Provenance of North American Phanerozoic sandstones in relation to tectonic setting

WILLIAM R. DICKINSON
L. SUE BEARD
G. ROBERT BRAKENRIDGE
JAMES L. ERJAVEC
ROBERT C. FERGUSON
KERRY F. INMAN
REX A. KNEPP
F. ALAN LINDBERG
PAUL T. RYBERG

Laboratory of Geotectonics, Department of Geosciences, University of Arizona, Tucson, Arizona 85721

ABSTRACT

Framework modes of terrigenous sandstones reflect derivation from various types of provenance terranes that depend upon plate-tectonic setting. Triangular QFL and QmFLt compositional diagrams for plotting point counts of sandstones can be subdivided into fields that are characteristic of sandstone suites derived from the different kinds of provenance terranes controlled by plate tectonics. Three main classes of provenance are termed "continental blocks," "magmatic arcs," and "recycled orogens." Sandstone suites from each include three variants, of which the subfields lie within the larger subdivisions. Average modes for sandstone suites can be classified provisionally according to tectonic setting using the subdivided QFL and QmFLt plots.

To test the validity of the classification, average modes for 233 Phanerozoic sandstone suites from North America were plotted on the triangular compositional diagrams and accompanying paleotectonic maps. Paired maps and ternary diagrams were prepared for eight different time slices, for each of which the tectonic setting of each major region within the continent remained relatively unchanged. Time slices are unequal in length but are controlled by the timing of major orogenic and rifting events that affected North America during the Phanerozoic. Comparison of the sandstone compositions with inferred tectonic setting through the Phanerozoic indicates that the proposed classification scheme is generally valid and yields satisfactory results when applied on a broad scale. Its application, together with other approaches, in regions of the world where over-all trends of geologic history are less well known could lead to important conclusions about the timing and nature of major tectonic events.

INTRODUCTION

Relative proportions of different types of terrigenous sand grains are guides to the nature of the source rocks in the provenance terrane from which sandy detritus was derived. Provenance terranes and related basins of deposition can be classified according to their plate-tectonic settings. Consequently, detrital framework modes of sandstone suites provide information about the tectonic setting of basins of deposition and associated provenances.

This paper evaluates the diverse compositions of Phanerozoic sandstone suites from North America as a function of changing tectonic setting. Our compilations generally support previous inferences about the regional relations between sandstone compositions and plate settings (Dickinson and Suczek, 1979; Dickinson and Valloni, 1980). The over-all framework that our general analysis provides can serve as a basis for further specific investigations.

In this study, we used published and unpublished data on detrital modes determined by point counts of sandstone suites from the United States, southern Canada, and northern Mexico. Our treatment here is confined accordingly to North America exclusive of Alaska, the Arctic, and Mesoamerica. Abundant data from coastal Alaska are discussed elsewhere (Dickinson, 1982).

FRAMEWORK MODES

The most significant compositional variations among terrigenous sandstones can be displayed as ternary plots on triangular diagrams. The three apices, or poles, represent recalculated proportions of key categories of grain types determined by modal point counts. Two alternate sets of poles (QFL and QmFLt) are useful (Graham and others, 1976):

A. For QFL diagrams, the poles are (1) total quartzose grains (Q), including polycrystalline lithic fragments such as chert and quartzite; (2) monocrystalline feldspar grains (F); and (3) unstable polycrystalline lithic fragments (L) of either igneous or sedimentary parentage, including metamorphic varieties.

B. For QmFLt diagrams, the poles are (1) quartz grains (Qm) that are exclusively monocrystalline; (2) feldspar grains (F), as before; and (3) total polycrystalline lithic fragments (Lt), including quartzose varieties.

Such ternary diagrams do not adequately display the composi-

Compilations of and references for data used to construct the figures in this article are available as an appendix in tabular form by requesting supplementary material 83-2 from Documents Secretary, Geological Society of America, P.O. Box 9140, Boulder, Colorado 80301. There are 233 data lines and 145 references included in the data summary.

Geological Society of America Bulletin, v. 94, p. 222–235, 10 figs., February 1983.

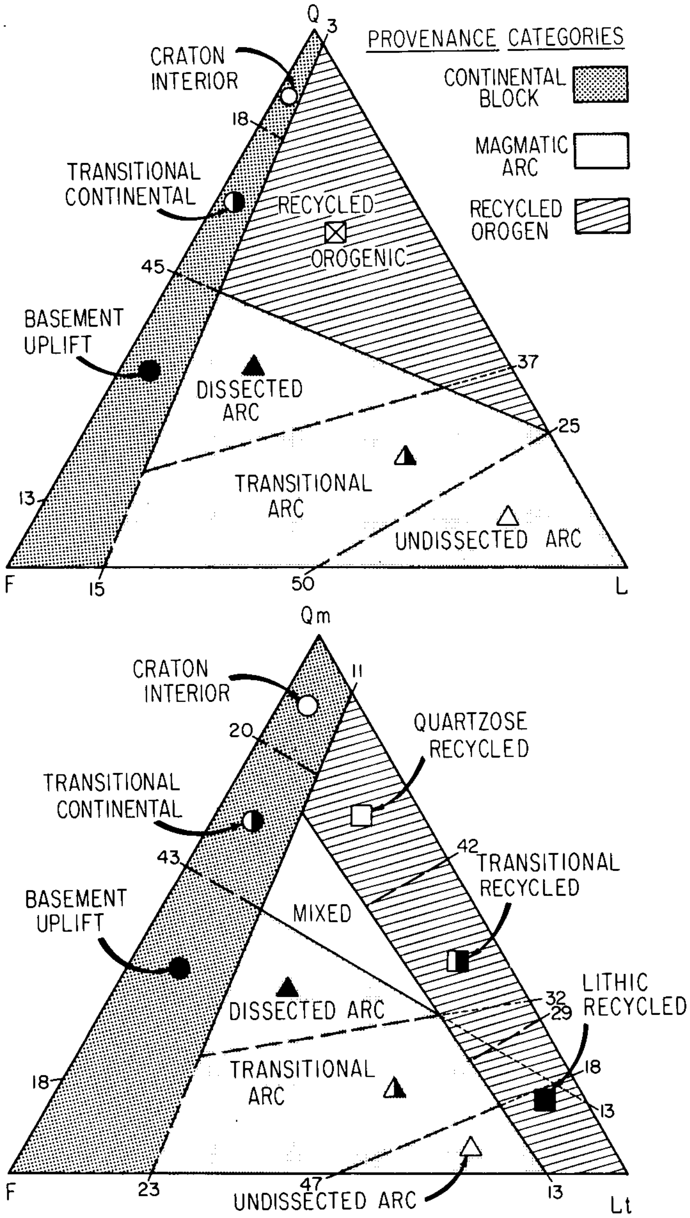

Figure 1. QFL (upper) and QmFLt (lower) plots for framework modes of terrigenous sandstones showing provisional subdivisions according to inferred provenance type, modified after Dickinson and Suczek (1979). Geometric symbols (filled, open, and half-filled triangles, circles, and squares) in various compositional fields indicate inferred provenance type on QFL/QmFLt plots and on paleotectonic maps (Figs. 3–10). Numbered ticks on legs of triangle denote positions of empirical provenance division lines in percentage units measured from nearest apical pole.

tions of sandstones in which special kinds of grains are important framework constituents. For example, only the terrigenous fraction of hybrid sandstones containing both carbonate and silicate grains can be shown properly by the QFL and QmFLt diagrams (Zuffa, 1980). In our study, we have thus ignored sandstones rich in limeclasts or other unusual grain types (for example, glauconite).

PROVENANCE TYPES

Dickinson and Suczek (1979) showed that mean compositions of sandstone suites derived from different kinds of provenance terranes controlled by plate tectonics tend to lie within discrete and separate fields on QFL and QmFLt diagrams. The three main categories of provenance terranes thus distinguished were those within continental blocks, magmatic arcs, and recycled orogens. Variants of each can be related to specific plate settings.

Figure 1 is a modification of this provenance classification. Both QFL and QmFLt diagrams are subdivided into compositional fields characteristic of sandstones derived from different types of provenances. The positions of the boundary lines of subdivision are empirical. They were determined initially by inspection of the diagrams in Dickinson and Suczek (1979, Figs. 1 and 2) and were then adjusted slightly, so as best to accommodate the additional data reported here without altering the assignment of any suites treated originally by Dickinson and Suczek (1979). Figure 1 thus represents a working diagram by means of which the approximate type of provenance can be inferred for any terrigenous sandstone suite. Further adjustments in the positions of the boundary lines could doubtless be made as even more information becomes available in the future.

Within continental blocks, sediment sources are either on stable shields and platforms or in uplifts marking plate boundaries and trends of intraplate deformation that transect the continental blocks. The basement uplifts occur along incipient rift belts, transform ruptures, deep-seated thrusts, and zones of wrench tectonism. Figure 1 denotes three gradational kinds of sand frameworks of which the provenances are within continental blocks. All are quartzofeldspathic sands poor in lithic fragments, although recycling of cover rocks overlying basement can introduce anomalous lithic fragments in variable amounts locally. The most quartzose sands are derived from stable craton interiors having low relief, somewhat more feldspathic sands form a transitional group, and the most feldspathic sands are arkoses derived from basement uplifts where erosion has cut deep into the continental crust.

Within active magmatic arcs, sediment sources are mainly in the volcanic carapace capping the igneous belt and in granitic plutons of the arc roots. Subordinate debris is derived from bounding envelopes of metamorphic rock and flanking sediment cover. Derivative sands form a spectrum of lithofeldspathic and feldspatholitic types of which the compositions typically spread across the central and lower parts of QFL and QmFLt plots (Fig. 1). The most lithic frameworks are largely volcaniclastic sands derived from essentially undissected arcs, somewhat less lithic sands form a transitional group, and the most quartzofeldspathic frameworks are volcanoplutonic sands derived from dissected arcs where erosion has exposed batholiths beneath volcanic cover. Arkosic sands derived mainly from the plutons of magmatic arcs are gradational to similar sands derived from basement uplifts that expose granite and gneiss elsewhere within continental blocks. Where compositional overlap occurs, the two kinds of arkosic suites are indistinguishable by petrographic methods.

Within recycled orogens, sediment sources are sedimentary strata and subordinate volcanic rocks, in part metamorphosed, exposed to erosion by the orogenic uplift of fold belts and thrust sheets. Varied tectonic settings include the subduction complexes of arc orogens, highlands along the suture belts of collision orogens, and thin-skinned foreland fold-thrust belts along the flanks of arc or collision orogens (Dickinson and Suczek, 1979, Fig. 7). Sands derived from such provenances are generally low in feldspar because igneous rocks are not prime sources. Three gradational kinds of framework modes are denoted on the QmFLt plot (Fig. 1): quartzose and lithic varieties plus a transitional variety intermediate in composition. The three variants cannot be distinguished on the QFL plot because many lithic fragments are chert grains that plot together with quartz at the same pole.

The quartzose variants of sands having orogenic provenances are doubtless recycled from sediments whose ultimate sources were cratonic. Compositions of the first-cycle and second-cycle materials are clearly gradational. Recycling of such quartzose sands typically involves deformation and uplift of miogeoclinal successions. By contrast, many of the chert-rich lithic variants had sources in uplifted oceanic terranes of eugeosynclinal belts where radiolarian cherts occur. Chert grains may also be derived, however, from nodules in carbonate sequences or from phosphatic shelf deposits, to name but two common occurrences.

Sedimentological factors may locally enhance the quartz content of sands such as beach-barrier deposits by selective removal of lithic grains and feldspars. Caution should thus always be exercised when interpreting the provenance of quartz-rich sands. In particular, the data compiled here show gradational relationships between some sandstone suites interpreted as having been derived from craton interiors and recycled orogenic belts. For such lithic-bearing quartzose sands, few, if any, strictly petrographic criteria are infallible as provenance indicators.

DATA PRESENTATION

Our data base consists of 233 sandstone suites made up of about 7,500 individual samples for which point counts are reported in 145 different references. Only a graphical summary of this information is presented here. We used all of the data available to us in a form that allowed us to calculate QFL and QmFLt framework modes in a reliable manner. Although voluminous, the data are sparse in relation to the large area involved and the long time span considered. About one-half of the data used has been reported since 1975, and nearly all of it has appeared since 1960. Future work can be expected to sharpen or modify the trends and patterns that we have detected. In some respects, our discussion of the data compiled may oversimplify complex relationships that cannot be perceived clearly without additional information.

A data-bank appendix[1] includes tabulations of mean QFL and QmFLt values for all of the sandstone suites considered in our analysis. Each suite constitutes a group of samples that are closely related both areally and stratigraphically. Typically, a suite is made up of samples from a single formation or a set of associated formations from the same district, basin, or sedimentary province. We required that each suite be petrologically homogeneous to the extent that suite means for individual QFL and QmFLt values have standard deviations less than 10 percentage points (where the values reported for individual samples are taken as the population). The

[1]For free copies of this appendix, call or write and request them from the Documents Secretary in the Publications Department of GSA.

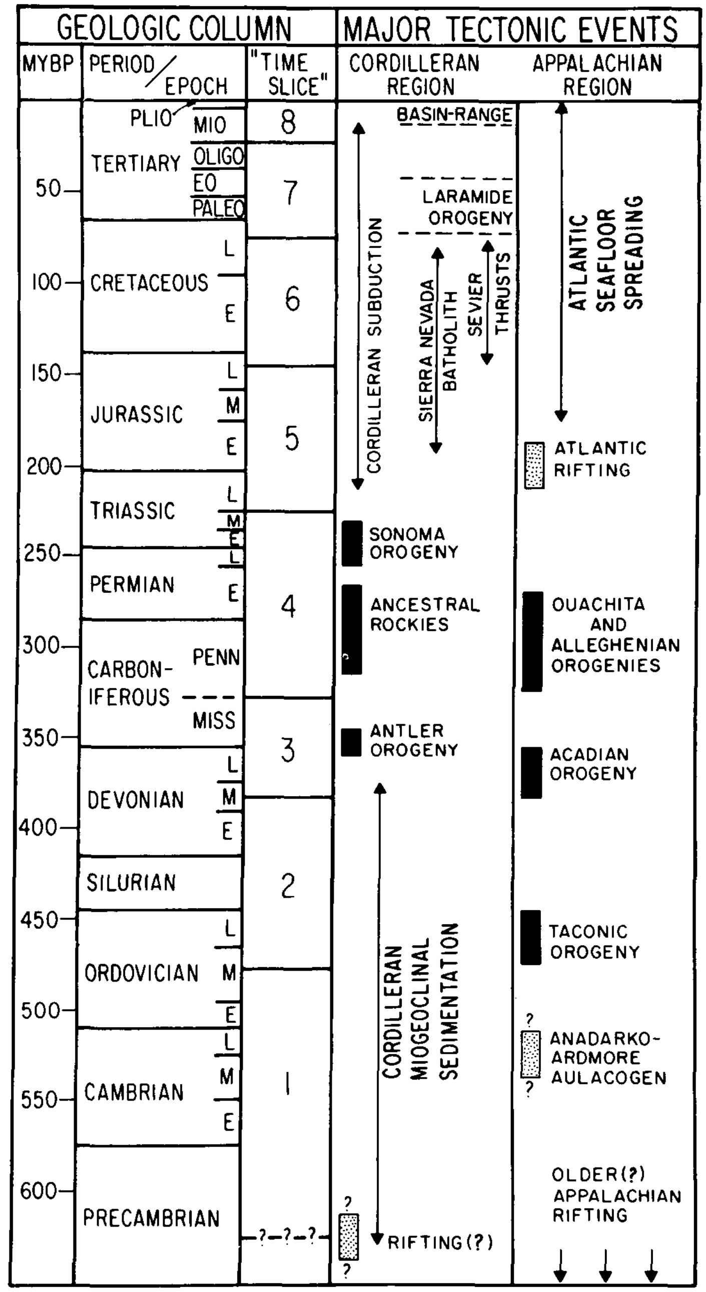

Figure 2. Chart identifying eight Phanerozoic time slices for which paleotectonic maps are drawn with accompanying QFL and QmFLt diagrams (Figs. 3–10). Cenozoic time scale after Berggren and Van Couvering (1974) and Hardenbol and Berggren (1978). Pre-Cenozoic time scale modified after Armstrong (1978).

number of points counted in individual samples by the various operators was such that the counting error for individual samples was of the order of five percentage points or less when expressed as a standard deviation with respect to the grain population present in the sample (Van der Plas and Tobi, 1965).

We had no effective means to evaluate operator variance. Consequently, the data compiled must include some degree of scatter that stems from the use of different criteria to distinguish relevant grain types. Additional scatter must exist from the partial dependence of sandstone composition upon grain size (Odom, 1975; Misko and Hendry, 1979), which we were unable to control within the sand range. From the systematic trends and patterns that we have detected in the data, we conclude that variances introduced by operator error and variations in grain size were not sufficient to outweigh the influence of provenance type, as controlled by tectonic setting.

Diagenetic growth of interstitial matrix or cement may also affect framework constituents through processes of intrastratal solution and replacement. In no instances can the influence of diagenetic effects on detrital modes be avoided entirely. To insure that diagenetic changes lay within acceptable limits, we arbitrarily excluded from our data compilation all sandstones containing more than 25% matrix or cement, or both in combination.

The suite means are plotted on QFL and QmFLt diagrams using the conventions of Figure 1 to subdivide the triangles and to denote the inferred type of provenance for each suite. Border-line compositions cause some suites to plot in two separate but adjacent provenance fields on the QFL and QmFLt diagrams. We have plotted the points for such suites using the provenance symbols derived from the one of the two ternary diagrams on which the suite in question plots farthest within one of the two adjacent provenance fields.

Given the fact of multiple operators and the interdependence of key variables, it is impossible to plot a meaningful halo of uncertainty about any of the plotted points for suite means. Each point represents an average of reported data that cluster closely, and the observed groupings of the plotted averages thus reflect real compositional trends. Caution should be exercised, however, in comparing point counts of individual samples with our plots.

To compare the compositions of North American sandstones with their tectonic settings, we have prepared separate sets of QFL and QmFLt diagrams for eight different slices of Phanerozoic time. For each time period, we have also prepared a paleotectonic map upon which the appropriate provenance symbol for each sandstone suite is plotted in its correct geographic position. Before discussing the data thus presented, we review briefly the reasons for selecting the particular eight slices of Phanerozoic time used for the maps and diagrams.

TIME FRAME

Ideally, each paleotectonic map should represent a period of time during which every part of the continent remained in an unchanging tectonic state for its duration. Because some tectonic events are diachronous and others are rapid, this condition cannot be satisfied rigorously. However, it is essential to avoid mixing data representing distinctly different stages of evolution in major orogenic belts. For example, sandstone suites representing passive miogeoclinal and orogenic foreland phases of sedimentation in the same basin at different times should be treated separately.

Figure 2 depicts graphically the eight time slices that we chose for this study and indicates generally how they relate to the major tectonic events that affected the Appalachian and Cordilleran regions. The time slices are designated simply as numbers 1 through 8, and the paleotectonic maps with their accompanying triangular compositional diagrams are numbered in sequence accordingly. The time slices are of unequal length, and most divisions between them do not correspond to the boundaries of geologic periods. The absolute time scale shown is our interpretation of the Armstrong (1978) file of critical Phanerozoic dates and is provided for internal consistency only. Biostratigraphic stages form the basis for operational definitions of the various time slices (see below).

The over-all time span that we consider actually began at some unknown date in the latest Precambrian when rifting delineated the margins of Paleozoic North America (Stewart, 1976). However, the only Precambrian strata included in our study are those that lie concordantly beneath basal Paleozoic strata of the Appalachian and Cordilleran miogeoclines. The following brief statements define the eight time slices stratigraphically, and indicate their relationships to key geologic events.

1. Latest Precambrian to mid-Ordovician; pre-Taconic phases of miogeoclinal sedimentation; ended ~477.5 m.y. B.P. at Llanvirnian-Llandeilian stage boundary in mid–Middle Ordovician.
2. Mid-Ordovician to mid-Devonian; Taconic orogeny and foreland, pre-Acadian and pre-Antler sedimentation; ended ~382.5 m.y. B.P. at Eifelian-Givetian stage boundary in mid–Middle Devonian.
3. Mid-Devonian to mid-Carboniferous; Acadian and Antler orogenies and foreland basins; ended ~327.5 m.y. B.P. at Mississippian-Pennsylvanian period boundary.
4. Mid-Carboniferous to mid-Triassic; Allegheny and Ouachita orogenies and foreland basins, Ancestral Rockies development, post-Antler overlap sequence, and Sonoma orogeny; ended ~225 m.y. B.P. at Middle–Late Triassic epoch boundary.
5. Mid-Triassic to mid–Late Jurassic; rifting of central North Atlantic, opening of Gulf of Mexico, initiation of Cordilleran arc-trench system; ended ~145 m.y. B.P. in mid-Kimmeridgian Stage.
6. Mid–Late Jurassic to latest Cretaceous; Nevadan and Sevier orogenies, intrusion of major Cordilleran batholiths, filling of Rocky Mountain foreland basin and Chihuahua trough; ended approximately 75 m.y. B.P. in mid-Campanian Stage.
7. Latest Cretaceous through Paleogene; Laramide orogeny and mid-Tertiary Cordilleran magmatism; ended ~22.5 m.y. B.P. at Oligocene-Miocene epoch boundary.
8. Neogene time; Columbia River Plateau and Snake River Plain volcanism, San Andreas transform system, Basin-and-Range deformation.

PALEOTECTONICS

Figures 3 through 10 are paleotectonic sketch maps with accompanying QFL and QmFLt diagrams for each of the time slices of Figure 2. The triangular diagrams are subdivided and annotated by symbols as in Figure 1. Note that symbols for sandstone suites plotted geographically on paleotectonic maps correlate with symbols on triangular diagrams to denote general compositions by provenance type. For some suites, limitations in the available data allowed us to calculate either QFL or QmFLt framework modes, but not both. Consequently, paired QFL and QmFLt diagrams for some time slices have different numbers of plotted points. In cases where suites from recycled orogenic provenances could be plotted only on the QFL diagram, the appropriate variant could not be determined. For such suites, a special symbol for recycled orogenic provenances of indeterminate character was plotted (see Figs. 1, 3–10). All suites were plotted on the paleotectonic maps, which thus show accurately the number of suites compiled for each time slice.

Map 1

From latest Precambrian to mid-Ordovician time (Fig. 3), both margins of the continent are shown subsiding passively to receive miogeoclinal sediments. The passive continental margins were delineated by rifting and continental separations that occurred mostly in the late Precambrian but may have persisted until the Late Cambrian in the Ouachita region (Dickinson, 1981). The tectonic setting of the continent during this time implies that the compositions of sandstones from nearly all regions should reflect provenances within the continental block.

This inference is borne out well by the data compiled here. A majority of the suites in all regions have quartzose framework modes reflecting derivation from stable parts of the craton. Some suites in each region have slightly more feldspathic framework modes characteristic of the transitional group derived from continental blocks. Sources for these latter suites probably had somewhat greater relief than the cratonic provenance but apparently did not experience enough uplift to provide truly arkosic debris. In the Cordilleran region, these two sand types of cratonic and transitional origin occur not only within the miogeoclinal belt but evidently were also transported off the edge of the continental block to be deposited as turbidites within the eugeoclinal belt.

In the Appalachian region and within the interior of the continent, a few suites have frameworks containing enough lithic fragments to plot within the provenance field for derivation from

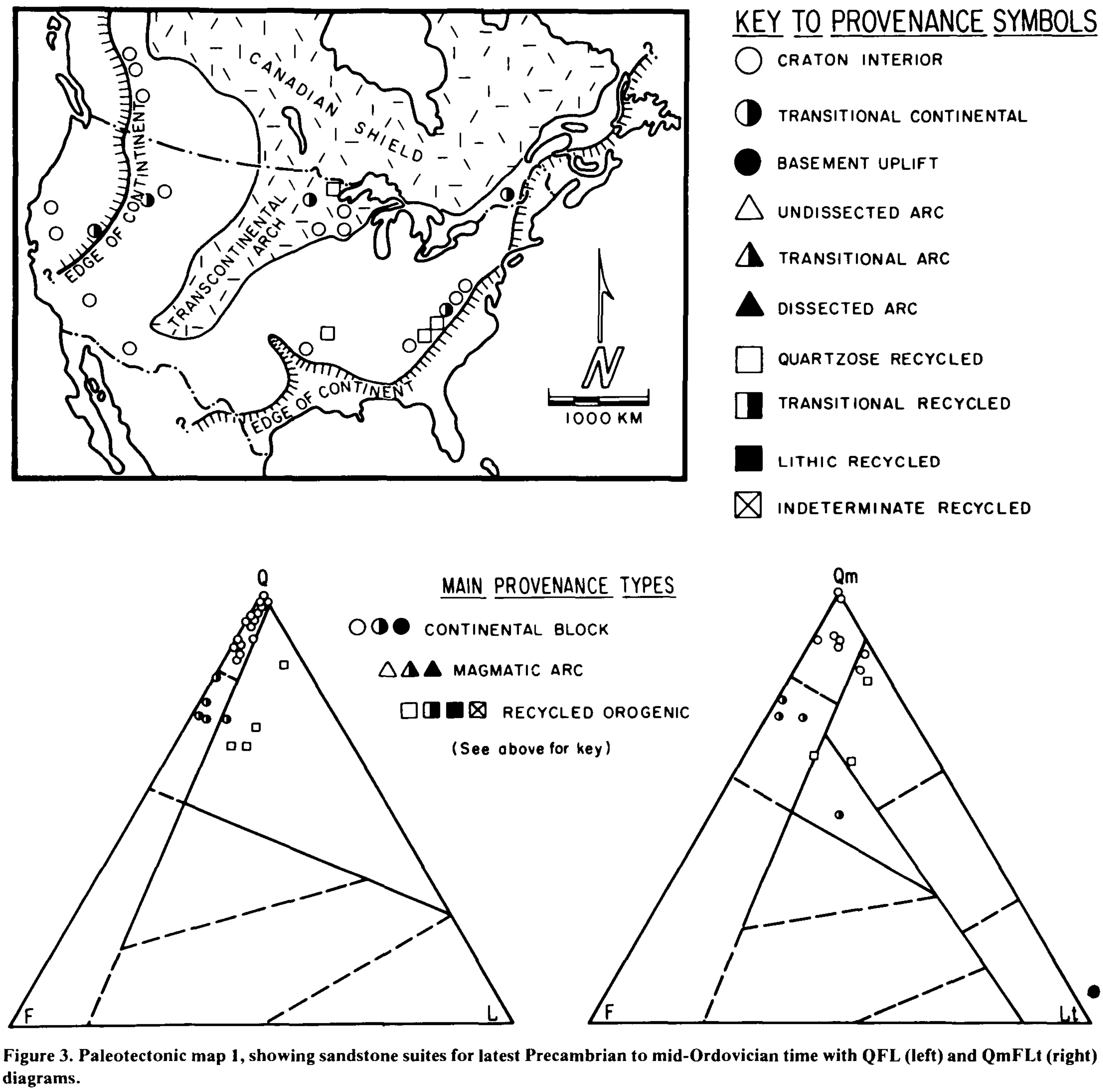

Figure 3. Paleotectonic map 1, showing sandstone suites for latest Precambrian to mid-Ordovician time with QFL (left) and QmFLt (right) diagrams.

recycled orogens on either the QFL or QmFLt plot, or on both in rare instances. In these cases, the lithic fragments were derived from platform cover overlying the basement, local volcanic fields that may have been related to rifting events, or belts of metamorphic rock associated with basement terranes.

Map 2

From mid-Ordovician to mid-Devonian time (Fig. 4), the Cordilleran and Ouachita margins continued to evolve as subsiding rifted margins, but the Appalachian margin is shown as deformed by the Taconic orogeny, which is inferred to reflect an arc-continent collision (Chapple, 1973). Sandstone suites from the Taconic foreland basin and adjacent thrust sheets have quartzolithic compositions characteristic of the quartzose variant of sands derived from recycled orogenic provenances. Their sources are inferred to have been dominantly miogeoclinal rocks that were deformed, partly metamorphosed, and uplifted orogenically during the Taconic event. Quartzose miogeoclinal and platform suites from the Cordilleran and Ouachita regions reflect derivation from the interior of the craton.

Suites from the Klamath Mountains within the Cordilleran eugeosynclinal belt include lithic sandstones that evidently were derived from a magmatic arc and its associated subduction complex. Chert-rich lithic variants of sands derived from recycled orogenic sources are characteristic of the latter provenance (Dickinson

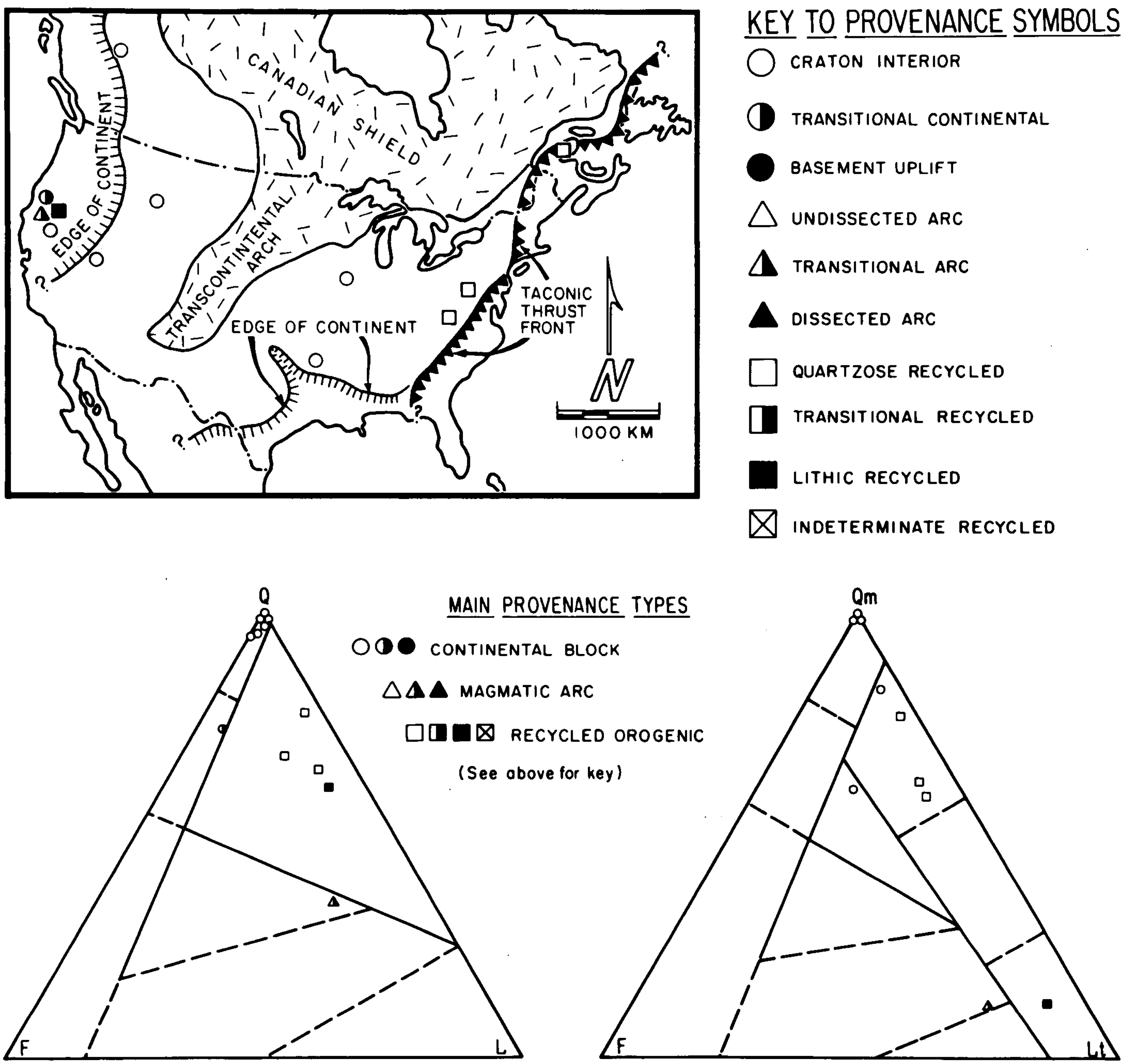

Figure 4. Paleotectonic map 2, showing sandstone suites for mid-Ordovician to mid-Devonian time with QFL (left) and QmFLt (right) diagrams.

and Suczek, 1979). These eugeosynclinal rocks lie within a coastal belt of terranes for which the positions with respect to North America are unknown for the Paleozoic (Coney and others, 1980). We infer that they were probably not close to the continental margin at that time.

Map 3

From mid-Devonian to mid-Carboniferous time (Fig. 5), the Appalachian margin is shown involved within the Acadian orogen. Acadian events in the northern Appalachians probably reflected collision between Europe and North America, but the plate setting of the southern Appalachians at that time is still unclear (Graham and others, 1975). The Cordilleran margin is shown overthrust by the Antler orogen, of which development in Nevada probably reflected an arc-continent collision (Dickinson, 1977), but of which the extent and location to the north remain uncertain (Nilsen and Stewart, 1980). The Ouachita margin remained passive to the west but may have begun to undergo deformation on the east.

Sparse data indicate that both the Antler and Acadian foreland basins received sands uniformly indicative of derivation from recycled orogenic sources. Framework modes are generally transitional between quartzose and lithic variants. We thus infer that detritus included both quartzose metamorphic debris of continental affinity and chert-rich lithic debris of oceanic affinity that were recycled together following joint uplift along suture belts. Most

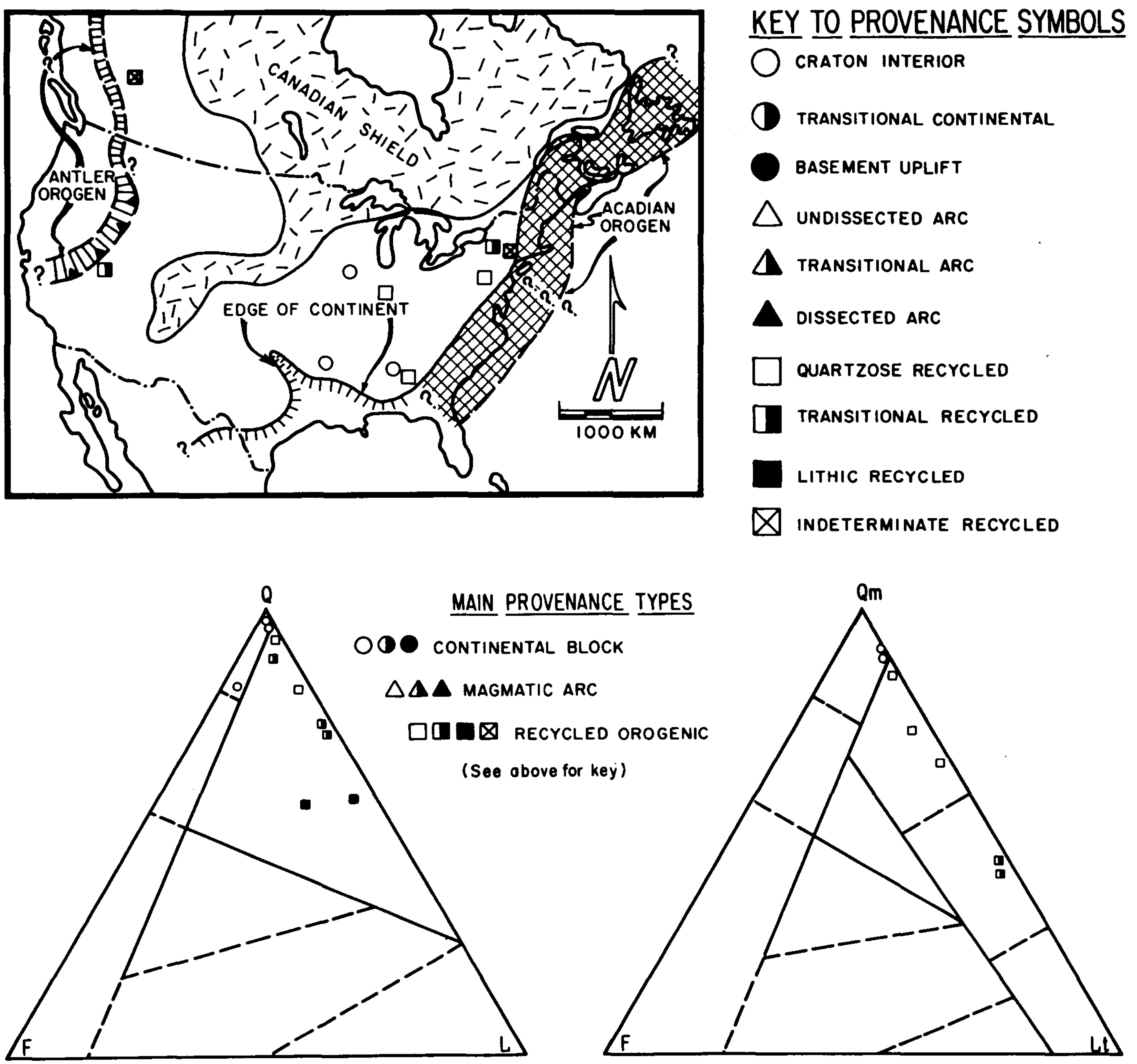

Figure 5. Paleotectonic map 3, showing sandstone suites for mid-Devonian to mid-Carboniferous time with QFL (left) and QmFLt (right) diagrams.

suites in the Ouachita region reflect continued derivation from cratonic parts of the adjacent continental block.

Map 4

From mid-Carboniferous to mid-Triassic time (Fig. 6), several complex orogenic events are depicted. The western extension of the Hercynian orogenic system in Eurasia affected both the Appalachian and Ouachita margins of the North American continent in Pennsylvanian and Early Permian time. The Alleghenian thrusts of the Appalachian region were probably emplaced mainly in the Pennsylvanian, but the Ouachita deformation was diachronous, involving Pennsylvanian thrusting on the east but including thrusting as late as Early Permian on the west (Graham and others, 1975). Alleghenian thrusting probably reflected collision between Africa and North America, whereas the Ouachita thrusting was associated with arc-continent or continent-continent collision between North America and parts of Gondwanaland now located within Mesoamerica and the Caribbean region. Basement uplifts and associated basins of the intracontinental Ancestral Rockies belt developed as a result of complex intraplate deformation induced by collision orogeny along the Ouachita belt (Kluth and Coney, 1981). On the Cordilleran margin, thrust sheets of the Sonoma orogen were emplaced across the older Antler orogen by subduction that began in Permian time but continued until the Early Triassic. An extensive composite arc terrane was accreted to the continent during the Sonoma event, which is interpreted as an arc-continent collision (Speed, 1979).

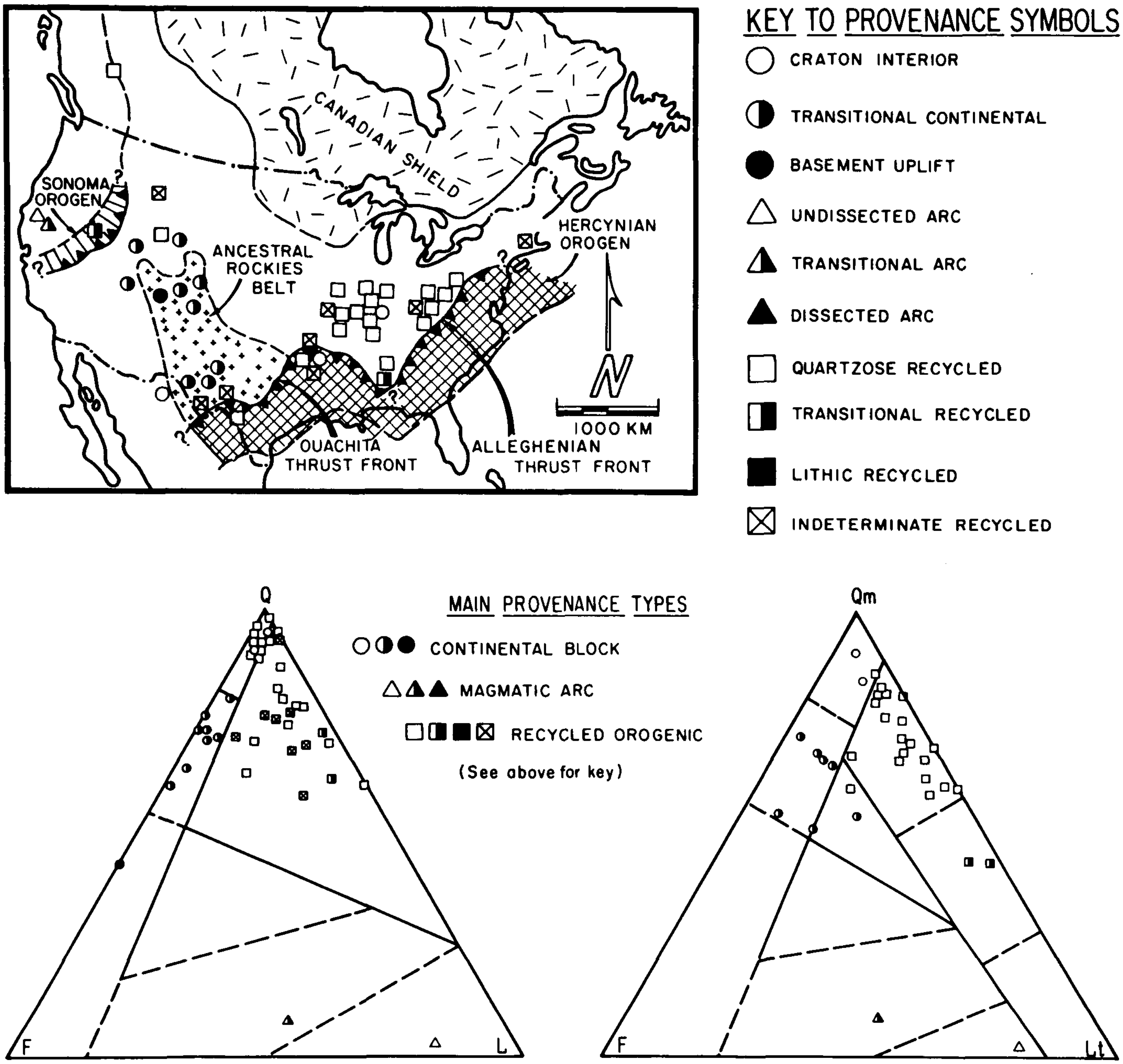

Figure 6. Paleotectonic map 4, showing sandstone suites for mid-Carboniferous to mid-Triassic time with QFL (left) and QmFLt (right) diagrams.

Suites from the Appalachian basin and other foreland basins along the trend of the Alleghenian-Ouachita thrust front have framework compositions uniformly indicative of derivation from recycled orogenic sources. Nearly all are quartzose variants that probably were recycled from deformed and uplifted terranes of dominantly miogeoclinal character. Similar recycled sands were deposited within the Illinois basin of the continental interior, to which they were transported by rivers draining around or across the Appalachian basin from sources within the Appalachian orogenic belt (Potter and Pryor, 1961; Pryor and Sable, 1974). Many suites within the Illinois basin, and some of those in the Appalachian basin, plot within the field for cratonic provenance on the QFL diagram, but their high chert content pulls them well into the field for derivation from recycled orogenic provenances on the QmFLt diagram. Some of the chert grains may have been recycled from chert nodules within successions of platform carbonate that had not undergone intense deformation.

Sandstones for which framework compositions indicate derivation from a recycled orogenic provenance also occur within the Ouachita allochthon. They are remnant-ocean turbidites largely derived from the Appalachian orogenic belt or from southern extensions of it by longitudinal transport parallel to the orogenic grain prior to final crustal collision along the Ouachita orogenic belt (Graham and others, 1975). Somewhat more lithic sandstones

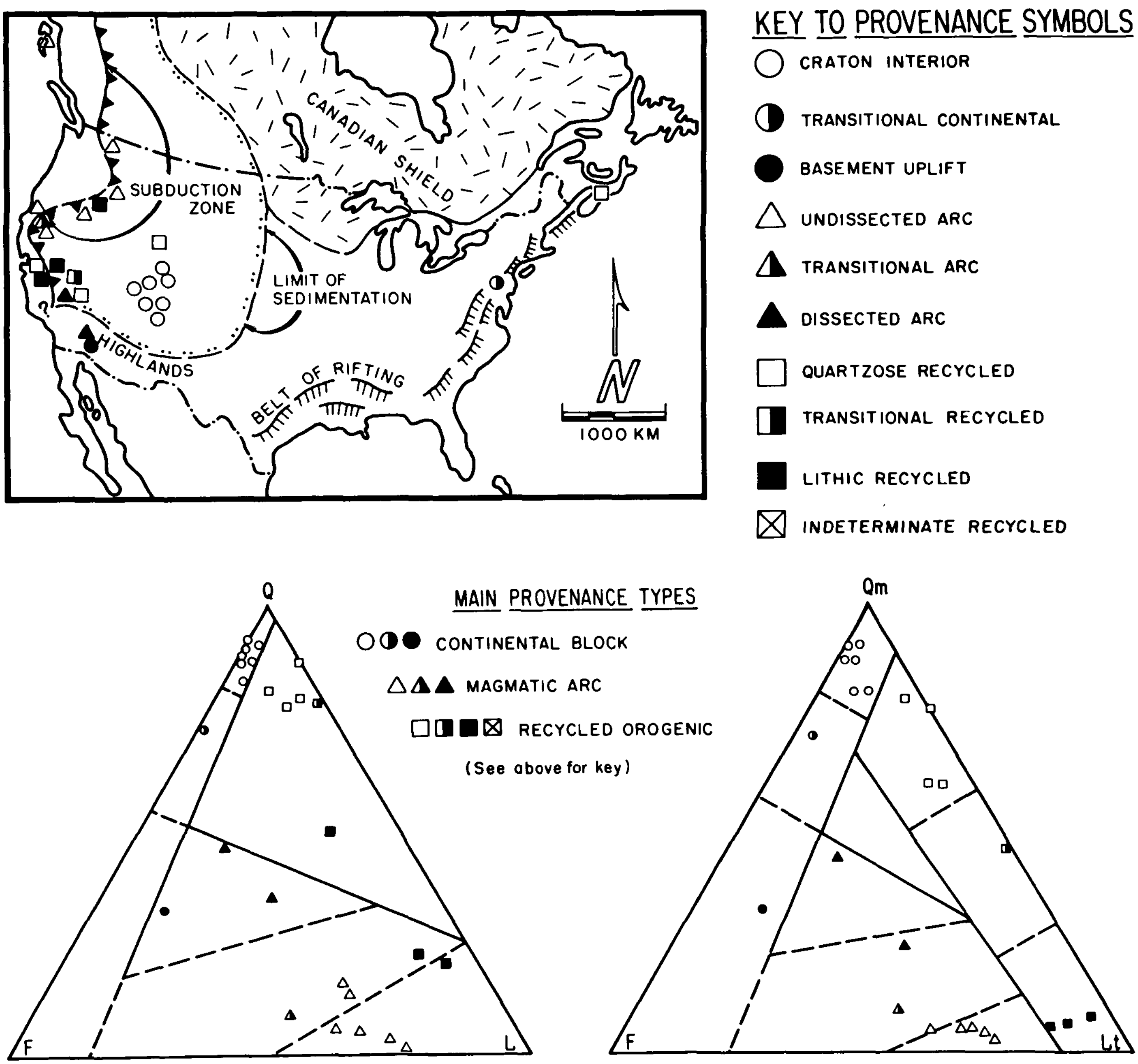

Figure 7. Paleotectonic map 5, showing sandstone suites for mid-Triassic to mid–Late Jurassic time with QFL (left) and QmFLt (right) diagrams.

shown within the Sonoma orogen rest depositionally upon the older Antler orogen and were overthrust by the younger Sonoma thrust sheets. Sandstones from sources in magmatic arcs occur farther west along the Pacific coast.

Suites from basins within the Ancestral Rockies belt have framework compositions that mainly reflect derivation from provenances within the continental block. Although feldspar-rich arkosic sandstones derived from rugged basement uplifts occur locally, most representatives of this assemblage belong to the transitional continental group. Sources for a few suites having compositions indicative of recycled orogenic provenances were probably cover strata eroded off the crests of subdued basement uplifts. The sandstones were derived from highlands within the Ancestral Rockies belt but were deposited in basins adjacent to the periphery of the belt as well as within it (Jordan and Douglas, 1980). Many Pennsylvanian and Permian strata of the Cordilleran region contain prominent amounts of hybrid sandstone produced by mixing terrigenous sand derived from the Ancestral Rockies uplifts with calcarenites generated on the extensive tropical shelves that occupied surrounding areas.

Map 5

From mid-Triassic to mid–Late Jurassic time (Fig. 7), the continent assumed a modern guise for the first time. During this period, rifting and sea-floor spreading opened the central North Atlantic

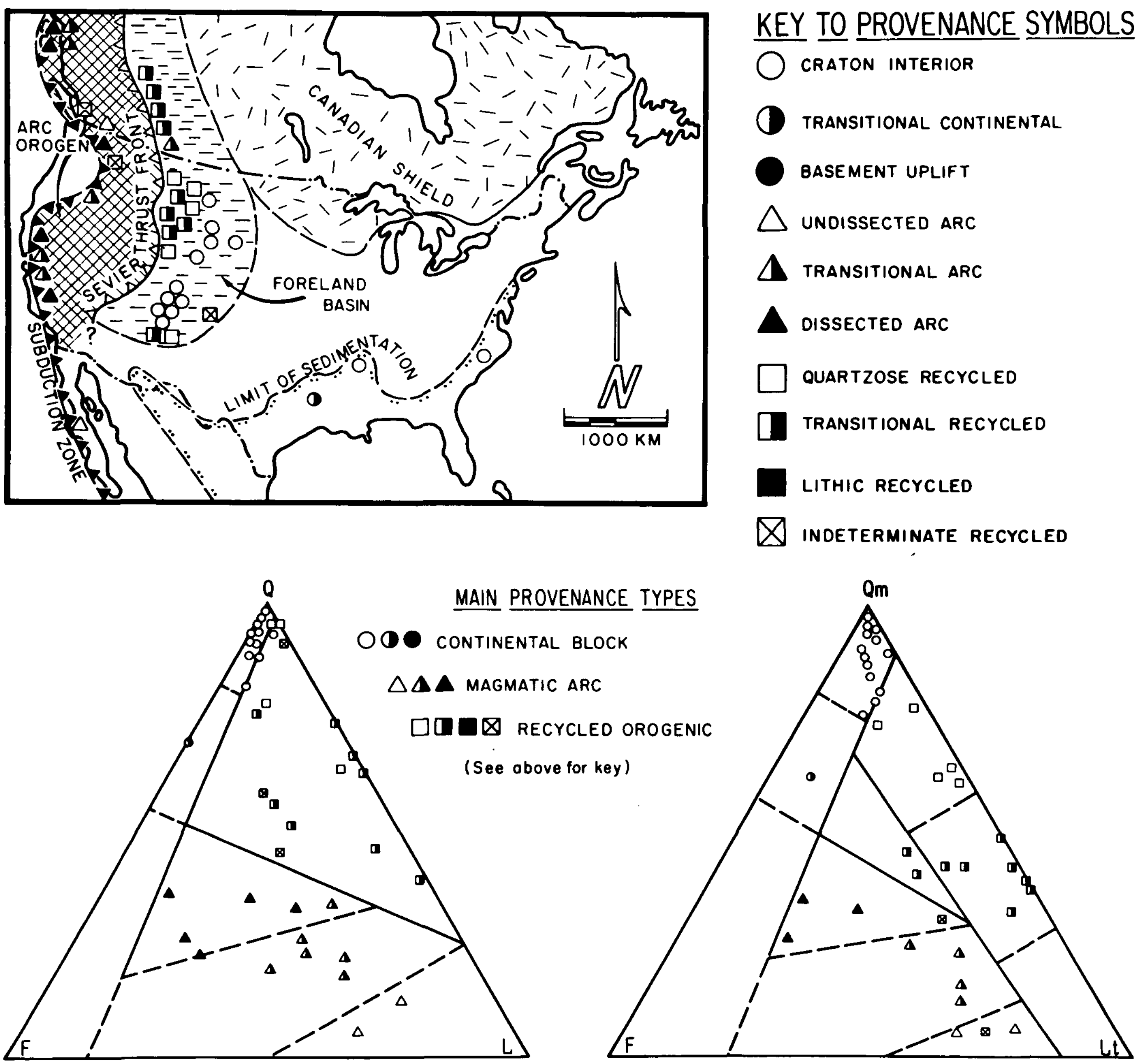

Figure 8. Paleotectonic map 6, showing sandstone suites for mid–Late Jurassic to latest Cretaceous time with QFL (left) and QmFLt (right) diagrams.

and the Gulf of Mexico (Pilger, 1980). On the Cordilleran margin, initiation of circum-Pacific subduction in Late Triassic or Early Jurassic time generated an arc-trench system along the edge of the continent for the first time (Dickinson, 1978). In the western interior, red-bed sedimentation on the Colorado Plateau graded northward and westward into coeval deposits of shallow epicontinental seas.

Sandstones deposited in rift valleys of the Appalachian region include a feldspathic suite derived from uplifted continental basement and a quartzose suite recycled by stripping of covering strata. Red-bed suites of the Colorado Plateau generally have quartzose frameworks indicative of provenances within the craton. Along the Pacific flank of the continent, the most characteristic sandstone suites have volcaniclastic frameworks indicative of derivation from undissected magmatic arcs. Varied associated suites were derived from somewhat more dissected transitional arc terranes, from uplifted subduction complexes, and from other recycled orogenic provenances. Such a mixture of suites related to nascent arc activity

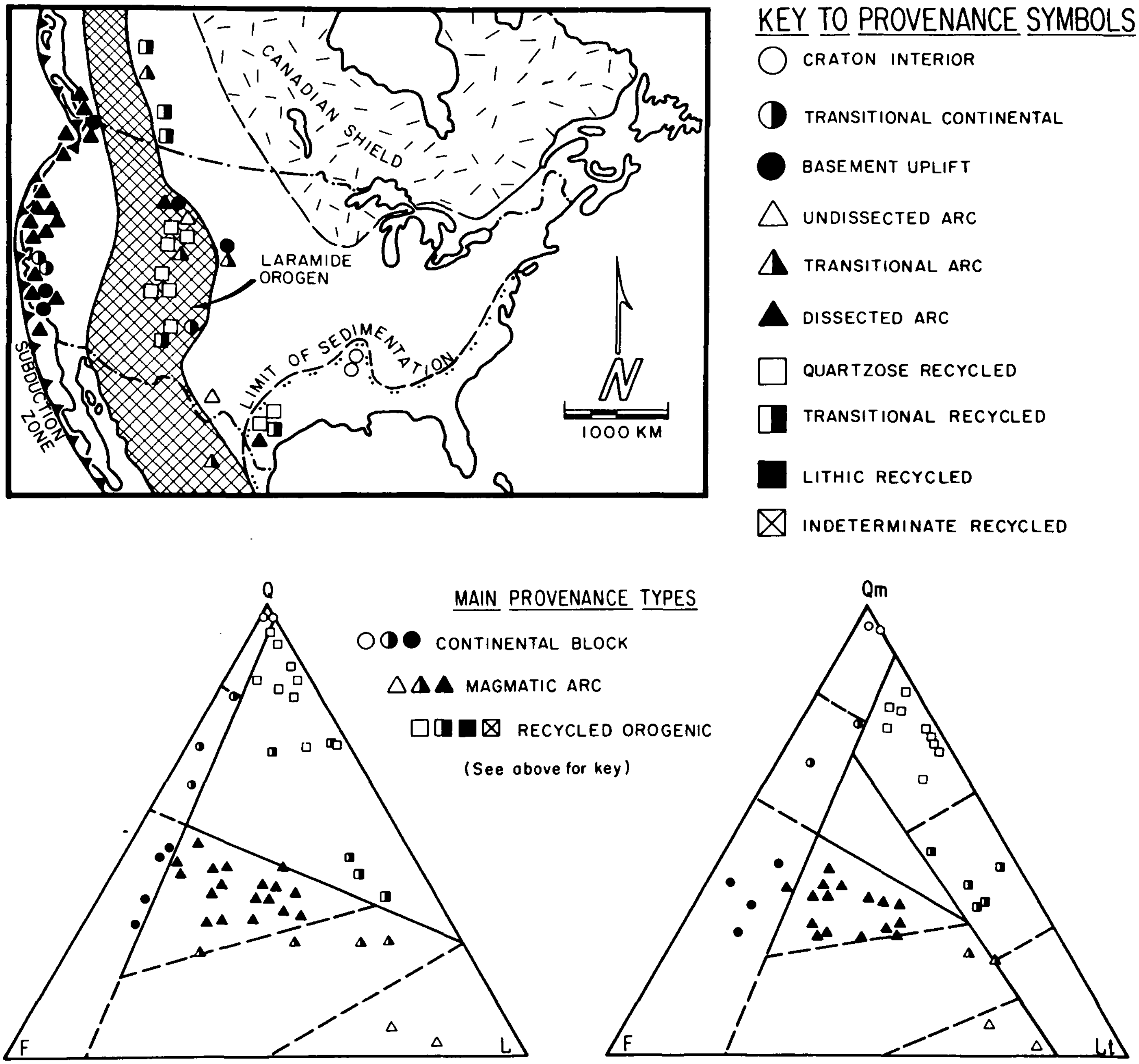

Figure 9. Paleotectonic map 7, showing sandstone suites for latest Cretaceous through Paleogene time with QFL (left) and QmFLt (right) diagrams.

is perhaps to be expected along a newly activated continental margin. The arc-derived suites in the Queen Charlotte Islands occupy part of a terrane that may have been accreted to the continental margin during this time or even later (Dickinson, 1976).

Map 6

From mid–Late Jurassic to latest Cretaceous time (Fig. 8), the Cordilleran arc-trench system was a fully developed arc orogen (Hamilton, 1969). The subduction zone lay within Franciscan and related terranes along the coastal fringe, major batholiths were emplaced and unroofed within the orogen, and a back-arc thrust system developed along the Sevier orogenic belt farther inland. The Rocky Mountain foreland basin lay between the thrust front and the interior of the craton. Along the Gulf and Atlantic coasts, the inland edge of a growing miogeoclinal sediment prism onlapped the flank of the continental block.

Cratonic suites derived from interior parts of the continental block are dominant in the miogeoclinal wedge and along the inland side of the foreland basin. Where the sedimentary sequence in the foreland basin is thickest near the thrust front, sandstone suites for which framework compositions reflect derivation from recycled

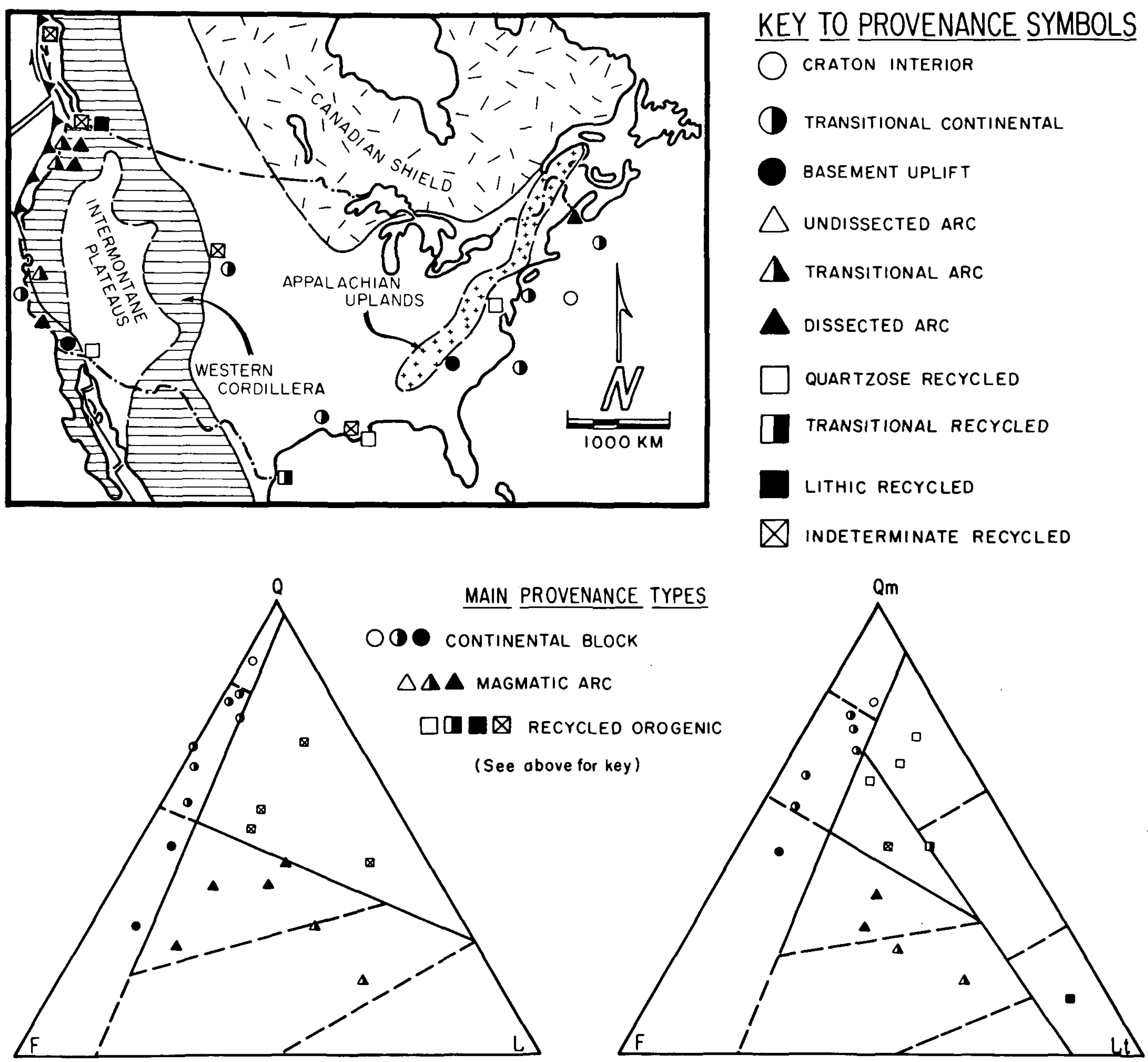

Figure 10. Paleotectonic map 8, showing sandstone suites for Neogene time with QFL (left) and QmFLt (right) diagrams.

orogenic provenances are dominant. Most of these sands are transitional variants with compositions intermediate between recycled quartzose and lithic end members. Their sources lay within complex thrust sheets from which a variety of mainly sedimentary and metasedimentary detritus was recycled.

In subduction complexes and forearc basins along the Pacific margin, nearly all suites have framework modes indicative of derivation from the erosion of magmatic arcs. Sands from undissected, dissected, and transitional arcs are all present in various places at various horizons. Rarely was arc debris shed toward the continental interior, although arc-derived suites are present locally along the orogenic flank of the foreland basin. Conversely, recycled debris was rarely transported into the forearc region, although recycled suites do occur in that setting locally.

Map 7

From latest Cretaceous through Paleogene time (Fig. 9), the dominant tectonic feature is the broad Laramide orogen, which expanded toward the interior of the continent during anomalously shallow plate descent beneath the Cordillera (Dickinson and Snyder, 1978). Arc magmatism, as well as the Laramide deformation, shifted eastward in response to the shallow plate descent (Coney and Reynolds, 1977). Sedimentation continued along the passive Gulf of Mexico and Atlantic margins.

Craton-derived sediment continued to accumulate along much of the passive margin, but suites indicative of recycled orogenic and magmatic arc provenances reached the western Gulf Coast region from the nearby Laramide orogenic belt. Within and adjacent to the complex Laramide orogen itself, suites are varied. Sandstones of which the frameworks have arc signatures were derived from scattered igneous provinces, and they display characteristics of undissected, dissected, and transitional arc terranes in different instances. More common are suites with framework compositions implying derivation from recycled orogenic provenances within the uplifted belt. Locally, sandstone suites deposited near fault-bounded blocks have framework constituents derived from uplifted continental basement rocks.

In subduction complexes and forearc basins along the Pacific margin, most suites were derived from the dissected magmatic arc of which the plutonic roots were extensively exposed by erosion when arc magmatism shifted eastward during the Laramide event. Plutonic sources in the Peninsular, Sierra Nevada, Idaho, and Coast Range batholiths mostly lay west of the main Laramide orogenic belt. Where erosion cut deepest into the batholithic terrane, all volcaniclastic components were lost in the derivative sands. Local suites in southern California thus reflect derivation from uplifted plutonic basement and are indistinguishable in our plots from other arkosic sands that were derived from basement uplifts in the interior of the continental block.

Map 8

In Neogene time (Fig. 10), the tectonic setting depicted is that of today. Notable features are the broad Appalachian uplands and the rugged western Cordillera with its intermontane plateaus, including the Basin-and-Range province. Transform motion dominates current plate interactions along the Pacific margin of the continent but was not so significant at the beginning of Neogene time. Subduction is under way now only in the Pacific Northwest but was active along much of the continental margin during Miocene time. Transform motion progressively supplanted subduction along the continental margin as the San Andreas system lengthened through the Neogene (Dickinson and Snyder, 1979).

Many Neogene suites considered here are unconsolidated sands rather than sandstones. This factor probably introduces some bias into our results as plotted. For example, the plotted point for arkosic sand derived from uplifted basement in the southern Appalachian region is a local stream sand. Its constituents probably will be mixed with more quartzose sands before arrival at any final site of deposition offshore along the passive Atlantic continental margin. Similarly, the apparently arc-derived sand suite farther north in the Appalachian region is unconsolidated Quaternary sand in the Bay of Fundy. Its provenance includes the rocks of a dissected Paleozoic arc terrane exposed nearby, and its occurrence locally along a much younger passive continental margin is a reminder that caution is required in making interpretations based on individual suites when regional data are limited. Offshore sand suites from the Atlantic shelf and sea floor are more characteristic of the composition of sands derived from mixed continental sources. They all reflect derivation from a relatively stable continental block as expected. The apparent dominance of transitional suites over truly cratonic suites probably reflects the influence of the Appalachian uplift during the Tertiary.

Holocene sands from Chesapeake Bay at the mouth of the Susquehanna River, from the Mississippi River delta, from the mouth of the Rio Grande, and from the Colorado River delta are all quartzose variants of recycled orogenic sands. This circumstance reflects the tendency for major rivers to drain complex orogenic highlands where feldspar-poor sources are rare, but lithic fragments are more common than within continental lowlands (Potter, 1978a, 1978b). Neogene sandstones of both recycled orogenic and transitional continental provenance occur along the High Plains adjacent to the modern Rocky Mountains.

Along the Pacific margin of the continent, three types of sandstone suites are dominant in different areas. Near the San Andreas transform in the south, arkosic and transitional continental suites were derived from blocks of continental basement uplifted along the associated zone of wrench tectonism. In the Pacific Northwest, arc-derived sands of dissected and transitional types are characteristic within the region where arc volcanism continues. Farther north in Canada, varied recycled orogenic sands, partly of the chert-rich lithic variant, occur where the modern Canadian Cordillera rises adjacent to the offshore Queen Charlotte transform fault.

CONCLUSIONS

Our results support the following inferences:

1. Standard QFL and QmFLt diagrams for plotting framework modes of terrigenous sandstones can be subdivided into three main fields indicative of derivation from provenance terranes within continental blocks, magmatic arcs, and recycled orogens; each of the three main fields can be further divided into three subfields representing variants of the main provenance classes.

2. The QFL and QmFLt diagrams as thus partitioned can be used for provisional classification of sandstone suites according to tectonic setting; average detrital modes of sandstone suites tend to fall within the appropriate field unless special influences or unusual circumstances alter the normal patterns.

3. Our test of the classification scheme using Phanerozoic sandstone suites of known composition and tectonic setting from North America yields generally satisfactory results; average modes for most sandstone suites plot in appropriate fields and subfields on the triangular compositional diagrams.

4. Application of the method demonstrated here to other regions for which tectonic evolution is less well known could yield useful results; the timing of major tectonic events is reflected by the compositions of sandstones derived from key provenance terranes. Schwab (1981) has recently illustrated this approach for the Alps.

5. Rigorous point counts of sandstones are an important tool for paleotectonic reconstructions and should be performed as routine practice during all comprehensive tectonic studies.

ACKNOWLEDGMENTS

This paper was prepared as a project of the Sedimentology Seminar at the University of Arizona. The work was supported by the Laboratory of Geotectonics in the Department of Geosciences. A preliminary version was presented in a poster session of Geoscience Daze at the University of Arizona. A meticulous review by A. R. Niem improved the final manuscript.

REFERENCES CITED

Armstrong, R. L., 1978, Pre-Cenozoic Phanerozoic time scale—Computer file of critical dates and consequences of new and in-progress decay-constag, J. A., 1974, The late Neogene: Biostratigraphy, geochronology, and paleoclimatology of the last 15 million years in marine and continental sequences: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 16, p. 1–216.

Chapple, W. M., 1973, Taconic orogeny: Abortive subduction of the North American continental plate?: Geological Society of America Abstracts with Programs, v. 5, p. 573.

Coney, P. J., Jones, D. L., and Monger, J.W.H., 1980, Cordilleran suspect terranes: Nature, v. 288, p. 329–333.

Coney, P. J., and Reynolds, S. J., 1977, Cordilleran Benioff zones: Nature, v. 270, p. 403–405.

Dickinson, W. R., 1976, Sedimentary basins developed during evolution of Mesozoic-Cenozoic arc-trench system in western North America: Canadian Journal of Earth Sciences, v. 13, p. 1268–1287.

—— 1977, Paleozoic plate tectonics and the evolution of the Cordilleran continental margin, *in* Stewart, J. H., Stevens, C. H., and Fritsche, A. E., eds., Paleozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium 1, p. 137–156.

—— 1978, Plate tectonic evolution of North Pacific rim: Journal of the Physics of the Earth, v. 26, supplement, p. S1–S19.

—— 1981, Plate tectonic evolution of the southern Cordillera, *in* Dickinson, W. R., and Payne, W. D., eds., Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 113–135.

—— 1982, Compositions of sandstones in circum-Pacific subduction complexes and forearc basins: American Association of Petroleum Geologists Bulletin, v. 66, p. 121–137.

Dickinson, W. R., and Snyder, W. S., 1978, Plate tectonics of the Laramide orogeny: Geological Society of America Memoir 151, p. 355–366.

—— 1979, Geometry of triple junctions related to San Andreas transform: Journal of Geophysical Research, v. 84, p. 561–572.

Dickinson, W. R., and Suczek, C. A., 1979, Plate tectonics and sandstone compositions: American Association of Petroleum Geologists Bulletin, v. 63, p. 2164–2182.

Dickinson, W. R., and Valloni, Renzo, 1980, Plate settings and provenance of sands in modern ocean basins: Geology, v. 8, p. 82–86.

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

Graham, S. A., Ingersoll, R. V., and Dickinson, W. R., 1976, Common provenance for lithic grains in Carboniferous sandstones from Ouachita Mountains and Black Warrior basin: Journal of Sedimentary Petrology, v. 46, p. 620–632.

Hamilton, W. B., 1969, Mesozoic California and the underflow of Pacific mantle: Geological Society of America Bulletin, v. 80, p. 2409–2430.

Hardenbol, J., and Berggren, W. A., 1978, A new Paleogene numerical time scale, *in* Cohee, G. V., Glaessner, M. F., and Hedberg, H. D., eds., The geologic time scale: American Association of Petroleum Geologists Studies in Geology No. 6, p. 213–234.

Jordan, T. E., and Douglas, R. C., 1980, Paleogeography and structural development of the Late Pennsylvanian to Early Permian Oquirrh basin, northwestern Utah, *in* Fouch, T. D., and Magathan, E. R., eds., Paleozoic paleogeography of the west-central United States: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, Rocky Mountain Paleogeography Symposium 1, p. 217–238.

Kluth, C. F., and Coney, P. J., 1981, Plate tectonics of the Ancestral Rocky Mountains: Geology, v. 9, p. 10–15.

Misko, R. M., and Hendry, H. E., 1979, The petrology of sands in the uppermost Cretaceous and Palaeocene of southern Saskatchewan; a study of composition influenced by grain size, source area, and tectonics: Canadian Journal of Earth Sciences, v. 16, p. 38–49.

Nilsen, T. H., and Stewart, J. H., 1980, The Antler orogeny—Mid-Paleozoic tectonism in western North America: Geology, v. 8, p. 298–302.

Odom, I. E., 1975, Feldspar-grain size relations in Cambrian arenites, upper Mississippi Valley: Journal of Sedimentary Petrology, v. 45, p. 636–650.

Pilger, R. H., Jr., ed., 1980, The origin of the Gulf of Mexico and the early opening of the central North Atlantic Ocean: Baton Rouge, Louisiana, School of Geoscience, Louisiana State University, 103 p.

Potter, P. E., 1978a, Significance and origin of big rivers: Journal of Geology, v. 86, p. 13–33.

—— 1978b, Petrology and chemistry of modern big river sands: Journal of Geology, v. 86, p. 423–449.

Potter, P. E., and Pryor, W. A., 1961, Dispersal centers of Paleozoic and later clastics of the upper Mississippi Valley and adjacent areas: Geological Society of America Bulletin, v. 72, p. 1195–1250.

Pryor, W. A., and Sable, E. G., 1974, Carboniferous of the eastern interior basin, *in* Briggs, Garrett, ed., Carboniferous of the southeastern United States: Geological Society of America Special Paper 148, p. 281–314.

Schwab, F. L., 1981, Evolution of the western continental margin, French-Italian Alps: Sandstone mineralogy as an index of plate tectonic setting: Journal of Geology, v. 89, p. 349–368.

Speed, R. C., 1979, Collided Paleozoic microplate in the western United States: Journal of Geology, v. 87, p. 279–292.

Stewart, J. H., 1976, Late Precambrian evolution of North America: Plate tectonics implication: Geology, v. 4, p. 11–15.

Van der Plas, L., and Tobi, A. C., 1965, A chart for determining the reliability of point counting results: American Journal of Science, v. 263, p. 87–90.

Zuffa, G. C., 1980, Hybrid arenites: Their composition and classification: Journal of Sedimentary Petrology, v. 50, p. 21–30.

MANUSCRIPT RECEIVED BY THE SOCIETY MAY 15, 1981
REVISED MANUSCRIPT RECEIVED JANUARY 11, 1982
MANUSCRIPT ACCEPTED MARCH 3, 1982