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INTERPRETING PROVENANCE RELATIONS FROM DETRITAL MODES OF SANDSTONES

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ABSTRACT

Detrital modes of sandstone suites primarily reflect the different tectonic settings of provenance terranes, although various other sedimentological factors also influence sandstone compositions. Comparisons of sandstone compositions are aided by grouping diverse grain types into a few operational categories having broad genetic significance. Compositional fields associated with different provenances can then be displayed on standard triangular diagrams.

The major provenance types related to continental sources are stable cratons, basement uplifts, magmatic arcs, and recycled orogens. Each provenance type contributes distinctive detritus preferentially to associated sedimentary basins that occupy a limited number of characteristic tectonic settings in each case. Sands of composite provenance can be described as mixtures of quartzose sand from stable cratons, quartzofeldspathic sand from basement uplifts or arc plutons, feldspatholithic sand from arc volcanics, and quartzolithic sands of several types from different kinds of recycled orogens that yield varying proportions of quartzose and lithic grains. Proportions of contributions from different provenance types can be estimated from mean compositions for ideal derivative sands represented by points or restricted areas on triangular plots.

Evolutionary trends in sandstone composition within individual basins or sedimentary provinces commonly reflect changes in tectonic setting through time, or erosional modification of provenance terranes. Forearc sandstone suites typically evolve

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from feldspatholitic petrofacies of volcaniclastic nature, through lithofeldspathic petrofacies of volcanoplutonic origin, to quartzofeldspathic petrofacies of plutonic derivation. Foreland sandstone suites commonly evolve from rift-related quartzofeldspathic petrofacies, through quartzose petrofacies of passive continental margins, to quartzolithic petrofacies derived from recycled orogens.

INTRODUCTION

The use of quantitative detrital modes, calculated from point counts of thin sections, to infer sandstone provenance is well established (Dickinson and Suczek, 1979). The tectonic setting of the provenance apparently exerts primary control on sandstone compositions (Dickinson et al, 1983), although relief, climate, transport mechanism, depositional environment, and diagenetic change all can be important secondary factors. Studies of sand compositions on modern sea floors have yielded analogous results (Dickinson and Valloni, 1980; Valloni and Maynard, 1981). As might be expected, fields of compositional variation for oceanic sands in general reflect a greater degree of mingling of detritus from different types of provenance than is the case for continental sands.

The generation of reproducible detrital modes requires the establishment of clearcut operational definitions for different grain types (Dickinson, 1970). There is no limit to the number of categories of grains that can be counted, but effective regional or global comparisons of sandstone compositions are aided by grouping grain types into a few general categories. It is universal practice to describe monocrystalline particles as mineral grains, and polycrystalline particles as lithic or rock fragments. Mineral grains are subdivided according to mineral species, whereas lithic fragments are classified, as are rocks, on the joint criteria of overall chemical composition, the mineral facies of modal constituents, and their internal texture and fabric.

There are two methodological approaches to the treatment of rock fragments during point counting (Zuffa, 1980; Ingersoll et al, 1984). On the one hand, all parts of all polycrystalline particles can be counted as lithic fragments. This seemingly rational approach leads to severe dependence of calculated sandstone compositions on clastic grain size. Coarse-grained source rocks, composed of crystals larger than the matrix limit (0.0625 mm), can then occur partly as lithic fragments in coarse sandstones, but generally disintegrate to form only individual mineral grains in fine sandstones. The severity of this procedural problem can be gauged from the fact that the sand range spans between one and two orders of magnitude in grain size.

Dependence of calculated sandstone compositions on clastic grain size can be reduced markedly by adopting a different point counting procedure that restricts lithic fragments to microcrystalline aphanitic materials containing no crystals larger than the matrix limit (= sand framework limit). Single crystals larger than this size (0.0625 mm) are then counted as mineral grains, regardless of whether they actually occur as separate clastic particles or as constituent crystals within polycrystalline particles. For example, phenocrysts within volcanic rock fragments are counted as mineral grains if their mean visible diameters exceed 0.0625 mm. Only when the microscope crosshair centers above part of the groundmass of a volcanic rock fragment, or a smaller microphenocryst, is the point counted as a lithic fragment. Similarly, constituent crystals within granitic rock fragments and coarser grained quartzite fragments are commonly large enough to be tallied as mineral grains for calculation of detrital modes.

There are two key points to be made about this procedure. First, raw counts should be performed in a way that retains full information about the occurrence of specific types of mineral grains within different kinds of lithic fragments. The information obtained can thus be recast into any desired format. Second, the method is merely a means for normalization of data with respect to grain size, and cannot correct for inherent or genetic variations in grain proportions with changing grain size. For example, where the quartz/feldspar ratio is actually different in sands of different grain size, this strictly procedural method does not improve compositional comparisons between sandstones of contrasting mean grain size. For this reason, it is good practice where possible to restrict provenance studies to sandstones of comparable grain size. Favorable counting statistics and ease of identification are best achieved jointly in thin sections of medium-grained to coarse-grained sandstone (mean grain size near 0.5 mm).

GRAIN TYPES

Table 1 presents the classification of grain types used for discussions in this paper. Detrital modes are recalculated to 100 per cent as the sum of Qm, Qp, P, K, Lv, and Ls. Intrabasinal grains (Zuffa, 1980) are ignored. In this summary, the occurrence of heavy minerals is also ignored, not because they convey no information about provenance, but simply because their different response to hydrodynamic and geochemical influences makes their volumetric distribution so variable.

TABLE 1. CLASSIFICATION AND SYMBOLS OF GRAIN TYPES

A. Quartzose Grains (Qt = Qm + Qp)
- Qt = total quartzose grains
- Qm = monocrystalline quartz (>0.625 mm)
- Qp = polycrystalline quartz (or chalcedony)

B. Feldspar Grains (F = P + K)
- F = total feldspar grains
- P = plagioclase grains
- K = Kspar grains

C. Unstable Lithic Fragments (L = Lv + Ls)
- L = total unstable lithic fragments
- Lv = volcanic/metavolcanic lithic fragments
- Ls = sedimentary/metasedimentary lithic fragments

D. Total Lithic Fragments (Lt = L + Qp)
- Lc = extrabasinal detrital limeclasts (not included in L or Lt)

Extrabasinal carbonate grains or detrital limeclasts (Lc) are not recalculated with other lithic fragments because of their vastly different geochemical response during weathering and diagenesis, as well as the ease of confusion with intrabasinal carbonate grains (intraclasts, bioclasts, ooliths, peloids). Calclithite is thus regarded here as a variety of calcarenite, rather than litharenite. Where the proportion of detrital limeclasts is discussed, percentage of total framework is reported, as is the case for micas (M). This practice is adopted provisionally, with the knowledge that inclusion of Lc within the Ls population may help to clarify provenance relationships in some studies (Mack, 1984).

Distinctions between Qm and Qp vary depending upon the grain size conventions used by different operators during point counting. When lithic points are restricted to microcrystalline aggregates of aphanitic materials, most Qp grains are chert or metachert, although foliated or microgranular metaquartzite fragments are abundant in some rocks. On the other hand, if points for coarse crystals in rock fragments are not reapportioned as mineral grains, Qp as reported may also include composite quartz grains and orthoquartzite fragments. Severe compaction may develop polygonal textures within single quartz crystals, which then resemble composite or aggregate grains but are not lithic fragments.

Reliable identification of P and K, and their distinction from quartz, requires routine staining for both feldspars.

Perthite is counted as K, and albite as P, but diagenetic albite may replace either original feldspar in some cases. Albite takes neither feldspar stain. Systematic replacement of Kspar by diagenetic albite may frustrate attempts to recover the detrital ratio of Kspar to plagioclase in some instances (Dickinson et al, 1982; Walker, 1984). However, albitization of plagioclase is a much more common process at moderate stages of diagenesis (Boles, 1982).

Unstable lithic fragments are identified by joint observation of texture and mineralogy. Volcanogenic (Lv) types display microlitic (lathlike), microgranular-felsitic, or vitric textures, and feldspar-rich or mafic mineralogy. Metamorphic variants of Lv may be foliated, but otherwise it is difficult or impossible to distinguish between transported fragments of low-grade metavolcanic rock and volcanic rock fragments that have been diagenetically altered in place within a sandstone. Felsitic volcanic rock fragments can only be distinguished from chert with confidence if they take one or both of the feldspar stains, contain microphenocrysts, or have groundmasses coarse enough to show the contrast in refringence between tiny quartz and feldspar crystallites. In general, chalcedonic volcanic rock fragments that are thoroughly silicified cannot be distinguished with confidence from sedimentary varieties of chert grains (Qp).

Sedimentary and metasedimentary lithic fragments (Ls) include chiefly microclastic siltstone, massive cryptocrystalline argillaceous grains, phyllosilicate-rich shaly or slaty grains showing mass extinction effects, and foliated or microgranular aggregates of quartz and mica from phyllite and/or hornfels. Firm distinctions between these various subtypes are commonly complicated by the presence of texturally and compositionally transitional grains. Gradations from chert (Qp) to argillite (Ls) are also common, and are best resolved by relegating siliceous argillite to Ls. The various Ls subtypes are more quartz-rich and/or phyllosilicate-rich than the various Lv subtypes.

In some sandstones, the presence of shaly intraclasts derived from syndepositional erosion of interbedded fine-grained sediments presents a special problem of interpretation. Where the true nature of such argillaceous grains can be established, they should be excluded from the detrital framework for most types of provenance studies. Their inclusion as part of the Ls population introduces unwanted bias into results. In some instances, apparently detrital limeclasts (Lc) may be of similar intrabasinal origin.

Some workers systematically separate metamorphic rock fragments (Lm) from volcanic and sedimentary rock fragments for diagnostic purposes (Ingersoll and Suczek, 1979). Consistent values for Lm are difficult to achieve, especially in studies involving multiple operators, because criteria are subtle or ambiguous in many instances. No attempt is made to resolve Lm values in the compilations reported here. Where such attempts are made, it is important to report the criteria used to define the threshold of metamorphism for counting purposes.

In determining detrital modes, it is vital to assess the effects of diagenesis and outcrop weathering on the framework. Every effort should be made to obtain fresh, unweathered samples. Where secondary porosity of any origin has developed, allowances for its effect on framework composition must be made in all interpretations of point-count data. Intrastratal solution presents the most severe potential problems for interpretation in cases where recompaction of the framework has removed all direct evidence for dissolution of selected grains. The correct classification of altered grains also involves questions of widely varying difficulty. The parent grains from which many alterites were derived can be inferred without serious doubt, but the antecedents of some may be indeterminate.

PROVENANCE TYPES

Compositional fields characteristic of different provenances are well shown on one or more of four triangular diagrams (Dickinson and Suczek, 1979; Dickinson et al, 1979, 1983a): QtFL, with emphasis on maturity; QmFLt, with emphasis on source rock; QpLvLs, with emphasis on lithic fragments; and QmPK, with emphasis on mineral grains. Table 2 lists major provenance types in terms of overall tectonic setting within or adjacent to continental blocks, and gives key aspects of derivative sand compositions.

Figure 1 shows nominal fields proposed within QtFL/QmFLt diagrams for discrimination of sands derived from various types of provenances in continental blocks, magmatic arcs, and recycled orogens. In this context, continental blocks are tectonically consolidated regions composed essentially of amalgamations of ancient orogenic belts that have been eroded to their deep-seated roots and lack any relict genetic relief. Magmatic arcs are belts of positive relief composed dominantly of penecontemporaneous associations of cogenetic volcanic and plutonic igneous rocks, together with associated metamorphic wallrocks, produced by continuing subduction along arc-trench systems. Recycled orogens include the deformed and uplifted supracrustal strata, dominantly sedimentary but also volcanic in part, exposed in varied fold-thrust belts of orogenic regions. Figure 2 shows the reported distribution of mean detrital modes for sand-

TABLE 2. MAJOR PROVENANCE TYPES AND KEY COMPOSITIONAL ASPECTS OF DERIVATIVE SANDS

Provenance Type	Tectonic Setting	Derivative Sand Composition
stable craton	continental interior or passive platform	quartzose sands (Qt-rich) with high Qm/Qp and K/P ratios
basement uplift	rift shoulder or transform rupture	quartzofeldspathic (Qm-F) sands low in Lt with Qm/F and K/P ratios similar to bedrock
magmatic arc	island arc or continental arc	feldspatholithic (F-L) volcaniclastic sands with high P/K and Lv/Ls ratios grading to quartzofeldspathic (Qm-F) batholith-derived sands
recycled orogen	subduction complex or fold-thrust belt	quartzolithic (Qt-Lt) sands low in F and Lv with variable Qm/Qp and Qp/Ls ratios

stone suites actually derived from the various types of provenance terranes.

Stable Cratons

The main sources for craton-derived quartzose sands are low-lying granitic and gneissic exposures, supplemented by recycling of associated flat-lying platform sediments. The sands either accumulate as platformal successions deposited within continental interiors, or are transported chiefly to passive continental margins and the cratonal flanks of foreland basins.

Ultimate sources for quartz grain populations can be inferred to some degree from the frequency and nature of undulose extinction and polycrystallinity (Basu et al, 1975). However, both properties can be affected markedly by grain deformation during diagenesis (Graham et al, 1976). Textural details of polycrystalline quartzose grains offer more reliable guides to specific source rock types in favorable instances (Young, 1976). High Qm/Qp ratios in the most mature quartzose sands indicate that monocrystalline quartz has greater potential for survival in the sedimentary cycle than polycrystalline lithic fragments. Experimental evidence that microcrystalline chert is more resistant to abrasion that monocrystalline quartz indicates

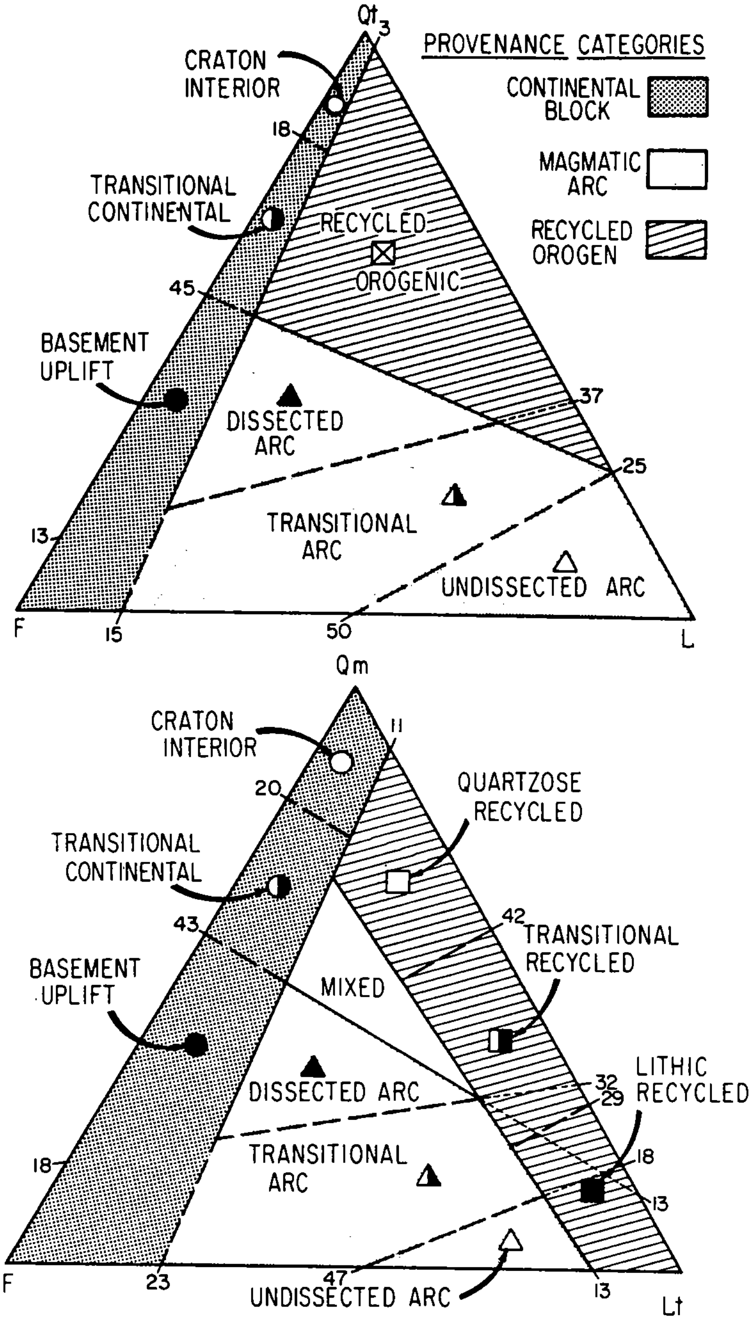

Figure 1. Provisional compositional fields indicative of sand derivation from different types of provenances (from Dickinson et al, 1983a).

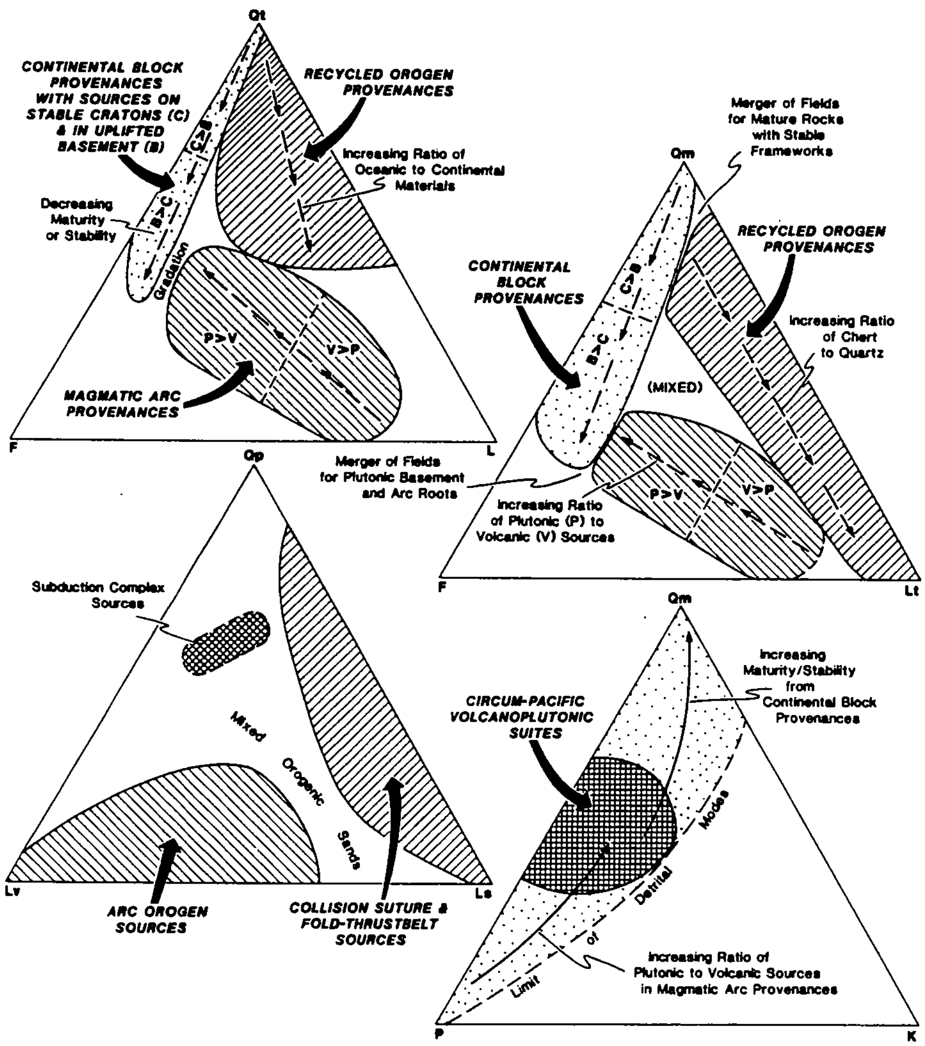

Figure 2. Actual reported distribution of mean detrital modes for sandstone suites derived from different types of provenances plotted on standard triangular diagrams; after Dickinson and Suczek (1979) as modified by Dickinson (1982; et al, 1982; and unpublished compilations).

that this capacity for survival stems fundamentally from greater chemical stability, rather than from greater mechanical durability (Harrell and Blatt, 1978).

Many have speculated that multicyclic reworking on cratons might be required to develop mature quartzose sands. However, recent work has shown conclusively that quartzose sand is being produced as first-cycle sediment from deeply weathered granitic and gneissic bedrock exposed in tropical lowlands of the modern Amazon basin (Franzinelli and Potter, 1983). Tributaries draining Precambrian basement (n=21), as well as Precambrian basement plus Paleozoic platform cover (n=13), carry sand containing 90-95% quartz, much more Kspar (1-5%) than plagioclase (which occurs in trace amounts only), and less than 5% lithic fragments on average.

The importance of intense weathering for concentrating quartz in relation to feldspar and/or lithic fragments deserves special emphasis. In most cases, fluvial transport alone is apparently ineffective as an influence on the proportion of quartz in sand. More than 600 km of transport on the Platte River in the Great Plains proves insufficient to change either the Q/F or K/P ratio of the stream sands to any significant degree (Breyer and Bart, 1978). On the Amazon, the Q/Lt ratio does not change appreciably for 2500 km from the rugged headwaters to the junction with the first major tributary whose drainage basin lies wholly within the deeply weathered Amazon lowlands (Franzinelli and Potter, 1983). For 1500 km below that point to the mouth, however, the quartz content rises markedly, presumably from steady dilution with quartzose tributary sands.

The necessity of low relief to allow prolonged weathering also deserves emphasis as a requirement for the development of first-cycle quartzose sand. Even where the climatic potential for intense equatorial weathering exists, tropical highlands develop quartz-rich regoliths only on restricted interfluves with gentle local relief; both fluvial and littoral Holocene sands derived from drainage basins in tropical highlands with high relief are quartz-poor (Ruxton, 1970). In evaluating the combined effects of climate and relief on the production of quartzose sands, however, it is important to include an evaluation of the possibility of appreciable weathering during temporary storage on low-lying floodplains along the continental dispersal path.

Basement Uplifts

Fault-bounded basement uplifts along incipient rift belts and transform ruptures within continental blocks shed arkosic sands mainly into adjacent linear troughs or local pull-apart

TABLE 3. AVERAGE Qm/(Qm+F) AND K/(K+P) RATIOS FOR SELECTED FIRST-CYCLE ARKOSIC SAND AND SANDSTONE SUITES IN SOUTHERN CALIFORNIA
See Table 1 for symblols of grain types.

Description	N	Qm/(Qm+F)*	K/(K+P)*	Reference
Eocene, Santa Ynez Mountains	25	0.39	0.35	Helmold, 1980
Upper Cretaceous, Simi Hills	20	0.39	0.38	Carey, 1981
Pliocene, Ridge Basin	60	0.43	0.41	Link, 1982
Holocene, Salton Basin	9	0.45	0.40	Van de Kamp, 1973
Cretaceous, Santa Monica Mountains	11	0.48	0.40	Carey, 1981

*Mean values within 0.40-0.45 for Qm/(Qm+F) and 0.35-0.40 for K/(K+P).

basins. Similar detritus can be derived from basement uplifts within broken foreland provinces, and from eroded plutons in deeply dissected magmatic arcs (see discussions below). A spectrum of lithic-poor quartzofeldspathic sands forms a roughly linear array on QtFL and QmFLT diagrams (Figs. 1,2) linking these arkosic sands with the craton-derived quartzose sands that plot near the Qt and Qm poles. This spectrum of sands reflects derivation from varius tectonic elements of continental blocks where basement rocks are exposed. Where erosion has been insufficient to remove cover rocks from basement, uplifts may shed sands having affinity with detritus derived from magmatic arcs or recycled orogens (Mack, 1984).

The composition of the arkosic end member of this spectrum of sand types is approximated well by the mean of first-cycle arkose in southern California (Table 3). Although granitic rock fragments may be abundant in coarser size grades, the proportion of true lithic fragments (see discussion above) is generally less than 10% and averages about 5%. Quartz forms about 40-45% of the quartzofeldspathic grain population, and Kspar averages 35-40% of the total feldspar present. These are values appropriate to areas of rugged relief in arid or semiarid climatic zones. The spectrum of sands derived from continental blocks can be viewed as forming a mixing array or evolutionary trend connecting this ideal arkosic composition to the cratonal quartzose sand composition (Fig. 3).

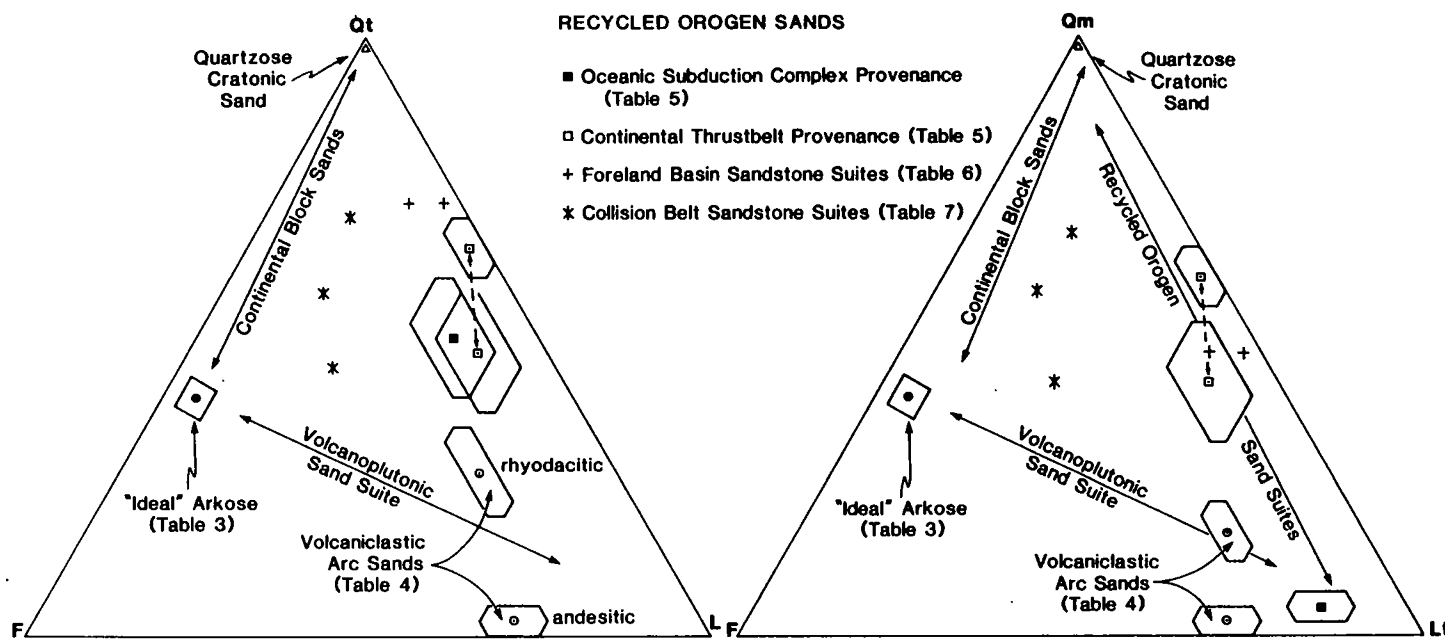

Figure 3. Compositional plots of key sandstone suites (see Tables 3-7); fields surrounding some points depict calculated standard deviations (see Tables 3-7); trend line for volcano-plutonic sand suites from Dickinson, 1982; see text for discussion.

Humid weathering raises the proportion of quartz relative to feldspar. In the southern Appalachians, first-cycle arkosic sands may have quartz:feldspar ratios as high as 2:1 (Basu, 1976). Plagioclase is less stable than Kspar in all climatic regimes, but the disparity is much more marked for humid areas. In stream sands from semiarid regions, the fraction of total feldspar that is plagioclase may be nearly as high as in the parent granitic rock; however, in stream sands from humid regions, the fractional value may fall to only a third of that for the parent rock (James et al, 1981). Consequently, Kspar:plagioclase ratios as high as 3:1 have been reported for some arkosic sands (Basu, 1976). The tendency for the Kspar:plagioclase ratio to rise as the quartz content of typical sands increases is shown by the QmPK diagram of Figure 2.

Magmatic Arcs

The most characteristic sands derived from active magmatic arcs constructed parallel to subduction zones are volcaniclastic materials erupted and eroded from stratovolcano chains and associated ignimbrite plateaus. Deep dissection of arc assemblages can expose their batholithic roots, and may give rise to quartzofeldspathic sands indistinguishable from the arkosic debris produced by other basement uplifts. Mixing of volcanic and plutonic contributions results in a spectrum of volcanoplutonic sands (Dickinson, 1982), which range from feldspatholithic to lithofeldspathic in composition, but display consistently high Lv/Lt ratios coupled with low to moderate quartz contents (Figs. 1,2). Arc-derived debris is typically deposited in forearc or interarc basins, but may also reach foreland basins locally. Sandstones incorporated into subduction complexes are commonly arc-derived variants of the volcanoplutonic suite deposited in trenches or on trench slopes (Dickinson, 1982). However, subduction complexes may also include quartzose turbidites derived from distant continental blocks, and rafted into subduction zones as sediment cover on an oceanic plate (Velbel, 1980).

The mean composition of the volcaniclastic end member of the array of volcanoplutonic sand types can be estimated from data for appropriate first-cycle sand suites from the circum-Pacific region (Table 4). Generally andesitic sands (columns A-D) are most abundant, and are used here to calculate an average modal composition. More silicic sands (columns E-F) include both rhyolitic and dacitic varieties. Volcanic rock fragments in the more common andesitic (to basaltic and/or dacitic) sands are dominantly microlitic varieties, whereas those in the rhyodacitic sands have felsitic or pyroclastic textures.

TABLE 4. AVERAGE MODAL COMPOSITIONS OF SELECTED VOLCANICLASTIC SAND AND SANDSTONE SUITES DERIVED FROM MAGMATIC ARC

A-D, normal mixed andesitic stratovolcano sources
E-F, special silicic ignimbrite sources
Frameworks also include 1-5% heavy minerals (mainly pyriboles) and traces of mica.
Ranges (±) are standard deviations for reported data.
Table 1 gives definitions of symbols for grain types.

	A	B	C	D	Ave	E	F
	Aleutians	SA	Oregon	New Zeal		Mex	[illegible]
N	27	55	6	11	(A-D)	7	19
Qm	2	3	tr	3	2	19±5	18±3
Qp	4	1	tr	?	1	1	18±3
P	32±8	24±5	30±2	25±5	28	8±2	19±5
K	1	tr	tr	tr	tr	11±3	2
Lv	60±8	71±6	67±4	69±5	67	59±8	42±7
Ls	1	1	2	3	2	2	1

A - Neogene marine sands, Atka Basin, Aleutian Ridge (Stewart, 1978)
B - Jurassic-Cretaceous Yahgan Formation, Tierra del Fuego (Winn, 1978)
C - Lower Jurassic Mowich Group and Middle Jurassic Snowshoe Formation, central Oregon (Dickinson et al, 1979)
D - Lower Triassic North Range Group, Hokonui Hills, Southland, New Zealand (Boles, 1974)
E - Holocene fluvial sands derived from Tertiary ignimbrite field in Sierra Madre Occidental of northwest Mexico (Webb and Potter, 1971)
F - Cretaceous Sandebugten sandstones of South Georgia Island derived from Jurassic Tobifera Volcanics of Patagonia (Winn, 1978)

As expected, the rhyodacitic volcaniclastic sands are more quartzose than the andesitic sands; the rhyodacitic field plots near a mixing line between the andesitic composition and the quartz pole (Fig. 3). The array of circum-Pacific volcanoplutonic sands lies along a mixing path between the volcaniclastic sands and the ideal arkosic composition (Fig. 2). Surprisingly, the position of the dominant volcanoplutonic compositional trend (Fig. 3) seemingly suggests mixture of arkosic materials mainly with silicic rather than andesitic volcaniclastic debris. This inference is probably spurious, for it fails to take into account the likelihood of minor admixtures of recycled quartzose contributions from metamorphic wallrocks of the magmatic arcs.

Recycled Orogens

Orogenic recycling occurs in several tectonic settings where stratified rocks are deformed, uplifted, and eroded: (a) subduction complexes, where oceanic and trench slope deposits are exposed as thrust panels, recumbent isoclines, and melange belts along tectonic ridges between trenches and forearc basins; (b) backarc thrustbelts, where folded sedimentary and metasedimentary strata of continental derivation override the flanks of retroarc foreland basins; and (c) suture belts, where structurally juxtaposed sequences of both oceanic and continental types can provide sources of sediment for transverse dispersal systems that feed adjacent peripheral foreland basins, and for longitudinal dispersal systems that feed nearby remnant ocean basins. Orogenic highlands also give birth to major river systems that can transport recycled orogenic sediment across the surfaces of adjacent continental blocks and into distant basins having a variety of tectonic settings (Potter, 1978).

By its nature, sediment from recycled orogens includes various proportions of materials whose compositions reflect ultimate derivation from cratonic, arkosic, or volcaniclastic sources, modified in part by metamorphic processes. In addition are materials generated by sedimentary processes, acting alone or in combination with diagenesis and metamorphism. These latter are lithic fragments of chert and metachert, or pelitic debris such as shale, argillite, slate, and phyllite. Given the potential diversity of recycled orogenic sediment, it is a severe challenge to devise a scheme for its identification and classification that has empirical validity for interpretation of the sedimentary record. As yet (see above), there is also no consensus on the way in which detrital limeclasts (Lc) should be treated during recalculation of detrital modes (Mack, 1984).

Sands derived from fold-thrust systems of indurated sedimentary and low-grade metamorphic rocks have consistently low contents of feldspar and volcanic rock fragments (Dickinson and Suczek, 1979). Consequently, they form a quartzolithic array of compositions that plot near the Qt-L, Qm-Lt, and Qp-Ls legs of standard triangular diagrams (Figs. 1,2). Van Andel (1958) early called attention to the abundance of this type of sand in the orogenic region of western Venezuela. In the modern Andean foreland (Franzinelli and Potter, 1983), the least mature sands derived directly from the adjacent highlands contain roughly equal amounts of quartz grains and rock fragments (with only 5-10% feldspar grains).

TABLE 5. AVERAGE MODAL COMPOSITIONS OF SELECTED SANDSTONE SUITES DERIVED FROM DEFORMED AND UPLIFTED SUPRACRUSTAL SOURCES

A, Upper Triassic Vester Formation in central Oregon derived from sand-poor subduction complex of chert-argillite-greenstone oceanic facies (Dickinson et al, 1979)
B and C, middle (B) and lower (C) Siwalik Group (Mio-Pliocene) in peninsular India derived from Himalayan fold-thrust system of sedimentary and metasedimentary strata (Parkash et al, 1980)
Ranges (±) are standard deviations for reported data

	N	Qm	Qp	Qt	F*	Lv	Ls	Lt
A	11	5	45±10	50±11	13±6	27±7	10±2	82±7
B	15	43±11	5	48±9	10±5	tr	42±7	47±8
C	14	59±7	7	66±5	3	tr	31±6	38±9

*Plagioclase (P) in A is 12±6; P and K not reported separately for B and C.

Relative proportions of resistant quartzose grains and unstable lithic grains are highly variable in recycled orogenic sands. Modern sands derived from such sources have Qt/L ratios that range from about 3:1 in humid regions to about 1:3 in semi-arid regions (Suttner et al, 1981a; Mack, 1981); polycrystalline Qp and Ls in the same sands tend to be subequal in abundance. Within the Amazon drainage, where both rugged highlands and tropical lowlands are present, the full range of Qm/Lt ratios in fluvial sands is virtually from zero to 100 (Franzinelli and Potter, 1981). In all these Holocene assemblages, the content of total feldspar averages about 5% or less.

Clastic sequences in foreland basins commonly display interstratified or intertonguing petrofacies with contrasting Qt/L and/or Qm/Lt ratios (e.g., Putnam, 1982). In some cases, the salient differences can be attributed to the mingling of contributions from disparate sources. For example, Carboniferous foreland clastics of the Trenchard Group in England are composed of a northern quartzarenite facies (Qt87, F8, L5), derived from the gentle cratonal flank of the basin, and a southern litharenite facies (Qt46, F5, L49) derived from the orogenic flank (Jones, 1972). In the Carboniferous Pottsville Group of West Virginia, however, an upward stratigraphic transition from litharenite (Qt73, F2, L25) to quartzarenite (Qt95, F0, L5) apparently was produced by weathering and recycling of detritus from the same source on a broad coastal plain at the

TABLE 6. AVERAGE MODAL COMPOSITIONS OF SANDSTONE SUITES FROM SELECTED FORELAND BASINS

A - Mississippian Antler deltaic (and turbidite) clastics (Chainman Shale and Diamond Peak Formation) derived from sand-rich chert-argillite subduction complex in peripheral foreland basin of central Nevada (Dickinson et al, 1983b).
B - Upper Cretaceous deltaic (and contourite) clastics (Cody Shale and Parkman Sandstone) derived from sedimentary-metasedimetnary thrustbelt in retroarc foreland basin of central Wyoming (Hubert et al, 1972).
C - Cretaceous-Paleocene deltaic (and associated) clastics (Difunta Group) derived mainly from arc volcanics in retroarc foreland basins of northeast Mexico (McBride et al, 1975).

	N	Qm	Qp	Qt	F	Lv	Ls	Lt
A	18	47	26	73	2	tr	25	51
B	35	48	24	72	7	tr	21	45
C	81	32	4	36	28	32	4	40

margin of the foreland basin (Houseknecht, 1980). In some sequences, recycled sands derived from uplifted quartzose strata cannot be distinguished compositionally from craton-derived sands, especially where humid weathering and intense reworking enhance the quartz content of the sands (Mack et al, 1981; Mack, 1984).

Chert-rich sand frameworks are characteristic in some recycled orogenic suites (Dickinson and Suczek, 1979). The supracrustal chert sources are typically either radiolarites within deformed oceanic assemblages, or replacement nodules in platform carbonate successions. The Qm/Qp ratios in derivative sands are largely a function of the extent to which turbidite or platform sandstones are intercalated within the chert-bearing sections. Table 5 shows the extremes to which the Qm/Qp ratio may vary (Fig. 3) by comparing (A) one sandstone suite derived from a chert-rich subduction complex composed of deep marine facies, deposited on an oceanic substratum and lacking any intercalated sandstones, with (B,C) two horizons within a sandstone suite derived from uplifted sandy clastics and metaclastics detached structurally from the edge of a continental block. By contrast, Table 6 shows the compositional similarity (Fig. 3) of two otherwise dissimilar foreland sandstone suites derived from (A) an allochthon of overthrust oceanic facies in a subduction complex emplaced adjacent to a peripheral foreland basin that developed during arc-continent collision, and (B)

TABLE 7. AVERAGE MODAL COMPOSITIONS OF SELECTED SAND AND SANDSTONE SUITES DERIVED FROM COLLISON OROGENS

A - Cenozoic sand, Indus Cone, Arabian Sea (Suczek and Ingersoll, 1984)
B - Neogene sand, Bengal-Nicobar Fan, Indian Ocean (Ingersoll and Suczek, 1979)
C - Pennsylvanian Haymond Formation, Marathon Basin, Texas (McBride, 1966)
A-B derived from Himalayan-Tibetan orogen, and C derived from Ouachita system
Ranges (±) are standard deviations for reported data

	N	Qm	Qp	Qt	P	K	F	Lv	Ls	Lt
A	15	44±6	1	45	21±3	11±3	32	2	21±6	24
B	22	56±6	1	57	19±4	9±3	28	1	13±5	15
C	33	68±7	3	71	14±6	3	17	tr	12±5	15

thrust sheets of miogeoclinal strata including carbonates within an intracontinental foldbelt that formed adjacent to a retroarc foreland basin. The chert is presumably of different origins in the two cases, but both source sequences contain a sufficient proportion of interbedded quartzose sandstone to impart essentially the same Qm/Qp ratio to derivative recycled sands.

Table 6 also gives the mode of an arc-derived sandstone suite (C), rich in feldspars and volcanic rock fragments, deposited within a retroarc foreland basin. Although generally not abundant within foreland regions, volcaniclastic detritus can be important in the evolution of retroarc foreland basins located close to arcs where backarc deformation is either minor or fails to create a drainage divide between eruptive centers and the foreland basin (Misko and Hendry, 1979). Basement uplifts in broken foreland provinces may also contribute arkosic debris locally to foreland basins. Both influences are present jointly in some foreland regions (Suttner et al, 1981b; Schwartz, 1982).

Table 7 indicates the nature of representative sands and sandstones derived from intercontinental collision orogens; similar sandstones may be derived from arc collision belts (Hiscott, 1978). Their recycled affinity is indicated by the consistently high Ls/Lv ratios. However, their coordinate feldspar content indicates that uplifted basement rocks or arc batholiths are exposed within the orogenic highlands in addition to deformed supracrustal strata. Longitudinal dispersal of collision-belt sands into remnant ocean basins is characteristic of many orogenic systems (Graham et al, 1975), but transverse dispersal into foreland basins also occurs.

Composite Provenances

Triangular compositional diagrams provide a convenient means to plot graphically in a quantitative format. Any point within the plot can obviously be interpreted as a certain mixture of the three entities represented by the poles of the diagram. In principle, any such point can also be interpreted as a particular mixture of various other arbitarily chosen entities whose compositions can be represented by other points within the diagram.

As noted previously, the array of quartzose and arkosic sands derived from various parts of continental blocks can be regarded as various mixtures or evolutionary stages along a linear trend connecting the ideal arkose composition to the quartz pole (Fig. 3). Similarly, the array of volcanoplutonic sands derived from magmatic arcs can be viewed as mixtures of ideal volcaniclastic debris and the ideal arkose composition. The exact proportions required for the appropriate mixtures can be scaled from the triangular plot as an inverse function of relative distances between the relevant points. More generally, any point within the interior of the diagram can be interpreted in terms of mixing any three compositional end members distributed near the perimeter of the diagram. Of course, any one of such controlling end members may itself be a mixture of two or three other compositions.

If the compositions of end members that are truly diagnostic of provenance type can be accurately defined, the actual parentage of specific sandstone suites can thus be inferred. For example, the three sandstone suites derived from collision orogens (Table 7, Fig. 3) can be described alternately as mixtures of (1) various pairs of sands derived from recycled orogens and continental blocks, or (2) three end members representing (a) quartzose cratonic sand (at or near the quartz pole), (b) ideal arkose from uplifted plutonic basement, and (c) some ideal recycled sand of quartzolithic composition. The particular degree of "mixing" defined compositionally by the graphical display of the plot need not in all cases be attributed to actual mechanical mixing. In the case of the sands derived from collision belts, for example, the variation in quartz content may be attributed either to different proportions of recycled quartzose sand derived from the orogenic belts in question, or to contrasting climatic influences within those same orogenic belts, rather than literally to an admixture of first-cycle cratonic detritus.

A significant task for the future is the use of sandstone detrital modes to help establish the nature of composite orogenic provenances composed of various genetic associations of source rock types. For example, a recent study of Paleogene fluvial sandstones within the complex Cascades arc orogen of the Pacific Northwest indicates that various parts of the sequence were derived from recycled orogenic sources, an eroded magmatic arc, and uplifted continental basement (Johnson, 1984). Sedimentary mixing of such detritus, followed by wider dispersal, would give rise to sands of composite provenance. In the Apennines, synorogenic turbidite sandstones derived mainly from the complex Alpine collision orogen have compositions indicative of derivation from similarly compound sources within a composite provenance (Valloni and Zuffa, 1984).

PETROFACIES EVOLUTION

Spatial patterns of correlative petrofacies within a sedimentary basin reflect simultaneous contributions of detritus from different sources. Successive time-dependent petrofacies reflect either the evolution of individual provenance terranes or changes in disperal patterns through time. Significant contrasts in petrofacies imply major differences in diagenetic processes within basin fill. For example, porosity-depth relationships are strikingly different for typical quartzose, feldspathic (arkosic), and lithic sandstones (Fig. 4). Stratigraphic variations in petrofacies within forearc and foreland regions suggest that an integrated view of basin evolution requires attention to petrofacies evolution, both as a record of tectonic events and as a means of understanding diagenetic conditions.

The main provenance for typical forearc basins is the adjacent magmatic arc. Consequently, forearc petrofacies generally reflect the igneous and morphologic evolution of the arc. Where eruptive rejuvenation of the surficial volcanic edifice counteracts uplift and erosion, volcaniclastic sandstones may be deposited across the forearc over long periods of time (Cawood, 1983). Volcaniclastic sandstone suites commonly become more quartzose upsection, because the normal evolution of many magmatic arcs leads to the eruption of more felsic materials as time passes (Korsch, 1984). Moreover, there is commonly a tendency for uplift and erosion to expose more and more of the plutonic roots of an arc as time passes. Consequently, forearc sandstones of the volcanoplutonic suite (Figs. 1-3) generally become more arkosic and less lithic with time (Dickinson and Rich, 1972). Recycled orogenic sources in exposed subduction complexes may influence petrofacies locally (Tennyson and Cole, 1978), and major changes in drainage patterns within arcs may cause abrupt shifts in petrofacies within adjacent forearc

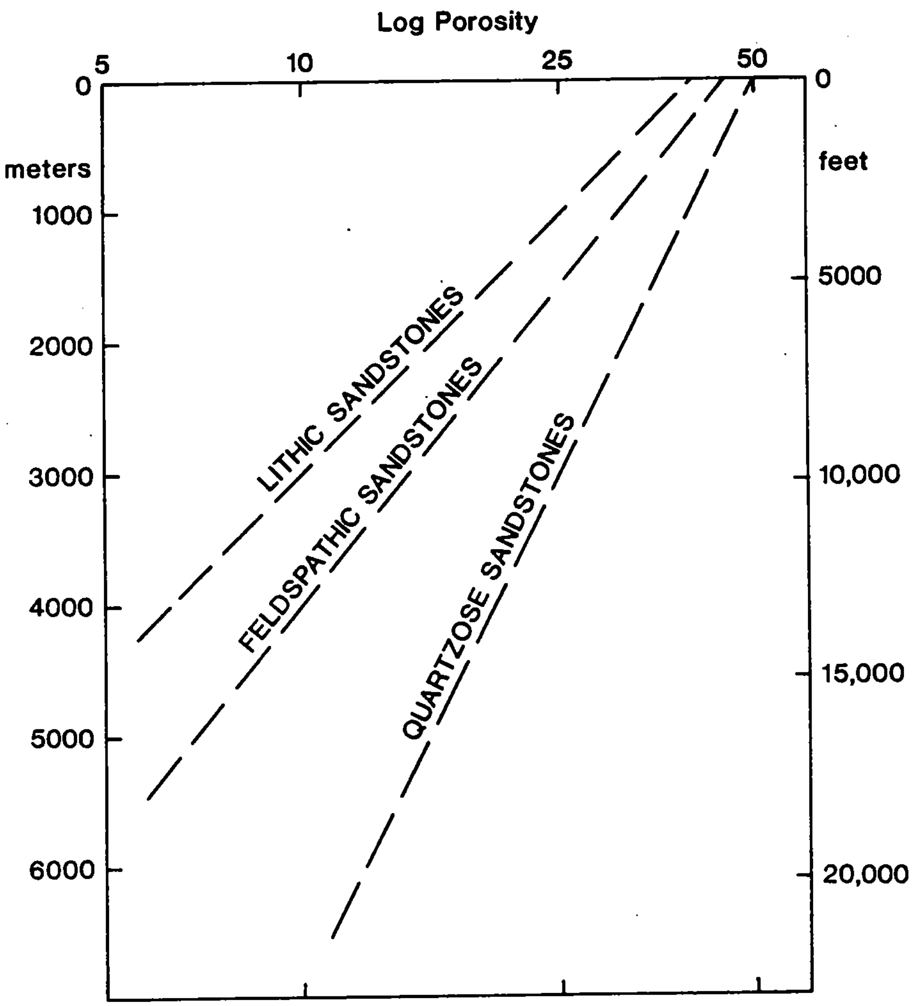

Figure 4. Graph showing typical relations of porosity to depth of burial for sandstone suites of varying composition; data from Galloway (1974), Zieglar and Spotts (1978), and Sclater and Christie (1980).

basins (Heller and Ryberg, 1983). Transform tectonics during oblique subduction may lead to especially complex patterns of forearc petrofacies in both time and space (Pacht, 1984).

Ingersoll (1983) has recently presented a thorough analysis of the evolution of petrofacies within the large and complex

Great Valley (California) forearc basin over a period of nearly 100 ma. Petrofacies become on average more quartzofeldspathic and less lithic upward, although some feldspatholithic sandstones occur throughout the section. In many parts of the sequence, lithofeldspathic and feldspatholithic petrofacies variants are intercalated within the same general horizons. The Kspar:plagioclase ratio increases systematically upward, as does mica content somewhat more irregularly. Both trends probably reflect increasing contributions from plutonic source rocks. The Lv/Ls ratio varies geographically as well as stratigraphically, and appears to reflect variations in the nature and amount of wallrocks exposed adjacent to batholithic sources as well as the extent of local volcanic cover in the arc.

Foreland basins adjacent to collision orogens experience drastic changes in provenance during their sedimentary history. Prior to collisional tectonics, sediment sources are dominantly within the adjacent continental block. Commonly, arkosic petrofacies of a rift phase lie at the base of the foreland succession, and are overlain by quartzose petrofacies of platform successions or passive margin sequences. These preorogenic strata are then succeeded by quartzolithic petrofacies derived from recycled orogenic sources developed during collision orogenesis. Arc-derived petrofacies may form a part of the orogenic succession. Schwab (1981) has described this general pattern of successive petrofacies for the western Alps. Perhaps the best region to study the evolution of foreland petrofacies is the Apennines, where multiple sources of detritus are inferred for both pre-orogenic and synorogenic phases (i.e., Zuffa et al, 1980; Gandolfi et al, 1983).

An important characteristic of many foreland sandstone suites, including those of the Apennines, is the comparative abundance of detrital limeclasts (Lc) of extrabasinal origin. In the synorogenic flysch of the Alps, for example, individual sandstone units vary widely in petrofacies, but essentially all contain some proportion of limeclasts reworked from deformed and uplifted sedimentary strata exposed as a recycled orogenic provenance within the developing collision orogen (Hubert, 1967). Limeclasts are also common in the Mesozoic retroarc foreland of the Rocky Mountains (work in progress).

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