations.

## PROVENANCE COMPARISONS

Figures 1 to 4 provide a summary of similarities and differences among the various types of sandstone suites, and reveal the prime criteria by which they may be distinguished.

On the QFL diagram (Fig. 1), points for continental block, magmatic arc, and recycled orogen provinces occupy discrete fields. However, fields for the first and last essentially merge where stable frameworks of high maturity are involved; most of these are probably multicyclic sands of cratonic origin recycled through platform successions. Magmatic arc suites are consistently less quartzose than nearly all the others. For continental block provenances, a trend of decreasing stability or maturity leads away from the Q pole toward the F pole for craton interior, transitional, and uplifted basement suites in that order. For magmatic arc provenances, a trend of decreasing lithic content leads away from the L pole toward the Q-F join for undissected, transitional, and dissected arc suites in that order. This trend reflects an increase in the proportion of monocrystalline mineral grains derived from plutonic rocks relative to polycrystalline lithic fragments derived from volcanic rocks. The two trends of framework variation thus defined for continental block and magmatic arc suites converge toward a point reflecting the mix of quartz and feldspar in plutonic basement rocks. No such clear trend is displayed by points for the various recycled orogen suites. In general, however, subduction-complex provenances plot distinctly toward the L pole from most foreland-uplift provenances near the Q pole. This relation suggests a trend away from the Q pole toward the L pole as the ratio of oceanic to continental materials increases in the recycled detritus from collision orogens and related terranes.

On the QmFLt diagram (Fig. 2), the shift of Qp from the Q pole to the Lt pole causes local merger of the fields for the three main classes of provenance, but the same general relations displayed by the QFL diagram are retained or enhanced. In particular, the low lithic content of continental block suites is confirmed and the low feldspar content of recycled orogen suites is highlighted. Owing to their high chert content, subduction complex suites plot far away toward the Lt pole from nearly all points for other recycled orogen suites. Foreland basin suites fall into two fields reflecting different proportions of quartz grains and lithic fragments, but most of the lithic-rich examples shown are from Alberta; the quartz-rich suites are apparently more characteristic.

The QpLvLs diagram (Fig. 3) is particularly useful for distinguishing magmatic arc suites, with sources in arc orogens, from recycled orogen suites, with sources mainly in collision orogens. The fields are far apart, with points for arc orogen sources well away toward the Lv pole from points for collision orogen sources. For subduction complex provenances, LvLs ratios are similar to those for magmatic arc provenances in arc orogens, rather than to other recycled orogen suites, but the Qp content is distinctly higher and similar to the few continental block suites shown. Most continental block suites do not appear on this diagram, for QpLvLs values were not calculated where the total content of lithic fragments is less than 10%.

On the QmPK diagram (Fig. 4), all points occupy a broad arcuate field curving slightly away from the Qm-P join, but linking those two poles. The more feldspathic end of the trend reflects an increase in the ratio of plutonic to volcanic detritus in sands derived mainly from magmatic arcs. The more quartzose end of the trend reflects increasing maturity or stability for detritus derived from continental blocks or recycled through derivative orogenic terranes.

## DISCUSSION

Two recent studies of selected modern sand samples are especially pertinent for interpretations of the means we present here for modes of ancient sandstones.

Vallone and Maynard (1979) counted samples of modern turbidites in piston cores and DSDP cores from the deep sea. Their results are largely coordinate with ours. Means for sands off "leading edges" or active margins of continental blocks, and in backarc or forearc positions relative to island arcs, plot within the fields for magmatic arc provenances on Figures 1 to 3. Means for sands off "trailing edges" or passive margins of continental blocks plot generally intermediate between fields for continental block and recycled orogen provenances on Figures 1 and 2. Where present, arc-trench systems thus dominate as provenance but, elsewhere, debris draining off continental lowlands or shed from foldbelts and thrust belts is jointly or alternately prominent.

Potter (1978) counted sands collected near the mouths of the major rivers whose combined discharge accounts for about a third of the streamflow reaching the world ocean. Means, QmFLt only, for rivers ending at "collision" (active) margins, "trailing" (passive) margins, and marginal sea coasts of continental blocks all plot within the field for recycled orogen provenances on Figure 2. Framework quartz contents range mostly from 25 to 75%, although a few tropical rivers carry quartz-rich sands with less than 5% of other constituents. Feldspar contents are less than 25% in all but a few of the rivers sampled, and are commonly only 5 to 15%.

The moderate quartz contents and low feldspar contents of typical sands carried by big rivers thus match the parameters we derive here for collision orogen and foreland uplift provenances. In these settings, foldbelt uplifts and stacked thrust sheets form rugged highlands adjacent to continental blocks. We conclude that truly large rivers able to traverse broad continental blocks typically head in such marginal highlands, whose drainage divides commonly shield the drainage basins of the large rivers from arc-derived detritus. The recycled detritus from rapidly eroding orogenic highlands tends to swamp contributions to the large rivers from continental lowlands. To these generalities for big rivers there are clearly major exceptions (see Potter, 1978, Fig. 4).

## CONCLUSIONS

The triangular diagrams thus confirm the utility of the standard QFL diagram (Fig. 1) for discrimination of provenance, and show how the other three auxiliary plots (Figs. 2-4) augment and amplify the criteria for distinction. Accurate framework modes permit a clear assessment of provenance type for most sandstone suites. As a limited number of basin types draws sediment from each kind of provenance, the same data allow useful inferences to be made relating framework modes to tectonic setting for any given basin.

## REFERENCES CITED

Andersen, D. W., and M. D. Picard, 1974, Evolution of synorogenic clastic deposits in the intermontane Uinta basin of Utah, *in* Tectonics and sedimentation: SEPM Spec. Pub. 22, p. 167-189.

Bartsch-Winkler, S., in press, Textural and mineralogical study of some surface and subsurface sandstones from the Nanushuk Group, western North Slope, Alaska, *in* Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geol. Survey Circ. 794.

Behrman, P. G., 1978, Paleogeography and structural evolution of a Middle to Late Jurassic volcanic arc, Sierra Nevada foothills, California: PhD thesis, Univ. California, Berkeley, 301 p.

——— and G. A. Parkison, 1978, Paleogeographic significance of the Callovian to Kimmeridgian strata, central Sierra Nevada foothills, California, *in* Mesozoic paleogeography of the western United States: SEPM Pacific Sec. Pacific Coast Paleogeography Symp. 2, p. 349-360.

Boggs, S., Jr., 1966, Petrology of Minturn Formation, east-central Eagle County, Colorado: AAPG Bull., v. 50, p. 1399-1422.

Boles, J. R., 1974, Structure, stratigraphy, and petrology of mainly Triassic rocks, Hokonui Hills, Southland, New Zealand: New Zealand Jour. Geology Geophysics, v. 17, p. 337-374.

Brady, L. L., 1969, Stratigraphy and petrology of the Morrison Formation (Jurassic) of the Canon City, Colorado, area: Jour. Sed. Petrology, v. 39, p. 632-648.

Breyer, J. A., and A. J. Ehlmann, 1980, The mineralogic composition of siliciclastic sediment on the insular shelf of Puerto Rico: in prep.

Cadigan, R. A., 1967, Petrology of the Morrison Formation in the Colorado Plateau region: U.S. Geol. Survey Prof. Paper 556, 113 p.

——— 1971, Petrology of the Triassic Moenkopi Formation and related strata in the Colorado Plateau region: U.S. Geol. Survey Prof. Paper 692, 70 p.

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

Carrigy, M. A., 1971, Lithostratigraphy of the uppermost Cretaceous (Lance) and Paleocene strata of the Alberta plains: Alberta Research Council Bull. 27, 161 p.

Chappell, B. W., 1968, Volcanic greywackes from the Upper Devonian Baldwin Formation, Tamworth-Barraba district, New South Wales: Geol. Soc. Australia Jour., v. 15, p. 87-102.

Cleary, W. J., and J. R. Conolly, 1974, Petrology and origin of deep-sea sands, Hatteras Abyssal Plain: Marine Geology, v. 17, p. 263-279.

Cole, M. R., 1973, Petrology and dispersal patterns of Jurassic and Cretaceous sedimentary rocks in the Methow River area, north Cascades, Washington: PhD thesis, Univ. Washington, 110 p.

Condie, K. C., and S. Snansieng, 1971, Petrology and geochemistry of the Duzel (Ordovician) and Gazelle (Silurian) Formations, northern California: Jour. Sed. Petrology, v. 41, p. 741-751.

Crook, K. A. W., 1960, Petrology of Parry Group, Upper Devonian–Lower Carboniferous, Tamworth-Nundle district, New South Wales: Jour. Sed. Petrology, v. 30, p. 538-552.

——— 1974, Lithogenesis and geotectonics: the significance of compositional variations in flysch arenites (graywackes), *in* Modern and ancient geosynclinal sedimentation: SEPM Spec. Pub. 19, p. 304-310.

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.

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

——— and D. R. Seely, 1979, Structure and stratigraphy of forearc regions: AAPG Bull., v. 63, p. 2-31.

——— K. P. Helmold, and J. A. Stein, 1979, Mesozoic lithic sandstones in central Oregon: Jour. Sed. Petrology, v. 49, p. 501-516.

Dott, R. H., Jr., 1965, Mesozoic-Cenozoic tectonic history of the southwestern Oregon coast in relation to Cordilleran orogenesis: Jour. Geophys. Research, v. 70, p. 4687-4707.

Duncan, J. R., and L. D. Kulm, 1970, Mineralogy, provenance, and dispersal history of late Quaternary deep-sea sands in Cascadia basin and Blanco fracture zone off Oregon: Jour. Sed. Petrology, v. 40, p. 874-887.

Enkeboll, R. H., 1979, Sedimentary petrology and provenance of sands and gravels from the Middle America Trench and trench slope, Guatemala and southern Mexico: Jour. Sed. Petrology, in press.

Galloway, W. E., 1974, Deposition and diagenetic alteration of sandstone in northeast Pacific arc-related basins: implications for graywacke genesis: Geol. Soc. America Bull., v. 85, p. 379-390.

Graham, S. A., 1976, Tertiary sedimentary tectonics of the central Salinian block of California: PhD thesis, Stanford Univ., 216 p.

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

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

Harbaugh, D. W., 1979, Depositional environments and provenance of Mississippian strata in central Diamond Range, Eureka County, Nevada: Master's thesis, Stanford Univ., in prep.

Harrold, P. J., and J. C. Moore, 1975, Composition of deep-sea sands from marginal basins of the northwestern Pacific: Initial reports of the Deep Sea Drilling Project, v. 31, p. 507-514.

Hayes, J. B., 1973, Petrology of indurated sandstones, leg 18, Deep Sea Drilling Project: Initial reports of the Deep Sea Drilling Project, v. 18, p. 915-924.

Helmold, K. P., 1979, Diagenesis of Tertiary arkoses, Santa Ynez Mountains, California: PhD thesis, Stanford Univ., in prep.

Higgs, R., 1978, Provenance of Mesozoic and Cenozoic sediments from the Labrador and western Greenland continental margins: Canadian Jour. Earth Sci., v. 15, p. 1850-1860.

Hiscott, R. N., 1978, Provenance of Ordovician deep-water sandstones, Tourelle Formation, Quebec, and implications for initiation of the Taconic orogeny: Canadian Jour. Earth Sci., v. 15, p. 1579-1597.

Hubert, J. F., and W. J. Neal, 1967, Mineral composition and dispersal patterns of deep-sea sands in the western North Atlantic petrologic province: Geol. Soc. America Bull., v. 78, p. 749-771.

Ingersoll, R. V., 1976, Evolution of the Late Cretaceous fore-arc basin of northern and central California: PhD thesis, 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 C. A. Suczek, 1979, Petrology and provenance of Neogene sand from the Nicobar and Bengal fans, DSDP sites 211 and 218: Jour. Sed. Petrology, v. 49, in press.

Jacobson, M. I., 1978, Petrologic variations in Franciscan sandstone from the Diablo Range, California, *in* Mesozoic paleogeography of the western United States: SEPM Pacific Sec. Pacific Coast Paleogeography Symp. 2, p. 401-407.

James, D. M. D., 1971, Petrography of the Plynlimon Group, west-central Wales: Sed. Geology, v. 6, p. 255-270.

Jones, P. C., 1972, Quartzarenite and litharenite facies in the fluvial foreland deposits of the Trenchard Group (Westphalian), Forest of Dean, England: Sed. Geology, v. 8, p. 177-198.

Ketner, K. B., 1966, Comparison of Ordovician eugeosynclinal and miogeosynclinal quartzites of the Cordilleran geosynclines: U.S. Geol. Survey Prof. Paper 550-C, p. C54-C60.

Krynine, P. D., 1948, The megascopic study and field classification of sedimentary rocks: Jour. Geology, v. 56, p. 130-165.

Lee-Wong, F., and D. G. Howell, 1977, Petrography of Upper Cretaceous sandstone in the Coast Ranges of California, *in* Cretaceous geology of the California Coast Ranges west of the San Andreas fault: SEPM Pacific Sec. Pacific Coast Paleogeography Field Guide 2, p. 47-55.

Lerbekmo, J. F., 1961, Genetic relationship among Tertiary blue sandstones in central California: Jour. Sed. Petrology, v. 31, p. 594-602.

Lobo, C. F., and R. H. Osborne, 1976, Petrology of late Precambrian–Cambrian quartzose sandstones in the eastern Mojave Desert, southeastern California: Jour. Sed. Petrology, v. 46, p. 829-846.

Mayer, W., 1969, Petrology of the Waipapa Group near Auckland, New Zealand: New Zealand Jour. Geology Geophysics, v. 12, p. 412-435.

McBride, E. F., 1966, Sedimentary petrology and history of the Haymond Formation (Pennsylvanian), Marathon basin, Texas: Texas Univ. Bur. Econ. Geology Rept. Inv. 57, 101 p.

McLane, M. J., 1971, Phanerozoic detrital rocks at the northern end of the Tobacco Root Mountains, southwestern Montana; a vertical profile: PhD thesis, Indiana Univ., 253 p.

——— 1972, Sandstone: secular trends in lithology in southwestern Montana: Science, v. 178, p. 502-504.

Mellon, G. B., 1967, Stratigraphy and petrology of the Lower Cretaceous Blairmore and Mannville Groups, Alberta foothills and plains: Alberta Research Council Bull. 21, 270 p.

Moore, J. C., 1973, Cretaceous continental margin sedimentation, southwestern Alaska: Geol. Soc. America Bull., v. 84, p. 595-614.

Morris, R. C., 1974a, Sedimentary and tectonic history of the Ouachita Mountains, *in* Tectonics and sedimentation: SEPM Spec. Pub. 22, p. 120-142.

——— 1974b, Carboniferous rocks of the Ouachita Mountains, Arkansas: a study of facies patterns along the unstable slope and axis of a flysch trough, *in* Carboniferous of the southeastern United States: Geol. Soc. America Spec. Paper 148, p. 241-279.

Parkison, G. A., 1976, Tectonics and sedimentation along a Late Jurassic(?) active continental margin, western Sierra Nevada foothills, California: Master's thesis, Univ. California, Berkeley, 160 p.

Pettijohn, F. J., P. E. Potter, and R. Siever, 1973, Sand and sandstone: New York, Springer-Verlag, 618 p.

Potter, P. E., 1978, Petrology and chemistry of modern big river sands: Jour. Geology, v. 86, p. 423-449.

——— and W. A. Pryor, 1961, Dispersal centers of Paleozoic and later clastics of the upper Mississippi Valley and adjacent areas: Geol. Soc. America Bull., v. 72, p. 1195-1250.

Pryor, W. A., 1971, Petrology of the Permian Yellow Sands of northeastern England and their North Sea basin equivalents: Sed. Geology, v. 6, p. 221-254.

Raam, A., 1968, Petrology and diagenesis of Broughton sandstone (Permian), Kiama district, New South Wales: Jour. Sed. Petrology, v. 38, p. 319-331.

Rapson, J. E., 1965, Petrography and derivation of Jurassic-Cretaceous clastic rocks, southern Rocky Mountains, Canada: AAPG Bull., v. 49, p. 1426-1452.

Schwab, F. L., 1970, Origin of the Antietam Formation (late Precambrian?–Lower Cambrian), central Virginia: Jour. Sed. Petrology, v. 40, p. 354-366.

——— 1971, Harpers Formation, central Virginia: a sedimentary model: Jour. Sed. Petrology, v. 41, p. 139-149.

——— 1974, Mechum River Formation: late Precambrian(?) alluvium in the Blue Ridge province of Virginia: Jour. Sed. Petrology, v. 44, p. 862-871.

——— 1975, Framework mineralogy and chemical composition of continental margin-type sandstone: Geology, v. 3, p. 487-490.

Sestini, G., 1970, Flysch facies and turbidite sedimentology: Sed. Geology, v. 4, p. 559-597.

Siever, R., 1957, Pennsylvanian sandstones of the Eastern Interior coal basin: Jour. Geology, v. 27, p. 227-250.

Skinner, D. N. B., 1972, Subdivision and petrology of the Mesozoic rocks of Coromandel (Manaia Hill Group): New Zealand Jour. Geology Geophysics, v. 15, p. 203-227.

Stanley, K. O., 1976, Sandstone petrofacies in the Cenozoic High Plains sequence, eastern Wyoming and Nebraska: Geol. Soc. America Bull., v. 87, p. 297-309.

Stewart, R. J., 1970, Petrology, metamorphism, and structural relations of graywackes in the western Olympic Peninsula, Washington: PhD thesis, Stanford Univ., 107 p.

——— 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: AAPG Bull., v. 61, p. 192-206.

——— 1978, Neogene volcaniclastic sediments from Atka basin, Aleutian Ridge: AAPG Bull., v. 62, p. 87-97.

Suczek, C. A., 1977, Tectonic relations of the Harmony Formation, northern Nevada: PhD thesis, Stanford Univ., 96 p.

Tennyson, M. E., and M. R. Cole, 1978, Tectonic significance of upper Mesozoic Methow-Pasayten sequence, northeastern Cascade Range, Washington and British Columbia, *in* Mesozoic paleogeography of the western United States: SEPM Pacific Sec. Pacific Coast Paleogeography Symp. 2, p. 499-508.

Teraoka, Y., 1977, Comparison of the Cretaceous sandstones between the Shimanto terrane and the Median zone of southwest Japan: Geol. Soc. Japan Jour., v. 83, p. 795-810 (in Japanese with English abs.).

Vallone, R., and J. B. Maynard, 1979, Detrital modes of recent deep-sea sands: influence of tectonics: Sedimentology, in press.

Van Andel, Tj. H., 1958, Origin and classification of Cretaceous, Paleocene, and Eocene sandstones of western Venezuela: AAPG Bull., v. 42, p. 734-763.

Van de Kamp, P. C., B. E. Leake, and A. Senior, 1976, The petrography and geochemistry of some Californian arkoses with application to identifying gneisses of sedimentary origin: Jour. Geology, v. 84, p. 195-212.

Van der Plas, L., and A. C. Tobi, 1965, A chart for determining the reliability of point counting results: Am. Jour. Sci., v. 263, p. 87-90.

Wright, R. M., and W. R. Dickinson, 1972, Provenance of Eocene volcanic sandstones in Jamaica—a preliminary note: Caribbean Jour. Sci., v. 12, p. 107-113.

Zieglar, D. L., and J. H. Spotts, 1978, Reservoir and source-bed history of Great Valley, California: AAPG Bull., v. 62, p. 813-826.