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FIGS. 1–8, SEPTEMBER 1976

COMMON PROVENANCE FOR LITHIC GRAINS IN CARBONIFEROUS SANDSTONES FROM OUACHITA MOUNTAINS AND BLACK WARRIOR BASIN[1]

STEPHAN A. GRAHAM,[2] RAYMOND V. INGERSOLL[3]
AND WILLIAM R. DICKINSON
Geology Department, Stanford University, Stanford, California 94305

ABSTRACT: To test the influence that carboniferous graywacke sandstones of the Ouachita Mountains and Black Warrior basin represent deposition in a linked dispersal system analogous in tectonic setting to the modern Ganges delta-Bengal fan system, sandstones from the two areas were compared petrographically. Two point counts, a standard QFL count and a special count of lithic grains, made for each of 24 selected samples, half from the Ouachitas and half from the Black Warrior basin, reveal that sandstones from both areas are rich in quartz and metasedimentary lithic grains, but poor in feldspar and volcanic lithic grains. QFL plots show that Ouachita rocks have quartz percentages consistently higher than coeval Black Warrior basin sandstones because of transport-related attrition of lithic grains and/or contributions of craton-derived, quartz-rich detritus to the Ouachita sandstones. However, Ouachita and Black Warrior basin samples cluster tightly together on triangular plots of polycrystalline quartz grain (Q$_p$), aphanitic sedimentary/metasedimentary grains (L$_s$), and volcanic/metavolcanic grains (L$_v$). Moreover, the lithic populations of the two sample suites are indistinguishable in detail. Eight lithic grain types, mostly metamorphic, can be recognized in point-counting, although care must be taken to discriminate between true matrix and pseudomatrix consisting of deformed, fine-grained lithic fragments.

We conclude that graywackes of the Ouachita Mountains and the Black Warrior basin had a common sedimentary/metasedimentary provenance, to the exclusion of significant igneous sources. This conclusion is compatible with the continental-collision model by which a sedimentary/metasedimentary terrane uplifted along a suture belt supplied sediment dispersed longitudinally through alluvial and deltaic systems to depositional sites in a remnant ocean basin. When plotted on QFL, Q$_p$L$_v$L$_s$ and other diagrams, Ouachita-Black Warrior sandstones and more arkosic sandstones from known arc-related settings form two distinct fields that reflect basic differences in provenance. The data thus appear to underscore the importance of collisional settings for the development of thick lithic-rich graywacke sequences of non-volcanic derivation.

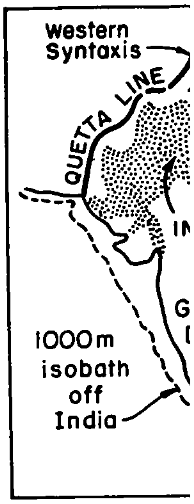
INTRODUCTION

Elsewhere (Graham, *et al.*, 1975) we have discussed the geographic plan and sequential development of the Appalachian-Ouachita orogenic system in the Carboniferous by analogy with the evolution of the Himalayan ranges and the Bengal subsea fan during the Tertiary. The outline of our argument is as follows (see Fig. 1):

(1) Prior to the Mesozoic opening of the Atlantic Ocean, the Appalachian-Mauritanide orogen of the late Paleozoic marked a suture belt along which North America and Africa collided when an intervening Paleozoic ocean closed. Similarly, the Himalayan ranges mark the position of a Tertiary suture belt between the Indian subcontinent and the bulk of Eurasia.

(2) The Pennsylvanian clastic wedge of the Appalachian foreland basin is a tectonic analogue of the fluviatile Siwalkis and associated upper Tertiary strata of the Indo-Gangetic lowland at the foot of the Himalayas. By implication, the so-called Alleghenian orogeny thus marked the time of final closure of the Paleozoic ocean that lay between North America and Africa.

(3) The Pennsylvanian turbidites of the Ouachita system represent a subsea fan complex poured longitudinally into a remnant ocean basin then remaining south of North America. Similarly, the turbidites of the Bengal fan have



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[2] Present address: Exxon Production Research Company, P.O. Box 2189, Houston, Texas 77001.

[3] Present address: Department of Geology, University of New Mexico, Albuquerque, N.M. 87131.

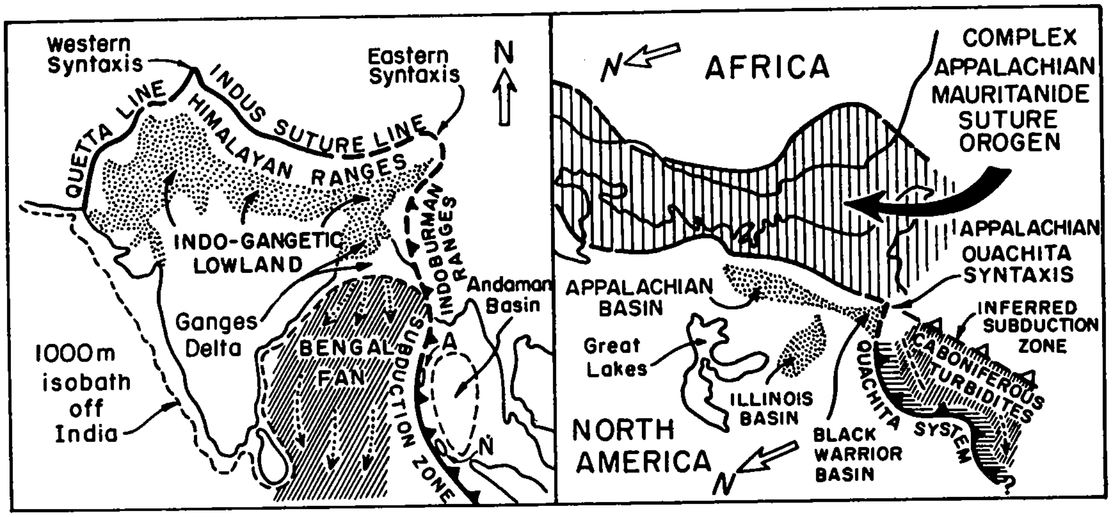


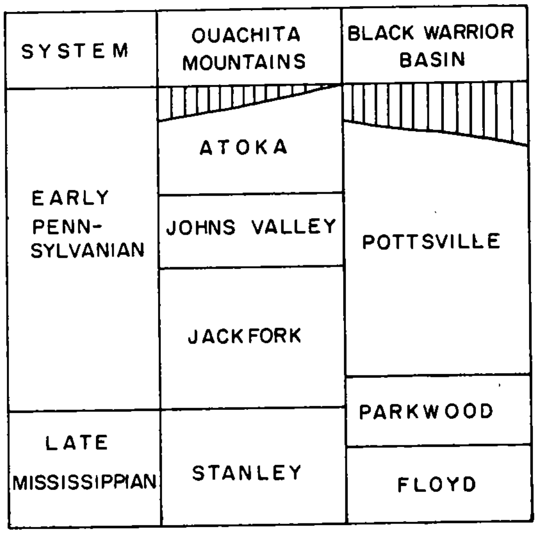
FIG. 1.—Analogical comparison (at same scales) of Cenozoic Himalayan-Bengal system (left) and Carboniferous Appalachian-Ouachita system (right). Stipples indicate major depocenters for nonmarine and shallow marine strata. Diagonal rules indicate deep-sea turbidite fans. On right, inferred subduction zone is analogous to Andaman (A)-Nicobar (N) subduction zone on left, and Carboniferous turbidite fan is shown occupying a remnant ocean basin prior to a Carboniferous arc-continent collision that formed the Ouachita orogenic system (also shown as known today by horizontal rules beside thrust front).

been fed into the head of the Bay of Bengal by generally longitudinal drainage of the Himalayan ranges. The immense Ganges delta lies at the head of the oceanic Bay of Bengal, and also lies along the trend of the continental Indo-Gangetic lowland. Similarly, thick Pennsylvanian deltaic complexes of the Black Warrior basin may form the depositional link between molasse-like deposits of the Appalachian basin and flysch-like deposits of the Ouachita system. The substratum upon which the Ouachita turbidites of Pennsylvanian age were deposited is represented by the earlier deep-marine Paleozoic strata now exposed in the core of the Ouachita Mountains.

(4) The Ouachita orogeny was a geologic event for which there is no analogy yet in the Himalayan-Bengal region. From the comparatively brief duration of thrusting and from the general lack of precursor effects along the southern continental margin of North America, we infer that the Ouachita orogeny was caused by an arc-continent collision. The orogeny thus marked the ultimate closure of the remnant ocean basin, whose turbidites were thereby deformed and thrust over the adjacent continental margin. An event of this kind could close the Bay of Bengal if activity along the flanking Andaman-Nicobar subduction zone were to continue until the island arc was juxtaposed against the margin of peninsular India.

PURPOSE

Sands of the Ganges delta and the Bengal fan clearly have the same provenace in part, for the delta is along the dispersal route for much of the fan sediment. Similarly, our tectonic analogy for the Pennsylvanian of the Appalachian-Ouachita region predicts that the



SYSTEM	OUACHITA MOUNTAINS	BLACK WARRIOR BASIN
EARLY PENNSYLVANIAN	ATOKA	POTTSVILLE
	JOHNS VALLEY	
	JACKFORK	
LATE MISSISSIPPIAN	STANLEY	PARKWOOD
		FLOYD

FIG. 2.—Generalized Carboniferous stratigraphy of the Ouachita Mountains (Morris, 1974a, b) and the Black Warrior basin (Thomas, 1972; Wanless, 1967).

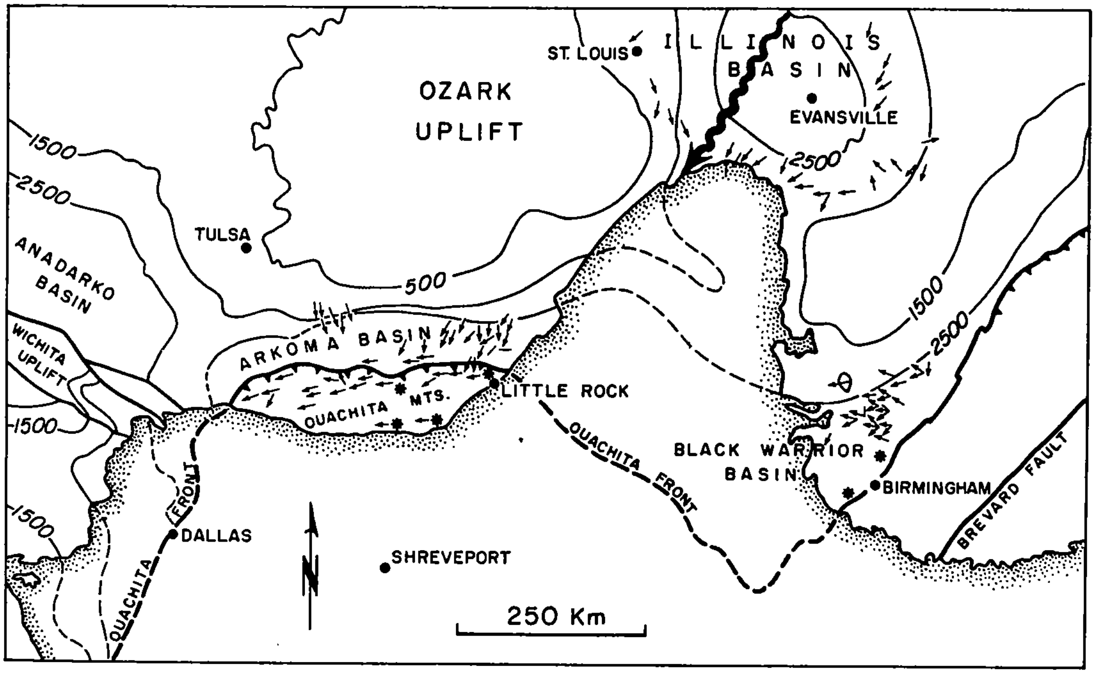


FIG. 3.—Regional tectonic sketch map showing geographic relations between Ouachita Mountains (and adjacent Arkoma basin), Illinois basin, and Black Warrior basin. Basement contours at 500 m, 1,500 m, and 2,500 m after King (1969). Stippled line is outcrop edge of Mesozoic-Cenozoic sequence of coastal plain. Carboniferous paleocurrents (indicated by arrows) from Morris (1974b) for Ouachita Mountains, Potter and Pryor (1961) and Pryor and Sable (1974) for Illinois basin, and Metzger (1965) for Black Warrior basin. Stars in Ouachita Mountains and Black Warrior basin indicate main collecting sites for this study.

fluvio-deltaic sandstones of the Black Warrior basin had the same provenance in part as did the turbidite sandstones of the Ouachita Mountains. The purpose of this paper is to report our petrographic test of this prediction. We show that the populations of lithic sand grains in selected samples from the two areas are indistinguishable. We conclude that Pennsylvanian sands of the Black Warrior and Ouachita areas probably were derived in part from the same source rocks. Moreover, the predominance of sedimentary and metasedimentary detritus in both areas is fully compatible with derivation from a collision orogen, as our tectonic analogy would suggest. The scarcity of detrital feldspar and volcanic lithic fragments apparently precludes derivation from an arc orogen.

PROVENANCE-DISPERSAL RELATIONS

Turbidite paleocurrents in the Stanley Shale, Jackfork Sandstone, and Atoka Formation (Fig. 2) of the Ouachita Mountains (Fig. 3) are generally westerly (Morris, 1974b), or longitudinal with respect to the overall trend of the Ouachita system. Following careful review of previous work on the provenance and dispersal of sediment in the Jackfork, Morris (1971, p. 396–402) reached the following conclusions (paraphrased here), which are also applicable with minor adjustments to the other Carboniferous turbidite units (Morris, 1974a):

(1) The dominance of quartzose grains in the sandstones suggests mainly sedimentary and low-grade metasedimentary source rocks.

(2) The paleocurrent pattern reflects sand deposition along the axis of a deep trough whose floor sloped west, and which received only minor contributions of clastic sediment from the shelf seas lying immediately to the north.

(3) Major sand delivery to the trough floor (or elongate subsea fan and abyssal plain) occurred at two places: (1) the terminus of fluvial systems crossing the Illinois basin (Fig. 3) reached the northern flank of the depositional basin near the present Mississippi River (*e.g.*, Pryor and Sable, 1974); (2) coeval deltaic deposits (Fig. 2) in the Black Warrior basin (Fig. 3) mark the shallow eastern end of the depositional basin from which the bulk of the clastic sediment was supplied.

The Black Warrior basin lies at the southern end of the Appalachian foreland basin (Graham, *et al.*, 1975). Carboniferous dispersal of sediment was northwestward off the Alleghenian orogen into the foreland basin, thence southwestward parallel to the axis of the basin. Paleocurrents on the outcrop in the Black Warrior basin are westerly as required by the Morris model. Southward thickening of fluvial clastics in the subsurface suggests that some contributions of sediment to the deltaic complex of the Black Warrior basin came also from uplifts near the buried juncture or snytaxis between the Appalachian and Ouachita systems. By analogy with the Assam-Bangladesh lowlands and Ganges delta within the curve of the Himalayan-Indoburman syntaxis, we propose that the Black Warrior basin in the Carboniferous was nestled within the curve of the Appalachian-Ouachita syntaxis, which thus served to funnel sediment westward into the Ouachita region of continued turbidite sedimentation (cf. Thomas, 1974; Hobday, 1974).

Morris (1971) noted the intercalation and mingling of sands of contrasting compositional maturity in the exposed carboniferous sequence of the Ouachita Mountains. He inferred that (1) the more quartzose sands reflect derivation mainly through the Illinois basin, although some doubtless came directly off the craton farther west, and (2) the less quartzose sands reflect derivation through the Black Warrior basin, where orogenic influences far outweighed cratonic ones. Pryor and Sable (1974) also show that sandstones deposited within the Illinois basin became progressively less quartzose during the Carboniferous as the influence of sediment shed westward from the Alleghenian orogen in the Appalachian belt became more pronounced in relation to sediment shed southward from the interior of the craton. Similarly, the increasing importance of orogenic sources through the Carboniferous apparently is evident in the Ouachita turbidites as well, for sandstones are generally less quartzose and more lithic in the Atoka Formation than in the older Jackfork Sandstone (see Morris, 1974a, b).

PROVENANCE-PETROLOGY RELATIONS

Effective comparison of detrital modes for Carboniferous sandstones in the Ouachita Mountains and the Black Warrior basin requires carefully designed observations. Information in the literature is inadequate, but it is clear from previous studies (see below) that the Ouachita rocks are typically more quartzose than the coeval Pottsville sandstones in the Black Warrior basin. This relationship is expected for two reasons: (1) mixing of the less quartzose Black Warrior sand with more quartzose sands with cratonic affinities, and (2) preferential loss of lithic fragments during further westward transport. Feldspar is a distinctly minor component in both areas. We conclude that primary emphasis must be placed on the types of lithic fragments in the two areas.

Consequently, standard QFL plots do not compare appropriate parameters in sandstones from the two areas. Accordingly, we have selected a set of a dozen Ouachita sandstones with relatively high contents of lithic fragments to compare in detail with a dozen typical Pottsville sandstones from the Black Warrior basin. In each rock we made special counts of lithic grains, in addition to standard QFL counts; the small number of samples treated in detail in this fashion would be troublesome were it not for the remarkable homogeneity of our results (see below).

The most ambiguous facet of the standard QFL population is the category to which polycrystalline quartzose lithic fragments of chert, quartzite, and the like are assigned. Assignment to Q, as is usual (Dickinson, 1970), emphasizes aspects of maturity; whereas, assignment to L emphasizes aspects of provenance. We here introduce a simple device to eliminate ambiguity on this point (see Table 1): Q_m designates monocrystalline quartz grains summed alone and L_t designates total lithic fragments including polycrystalline quartzose grains. Thus, a QFL plot emphasizes maturity and a Q_mFL_t plot emphasizes provenance. Although we here compare types of lithic grains in more detail by means of tables, we also introduce the $Q_pL_vL_s$ plot to display proportions of lithic fragments of quartzose, volcanic-metavolcanic-hypabyssal and unstable sedimentary-metasedimentary character, respectively (see Table 1 for specified relations of L_v and L_s to L, L_t and Q).

PREVIOUS STUDIES

Surprisingly little petrographic data exist in the literature for Ouachita and Black Warrior basin Carboniferous sandstones. In the Ouachita literature, the most valuable and recent information, incorporating some unpublished thesis data, is contained in a summary article by Morris (1974b). Reported clast types and abundances are in good agreement with those recognized in this study (see below): abundant strained and unstrained quartz, polycrystalline quartz, chert, low-rank metamorphic lithic frag-

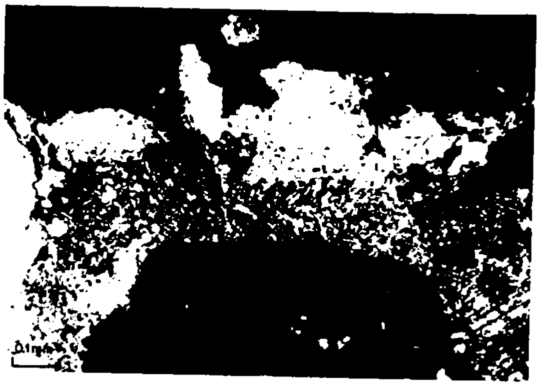


FIG. 4.—Photomicrograph of deformed fine-grained metamorphic lithic fragment surrounded by rigid and undeformed grains, primarily monocrystalline quartz (crossed nicols). This example of pseudomatrix is distinguishable from true matrix (orthomatrix) on the basis of the following criteria: a. wisps extending between rigid grains, b. semi-homogeneity of "gap-filling" which contrasts with "gap-filling" elsewhere in rock, c. compositional and textural similarities between "gap-filling" and known lithic fragments. (See Dickinson, 1970, for discussion.)

ments, minor feldspar, and minor volcanic lithic fragments. Heavy-mineral assemblages (Bokman, 1953; Goldstein, 1959) including garnet, rutile, tourmaline, zircon, and opaque minerals are not diagnostic, but are compatible with the low-rank metamorphic provenance suggested by the light-mineral petrology.

High matrix values frequently have been reported for Ouachita Carboniferous rocks, and the sandstones hence have been classified as textural graywackes and subgraywackes (*e.g.*, Bokman, 1953). Similarly, recent studies (Morris, 1974b) report 19.5% and 11.4% matrix, respectively, for Atoka and Jackfork sandstones. However, as the Carboniferous of the Ouachita Mountains is recognized as a turbidite-bearing flysch facies (Cline, 1970), the high matrix values are at odds with the low matrix values (< 10%) observed in experimentally produced and naturally occurring recent turbidites (Kuenen, 1966). This contradiction, the so-called "graywacke problem" (Cummins, 1962), is largely resolved by recognition of interstitial material as new-growth phyllosilicate cement and deformed pore-filling, fine-grained lithic fragments (Dickinson, 1970). In Ouachita rocks we have observed a continuum of deformation of relatively plastic fine-grained metamorphic

TABLE 1.—*Grain parameters*

(a) $Q = Q_m + Q_p$
where Q = total quartzose grains
Q_m = monocrystalline quartz grains
Q_p = polycrystalline quartzose grains

(b) $L_t = L + Q_p$
where L_t = total aphanitic lithic fragments

(c) $L = L_v + L_s$
where L_v = volcanic-metavolcanic-hypabyssal lithic fragments
and L_s = aphanitic sedimentary-metasedimentary lithic fragments

Note: Metamorphosed variants of L_v and L_s can also be grouped together and designated separately as L_m for some purposes, but this approach is not necessary or helpful in the present case.

TABLE 2.—*Means and standard deviations for each operator*

Each value is calculated with respect to results from independent point counts of 12 Black Warrior basin (BWB) or Ouachita (OUA) thin sections by Graham (SAG), Ingersoll (RVI), and Dickinson (WRD); see Table 1 for symbols.

	SAG	RVI	WRD
Interstitial (% total rock)			
BWB	6.5 ± 1.7	5.1 ± 1.9	6.0 ± 2.2
OUA	7.4 ± 1.6	8.8 ± 3.2	6.0 ± 2.4
Mica (% total framework)			
BWB	2.2 ± 1.6	2.3 ± 1.1	3.1 ± 2.0
OUA	2.5 ± 1.5	0.9 ± 0.6	1.0 ± 0.8
Q_m (% QFL)			
BWB	43.6 ± 7.9	44.0 ± 6.6	44.2 ± 6.0
OAU	69.5 ± 8.0	69.3 ± 9.6	67.0 ± 10.0
F (% QFL)			
BWB	5.7 ± 1.0	6.9 ± 2.2	6.3 ± 2.4
OAU	2.6 ± 1.5	1.6 ± 1.3	3.8 ± 1.6
L_t (% QFL)			
BWB	50.5 ± 7.9	49.2 ± 7.7	49.5 ± 5.3
OAU	27.9 ± 7.6	29.1 ± 9.0	29.2 ± 10.1
Q_p (% L_t)			
BWB	38.2 ± 5.0	31.6 ± 7.7	36.3 ± 5.0
OAU	39.4 ± 6.6	38.1 ± 8.5	37.2 ± 5.0
L_v (% L_t)			
BWB	5.4 ± 2.2	3.5 ± 1.6	5.4 ± 2.8
OAU	3.3 ± 2.5	2.6 ± 1.5	3.1 ± 2.1
L_s (% L_t)			
BWB	55.3 ± 5.0	59.9 ± 8.4	58.4 ± 5.7
OAU	56.7 ± 8.5	57.2 ± 7.4	59.7 ± 5.3

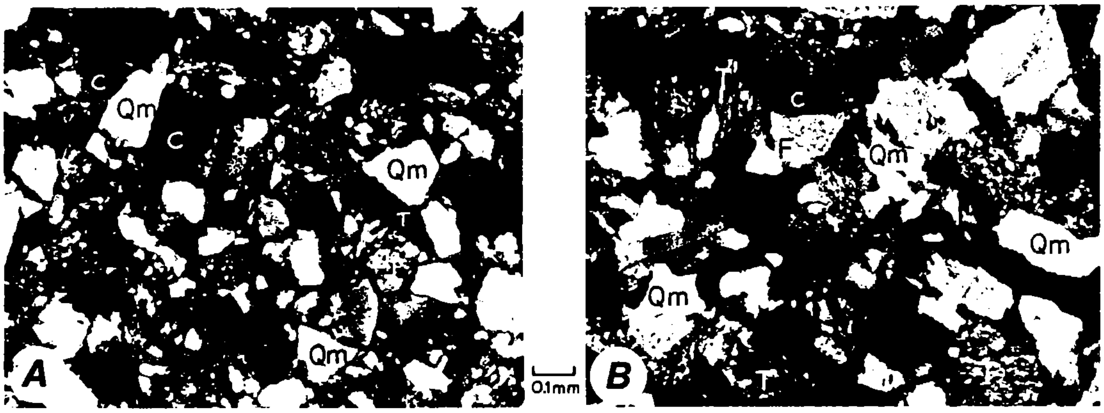


FIG. 5.—Photomicrographs of general fields of view (crossed nicols). Selected diagnostic grains are labelled as follows: C: chert, F: feldspar, M: mica, Q_m: monocrystalline quartz, Q_p: polycrystalline quartz, T: tectonite lithic fragment. Many of the obscure grains would be readily identifiable at higher magnifications. A. Lithic-rich Ouachita sandstone (sample O12). B. Lithic-rich Black Warrior basin sandstone (sample B7). (See Tables 3 and 4 for compositional data.)

lithic fragments, from rounded detrital grains, through flattened but recognizable lithic fragments (Fig. 4), to pseudomatrix composed of extensively deformed lithic fragments. In the latter instance, careful study of fabric in interstitial areas is critical for discriminating between deformed lithic pseudomatrix and true matrix. Whole rock interstitial percentages reported here are less than 10% (Table 2) and are compatible with a turbidite origin for the sandstones. It should be noted, however, that the coarsest sandstones available were sampled in the present study, whereas many Ouachita sandstones are fine-grained. Consequently, previously reported high matrix values alternatively may reflect (1) operator judgment of the matrix grain-size threshold, or (2) actual high original matrix values, which are possible in very fine-grained turbidite sandstones (Kuenen, 1966).

Petrographic studies of Black Warrior basin sandstones are few in number. Ehrlich (1965) noted that his outcrop and core samples from Alabama are composed on the average of 90% "greenschist detritus" and quartz. Quartz content ranges between 50 and 100%. Chert and feldspar are present in minor amounts. In another unpublished study, Bryan (1963) locally found a heavy mineral assemblage of staurolite, kyanite, epidote, garnet, muscovite, chlorite, tourmaline, and zircon. The available literature thus suggests important low-rank metamorphic source terranes for Carboniferous sandstones of both the Ouachitas and the Black Warrior basin. Davis and Ehrlich (1974, p. 117) report a local increase in the content of volcanic lithic fragments in the southernmost Black Warrior basin, but our results (see below) do not reflect such a trend.

SAMPLE COLLECTION

Samples of Carboniferous sandstones were collected by Graham and Dickinson during reconnaissance visits to the Ouachita Mountains and Black Warrior basin in 1973 and 1974. Coarse-grained, unweathered, lithic sandstones (Fig. 5) were sampled preferentially to facilitate determination of lithic modes. From the $\sim$250 total samples collected, twenty-four of the most suitable, twelve from each area, were point-counted as described below.

Black Warrior basin samples represent the lower, middle, and upper Pottsville section exposed in Alabama. Sampling was coordinated with sections described by Metzger (1965). The Ouachita samples, all from Arkansas, represent the lower Atoka of the frontal Ouachitas, and the lower and upper Jackfork, Johns Valley, and lower Atoka of the southern Ouachitas. Most of the Ouachita localities are included in Stone and others (1973) and Walthall (1967). Specific sample localities are listed in the Appendix.

PETROGRAPHIC PROCEDURES

Accurate determination of detrital modes of lithic types is essential in paleogeographic reconstructions based on sandstone petrology (Dickinson, 1970; Suttner, 1974). To insure reproducibility of results (always a problem with fine-grained, slightly altered lithic grains) we employed a multiple-operator method of

TABLE 3.—*Modal point counts of selected Black Warrior basin samples*

Values shown are based on 600 total rock points and 300 total lithic points (see text for counting procedures); I is interstitial material and M is mica; see Table 1 for other symbols.

Sample No.	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	Ave
% total rock													
I	6	8	7	6	8	6	3	7	5	6	8	7	6
% total framework													
M	4	3	4	1	4	1	1	3	3	2	2	4	3
% QFL													
Q	58	67	60	63	60	66	64	58	57	58	68	59	62
F	7	8	5	6	7	5	6	7	8	5	5	7	6
L	36	24	36	31	33	28	30	35	35	37	27	35	32
% L_t													
1. Volcanic-hypabyssal	5	2	3	5	5	5	7	6	5	6	4	4	5
2. Polycrystalline mica	10	5	7	7	5	4	6	6	6	5	3	4	6
3. Quartz-mica tectonite	50	46	49	50	43	42	34	48	47	44	45	46	45
4. Foliate metaquartzite	12	15	14	13	16	16	11	9	18	18	15	19	15
5. Chert	6	8	7	5	9	9	11	8	5	7	8	7	8
6. Argillite-shale	6	6	5	7	8	7	10	10	4	5	9	7	7
7. Aggregate quartz	12	16	12	13	10	14	19	11	13	13	13	12	13
8. Indeterminate-miscellaneous	0	3	3	1	4	2	2	3	1	2	2	1	2
% (L_t-8)													
Q_p $(4+5+7)$	30	40	34	31	37	40	42	28	37	39	37	39	36
L_s $(2+3+6)$	65	58	63	64	58	55	51	66	58	55	59	57	59
L_v (1)	5	2	3	5	5	5	7	6	5	6	4	4	5

TABLE 4.—*Modal point counts of selected Ouachita Mountains samples*

Values shown are based on 600 total rock points and 300 total lithic points (see text for counting procedures); I is interstitial material and M is mica; see Table 1 for other symbols.

Sample No.	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	Ave
% total rock													
I	9	6	11	6	5	5	6	10	8	8	8	8	7
% total framework													
M	1	1	2	2	1	1	2	1	1	2	2	3	2
% QFL													
Q	81	88	80	81	83	90	70	80	76	75	80	71	79
F	3	3	4	4	2	1	3	2	2	2	1	4	3
L	16	9	16	15	16	9	28	18	22	23	19	25	18
% L_t													
1. Volcanic-hypabyssal	1	2	1	1	6	5	4	2	1	4	4	4	3
2. Polycrystalline mica	3	9	6	2	7	2	8	4	4	4	3	2	5
3. Quartz-mica tectonite	47	42	45	51	40	37	52	55	55	48	49	45	47
4. Foliate metaquartzite	17	17	13	15	14	15	7	12	11	9	8	15	13
5. Chert	4	10	9	10	11	15	8	10	9	10	7	15	10
6. Argillite-shale	2	4	8	6	10	9	4	6	8	6	4	4	6
7. Aggregate quartz	25	16	15	14	12	15	17	9	10	18	24	12	16
8. Indeterminate miscellaneous	0	0	2	0	0	2	0	2	2	0	0	1	1
% (L_t-8)													
Q_p $(4+5+7)$	46	43	38	39	36	46	32	32	31	37	39	43	39
L_s $(2+3+6)$	53	55	61	60	57	49	64	66	68	58	57	52	58
L_v (1)	1	2	1	1	6	5	4	2	1	4	4	4	3

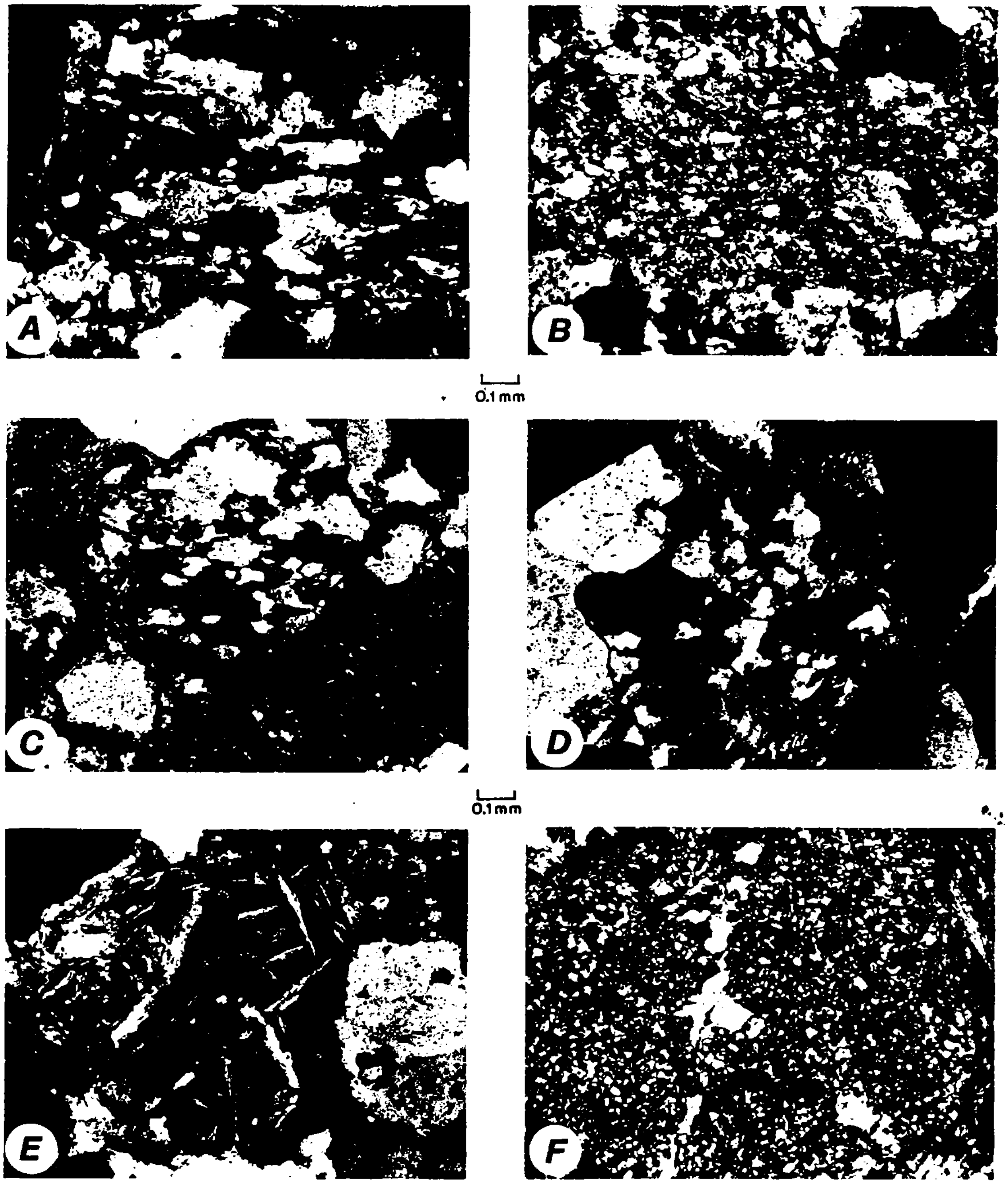


FIG. 6.—Photomicrographs of lithic fragments from the Ouachitas and the Black Warrior basin. A. Quartz-mica tectonite with planar fabric. B. Fine-grained tectonite of uncertain composition, probably a low-grade metasediment. C. Quartz tectonite with planar fabric. D. Polycrystalline quartz aggregate without significant planar fabric. E. Microlitic volcanic. F. Chert. All photomicrographs were taken with crossed nicols.

point-counting. Each operator (SAG, RVI, and WRD) counted one-third of each section (12 from each area), results were compared, and slides were recounted if significant discrepancies occurred. Table 2 shows means and standard deviations for each operator for the important parameters. Each quantity represents 12 counts of different parts of 12 slides by each operator. Standard deviation values for each operator overlap in every case. Large standard deviations for individual operators for a given parameter with very similar means for all operators suggest that variations between slides are significantly greater than variations between operators or within slides. These results increase our confidence in the reproducibility of our data.

Our counting involved two steps: (1) Q_mFL_t and (2) lithic types. The Q_mFL_t data were obtained by each operator counting 200 total points on his third of a slide (*i.e.*, 600 total points per slide). Interstitial (matrix and cement), mica, and miscellaneous-indeterminate were included. A rough count of feldspar type was tallied based on a doubly-stained portion of each slide and twinning types. Plagioclase is approximately twice as abundant as potassium-feldspar, but the feldspar population is too small for a statistically valid determination. Data on relative abundances of lithic types were obtained by a second count of 100 lithic points by each operator on one-third of each slide (*i.e.*, 300 total points per slide).

LITHIC TYPES

Tables 3 and 4 list the eight categories of lithic fragments used in this study. A brief description of each type is as follows:

(1) *Volcanic-metavolcanic-hypabyssal*: primarily fine-grained felsitic and microlitic fragments with minor lathwork textures and rare metavolcanics (see Fig. 6e);

(2) *Polycrystalline mica*: metamorphic mica with prominent planar fabric;

(3) *Quartz-mica tectonite*: metamorphic mica and quartz in varying proportions and commonly, but not necessarily, with planar fabric (see Figs. 6a, 6b, and 4);

(4) *Foliate metaquartzite*: polycrystalline quartz with a planar fabric (see Fig. 6c);

(5) *Chert*: microcrystalline but monomineralic silica aggregates with most domains smaller than the thickness of a standard thin section (see Fig. 6f);

(6) *Argillite-shale*: murky fine-grained argillaceous fragments with occasional enclosed detrital silt clasts;

(7) *Aggregate quartz*: intergrown crystalline quartz without significant planar fabric (see Fig. 6d);

(8) *Indeterminate-miscellaneous*: lithic fragments of unknown or obscure nature.

The polycrystalline mica (2), quartz-mica tectonite (3), and foliate metaquartzite (4) fragments form a continuum of related metamorphic types that are primarily metasedimentary. Similarly, distinguishing unmetamorphosed argillite-shale (6) from metamorphic quartz-mica tectonite (3) is difficult, and at times, arbitrary. Also, foliate metaquartzite (4), chert (5), and aggregate quartz (7), consisting of fine-grained vein quartz, non-foliate quartzite, and other non-foliate quartz aggregates) are textural variants of polycrystalline quartz grains that are operationally difficult to differentiate with consistency. Significant discrepancies in counts by different operators occurred for some slides due to a combination of factors: (1) operator disagreement, (2) intra-slide variations, and (3) grain obscurity. Intra-slide variations become significant when dealing with parameters present in small proportions. Despite these discrepancies, variations between operators are significantly reduced by calculating Q_p $(4 + 5 + 7)$ and L_s $(2 + 3 + 6)$ for each operator (see Table 2). Therefore, our ability to distinguish general lithic types (Q_p, L_v and L_s) is confirmed, although distinguishing sub-types is more arbitrary.

PETROGRAPHIC RESULTS

Tables 3 and 4 present the results of the point counts, and Fig. 7 displays key aspects of the data obtained. The internal consistency of the data from each of the two areas, the Black Warrior basin (Table 3) and the Ouachita Mountains (Table 4), is evident from the numerical arrays in the tables. The more quartzose nature of the Ouachita rocks is clear from Figs. 7a, 7b, and 7c, whereas Fig. 7d shows that the populations of lithic grains in the two sets of sandstones are essentially indistinuguishable quantitatively as well as qualitatively.

Tables 3 and 4 contain recalculated data based on sums of three operators' counts for each sample. I, M, Q_m, F, and L_t are based on counts of 600 points per slide, whereas other parameters are based on either 300 points (lithic types, including Q_p and L_s) or a combination of 600 and 300 points (Q and L). Careful note should be made of how each parameter is normalized for plotting and comparisons. For instance, note that Q_p and L_s in Table 3 are calculated as percentages of L_t minus indeterminate-miscellaneous so that $Q_p + L_v + L_s = 100$ (L_v is always small enough so that its percentage with respect to L_t does not change significantly when the indeterminate-miscellaneous category is accounted for).

Figure 7a is the QFL plot, which clearly shows the more quartzose nature of the Ouachita rocks, as compared to those from the

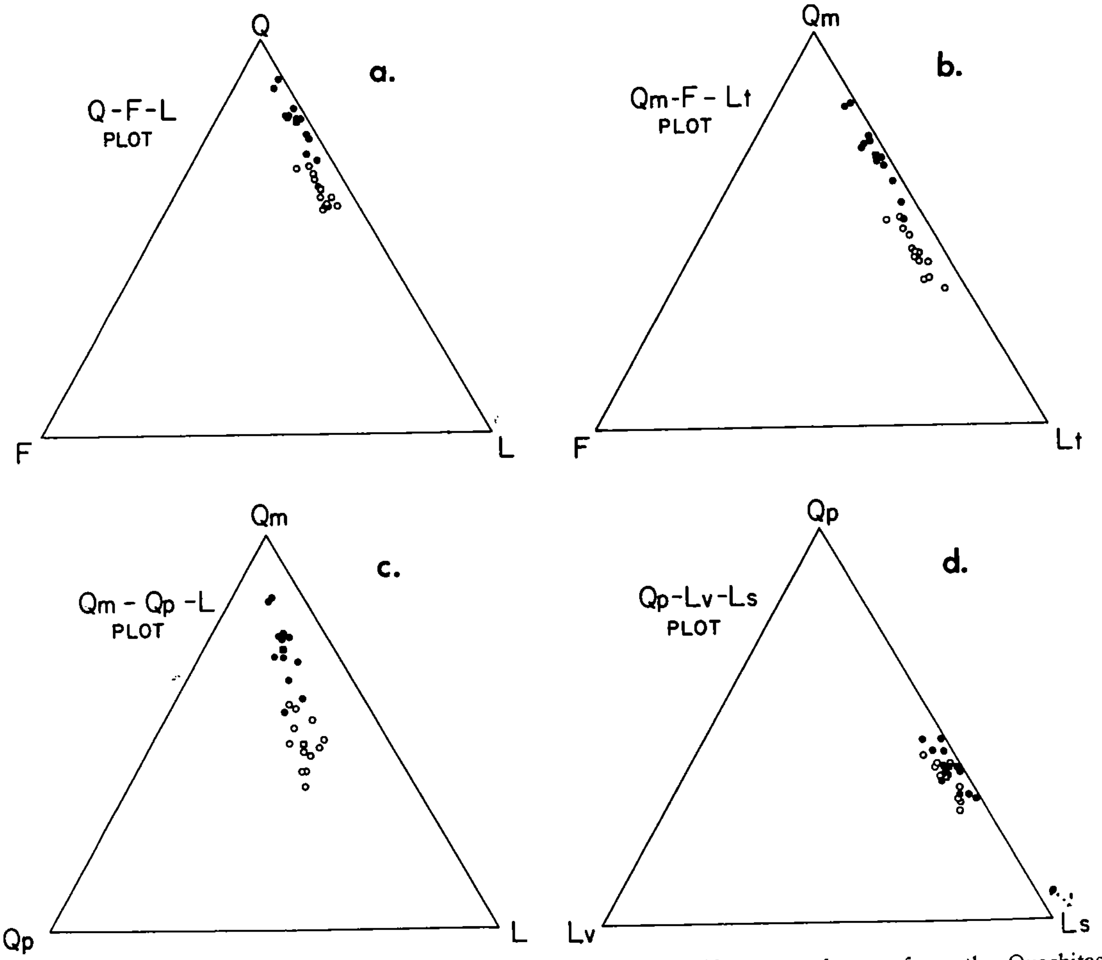


FIG. 7.—Triangular diagrams comparing detrital modes of Carboniferous sandstones from the Ouachitas (solid symbols) and the Black Warrior basin (open symbols); circles represent single samples (see Tables 3, 4), and squares are means for the two populations; see Table 1 for definition of parameters used as end-members and text for discussion of the plots: a, QFL plot; b, Q_mFL_t plot; c, Q_mQ_pL plot; and d, $Q_pL_vL_s$ plot.

Black Warrior basin, and the low feldspar content of both sets of samples. Figure 7b, the Q_mFL_t plot, demonstrates the effect of including Q_p in L_t rather than Q, and again emphasizes the more quartzose nature of the Ouachita rocks. Figure 7c, a special Q_mQ_pL plot, indicates that the Ouachita rocks become more quartzose at the expense of both L and Q_p, although the former declines more rapidly. The combined array of points representing samples from the two areas appear to define a trend directly toward the Q_m pole. This effect could be due to either addition of Q_m from an outside source (Illinois Basin) or subtraction of lithic grain types. It is likely that both these processes operated. Figure 7d, the $Q_pL_vL_s$ plot emphasizes the indistinguishable nature of the lithic populations from the two areas. We also note for emphasis that no lithic fragment in the 3,600 grains counted in either set of samples was compositionally anomalous with respect to lithic fragments from the other set.

GENERAL IMPLICATIONS

The low proportions of feldspars and volcanic lithic fragments among the non-quartzose grains in the Ouachita and Black Warrior rocks virtually preclude the possibility of any major exposures of igneous rocks in the provenance. Instead, sedimentary and metasedimentary rocks must have been the dominant sources. This relation is compatible with the inference that the sediment was derived from a collision oro-

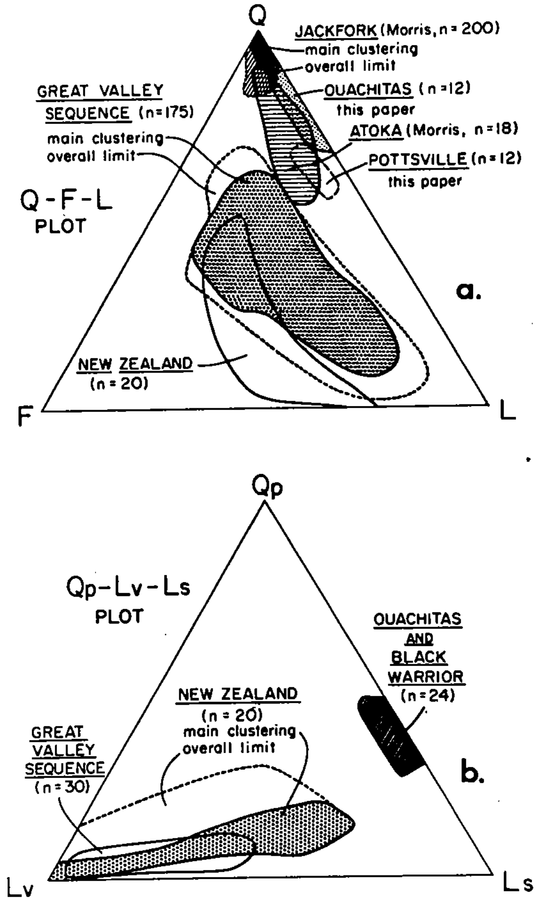


FIG. 8.—Triangular diagrams comparing detrital modes of quartz-rich and more feldspathic suites of graywackes: a, QFL plot; b, $Q_pL_vL_s$ plot. See text for discussion of suites from New Zealand and Great Valley Sequence. Data for the Ouachitas and the Black Warrior basin are taken from this paper; a, fields for Ouachita rocks and for Pottsville rocks of Black Warrior basin are shown separately; b, combined field is plotted for Ouachita and Black Warrior rocks as the two suites are indistinguishable. Data for the Jackfork Sandstone and the Atoka Formation reported by Morris (1974b) from the Ouachitas are also included on the QFL plot to supplement our data and to show the generality of our selective data as a valid index to overall Ouachita petrology.

gen where sedimentary sequences were squeezed and uplifted along a suture belt. Sediment shed from arc orogens, on the other hand, contains higher proportions of igneous feldspars and volcanic lithic fragments (*e.g.*, Dickinson and Rich, 1972). Where thick sequences of graywacke turbidites within orogenic provinces are largely composed of Q and L_s grains, the sandstones likely represent deposition on subsea fans and abyssal plains within remnant ocean basins that were successively filled with sediment shed from the ends of closing suture belts by the longitudinal drainage of highlands along developing collision orogens. Sediment shed directly from arc orogens is conversely characterized by abundant F and L_v grains.

These inferences are supported by fields of variation (Fig. 8) plotted to compare the suites of quartz-rich sandstones reported here with more feldspathic suites from the circum-Pacific region. The two more feldspathic suites represented are the late Paleozoic and early Mesozoic rocks of the so-called New Zealand geosyncline (Dickinson, 1971), and the late Mesozoic rocks of the Great Valley sequence of California (Dickinson and Rich, 1972). The provenance of both the feldspathic suites is inferred to have been an eroding volcano-plutonic orogen along the trend of an active magmatic arc related directly to a convergent plate juncture.

Figure 8a, the QFL plot, shows clearly the contrast in feldspar content between the two types of graywacke suites. Figure 8b, the $Q_pL_vL_s$ plot, shows clearly that the more feldspathic suites, interpreted here as derived from arc orogens, are rich in volcanic and metavolcanic lithic fragments. By comparison, the quartz-rich suites, interpreted here as derived from a collision orogen, are rich in sedimentary and metasedimentary lithic fragments.

Other explanations of the marked differences in sedimentary petrology displayed by the plots of Fig. 8 are less satisfactory. That the differences are quite fundamental deserves emphasis, for the Ouachita, Great Valley, and New Zealand suites as plotted each represent sequences of interbedded graywacke and shale more than 10 km thick. The quartz-rich and more feldspathic suites thus form two contrasting graywacke assemblages of distinctly different types. Only a major difference in provenance of the sort suggested here seems adequate to explain this contrast in graywacke petrology.

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APPENDIX

Sample Locations

B1, B2: Highway cut, Pottsville "A interval," NE ¼ NW ¼, sec. 11, T. 14 S., R. 3 W., Jefferson Co., Ala.

B3, B4: Highway cut, Pottsville "A interval," NE ¼ NW ¼, sec. 14, T. 14 S., R. 3 W., Jefferson Co., Ala.

B5: Highway cut, Pottsville "B interval," NE ¼ SW ¼, sec. 23, T. 14 S., R. 3 W., Jefferson Co., Ala.

B6, B7: Highway cut, Pottsville "C interval," center south line, sec. 23, T. 15 S., R. 3 W., Jefferson Co., Ala.

B8, B9, B10, B11, B12: Road cuts, Pottsville "E and F intervals," S ½, sec. 17, T. 19 S., R. 7 W., Tuscaloosa Co., Ala.

O1: Highway cut (S.R. 365), Atoka Fm., south of Mayflower, Faulkner Co., Ark.

O2: Highway cut, lower Atoka Fm., SE ¼ SE ¼, sec. 32, T. 4 N., R. 20 W., Perry Co., Ark.

O3, O4: Highway cut, lower Atoka Fm., SE ¼

SE ¼, sec. 5, T. 3 N., R. 20 W., Perry Co., Ark.

O5: Highway cut, lower Jackfork Sandstone, E ½, sec. 11, T. 6 S., R. 20 W., Clark Co., Ark.

O6, O7: Spillway cut, upper Jackford Sandstone, cec. 14, T. 6 S., R. 20 W., Clark Co., Ark.

O8: Road cut, Johns Valley Shale, NW ¼, sec. 18, T. 6 S., R. 19 W., Clark Co., Ark.

O9: Road cut, upper Jackfork Sandstone, NW ¼ NW ¼, sec. 18, T. 7 S., R. 25 W., Pike Co., Ark.

O10: Road cut, lower Atoka Formation, NW ¼ SW ¼, sec. 20, T. 7 S., R. 25 W., Pike Co., Ark.

O11, O12: Road cut, lower Atoka Formation, NE ¼ SW ¼, sec. 20, T. 7 S., R. 25 W., Pike Co., Ark.