CHARACTERISTICS AND PROVENANCE OF LOG-TRANSPORTED GRAVELS IN A CARBONIFEROUS CHANNEL DEPOSIT[1]

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ABSTRACT: Gravel, ranging from pebble to boulder size, is preserved inside or dispersed among vitrinized logs within a coastal-channel sandstone sequence of the Upper Pottsville Formation, Black Warrior Basin, northwestern Alabama. The gravel was transported from extrabasinal areas to the coastal regime in log rafts composed of hollow trees. Pebble accumulations represent a partial infilling of the logs while they lay on a gravel-covered stream bed at extrabasinal sites. Cobbles and boulders were transported entrapped within root structures of trees introduced into the river, or may have been trapped on or within log rafts. Only a limited number of clasts were available for study because the mining bench from which they were collected was exposed for a limited time and is now reclaimed. A suite of 300 clasts consists of metamorphic rocks (phyllite, quartzite, schist, and gneiss), igneous rocks (granodiorite and pegmatitic quartz), and sedimentary rocks (coarse- to fine-grained subarkose). The dominance of low- and high-grade metamorphic, plutonic igneous, and sedimentary rocks, and the absence of volcanic or volcaniclastic rocks, indicates an intensely deformed and uplifted source area. When this suite of rocks is compared with the two possible orogenic sources, Ouachitas or southern Appalachian, the southern Appalachian orogen conforms best. This interpretation modifies presently accepted models and indicates an eastern expansion of the source area from the Ouachitas to the adjacent part of the Appalachians during the Early Pennsylvanian.

INTRODUCTION

Except for fragmental ironstone and shale or siltstone chips, gravel is a rare feature in the Carboniferous coal-bearing deposits of the Appalachian region. Where gravel is found, it is commonly encountered as lag deposits at the base of fining-up sandstone sequences. Although gravels of cobble and boulder size occur within coal beds in a geographic range extending from Oklahoma to Ohio (Andrews 1871; Newberry 1874; Orton 1892; Dana 1895; Gresley 1896; McCallie 1903; White 1915; Price 1932; Branson and Merritt 1963; Hemish 1982), it is difficult to assess their mode of transport, because they are generally observed on mine dumps or, under less than desirable conditions, in underground coal mines. This has led to considerable speculation about their manner of emplacement and the source area from which they were derived. A unique accumulation of pebbles, cobbles, and boulders was recently discovered in a Pennsylvanian coal-bearing deposit in the Black Warrior basin of Alabama. The gravels occur at the top of a fining-up sandstone sequence within the Mary Lee coal bed which was well exposed in a surface mine, where critical sedimentological conditions responsible for the emplacement of the gravels are readily observable. Pebbles are common within thin elliptically-shaped envelopes of vitrain, representing coalified logs. Cobbles and boulders are dispersed among these fossilized, prostrate trees. This unusual gravel accumulation provides a precise means to interpret the mode of transport, and it documents a rare taphonomic mechanism for the first time in the geological record.

This gravel accumulation also provides an opportunity for characterizing the rock types exposed in the source area. Previous studies of regional facies distribution and sandstone petrofacies have indicated that terrigenous Carboniferous sediments were derived from both the southern Ouachita and the eastern Appalachian orogens. It has been suggested that an eastern expansion of the source area from the Ouachitas to the adjacent part of the Appalachians occurred as a result of the beginning of the Appalachian orogeny (Mack et al. 1983; Thomas 1988). Precise evidence, however, is needed for the exact timing and areal influence of this expansion. Our results provide direct evidence for the tectonic signature of the southern Appalachian orogen and document the beginning of orogeny that initiated the northwest dispersal of sediment during the Early Pennsylvanian.

The purpose of this report is to describe a unique mechanism for transport of extrabasinal gravel into coastal terrestrial environments and to use the gravel to interpret the most probable provenance for the Black Warrior basin sediments. The result is improvement in the paleogeographic and paleotectonic reconstructions for the basin.

STUDY AREA

The Black Warrior basin is a triangular foreland basin located at the southern end of the Appalachian orogen and is composed of Mississippian and Lower Pennsylvanian strata (Thomas 1974; Horsey 1981). The Pennsylvanian Pottsville Formation is greater than 3000 m thick in the southern part of the Black Warrior basin (Hewitt 1984) but thins to the north due to depositional thinning and post-Pennsylvanian erosion. The study area, located near Carbon Hill (Carbon Hill USGS 7.5 minute quadrangle), Walker County, northwestern Alabama (Fig. 1), is characterized by extensive surface mining that has exposed the Mary Lee coal zone (Lyons et al. 1985). The Mary Lee coal zone is one of seven recognized coal zones in the Black Warrior basin and represents ancient peat accumulation in a coastal regime (Gastaldo et al. 1990). The gravels occur at the top of a local sandstone parting within the Mary Lee coal bed (Fig. 2) at the Gateway Malls Inc. Hope Galloway mine (Secs. 12, 13, and 24, T

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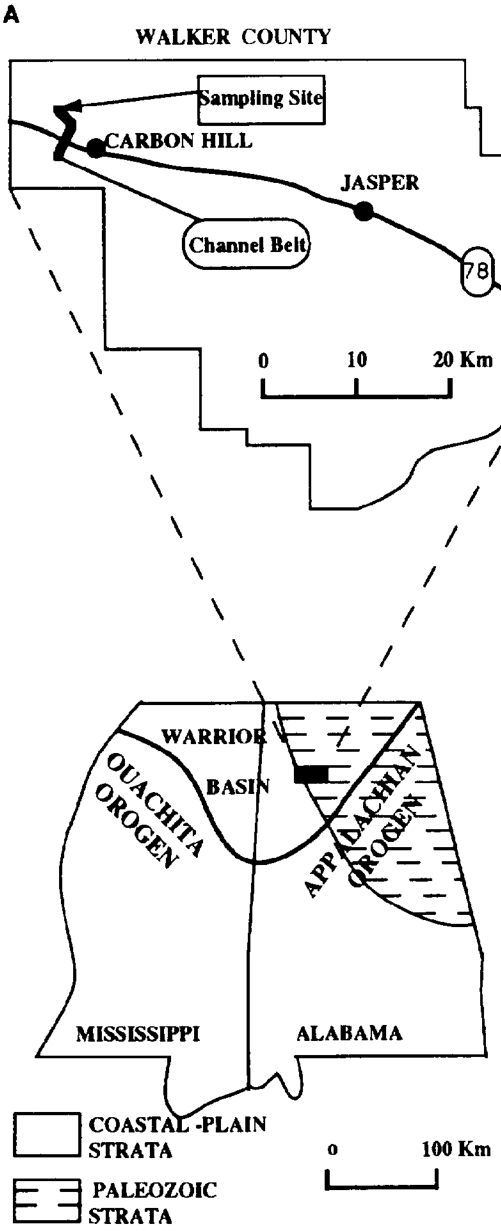

B

	FORMATIONS	COAL ZONES
LOWER PENNSYLVANIAN	UPPER POTTSVILLE (Sandstone, Shale, and Coal, ~ 750 m)	Brookwood Utley Gwinn Cobb Pratt Marry Lee Black Creek
	LOWER POTTSVILLE (mostly Quartzose Sandstone, ~ 350 m)	
MISSISSIPPIAN	PARKWOOD (Sandstone and Shale, ~ 250 m)	
	BANGOR FLOYD TUSCUMBIA (Shale and Limestone, ~ 250 M)	

FIG. 1.—A) Generalized map of the Warrior basin showing location of the study area. (B) General stratigraphic section.

13 S, R 10 W). This parting represents a channel-fill sequence (Degges and Gastaldo 1988). The gravel-bearing layer is overlain by the minable upper bench of the Mary Lee. Surface mining of this bench at several mine sites provided a three-dimensional exposure of the channel sandstone and associated gravel layer. While this bench was exposed, we were able to assess critically the conditions responsible for emplacement of the gravels. Reclamation of the mine was completed in late 1990. The sandstone split is still exposed in abandoned, unreclaimed mine highwalls, but the number of recoverable gravel clasts is small compared to what was available during our 1988–89 field work.

CHARACTERISTICS OF THE GRAVEL-BEARING FACIES

The channel-form sandstone ranges from 0.4 to 2.8 m thick and is characterized by three distinct units (Fig. 2). The lower unit A consists of medium- to fine-grained sandstone with large-scale cross stratification (set thickness > 5 cm) and has a sharp contact with the underlying lower bench of the Mary Lee coal. Erect sandstone-cast lycophyte trunks with associated prostrate log casts and abundant vertical burrows (cf. *Skolithos* or *Monocraterion;* C. Degges, personal communication 1989) are preserved. In at least one case, burrows appear to be associated at the same level with nearby erect lycophyte trunks.

TABLE 1.—*Modal composition of sandstone from unit B*[1]

	Q %	Qm %	Qp %	F %	L %	Lt %
S1	58.9	55.7	3.2	5.1	36.0	39.2
S2	61.0	59.0	2.0	5.0	34.0	36.0
S3	54.7	52.2	2.5	6.3	39.0	41.5
S4	62.7	59.7	3.0	3.7	33.6	36.6
S5	59.0	55.0	4.0	7.3	33.7	37.7
Average	59.2	56.3	2.9	5.5	35.3	38.2

Q: Total quartz (Qm + Qp). Qm: Monocrystalline quartz. Qp: Polycrystalline quartz. F: Total feldspar. L: Micaceous metamorphic fragments + some mica flakes. Lt: Total lithic fragments (L + Qp).

[1] 300 points counted per thin section.

The middle unit B is a fine- to medium-grained sandstone with small-scale cross lamination. Preserved in this unit are numerous, oriented, prostrate, sandstone-cast logs and log compression/impressions or cordaite, lycophyte, and sphenophyte affinities. Abundant vertical (cf. *Skolithos*) and horizontal (*Asterichnus*) burrows are found in this unit. No gravel is found in units A or B.

Five thin sections of sandstone from the unit B were examined microscopically. The sandstone is a fine-grained litharenite composed of well-sorted, subangular quartz, metamorphic rock fragments, and sparse microcline and plagioclase (Table 1). This composition is similar to that reported by Mack (1982) for Black Warrior basin sandstone in Alabama.

The uppermost unit C is gravel-bearing, 0.35 m thick, and consists of alternating bright vitrain bands and very fine-grained sandstone laminations and bands. This unit is in gradational contact with the underlying unit B. The vitrain bands are thin and laterally traceable for meters, and they represent coalified logs of various systematic affinities. Although the logs are flattened and broken on the ends, some general dimensions can be reconstructed. The largest log is on the order of 7 m in length and about 0.5 m in diameter, but most are about 2 m long with a diameter of about 0.3 m. The concentration of vitrinized logs is greatest below the overlying coal bench. Sandstone laminations are lenticular, ranging from a few millimeters to centimeters in thickness, and they pinch out laterally in 2 to 5 m.

Gravels were collected from within and between vitrinized logs at the top of a temporarily abandoned mine bench in an area of more than 2000 m^2. A large number of clasts could not be recovered from other localities because of the limited highwall exposure or the occurrence of mine spoil. The longest axial dimension of 300 gravel clasts was measured, and percentage frequency for each size class was calculated (Fig. 3). The gravel suite consists of mainly pebbles (92%), with minor amounts of cobbles (7.7%) and a single boulder (0.3%). The size frequency distribution of pebbles roughly approximates a log normal distribution with median size 1.9 cm and mean size

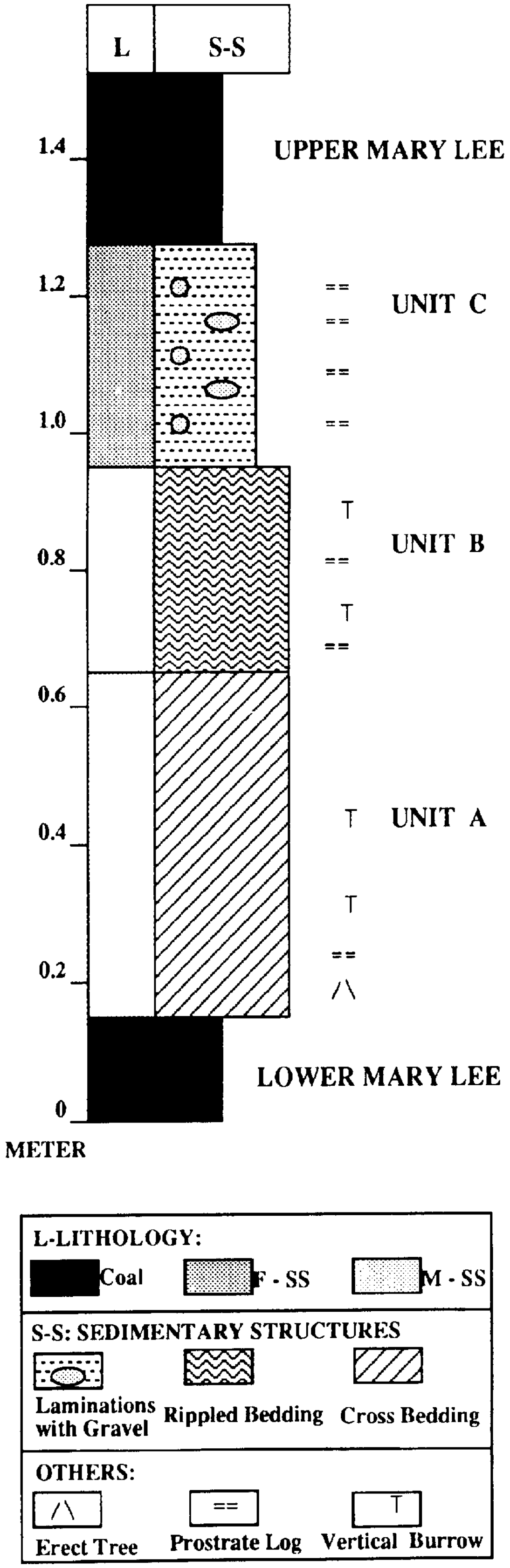

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FIG. 2.—Sandstone channel deposits within the Mary Lee coal at the Carbon Hill locality. The gravel-bearing layer is unit C at the top of the channel sequence.

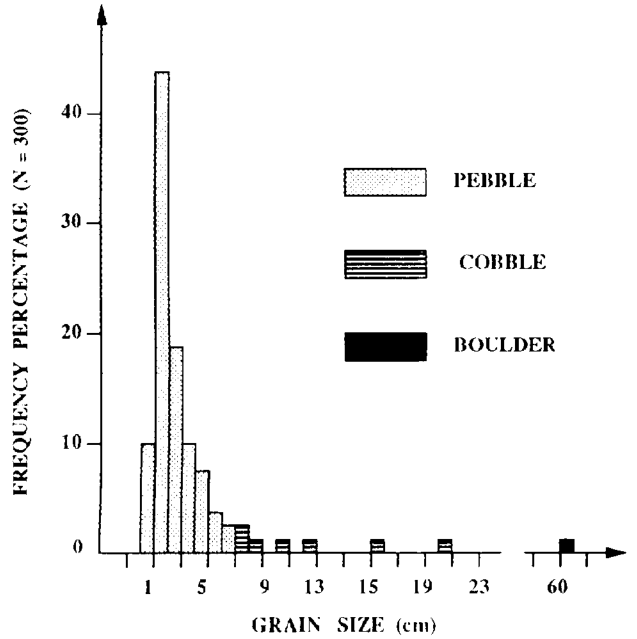

FIG. 3.—Frequency distribution of the gravel size particles from unit C (Fig. 2).

2.3 cm. The numbers of cobbles and boulders are too small to determine distribution characteristics.

Pebbles are concentrated within thin envelopes of vitrain, and individual pebbles are commonly covered with coalified debris. The bands in which pebbles are clustered are elliptically shaped in vertical profile (Fig. 4) and, when viewed on the bedding surface, they are rectangular with impressions of lycophyte or sphenophyte morphofeatures. Vitrain bands surrounding the clustered pebbles represent hollowed trees that have undergone coalification. The pebbles occur as aggregates or as isolate particles inside the logs. In either case the pebbles do not completely fill the logs but are concentrated near their ends. This suggests an early stage of infilling (Rex 1985; Degges and Gastaldo 1989). Pebbles are not associated with the very fine-grained sand matrix among or within logs that are sandstone filled. Neither are pebbles found in other parts of the sandstone-channel facies (units A and B). This mode of occurrence indicates that there is no hydrodynamic relationship between the sand within the channel fill and the pebbles associated with the logs. The pebbles, then, were transported and deposited by a mechanism different from the bedload now represented by the sand layers.

In contrast to the pebble distribution, cobbles and boulders are isolated and dispersed randomly within the log-bearing layer. The largest boulder found has an exposed diameter of 60 cm, but the actual size is larger because part of the boulder was still embedded and difficult to excavate. It truncates the surrounding sandy laminations, and overlying laminations curve around the boulder. This demonstrates that the boulder was deposited earlier and had a transport mechanism different from that of the surrounding sand beds.

FIG. 4.—Photograph of elliptical vitrain bands (V) enclosing aggregate of pebbles (P). The vitrain bands represent a coalified hollowed log.

The 300 clasts from the gravel-bearing layer were identified on the basis of mineralogical and textural characteristics (Table 2; Figs. 5, 6). A histogram of the composition is illustrated in Figure 7. These gravels are petrologically diverse, consisting of sedimentary rocks (coarse- to fine-grained lithic sandstone), metamorphic rocks (phyllite, schist and gneiss), and igneous rocks (granodiorite and pegmatitic quartz). In addition, there are clasts of quartz arenites that display, in thin section, in-

TABLE 2.—*Petrographic characteristics of gravel clasts*

Rock Types (N = 95)[1]	Mineralogy[2]	Textures
Gneiss (N = 2)	Quartz (90%) Feldspar (5%) Muscovite (5%)	Alternation of parallel-orientated muscovite and quartzo-feldpathic layers. Myrmekitic texture in feldspars.
Schist (N = 12)	Quartz (83%) Muscovite & Biotite (16%) Feldspar (1%)	Anhedral quartz grains are recrystallined. Interlayered mica and quartz.
Quartzite (N = 20)	Quartz (> 95%) Few Feldspars and Biotite	Anhedral interlocked quartz.
Granodiorite (N = 25)	Plagioclase (57%) Quartz (31%) Muscovite (10%) Few K-feldspars and Garnet	Plagioclase and muscovite grains are subhedral; quartz is anhedral. Coarse-grained hypidiomorphic texture.
Sandstone (N = 36)	Quartz (82.7%) Feldspar (15.7%) Sedimentary rock fragments (1.7%)	Medium- to coarse-grained, moderate sorting. Mixture of rounded and subangular grains.

[1] Numbers of gravel clasts examined. Remainder of the collection includes 125 phyllite and 80 pegmatitic quartz clasts.

[2] Percentage from 300 point counts of one representative thin section per rock type.

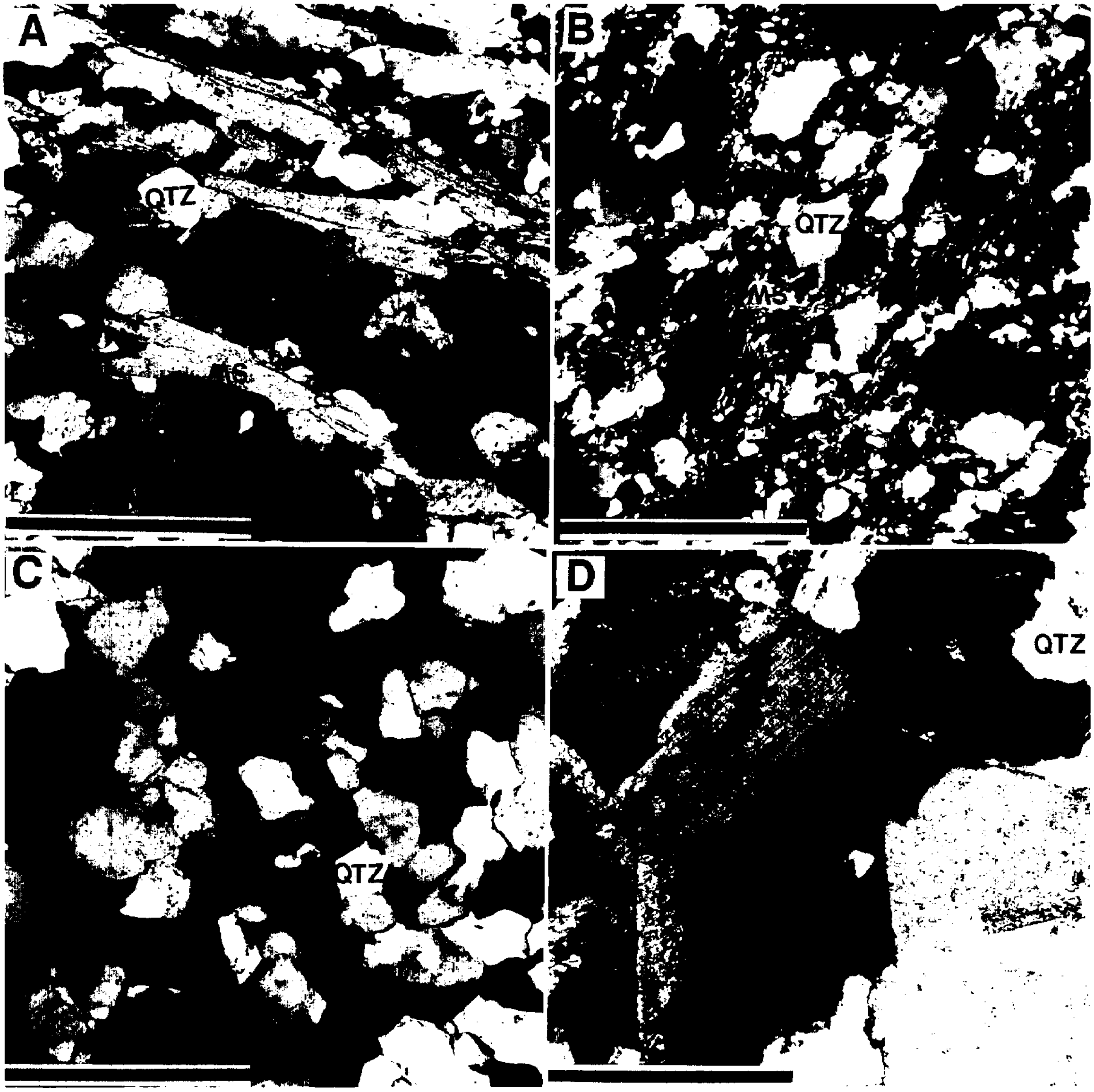

FIG. 5.—Photomicrographs of gravel clasts. **A**) Gneiss composed of parallel layers of muscovite (MS) and quartz (QTZ) and feldspar. **B**) Schist with a parallel arrangement of muscovite (MS), showing fissility. **C**) Metamorphosed quartz arenite with intergrown grains and overgrowths in intergrain areas. **D**) Granite with plagioclase (Pl), muscovite, and quartz, showing a hypidiomorphic texture. Bar scale = 1 mm.

tergrown grains and overgrowths. While the textural characteristics of these rocks suggest only a modest degree of metamorphism, the complete absence of sedimentary structures in large specimens indicates a degree of metamorphism beyond minor deformation, and such clasts have been included among the metamorphic rocks as quartzite. Rocks classified as metamorphic rocks are the dominant rock types and comprise more than half of the gravel clasts. Each size class of the gravel contains distinct rock types, and the composition varies with grain size (Fig. 8). This may be attributed to the varying block-forming capability of different rock types and their resistance to abrasion during transport.

To compare the composition of the channel sandstone with that of the sandstone cobbles recovered from the gravel accumulation, five thin sections of sandstone clasts were examined, and 300 grains were point-counted for each thin section. The sandstone clasts are a medium- to coarse-grained subarkose, consisting of quartz, plagioclase plus potassium feldspars, and sedimentary rock fragments (Table 3)

Based on the sedimentological, geomorphological, and paleontological features of this coal split, the gravel-bearing layer is interpreted to be an ancient log-jam (Degges and Gastaldo 1988). The gravel-bearing layer was deposited during, or resulted in, the abandonment of the sandstone channel transecting the peat swamp. Subsequent to abandonment and channel filling, peat accu-

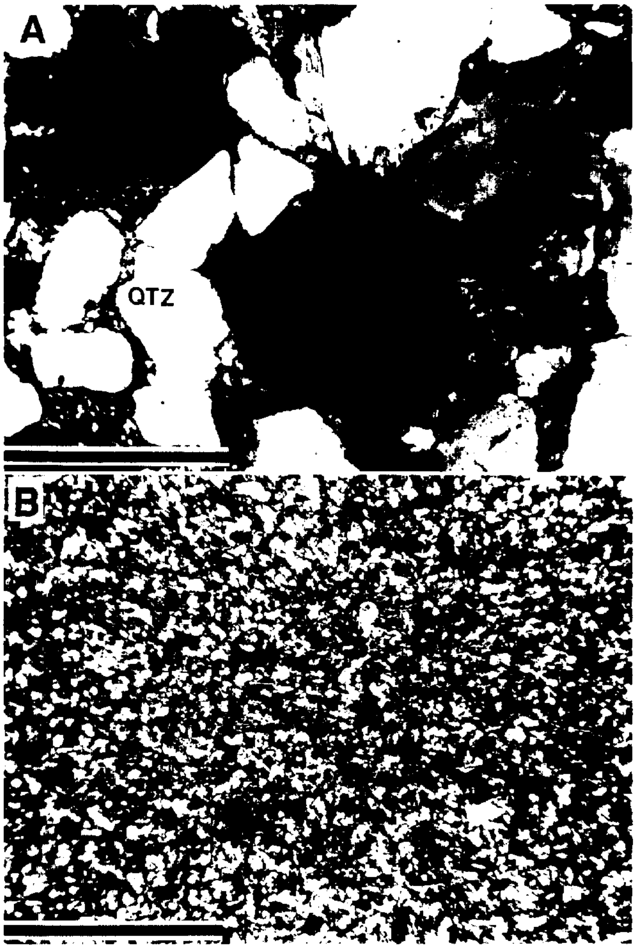

FIG. 6.—Photomicrographs of representative samples of gravel and channel sandstone. A) A coarse-grained subarkose from gravel clast consisting of quartz (82.7%), feldspar (15.7%), and sedimentary rock fragments (1.6%). B) A fine-grained litharenite from the channel sandstone deposit composed of quartz (59.2%), feldspar (5.5%), and metamorphic fragments and some mica (35.3%). QTZ—quartz, PL—plagioclase. Bar scale 1 mm.

mulation resumed, resulting in the upper bench of the Mary Lee coal.

TRANSPORT MECHANISMS

Most gravel clasts are found inside the logs, and only larger clasts are dispersed among them. This suggests that the pebbles are hydrodynamically unrelated to the larger clasts. The emplacements of the two clast groups, therefore, may owe their origins to different transport mechanisms.

Infilling Processes and Transport of Pebble-Cast Logs

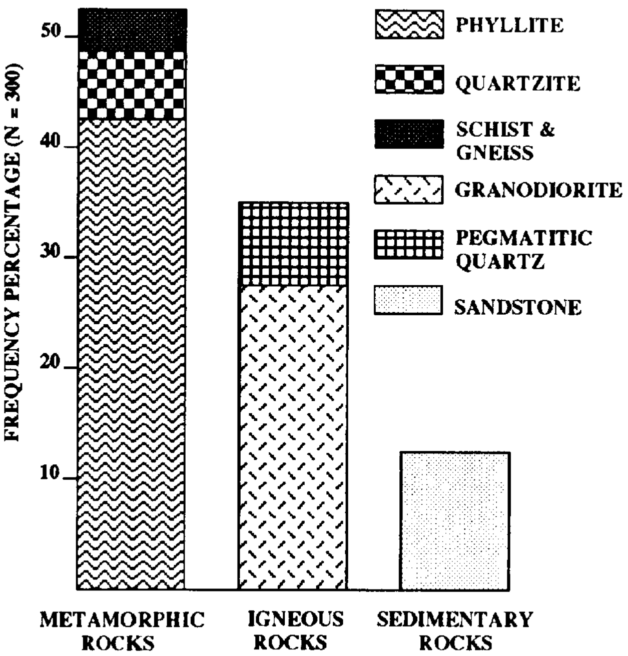

FIG. 7.—Composition of 300 gravel clasts from unit C (Fig. 2).

There are two possible explanations for the phenomenon that pebbles are preserved inside the logs at the top of a channel-fill sequence within a coastal coal. The first is that the log-infilling process occurred far upstream, after which the pebble-bearing logs were transported to the coastal regime where they were deposited and preserved. The second is that, following the infilling process, the logs were buried in place without subsequent transport. A discussion of infilling mechanisms of hollowed logs is needed to help resolve these hypotheses.

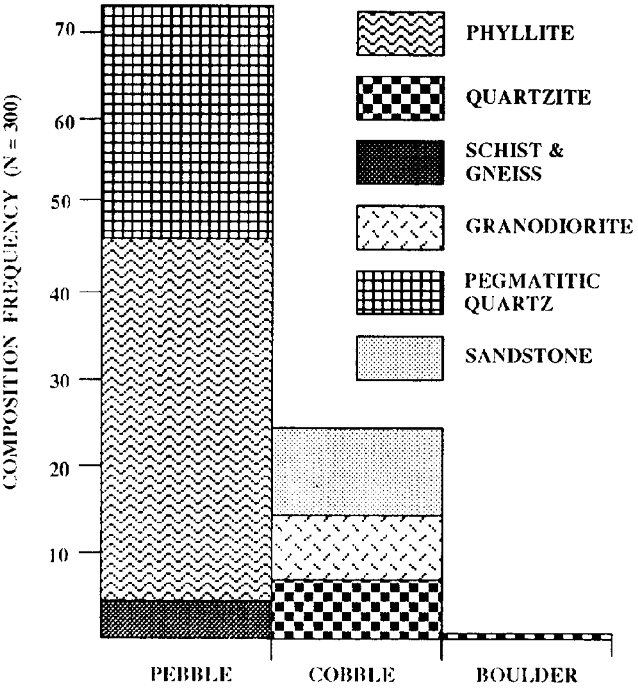

FIG. 8.—Distribution of composition of gravel by grain size, based on 300 clasts.

TABLE 3.—*Modal composition of sandstone from gravel*[1]

	Q %	Qm %	Qp %	F %	L %	Lt %
C1	86.0	76.0	10.0	12.5	1.5	11.5
C2	73.3	63.3	10.0	26.3	0.4	10.3
C3	82.7	72.0	10.7	15.6	1.7	12.3
C4	86.5	81.3	5.2	10.0	3.5	8.7
C5	85.0	70.0	15.0	14.0	1.0	16.0
Average	82.7	72.5	10.2	15.7	1.6	11.8

Q: total quartz (Qm + Qp). Qm: Monocrystalline quartz. Qp: Polycrystalline quartz. F: Total feldspar. L: Sedimentary rock fragments. Lt: Total lithic fragments (L + Qp).

[1] 300 points counted per thin section.

Preserved sphenophytes (arborescent horsetails) and lycophytes (arborescent club mosses) in the gravel-bearing layer are two major groups typical of terrestrial vegetation during the Carboniferous. In the Mary Lee coal zone, internal casts of both types of plants are found; they may be autochthonous or allochthonous (Gastaldo et al. 1989). Casting is directly related to their anatomical and histological characteristics. Sphenophytes have a hollow central cavity which developed during growth and is surrounded by a cylinder of pycnoxylic wood (Taylor 1981). Lycophytes do not possess a hollow pith but consist structurally of a small amount of wood and a vast quantity of bark (DiMichele 1981). Following death, the outer bark tissues resist degradation and conserve the overall plant form (Gastaldo 1986a, 1986b). These voids provide sites for the introduction of sediment, resulting in internal casts.

Although Carboniferous pebble-cast logs have not been reported previously, the processes of infilling may be similar to those resulting in sand- and mud-cast logs (Rex 1985; Degges and Gastaldo 1989; Gastaldo et al. 1989). Once a hollowed or decaying trunk is emplaced into an active channel floor, either by gravitational fall from the channel banks or by transport from upstream areas, the plant acts as a pipe (Gastaldo et al. 1989). The process of infilling begins at the ends of the log, then progresses toward the center (Rex 1985; Degges and Gastaldo 1988). The degree of infilling depends on the size of the log, the continuity of the void, the long-term integrity of the tissues surrounding the cavity, and the hydrodynamic conditions in the channel.

If the infilling process occurred at the study site, one would expect to find additional pebbles outside the logs and as a conglomeratic pebble lag in the lower sandstone units. On the contrary, the gravel-bearing layer is located at the top of the sandstone-channel sequence, and the pebble-casts are associated with very fine-grained sandstone layers. The fining-upward sequence of the channel from medium- to very fine-grained sand indicates decreasing hydraulic conditions with time (William 1983). The small-scale sedimentary structures and very fine-grained sand outside the logs in the gravel-bearing layer suggest a lower flow regime for the channel paleohydraulics at the time of pebble-cast log accumulation. The channel hydraulic conditions were apparently sufficient to transport very fine-grained sand but not pebbles as bedload. Therefore, it is reasonable to infer that the log infilling occurred in a channel environment where bedload was dominated by pebbles, presumably an upstream area. Subsequently, the partially-casted logs were transported downstream and deposited in the channel in which very fine-grained sand was the largest bedload size. The pebbles inside the logs, therefore, have preserved the upstream bedload and represent extrabasinal material not available downstream.

Transport of Cobbles and Boulders

Several recognized transport mechanisms have been used to explain the transport of cobbles and boulders (Gage 1953). These include water-traction by rare, high-magnitude floods, mud-flow transport, ice-transport during glaciation, and gravitational fall from a valley wall or cliff. All of these mechanisms are unlikely to account for the transport of cobbles and boulders found in a tropical, coastal regime represented by the rocks in our study area (Gastaldo et al. 1990, 1991). Although rare floods may have been able to transport large amounts of variously sized sediment to coastal areas, the cobbles and boulders would normally be found as channel lag if they were moved by bedload traction rather than localized in the top of a channel fill. Moreover, sedimentological features indicative of rare high-magnitude flood deposition do not exist in the Carbon Hill sandstone.

The cobbles and boulders are closely associated with large numbers of the pebble-bearing logs. Therefore, a parsimonious explanation to account for their presence is that they were transported along with the logs. This explanation may resolve the hydrological inconsistency necessary to directly transport large clasts with very fine-grained sand. Where logs are pebble-bearing, they are only partially filled, and not all of the logs (estimated in number to be several thousand) are filled. The large volume and lower density of the logs would have provided buoyancy for cobbles and boulders to be transported entrapped within roots or nestled between several logs floating as a raft.

One possible process responsible for the emplacement of these clasts into rafts would be gravitational fall from stream banks containing cobbles and boulders. This is caused by stream erosion scouring the base of the bank, bringing about gravitational failure of the intact deposit including vegetation growing on the bank (Thorne 1982; Spicer 1989). Felled trees entwined by their crown or roots could have formed a mesh-like structure in which cobbles and boulders became wedged. In addition, the roots may have grown around cobbles and boulders which would have been carried with them when the bank failed. In either case, some logs may have been partially filled with pebbles in response to bedload movement in the stream bottom.

Such rafting phenomena have been reported more frequently by naturalists than sedimentologists. During the voyage of the Beagle, Darwin (1906, p. 444) notes that stones are commonly found on coral islands, such as Keeling (now Cocos) Island, thousands of miles from land. He was hesitant to ascribe the mode of transport to rafting within tree roots until learning of the inhabitants of the Radack Archipelago (part of the Marshall Islands) who obtained stones for sharpening their tools by searching the roots of trees cast upon the shore.

Another possible mode of transport is the movement of an intact island of trees en masse down river with the larger gravel clasts remaining bound within the roots of the vegetation. It is reported that in the Pahang River of the Malay Peninsula, riverine islands, vegetated with trees, shrubs and herbs that choke the channels during low discharge, have been moved in their entirety downstream for long distances with their "soil" intact (Ridley 1930, p. 186). Although we have no evidence to suggest that the accumulation of logs and gravel in Alabama may represent material similar to that of tropical southeast Asia, this mode of transport of trees and gravels cannot be discounted.

Minimum Dimension of a Raft

Our interpretation of rafting as the mode of transporting gravel depends on the capability of logs to carry gravels within or on them. Feasibility of this model can be verified by calculating the minimum dimension of a raft using the Archimedes' principle of buoyancy. If the largest quartzite boulder from the deposit (0.6 m) is assumed to be carried on a raft composed of parallel logs each with diameter of 0.3 m (approximately the size of the logs in the deposit), and the boulder is completely exposed on the water surface, the approximate size of the raft can be calculated from:

$$Lw = 2D_l{}^3P_l/3NDw^2(P - P_2) \qquad [1]$$

where Lw and Dw are length and diameter of the logs; D_l is the diameter of the boulder; N is the number of logs required to stabilize the boulder on the raft (N = 3 in this case); P, P_l, and P_2 are the densities of the water, quartzite boulder, and logs, respectively. Using $P_l = 2.65$ (quartz density), $P = 1$ (water density), and $P_2 = 0.5$ (average log density), the length of the raft required to support the largest quartzite boulder is 2.83 m. Therefore, the minimum size of the raft is 2.83 m long and 0.9 m wide. These values are consistent with field measurements of the log compressions/impressions in which the largest tree could be traced for greater than 7 m with a diameter of 0.5 m. While it is unlikely that the rafts would have been this small, this calculation is sufficient to show that the log rafts could supply the buoyancy necessary to support the gravel load.

Proposed Model

The complex of logs within a coastal lowland regime presents two distinct modes of transport for clasts hydrodynamically discordant with the sand bedload of the underlying channel sandstone and with the sandstone beds within the gravel deposits. These transport mechanisms have preserved two clast sizes of extrabasinal material. Pebbles were transported inside partially hollowed or hollow logs; cobbles and boulders must have been carried on or within log rafts. The cobbles and boulders may have been derived from gravel deposits originally deposited near or within the source area, whereas the pebbles infilling hollowed or hollow logs may record younger upstream deposits. These processes can be visualized in the three stages shown in Figure 9. Part A illustrates the cross-section of an upland stream with initial cobble-boulder and pebble dominated bars. B illustrates undercutting of the bank, introducing matted logs, cobbles and boulders into the stream, and filling of logs with pebbles. C shows flotation of the gravel-bearing log raft during high-water stage. The raft with its gravel load could then be transported to the coastal lowland where it would be the last stage of deposition of the Carbon Hill channel. This transport mechanism, while uncommon, could have produced the unique sample of source rocks from which the Mary Lee sediments were derived.

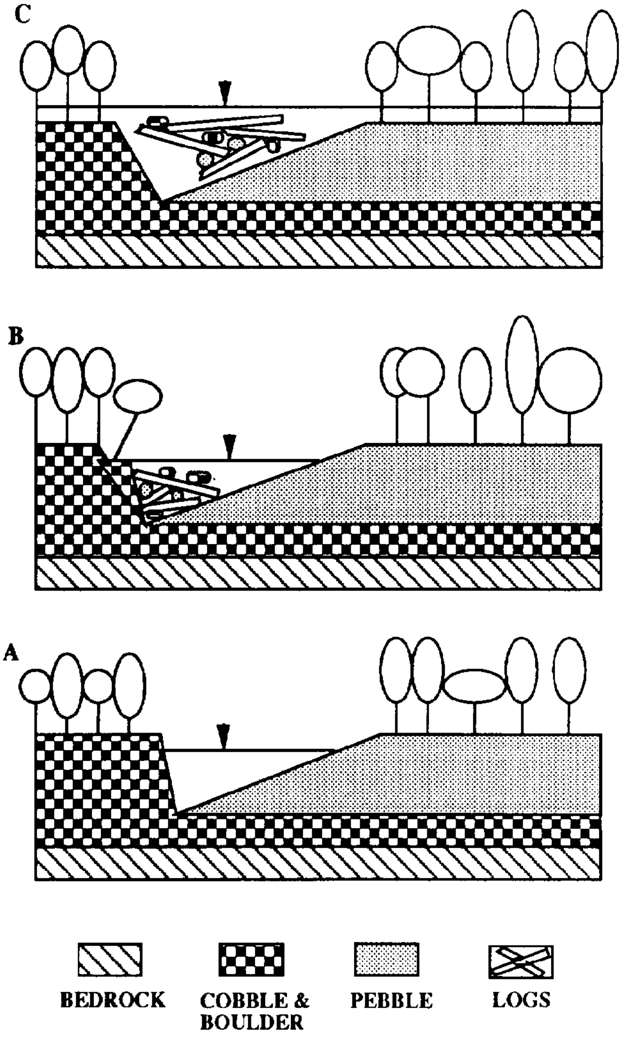

FIG. 9.—Schematic stages of development. A) Stage 1—Deposition of cobble-boulder bars in an upstream valley. B) Stage 2—Introduction of cobbles, boulders, and logs by bank collapse and filling of logs with pebbles. C) Stage 3—Flotation log raft during high stream discharge.

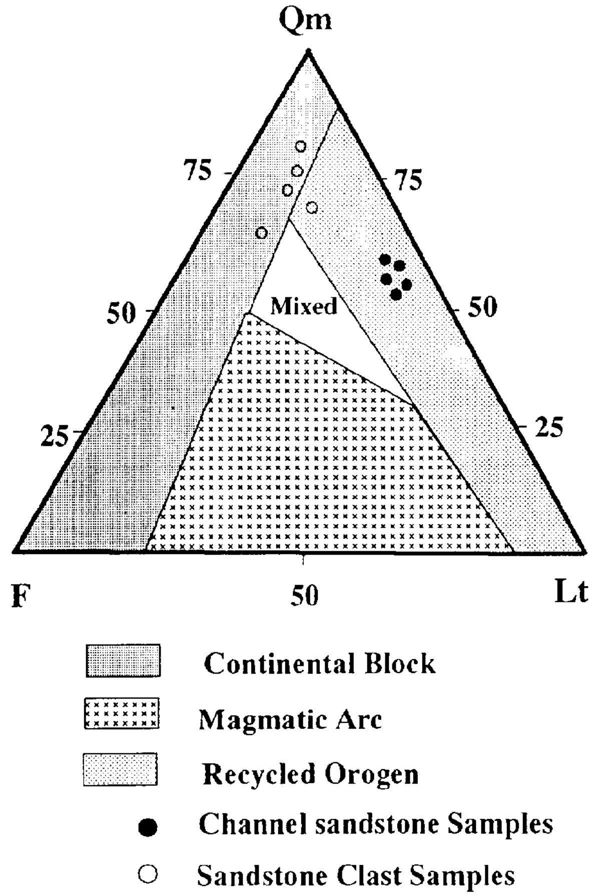

FIG. 10.—Petrofacies QmFLt diagram after Dickinson et al. (1983). The channel sandstones are in the area of recycled orogen provenance, whereas the sandstones from gravels are located in the area of continental block provenance. Qm—monocrystalline quartz, F—total feldspar (plagioclase + K-feldspar), Lt—unstable lithic fragments + polycrystalline quartz.

PROVENANCE AND TECTONIC IMPLICATIONS

Provenance

The significant features of gravel composition at Carbon Hill are the dominance of metamorphic (especially high-grade metamorphic), granitic igneous, and sedimentary rocks, and the absence of volcanic or volcaniclastic rocks. This composition indicates a high-grade metamorphic and acid plutonic terrane accompanied by some sedimentary rocks. The absence of volcanic and volcaniclastic rocks excludes the influence of contemporaneous volcanic activity. The regions characterized by this rock association are classified as suture belts by Dickinson and Suczek (1979), where plutonic igneous activity and regional metamorphism, rather than extrusives, are the norm (Pettijohn et al. 1987).

The gravels recovered from this study are indistinguishable from rocks in the present Piedmont province (W.A. Thomas, D.N. Bearce, T.J. Carrington, R.B. Cook, and R.W. Deininger, personal communications 1989). It is difficult to determine the exact rock units within the Piedmont from which the gravels were derived, but the probable sources include the Talladega Belt, and the Chattahoochee, Brevard, and Towaliga zones (D.N. Bearce and R.B. Cook, personal communications 1989). Given these strong similarities, the most probable provenance for Mary Lee deposits appears to be the deformed and uplifted southern Appalachian orogen, including its subsurface extension under the Coastal Plain.

Tectonic Implications

Our interpretation of the southern Appalachians as a source is consistent with the tectonic framework of the Alleghenian orogen in this area. Orogenic activity is dated at late Paleozoic as a result of a continent-continent collision between Laurentia and Gondwana in the late Paleozoic (Secor et al. 1986). The Piedmont terrain, which is composed mainly of biotite schist and paragneiss deformed and metamorphosed in the early to middle Paleozoic (Glover et al. 1983), was thrust northwestward onto the Laurentian plate during the Alleghenian orogeny (Cook et al. 1979). Therefore, in terms of both spatial and temporal aspects, the Piedmont terrain would have been able to contribute the variety of rocks now found in the Mary Lee deposits.

There have been several diverse hypotheses concerning the source of Carboniferous sediments in the Black Warrior basin. Ferm and Ehrlich (1967) and Davis and Ehrlich (1974) proposed a Ouachita source beneath the present coastal plain in Alabama, but Graham et al. (1976) suggested a southern Appalachian source for both the Black Warrior basin and the Ouachita trough. This link of two systems is based on the general similarity of the modal composition of the sandstones of the Atoka, Johns Valley, and Jackfork formations in Arkansas and that of the Black Warrior basin and is said to represent a tectonic setting similar to the Himalayan-Bengal system.

This interpretation has been challenged by Thomas (1977) and Mack et al. (1983). Using regional facies distribution and sandstone petrofacies, these authors suggested that Carboniferous deposits in the Black Warrior basin consist of two separate clastic wedges derived from both the Appalachian and the Ouachita orogens. (Thomas, 1974, 1977). A southwestward-prograding wedge was derived from an Appalachian source (Mack 1984). A northeastward-prograding wedge was derived from the now-buried Ouachitas which is interpreted as a product of arc-North America plate collision (Mack et al. 1983; Thomas 1985). Furthermore, the vertical increase of volcanic rock fragments and chert from the Parkwood to Pottsville formations in the northeastward-prograding wedge was used to emphasize the increasing importance of the arc and subduction complex as source rocks during the Late Namurian to Westphalian A (Mack et al. 1983). A southeastward expansion of the source area from the Ouachitas to the adjacent part of the Appalachians in the northeastward-prograding wedge was suggested as a possibility for the deposition of the uppermost part of the Upper Pottsville as a result of initiation of Appalachian orogeny (Mack et al. 1983; Thomas 1988).

Although the gravel deposit at Carbon Hill represents a miniscule portion of the entire mass of the Black Warrior basin deposits, its peculiar mode of transport does contribute definitive data for the interpretation of the provenance and the timing of the orogenic events. Our interpretation of provenance and tectonic setting based on the gravels, which are found within the supposedly northeastward-prograding wedge, conflicts with that of Mack et al. (1983) who suggest an Ouachita source. Our data indicate that at least a portion of the lower part of the Upper Pottsville Formation was derived from the deformed and uplifted southern Appalachian orogen, not the Ouachitas. If the Ouachita orogen was the source for a northeastward-prograding wedge during Early Pennsylvanian time (Mary Lee coal zone), then gravels recovered from the log accumulation should have provided evidence of increasing island arc and subduction activities. The gravel clasts should also reflect the character of lithologic units recognized in the Ouachitas. No volcanic rocks or chert were found in the gravel suite (Fig. 5). Mack et al. (1983) emphasize the fact that low-grade metamorphic rock fragments are a significant component in Black Warrior basin sandstones. The lithologic association represented in our gravel suite is therefore quite different from the inferred sedimentary and low-grade metasedimentary rocks of an Ouachita source (Morris 1971, 1974). Our suite of rocks includes high-grade metamorphics (gneiss), a lithology not common in the Ouachitas. Granite and meta-arkose clasts have been reported from Ordovician sandstones in the Ouachita system (Stone and Haley 1977), but not in younger rocks. Therefore, the presence of typically Appalachian rocks leads us to suggest that the initiation of a southeastern source associated with the Appalachian orogen began at least by the Mary Lee coal time, which is older than that suggested by Thomas (1988).

Whether or not sediments before or after the Mary Lee coal zone were derived from the Ouachitas or the Appalachians is not shown by our data, but a recently published study by Pashin et al. (1990) supports the notion of a southeast sediment source for the Carbon Hill locality. This study, which included the entire upper Pottsville sequence, showed northeast-trending barrier shoreline sandstones slightly northwest of Carbon Hill interfingering southeastward with fluvial deltaic sediments derived from an Appalachian highland. These results are in accord with ours from Carbon Hill and do not support the northeastward and southwestward prograding wedges of Mack et al. (1983).

Sandstone Petrofacies Implications

A comparison of the modal composition of the sandstone gravel clasts and the channel sandstone deposits at Carbon Hill provides a contrast in tectonic setting between the source rocks of the two materials. The data from Tables 1 and 3 are plotted on a QmFLt diagram (Fig. 10). Using the tectonic fields proposed by Dickinson and Suczek (1979) and Dickinson et al. (1983), the sandstone clasts from the gravel appear to have been derived from a continental block which is in accord with the character of the inferred source of early Paleozoic and late Precambrian rocks in the Appalachian region (Rast 1989). The sand from the channels, however, falls within the field of a recycled orogen which would represent the metamorphosed rocks of Piedmont which we propose as a source for the Mary Lee deposits.

SUMMARY

Gravel clasts consisting of pebbles, cobbles, and boulders occur capping a fining-upward sandstone channel sequence in Carboniferous coastal deposits of the Black Warrior basin of Alabama. Pebbles are common within thin elliptical envelopes of vitrain, representing coalified logs. Cobbles and boulders are encountered dispersed among these fossilized prostrate trees. The gravel represents extrabasinal detritus formed at or near the source area and transported to the coastal regime by log rafts. Pebble accumulations represent a partial infilling of the logs whereas cobbles and boulders were transported entrapped within root structures of trees or trapped on top of log rafts.

This unique transport mechanism for gravels has preserved two clast sizes of extrabasinal material relevant to the source rocks for the Upper Pottsville Formation. The dominance of metamorphic (particularly high-grade metamorphic), plutonic igneous, and sedimentary rocks, and the absence of volcanic or volcaniclastic rocks imply a provenance from the deformed and uplifted southern Appalachian orogen for this part of the Upper Pottsville Formation.

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REFERENCES

ANDREWS, E.B., 1871, Report of labors in the second Geological District during the year 1870: Ohio Geological Survey, Report of Progress in 1870, p. 57–251.

BRANSON, C.C. AND MERRITT, C.A., 1963, An igneous cobble in an Oklahoma coal bed: Oklahoma Geology Notes, v. 23, p. 235–241.

Cook, F.A., Albaugh, D.S., Brown, L.D., Kaufman, S., Oliver, J.E., and Hatcher, R.D., Jr., 1979, Thin-skinned tectonics in the crystalline southern Appalachian: COCORP seismic-reflection profiling of the Blue Ridge and Piedmont: Geology, v. 7, p. 563–567.

Dana, J.D., 1895, Manual of Geology, 4th edition: New York, American Book Company, 504 p.

Darwin, C., 1906, The Voyage of the Beagle: London, J.M. Dent, 496 p.

Davis, M.W. and Ehrlich, R., 1974, Late Paleozoic crustal composition and dynamics in the southeastern United States: Geological Society of America Special Paper 148, p. 171–185.

Degges, C.W. and Gastaldo, R.A., 1988, The use of fossilized logs as paleocurrent indicators in fluvial systems—a note of caution: Geological Society of America, Abstracts with Programs, v. 20, p. A264.

Degges, C.W. and Gastaldo, R.A., 1989, Mechanism of Carboniferous pith cast infilling: Geological Society of America, Abstracts with Programs, v. 21, p. 1.

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., Beard, L.S., Brakenridge, G.R., Erjavec, J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindberg, F.A., and Ryberg, P.T., 1983, Provenance of North American Phanerozoic sandstones in relation to tectonic setting: Geological Society of America Bulletin, v. 94, p. 222–235.

DiMichele, W.A., 1981, Arborescent lycopods of Pennsylvanian age coals: *Lepidodendron* with description of a new species: Palaeontographica B, v. 175, p. 85–125.

Ferm, J.C. and Ehrlich, R.L., 1967, Petrology and stratigraphy of the Alabama coals, *in* Ferm, J.C., Ehrlich, R.L., and Neathery, T.L., eds., A Field Guide to Carboniferous Detrital Rocks in Northern Alabama: Geological Society of America, Coal Division, 1967 Field Trip, p. 11–15.

Gage, M., 1953, Transport and rounding of large boulders in mountain streams: Journal of Sedimentary Petrology, v. 23, p. 60–61.

Gastaldo, R.A., 1986a, Implications on the paleoecology of autochthonous Carboniferous lycopods in clastic sedimentary environments: Palaeogeography, Palaeoclimatology and Palaeoecology, v. 53, p. 191–210.

Gastaldo, R.A., 1986b, An explanation for lycopod configuration, "Fossil Grove" Victoria Park, Glasgow: Scottish Journal of Geology, v. 22, p. 191–212.

Gastaldo, R.A., Demko, T.M., Liu, Y., Keefer, W.D., and Abston, S.L., 1989, Biostratinomic processes for the development of mud-cast logs in Carboniferous and Holocene swamps: Palaios, v. 4, p. 356–365.

Gastaldo, R.A., Demko, T.M., and Liu, Y., eds., 1990, Carboniferous coastal environments and paleocommunities of the Mary Lee coal zone, Marion and Walker Counties, Alabama: Field Trip Guidebook, Southeastern Section of the Geological Society of America, Alabama Geological Survey Publication, 139 p.

Gastaldo, R.A., Demko, T.M., and Liu, Y., 1991, A mechanism to explain persistent alternation of clastic and peat-accumulating swamps in Carboniferous sequences: Société Géologique Française Bulletin, Sér. 8, t. 162, p. 155–161.

Glover, L. III, Speer, J.A., Russell, G.S., and Farrar, S.S., 1983, Ages of regional metamorphism and ductile deformation in the central and southern Appalachians: Lithos, v. 16, p. 223–245.

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.

Gresley, W.S., 1896, A granite boulder near Pittsburgh, Pennsylvania: American Geologist, v. 18, p. 331–332.

Hemish, L.A., 1982, Okmulgee County coal bed yields exotic quartzite cobble: Oklahoma Geology Notes, v. 42, p. 48–59.

Hewitt, J.L., 1984, Geological overview, coal and coalbed methane resources of the Warrior Basin—Alabama and Mississippi, *in* Rightmire, C.T., Eddy, G.E., and Kirr, J.N., eds., Coalbed Methane Resources of the United States: America Association of Petroleum Geologists Studies in Geology Series, No. 17, p. 73–104.

Horsey, C.A., 1981, Depositional environments of the Pennsylvanian Pottsville Formation in the Black Warrior Basin of Alabama: Journal of Sedimentary Petrology, v. 51, p. 3–20.

Lyons, P.C., Meissener, C.R., Jr., Barwood, H.L., and Adinolfi, F.G., 1985, Megaflora sequence and North American and European correlations of the upper part of the Pottsville Formation of the Warrior coal field, Alabama, U.S.A., *in* Escobedo, J.L., Granados, L.F., Melendez, B., Pignatelli, R., Rey, R., and Wagner, R.H., eds., Dixième Congrès International de Stratigraphie de Géologie du Carbonifère, Madrid, v. 2, p. 203–245.

Mack, G.H., 1982, Composition of Carboniferous sandstones in the Black Warrior basin, Alabama: implications on plate tectonic setting, *in* Thomas, W.A., and Neathery, T.L., eds., Appalachian Thrust Belt in Alabama: Tectonic and Sedimentation: Geological Society of America, Field Trip Guidebook, p. 67–74.

Mack, G.H., 1984, Exception to the relationship between plate tectonics and sandstone composition: Journal of Sedimentary Petrology, v. 54, p. 212–220.

Mack, G.H., Thomas, W.A., and Horsey, C.A., 1983, Composition of Carboniferous sandstones and tectonic framework of southern Appalachian-Ouachita orogen: Journal of Sedimentary Petrology, v. 53, p. 931–946.

McCallie, S.W., 1903, An erratic boulder from the Coal Measures of Tennessee: American Geologist, v. 31, p. 46–47.

Morris, R.C., 1971, Stratigraphy and sedimentology of Jackford Group, Arkansas: American Association of Petroleum Geologists Bulletin, v. 55, p. 387–402.

Morris, R.C., 1974, Carboniferous rocks of the Ouachita Mountains, Arkansas: a study of facies patterns along the unstable slope and axis of a flysch trough: Geological Society of America Special Paper 148, p. 241–279.

Newberry, J.S., 1874, The Carboniferous System: Ohio Geological Survey Report, v. 2, part 1, p. 174–175.

Orton, E., 1892, On the occurrence of a quartz boulder in the Sharon coal of northeastern Ohio: American Journal of Science, v. 144, p. 62–63.

Pashin, J.C., Ward, W.E., II, Winston, R.B., Chandler, R.V., Bolin, D.E., Hamilton, R.P., and Mink, R.M., 1990, Geologic evaluation of critical production parameters for coalbed methane resources, Part II. Black Warrior Basin: Gas Research Institute, Chicago, 177 p.

Pettijohn, F.H., Potter, P.E., and Siever, R., 1987, Sand and Sandstone, 2nd edition: New York, Springer-Verlag, 553 p.

Price, P.H., 1932, Erratic boulders in Sewell coal of West Virginia: Journal of Geology, v. 40, p. 62–73.

Rast, N., 1989, The evolution of the Appalachian chain, *in* Bally, A.W. and Palmer, A.R., eds., The Geology of North America—An Overview: Boulder, CO, Geological Society of America, The Geology of North America, v. A, p. 323–348.

Rex, G.M., 1985, A laboratory flume investigation of the formation of fossil stem fills: Sedimentology, v. 32, p. 245–255.

Ridley, H.N., 1930, The dispersal of plants throughout the world: Ashford, Kent, L. Reeve, 744 p.

Secor, D.T., Jr., Snoke, A.W., and Dallmeyer, R.D., 1986, Character of the Alleghenian orogen in the southern Appalachians, Part III. Regional tectonic relations: Geological Society of America Bulletin, v. 97, p. 1345–1353.

Spicer, R.A., 1989, The formation and interpretation of plant fossil assemblages: Advances in Botanical Research, v. 16, p. 96–191.

Stone, C.G. and Haley, B.R., 1977, The occurrence and origin of the granite-meta-arkose erratics in the Ordovician Blakely Sandstone, Arkansas, *in* Stone, C.G., ed., Symposium on the Geology of the Ouachita Mountains, Arkansas Geological Commission, v. 1, p. 107–111.

Taylor, T.N., 1981, Paleobotany: An Introduction to Fossil Plant Biology: New York, McGraw-Hill Inc., 589 p.

Thomas, W.A., 1974, Converging clastic wedges in the Mississippian of Alabama, *in* Briggs, G., ed., Carboniferous of the Southeastern United States: Geological Society of America Special Paper 148, p. 187–207.

Thomas, W.A., 1977, Evolution of Appalachian-Ouachita salients and recesses from reentrants and promontories in the continental margin: American Journal of Science, v. 13, p. 175–199.

Thomas, W.A., 1985, The Appalachian-Ouachita connection: Paleozoic orogenic belt at the southern margin of North America: Annual Review of Earth and Planetary Science, v. 13, p. 175–199.

Thomas, W.A., 1988, The Black Warrior basin, *in* Sloss, L.L., ed., Sedimentary Cover—North American Craton: U.S.: Boulder, CO, The Geological Society of America, The Geology of North America, v. D-2, p. 471–492.

Thorne, C.R., 1982, Processes and mechanisms of river bank erosion, *in* Hey, R.D., Bathurst, J.C., and Throne, C.R. eds., Gravel Bed Rivers: New York, Wiley, p. 227–271.

White, D., 1915, The occurrence of transported boulders in coal beds (abstract): Washington Academy of Sciences Journal, v. 5, p. 407.

William, G.P., 1983, Paleohydrological methods and some examples from Swedish fluvial environments: Geografiska Annalar, v. 65A, p. 227–243.