Figure 52. Dip directions of crossbeds in the sandstones of the Lee Formation measured by Mitchum (1954, pl. 35).

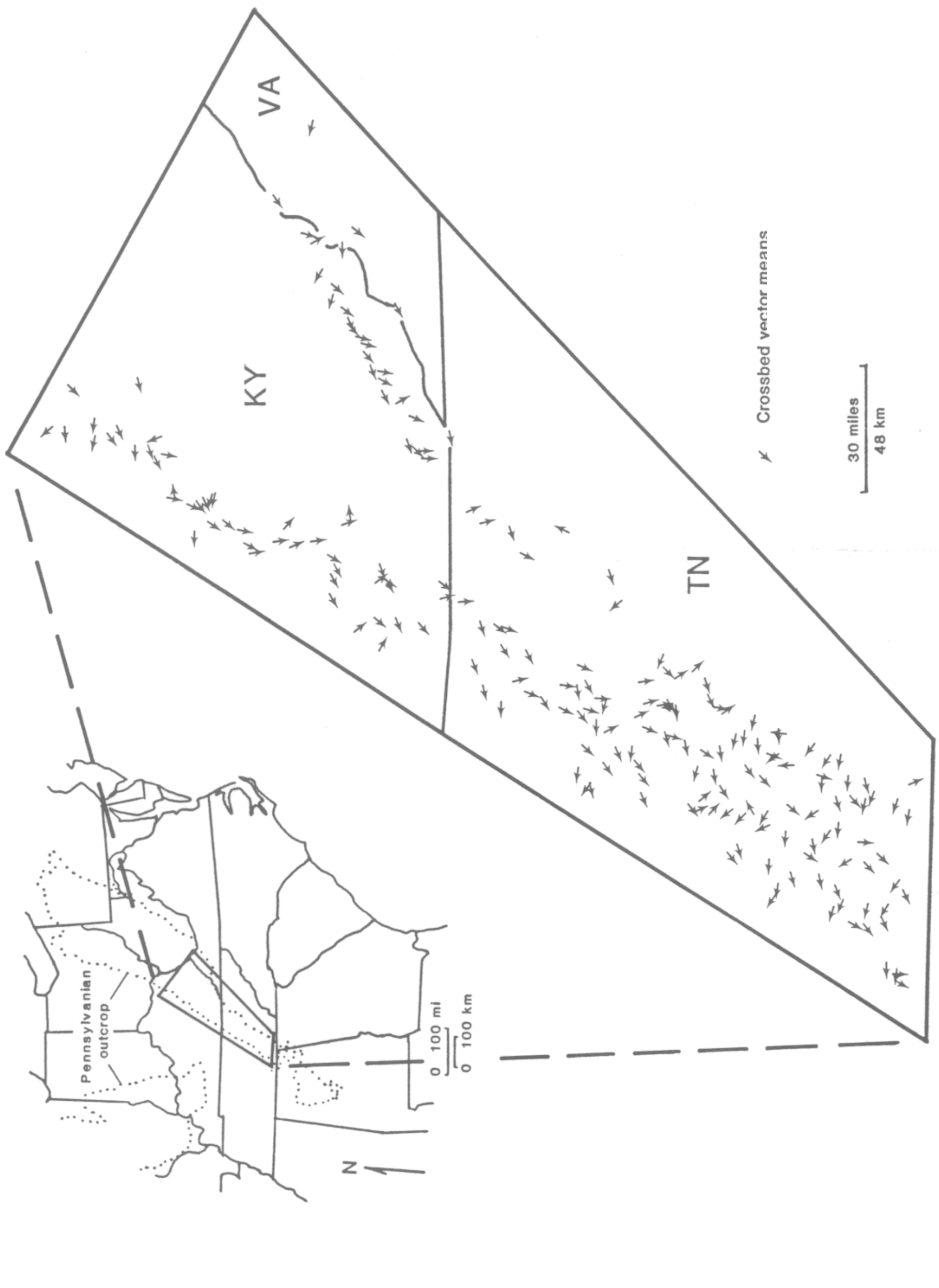
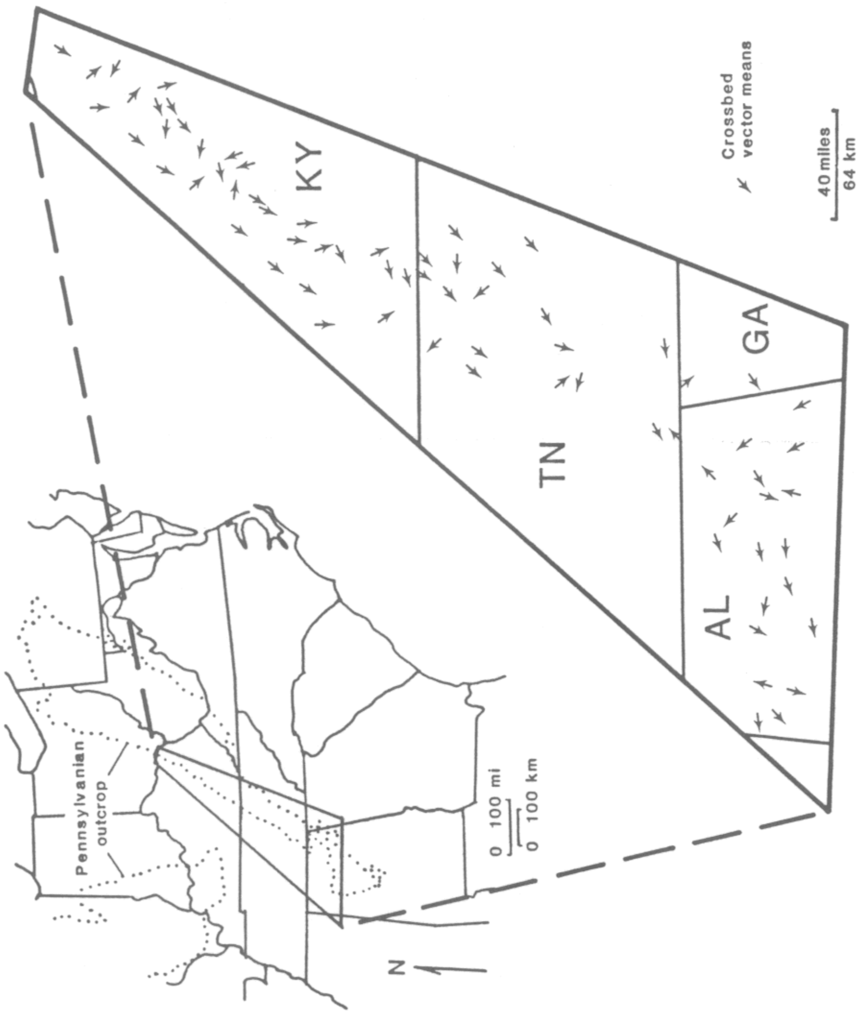

VA
KY
TN
Crossbed vector means
30 miles
48 km
Pennsylvanian
outcrop
0 100 mi
0 100 km
N

Figure 53. Dip directions of crossbeds in the sandstones of the Lee Formation compiled by Horne (1979, fig. 2, p. 514).


KY
TN
GA
AL
Crossbed vector means
40 miles
64 km
Pennsylvanian outcrop
0 100 mi
0 100 km
N

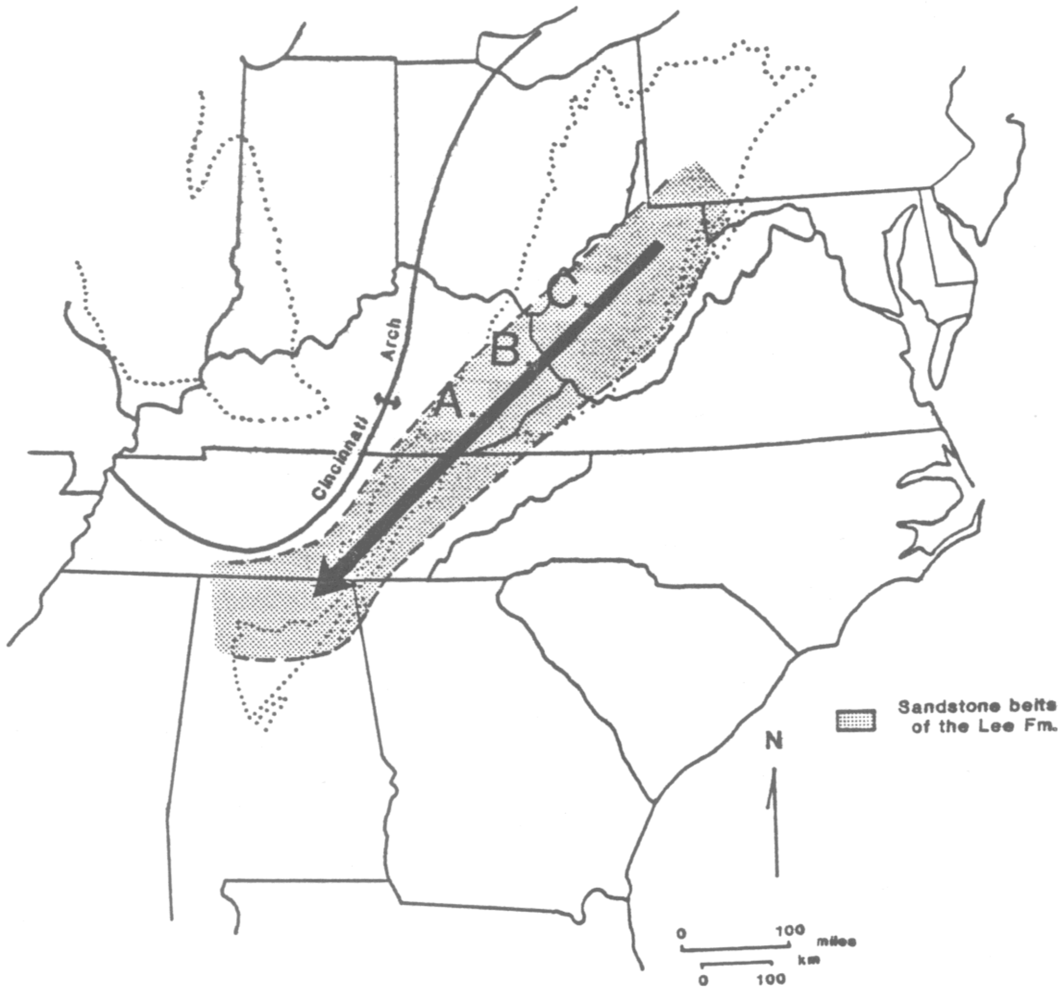
northern Tennessee, and to the west in southern Tennessee, Georgia, and Alabama (Fig. 54).

Five depositional models incorporating the features of the Lee Formation discussed above will be examined to determine which best represents the Lee and Breathitt deposition.

Lee-Newman Barrier-Shoreline Model

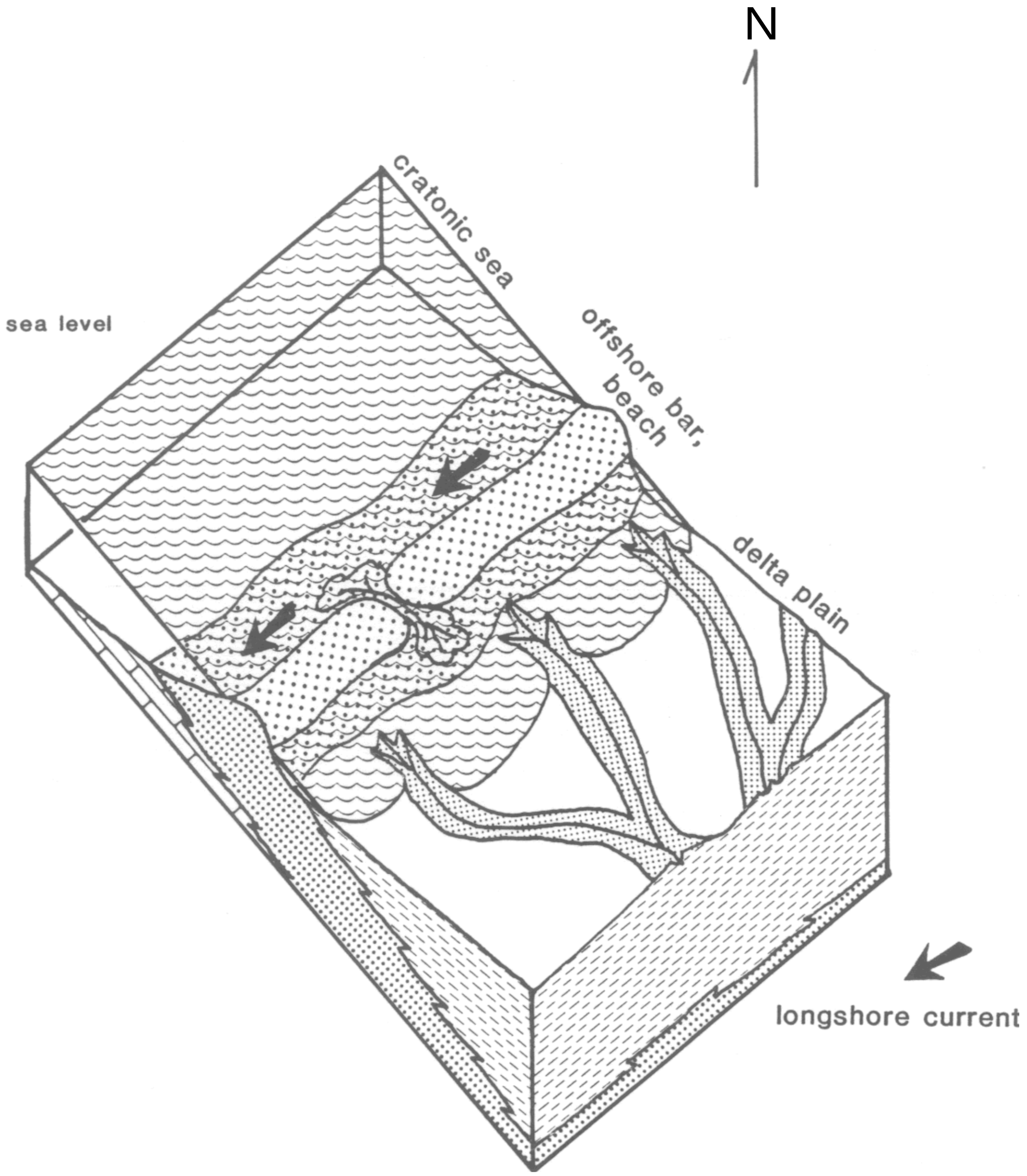
The quartzose content of the sandstones of the Lee Formation and the juxtaposition of the sandstones over marine rocks (Slade or Newman, and Pennington) and under terrestrial rocks (Breathitt Formation) was used as evidence for a beach or barrier-bar origin (Fig. 55) for these sandstones by Hobday (1969, 1974, 1979), Horne, and others (1971, p. 5-9; 1979, p. 386-403), Ferm, and others (1972). Barwis and Horne (1979, p. 460-471), Hobday and Horne (1979, p. 436-459), and Milici (1979, p. 404-421). The scoured bases, fining-upward sequences, and unimodal crossbed directions observed in the Lee Formation were interpreted by them (e.g. Ferm and others, 1972) as having been formed by erosion due to tidal currents oriented perpendicular to the beach-bars, and deposition controlled by longshore-currents flowing to the southwest along the ancient beach-bar (Fig. 55). A large sea was inferred to have existed west of the barrier system.

Figure 54. Major trends in sandstones of the Lee Formation recognized by BeMent (1976, fig. 37) superimposed on trend of sandstone belts determined by this study (Fig. 49).



A.) Average dip of crossbeds
B.) Decrease in quartz–pebble size
C.) Decrease in content of monocrystalline quartz

Figure 55. Lee-Newman Barrier-shoreline model.


N
cratonic sea
sea level
offshore bar,
beach
delta plain
longshore current

According to this study, however, only land, represented by the unconformity surface, existed west of the supposed barrier system. A Lee-Newman-type barrier bar could not have existed to form the Lee Formation.

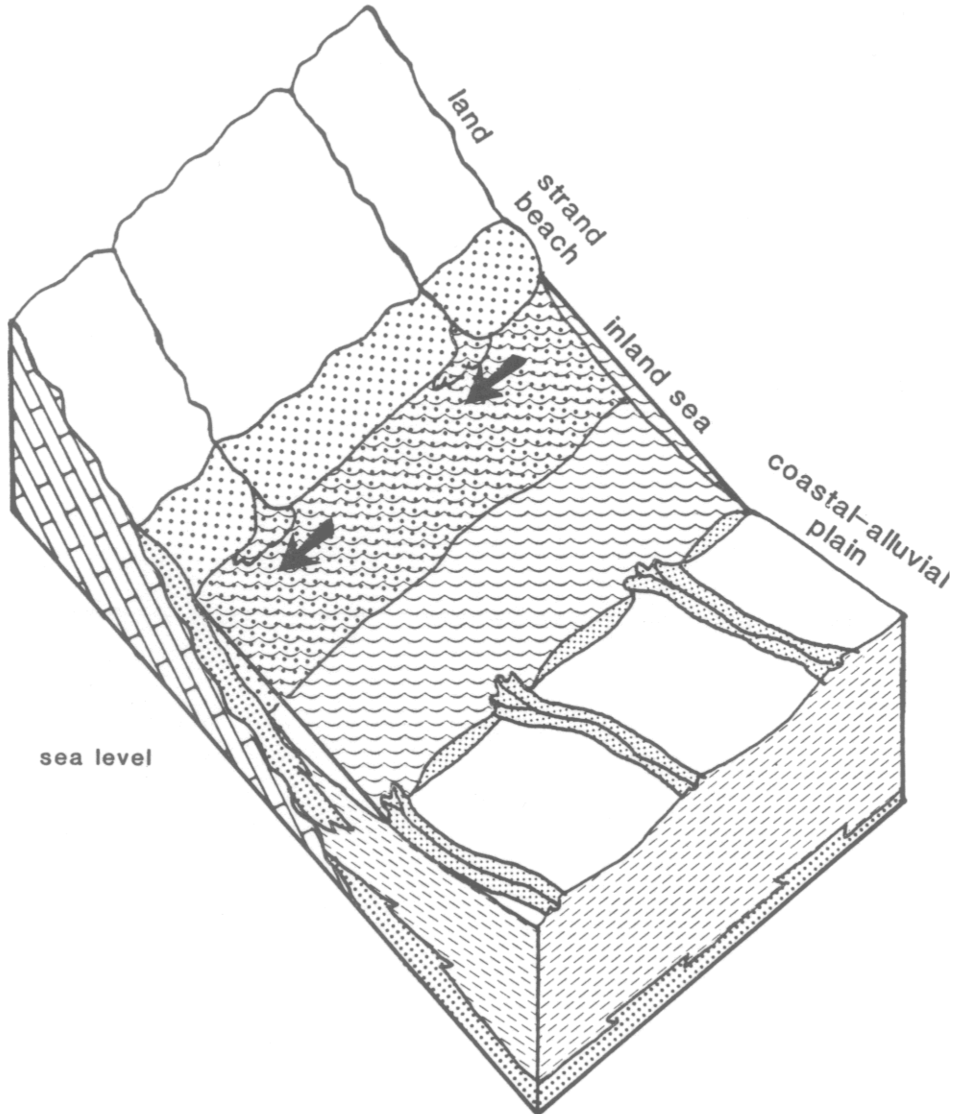
The following four models on the other hand contain the erosional surface as a feature of each model.

Early Pennsylvanian Beach-Bar Model

Another type of beach-bar model is possible with the unconformity surface (Fig. 56). In this model, a beach-bar (Lee Formation sandbelts) formed at the strand line where the Early Pennsylvanian sea met the unconformity surface. Longshore currents provided the southwest-dipping crossbeds. The coastal-alluvial plain (Breathitt Group) prograded into the sea toward the strand beach. Ephemeral beaches along this prograding coastal plain may also have formed.

Strand deposits, however, form parallel to the topographic trend and would not be expected to show a gradient along the length of the deposit as do the Lee sandbelts. In addition, foreshore accretion beds dipping to the southeast should be common, but, in fact, southeastern-dipping beds are uncommon in the Lee Formation. This model, therefore, is not a good analog for the Early Pennsylvanian of the Appalachians.

Figure 56. Early Pennsylvanian Beach-bar model.


land
strand
beach
inland sea
coastal-alluvial
plain
sea level

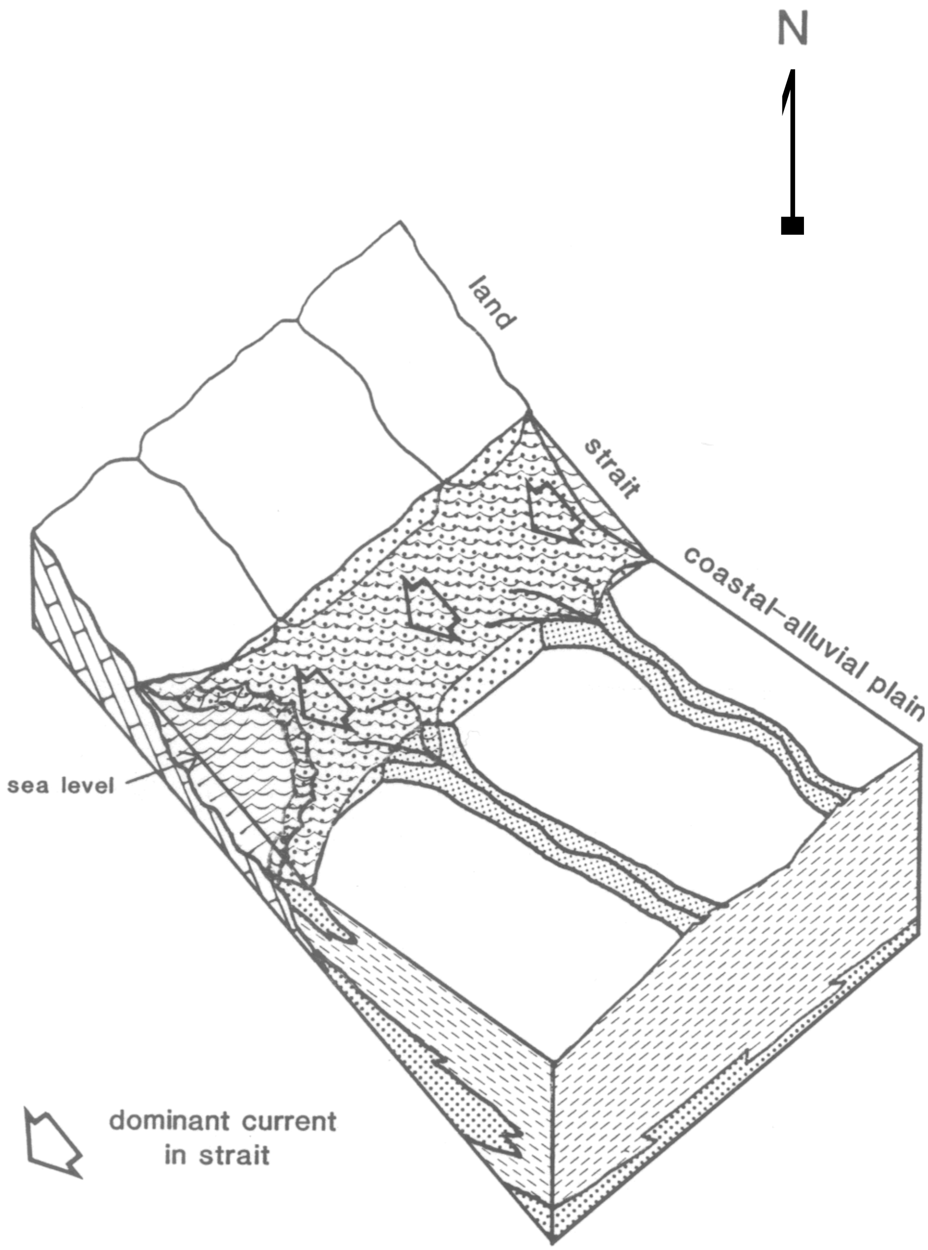
Straits Sandbelt Model

Possible analogs from Indonesia have also ben used to explain Breathitt coal beds and have been extended to include the unconformity surface and the Lee Formation (C. B. Cecil, U.S Geological Survey, 1988, personal communication). Geostrophic currents in the Straits of Mollucca erode the substrate, and sands are deposited upon this surface in protected areas in the strait.

A straits model is illustrated in Figure 57 which incorporates the Lee sandstone belts. Sands were introduced into the strait by rivers which flowed northwest through a coastal-alluvial plain (Breathitt Group). Currents in the strait reworked the sands into a sandbelt and produced the southwest-dipping crossbeds observed in the Lee Formation.

In this model it is necessary for the strait to have had contact with an open ocean to the northeast as well as to the southwest in order for the geostrophic currents to develop. However, an Early Pennsylvanian connection to an ocean to the northeast has not been recognized in Appalachian geology. In addition the sandbelts deposited in the straits are not likely to have developed a gradient as existed for the Lee sandbelts (previously discussed). This model does not appear to be the best scenario for the deposition of the Lee and Breathitt formations.

Figure 57. Straits-sandbelt model.

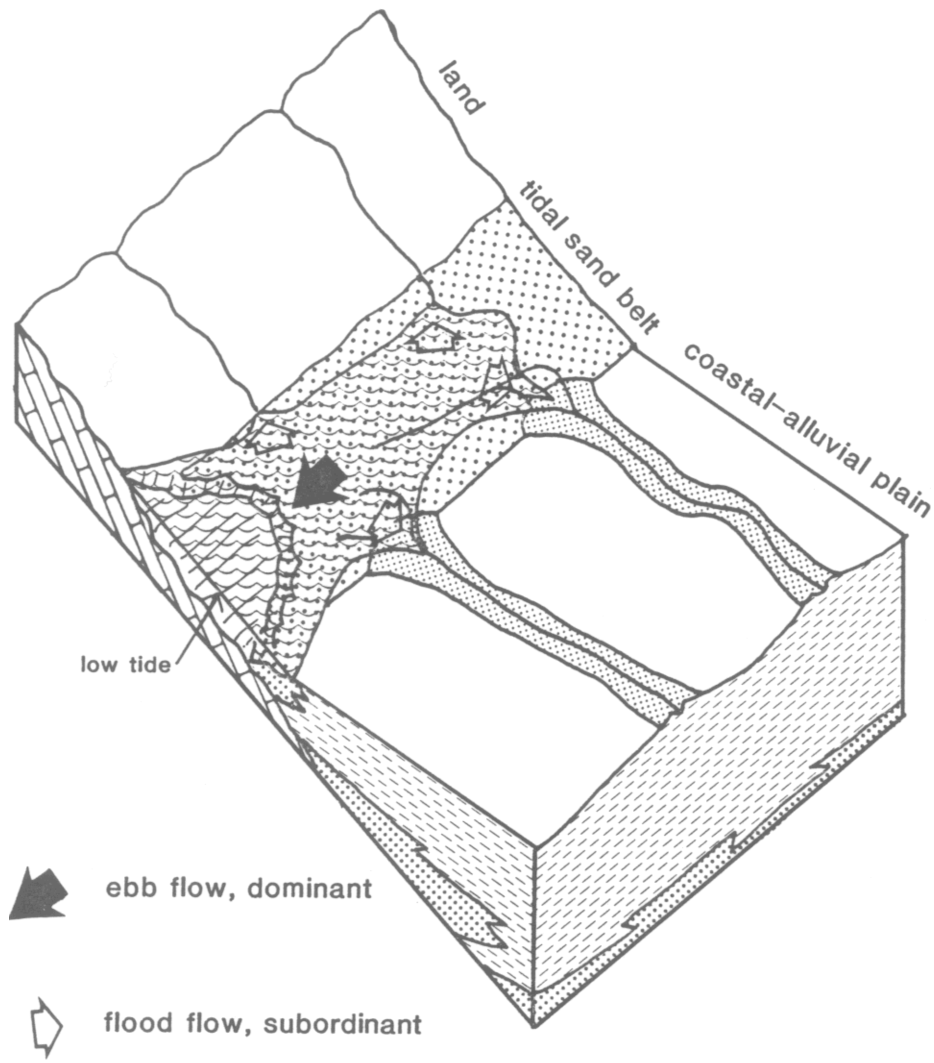

N
land
strait
coastal-alluvial plain
sea level
dominant current
in strait

Tidal Sandbelt Model

The Lee Formation has recently been reinterpreted as tidal-channel deposits (James Cobb, 1987, personal communication). The configuration for this model (Fig. 58) is similar to the straits model (Fig. 57) except that contact with an open ocean is necessary only to the southwest. Rivers which flowed northwest through the coastal-alluvial plain (Breathitt Group) entered the area of tidal influence where the sands were reworked by tidal currents. In this model a large-scale tidal-channel system was oriented northeast-southwest, with ebb-flow dominated currents flowing to the southwest. Ebb-flow dominated tidal channels are interpreted from the largely unimodal crossbed directions reported for the Lee Formation. The lack of body fossils, marine trace fossils, and the abundance of plant fossils and debris in the Lee Formation are attributed to the ebb-flow dominated currents and high bed load. Tidal action is interpreted to have reworked clastic sediments derived from northwest-flowing rivers (Breathitt Group) with headlands in the early Appalachian Mountains.

Some flood-flow channels likely existed in an ebb-flow dominated system, and marine shells would probably have been transported into these channels. However, even in ebb-flow tidal channels, landward transport of invertebrate shells is common (Henderson and Frey, 1986). Therefore, marine shells

Figure 58. **Tidal sandbelt model.**


land
tidal sand belt
coastal-alluvial plain
low tide
ebb flow, dominant
flood flow, subordinant

would be expected in some of the tidal lag deposits, especially in a system as large as the Lee sandstone belts. However, only plant fossils are found in the lag deposits of the Lee Formation.

Studies by EeMent (1976) indicated that size of quartz pebbles increases to the northeast (Fig. 54), not to the southeast as expected if they were introduced by westward-flowing rivers that deposited the Breathitt Group (Fig. 57). Hence, the above factors do not support a tidal-channel origin for the Lee sandbelts.

Mathematical modelling of tidal ranges in a similar basin also does not support mesotidal or macrotidal conditions for the Appalachian Basin during the Early Pennsylvanian. Slingerland (1986) mathematically modelled the tidal ranges of the Catskill Sea for three different bathymetric scenarios: (1) for shallow water depths (Appalachian and Eastern Interior basins as deep as 150 feet or 45 meters), (2) for intermediate depths (basin depth as deep as 490 feet or 150 meters), and (3) for deep water (basins as deep as 985 feet or 300 meters). He concluded for the shallow-water scenario (p. 492), "These results support the suggestion of many previous researchers that sufficiently shallow epicontinental seas [his shallow water scenario] will be microtidal for average to high friction factors regardless of open ocean tidal range." Water depths for the Pennsylvanian in the Appalachian Basin were most definitely well within his shallow water range (indicated by the repeated occurrence of coals and seatrock associated with the Lee Formation). Because the inland seas were smaller, more shallow, and had more restricted connection with the open ocean in the Pennsylvanian than in the Late Devonian, a very low tidal range is most probable. Microtidal conditions are not likely to have formed large-scale tidal features and deposits on the order of the sandstones of the Lee Formation.

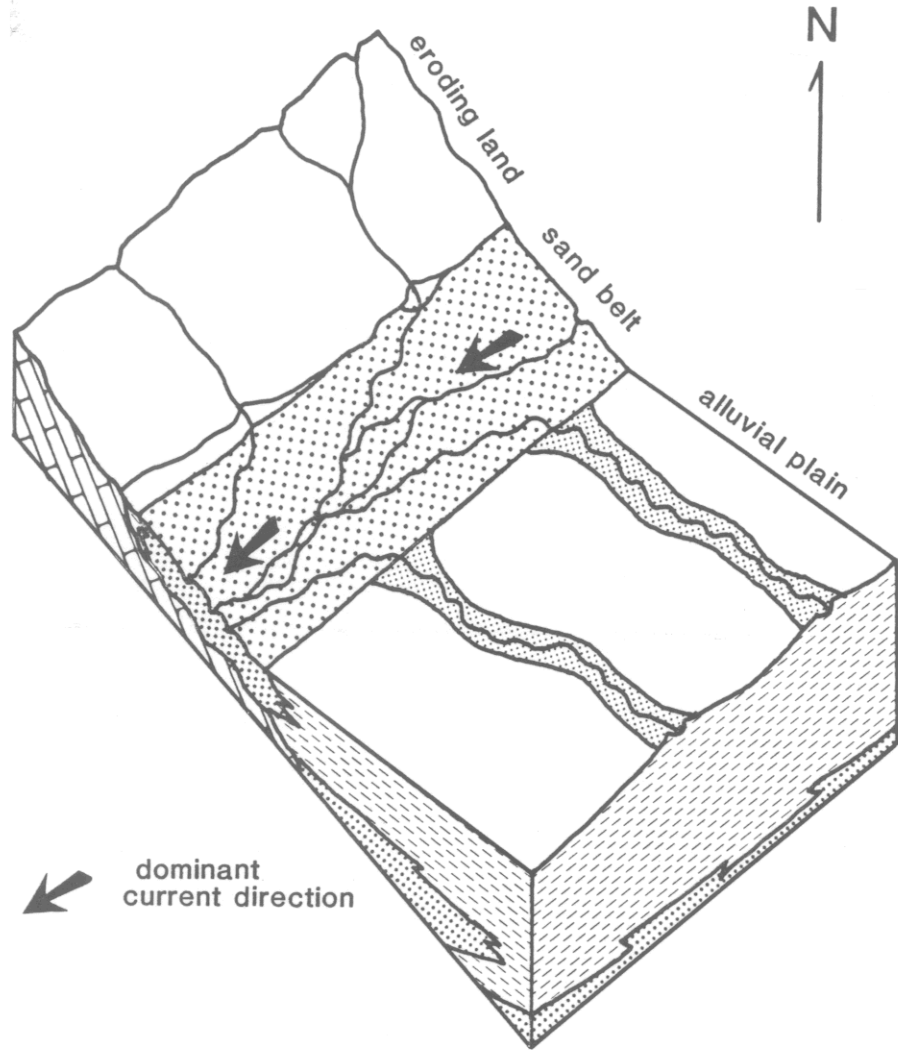
Fluvial Sandbelt Model

The sandstone bodies of the Lee Formation are composed of a series of truncated, fining-upward sequences (e.g. Hester, 1981a,b; Churnet and Bergenback, 1983, p. 544). Very large crossbeds are commonly found in the lower parts, and quartz pebbles are a common occurrence (Rice, 1984). Crossbed directions are largely unimodal and indicate a current direction to the south or southwest for most of the sandstone beds. The sandstone beds are commonly underlain and overlain by coal beds, and plant fossils and plant debris are abundant (e.g., Cobb and others, 1986). Horizontal logs are also common near the bases of the sandstones. In addition, freshwater trace-fossil assemblages have been reported in these sandstones (Jackson and Miller, 1984, p. 148; Miller, 1984, p. 180). All of the above features have been used as evidence of a fluvial model for the Lee Formation.

In the fluvial sandbelt model (Fig. 59) an alluvial plain (Breathitt Group) prograded to the northwest toward the Lee sandstone belt. In addition, entrenched rivers on a land surface being eroded (represented by the unconformity surface and channel-form occurrences of the Lee) flowed southward toward the sandbelt. The sandbelt represents reworked sands deposited by major rivers which flowed to the southwest.

The fluvial model best incorporates the features interpreted from this study. The gradient and dominant crossbed directions, both parallel with the sandstone belt, would be expected in a fluvial system. The average slopes of the Lee sandbelts (0.0004-0.0007, previously discussed) are similar to those of modern rivers; e.g., the sandy, braided South Sasketchewan River, Canada (0.0003, Reineck and Singh, 1980, p. 285). the meandering Congaree River, U.S.A. (0.0007, calculated from values in Reineck and Singh, 1980, p. 276), and the braided Ganges River (at the Upper Ganges in the plains below the Himalayas the slope is 0.0004; the middle and lower Ganges has a slope of 0.00007 or less; calculated from information in Fairchild, 1967). Because of the good agreement between recognized features in

Figure 59. Fluvial sandbelt model


N
eroding land
sand belt
alluvial plain
dominant
current direction

the Lee Formation and the fluvial sandbelt model, this model will be examined in greater detail in following sections.

If the sandstones of the Lee Formation were fluvial, then the thin Breathitt lithologies within the Lee sandstone belts represent local overbank deposits and peat swamps. On the other hand, the extensive Breathitt lithologies occurring between the Lee Formation sandstone belts (members), represent either: a.) westward progradation of the Breathitt deltas over the Lee sandbelts, or b.) marine transgressions. The westward progradation of Breathitt facies over the sandbelts could have been caused by either (1) elevation of the Breathitt headlands, thereby increasing gradient of the Breathitt rivers and introducing more sediment into the drainage basin; or (2) abandonment of the Lee fluvial system in a subsiding basin allowing the Breathitt facies to prograde over the belts. Marine transgressions from the Ouachita Basin (discussed later) up the Appalachian Basin, however, would have raised the base-level and halted deposition of the Lee sands. Marine, and coastal-deltaic sediments would then overlie the sandbelts. In fact, coal and marine shales are interpreted to overlie the Lee in places; e.g., the restricted-marine Betsie Shale and Manchester coal overlie the Corbin Sandstone. In the subsurface, gamma-ray logs commonly show that coals and marine-like shales overlie the Lee members.

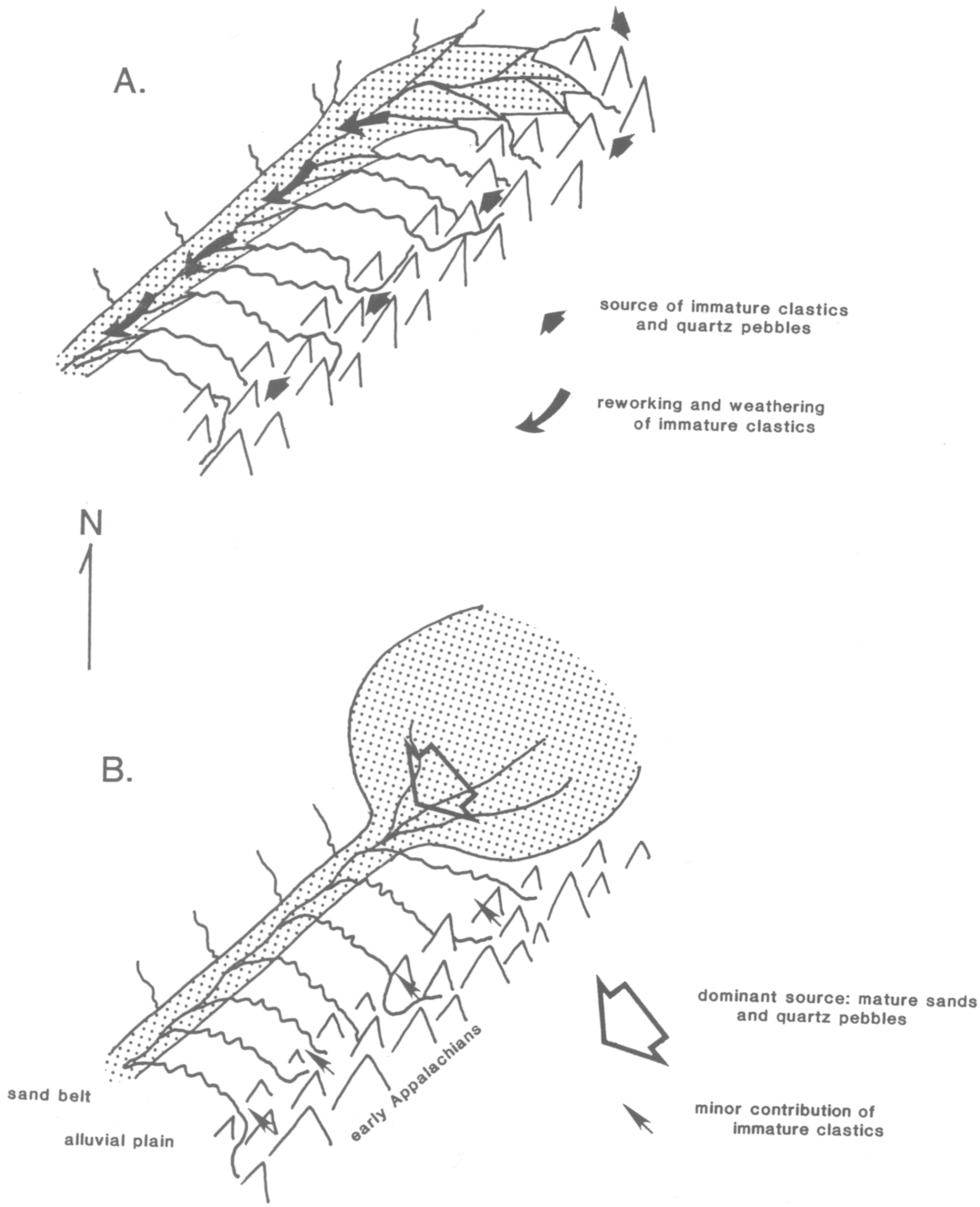
Origin Of Quartzose Sands

Two possibilities for the origin of quartzose sands in fluvial systems are illustrated in Figure **60a**. b. In the first case (Fig. 60a), the source for all the clastics entering the fluvial sandbelt was from the Appalachian highlands, and included quartz, feldspars, and lithic fragments. Tropical weathering (Johnson and others, 1988) and fluvial reworking of the immature clastics preferentially enriched the quartz content of the sandbelt.

In the second case (Fig. 60b), the dominant source for the quartzose clastics was previously-enriched "mature" clastics from an area to the northeast. Such a source may have been concentrated quartzose sediments deposited prior to the Early Pennsylvanian. In this model minor additions of immature clastics were introduced to the sandbelt by northwest flowing rivers represented by the Breathitt Group.

The origin of the quartz pebbles in the Lee sandstones has also been a problem, because the Breathitt sediments which prograded toward the Lee sandbelts only rarely contained quartz pebbles, and the rocks which subcrop at the regional unconformity in the Central Appalachian basin do not contain quartz pebbles. Regional sedimentological studies by BeMent (1976) indicated that the quartz pebbles increase in size to the northeast (Fig. 54), a feature that can be explained by a northeastern source. However, the

Figure 60. Source of quartz in the Lee sandbelts: (A) Appalachian highlands, (B) external source to the northeast.


A.
source of immature clastics
and quartz pebbles
reworking and weathering
of immature clastics
N
B.
dominant source: mature sands
and quartz pebbles
minor contribution of
immature clastics
sand belt
alluvial plain
early Appalachians

exact source for the pebbles remains unknown. The pebbles appear to be derived from quartz veins, possibly from granite (N. Rast, personal communication, 1988).

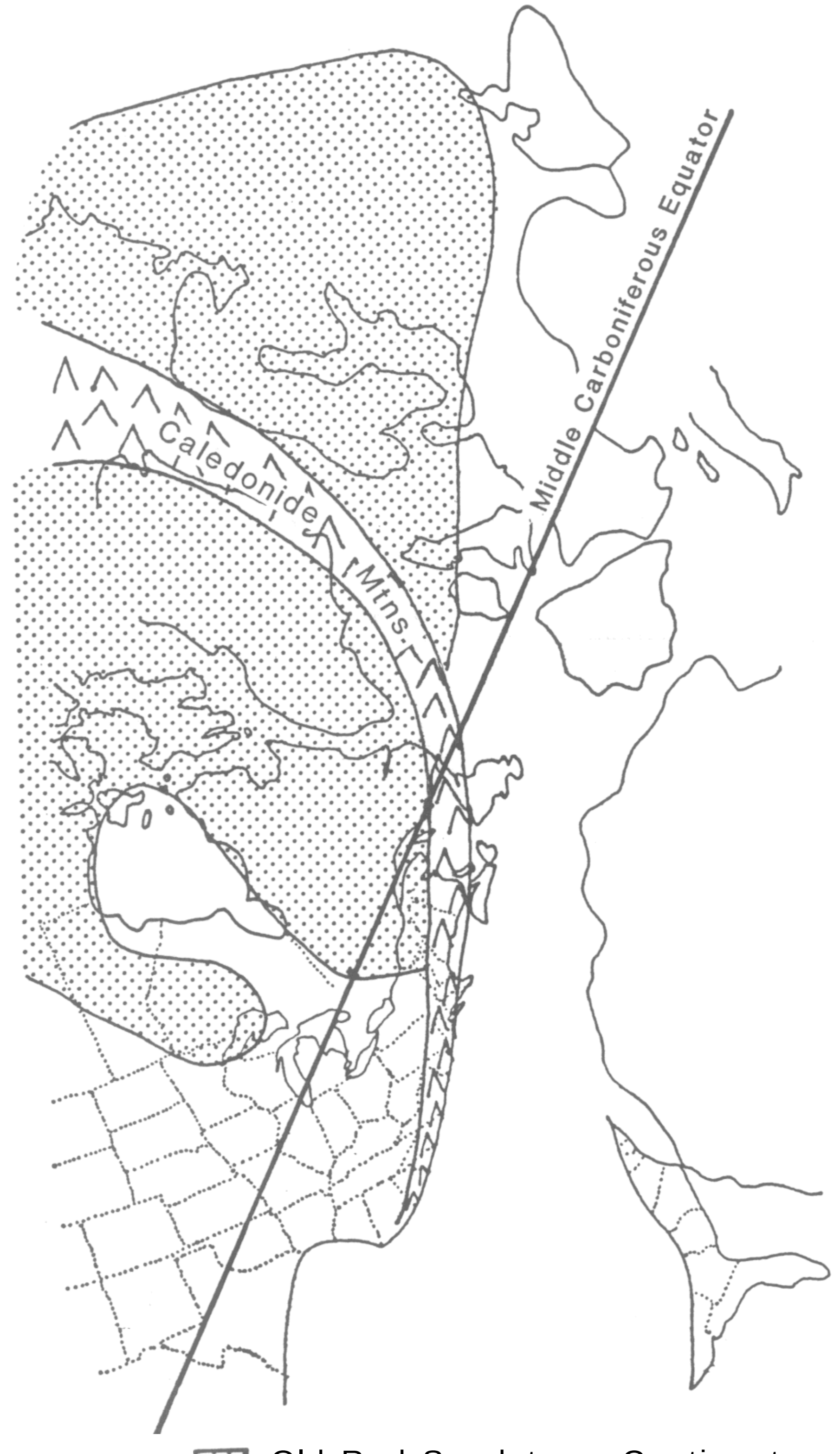
The Caseyville Formation (Early Pennsylvanian) in the Eastern Interior (Illinois) Basin is similar in composition and in age to the Lee Formation. Moreover, the Caseyville overlies the Mississippian-Pennsylvanian unconformity in this basin. The Caseyville is interpreted to represent a south- or southwest-flowing deltaic-fluvial system (Howard, 1979; Koeninger and Mansfield, 1979), which parallelled the dominant current direction in the Lee Formation. The source for these quartz-rich sands is inferred to have been from the north or northeast (Potter and Sevier, 1956). Coeval rocks northeast of the Eastern Interior Basin lie in the Michigan Basin. In the Michigan Basin the quartz-rich Parma Sandstone is the correlative of the Caseyville Formation. A subsurface study of the Parma reveals a thickness trend oriented northeast-southwest (Vugrinovich, 1984, p. 9-12). Average crossbed directions in the Parma are also to the southwest (Potter and Siever, 1956, fig. 5, p. 236). The Caseyville and Parma were probably part of the same sandbelt system, herein called the Caseyville sandbelt. The source for the quartzose sand and quartz pebbles of the Caseyville sandbelt would most likely be northeast of the Michigan Basin. The source of the Caseyville sandbelt was apparently very similar to that suggested in the second scenario (Fig. 60b) for the origin of the quartzose sand.

Some observations in the Lee and Caseyville sands suggests a multi-cycled origin. The occurrence of rounded grains of zircon, tourmaline, and abraded quartz overgrowths in the Caseyville (Gopinath, 1972; Koeninger, 1978; Koeninger and Mansfield, 1979) suggests recycled sediments. A sedimentological study by Pryor and Potter (1979, p. 59-60) also indicated a multicycled origin (and perhaps one exposed to tropical and subtropical weathering) for the quartz sands of the Kyrock Sandstone (Caseyville Formation, west-central Kentucky). In addition, Green (1982) reported rounded zircon and tourmaline in the Bee Rock Sandstone (Rockcastle Sandstone) of south-central Kentucky (Appalachian Basin), which also suggests a multi-cycled origin.

If the sands of the Lower Pennsylvanian Lee and Caseyville are polycyclical, then they were derived from pre-Pennsylvanian deposits. The substantial amount of sandstones in the Lee and Caseyville formations in the Appalachian, Eastern Interior, and Michigan Basins, as well as that which must have been subsequently eroded between these basins, indicates a large source for these sands. A northeastern source suggests some interesting possibilities.

Northeastern North American areas that still retain their mid-Paleozoic cover would obviously not have been the source areas for the vast quantities of sand in the Lee and Caseyville sandbelts. Areas in northeastern North America where mid-Paleozoic and older rocks are missing, however, may have been possible source areas. Figure 61 is the author's reconstruction of continents and tectonic features at mid-Carboniferous time adapted from information from Bambach, Scotese and Ziegler (1980), Ettensohn (1985a, b), and Rast (in press). The (by then) ancient Caledonide and Acadian mountain chain and the extent of the Devonian Old Red Continent is illustrated as well. The Caledonide and Acadian orogenic belts would have been the major source for clastic sediments deposited during mid-Paleozoic time. The Catskill Delta represents one of these deposits. Caledonide and Acadian foreland basins and proximal cratonic areas would have been covered by deltaic and alluvial deposits along a wide belt parallel to the Caledonide and Acadian trends. In addition, soil zones or aeolian deposits, produced by the weathering of the igneous and metamorphic rocks of the Canadian Shield, may have existed over large areas. However, a vast area of northeastern North America (Canadian Shield) has been denuded of any pre-Pennsylvanian cover. Only Precambrian metamorphic and igneous rocks are exposed now. Perhaps variously consolidated strata on part

Figure 61. Mid-Carboniferous reconstruction of North America, western Europe and northwestern Africa. Reconstructions adapted from Bambach, Scotese and Ziegler (1980 and from Rast (in press). Devonian features including the Old Red Sandstone Continent and the Caledonide-Acadian Mountains were taken from Ettensohn (1985a,b).



Old Red Sandstone Continent

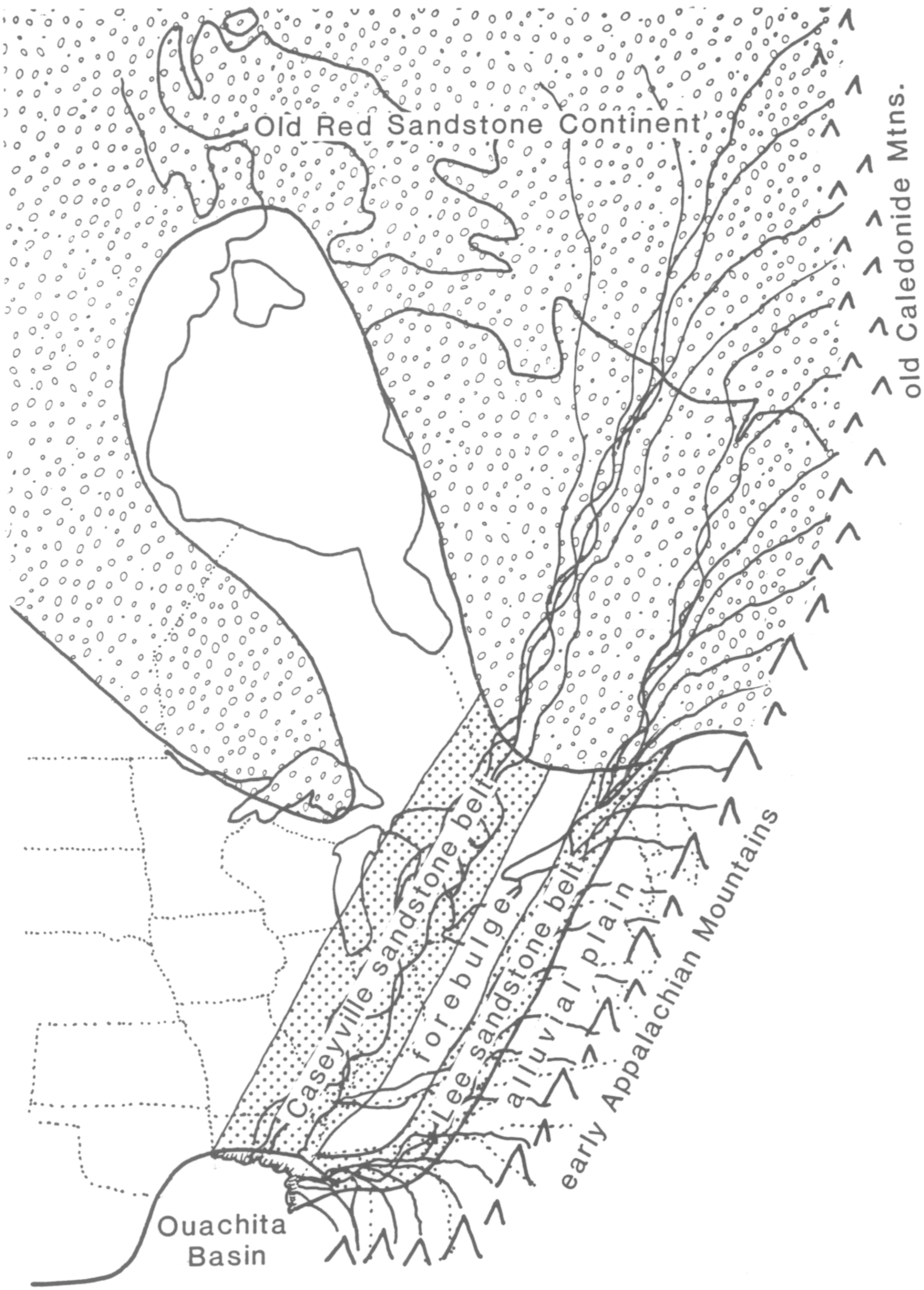
of the Canadian Shield and adjacent areas were the source for the recycled sands which were later transported and deposited to the southwest.

Early Pennsylvanian Scenario

During mid-Carboniferous time, some rivers carrying recycled Devonian (and older) clastics flowed to the south or southwest of the Old Red Sandstone Continent along the Lee and Caseyville sandbelts (Fig. 62; only the eastern half of this diagram will be discussed). Additional recycled Acadian and earlier sediment, as well as clastics derived from crystalline rocks along the early Appalachian chain and the Ouchita trend, were added to the Lee sandbelt rivers by tributaries flowing out of the mountains and across alluvial plains (Breathitt Group).

The orientation of both sandbelts was probably controlled by the location of the Appalachian forebulge. Major river systems are sometimes oriented parallel to the mountain chain between the forebulge and the belt of alluvial fans emanating from the mountains. For example, the Ganges River parallels the Himalayan mountain chain in a similar fashion. In fact, Graham and others (1975) applied the Himalayan Mountains-Ganges River-Bengal Delta model to the Appalachian-Ouachita chains (Fig. 62). In the following adaptation of their model, the Lee Formation and

Figure 62. Reconstruction of eastern North America during the Early Pennsylvanian. The "Old Red Sandstone Continent" represents an old land surface exposed during the middle Paleozoic. Old highlands of the Caledonide-Acadian mountain chains probably occurred to the northeast.


Old Red Sandstone Continent
old Caledonide Mtns.
Caseyville sandstone belt
forebulges
Lee sandstone belt
alluvial plain
early Appalachian Mountains
Ouachita Basin