U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

The Mississippian Loyalhanna Limestone (Formation)--A Paleozoic eolianite in the Appalachian basin, in--Cecil, C.B., ed., Predictive stratigraphic analyses guidebook series no. 1--The Mississippian and Pennsylvanian systems in West Virginia

by

Thomas S. Ahlbrandt[1]

Open-File Report 95-240

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

[1] U.S. Geological Survey, Box 25046, MS 934, Denver Federal Center, Denver, Colorado 80225 U.S.A.

1995

The Mississippian Loyalhanna Limestone--A Paleozoic Eolianite in the Appalachian Basin

by
Thomas S. Ahlbrandt

Introduction

The Loyalhanna Limestone is a significant petroleum producing unit in the Appalachian Basin (fig. 1). Much of West Virginia's total oil production has come from the Loyalhanna (Big Injun Sand and/or Big Lime) which has produced in excess of 200 million barrels of oil in West Virginia alone (Carney and Smosna, 1985). This Late Mississippian unit represents a wide-spread arenaceous calcarenite/orthoquartzite known from central and south-western Pennsylvania, western Maryland and northern West Virginia (fig. 1) and rocks equivalent in facies and age (Greenbrier Limestone) extend into central and southeastern West Virginia. Internal sedimentologic characteristics, notably the large scale cross-bedding, have led to both marine and eolian interpretations. I hope to demonstrate through application of eolian sedimentologic and textural criteria that the Loyalhanna Limestone indeed represents a Paleozoic eolianite. This interpretation provides new potential for hydrocarbon development of the Loyalhanna Limestone because of the significant internal production complications of eolianites which may now be addressed.

Some early investigators (Butts, 1924; Hickok and Moyer, 1940, and more recently Berg, 1980) considered the Loyalhanna Limestone (Formation) to have an eolian origin, and recently Hunter (1993) described an eolian facies in the Ste. Genevieve Limestone, a Loyalhanna equivalent, in southern Indiana.
Other early investigators considered the Loyalhanna Limestone to be a nearshore marine complex of beach, dune, bar, and sheet sands (Campbell, 1902; Rittenhouse, 1949, Flowers, 1956; and Flint, 1965). In his 1970 study of the Loyalhanna Limestone, based on textural, petrologic, and sedimentologic criteria, Adams concluded that the depositional environment was most likely shallow high-energy marine. He rejected eolian, beach, and fluviodeltaic environments of deposition principally based on his conclusions related to textural analyses (figs. 1,2, 3). Other investigators (Brezinski, 1984, 1989a,b; Katkins and Brice, 1990) also interpret the Loyalhanna Limestone to be a marine sequence and reject the eolian interpretation.

The age of the Loyalhanna Limestone has been poorly constrained due to the paucity of mega- and micropaleontologic analyses (Adams, 1970). Its age has largely been bound to correlations well outside of its type area on the basis of petrologic criteria. Although early workers (Reger, 1926; Butts, 1924) regarded the Loyalhanna to be an equivalent of the Mid-continent Ste. Genevieve Limestone, at that time and even today, the Genevievian stage lacked definitive assignment to either the Mermecian or Chesterian series (Maples and Waters, 1987).

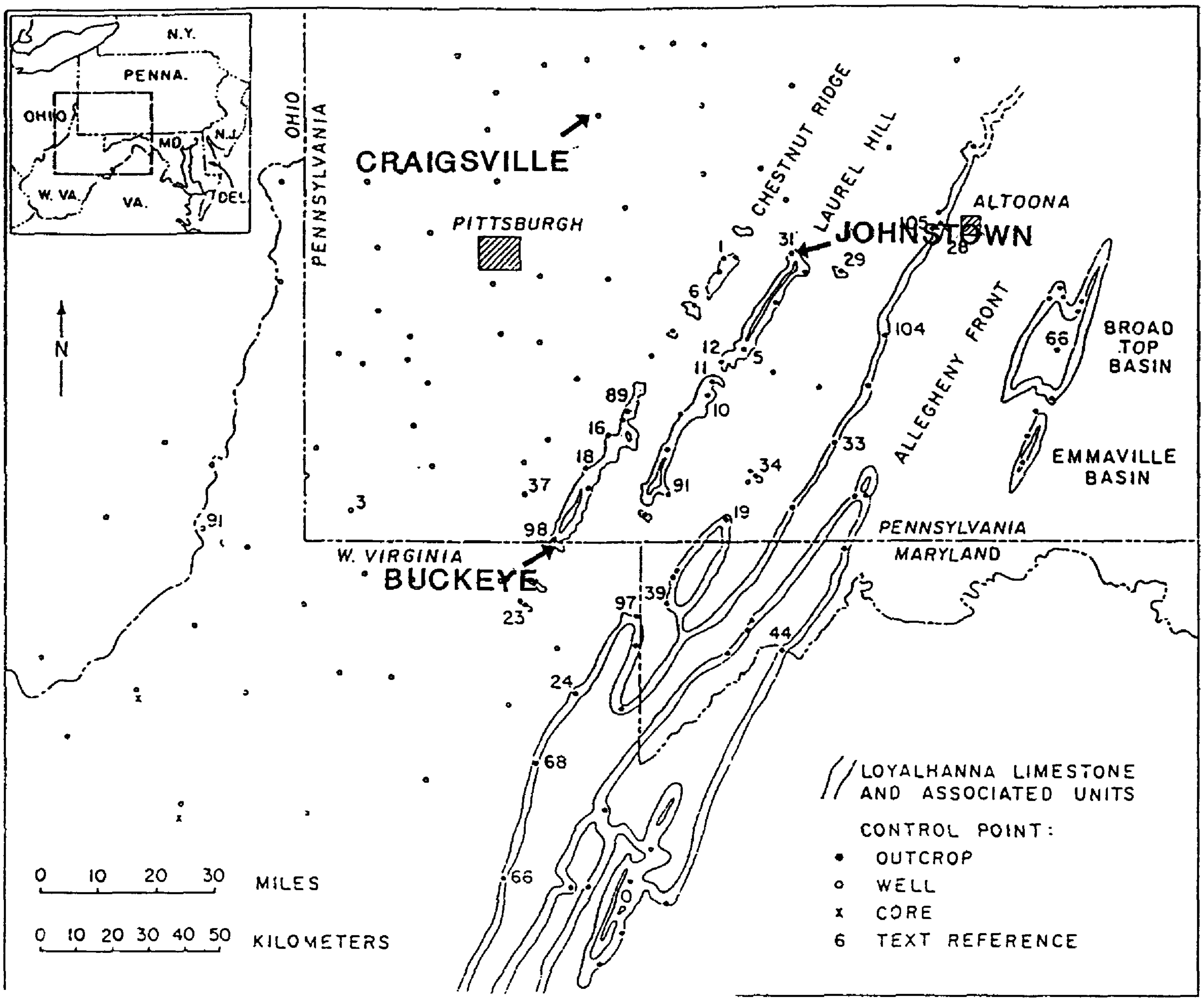
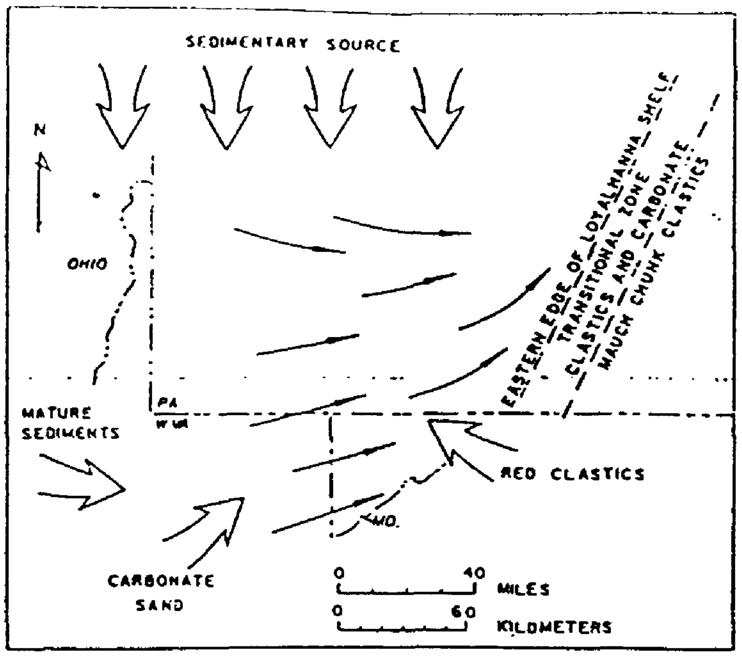
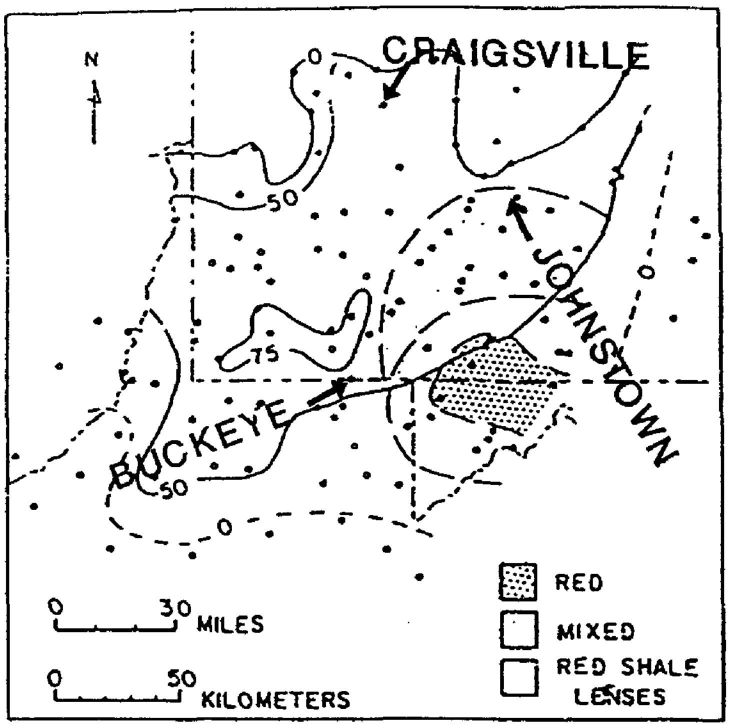


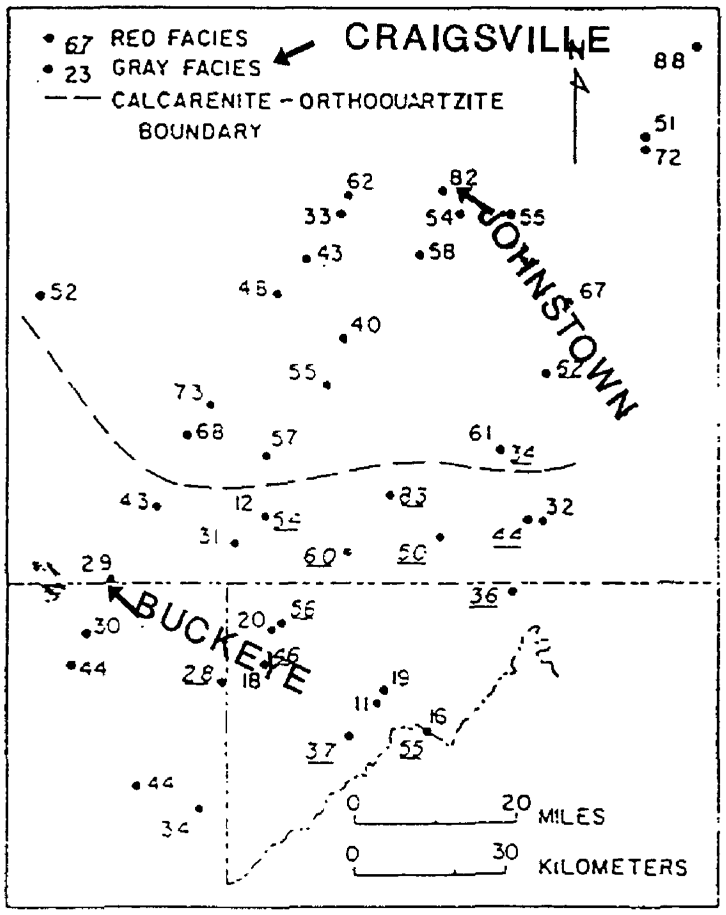
Figure 1. Map of Loyalhanna Limestone and associated units, showing outcrop, well and core occurrences. Numbers refer to localities defined by Adams (1970). Johnstown, Craigsville and Buckeye study localities shown on base map by Adams (1970).



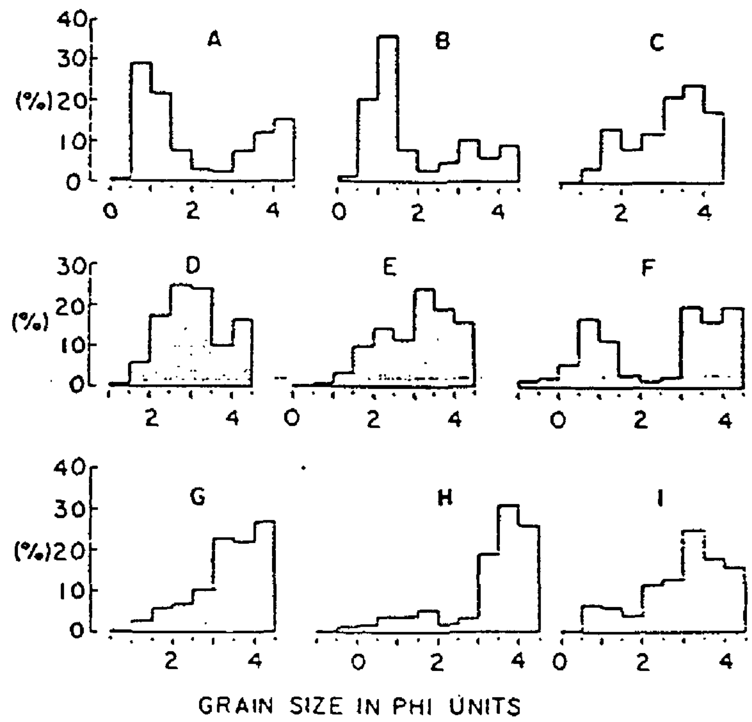
2A



2B



2C



2D

Figure 2. A, Loyalhanna Limestone depositional framework and dispersal system. B, Loyalhanna Limestone isopach map--note red color to southeast. C, percentage of terrigenous grains in the Loyalhanna Limestone--numbers refer to orthoquartzite content in percent, dashed line separates orthoquartzitic composition on north from calcarenitic composition to south. D, histograms of size distributions of Loyalhanna Limestone terrigenous grains. Plots A-E are cross-bedded units, F is a horizontally laminated unit, G is a wavy bedded unit, H and I are massive units (study localities are shown on base maps for A, B, C, and D which are from Adams, 1970).

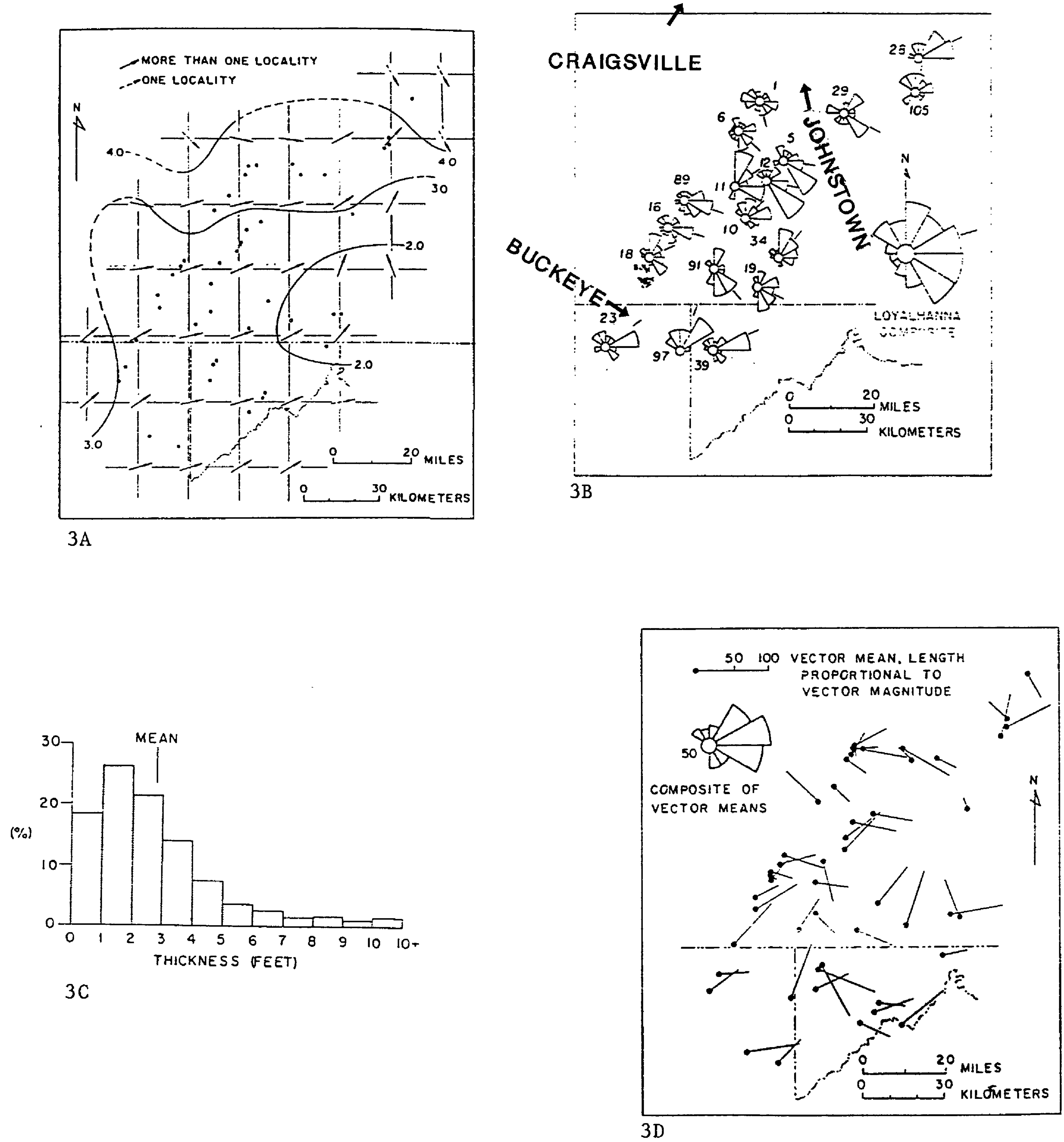


Figure 3. Cross-bed information on the Loyalhanna Limestone: A, moving average of cross-bedding vector means and contoured moving average of cross-bedding in feet. B, rose diagrams with vector means for Loyalhanna cross-bedding dip azimuths--all localities have 15 or more readings, numbers indicate Adams (1970) study localities, total 651 readings for composite diagram. C, histogram of thickness of Loyalhanna cross-bed sets--mean thickness if 2.78 feet (0.85m). All maps from Adams (1970). D, locality vector means of cross-bedding dip azimuths.

The age of the Loyalhanna Limestone is largely based on lithostratigraphic correlation with the Greenbrier Series of southeastern West Virginia and southwestern Virginia (Reger, 1926, Butts, 1940, Wells, 1950). Many workers (deWitt and McGrew, 1979; Berg and others, 1986 (Trough Creek Limestone); Brezinski, 1984, 1989a, 1989b) considered the Loyalhanna Limestone to be late Meramecian in age, based largely on original lithostratigraphic correlation of Reger (1926) and Butts (1940) to the Union Limestone (Fredonia Oolite) and Ste. Genevieve Formation respectively. Wells (1950) disagreed with Reger's age of the Union Limestone instead correlating it with the early Chesterian "Gasper" rather than the late Meramecian Fredonia Oolite. Wells (1950) contended that Meramecian age strata were not present north of Randolph County, West Virginia; therefore the Loyalhanna Limestone was Chesterian in age. Investigators in Pennsylvania include the Loyalhanna in the lower part of the Chesterian Mauch Chunk Formation (Butts, 1945, Trough Creek Limestone); Berg, 1980; Gallagher and Parks, 1983; Edmunds, 1993), both of which intertongue with the Greenbrier Formation of western Maryland and northern West Virginia where the Loyalhanna is considered Meramecian (Brezinski, 1984, 1989a, 1989b).

Conodont collections of the Greenbrier Formation of northern West Virginia and western Maryland, and the Loyalhanna, Deer Valley, Wymps Gap, and Trough Creek Limestones of Pennsylvania yield early (but not earliest) to middle Chesterian age faunas (R. Stamm, USGS, written commun, 1995). Of particular interest is the recovery of reworked Late Devonian to Early Mississippian polygnathid conodonts from the Loyalhanna and Deer Valley Limestones and their implications for possible basin dynamics and provenance. The abrasions on and reworking of conodonts contained in the Loyalhanna Limestone are consistent (R. Stamm, USGS, written commun., 1995) with observations of conodont reworking by eolian action as described by Broadhead and Driese (1994).

The Mississippian Loyalhanna Limestone exhibits striking stratigraphic and sedimentologic similarities to Paleozoic eolianites or ancient sand seas in Wyoming and Colorado. Sand seas or ergs are described by Wilson (1973) as areas covered by wind blown sand covering an area of at least 8,000 sq km generally ergs encompass 12,000 sq km (4,600 sq mi) or more. The Loyalhanna Limestone covers 44,000 sq km (17,000 sq mi) of West Virginia, Maryland, Pennsylvania and Ohio (Adams, 1970) and averages 18.5m (60 feet) in thickness with a maximum thickness of 31.5m (103 feet) and is described as a very thin sheet or blanket sand body (Adams, 1970). Studies of ancient eolianites such as the Permian Lyons Sandstone in northern Colorado and southern Wyoming (Walker and Harms, 1972, Maughan and Ahlbrandt, 1985) or the Permo-Pennsylvanian Casper Formation (southern Wyoming) or its stratigraphic equivalent in Colorado, the Ingelside Formation, (Hanley and Steidtmann, 1973; Steidtmann, 1974; Kelly, 1985; Maughan and Ahlbrandt, 1985) have documented many of the same features seen in the Loyalhanna Limestone. Comparable features include vertical sequence stratigraphy, red and gray color changes, intercalated marine sequences and fauna, eolian abrasion of conodonts, and lateral facies changes to non-eolian sequences. A review of criteria for identification of eolianites and a comparison of these western Paleozoic eolianites with the Mississippian Loyalhanna Limestone will follow.

Exposures of the Loyalhanna Limestone were visited in West Virginia, Maryland and Pennsylvania; however, only the Craigsville (PA), Johnstown (PA), and Buckeye (WV) localities as shown on figure 1 will be discussed. These localities represent a wide geographic distribution in the eolian sand sea, and allow us to discuss similarities and differences in sand composition, sedimentary bedforms and textural criteria.

Review of Eolian Deposits

The geologic literature in the late 1960's and 1970's is replete with discussions and debates about interpreting or reinterpreting eolian sequences as marine tidal bedforms. These studies are based upon either textural criteria or the misinterpretation of exaggerated high resolution profiles of marine bedforms. During this same period there was an increased understanding of eolianites, their sequences, their deposits, the processes that created the deposits, and the lateral and vertical relationship of eolian deposits to non-eolian or "extradune" deposits. In the late 1970's, a series of investigations of eolian deposits, sand seas, and eolianites permitted a much better understanding of wind-blown deposits. McKee (1979) edited a volume entitled "A Study of Global Sand Seas" which discussed the many complex attributes of eolian sequences and their intimate association with non-eolian environments. Hunter (1977) provided detailed sedimentologic evidence to differentiate eolian deposits from non-eolian deposits and introduced the term translatant stratification. This is the process whereby migrating trains of wind ripples leave diagnostic evidence of eolian ripple sedimentation in a variety of conditions. Ahlbrandt and Fryberger (1982) summarized the criteria for recognition of eolian deposits including dune, interdune, sand sheet or low angle eolian and sabkha environments. It is critical to understand that these types of eolian deposits may occur amid and among non-eolian deposits see the dune-extradune model of Lupe and Ahlbrandt (1979), the eolian system prograding into an ocean (Fryberger and others, 1983), or the allocyclic model of Loope and Simpson (1992) and Shanley and McCabe (1994). Publications by Brookfield and Ahlbrandt (1983), Pye and Tsoar (1990), and Fryberger and others (1990) represent some of the more recent and comprehensive works to refine aspects of the eolian environment.

Eolian deposits are dynamic and very sensitive to changes in climate, texture change and moisture conditions. Eolian deposits are important indicators of climate change such as from wet to dry periods or warm to cold as discussed by Ahlbrandt and Fryberger (1982). The juxtaposition of dry dune sands next to wet interdune deposits and the short term process of infiltration of clays by meteoric precipitation dislodging clay rims from eolian grains and forming infiltration structures known as dissipation structures are to be expected in eolian deposits rather than interpreted as contradicting an eolian environment.

The role of water in dune formation, migration, preservation and modification is extensively discussed by Fryberger (1990). Textural aspects of eolian deposits including grain size parameters, shape, roundness, mineralogical maturity and heavy mineral suites are discussed by Ahlbrandt (1979), Moiola and Spencer (1979), Pye and Tsoar (1990) and Shebl and Surdam (in press) among many others. Certain eolian environments such as the interdune are characterized by very bimodal, poorly sorted sediment (e.g. Ahlbrandt, 1979). Remobilization of silt and clay particles originally deposited either as suspension deposits or as rims on coarser grains is much discussed in the literature (Walker, 1979, Ahlbrandt and Fryberger, 1980; Ahlbrandt and Fryberger, 1982; Pye, 1983; Pye and Tsoar, 1990; Schenk, 1990).

In certain eolian settings, low angle eolian deposits (<20 degree dips), which commonly are vegetated even in very arid settings, areally constitute 90% of a dune field whereas high angle eolian deposits (>20 degree dips) constitute the remaining 10% (Ahlbrandt and others, 1994). In such deposits, a variety of detailed sedimentary features including inversely graded laminae, the translatant strata of Hunter (1977), avalanche or sand flow toes (Ahlbrandt and Fryberger, 1982), Type a and type b low angle eolian deposits (Fryberger and others, 1979), secondary eolian structures such as dissipation or infiltration and soil structures in eolian deposits (Bigarella, 1972; Ahlbrandt and Fryberger, 1980; Pye, 1983; Schenk, 1990) occur demonstrating the great variety of features found within just one type of eolian deposit.

In brief summary, certain criteria known from modern eolian deposits are diagnostic of an eolian environment. These include:

(1) wind ripple, pin stripe or translatant stratification --these appear as if the sand had been painted with a brush; laminations are finely subdivided, relatively continuous and texturally variable from one lamination to another, and are commonly inversely graded on a scale of millimeter to a few millimeters (Schenk, 1983)

(2) avalanche or sand flow strata-- these strata are commonly about a centimeter in thickness and commonly pinch out along or above the lower bounding surface of a cross-bed set; they may intercalate laterally with wind ripple or low angle eolian deposits; distinct types of graded bedding and bed thickness are formed during this process (Ahlbrandt and Fryberger, 1982)

(3) high ripple indices--modern eolian deposits generally have low, widely spaced ripples, commonly with a width to height ratio (ripple index) in excess of 15; as opposedto subaqueously produced ripples whose indices are generally less than 10 (Reineck and Singh, 1975).

(4) large scale, moderate to high angle cross-strata--these are commonly wedge planar or tabular planar sets in siliciclastics (Ahlbrandt and Fryberger, 1982) and trough or festoon cross-bedded in carbonates (McKee and Ward, 1983) with diagnostic sand transport patterns which allow interpretation of bedform type.

(5) intercalated, poorly sorted, bimodal lag deposits along erosional bounding surfaces--if deposition occurs along such surfaces discontinuous/lenticular

interdune deposits may occur which can be clastic, carbonate/evaporite or simply granule lags; lags are generally evenly distributed along surface or may be concentrated into granule ripples (Fryberger and others, 1979; Ahlbrandt, 1979)

(6) large and small scale deformational structures-- such as break apart structures (McKee and others, 1971; McKee, 1979), and dissipation or infiltration structures which indicate both moisture content and cohesiveness of sand at or near the time of deposition (Ahlbrandt and Fryberger, 1982)

(7) normally and inversely graded, laminated and ungraded strata--these are produced by processes of avalanching, ripple migration, grainfall or suspension sedimentation, all of which may be intermixed (Ahlbrandt and Fryberger, 1982)

(8) frosting of sand grains or etching of surfaces (Walker, 1979)

(9) light and heavy mineral separation ratios (Steidtmann, 1974)

(10)Bioturbation is ubiquitous in eolian deposits--it generally occurs in response to subtle moisture changes in the deposits as organisms seek the most beneficial position (Ahlbrandt and others, 1978b). Careful investigation is needed to differentiate terrestrial and marine traces because they can be quite similar.

Common misconceptions about eolianites include:

(1) cross-bedding is all high angle (>30 degrees) and dips in one direction
(2) subaqueous deposits do not occur within eolian deposits
(3) bioturbation traces do not occur in eolian deposits
(4) eolianites are well sorted, mature (quartzose), texturally homogeneous, well rounded sand grains
(5) eolianites are very homogeneous deposits reflecting essentially only the arid end of the climate spectrum (this will be discussed below):

Reinterpreting Existing Loyalhanna Limestone Data

Adams (1970) carefully determined the texture, composition, cross-bedding azimuths and foreset dip angles of the Loyalhanna Limestone (figs. 1,2,3). The Loyalhanna Limestone was deposited in a paleographic setting in the southern hemisphere oriented as shown in the late Mississippian (early Chesterian time reconstruction, fig. 4). Many of his interpretations reflect the literature of that time, and he and (Brezinski, 1984, 1989a,b) interpreted the Loyalhanna as submarine sand waves complete with red shale interswale deposits. If viewed within the context of recent eolian studies; however, the data presented by Adams (1970) are entirely consistent with an eolian interpretation. If we focus on a few areas of analyses we may compare possible interpretations.

Cross-bedding: The term eolianite was originally applied to calcarenite deposits as described by McKee and Ward (1983). Calcarenites produce a true festoon cross-bedded pattern (McKee and Ward, 1983) more commonly than the wedge-planar type described for their siliciclastic counterparts, although both are superficially similar eolian deposits. Festoon cross-bedding, however, is a more common feature in carbonate eolian sequences. The reader is referred to McKee and Wier (1953) and

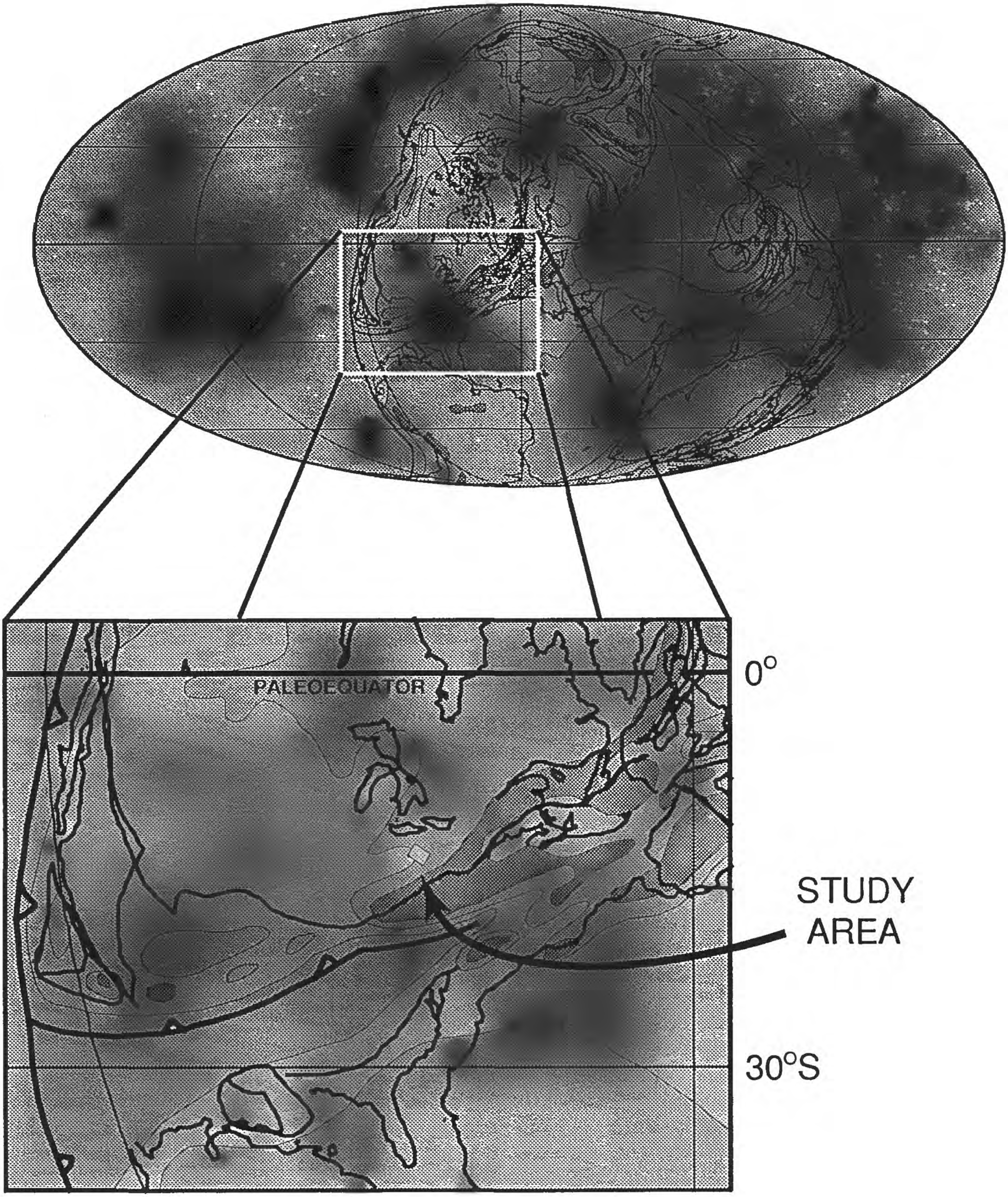


Figure 4 . Late Mississippian (early Chesterian) paleogeographic reconstruction and location of Loyalhanna Limestone study area (modified fron Scotese, 1993).

McKee (1979) for a more elaborate treatment of wedge-planar versus festoon cross-bedding. Adams, (1970) discussion of festoon cross-bedding in the Loyalhanna cites Knight's (1929) work . Knight (1929) described festoon cross-bedding in the Permo-Pennsylvanian Casper Formation in the southern Laramie Basin of Wyoming. The Casper Formation is now considered to be a classic eolian unit (Hanley and Steidtmann, 1973; Steidtmann, 1974; Kelly, 1985; Maughan and Ahlbrandt, 1985) that grades laterally into marine carbonate units along the Ancestral Front Range.

Low angle eolian deposits are very common and important parts of eolian systems (Fryberger and others, 1979; Kocurek, 1986; and Ahlbrandt and others, 1994). The cross-bedding of the Loyalhanna Limestone, as measured by Adams (1970), has a mean dip of 20 degrees, a mode as 20 to 25 degrees and a range from 5-40 degrees (table 1). These measurements are entirely consistent with eolian deposits; e.g. Ahlbrandt and Fryberger (1980, 1982) describe mean dips of barchan, transverse ridge and blowout dunes respectively as 22, 24 and 16 degrees. The scale and dip of Loyalhanna cross-bed sets (fig. 3) are entirely consistent with the relatively small bedforms preserved in the Loyalhanna Limestone have a maximum thickness is about 100 feet and its average thickness is about 60 feet; however the maximum cross-bed set thickness is 16 feet (table 1). Even at the average thickness of the entire Loyalhanna at 60 feet, a 60 foot dune is a relatively small bedform when compared to barchan and barchanoid ridge dunes in the Nebraska Sand Hills which are commonly 200 to 300 feet high (Ahlbrandt and Fryberger, 1980).

Table 1.--Loyalhanna Limestone Cross-bedding Statistics (from Adams, 1970)

Azimuth	Mean direction: 072 degrees Modality: unimodal and bimodal Variance (standard deviation): 5776 (76 degrees)
Scale (feet, meters)	Mean: 2.78, 0.85 Mode: 102, 0.3-0.6 Range: 0.3-16, 0.1-4.9
Inclination (degrees)	Mean: 20.0 degrees Mode: 20-25 degrees Range: 5-40 degrees

Color Changes: Eolianites are typically variously colored red and white, or gray. These colors may be syndepositional, produced by such agents as the intercalation of oxidized interdune shales or plant growth; or they may be post- depositional results of diagenesis and fluid movement.

The red shale lenses intercalated within the cross-bedded sequence in the Loyalhanna Limestone are here interpreted to be interdune deposits, and are known from both modern (Ahlbrandt and Fryberger, 1981; Kocurek, 1981) and ancient environments (Hanley and Steidtmann, 1973; McKee, 1979). The red color in eolian deposits often indicates an oxidizing environment, particularly where sediments are periodically dampened by ground water. Red oxidized interdune sediments occur in both siliciclastic and carbonate sequences in the Permian Casper Formation (Hanley and Steidtmann, 1973). Plants can also provide the reducing/oxidizing conditions needed to precipitate hematite, limonite, or other clay minerals which give both color and textural changes to eolianites. In the eolian literature, evidence of this vegetation are referred to as dikaka (Glennie and Evamy, 1968) or hematized root tubules (Ahlbrandt and Fryberger, 1982)

Alteration of clay rims on sand grains of eolianites can also produce red or gray coloration (Walker, 1979). Examples include the Permian Lyons Sandstone (Levandowski and others, 1973; Walker and Harms, 1972; Maughan and Ahlbrandt, 1985; Shebl and Surdam, 1994). Lastly, complex and multiple fluid movement, particularly of hydrocarbons, is common to eolianites and may cause color changes as discussed by Panda and Lake (1994), Shebl and Surdam (1994, in press). The variety of colors in the Loyalhanna Limestone (fig. 2b) are comparable to those observed in many modern and ancient eolianites.

Lenticular Siltstones and Shales: As discussed above, lenticular siltstones and shales which may be red in color are entirely consistent with interdune and sand sheet deposition within an eolian environment (e.g. McKee, 1979, Ahlbrandt and Fryberger, 1981, 1982; Ahlbrandt and others, 1994). Lenticular siltstones and shales of the Loyalhanna Limestone, commonly red in color, are described by Adams (1970) and located geographically in figure 2b .

Textural Analyses: Adams (1970) documented the Loyalhanna Limestone to generally be a very fine grained sand in cross-bedded units, and bimodal and more poorly sorted in the horizontally laminated units (fig. 2d). In a study of eolian sands from around the world, Ahlbrandt (1979) determined bimodal, poorly sorted, subangular to subrounded grains characterize interdune or sand sheet deposits, while uniformly fine sand characterizes sand dunes.

Loess, or silt-sized eolian particles, and clay are common and often integral constituent particles of eolian sequences. Clay coatings on eolian sand grains are virtually ubiquitous in modern eolian environments. Electrostatic charging of active saltating sand grains (+) attract clay dust particles (-) during periodic breaks in the sand-moving winds. Daily climatic states, such as quiescence, allow fine grained wind-born silt and clay to settle and accumulate as surface deposits on the coarser eolian sand grains (e.g. Walker, 1979; Greeley and others, 1983; Pye, 1983). Silt and clay are known to accumulate from suspension in any sheltered area.

Heavy Minerals: The heavy mineral assemblage of the Loyalhanna Limestone is mature, consisting of greater than 85 percent tourmaline and zircon with garnet and rutile being present in most samples (Adams, 1970). The heavy minerals are well rounded possibly indicating prolonged abrasion or multicyclic source areas as discussed by Adams (1970). The tourmaline to zircon ratios and the sandstone compositional analyses documented by Adams (1970) are consistent with the light/heavy separation ratios documented by Steidtmann (1974) for the eolian Casper Formation.

New Observations at Loyalhanna Localities

The **Johnstown** locality (Loc. 40° 21' 40" N, 78° 57' 15" W) includes several exposures north of Johnstown, Pennsylvania where Route 403 transects the Conemaugh River Gorge as described by Katkins and Brice (1990) (figs. 1,2). Here, exposures of the red to gray Loyalhanna Limestone are approximately 60-65 feet thick, and grade from an arenaceous calcarenite at the base to orthoquartzites at the top. The **Craigsville,** Pennsylvania locality (Loc. 40° 51' 17" N, 79° 39' 8"W) is about 45 miles northwest of the Johnstown, hence these exposures were upwind at the time of deposition (fig. 2b). Here, the Loyalhanna Limestone is relatively more quartzose (fig. 2c) and gray in color. The **Buckeye** Stone Quarry near Morgantown, West Virginia (39°41' 54"N, 79° 46' 59" W) is the third study locality. Here, exposures are of comparable thickness to Johnstown (fig. 2b), however, the lower quartz sand composition classifies the Loyalhanna at this locality as a calcarenite, while the color is transitioning from gray to red (fig. 2c). At these localities, the Loyalhanna Limestone includes diagnostic sedimentary features which are consistent with an eolian depositional environment. Each locality will be discussed below.

Johnstown Locality: Several Loyalhanna outcrops were visited north of Johnstown, Pennsylvania. An abandoned quarry at the Clark Run Nature Area on the west side of Highway 403 is described by Katkins and Brice (1990). Eolian features observed here are interpreted to be both low and high angle eolian deposits as pictured in figures 5, 6, and 7. The low angle eolian deposits exhibit well preserved type a and type b deposits as shown in general view in figures 5b and 5c, and in detailed view in figure 5d. The detailed photograph (fig. 5d) illustrates a coarser grained type b ripple, which is produced during erosional phases of eolian sequences. During erosional or deflational periods, coarser grains are left at the sediment surface as finer material is deflated downwind. The coarser grains tend to be dispersed as either evenly distributed lags (Bagnold, 1941), or granule ripples or eventually mega-granule ripples if coarse material is sufficiently abundant (Fryberger and others, 1979). Type b deposits of erosional events are commonly interspersed with type a deposits of depositional events. Type a deposits are very different, consisting mostly of millimeter to several millimeter laminae, and are commonly inversely graded; they are and described in great detail as translatant strata by Hunter (1977). The type a deposits look finely laminated or pin striped, or as having been brushed with a paint brush, and may be interspersed with type b deposits; here a coarser grained ripple form or lag deposits (fig. 5d). Evenly distributed lags along bounding surfaces and coarser grained ripple forms of type b deposits, are abundant and well

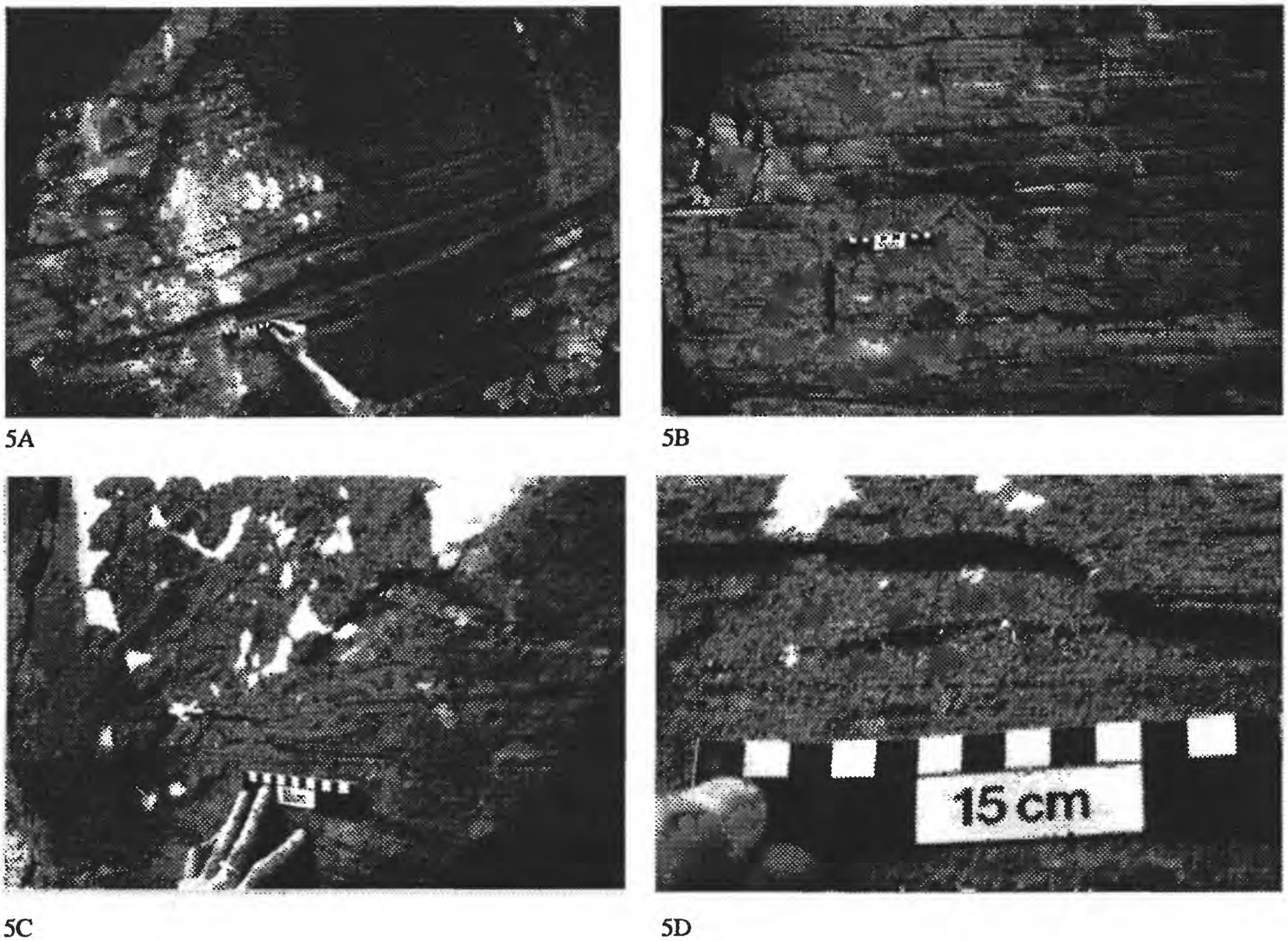
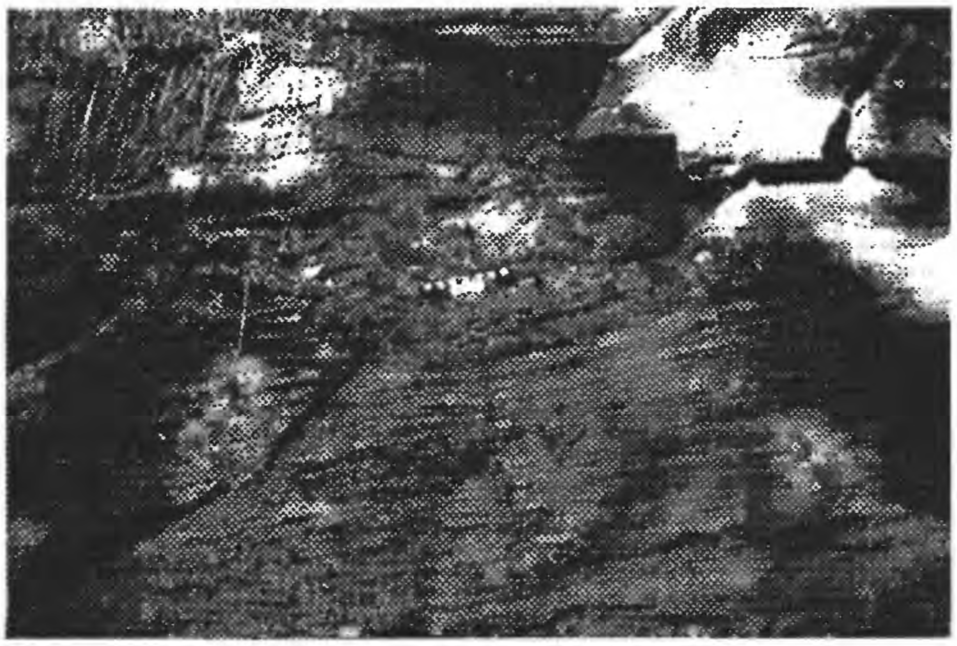


Figure 5.--Eolian sedimentary features in Loyalhanna at Johnstown site: A, sand flow toes near base of cross-bed set in vicinity and above scale--view parallel to sediment transport, bounding surface with low angle eolian deposits in upper part of photo. B, mixed type a and type b deposits in low angle eolian deposits. C, view of low angle eolian deposits and interdune deposits beneath a high angle dune deposits. D, detail of a coarse grained type b ripple deposit surrounding type a wind ripple deposits in the low angle deposits shown in 5C.

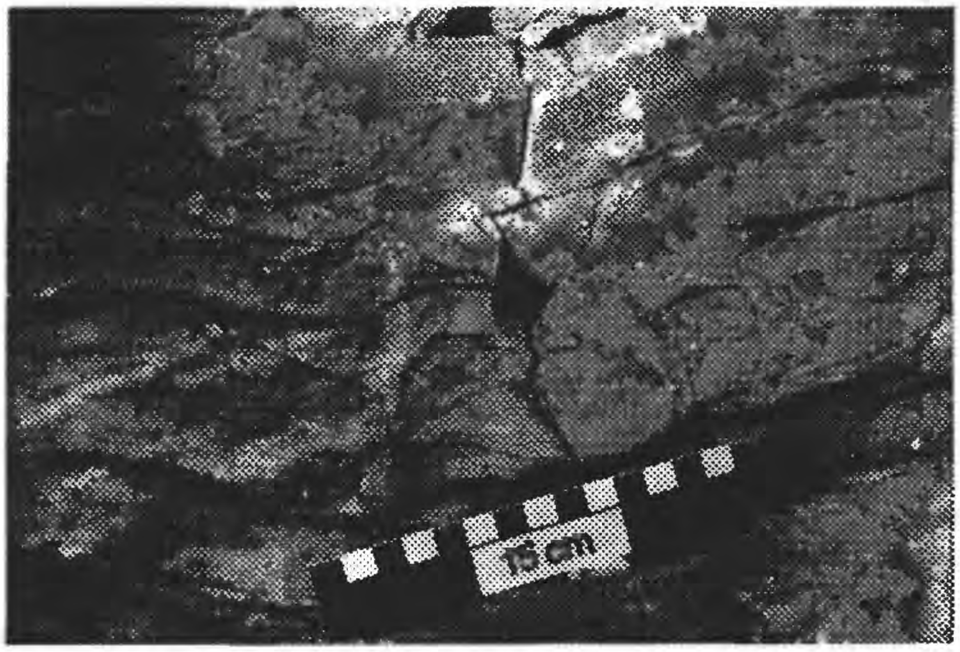
exposed at this locality (figs. 5b, 5c, 5d). Sand sheet or low angle eolian deposits, as described by Ahlbrandt and others (1994), are shown here as well (figs. 5c, 5d). Dissipation or infiltration structures (figs. 6a, 6b, 6c), are well preserved in the Loyalhanna at this locality. These structures were originally described by Bigarella (1972) from coastal dunes in Brazil and indicate periodic wet conditions. Meteoric infiltration mobilizes silt and clay particles, translocating and concentrating them along irregular boundaries and obscuring the primary stratification, or "dissipating the structures". Dissipation structures were also observed (figs. 6a, 6b, 6c) and at the Buckeye locality (fig. 6d), and suggest these wetter events were widespread throughout the geographic region of the Loyalhanna sand sea. Dissipation structures here demonstrate no evidence of cold climate origin as discussed by Ahlbrandt and Andrews (1978a), and I suggest the Loyalhanna was deposited in a cyclic wet/dry warm climate.

Other eolian features observed include well developed sand flow toes and attendant avalanche stratification interspersed with wind ripple or translatent strata (figs. 5a, 7a, 7b, 7c). Regional cross-bed dispersion studies of the Loyalhanna by Adams (1970), and observations of the trough and or wedge planar cross-bedding at the site, are consistent with sinuously crested eolian bedforms including barchan, barchanoid ridge and parabolic dunes (figs. 7a, 7b, 7c). The general absence of convex-upward cross-bed sets is an indicator of parabolic or blowout dune deposition. Also, the dispersion and dip angle of abundant avalanche deposits (fig. 3b) (see Adams, 1970, locality 58) are best correlated with a barchan or barchanoid ridge dune environment with a considerable sand sheet component. These cross-bedding features at Johnstown are consistent with the observation of sediment transport, i.e. dune migration, in an easterly direction as illustrated by Adams (1970) (fig. 2a). During the Mississippian, this portion of North America would lie at low latitudes below the paleoequator consistent with wind circulation patterns for that time (fig. 4). Variation in direction of paleowinds should be expected over such a large area reflecting major circulation patterns. For example, during the Pennsylvanian and Permian, higher latitude sand seas in the west, such as the Tensleep, Weber, Minnelusa and Casper Formations, reflect wind circulation patterns with more southerly sediment transport (Steidtmann, 1974, Fryberger, 1984) or essentially a 90 degree clockwise rotation of principal sediment movement, not unlike modern sand seas north of the equator. For example, Fryberger (1979) demonstrates such rotational changes of circulation patterns in the Mauritania and Sahara deserts of north and central Africa.

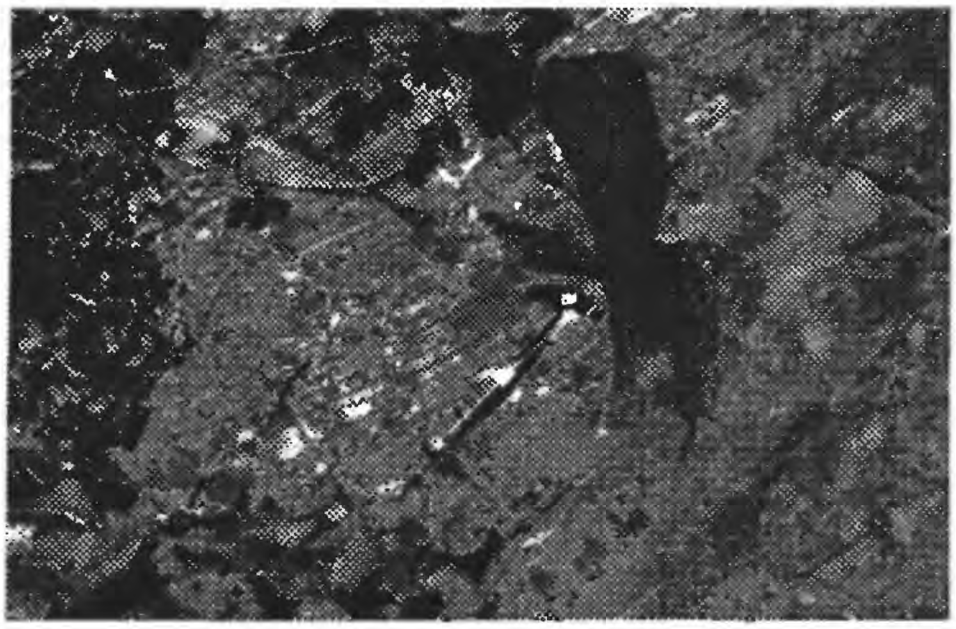
Craigsville Locality: Craigsville is approximately 80 km (50 miles) to the northwest of Johnstown, and would be both upwind and closer to the proposed sediment source in this Mississippian sand sea. This would reflect erg dynamics which produce a greater component of lower angle eolian material; i.e. the material left behind after bedform migration occurs but proximal to the sediment source (figs. 1, 2, 3). Field observations suggest that the sand is relatively coarser grained here than at other localities, and according to calcarenite-orthoquartzite plots of Adams (1970) this locality occurs on the extreme orthoquartzitic end of the Loyalhanna (fig. 2c).



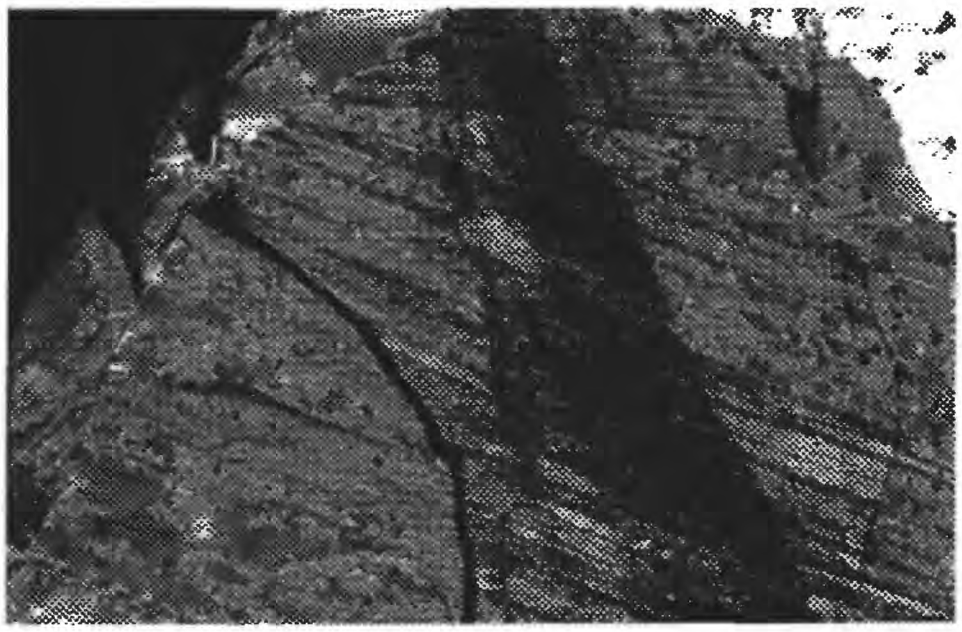
6A



6B



6C



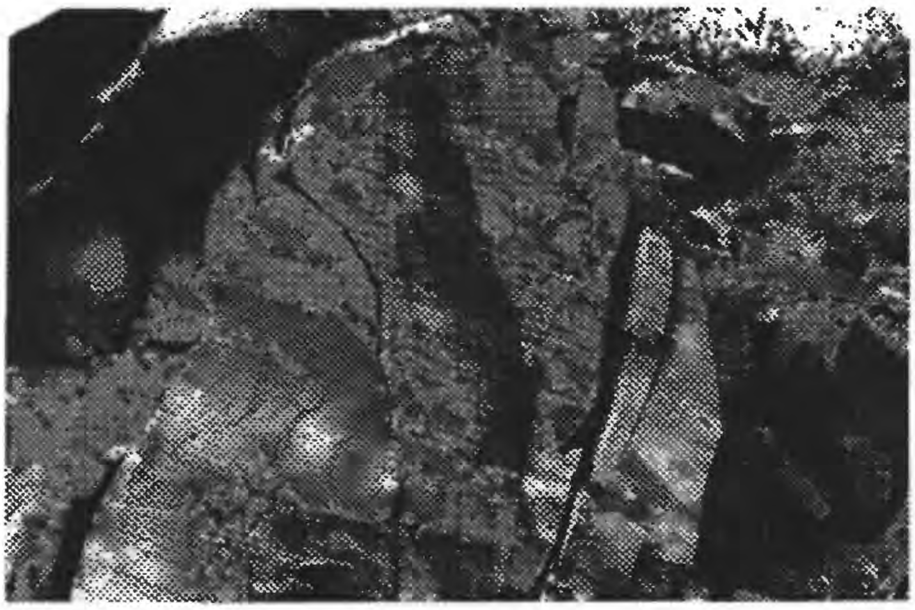
6D

Figure 6.--Secondary sedimentary features--infiltration structures or dissipation structures: A, dissipation structures heavily modifying low angle eolian deposits at Johnstown site--note dissipation structure above scale. B, detail of (A) showing dissipation structure crossing primary bedding, wavy to undulatory dark bands are dissipation structures which are enriched in finer grained silt and clay particles relative to host sediment. C, view from above parallel to wind direction showing avalanche lobes partially obscured by darker colored dissipation structures (immediately above hammer)--Johnstown site. D, dissipation structures modifying low angle eolian cross-bed set (above hammer upper left) and upper part of a high angle dune cross-bed set at Buckeye site.

7A

7B

7C



7D

Figure 7.--Primary large scale eolian sedimentary features: A, tabular planar high angle eolian cross-bed set, overlain by two trough cross-bed sets-(one small scale, one moderate scale); all sets separated by bounding surfaces with associated lags, dissipation structures have modified the appearance of the lower two cross-bed sets, Johnstown site. B, two wedge planar cross-bed sets overlain by a low angle eolian deposit--note prominent weathering of sand flow toe deposits which have been etched due to textural differences; i.e. sand flow toe deposits are texturally coarser and commonly more susceptible to calcite cement dissolution, causing them to weather differentially-Johnstown site. C, closer view of wedge planar sets seen in B with prominent sand flow toes generally showing up in negative relief; dissipation structures are not prominent in either B or C. D, high angle eolian cross-bed set, principally composed of wind ripple laminae with few sand flow toes overlain by low angle eolian deposit; dissipation structures are common in the upper part of this sequence which is a calcarenite--Buckeye site.

In fact, more low angle eolian sand sheet deposits are present at Craigsville. Upper exposures of the outcrop exhibit higher angle (>20 degrees) crossbed sets, which are dominated by type a wind ripple or translatant stratification. Common trough cross-bedding, some type b deposits and relatively uncommon avalanche or sand flow stratification are also present. These criteria, particularly the orthoquartzitic low angle and sand sheet eolian deposits would be expected of a locality which is both upwind and closer to the proposed northern clastic source area (figs. 1, 2a, 2c).

Buckeye Stone Quarry: The Buckeye Stone Quarry near Morgantown, West Virginia is about 91 km (85 miles) south of the Craigsville locality and about 100 km (70 miles) southwest of the Johnstown locality (figs. 1, 2, 3). Here the Loyalhanna is classified as a limestone (70% calcarenite and 30% orthoquartzite), which is consistent with the paleogeographic reconstruction of being more proximal to carbonate sources (marine) and distal to the northern clastic source area (figs. 2a, 2c). Nonetheless, sedimentary features exposed at the Buckeye Quarry, which can be observed in extraordinary detail on fresh surfaces, are consistent with an eolian interpretation. High angle cross-bedded dune deposits are the dominate eolian feature, rather than sand sheet deposits at Craigsville (figs. 6a, 6d). Also, avalanche bedding and sand flow features are relatively less common here as compared to Johnstown, perhaps suggesting parabolic dunes were more common at Buckeye. Wind ripple sedimentation (i.e. translatant stratification) and a heavy imprint of abundant dissipation structures in the upper part of cross-bed sets (figs. 6d, 7d), particularly near the top of the outcrop, are the dominant sedimentary structures. The dissipation structures observed at Buckeye are identical to those observed in modern eolian deposits (Bigarella, 1972; Ahlbrandt and Fryberger, 1980; Ahlbrandt and Andrews, 1978a; Pye, 1983) and provide striking testimony to periodic wetting, probably by meteoric water, shortly after dune deposition. The finer grain size of quartz sand at the Buckeye quarry may reflect the greater distance from the clastic source relative to the other localities. In general the Buckeye and Johnstown localities are dominantly high angle dune deposits, whereas the Craigsville locality is dominated by low angle eolian or sand sheet deposits.

Summary

An extension of this revised eolian depositional interpretation of the Loyalhanna Limestone helps to explain the enigma of the red siltstone and shale lenses which predominate in the southern part of the study area (underlined numbers in fig. 2c). If interpreted in an eolian context the red siltstone and shale lenses represent interdune deposits in the downwind portion of a sand sea in a "metasaturated" condition (Loope and Simpson, 1992). Under such conditions of reduced sand supply, the occurrence and preservation of eolian bed forms are less likely, and interdune and/or non-eolian sediments (extradune sediments of Lupe and Ahlbrandt, 1979) become the more important and pervasive sediment types. In metasaturated zones interdune sediments are often hematized, oxidized, and authigenically cemented, particularly where wet conditions occur, and preserved because they are near to local base level (Ahlbrandt and Fryberger, 1981; Ahlbrandt and others, 1994). As discussed previously, bimodal, poorly sorted sediments in such interdune settings are to be expected (Ahlbrandt, 1979) and should be considered entirely consistent with a metasaturated zone of a sand sea. Adams (1970) documents such textural bimodality in horizontally laminated units (fig. 2d) which I would interpret as either interdune or low angle eolian deposits. As sand supply diminishes and extradune deposits prevail, sediments of nearshore marine, sabkha or alluvial deposits become intercalated with and ultimately replace eolian deposits, as apparently occurs along the eastern margins of the Loyalhanna Limestone (Brezinski, 1989a,b).

Economic Considerations: The Loyalhanna Limestone and facies-equivalent strata of West Virginia, Pennsylvania, Ohio, and perhaps Kentucky are known hydrocarbon producing units (Youse, 1968; Carney and Smosna, 1985). Locally known to drillers as the "Big Injun Sand" and/or "Big Lime" it has produced in excess of 200 million barrels of oil in West Virginia (Carney and Smosna, 1985). The complexities of producing hydrocarbons from dune-interdune and dune-extradune sequences is well documented in the literature (e.g. Lupe and Ahlbrandt, 1979; Lindquist, 1983; Glennie, 1983; Fryberger, 1984; Goggin and others, 1988; Chandler and others, 1989; Krystinik, 1990; Panda and Lake, 1994; Ahlbrandt and others, 1994; Shebl and Surdam, in press). If such fluid flow, sequence stratigraphic and depositional models are reapplied to the Loyalhanna, considerable reevaluation of its resource potential and field growth may occur as has been the experience of petroleum producing eolianites in Colorado and Wyoming (Ahlbrandt and Fryberger, 1982; Krystinik, 1990).

REFERENCES

Adams, R.W., 1970, Loyalhanna Limestone--cross-bedding and provenance, *in* Fisher, G.W., Pettijohn, F.J., Reed, J.C., and Weaver, K.N., eds., Studies in Appalachian Geology--central and southern: John Wiley and Sons, New York, p. 83-100.

Ahlbrandt, T.S., 1979, Textural parameters in eolian deposits, *in* McKee, E.D., ed., A Study of Global Sand Seas: U. S. Geological Survey Professional Paper 1052, p. 21-52.

Ahlbrandt, T.S., in press, Low angle eolian sand sheet deposits, Great Sand Dunes National Monument, *in* Schenk, C.J., ed., Southwest Parks and Recreation Special Publication, 13 p.

Ahlbrandt, T.S., and Andrews, S., 1978a, Distinctive sedimentary features of cold-climate eolian deposits, North Park, Colorado: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 25, p. 327-351.

Ahlbrandt, T.S., Andrews, S., and Gwynne, D.T., 1978b, Bioturbation in eolian deposits: Journal of Sedimentary Petrology, v. 48, p. 839-848.

Ahlbrandt, T.S., and Fryberger, S.G., 1980, Eolian deposits in the Nebraska Sand Hills: U.S. Geological Survey Professional Paper 1120A, p. 1-24.

Ahlbrandt, T.S., and Fryberger, S.G., 1981, Sedimentary features and significance of interdune deposits, *in* Ethridge, F.G. and Flores, R.M., Recent and Ancient Nonmarine Depositional Environments--Models for Exploration: SEPM Special Publication #31, p. 293-314.

Ahlbrandt, T.S., and Fryberger, S.G. 1982, Introduction to eolian deposits, *in* Scholle, P.A., and Spearing, D.R., eds., Sandstone Depositional Environments: American Association of Petroleum Geology Memoir 31, p. 11-47.

Ahlbrandt, T.S., Gautier, D.L., and Bader, T.A., 1994, Low-angle eolian deposits in coastal settings--Significant Rocky Mountain exploration targets: Mountain Geologist, v. 31, no. 4, p. 95-114.

Bagnold, R.A.,1941, The physics of blown sand and desert dunes: Methuen and Co., Ltd., London, 265 p.

Berg, T.M., 1980, Ancient eolianite (wind blown sand) in Centre County: Pennsylvania Geology, v. 11, no. 6, p. 13-15.

Berg, T.M., Dodge, C.H., and Lentz, L.T., 1986, Upper Devonian and Mississippian stratigraphy of the Broad Top Basin, *in* Sevon, W.D., Selected geology of Bedford and Huntingdon Counties: Annual Field Conference of Pennsylvania Geologists, 51st, Huntingdon PA, Guidebook, p. 81-91.

Bigarella, J.J., 1972, Eolian environments: Their characteristics, recognition and importance, *in* J.K. Rigby and W.K. Hamblin,eds., Recognition of ancient sedimentary environments: SEPM Special Publication 16, p. 12-62.

Brezinski, D.K., 1984, Dynamic lithostratigraphy and paleoecology of Upper Mississippian (Chesterian) strata of the north central Appalachian Basin: University Microfilms International, Ann Arbor, Michigan, 121 p.

Brezinski, D.K., 1989a, The Mississippian system in Maryland: Maryland Geological Survey, Report of Investigations, no. 52, 73 p.

Brezinski, D.K., 1989b, The Mississippian System in Maryland, Maryland Geological Survey, Report of Investigations, no. 52, 75 p.

Broadhead, T.W., and Driese, S.G., 1994, Experimental and natural abrasion of conodonts in marine and eolian environments: Palaios, v. 9, p. 546-560.

Brookfield, M.E.,1977, The origin of bounding surfaces in ancient aeolian sandstones: Sedimentology, 24, p. 303-332.

Brookfield, M.E., and Ahlbrandt, T.S., eds., 1983, Eolian Sediments and Processes: Developments in Sedimentology #38, Elsevier, Amsterdam, 660 p.

Butts, Charles, 1924, The Loyalhanna Limestone of south-western Pennsylvania-especially with regard to its age and correlation: American Journal of Science, 5th Series, v. 8, p. 249-257.

Butts, Charles, 1940, Geology of the Appalachian Valley in Virginia, Virginia Division of Mineral Resources Bulletin 52, Part 1, 568 p.

Butts, Charles, 1945, Description of the Hollidaysburg and Huntingdon quadrangles, Pennsylvania, U.S. Geological Survey Geologic Atlas of the United States, Folio 227, 20 p. [1946].

Campbell, M.R., 1902, Description of the Masontown-Uniontown quadrangles: U.S. Geological Survey Geologic Atlas of the United States, Folio 82, 21 p.

Carney, C., and Smosna, R., 1985, Sedimentology of Loyalhanna Member ("Big Injun Sand") of Mississippian Greenbrier Limestone: American Association of Petroleum Geology, v. 69, no. 9, p. 1434.

Chandler, M.A., Kocurek, G., Goggin, D.J., and Lake, L.W., 1989, Effects of stratigraphic heterogeneity on permeability in eolian sandstone sequence, Page Sandstone, Northern Arizona: American Association of Petroleum Geology, v. 73, p. 658-665.

deWitt, W., and McGrew, L.W., 1979, The Appalachian Basin Region, *in* Craig, C.W., and Connor, L.C., coordinators, Paleotectonic investigation of the Mississippian System in the United States- Part 1, Introduction to regional analyses of the Mississippian System: U.S. Geological Survey Professional Paper 1010-C, p. 13-48.

Edmunds, W., 1993, Regional aspects of the Maugh Chunk Formation: The hard luck delta revisited, *in* Shaulis, J.R., Brezinski, D.K., Clark, G.M., and others, Geology of the southern Somerset County region, southwestern Pennsylvania: Annual Field Conference of Pennsylvania Geologists, 58th, Somerset PA, Guidebook, p. 11-20.

Flint, N.K., 1965, Geology and mineral resources of southern Somerset County, Pennsylvania: Pennsylvania Geological Survey County Report no. C56A, 267 p.

Flowers, R.R., 1956, A subsurface study of the Greenbriar Limestone in West Virginia: West Virginia Geological and Economic Survey, Report of Investigations, no. 15, 17 p.

Fryberger, S.G., 1979, Dune forms and wind regime, *in* McKee, E.D., ed., A Study of Global Sand Seas: U.S. Geological Survey Professional Paper 1052, p. 137-169.

Fryberger, S.G., 1984, The Permian Upper Minnelusa Formation, Wyoming: Ancient example of an offshore-prograding eolian sand sea with geomorphic facies, and system-boundary traps for petroleum, *in* J. Goolsby and D. Morton, eds., The Permian and Pennsylvanian of Wyoming: Wyoming Geological Association Guidebook, p. 241-271.

Fryberger, S.G., 1990a, Coastal eolian deposits of Oregon, U.S.A., Guererro Negro, Mexico and Jafurah Sand Sea, Saudi Arabia, *in* Fryberger, S.G., Krystinik, L.F. and Schenk, C.J., eds., Modern and Ancient Eolian Deposits--Petroleum Exploration and Production: Rocky Mountain Section SEPM Special Publication, Denver, Colorado, p. 11-1 to 11-15.

Fryberger, S.G., 1990b, Role of water in eolian deposition, *in* Fryberger, S.G., Krystinik, L.F. and Schenk, C.J., eds., Modern and Ancient Eolian Deposits: Petroleum Exploration and Production, Rocky Mountain Section SEPM Special Publication, Denver, Colorado, p. 5-1 to 5-11.

Fryberger, S.G., Ahlbrandt, T.S., and S. Andrews, 1979, Origin, sedimentary features and significance of low-angle eolian sand sheet deposits, Great Sand Dunes National Monument and vicinity, Colorado: Journal of Sedimentary Petrology, v. 49, p. 733-746.

Fryberger, S.G., Al-sari, A.M., and Clisham, T.J., 1983, Eolian dune, interdune, sand sheet and siliciclastic sabkha sediments of an offshore prograding sand sea, Dhahran area, Saudi Arabia: American Association of Petroleum Geology, v. 67, p. 280-312.

Gallagher, R.A., and Parks, J.M., 1983, Depositional environments of the Loyalhanna member of the Mauch Chunk Formation, north central Pennsylvania: Geological Society of America Abstracts, v. 15, no. 3, p. 127.

Glennie, K.W., and Evamy, B.D., 1968, Dikaka: plants and plant-root structures associated with eolian sand: Palaeogeograpy, Palaeoclimatology, Palaeoecology, v. 23, p. 77-87.

Glennie, K.W., 1983, Lower Permian Rotliegend desert sedimentation in the North Sea area, *in* Brookfield, M.E., and Ahlbrandt, T.S., eds., Eolian Sediments and Processes: Developments in Sedimentology #38, Elsevier, p. 521-542.

Goggin, D.G., Chandler, M.A., Kocurek, G., and Lake, L.W., 1988, Patterns of permeability in eolian deposits--Page Sandstone (Jurassic), northeastern Arizona: Society of Petroleum Engineers Formation Evaluation, v. 3, p. 297-306.

Greeley, R., Williams, S.H., and Marshall, J.R., 1983, Velocities of windblown particles in saltation: preliminary laboratory and field measurements, *in* Brookfield, M.E., and Ahlbrandt, T.S., eds., Eolian Sediments and Processes: Elsevier, p. 133-148.

Hanley, J.H., and Steidtmann, J.R., 1973, Petrology of limestone lenses in the Casper Formation, southernmost Laramie Basin, Wyoming and Colorado: Journal of Sedimentary Petrology, v. 43, p. 428-434.

Hickok, W.O., IV., and Moyer, F.T., 1940, Geology and mineral resources of Fayette County, Pennsylvania: Pennsylvania Geological Survey 4th Ser., Bulletin, C26, 530 p.

Hunter, R.E., 1977, Basic types of stratification in small eolian dunes: Sedimentology, v. 24, p. 361-387.

Hunter, R.E., 1993, An eolian facies in the Ste. Genevieve Limestone of southern Indiana: *in* Keith, B. and Zuppann, C., eds., Mississippian Oolite and Modern Analogs: American Association of Petroleum Geology Studies in Geology 35, p. 31-48.

Katkins, U., and Brice, W.R., 1990, The Conemaugh River Gorge, Northeastern Geol., v. 12, no. 1-2, p. 59-68.

Kelly, A.O., 1985, An exhumed oil reservoir in upper member of Casper Formation, Flat Top Anticline, Wyoming, *in* Macke, D.L., and Maughan, E.K., eds., Rocky Mountain Section SEPM Field Trip Guide, p. 121-126.

Knight, S.H., 1929, The Fountain and Casper Formation of the Laramie Basin: University of Wyoming Scientific Publications, Geology 1, no. 1, p. 1-82.

Kocurek, G., 1981, Significance of interdunes deposits and bounding surfaces in aeolian sands: Sedimentology, v. 28, p. 753-780.

Kocurek, G., 1986, Origins of low-angle stratification in aeolian deposits, *in* Nickling, W.G., ed., Aeolian Geomorphology, Annual Binghamton Geomorphology Symposium, 17th, Allen and Unwin, New York, p. 77-193.

Krystinik, L. F., 1990, Development geology in eolian reservoirs, *in* Fryberger, S.G., Krystinik, L.F. and Schenk, C.J., eds., Modern and Ancient Eolian Deposits: Petroleum Exploration and Production: Rocky Mountain Section SEPM Special Publication, Denver, Colorado, p. 13-1 to 13-12.

Levandowski, D.W., and others, 1973, Cementation in Lyons Sandstone and its role in oil accumulation: American Association of Petroleum Geology, v. 57, p. 2217-2244.

Lindquist, S.J., 1983, Nugget Formation reservoir characteristics affecting production in the Overthrust Belt of southwestern Wyoming: Society of Petroleum Engineers Journal of Petroleum Technology, v. 35, p. 1355-1365.

Loope, D.B., and Simpson, E.L., 1992, Significance of thin sets of eolian cross-strata: Journal of Sedimentary Petrology, v. 62, p. 849-859.

Lupe, R., and Ahlbrandt, T.S., 1979, Sediments of ancient eolian environments: Reservoir inhomogeneity, *in* McKee, E.D., ed., A Study of Global Sand Seas: U.S. Geological Survey Professional Paper 1052, p. 241-252.

Maples, C.G., and Waters, J.A., 1987, Redefinition of the Meramecian/Chesterian boundary (Mississippian): Geology, v. 15, p. 647-651.

Maughan, E.K., and Ahlbrandt, T.S., 1985, Pennsylvanian and Permian rocks, northern Front Range, Colorado; *in* , Macke, D.L., and Maughan, E.K., eds., SEPM Field Trip Guide: American Association of Petroleum Geology Rocky Mountain Section, p. 99-113.

McKee, E.D., 1979, Introduction to the study of global sand seas, *in* McKee, E.D., ed., A Study of Global Sand Seas: U.S. Geological Survey Professional Paper 1052, p. 1-19.

McKee, E.D., and Wier, G.W. , 1953, Terminology for stratification and cross-stratification in sedimentary rocks: Geological Society of America Bulletin, v. 64, p. 381-390.

McKee, E.D., Douglass. J.R., and Rittenhouse, G., 1971, Deformation of leeside laminae in eolian dunes: Geological Society of America Bulletin, v. 82, p. 359-378.

McKee, E.D., and Ward, W.C., 1983, Eolian environment, *in* Scholle, P.A., Bebout, D.G., and Moore, C.H., eds., Carbonate Depositional Environments: American Association of Petroleum Geology Memoir 33, p. 131-170.

Moiola, R.I., and Spencer, A.B., 1979, Differentiation of eolian deposits by discriminant analysis, *in* McKee, E.D.,ed., A Study of Global Sand Seas: U. S. Geological Survey Professional Paper 1052, p. 53-60.

Panda, M.N., and Lake, L.W., 1994, Estimation of single-phase permeability from parameters of particle-size distribution: American Association of Petroleum Geology, v. 78, p. 1028-1039.

Pye, K., 1983, Early post-depositional modification of aeolian dune sands, *in* Brookfield, M.E., and Ahlbrandt, T. S., Eolian Processes and Sediments: Elsevier, p. 197-222.

Pye, K., and Tsoar, H., 1990, Aeolian sand and sand dunes: Unwin Hyman Ltd., Cambridge, Mass., 396 p.

Reger, D. B., 1926, Mercer, Monroe and Summers Counties: West Virginia Geological Survey, 963 p.

Reineck, H.E., and Singh, I.G., 1975, Depositional sedimentary environments: Springer-Verlag, New York, 439 p.

Rittenhouse, Gordon, 1949, Petrology and paleogeography of Greenbrier Formation: American Association of Petroleum Geology, v. 33, p. 1704-1730.

Schenk, C.J., 1983, Textural and structural characteristics of some experimentally formed eolian strata, *in* Brookfield, M.E., and Ahlbrandt, T.S., eds., Eolian Sediments and Processes: Developments in Sedimentology #38, Elsevier, p. 41 - 50.

Schenk, C.J., 1990, Early diagenesis in Holocene coastal eolian sands, Guerrero Negro, Baja California, Mexico, *in* Fryberger, S.G., Krystinik, L.F., and Schenk, C.J., Modern and Ancient Eolian Deposits--Petroleum Exploration and Production: Rocky Mountain Section SEPM Special Publication, Denver, Colorado, p. 9-1 to 9-10.

Scotese, C.R., and Golonka, J., 1993, Paleogeographic Atlas, Paleomap Project, Dept. of Geology, University of Texas, Arlington.

Shanley, K.W., and McCabe, Peter, 1994, Allocyclic controls on deposition of continental sediments: a matter of time: American Association of Petroleum Geology Annual Convention , 1994, Abstracts, p. 256.

Shebl, M.A., 1994, The role of hydrocarbons in sandstone porosity enhancement: American Association of Petroleum Geology Annual Convention, 1994, Abstracts, p. 257.

Shebl, M.A., and Surdam, R.C., in press, Reservoir heterogeneity and its effect on fluid flow in Tensleep Sandstone reservoirs, Bighorn Basin, Wyoming: Institute for Energy Research, Laramie, Wyoming, 37 p.

Steidtmann, J.R., 1974, Evidence for eolian origin of cross-stratification in sandstone of the Casper Formation, southernmost Laramie Basin, Wyoming: Geological Society of America Bulletin, v. 85, p. 1835-1842.

Walker, T.R., 1979, Red color in dune sand, *in* E.D. McKee, ed., A Study of Global Sand Seas: U.S. Geological Survey Professional Paper 1052, p. 61-82.

Walker, T.R., and Harms., J.C., 1972, Eolian origin of flagstone beds, Lyons Sandstone (Permian), type area, Boulder County, Colorado: Mountain Geologist, v. 9, p. 279-288.

Wells, Dana, 1950, Lower Middle Mississippian of southeastern West Virginia: American Association of Petroleum Geology, v.34, p. 882-922.

Wilson, I.G., 1973, Ergs: Sedimentary Geology, v. 10, no. 2, p. 77-106.

Youse, A.C., 1968, Gas producing zones of the Greenbriar (Mississippian) Limestone, southern West Virginia and eastern Kentucky: American Association of Petroleum Geology, v. 48, p. 465-486.