28th International Geological Congress

Sedimentology and Thermal-Mechanical History of Basins in the Central Appalachian Orogen

Field Trip Guidebook T152

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relief. Our interpretation is that the orogen varied along strike among states III-V in Figure 4 of Slingerland and Beaumont (this volume) by the end of the Taconian orogeny.

Following the Taconian orogeny, sedimentation rates declined in the basin. Approximately 900 m of carbonates, salt, fine-grained clastics, and thin, mature shelf sandstones were deposited during Middle Silurian to Early Devonian time (Fig. 2), reflecting relative tectonic quiescence along the orogen. Although plate convergence continued along the eastern Laurentian margin during this interval (Van der Voo, 1988), crustal loading by overthrusting apparently was minor.

Commencing in the Early Devonian in New England and ending in the Early Mississippian in Pennsylvania, convergence between Laurentia and an unspecified plate (Ferrill and Thomas, 1988) produced a metamorphic, plutonic, and loading event called the Acadian orogeny. The resulting foreland basin fill in the central Appalachians is called the Catskill-Pocono clastic wedge (Marcellus through Pocono Formations, Fig. 2), and is the subject of our field trip on days 3 and 5.

Closing of the proto-Atlantic continued during the Mississippian to Permian, culminating in the collision of Gondwana with eastern North America and the third Paleozoic deformation event, the Alleghanian orogeny. Outboard loading rejuvenated the Acadian foreland basin, and it received a minimum of 7.5 km of sediments from the orogenic highlands to the east (Mauch Chunk through Conemaugh Fms. of Fig. 2 seen on field trip days 4, 5, and 6). Subsequently the whole eastern half of the orogen was subjected to folding and thrusting, and, to a lesser extent, metamorphism and plutonism from relative transpression. (see Slingerland and Beaumont, this volume for details).

The Permian and Early Triassic history of the Appalachian orogen is uncertain, because there are no preserved deposits of that age. It is clear however (Fig. 2), that by the Carnian or late Landinian (230-225 Ma) sediments had begun accumulating in basins along reactivated strike-slip and thrust faults (Manspeizer and Cousminer, 1988; Traverse, 1987), recording the initial breakup of Pangea (days 6 and 7). Rupture occurred roughly along the present continental shelf edge (see Manspeizer and Huntoon, this volume, for details) and sea-floor spreading began between late Early to Middle Jurassic (190-175 Ma)(Klitgord and Schouten, 1986, p.364).

A second passive margin developed, of broad platforms having fairly thin sediment cover and basins whose margins probably mark the sites of transform faults active during the initial breakup (Folger et al., 1979). Jurassic sediments of the passive margin tend to be terrigenous lagoonal, fluvial, or deltaic nearshore lithosomes ponded behind widespread carbonate build-ups at the shelf edge. During the Cretaceous and into the Cenozoic, a thick sequence of fluvial, deltaic, and shelf sediments prograded seaward to form a well defined slope and rise. The result is an eastward-thickening wedge of primarily unconsolidated sediments, about 2.4 km thick in the Delmarva area, thickening to 9 km in the Baltimore Canyon Trough (Folger et al., 1979) (day 8.)

TECTONICS AND SEDIMENTATION OF THE UPPER PALEOZOIC FORELAND BASIN IN THE CENTRAL APPALACHIANS

Rudy Slingerland and Christopher Beaumont

INTRODUCTION

Foreland basins are sedimentary basins lying cratonward of major compressional zones. They are formed during continent-continent collisions as a result of outboard crustal loading, or by a combination of loading and subduction of oceanic lithosphere. Those due primarily to outboard loading are especially interesting because the creation of the basin and the source terrain both arise from the same cause --- thickening of the crust by overthrusting. In these basins we expect to see a pattern of evolution that reflects adjustments to the size and rate of application of the overthrust load, variations in time and space of the lithospheric rheology, and feedback between sedimentation in the basin and rates of erosion of the thrust stack.

Our intention here is to illustrate just such an interplay between tectonics and sedimentation in a particularly revealing example, the Appalachian foreland basin of the Appalachian Orogenic Belt. Our method is to first describe some concepts of basin creation using models of flexural response of the lithosphere and then to describe and interpret the character of two orogenies---the Acadian and Alleghanian---and the foreland clastic wedges that resulted from them. The treatment is general; details of the geodynamic modelling can be found in Quinlan and Beaumont (1984), Stockmal et al. (1986), Beaumont et al. (1987), Beaumont et al. (1988), and Jamieson and Beaumont (1988). More in-depth discussions of the field relationships and tectonic evolution can be found in Fisher et al. (1970), Williams and Hatcher (1982), Donaldson and Shumaker (1981), Tankard (1986), Rodgers (1987), and Van der Voo (1988).

FLEXURAL MODELS: CONCEPTS AND BASIC RESULTS

The best starting point for a discussion of the models is a review of the flexural response of the lithosphere to supracrustal loading. The lithosphere's flexural properties determine the form of the foreland basin produced by a given overthrust load as shown diagrammatically in the cross section cartoon of Figure 1. A load emplaced on the surface of an originally flat lithosphere deforms the plate into the profile indicated by curve 1. If the lithosphere's response is effectively elastic, then it will maintain this flexural shape while the surface load changes. If, however, the lithosphere can relax the bending stresses set up by the surface load by creep, then its flexural profile will evolve through time to assume the shapes indicated by curves 2 and 3, even though the magnitude of the load remains constant. The timescale over which stress relaxation occurs depends on the mechanism by which stress is relaxed. If viscoelasticity provides a valid model of the relaxation mechanism (e.g. Quinlan and Beaumont, 1984; Beaumont et al., 1988), then it is the viscosity distribution within the lithospheric plate that determines the relaxation timescale. Given that the viscosity of rocks decreases with increasing temperature and that the viscosity of the mantle apparently determines the approximately 10^4-10^5 year relaxation timescale of glacial rebound, relaxation times spanning the range 10^5-10^8 years are expected for the lithosphere. Note that in Figure 1 the peripheral bulge adjacent to the flexurally downwarped region migrates toward the surface load as stress is relaxed and the basin deepens and narrows. This migration may uplift and allow erosion of sediments deposited earlier within the foreland basin. In principle therefore, erosional patterns at the distal edge of the basin can be used to determine whether the lithosphere is able to relax stress and the timescale over which this relaxation occurs. However, there are other mechanisms, such as sea level change, that may also create unconformities, and it is therefore difficult to attribute any particular unconformity unequivocally to lithospheric stress relaxation.

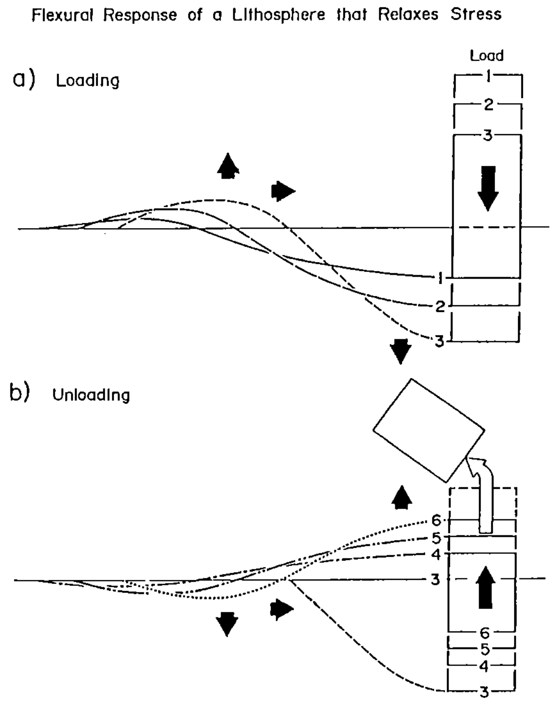


FIGURE 1 Qualitative representation of the loading and unloading response of a model lithosphere that releases stress by some form of thermally controlled creep mechanism. See text for discussion.

Panel (b) of Figure 1 assumes that part of the orogenic load is removed from a surface made horizontal by erosion of uplifted areas and sedimentary infilling of depressed areas (curve 3). Note that the foreland response to unloading is a mirror image of the response to loading. Uplift first occurs over a broad region (curve 4) and becomes successively concentrated near the unloaded region (curves 5 and 6) if there is stress relaxation. Net reduction of orogenic loading should therefore be recorded in the foreland stratigraphy as an erosional unconformity present over wide areas and having the greatest missing section near the unloaded orogenic region.

Two additional points can be made from these simple concepts. First, each load change applied to the lithosphere evolves through the same sequence of flexural deformation. If the lithospheric response to loading is linear, their superimposed effect in time and space is the sum of the individual effects. Second, an overthrust load that migrates laterally toward the foreland faster than relaxation allows the peripheral bulge to migrate in the opposite direction will create an unconformity as the peripheral bulge is driven across the foreland ahead of the overthrust load (Jacobi, 1981; Quinlan and Beaumont, 1984).

These concepts can be combined to give a first-order explanation of the sequence of events in the development of a multistage foreland basin, like the Appalachian basin (Fig. 2). The first stage shows the development of a basin-wide unconformity as the peripheral bulge migrates ahead of the thrust loads. This phase is followed by subsidence and the formation of a foreland basin. During the quiescent (relaxation) phase, the peripheral bulge is uplifted and migrates toward the thrust load, only to be halted by the next orogeny and loading phase which superimposes the next major sedimentary package of the foreland basin. Thus, as earlier workers recognized in principle, the stratigraphy and sedimentology of the basin fill and the positions of the unconformities in space and time contain important evidence on activity in the adjacent orogen, a point we will return to later.

The question of antecedent conditions and inheritance is important for the style of foreland basins. Although the role of these conditions and details of their effect have yet to be worked out in detail, some aspects have been modelled (Karner and Watts, 1983; Royden and Karner, 1984; Stockmal et al., 1986; Stockmal and Beaumont, 1987). Figure 3 illustrates how Stockmal et al., (1986) incorporated thermal effects and lateral changes in the flexural properties of the lithosphere into models of rifting, passive margin development, plate collision, and overthrusting. Simple elastic plates, the bases of which are defined by a given isotherm were used in the flexural models (Beaumont et al., 1982; Keen and Beaumont, in press).

The significance of these model results (Fig. 4) is that some sense of the geometrical relationship between the overthrusts, their topography, and the flexed crust of the inherited margin is obtained. For example: about 20 km thick loads can overthrust the outboard part of the margin before they need be subaerially exposed (Panel IV); mountain roots beneath orogens of Himalayan proportions may be in excess of 60 km thick (Panel VII); the ultimate preservation of a foreland basin, once the orogen has been eroded to base level, can be attributed to that part of the overthrust load that still remains on or outboard of the antecedent rifted margin (Panel VIII), and; the characteristic Bouguer gravity anomaly common to many compressional orogens (Fig. 5) may be interpreted as the superposition of the anomaly from the inherited rifted margin (the steep gradient above the transitional zone of crustal thinning, Figure 5)

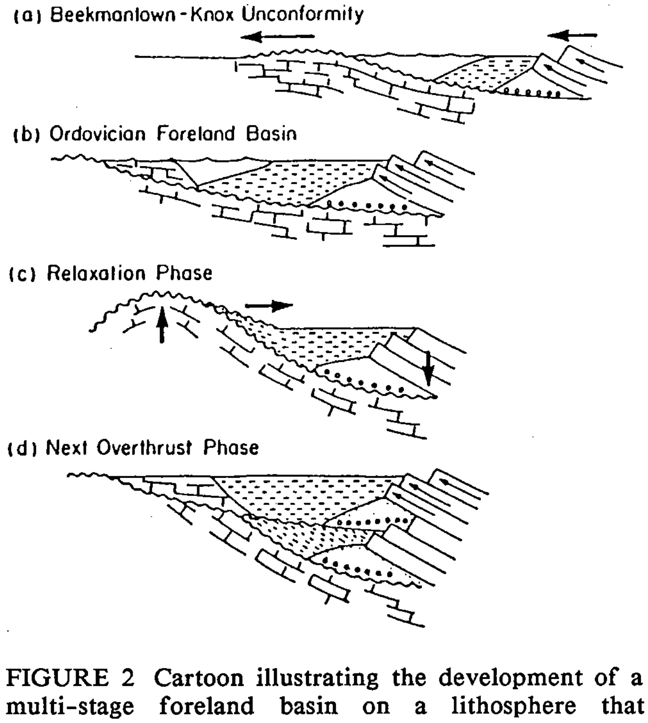


FIGURE 2 Cartoon illustrating the development of a multi-stage foreland basin on a lithosphere that relaxes load-induced stress. The uplift of the peripheral bulge is shown exaggerated by a factor of 10 in (c). Circles represent conglomerates, dots represent sandstone, dashed pattern represents shale, and the brick pattern represents carbonates. Bold arrows show overthrust and peripheral bulge migration. Fine arrows illustrate active overthrusting.

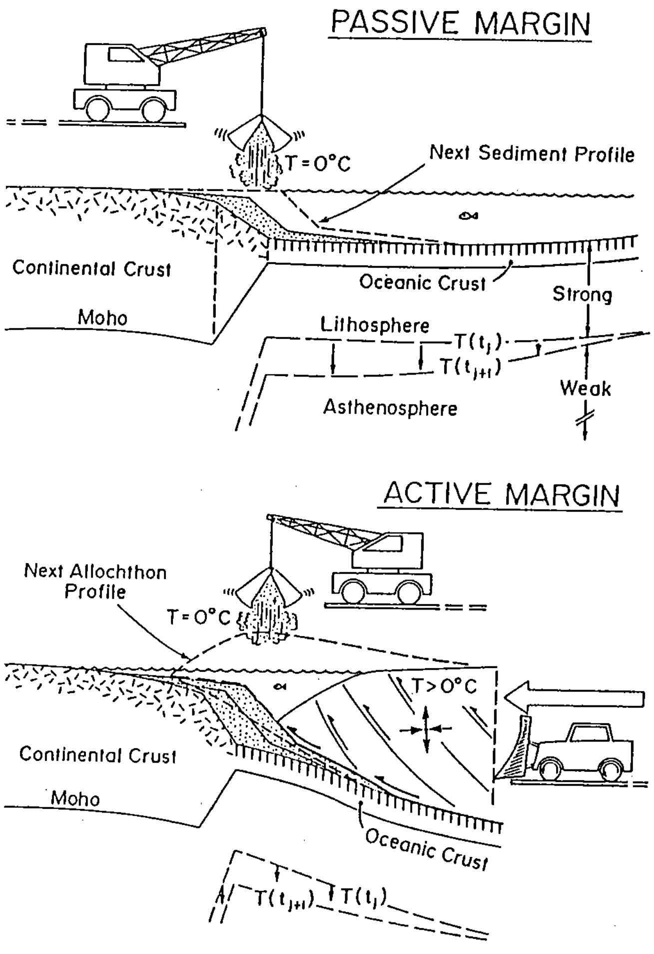


FIGURE 3 Schematic diagram of the quantitative approach to modelling the transition from passive (rifted) to active (convergent) margin used by Stockmal et al., (1986). Stages are constructed in steps following geologically instantaneous rifting; stretched continental crust beneath the margin is located between vertical dashed lines of the upper panel. Steps involving the addition of sediments to a specified bathymetric profile (upper panel) are alternated with thermal time steps during which thermal relocation occurs (shown schematically as a single isotherm T at two times, t_j and t_{j+1}). The flexural response of the lithosphere changes through time because the thermally controlled effective thickness of the lithosphere also changes. The tectonic switch from passive to active margin is modelled by overthrusting loads sequentially onto the passive margin (lower panel). These loads are shoveled into position up to a specified topography (dashed line of lower panel) instead of being pushed in a geologically correct manner. This approximation is reasonable when considering subsidence and sedimentation in the undisturbed part of the foreland.

and the longer wavelength flexural component above the foreland. The position of the steep Bouguer gradient may therefore give the approximate location of the inherited rifted margin beneath an orogen (Stockmal and Beaumont, 1987). The change in geometry with increasing amounts of convergence between the overthrusts and the inherited margin can also explain the major change in the associated sedimentary facies from flysch to molasse. Figure 4 (Panels II and IV) also shows that in the early stages of convergence, before the overthrusts have completely mounted the margin, the foreland basin may take the form of a deep asymmetric trough that does not have a characteristic flexural shape.

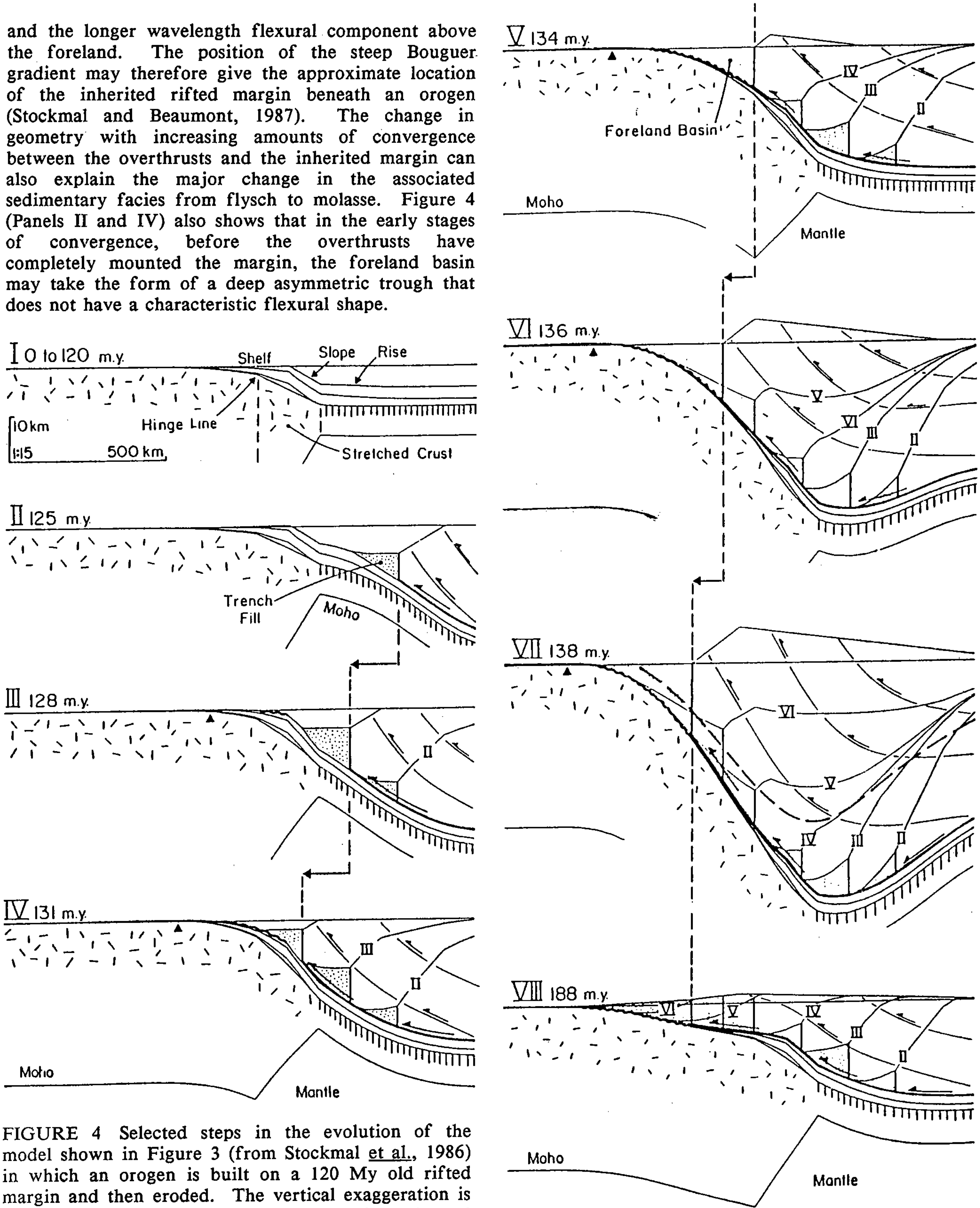


FIGURE 4 Selected steps in the evolution of the model shown in Figure 3 (from Stockmal et al., 1986) in which an orogen is built on a 120 My old rifted margin and then eroded. The vertical exaggeration is 15:1. Random-line pattern is continental and stretched continental crust. Vertical ruled pattern is ocean crust. Bold lines with bold arrows represent the decollement. Bold wavy line represents an unconformity. Stipple pattern marks sedimentary basins. Solid triangles mark the position of the peripheral bulge. Bold dashed line (panel VII) marks the depth within the orogen that is exhumed to the surface during erosion and isostatic rebound between stages VII and VIII.

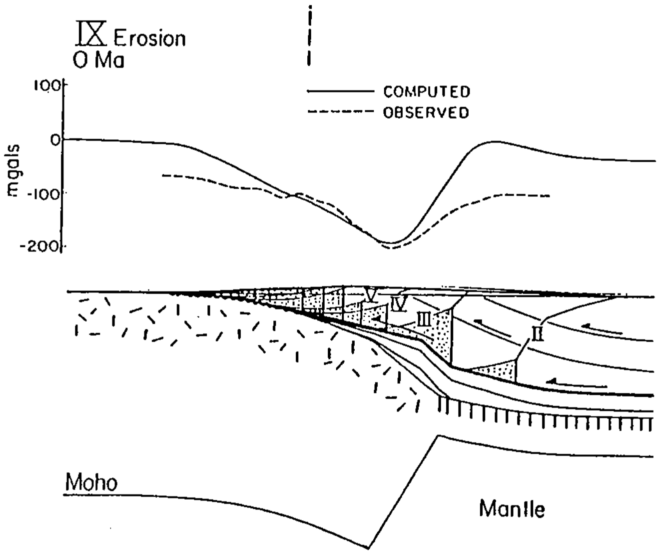


FIGURE 5 Bouguer gravity anomaly (solid line) predicted for a model (lower panel) similar to that of stage VIII in Figure 4. Although larger in amplitude, this anomaly has the same character as that from a typical profile across the western Canada basin and Canadian cordillera (dashed line). The importance of the two parts of the gravity anomaly in relocating the position of the rifted continental margin is explained in the text and in greater detail by Stockmal and Beaumont (1987).

So far in this summary we have concentrated on cross-sectional views, however, the strike variation in loading along an orogen and the interaction of the foreland basin with other sedimentary basins adds considerable variety to the concepts already developed. The cartoon (a) in Figure 6 illustrates the plan view of a foreland basin and peripheral bulge produced by a square load pattern. Figure 6b illustrates the style of coupling between a foreland basin and an intracratonic basin like the Michigan basin. Figure 6c illustrates how superposition of peripheral bulges can generate broad cratonic arches and domes. Our interpretations suggest that all of these features exist within the Eastern Interior region of North America and these figures illustrate the archetypes for the geometrically more complex examples that are presented later. The principles are, however, no more complicated than those illustrated here. The importance of the strike variability in loading is clear when it is remembered that loading in one part of an orogen can cause flexural subsidence and sediment accumulation in the neighboring part of the foreland basin at the same time that it is producing flexural uplift and erosion further along strike.

ANTECEDENT CONDITIONS IN THE APPALACHIANS

The Appalachian foreland basin lies on Grenvillian (1 Ga) North American basement, inboard of the

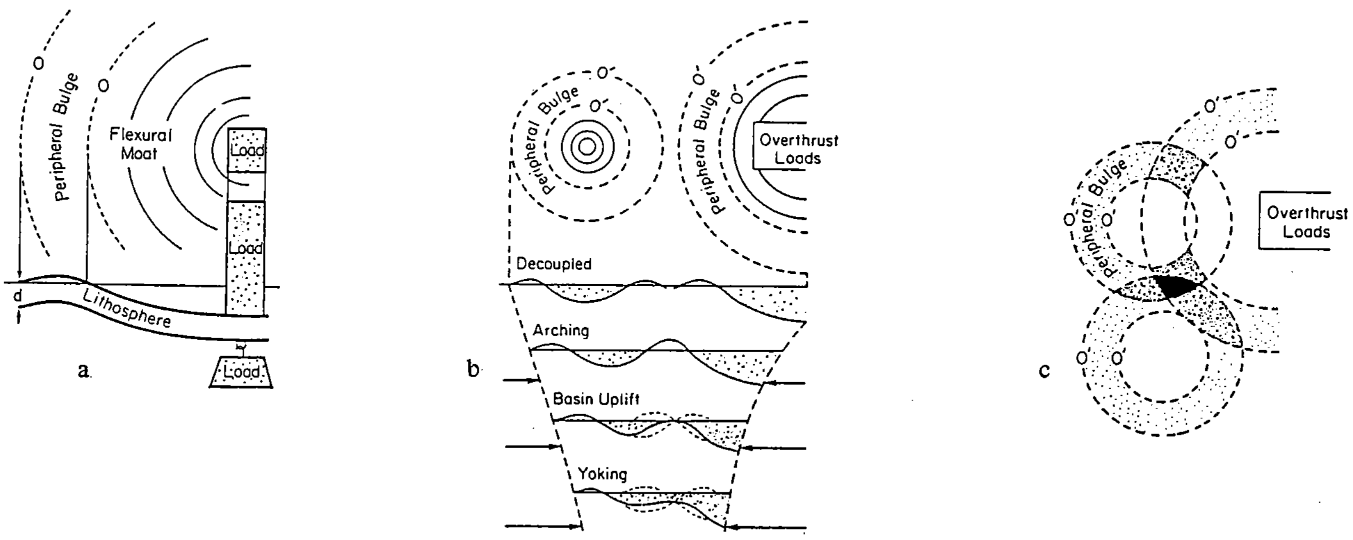


FIGURE 6 a) Cartoon illustrating initial deformation of a uniform lithosphere produced by a square load either deposited on the surface or intruded at depth. The upper panel depicts a plan view (not drawn to scale). b) Flexural interaction between a foreland basin (right) and an intracratonic basin (left). The upper panel shows a plan view of the basins in the decoupled position corresponding to the first cross-section (below). Subsequent cross-sections show the nature of the interaction when basins are closer together. Note that the effect of lithospheric relaxation is not included. This has the tendency to decouple yoked basins with a progression somewhat like that moving upward from the bottom cross-section. c) Flexural interaction between a foreland basin (right) and two intracratonic basins (left). Arched (light stipple) and domed (successively darker stipple) regions are produced by superposition of the peripheral bulges. Note, for the configuration shown, that the deformation yokes the foreland basin with the upper intracratonic basin yet raises an arch between the foreland basin and the lower intracratonic basin because of their greater distance of separation.

crystalline Appalachian Mountains and primarily south of New York State (Fig. 7, Appalachian Basin). It came into existence as early as Middle Ordovician time during the Taconian orogeny, was more-or-less continuously active through the Acadian and Alleghanian orogenies, and ceased receiving sediments sometime in the Permian (see the Introduction for a more complete account of Appalachian orogenesis).

At the start of the Early Devonian and immediately prior to the Acadian orogeny, the Appalachian orogen consisted of an inboard marine foreland basin filled with a maximum 7.3 km of Eocambrian to Late Silurian sediments resting on Grenvillian crystalline basement, and an outboard source terrane consisting of overthrust Taconian island arc, ocean crust, and microcontinent fragments. The source terrane for the most part, rested on attenuated continental crust and ocean lithosphere, and therefore was of low relief.

CHARACTER OF THE OROGENIES AND BASIN FILL

Acadian Orogeny

The Acadian orogeny is characterized by a region of deformation, metamorphism, and plutonism centered in New England and the Maritime Provinces of Canada, but is recognizable as far south as Alabama. In New England the earliest signs of the Acadian orogeny are clastics of late Early Devonian age (Seboomook-Littleton Fms.) overlying carbonates (Rodgers, 1987). By the Middle Devonian, polyphase deformation and metamorphism involved rocks as young as early Middle Devonian. Metamorphism in New England was regional, in places reaching sillimanite grade, and coeval with the emplacement of gneiss domes and intrusion of the voluminous New Hampshire plutonic series. Although deformation continued into the Carboniferous, its style changed to dextral strike slip and normal faulting (Bradley, 1982; Ferrill and Thomas, 1988) with very low grade metamorphism, indicating that the Acadian orogeny, sensu stricto, ended in New England in the Late Devonian (Faill, 1985).

Acadian features can be traced southward from New England where they disappear underneath Long Island Sound and the Coastal Plain deposits. They reappear in central Virginia (Drake, 1980). Surprisingly, the central Appalachians contain no definitive unconformities or intrabasin deformation (Faill, 1985), and no plutonism or widespread metamorphism in the exposed portions. In fact, cooling dates for biotite in the central Piedmont suggest that during the Devonian this terrane mainly experienced westward movement and slow exhumation (Dallemeyer, 1988; Jamieson and Beaumont, 1988). Yet it is here that the largest clastic wedge is preserved, the 3.5 km thick Middle Devonian to Lower Mississippian Catskill-Pocono wedge.

In the southern Appalachians evidence for Acadian orogenesis consists largely of greenshist metamorphism (Hatcher, 1978; Jamieson and Beaumont, 1988), ash fall deposits (Tioga metabentonite) from an early Middle Devonian volcanic center in Virginia (Dennison and Textoris, 1970), and a thick Early to Middle Devonian clastic succession preserved in a thrust slice (Talladega slate belt) (Ferrill and Thomas, 1988).

The explanation of the Acadian orogeny by the over-all plate tectonic movements of the major continents and displaced terranes is controversial. The most recent reconstructions by Van der Voo (1988) (Fig. 8) attribute the Acadian orogeny to the Late Silurian-Early Devonian collision between the Appalachian margin of Laurentia and Gondwana's margin in northwest Africa (with the Avalonian and Armorican accreted terranes caught in between). During Middle and Late Devonian time a newly opened ocean was forming between Laurentia (with its newly accreted Avalonian and Amorican terranes) and Gondwana. This would be consistent with Early and Middle Devonian clastic wedges and associated deformation in New England (Rodgers, 1987) and Alabama (Ferrill and Thomas, 1988), but difficult to reconcile with the Late Devonian clastic wedge of the central Appalachians. Other paleogeographic reconstructions attribute the Acadian orogeny to

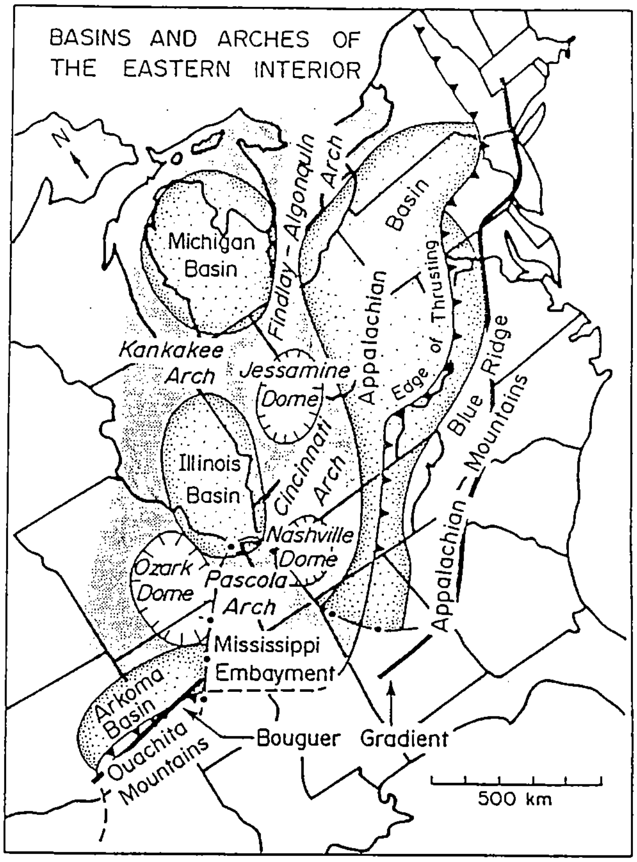


FIGURE 7 General basin configuration of eastern U.S. showing the Appalachian foreland basin (labelled Appalachian Basin), the western extent of Alleghanian thrusting, and the Bouguer gravity gradient thought to reflect the location of the inherited rifted margin (from Beaumont et al., 1988).

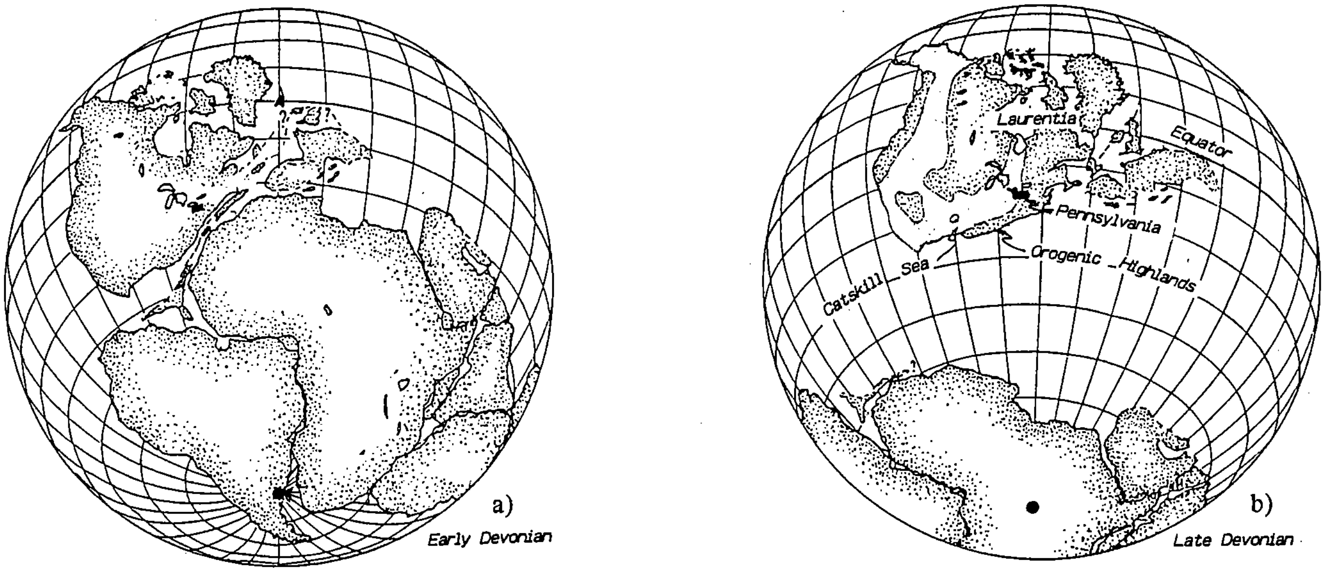


FIGURE 8 Devonian paleogeographic reconstructions using paleomagnetic paleolatitudes and biogeographical and paleoclimatological indicators. The extent of the Catskill epeiric sea is indicated for the Late Devonian (modified from Van der Voo, 1988).

oblique convergence or major transcurrent movement along a sinistral strike-slip zone separating Laurentia and the Avalon terrane during the mid-Paleozoic (Williams and Hatcher, 1982; Ettensohn, 1985) or, more recently, oblique convergence or transcurrent movement along a dextral strike-slip zone separating Laurentia and an unspecified plate during the whole of the Devonian (Ferrill and Thomas, 1988). The southward migration of orogeny, the dextral wrench-fault systems in New England and Alabama, and the discrete location of clastic wedges are attributed to collision of promontories along the irregularly-shaped

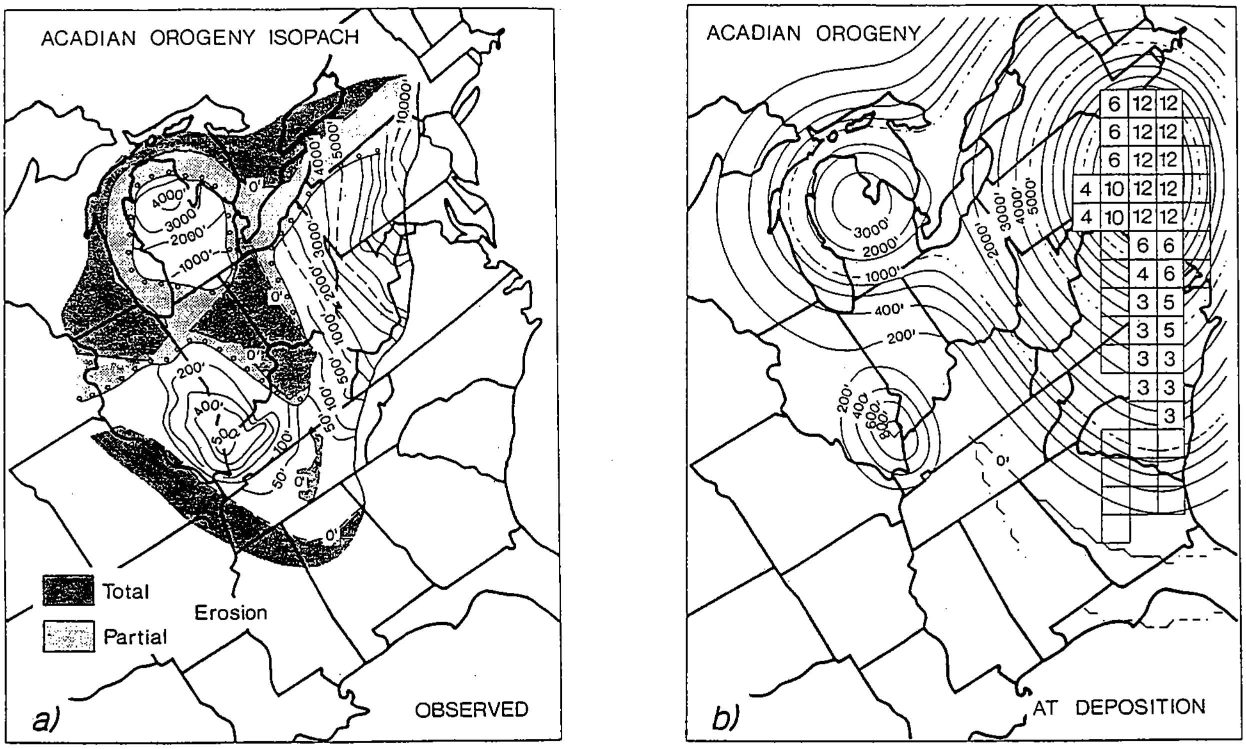


FIGURE 9 Predicted evolution of the total sedimentary isopach associated with the model Acadian orogeny showing its configuration at the end of the Acadian orogeny (panel b) and at present (panel c). Panel b should be compared with panel a, which shows the observed isopach. Shading shows areas of partial and total erosion. All contours are in feet and the numbered grids in panel b are the thicknesses (km) of the overthrust loads necessary to produce the model subsidence in the Appalachian basin.

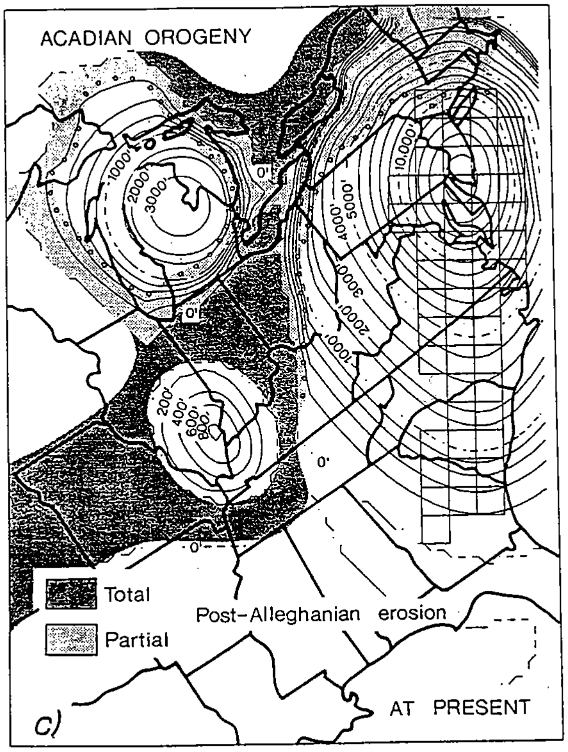


FIGURE 9 (cont.)

plate margins. The modelling presented below suggests compression must have continued into the Late Devonian to produce the basin for the Catskill-Pocono clastic wedge, and therefore we favor this latter view.

Acadian Basin Fill in the Central Appalachians

The most notable manifestation of Acadian orogenesis in the central Appalachians is a pulse of clastic sediments, commonly called the Catskill-Pocono clastic wedge. For the purposes of this discussion, the base of the wedge is placed at the base of the Middle Devonian (in central Pennsylvania, the Needmore Shale) and the top is placed at the base of the Lower Mississippian Loyalhanna Fm. in central Pennsylvania (see Fig. 2 of the Introduction to this volume).

The wedge obtains its thickest expression in eastern Pennsylvania where up to 3500 m (11,400 ft) of predominately alluvial deposits are preserved (Fig. 9a). This accumulation can be explained by the combined effects of the load distribution (Fig. 9b) and the tectonic subsidence of the Michigan and Illinois intracratonic basins by about 830 m and 210 m, respectively. Although the reason for the subsidence of the intracratonic basins is not properly understood, the regional isopach distributions cannot be explained

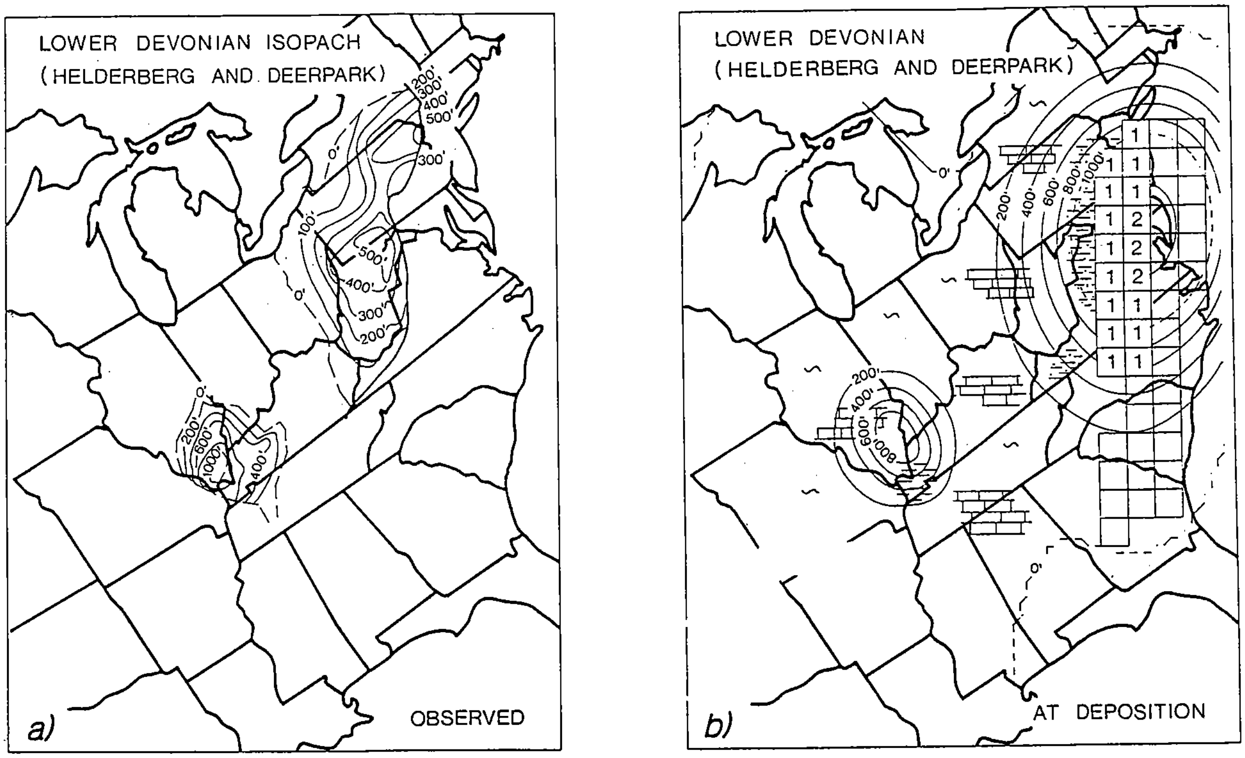
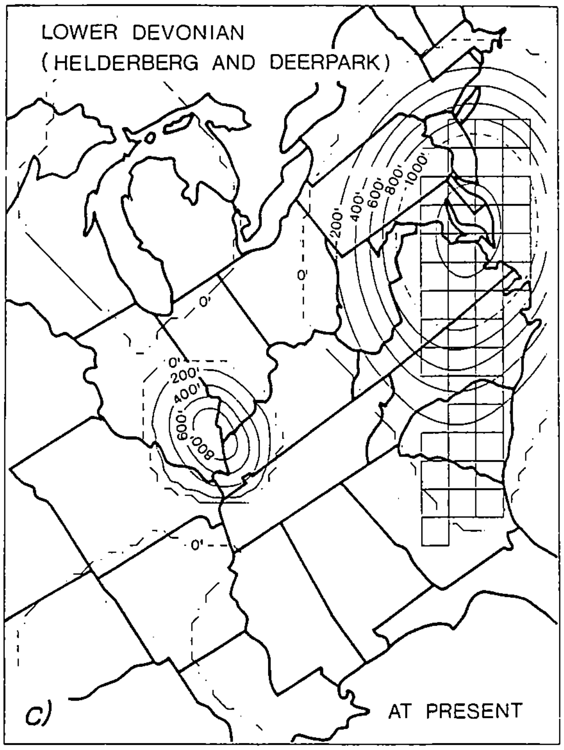


FIGURE 10 Isopach maps of observed (panel a) and predicted (panels b and c) sediment distribution for the Lower Devonian (contours in feet). Panel (d) shows the sediment accumulation rate for Pennsylvania and adjacent regions. The numbered grids in panel (b) are the thicknesses (km) of the overthrust loads necessary to produce the model subsidence in the Appalachian basin. Brick and tilda patterns denote observed and restored chemical sedimentation and marine conditions. Dash and dot patterns denote observed shale and sandstone sediments.



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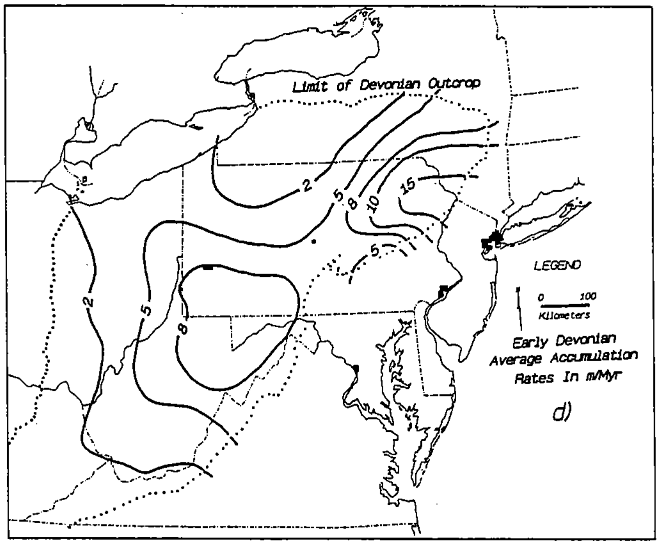


FIGURE 10 (cont.)

without including them. Figure 9b shows the model isopach distribution at the end of deposition, whereas Figure 9c shows the predictions of the present distribution (after uplift and erosion), which agrees quite closely with the observations (Fig. 9a). The model predicts that some erosion occurred before the Alleghanian orogeny but that the majority occurred

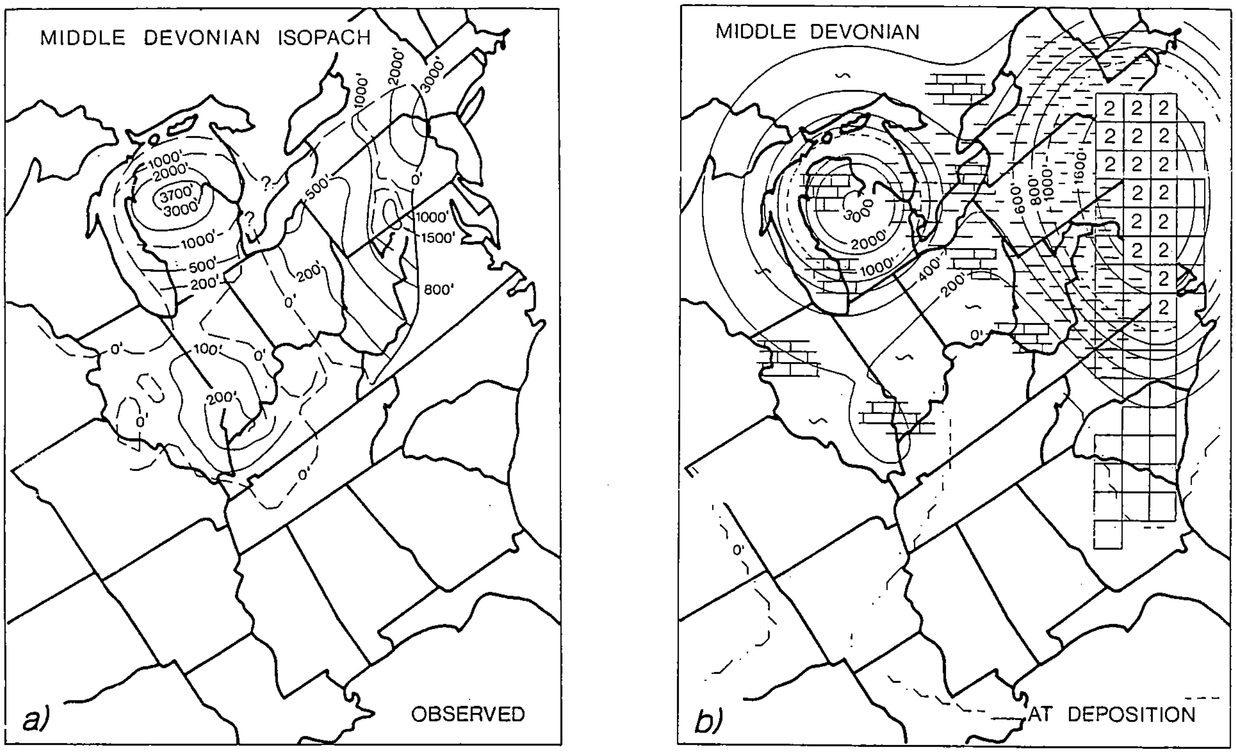
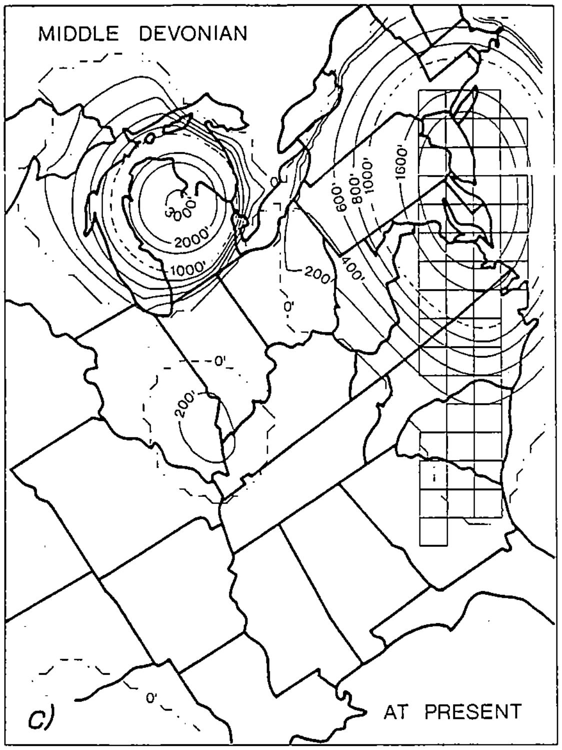


FIGURE 11 Isopach maps of observed (panel a) and predicted (panels b and c) sediment distribution for the Middle Devonian (coutours in feet). Panel (d) shows the sediment accumulation rate for Pennsylvania and adjacent regions. The numbered grids in panel (b) are the thicknesses (km) of the overthrust loads necessary to produce the model subsidence in the Appalachian basin. Brick and tilda patterns denote observed and restored chemical sedimentation and marine conditions. Dash and dot patterns denote observed shale and sandstone sediments.



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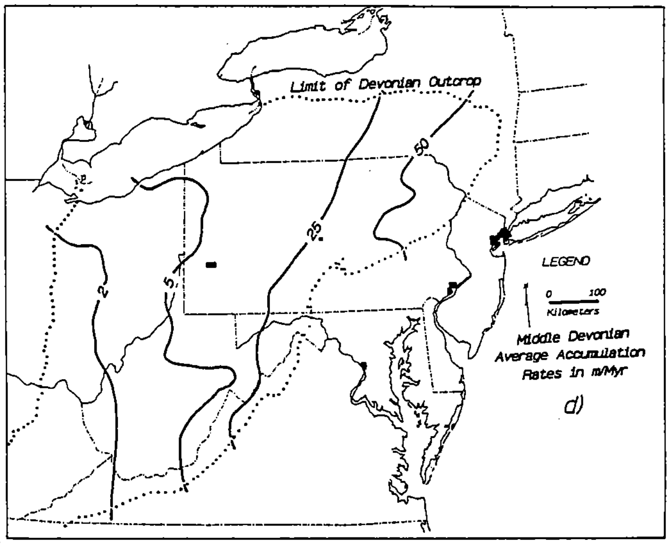


FIGURE 11 (cont.)

between the Permian and present (Beaumont et al., 1988). Erosion predominates on the arches and domes (Figs. 7 and 6c), reflecting the process of stress relaxation and uplift of those regions due to the superposition of the peripheral bulges. It is important to note that a purely elastic model of the lithosphere cannot correctly reproduce this pattern of erosion.

Sediment accumulation rates (as indicated by the thickness remaining per unit time) varied dramatically over the interval of the Acadian orogeny (Figs. 10d, 11d, and 12d). In the Early Devonian two accumulation centers existed in the central Appalachians, with the northern receiving carbonate sediment at a rate of 15 m/Myr (Fig. 10d). This pattern (Oliver et al., 1967), which was originally established in the Upper Silurian (Colton, 1970), cannot be explained by the flexural model if sedimentation completely filled the foreland basin. It is in cases like this that geodynamic models can point to problems requiring a solution. That the flexural model is so successful for other intervals, when there was a large clastic influx into the basin, lends credence to our faith in the model for this Early Devonian interval, yet two closely separated depocenters (Fig. 10a) should be flexurally connected along strike (Figs. 10b and 10c). The obvious explanation is that in central Pennsylvania the basin remained underfilled with paleobathymetry as large as 50 m at the end of the interval. This can be substantiated in part because at the end of Deerpark Age a sizable sea level drop occurred producing the Wallbridge Discontinuity (Dennison, 1985). This discontinuity is absent in western Maryland, northern West Virginia, and southwestern and eastern Pennsylvania, suggesting that the sea was deep there at the end of Deerpark time.

By the Middle Devonian, accumulation rates had increased to a maximum 50 m/Myr along the southwestern border of the basin in response to Acadian overthrusting, whereas on the west side of the basin in Ohio rates remained constant (Fig. 11d). The model results (Figs. 11b and 11c) that best match the observed thicknesses (Fig. 11a) indicate that there was no great increase in the rate of loading between the Early and Middle Devonian, although the load distribution may have migrated somewhat to the north. The increase in sedimentation is most likely a response to the initiation of Acadian mountains outboard of the central Appalachians which provided a good source of detrital sediments to this part of the basin. That these sediments most probably filled the basin completely is reflected in the flexural shape of the preserved isopach (Fig. 11c).

In the Late Devonian, accumulation rates increased by almost fourfold in the east and an order of magnitude in the west (Fig. 12d). As expanded upon below, these rates overwhelmed subsidence rates and a subaerial alluvial plain was created that prograded westward. The preserved sediment distribution is one of the most convincing pieces of evidence in favor of a flexural model of the Appalachian foreland basin in which loads up to 10 km thick were overthrust in the vicinity of what is now southern New York, New Jersey, and Maryland. That the preserved isopach is asymmetric along strike with respect to this depocentre suggests that there was also loading further south within the orogen (compare Figs. 12a and 12c).

There is little doubt that the clastic sedimentation covered the whole of the Eastern Interior as far south as Tennessee (Fig. 12b). Preserved clastic sediments from this time within the intracratonic basins is further evidence that the arches and domes were flexurally depressed. If this interpretation is correct, the initial, or loading, flexural wavelength of

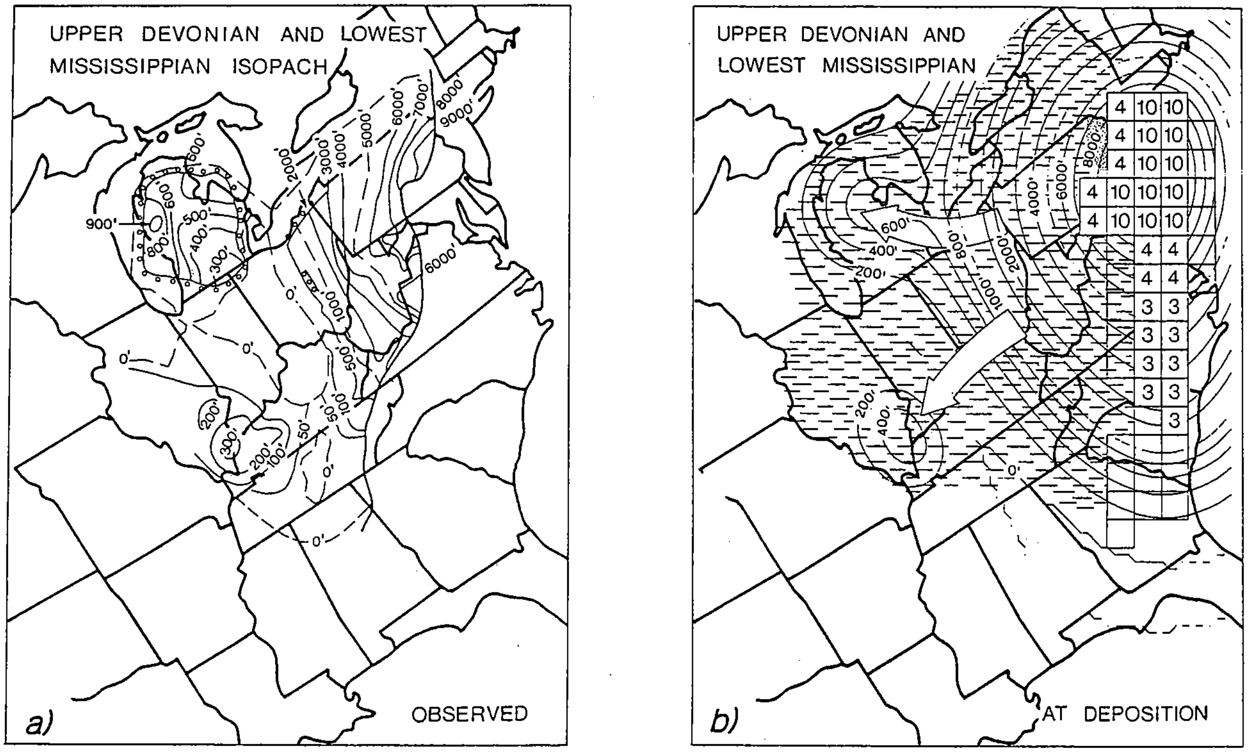


FIGURE 12 Isopach maps of observed (panel a) and predicted (panels b and c) sediment distribution for the Upper Devonian (coutours in feet). Panel (d) shows the sediment accumulation rate for Pennsylvania and adjacent regions. The numbered grids in panel (b) are the thicknesses (km) of the overthrust loads necessary to produce the model subsidence in the Appalachian basin. Dash and dot patterns denote observed shale and sandstone sediments.

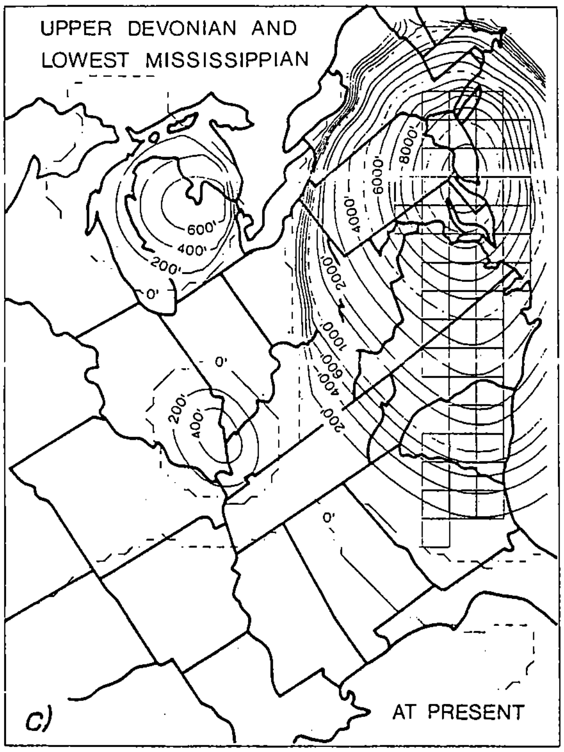


FIGURE 12 (cont.)

the lithosphere under the Eastern Interior must have been sufficiently large to couple the intracratonic basins into the Appalachian foreland basin as shown in Figure 12b.

Middle Devonian Depositional History. Immediately following deposition of the Tioga metabentonite, organic rich, black and grey shales (Marcellus Shale) spread westward through the epeiric sea into Ohio at the same time that 300 m of siltstones and sandstones

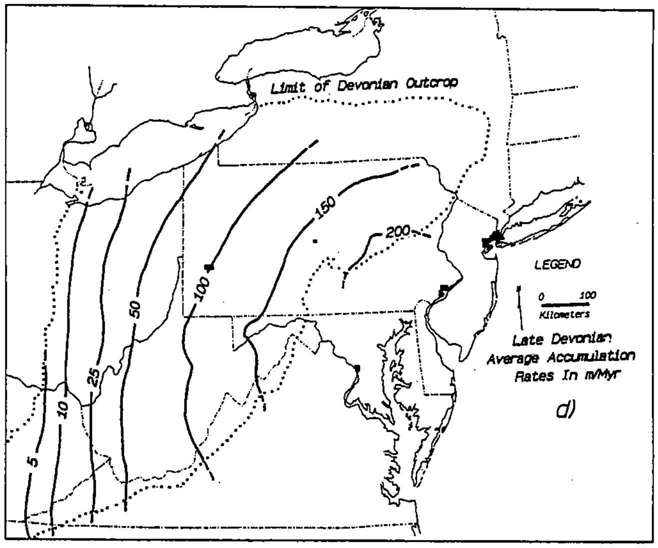


FIGURE 12 (cont.)

of the Mahantango Formation were deposited in eastern Pennsylvania (Fig. 13). These units are interpreted by Kaiser (1972) to be the result of a delta complex that prograded northwestward from Maryland into eastern Pennsylvania during upper Middle Devonian time. The shoreline at the time of maximum progradation in the Givetian Stage is given in Figure 14 as number 3. This first phase of shoreline progradation, was terminated by a eustatic (?) sea level rise, the Taghanic onlap, which transgressed the shoreline to position 4 (Fig. 14) and deposited the Tully Limestone Mbr. (Fig. 13), a deep water micrite interbedded with black shale.

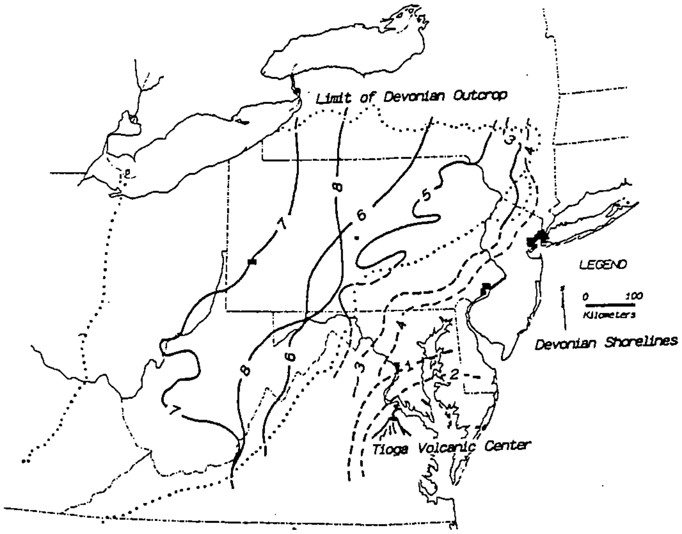


FIGURE 14 Devonian shorelines in the central Atlantic states. Dotted line encompasses the preserved Devonian strata; dashed lines are inferred from clastic wedges preserved further into the basin. Variation in age along any one shoreline can be millions of years: 1 = early Onesquethawan (377 Myr); 2 = late Onesquethawan; 3 = Tioughniogan; 4 = Taghanican; 5 = Finger Lakesian; 6 = Cohocton; 7 = early Bradfordian; 8 = late Bradfordian (346 Myr) (modified from Dennison, 1985).

Late Devonian Depositional History. By the Late Devonian, the Appalachian orogen was in the subtropics (Fig. 8) where southeasterly trade winds created a tropical climate with alternating wet and dry seasons restricting plants to the fringes of rivers, lakes, and the shoreline, and promoting redbed formation. A large epeiric sea, the Catskill Sea of Woodrow and Sevon (1985), covered the eastern interior. Increasingly higher rates of clastic sediment flux to the basin quickly prograded the shoreline of this sea back to the west (Fig. 14, position 5), producing the famous Catskill regressive sequence (Figs. 13, 14, and 15). At most stratigraphic sections in Pennsylvania (Fig. 15), the sequence starts with deposits of distal-basin dark shales, passes upwards into grey turbidites (eg., Brallier Fm. of Day 3, Site 2, Outcrop 1) of the shelf slope rise or clinoform (Woodrow, 1985), that in turn give way to upper slope and storm-dominated shelf facies (eg., Loch Haven and "Chemung" Fms. of Day 3, Site 2, Outcrop 2)(Slingerland and Loule, in press). Lying above the shelf facies are marginal marine deposits (eg., Irish Valley Mbr., Catskill Fm. of Day 3, Site 2, Outcrop 3) that, in Pennsylvania (Fig. 15), consist of two tide-dominated deltaic depocenters separated by the extensive tidal flat facies of a muddy shoreline (Rahmanian, 1979; Williams, 1985; Warne, 1986; Slingerland and Loule, in press). Petrographic differences among the depocenters to the south (Kirchgessner, 1973) indicate variations in the source

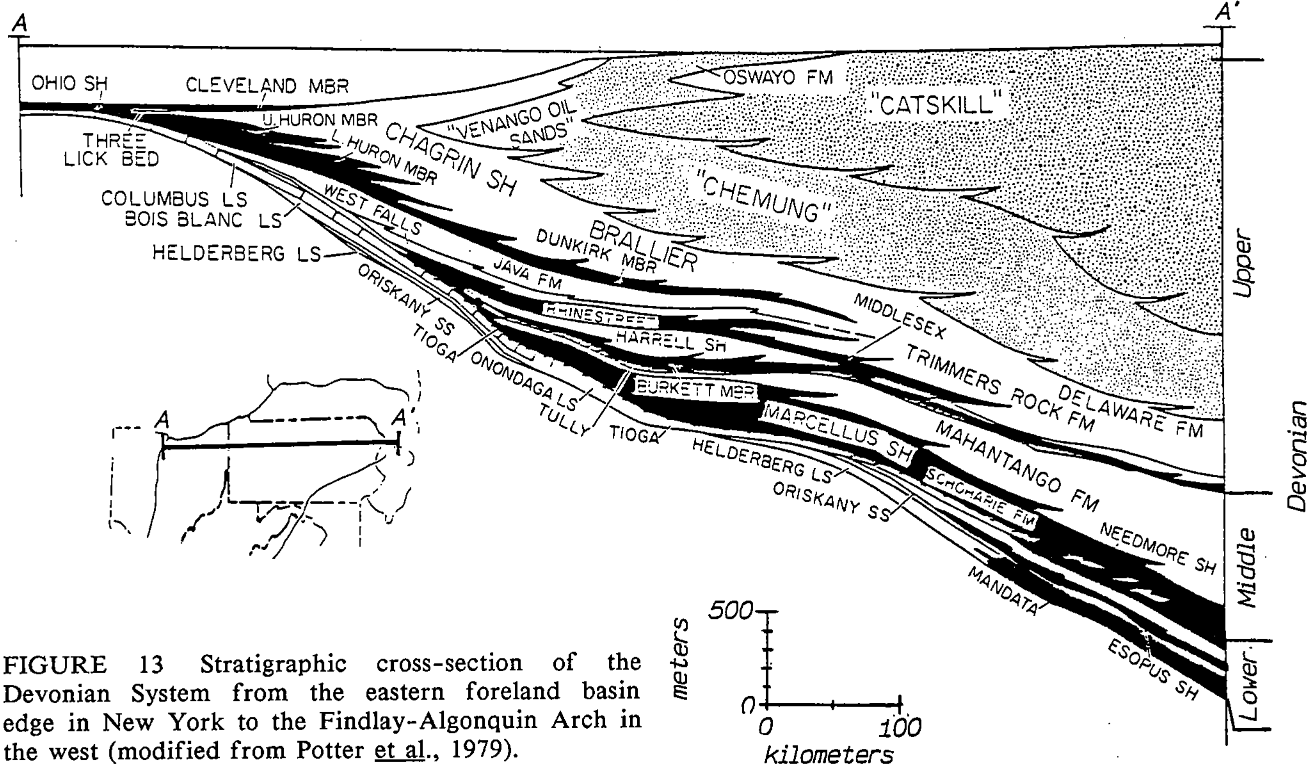


FIGURE 13 Stratigraphic cross-section of the Devonian System from the eastern foreland basin edge in New York to the Findlay-Algonquin Arch in the west (modified from Potter et al., 1979).

terrain from a greenschist facies provenance to the south to a higher grade or more igneous provenance to the north. The shoreline deposits are overlain by fluvial deposits of a vast alluvial plain that extended east to the Acadian Highlands. Low on the plain the rivers meandered (Bridge and Gordon, 1985) whereas higher on the plain the streams were low sinuosity meandering or braided (eg., Day 3, Site 2, Outcrop 4 and Day 5, Site 1 of Duncannon Mbr., Catskill Fm.)(Sevon, 1985; but see Bridge and Nickelsen, 1986 for an alternative view). The locations of the major streams across Pennsylvania were relatively fixed (Williams, 1985; Slingerland and Loule, in press; Sevon, 1985), probably by topography in the source region or basement tectonics.

During early and middle Famennian time the Catskill alluvial plain prograded an additional 167 km (100 miles) across the central Atlantic states (Fig. 14, shoreline 6), reaching its maximum westward position (shoreline 7) in late middle Famennian time. The world's first commercial oil well was drilled by Col. Edwin Drake in offshore shelf sandstones of this age (Fig. 13, "Venango Oil Sands"). Subsequently, a widespread and rather abrupt marine transgression overran the alluvial plain for 80-160 km (50-100 miles) (shoreline 8), depositing the Riceville Shale and Oswayo Fm. The time-equivalent alluvial rocks (eg. lower two-thirds of the Pocono [Rockwell] Fm. in outcrop 4 of Stop 3) have lost their red color but otherwise show little evidence of this change in base level. In fact, most interpretations of depositional environments in this interval (Rahmanian, 1979; Berg, 1981; Williams, 1985) imply that westward progradation of the steeper, upper alluvial plain continued uninterrupted, suggesting the transgression was primarily eustatic in origin. This is substantiated by its effects as far away as the Canadian Rockies (Dennison, 1985).

Early Mississippian Depositional History. The last phase of Acadian deposition is represented by rocks of the Pocono Fm. of Pelletier (1958) (Fig. 16). The braided alluvial plain (eg., Burgoon Ss. of Day 3, Site 2, Outcrop 5) depicted in Figure 16 in Kinderhookian time, prograded westward again, displacing shallow marine facies (eg., Shenango Fm. and Berea Ss.). Average accumulation rates across southern Pennsylvania were more similar to the Middle than Upper Devonian however, being only 49 m/Myr in the east and 15 in the west (Pelletier, 1958). This decrease in accumulation rate defines the end of the Acadian orogeny and its effects.

Alleghanian Orogeny

The Permo-Carboniferous Alleghanian orogeny is characterized by a molasse sequence in the foreland, thrusting and folding of the whole orogen but especially the foreland in the southern and central Appalachians, and regional metamorphism and plutonism along the entire eastern margin of the Appalachians. Its earliest effect in the central Atlantic region was a warping of the foreland basin in Meramecian time with uplift and erosion inboard, renewed sediment influx outboard, and development of a marine embayment in between. Deposition of shales in Arkansas also signals the onset of thrusting in the Ouachita part of the orogen. As discussed below, deformation outboard of the fold and thrust belt must have taken place continuously into the Permian to provide the necessary loads for the foreland. Numerous S-type granitic plutons were emplaced in the eastern Piedmont from mid-Carboniferous to Permian time (Hatcher, 1987; Jamieson and Beaumont, 1988) and most seem to be post-tectonic (Rodgers,

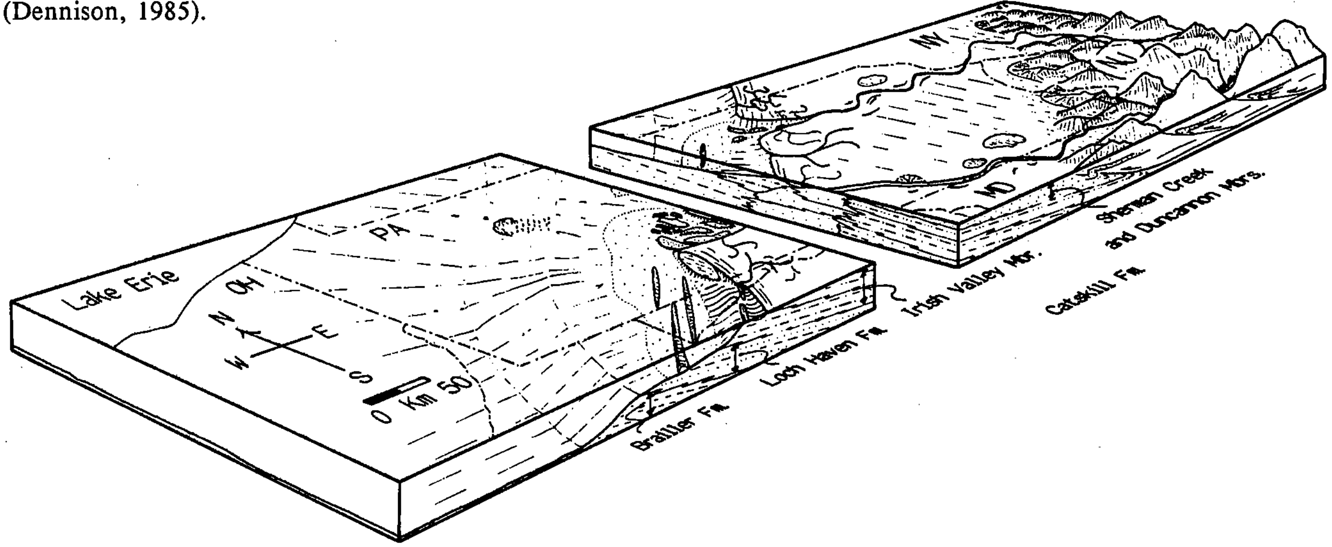


FIGURE 15 One-point perspective sketch of Devonian shoreline 6 (Fig. 14) showing the paleogeography, sedimentary paleoenvironments, and deposits across Pennsylvania. Two major meandering river systems are inferred to have drained the Acadian Highlands (interpreted as thrust sheets), and debouched into the Catskill Sea through trumpet-shaped, tidally influenced estuaries. Offshore, wind-driven geostrophic flows transported sediment plumes to the southwest, forming shelf sand sheets with ridges on an otherwise muddy shelf. Dilute silty turbidity currents carried sediments onto the basin floor.

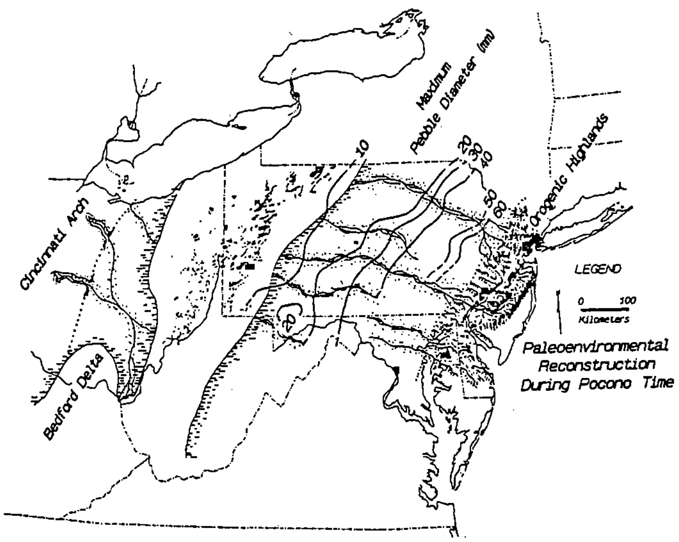


FIGURE 16. Paleogeography of middle Atlantic states during the Kinderhookian (Early Mississippian). Acadian Highlands to the east fed braided streams draining westward across Pennsylvania, producing the Pocono (Rockwell and Burgoon) Fm. The Cincinnati (Findlay-Algonquin) Arch, uplifted by lithospheric relaxation, fed a delta system which prograded south-southeast. Hydrocarbon reservoirs (shown in black) were formed in the narrow seaway (modified from Pelletier, 1958, and Donaldson and Shumaker, 1981).

1987). Folding in the preserved part of the fold and thrust belt of Pennsylvania did not occur prior to early Permian however, as evidenced by the fact that early Permian strata in western Pennsylvania are concordantly folded. These facts suggest that a wave of deformation and heating moved cratonward over the interval from mid-Mississippian to late Early Permian. The orogeny in the vicinity of Pennsylvania was completed by the end of Early Permian time because a remnant magnetization on fold limbs in central Pennsylvania is independent of bedding attitude and follows the cratonic polar wander path after that time (Van der Voo, 1988). Elsewhere in the Appalachians the Alleghanian orogeny probably ended by the end of the Permian because the plutons are no younger than 260 Myr (Jamieson and Beaumont, 1988).

Alleghanian deformation in the foreland is characterized by thin-skinned thrusting towards the continent (Rodgers, 1983, 1987; Hatcher, 1981; Mitra, 1986)(Fig. 17). All along the central and southern portions of the orogen, portions of the western Piedmont and Blue Ridge crystalline rocks moved westward, acting as a plunger to deform the sedimentary rocks of the foreland (Fig. 18). There seems little doubt that the ultimate cause was the final collision of Laurentia and Gondwana. The result in the foreland is the classic fold and thrust belt we see today, exhumed by up to 12,000 m (40,000 ft) of Mesozoic and Cenozoic erosion (Fig. 19).

Alleghanian Basin Fill

We consider the Alleghanian basin fill to commence with deposition of the Loyalhanna Fm. or Mauch Chunk equivalent and end sometime in the Permian. Because the Permian section is partially eroded, the total thickness of Alleghanian molasse is unknown. In eastern Pennsylvania at least 5-7 km of additional overburden are required to account for the level of organic metamorphism of the anthracite (Levine, 1983; 1986), sediment bulk densities and porosities (Paxton, 1983), fluid inclusion paleopressures (Orkan and Voight, 1985), and fission track thermochronometry (Beaumont, et al., 1987). The bulk of this may have been tectonically emplaced however. In western Pennsylvania where overthrusts are not a factor, the moisture content of the coals indicates an additional 2400 m (8000 ft) of Permian strata (Beaumont, et al., 1987). An estimated 2500 m maximum of preserved Alleghanian fill in the Southern Anthracite Field of Pennsylvania plus 2400 m of Early Permian strata (now eroded), yields an accumulation rate of 196 m/Myr, similar to the highest rates of the Late Devonian.

The model reconstruction of total Alleghanian loading and molasse deposition in the Appalachian and Arkoma basins (Fig. 20) is in agreement with data from preserved sediments and reconstruction of eroded section based on coal moisture content (Beaumont et

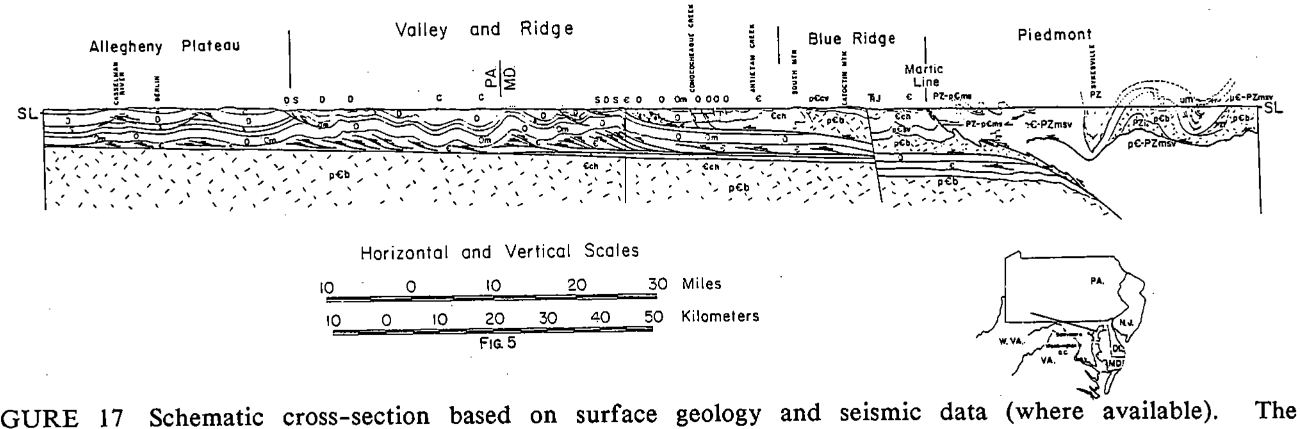


FIGURE 17 Schematic cross-section based on surface geology and seismic data (where available). The northwestward-directed folds and thrusts of the foreland (Valley and Ridge and Allegheny Plateau regions) are due to Alleghanian orogenesis (modified from Hatcher, 1981).

al., 1987). This reconstruction shows the scale of the foreland basin at the end of the orogeny and the magnitude of thrust loads which by this time were concentrated in the southern Appalachians and the region within and to the south of the Ouachita mountains. The model assumes minimum tectonic subsidence of the Michigan and Illinois basins of 160 m and 1115 m, respectively. Cumulative thicknesses of overthrust loads required by the model to reproduce the total foreland basin subsidence are shown in Figure 18.

Late Mississippian Depositional History. The foreland basin in the central Atlantic region responded to Alleghanian orogenesis in early Late Mississippian (Meramecian) time by subsidence along a northeast-southwest axis across Pennsylvania, creating a trough in which transgressive marine carbonates (eg., Greenbrier Ls. of West Virginia and Loyalhanna Fm. of Pennsylvania) were deposited (Fig. 21). Simultaneously, the region to the northwest experienced uplift and became a source for the trough. To the southeast, the orogenic source created earlier, continued to supply sediments, and a delta complex (Mauch Chunk Fm., Day 6, Site 1) built northwestward. By the end of the Chesterian Stage the Loyalhanna embayment was completely filled. Continued uplift to the northwest allowed streams to erode the Mauch Chunk margin soon after deposition and transport the sediment along the basin axis to the Kentucky region (Fig. 22). On the southeastern margin of the basin where Mauch Chunk sedimentation was continuous, approximately 1140 m (3800 ft) of alluvial redbeds are preserved (Arkle, 1974), yielding a maximum accumulation rate over the interval of 38 m/Myr.

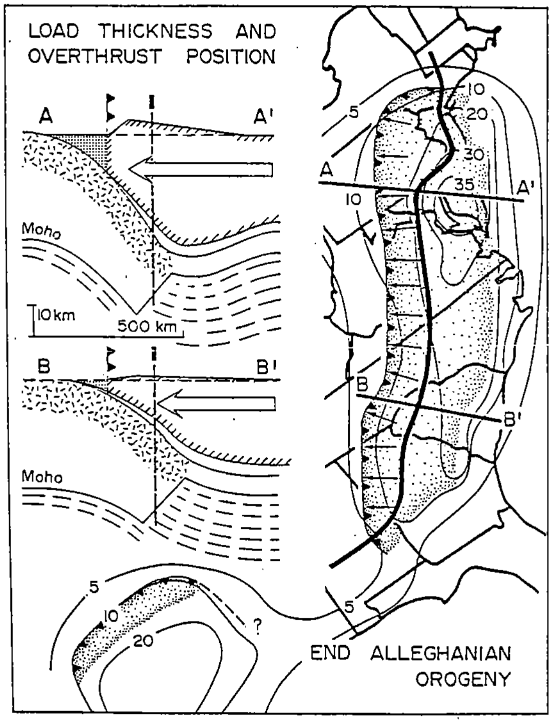


FIGURE 18 Interpretation of the cumulative model loads (fine line contours in km) in terms of overthrusting and thickening in the Appalachian and Ouachita orogens by the end of the Alleghanian orogeny. The bold lines show the location of the Bouguer gravity gradient in relation to the overthrust loads. Note that the thickest loads are to the east and south of this gradient. Barbed lines show the edge of basement involved thrust sheets and stippled areas are the inferred mountainous regions. Fine arrows illustrate the inferred advance of the thrust front during the Alleghanian orogeny in the Appalachian part of the orogen. The cross sections are based on results from Stockmal et al. (1986) and Stockmal and Beaumont (1987) and should be compared with Figures 4 and 5.

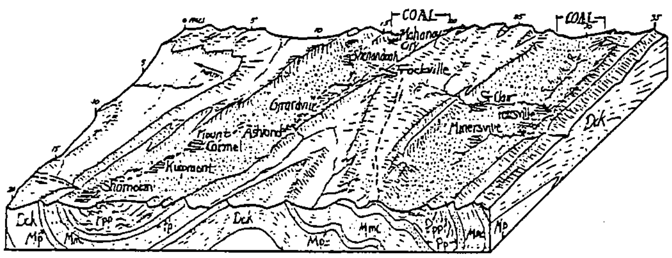


FIGURE 19 Schematic relationships among differentially resistant foreland strata, Alleghanian folds, present geomorphology, and coal in the Southern Anthracite Field. Days 5 and 6 will be spent in Ashland and Pottsville.

The Mississippian sediment distribution can be explained approximately by the two model timesteps

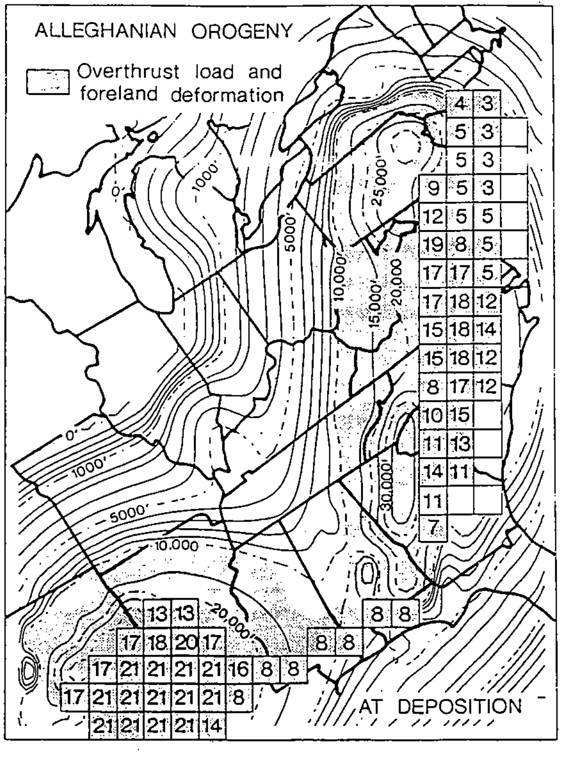


FIGURE 20 Total Alleghanian orogeny isopach map. Model prediction at deposition showing the cumulative load thickness for the Pennsylvanian and Permian (km). Contours of sediment isopach are in feet.

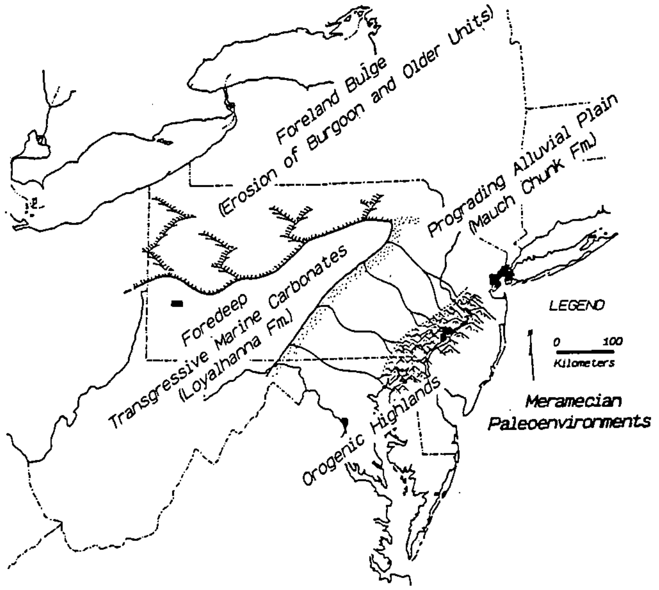


FIGURE 21 Paleogeography of the middle Atlantic states during the Meramecian (early Late Mississippian). Continued relaxation of the forebulge allowed transgression of the Loyalhanna sea into Pennsylvania as the Acadian orogenic highlands continued to downwaste, depositing the Mauch Chunk Fm. (modified from Edmunds, et al, 1979).

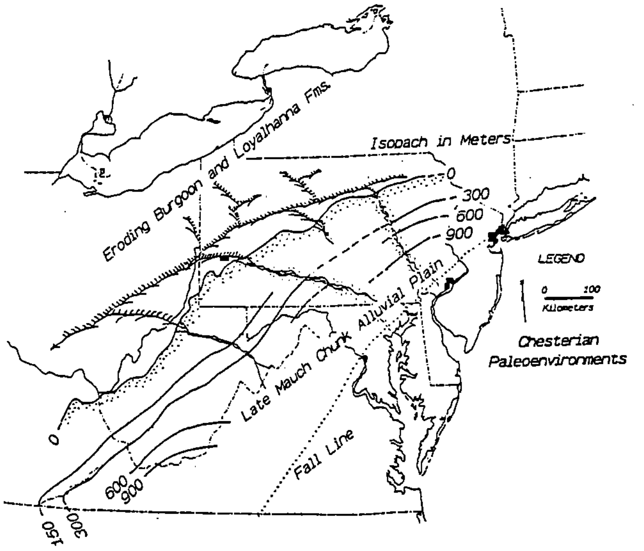


FIGURE 22 Paleogeography of the middle Atlantic states during the Chesterian (middle Late Mississippian). Increased loading to the south (Fig. 24) renewed uplift of the forebulge region, causing erosion of previously deposited formations to the northwest as Mauch Chunk alluvium continued to accumulate to the southeast (modified from Edmunds et al., 1979).

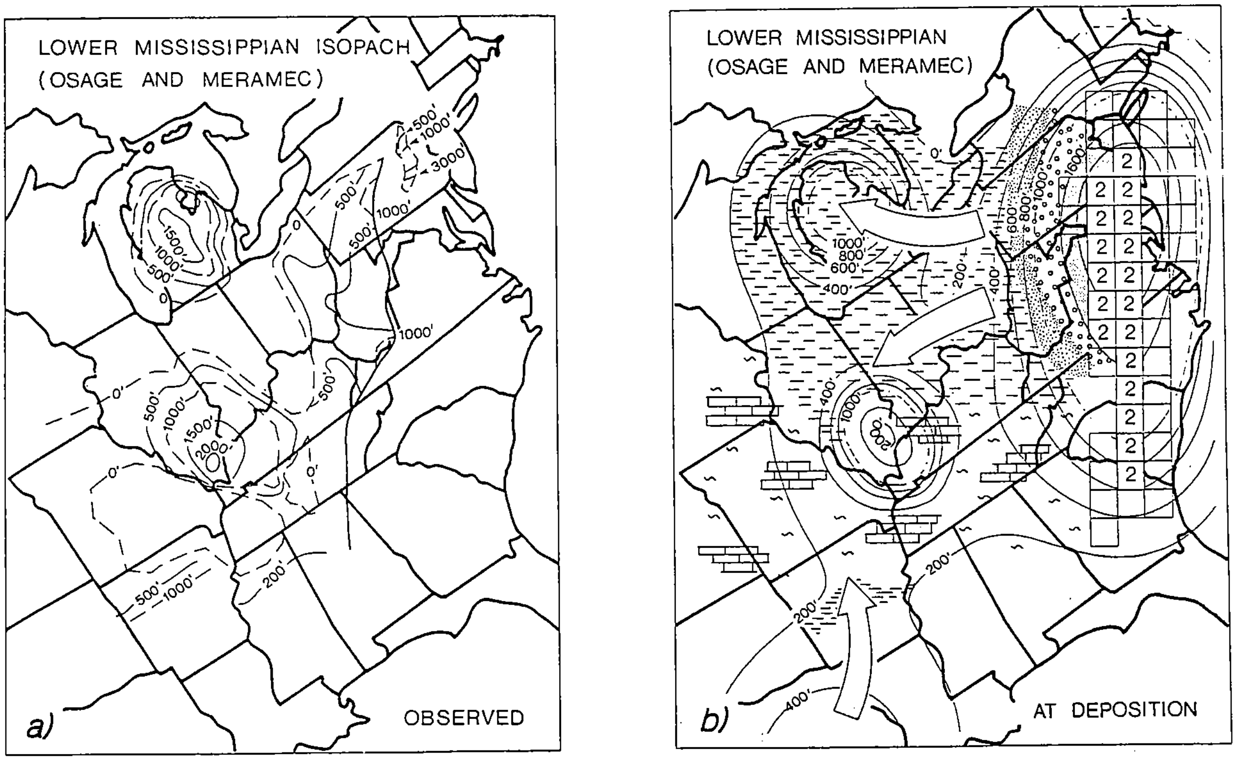


FIGURE 23 Isopach maps of observed (panel a) and predicted (panels b and c) sediment distribution for the Lower Mississippian (contours in feet). The numbered grids in panel (b) are the thicknesses (km) of the overthrust loads necessary to produce the model subsidence in the Appalachian basin. Brick and tilda patterns denote observed and restored chemical sedimentation and marine conditions. Dash and dot patterns denote observed shale, and fine and coarse sandstone sediments. Large arrows show the inferred major sediment dispersal directions.

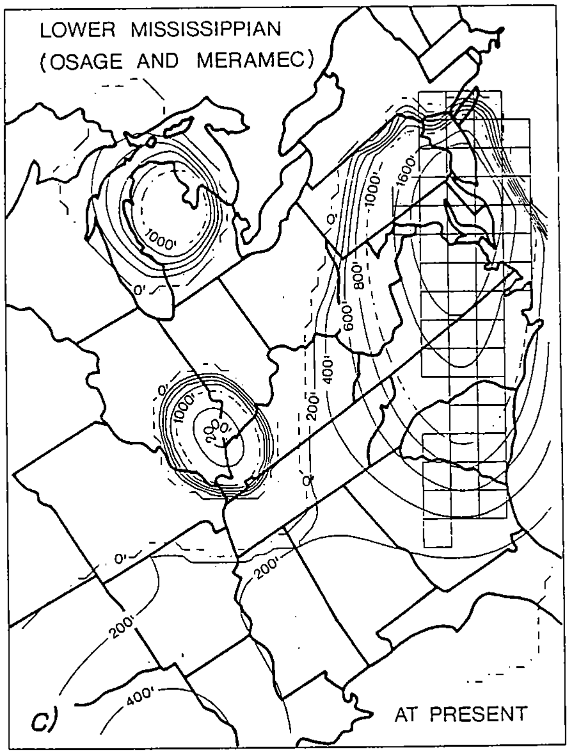


FIGURE 23 (cont.)

given in Figures 23 and 24. Although more subdivisions would be necessary to capture the dynamics of evolution during this period, the change appears to be the consequence of a southward migration of the load distribution and uplift of and erosion from the Findlay-Algonquin arch during an interval of lithospheric stress relaxation.

The southward load migration from the Late Devonian into the Mississippian meant that the areas of western New York and Pennsylvania became progressively closer to the edge of the foreland basin and, therefore, were more influenced by sediment influx from the uplifted arches (Figs. 12b, 23b, and 24b). The Bedford Delta (Fig. 16) is the first evidence of reworked cratonic sediments, presumably from a source that could have been as proximal as the vicinity of southern Ontario by the Kinderhookian to Osagean transition. During the Meramecian and Chesterian the edge of the basin retreated into Pennsylvania (Figs. 24b and 21), and older Mississippian sediments were uplifted, exposed, eroded, and reworked into the southeasterly retreating basin.

Pennsylvanian Depositional History. Commencing in latest Mississippian time in eastern Pennsylvania and continuing through the Middle Pennsylvanian, a wedge of braided stream gravels (eg., Pottsville Fm., Day 6, Site 1) flooded northwestward over the Mauch Chunk delta complex from a south-southeastern source terrane (Fig. 25). Although this has traditionally been

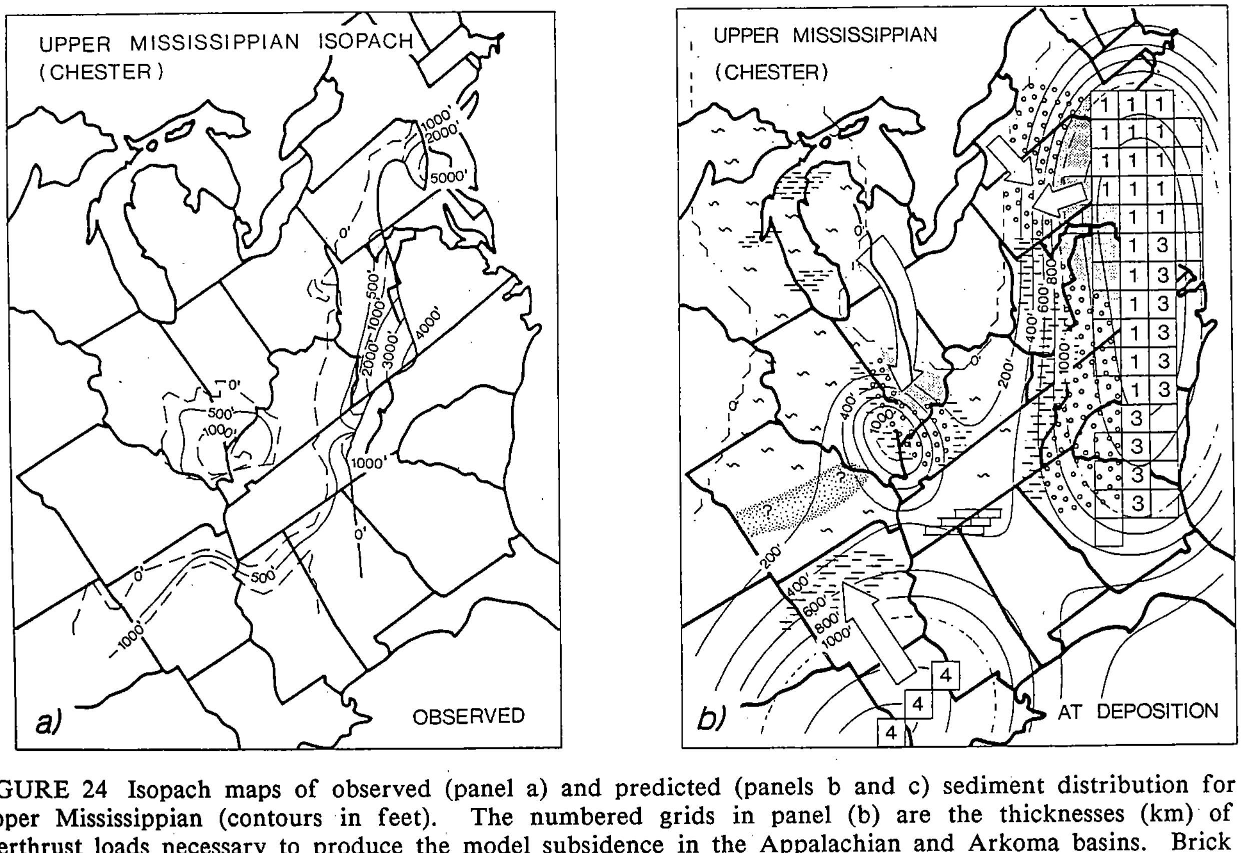


FIGURE 24 Isopach maps of observed (panel a) and predicted (panels b and c) sediment distribution for the Upper Mississippian (contours in feet). The numbered grids in panel (b) are the thicknesses (km) of the overthrust loads necessary to produce the model subsidence in the Appalachian and Arkoma basins. Brick and tilda patterns denote observed and restored chemical sedimentation and marine conditions. Dash and dot patterns denote observed shale, and fine and coarse sandstone sediments. Large arrows show the inferred major sediment dispersal directions.

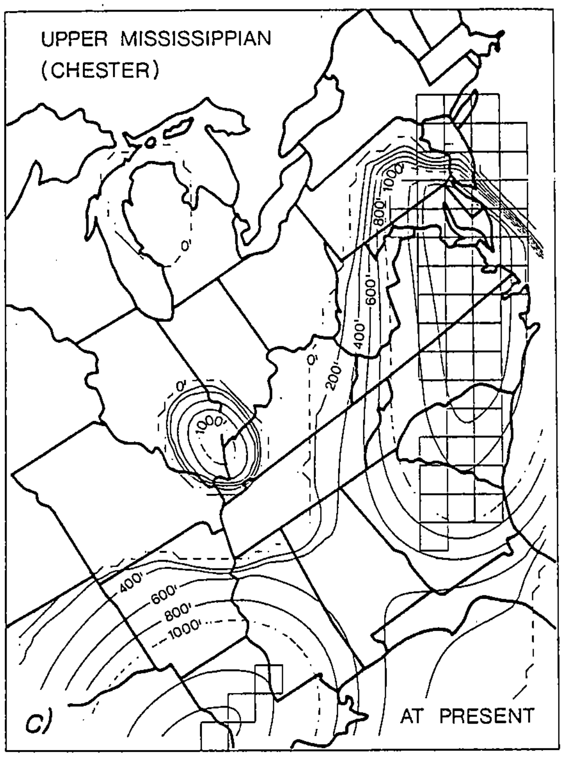


FIGURE 24 (cont.)

interpreted as evidence of dramatic orogenesis immediately to the southeast (cf. Meckel, 1967), the maximum accumulation rate at Pottsville, PA was only 19 m/Myr, and clast and rock fragment lithologies suggest the source terrain was composed primarily of sedimentary and low grade metamorphic rocks (Meckel, 1967; Houseknecht, 1979). The flexural modelling presented below (Fig. 27), suggests only modest additional thrust loads were present outboard of Pennsylvania during the Early Pennsylvanian. As described at Site 1 on Day 6, an alternative explanation for these gravels is a change to a wetter climate and higher discharge, perennial streams draining the Virginia orogenic belt.

At approximately the same time, gravels derived from older Paleozoic sedimentary rocks to the north filled incised stream channels along the northern tier of Pennsylvania (Meckel, 1967). This was apparently in response to subsidence below base level caused by crustal loading in Virginia and further south and is the first evidence of the type of transition in loading between that shown in Figures 27 and 28.

By early Desmoinesian (Middle Pennsylvanian) time, subsidence and eustatic sea level rise (Heckel, 1986) were sufficient to flood western Pennsylvania (Figs. 26 and 28), creating broad delta plains conducive for the formation of coal swamps (eg., Allegheny Group, Day 4). At the same time, alluvial plain slopes

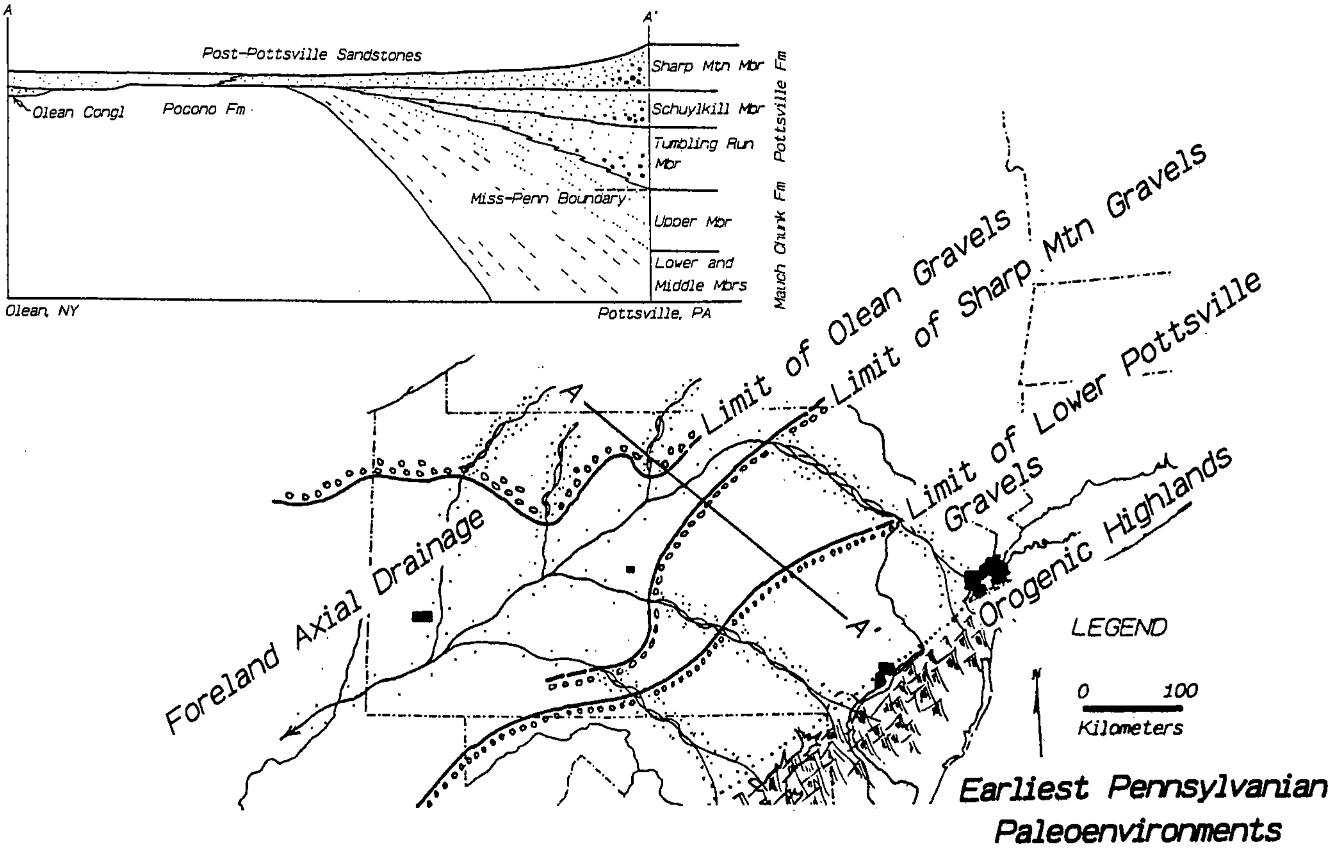


FIGURE 25. Paleogeography of the middle Atlantic states during the earliest Pennsylvanian. Major loads to the south-southeast (Fig. 27) depressed Pennsylvania and created differential relief such that a flood of gravels (Pottsville, Olean, Sharon Fms.) swept over the region from the north as well as the southeast (modified from Meckel, 1967).

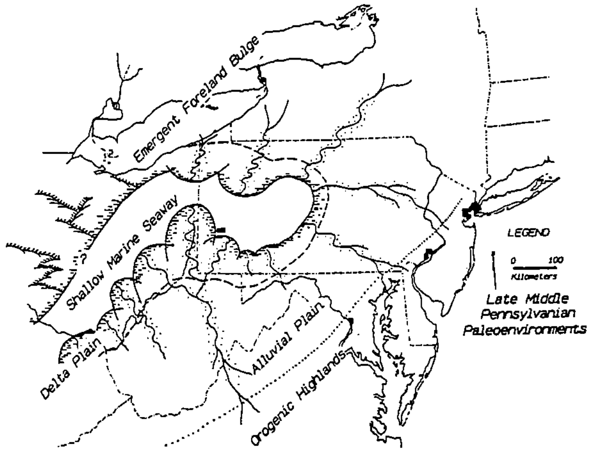


FIGURE 26 Paleogeography of the middle Atlantic states during the late Middle Pennsylvanian. As the overthrust loads migrated northward (cf. Figs. 27 and 28), a narrow seaway returned to the area and the alluvial plain spread further northwestward from the orogenic highlands (modified from Donaldson and Shumaker, 1981).

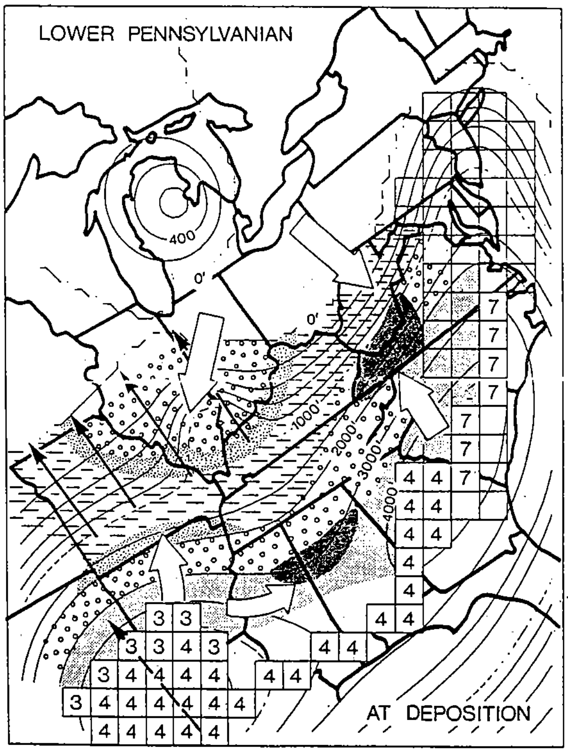


FIGURE 27 Lower Pennsylvanian isopach map (contours in feet). Model prediction at time of deposition showing the load thicknesses (km) necessary to produce the model subsidence in the Appalachian and Arkoma basins. Dash and dot patterns denote observed and restored shale, and fine and coarse sandstones. Light and dark shading represent coastal plain and coal swamp environments. Large arrows show the inferred major sediment dispersal directions. Fine arrows show the migration of the peripheral bulge during the advance of the overthrust loads in the Ouachita orogen.

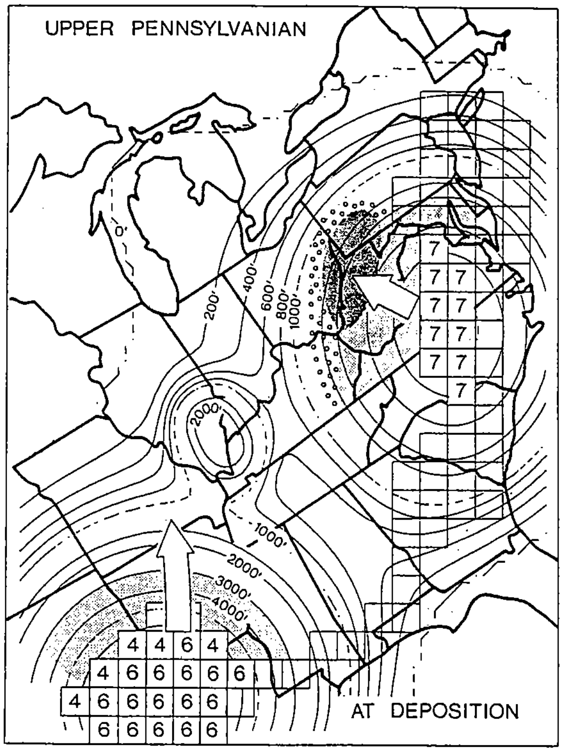
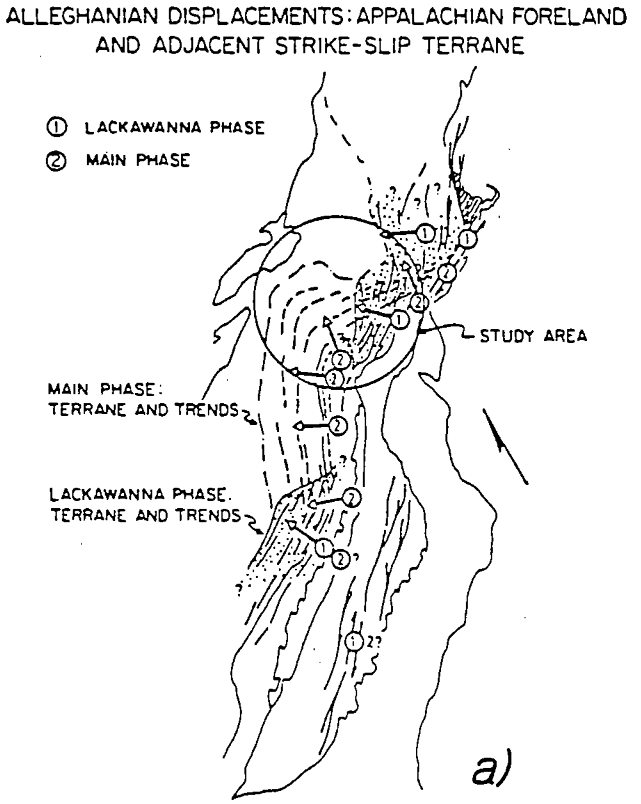


FIGURE 28 Upper Pennsylvanian isopach map (contours in feet). Model prediction at time of deposition showing the load thicknesses (km) necessary to produce the model subsidence in the Appalachian and Arkoma basins. Dot pattern denotes sandstones. Light and dark shading represent coastal plain and coal swamp environments. Large arrows show the inferred major sediment dispersal directions.

declined, probably due to increased loads and subsidence near the source, and thick peat swamps developed as close to the source terrane as Pottsville, PA (eg., Llewellyn Fm., Day 5, Site 2, and Day 6, Site 1).

Throughout the Upper Pennsylvanian into the Permian, base level oscillated, producing the famous cyclothems of the coal measures (Busch and Rollins, 1984; Heckel, 1986). Accumulation rates increased, presumably in response to increased thrust loading to the east. By the time the youngest preserved strata were deposited, accumulation had so outstripped subsidence, that the northeastern end of the Appalachian foreland basin was a subaerial alluvial plain stretching from its southeastern source terrane to the Cincinnati Platform.

The regional setting of Pennsylvanian subsidence and sedimentation can be explained in terms of the flexural model results (Figs. 27 and 28). Like the Mississippian, more subdivisions would be necessary to represent details, but the pattern is apparently explained by the initiation of substantial overthrusts along the southern rim of North America and the progressive migration of overthrusting northward into Virginia during the middle and later part of the Pennsylvanian. The shift in the locus of loading from



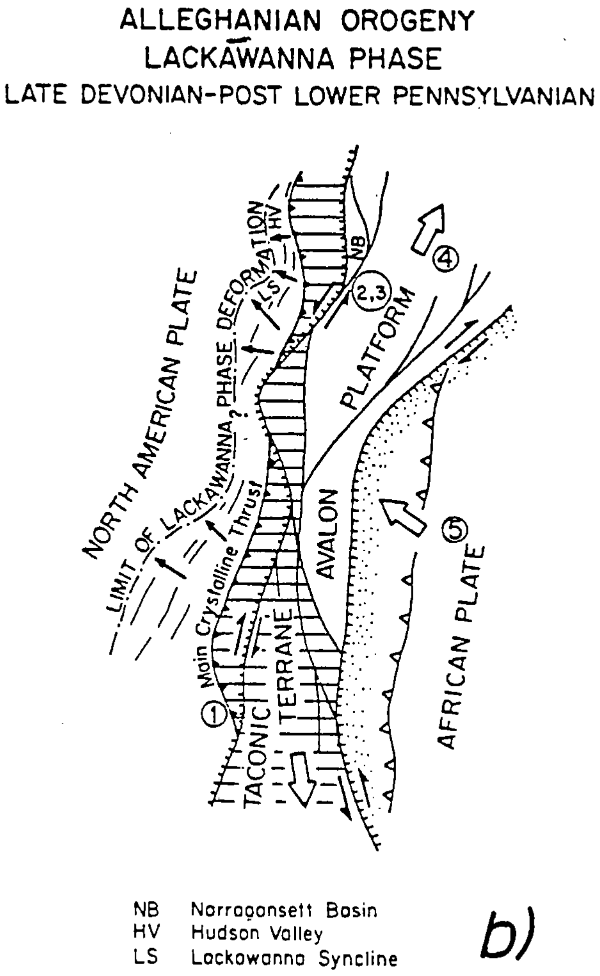


FIGURE 29. a) Directions of layer parallel shortening during the Lackawanna (Pennsylvanian?) and main (Permian?) phases of the Alleghanian orogeny. b) and c) Tectonic interpretation of deformation within the Appalachian orogen during these phases (modified from Geiser and Engelder, 1983). The inferred directions of thrusting should be compared with the positions of overthrust loads shown in Figures 24, 27, 28, and 30.

that of the Late Mississippian causes uplift and exposure of sediments on a broad east-west peripheral bulge (Fig. 27), which explains the increasing importance of this region as a source of reworked sediments and the development of an unconformity over this area.

The northward sweep in the development of the unconformity can be attributed to the migration of the peripheral bulge at the time of rapid convergence between the loads and the continental margin (Beaumont et al, 1988; Ettensohn and Chestnut, sub.). The development of the unconformity in this southern region therefore parallels that of the Ordovician post-Beekmantown Knox unconformity in the central Appalachian foreland north of Alabama. During the early stages of convergence of overthrusts on a rifted margin, these loads migrate large distances laterally as subduction continues. The peripheral bulge therefore sweeps across a much larger area than in subsequent orogenies at the same margin where the loads tend to grow in situ by shortening and thickening of terranes that have already accreted.

Erosion in central and northwestern Pennsylvania in the Early Pennsylvanian is therefore attributed to uplift of the Findlay-Algonquin arch during stress relaxation that continued from the Mississippian compounded with the superimposed peripheral bulge from the newly arrived southern loads. Although eustatic sea level changes cannot be entirely dismissed as the cause of the Pennsylvanian unconformity, the tectonic-flexural model provides an internally consistent explanation.

Upper Pennsylvanian sedimentation in the central Appalachian basin is attributed to the completion of the Lackawanna phase of the Alleghanian orogeny (Fig. 28). Deformation caused by thrusting from load emplacement in central Virginia also agrees with the explanation of layer parallel shorting during the Lackawanna phase (Geiser and Engelder, 1983)(Fig. 29) which requires northwesterly directed compression in Pennsylvania. This phase of layer parallel shortening should be contrasted with the later, "main" phase related to Permian compression and loading (Figs. 29 and 30) when the compression was directed towards the west. Although all of the loading of this later phase cannot be unequivocally termed Permian, structural, sedimentological, coal metamorphic and moisture, and fission track data (summarized in Beaumont et al., 1987) require a further stage of loading which to first order is satisfied by the model (Fig. 30).

The main phase of Early Permian compression deformed the foreland itself, thus ending its life as a

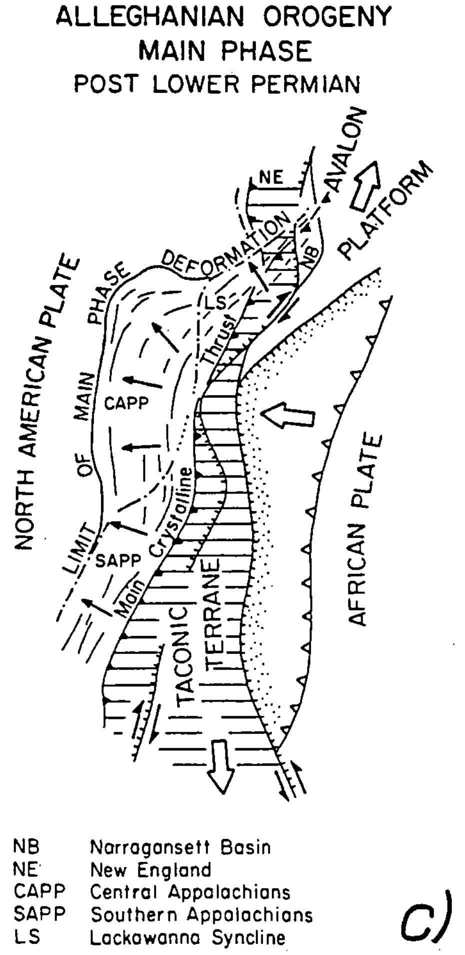


FIGURE 29 (cont.)

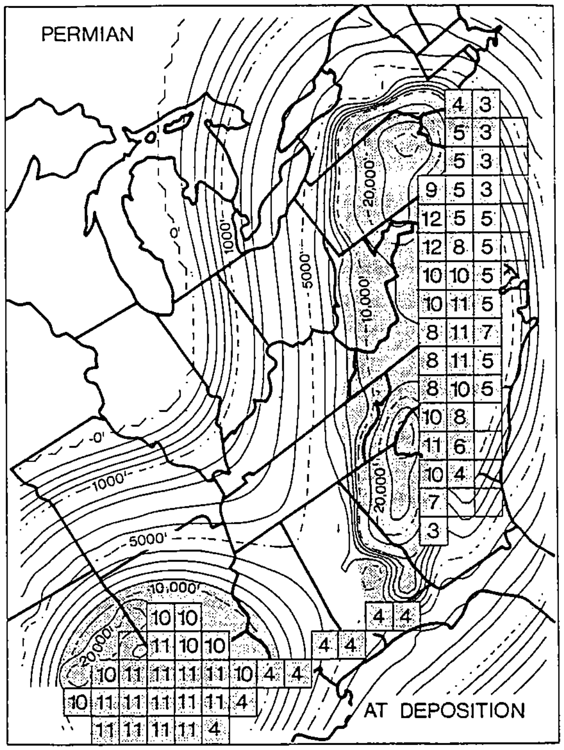


FIGURE 30 Permian isopach map (contours in feet). Model prediction at time of deposition showing the load thicknesses (km) necessary to produce the model subsidence in the Appalachian and Arkoma basins. Shading represents regions deformed by thrusting in which the extra thickness of sediment may, in part, be occupied by older sediments that were shrotened and thickened during thrusting.

sedimentary basin. Significant erosion at a rate of 200 m/Myr started almost immediately as evidenced by the fact that Late Triassic rift basin sediments overlie Cambro-Ordovician carbonates in southeastern Pennsylvania (see Manspeizer and Huntoon, this volume, for more details). By comparison with denudation rates as functions of relief for present-day mountain belts in similar latitudinal (and therefore climatic) settings, and given the thickness of the loads (Fig. 30), the ancestral Appalachians must have had considerable relief.

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