Phanerozoic Evolution of Sedimentary Basins in the Uinta-Piceance Basin Region, Northwestern Colorado and Northeastern Utah

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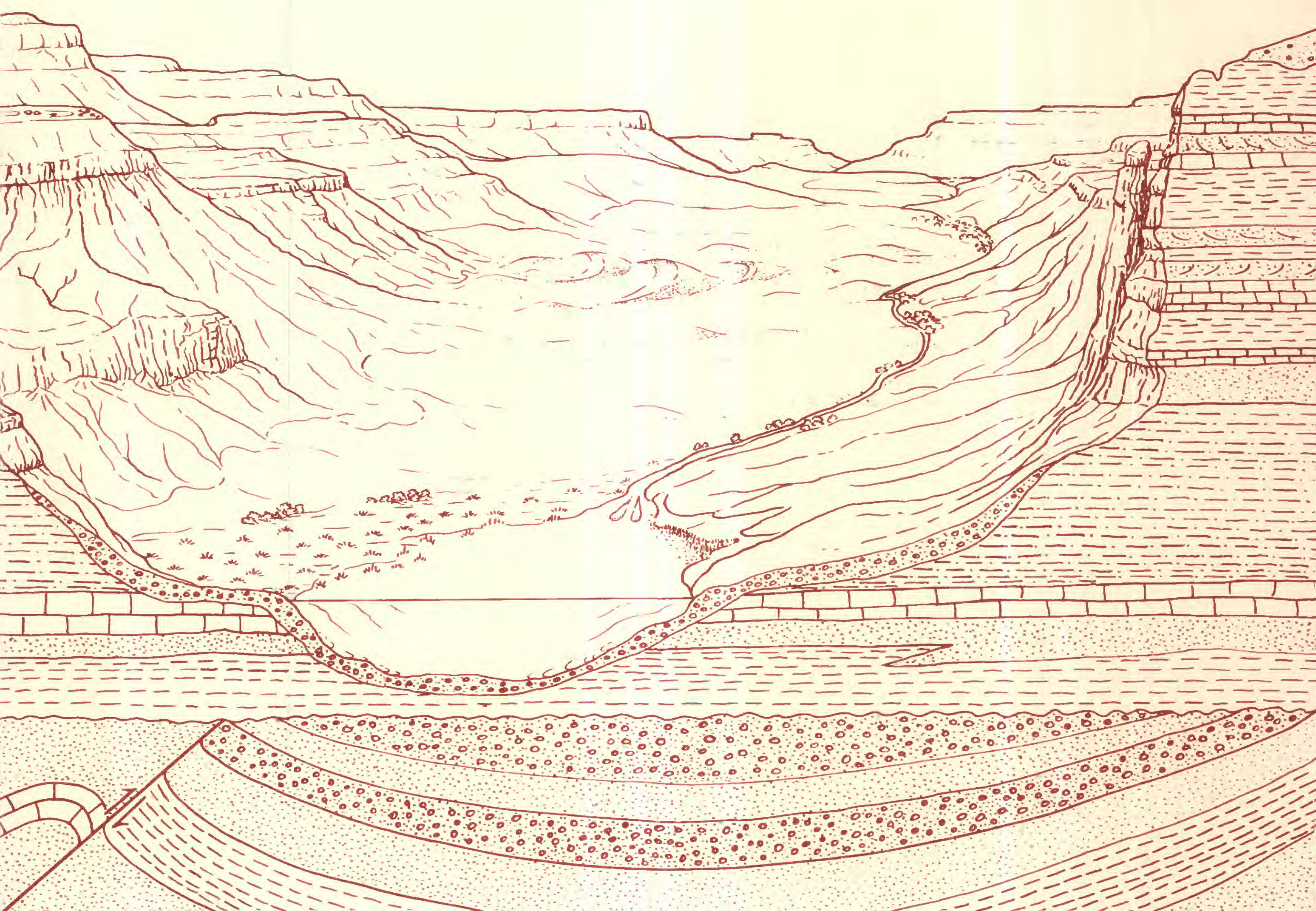

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Chapter FF

Phanerozoic Evolution of Sedimentary Basins in the Uinta-Piceance Basin Region, Northwestern Colorado and Northeastern Utah

By SAMUEL Y. JOHNSON

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1787

EVOLUTION OF SEDIMENTARY BASINS—UINTA AND PICEANCE BASINS

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

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Phanerozoic Evolution of Sedimentary Basins in the Uinta-Piceance Basin Region, Northwestern Colorado and Northeastern Utah

By Samuel Y. Johnson

Abstract

The Uinta-Piceance basin region of northwestern Colorado and northeastern Utah has occupied an intraplate geologic setting throughout Phanerozoic time and is mostly underlain by Phanerozoic strata that were deposited over a heterogeneous Precambrian basement. Six phases of Phanerozoic basin evolution are recognized, each of which was initiated by a pulse of rapid subsidence that is correlated with a tectonic event driven by interactions on adjacent plate margins. (1) The Cambrian to Middle Devonian phase of basin evolution is correlated with rifting on the western margin of North America and subsequent development of a passive margin. (2) The Late Devonian to early Late Mississippian phase is correlated with the contractional Antler orogeny of east-central Nevada. (3) The entire mid-Late Mississippian to early Early Permian phase of basin evolution is correlated with the transtensional(?) Humboldt orogeny of Nevada. The ancestral Rocky Mountain orogeny, driven by the distant collision of the Gondwana and Laurasian continental plates on the southeastern flank of North America, was also a major influence on basin evolution during the late Early Pennsylvanian to early Early Permian. (4) The late Early Permian to Early Jurassic phase is correlated in part with the contractional Sonoma orogeny of central and eastern(?) Nevada. (5) The Middle Jurassic to early Early Cretaceous phase is correlated with a Middle Jurassic episode of thrusting in eastern Nevada and western Utah. (6) The late Early Cretaceous to late Eocene phase of basin evolution is correlated with thin-skinned contractional deformation of the Sevier orogeny of western and central Utah and with thick-skinned contractional deformation of the Laramide orogeny, east of and in the foreland of the Sevier thrust belt. The latter parts of phases one two, four, and five were marked by relative tectonic quiescence. Reactivation of Precambrian structural grain was an important recurrent control on patterns of deformation and subsidence during these phases. Extensional deformation and uplift characterize the Oligocene to Holocene history of the region.

During the six phases of Phanerozoic basin evolution, deposition of specific facies was dependent on subsidence rate, sediment supply, eustasy, and climate. When subsidence rates were high, alluvial clastic deposits were generally confined to narrow bands adjacent to tectonic highlands. At these times, distal parts of basins were characterized by deposition of fine-grained clastic sediments that were interbedded with evaporites when circulation was restricted and the climate arid. Deposition of carbonate sediments also occurred in rapidly subsiding areas when the supply of clastic sediment was negligible. Phosphatic deposits reflect synorogenic basin deepening and associated upwelling of cool, nutrient-rich waters. Periods of tectonic stability were characterized by emergence and erosion or by widespread deposition of alluvial clastic sediments and (or) eolianites and (or) marine carbonate sediments. Relatively humid and arid climates favored alluvial and eolian deposition, respectively, whereas low sediment supply and high sea level favored carbonate deposition.

INTRODUCTION

The Uinta-Piceance basin region of northwestern Colorado and northeastern Utah (fig. 1) encompasses the Laramide (latest Cretaceous to Paleogene) Uinta and Piceance basins and their surrounding uplifts. The region has occupied an intraplate geologic setting throughout Phanerozoic time and is mostly underlain by Phanerozoic strata that were deposited over a heterogeneous Precambrian basement. These Phanerozoic strata record six phases of basin evolution, characterized by distinct structural controls and depositional processes, geometries, and histories: (1) Cambrian through Middle Devonian, (2) Late Devonian through early

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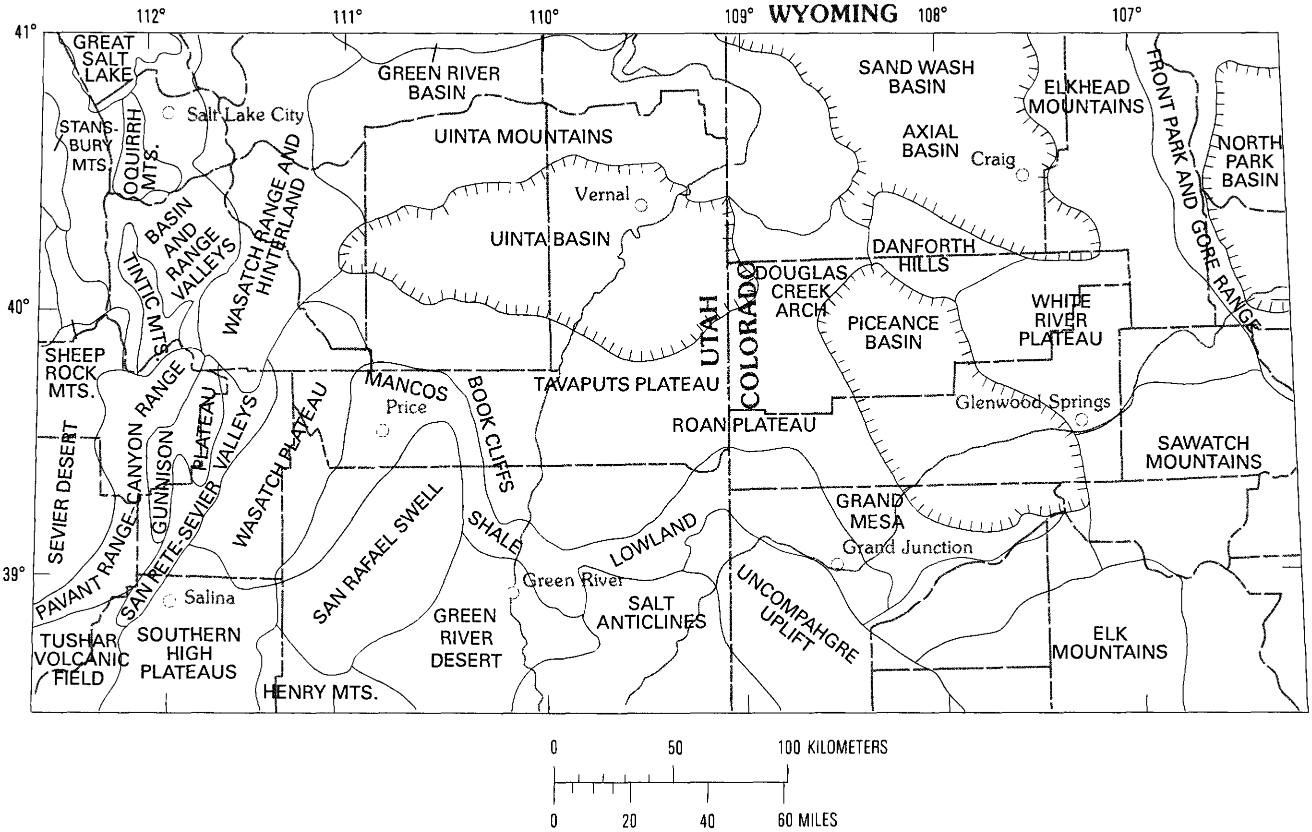


Figure 1. Physiographic provinces of Uinta-Piceance basin region. Modified from Raisz (1972) and Stokes (1977).

Late Mississippian, (3) mid–Late Mississippian through early Early Permian, (4) late Early Permian through Early Jurassic, (5) Middle Jurassic through early Early Cretaceous, and (6) late Early Cretaceous through late Eocene. Because of this long multiphase history, the Uinta-Piceance region provides an ideal opportunity to study intraplate basin evolution.

The purpose of this report is to describe patterns of subsidence and deposition and their controls in the Uinta-Piceance basin region. Results include the following. (1) Initiation of each phase of basin evolution can be correlated with a regional tectonic event. (2) Basin evolution in intraplate regions can be a sensitive indicator of interactions on adjacent continental margins. (3) Flexural loading and extensional and (or) transtensional(?) rifting were the principal structural controls on basin formation. (4) Precambrian structural zones were reactivated continually during the Phanerozoic and had major effects on deformational and depositional trends. (5) New generalizations concerning the controls of tectonics, sediment supply, eustasy, and climate on deposition may be compared with data from other regions in order to develop models of intraplate sedimentation.

This synthesis is the one of the last chapters in U.S. Geological Survey Bulletin 1787, which presents many of the results of the Uinta-Piceance basin project of the Evolution of Sedimentary Basins Program. This volume and other project maps and charts, in particular the stratigraphic cross sections of S.Y. Johnson and R.C. Johnson (1991), Franczyk (1991), R.C. Johnson and S.Y. Johnson (1991), and Sprinkel (in press), present many details of stratigraphic nomenclature and relationships that for the sake of brevity are not described here.

Acknowledgments.–The distillation of data and interpretations presented in this report benefitted greatly from informative and stimulating conversations with many geologists, including Harry E. Cook, Russell F. Dubiel, Thomas D. Fouch, Karen J. Franczyk, James R. Herring, Ronald C. Johnson, Keith B. Ketner, Fred Peterson, Christopher J. Potter, Charles A. Sandberg, Christopher J. Schenk, Norman J. Silberling, Douglas A. Sprinkel, Sherilyn Williams-Stroud, and Charles H. Thorman. Thomas D. Fouch, Fred Peterson, and Christopher J. Potter provided helpful reviews. Some of the above geologists will not agree with some of the interpretations expressed in this report, for which I assume responsibility.

PRECAMBRIAN BASEMENT ROCKS

Phanerozoic sedimentary rocks of the Uinta-Piceance basin region (fig. 1) were deposited over a heterogeneous basement of Precambrian crystalline and sedimentary rocks. Exposures of basement rocks are limited to the Gore Range, Park Range, and Sawatch Mountains on the eastern flank of the region, on and adjacent to the Uncompahgre Plateau in the southeastern part of the region, in the Uinta Mountains in the north-central part of the region, and in the Wasatch Mountains, Sheeprock Mountains, and Canyon Range in the western part of the region (fig. 1). These exposures are not widespread. Inferences regarding the continuity of basement units in the subsurface are therefore speculative, based primarily on (1) the lithology of rocks in nearby exposed basement, rare boreholes, and xenoliths, (2) interpretations of geophysical data, and (3) concepts of genetic processes and settings (for example, Tweto, 1987).

Crystalline Basement Rocks

The Uinta-Piceance basin region is on the southern flank of the Archean Wyoming province, which comprises the oldest continental crust in the western United States and represents the Archean craton (Hedge and others, 1983, 1986). The boundary between this province and younger basement rocks to the south trends west-southwest, approximating the trend of the Uinta Mountains (fig. 2) (Tweto, 1980, 1987). Representative rocks of the Archean Wyoming province crop out in two areas in the Uinta-Piceance region. (1) Granitic gneiss, migmatite, schist, gneiss, and quartzite of the Farmington Canyon Complex crop out in the northern Wasatch Mountains (Bryant, 1984, 1988). Protolith for the Farmington Canyon metamorphic rocks may be as old as 3,600 Ma. (2) Gneiss (about 2,700 Ma) and a 4-km-thick section of amphibolite-facies metaquartzite, quartz-muscovite schist, and minor marble of the Red Creek Quartzite crops out in a small area on the northern flank of the eastern Uinta Mountains (Tweto, 1987).

Three main groups of Precambrian crystalline rocks have been recognized in outcrops in the Colorado part of the Uinta-Piceance basin region (Tweto, 1987). These rocks formed in a continental-margin setting, on the southern flank of the Archean craton. The oldest group, the Early Proterozoic gneiss complex, consists of structurally complex, amphibolite-facies, metasedimentary and metavolcanic gneiss. The protolith for this gneiss complex is probably younger than 1,800 Ma, and metamorphism is thought to have peaked about 1,740 Ma. The second group of basement rocks comprises mainly granitoid intrusive rocks of the Routt Plutonic Suite, about 1,665–1,700 Ma in age. Tweto (1987, pl. 1) inferred that these older two units form the basement for much of the northeastern part of the Uinta-Piceance region. Intrusion of the Routt Plutonic Suite was influenced by northeast-trending fault-shear zones that are elements of the Colorado lineament (fig. 2) (Warner, 1978). Granite and quartz monzonite of the Berthoud Plutonic Suite, ranging in age from about 1,400 to 1,450 Ma, form the third, and youngest, group of basement rocks in this area. Within the Uinta-Piceance region, these younger crystalline rocks crop out mainly in the Sawatch Mountains (fig. 1), where they are cut by and also intrude the 11-km-wide Homestake shear zone (fig. 2); (Tweto, 1980). Precambrian faults of north-northwest trend have also been described from Colorado (Tweto, 1980, 1987), but their effects are less obvious. Minor igneous activity continued after 1,400 Ma. Intrusion of the Gore fault zone (fig. 2) by a 1,000-Ma dike indicates that activity on this major, long-lived north-northwest-trending structure began in the Precambrian.

Early Late Proterozoic Sedimentary Rocks

The early Late Proterozoic Uinta Mountain Group and the Big Cottonwood Formation are the oldest Precambrian sedimentary rocks in the Uinta-Piceance region. The Uinta Mountain Group crops out in the Uinta Mountains and consists of as much as 7,300 m of primarily nonmarine sandstone, quartzite, shale, and argillite (Hansen, 1965). In the subsurface, the Uinta Mountain Group probably extends as far east as Craig (fig. 2) (Tweto, 1980). Tweto (1987) suggested that the group was deposited from about 925 to 1,100 Ma in the late Middle Proterozoic, consistent with paleomagnetic data reported by Elston and McKee (1982). Elston and others (in press), however, modified the age of the Uinta Mountain Group to early Late Proterozoic based on the presence of *Chuaria*-bearing acritarchs and vase-shaped chitinozoanlike microfossils and paleomagnetic data. The Big Cottonwood Formation of the central Wasatch Range consists of about 4,800 m of quartzite and argillite of inferred marine origin (Crittenden and Wallace, 1973; Crittenden, 1976). The Big Cottonwood is lithologically and stratigraphically distinct from the Uinta Mountain Group, but differences have been ascribed to lateral facies changes, and the two units are presumed to have been deposited in the same fault-bounded basin (Crittenden and Wallace, 1973; Crittenden, 1976; Christie-Blick and Levy, 1989). The tectonic significance of early Late Proterozoic sedimentary rocks in the western United States is uncertain, but these rocks have been interpreted by most authors as the deposits of either a passive continental margin or isolated intracratonic basins (for example, Burchfiel and Davis, 1972; Stewart, 1976; Winston, 1986).

Hansen (1965) suggested that the Uinta Mountain Group was deposited in an east-west-trending, fault-bounded trough with sediment sources to the north and northeast. The northern margin of this basin was approximately along the suture zone at the southern margin of the Wyoming province (fig. 2), suggesting reactivation of a pre-existing structural zone. The Big Cottonwood Formation thins abruptly to the north in the Wasatch Range (fig. 2) and is absent north of Salt Lake City, where the Farmington Canyon Complex is overlain directly by Cambrian strata in a Cretaceous thrust

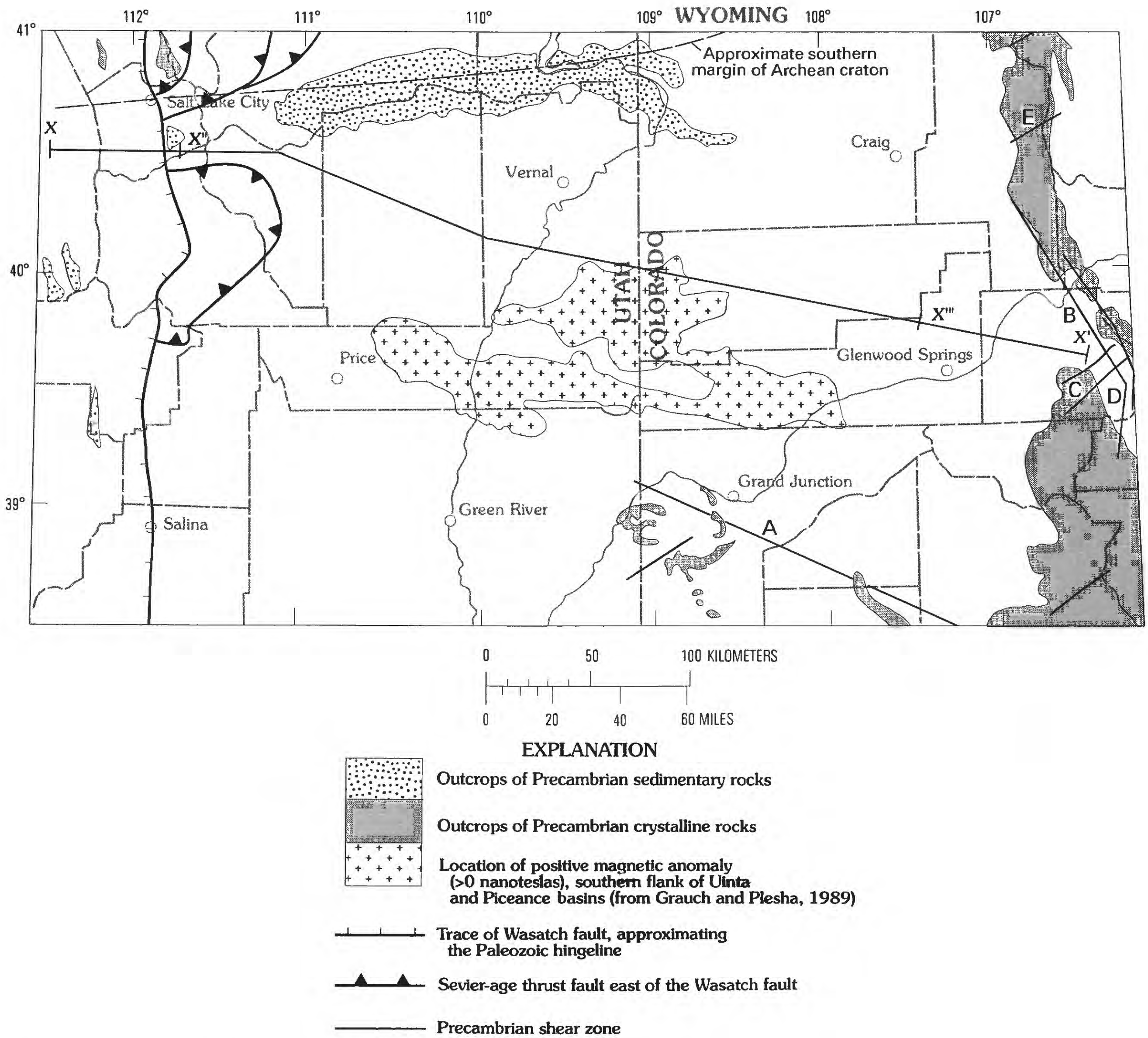


Figure 2. Outcrops of Precambrian rocks and structural features, Uinta-Piceance basin region. Abbreviations for shear zones (Warner, 1978; Tweto, 1987): A, Cimarron–Red Rock fault zone; B, Gore fault zone; C, Homestake shear zone (part of the Colorado lineament); D, Mosquito fault; E, Soda Creek–Fish Creek shear zone. Wasatch fault approximates location of latest Proterozoic to early Paleozoic hingeline. *X–X'* is line of stratigraphic cross section of figures 3, 7, 8, and 11; *X"–X'''* is line of stratigraphic cross section of figure 13.

sheet (fig. 2) (Crittenden and Wallace, 1973; Bruhn and others, 1986; Bryant and Nichols, 1988). Eardley (1939) referred to this area as the northern Utah highland, and Christie-Blick and Levy (1989) suggested that the thinning was depositional.

The southern margin of this inferred east-west-trending early Late Proterozoic sedimentary basin has not been identified. A recent aeromagnetic compilation of the Uinta-Piceance region (Grauch and Plesha, 1989) reveals two large, positive, east-west-trending anomalies in the central Uinta and Piceance basins (fig. 2) that do not correlate with surface geology or known subsurface geology. Accordingly, V.J.S. Grauch (U.S. Geological Survey, 1990, oral commun.) suggested that these east-west anomalies reflect the presence of deeply buried magnetic bodies that could represent the uplifted shoulder on the southern margin of the early Late Proterozoic basin. Less likely, the anomalies could reflect buried Tertiary intrusive bodies similar to the Snowmass pluton in the Elk Mountains west of Aspen (fig. 1) (Mutschler, 1970), on strike with the anomalies to the east. Even if this second hypothesis were true, the continuous trend of this large anomaly must reflect major structural

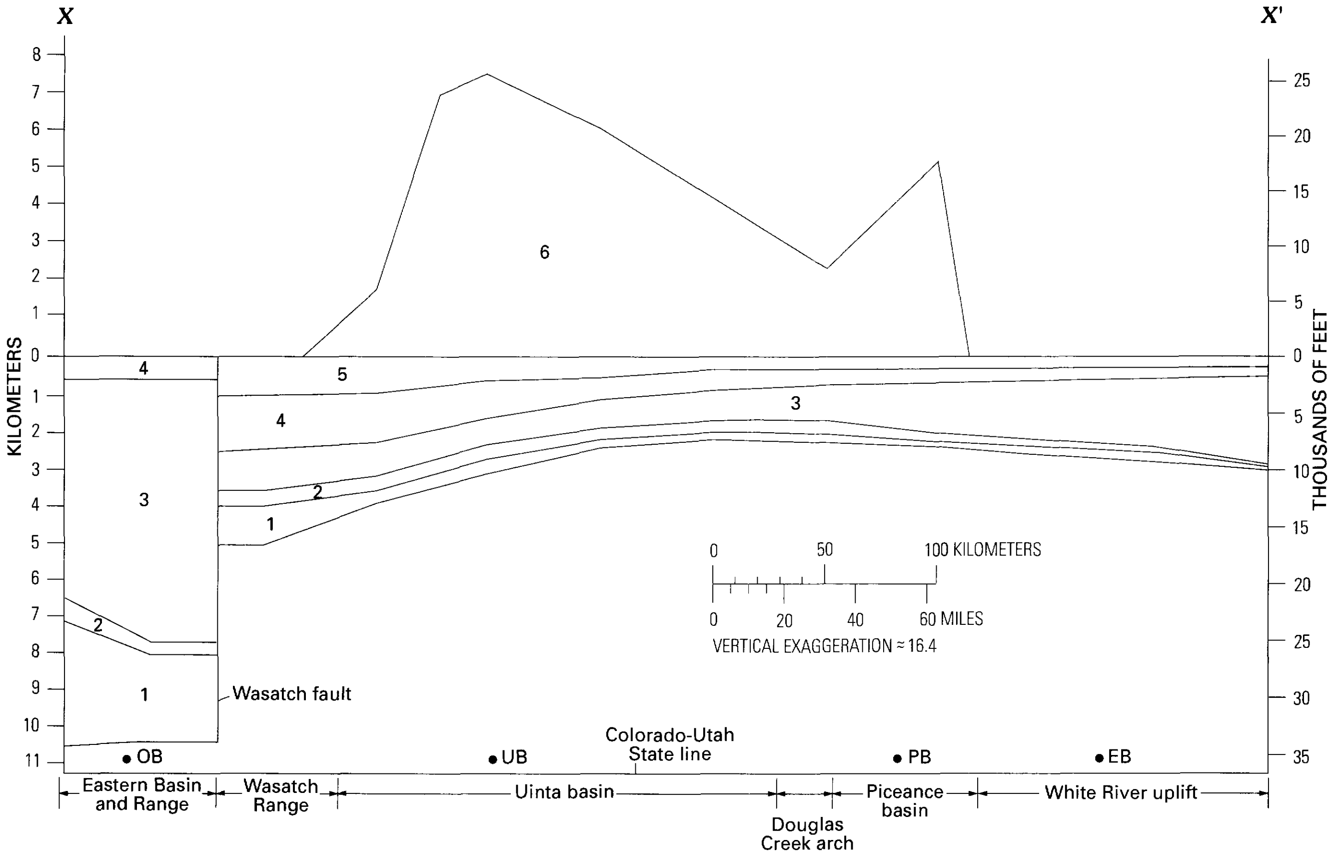


Figure 3. Schematic stratigraphic cross section along line *X–X′* showing thicknesses of Cambrian through Eocene rocks, Uinta-Piceance basin region. Ages of numbered units: (1) Cambrian to Middle Devonian, (2) Late Devonian to early Late Mississippian, (3) mid–Late Mississippian to early Early Permian, (4) late Early Permian to Early Jurassic, (5) Middle Jurassic to early Early Cretaceous, (6) late Early Cretaceous to late Eocene. About 33 km of Neogene extension was subtracted from eastern Basin and Range area (westernmost part of section) following Levy and Christie-Blick (1989, fig. 3A). Thickness data from compilations of S.Y. Johnson and R.C. Johnson (1991) and R.C. Johnson and S.Y. Johnson (1991). Approximate locations of sections used for geohistory analysis of figure 4 are shown along base of diagram (OB, Oquirrh basin; UB, Uinta basin; PB, Piceance basin; EB, Eagle basin). Line of section shown in figure 2.

control in the basement that is probably of Precambrian origin and related to the development of the early Late Proterozoic sedimentary basin. There is no gravity expression of this magnetic anomaly (Abrams and others, 1990).

Late Late Proterozoic Sedimentary Rocks

Late Late Proterozoic strata crop out only in the westernmost part of the Uinta-Piceance basin region, in the Sheeprock Mountains (Sheeprock Group and lower part of Brigham Group) and in the Wasatch Range near Salt Lake City (Mineral Fork Tillite and Mutual Formation) (figs. 1, 2). In these areas, the Precambrian-Cambrian contact is in a sequence of unfossiliferous quartzite, and placement of the boundary is largely a matter of convention (Christie-Blick and Levy, 1989). Late Late Proterozoic strata consist mainly of diamictite, argillite, sandstone, quartzite, conglomerate, and carbonate rocks (for example, Christie-Blick and Levy, 1989). Diamictites and associated strata are of inferred glacial origin and are thought to have been deposited between about 720 and 770 Ma based on correlation with similar rocks to the north in Canada (Armstrong and others, 1982; Evenchick and others, 1984; Devlin and others, 1985). The inferred glacial rocks are widely associated with mafic- to intermediate-composition sills and flows, including some pillow lavas.

Late Late Proterozoic and lower Paleozoic strata record a transition from intracontinental rifting to the formation of a passive continental margin, but the location of the transition in the stratigraphy is controversial (see discussion in Christie-Blick and Levy, 1989). Geologic data (including widespread volcanic rocks) suggest that the main rifting event occurred between 700 and 800 Ma (Stewart, 1972; Stewart and Suczek, 1977; Link, 1984; Link and others, 1987). In contrast, quantitative analysis of tectonic subsidence for Cambrian and Ordovician strata indicates that thermally driven subsidence of the passive margin began after about 590 Ma, in latest Proterozoic or earliest Cambrian time (Armin and Mayer, 1983, 1984; Bond and others, 1983, 1985). Christie-Blick and Levy (1989, p. 19) reconciled the geologic data with the results of subsidence modeling by suggesting that "at least two extensional events took place in the western United States during Late Proterozoic and Early Cambrian time." By the Early Cambrian, the Uinta-Piceance region clearly occupied a position on the cratonic flank of a passive continental margin.

PHANEROZOIC BASIN EVOLUTION

Six phases of basin evolution are recognized in the Uinta-Piceance region: (1) Cambrian through Middle Devonian, (2) Late Devonian through early Late Mississippian, (3) mid-Late Mississippian through early Early Permian, (4) late Early Permian through Early Jurassic, (5) Middle Jurassic through early Early Cretaceous, and (6) late Early Cretaceous through late Eocene. Figure 3 shows approximate thicknesses for these intervals along an east-west line from west-central Utah to central Colorado. Geohistory diagrams for four areas along this line of section are presented in figure 4. Figure 5 summarizes regional depositional and structural events, paleolatitude, and global eustasy.

Cambrian to Middle Devonian (phase one)

For about 200 million years from the Cambrian through the Middle Devonian, the Uinta-Piceance basin region occupied part of the craton and shelf on the eastern margin of the Cordilleran miogeocline. Paleolatitude for the region during this interval ranged from about 5° N. in the Early Cambrian to about 19° S. in the Early Devonian (fig. 5) (Scotese and McKerrow, 1990). A prominent element of the passive continental margin was the Cordilleran hingeline, defined by Hill (1976, p. 6) as "the zone of westward downwarping or flexure of the basement rocks required to accommodate the thick, upper Precambrian to Mesozoic stratigraphic section of the Cordilleran geosyncline." This hingeline extends through the western part of the Uinta-Piceance region and corresponds approximately with the Wasatch fault and the eastern boundary of the Neogene Basin and Range province (fig. 2). The Uinta-Piceance region is east of the $I_{Sr} = 0.706$ isopleth for Mesozoic and Cenozoic igneous rocks (fig. 6) and hence entirely on Precambrian continental crust (Kistler and Peterman, 1978; Elison and others, 1990).

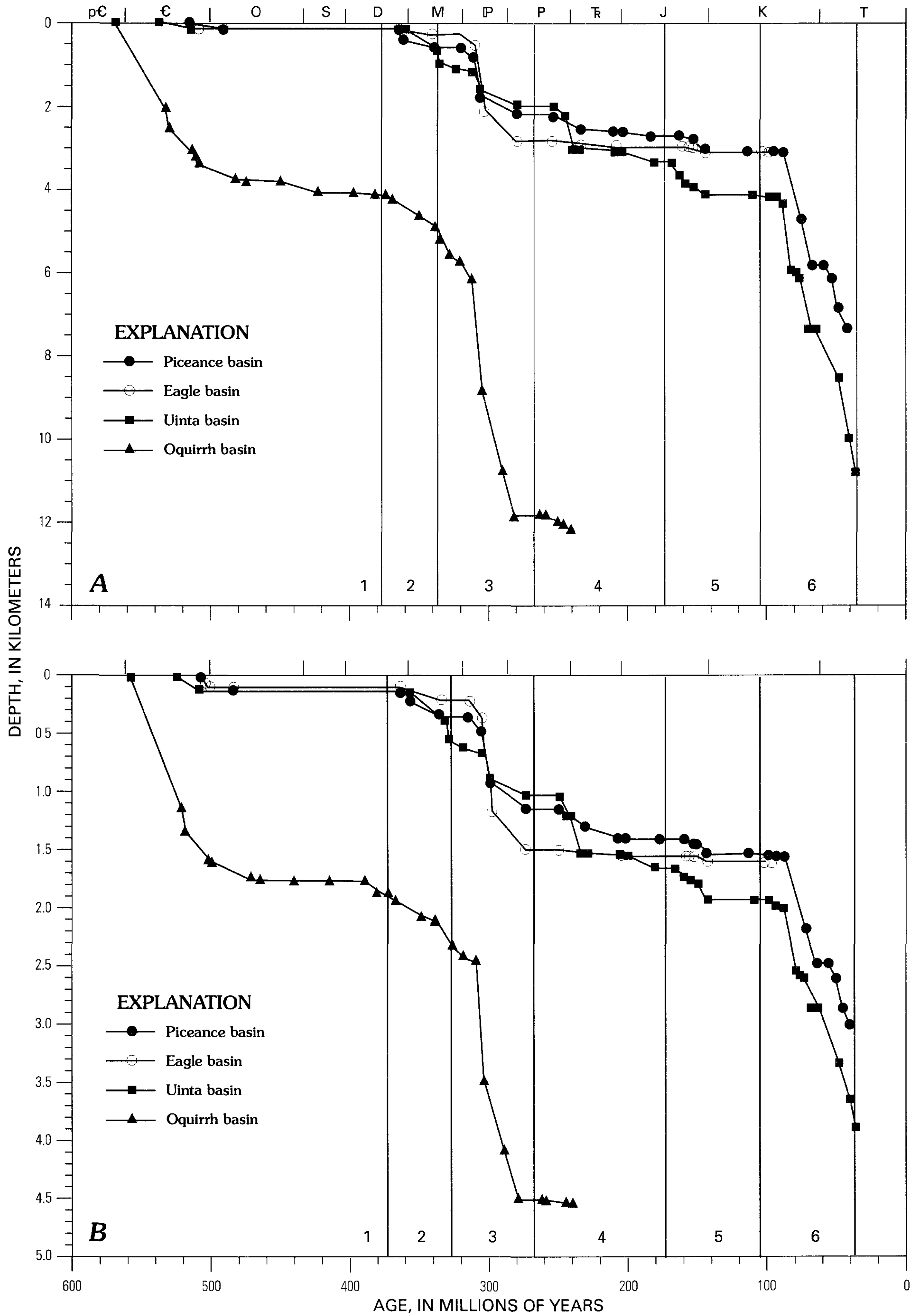
Geohistory analysis (for example, fig. 4, Oquirrh basin) indicates that thermally driven subsidence, characteristic of rifted passive margins, began about 590 Ma (Armin and Mayer, 1983, 1984; Bond and others, 1983, 1985). The presence of volcanic rocks interbedded with the lower part of the Lower and Middle Cambrian Tintic Quartzite in western Utah (Morris and Lovering, 1961; Crittenden and others, 1971) supports Early Cambrian rifting. Subsidence was more continuous and subsidence rates much higher in the hingeline area than they were farther east on the craton (figs. 4, 7). The thickness of Cambrian through Middle Devonian strata ranges from about 3,050 m along the hingeline to less than about 300 m on the White River uplift on the eastern edge of the Uinta-Piceance region (figs. 1, 3, 7).

During the Cambrian, shallow-marine siliciclastic and carbonate strata progressively onlapped Precambrian basement from west to east in the Uinta-Piceance region (fig. 7) (Lochman-Balk, 1972). Lower Cambrian strata are present only in the western part of the region, Middle Cambrian strata onlap the craton to about the Utah-Colorado State line, and Upper Cambrian strata are present across the entire region (fig. 7). Lochman-Balk (1972) described a range of depositional environments, including sandy beach and shelf, sandy and muddy tidal flat, carbonate lagoon, and supratidal to tidal stromatolite reef. Siliciclastic and carbonate sediments dominated nearshore and offshore environments, respectively. Subsidence rates slowed in the Late Cambrian, and westward thickening of Upper Cambrian rocks is notably less pronounced (fig. 7) than for Lower and Middle Cambrian strata. These trends indicate progressive decay of the thermal anomaly associated with rifting and the increased importance of sediment loading as a control on subsidence.

Lower Ordovician strata conformably overlie Upper Cambrian rocks in the hingeline area and in most of the Colorado part of the Uinta-Piceance region (fig. 7) and similarly consist of shallow-marine siliciclastic and carbonate rocks. These strata are absent from the central and eastern Utah parts of the Uinta-Piceance region, where they were probably removed by erosion during a Middle Ordovician regression (Webb, 1958) and eustatic lowstand (fig. 5) (Ross and Ross, 1988).

Upper Ordovician dolomitic rocks of shallow-marine origin locally unconformably overlie Lower Ordovician rocks in the hingeline area, and Upper Ordovician shallow-marine

Figure 4 (facing page). Geohistory diagrams showing subsidence histories of four areas in Uinta-Piceance basin region for the Phanerozoic. Approximate locations of areas shown on figure 3. Numbers (1–6) across bottom of graph refer to phases of basin evolution described in text. *A*, Total subsidence corrected for compaction. *B*, Subsidence of basement corrected for load induced by weight of sediment through time and, thus, inferred amount of tectonic subsidence. Corrections for compaction were based on lithology and follow the exponential porosity function presented by Sclater and Christie (1980). No corrections were made for bathymetry. Because of uncertainties involving ages of units and their compaction-diagenetic histories, the plots should be regarded as approximations. Thickness data for Oquirrh, northern Piceance, and Eagle basins from compilation of S.Y. Johnson and R.C. Johnson (1991); thickness data for Uinta basin from compilation of R.C. Johnson and S.Y. Johnson (1991). Time scale from Harland and others (1990).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sandstone unconformably overlies Lower Ordovician rocks on the eastern part of the White River uplift in Colorado (fig. 7). Ross and Ross (1988) noted a major Late Ordovician eustatic highstand (fig. 5), and Poole and Sandberg (in press) suggested that the North American continent was flooded during the Late Ordovician. Upper Ordovician strata were therefore probably deposited over the entire Uinta-Piceance region and subsequently eroded, perhaps during the regression synchronous with the latest Ordovician eustatic lowstand (fig. 5).

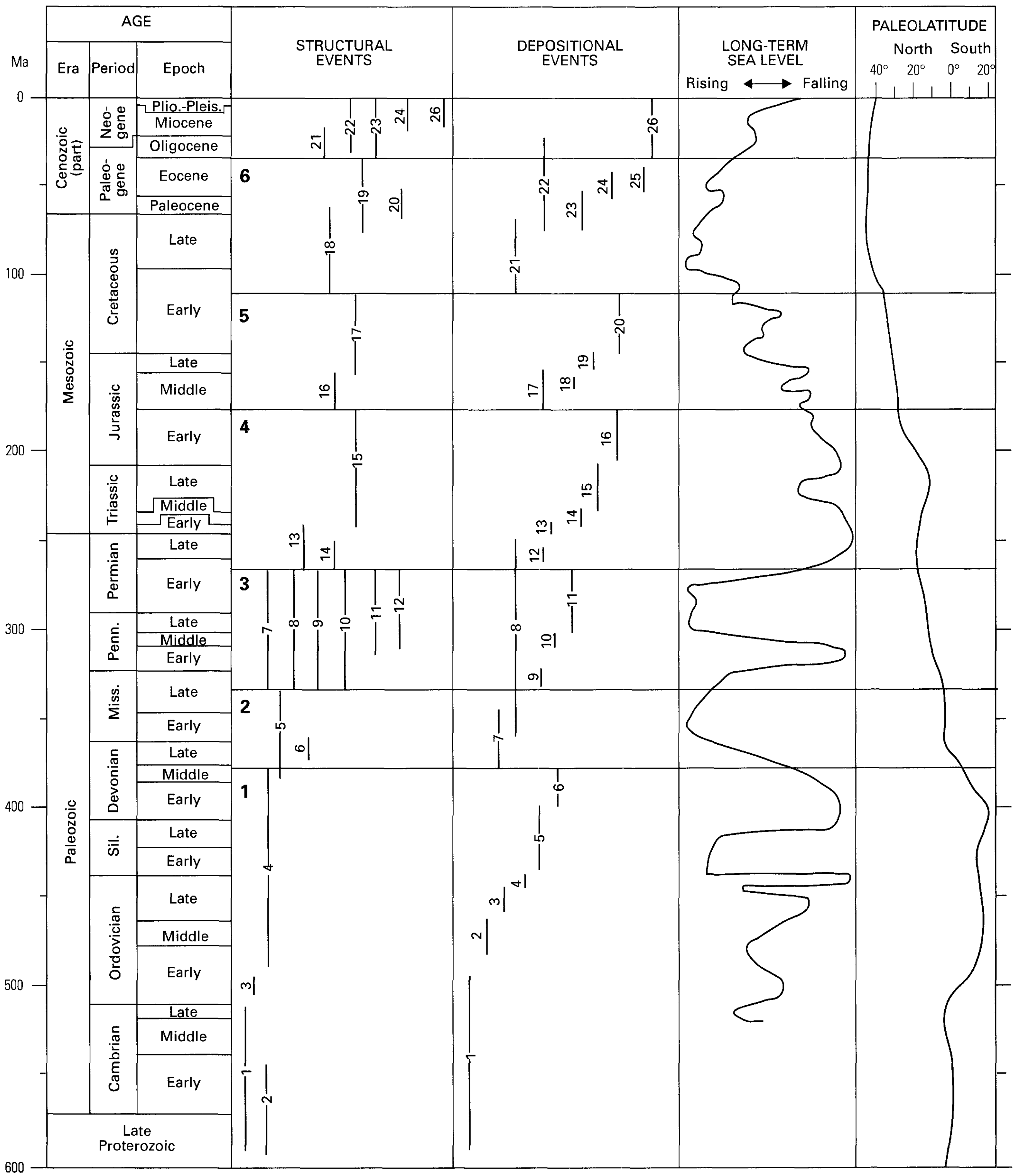
Berry and Boucot (1970) inferred that a Silurian carbonate blanket extended across the entire North American craton, but Silurian stratified rocks (Lower Silurian dolomites) in the Uinta-Piceance region are present only west of the hingeline (fig. 7), where they unconformably overlie Upper Ordovician strata. In Colorado, Silurian rocks are present only as exotic blocks in Devonian kimberlite diatremes in the northern Front Range (Chronic and others, 1969). Lower and Middle Devonian rocks in the Uinta-Piceance region are also present only west of the hingeline, where they unconformably overlie the Lower Silurian dolomites. The original regional distribution of Lower and Middle Devonian deposits is not known, but sea level was low in the Early Devonian (fig. 5) and it is possible that this time interval was characterized by regression and erosion.

Despite its location on the craton adjacent to a passive margin, there is some evidence of early Paleozoic tectonic activity east of the hingeline in the main, cratonic part of the Uinta-Piceance region. Hansen (1986a) and Stone (1986) described late Precambrian or Early Cambrian faulting and tilting of the Uinta Mountain Group in the Uinta Mountain area (figs. 1, 2) and attributed this deformation to reactivation of structures associated with the east-west structural trough in which the Uinta Mountain Group was deposited.

Figure 5 (facing page). Summary of inferred structural and depositional events that affected the Uinta-Piceance basin region. Large numbers (1–6) refer to phases of basin evolution described in text. Key for structural events: 1, rifting and development of passive continental margin of western North America; 2, faulting and folding of Uinta Mountain Group; 3, intrusion of mafic dikes in Cimarron–Red Rocks fault zone; 4, gentle warping of pre-Upper Devonian rocks in northwestern Colorado; 5, development of Antler orogenic belt in eastern Nevada and associated downflexing-subsidence of the Antler foreland basin; 6, minor uplift of Front Range (?); 7, development of transtensional(?) Humboldt orogeny in the western United States; 8, development of Marathon-Ouachita orogenic belt in the southeastern United States; 9, reactivation of structures along Uinta Mountain trend; 10, subsidence of Oquirrh basin as a discrete tectonic element; 11, uplift of ancestral Front Range and Sawatch uplifts and subsidence of Eagle basin; 12, uplift of Uncompahgre uplift and subsidence of Paradox basin; 13, development of Sonoma orogenic belt in Nevada and inferred associated downflexing-subsidence of foreland basin in eastern Nevada and western Utah; 14, minor activity on structures along Uinta Mountain trend; 15, relative tectonic quiescence; 16, development of Middle Jurassic orogenic belt in eastern Nevada and western Utah and inferred associated downflexing-subsidence of linked foreland basin in west-central Utah; 17, relative tectonic quiescence; 18, development of Sevier orogenic belt in western Utah and associated downflexing-subsidence of linked foreland basin to the east; 19, development of Laramide uplifts cored by crystalline basement and subsidence of large intermontane basins between Laramide structures; 20, development of small intermontane basins on thrust sheets; 21, back-arc extension, magmatism, and development of metamorphic core complexes in central and western Utah; 22, extensional deformation along Uinta Mountain trend; 23, sporadic magmatism in western Colorado, possibly associated with Rio Grande rift; 24, development of Basin and Range province in Nevada and western Utah, characterized by extensional deformation and bimodal magmatism; 25, regional uplift. Key for depositional events: 1, eastward onlapping of mainly clastic (nearshore) and carbonate rocks (offshore); 2, regional regression accompanied by erosion; 3, regional deposition of shallow-marine clastic and carbonate rocks; 4, regional regression accompanied by erosion; 5, regional deposition of shallow-marine carbonate rocks; 6, regional regression accompanied by erosion in main part of Uinta-Piceance region, deposition of shallow-marine deposits west of hingeline; 7, widespread, shallow-marine deposition punctuated by numerous transgressions and regressions; 8, Gondwana continental glaciation characterized by repetitive cyclic global eustatic and climate fluctuations, which, in the Uinta-Piceance basin region, led to repetitive transgressions and regressions and deposition of stacked depositional cycles; 9, deposition of Humbug deltaic complex on Wyoming shelf; 10, evaporite deposition in Eagle and Paradox basins; 11, eolianite deposition prominent on Wyoming shelf and in Eagle basin; 12, deposition of phosphatic rocks in western Uinta-Piceance region; 13, deposition of marine and nonmarine fine-grained siliciclastic rocks in eastern and western Uinta-Piceance region, respectively; 14, emergence of Uinta-Piceance region; 15, regional deposition of fine-grained nonmarine sediments; 16, regional deposition of eolianite; 17, deposition, from west to east, of evaporite and mudstone, limestone, and shallow-marine siliciclastic rocks in inferred foreland basin; 18, widespread deposition of eolianite in the eastern Uinta-Piceance region; 19, widespread alluvial deposition; 20, nondeposition and (or) minimal deposition and erosion; 21, multiple eustatic- and tectonic-controlled transgressions and regressions in Cretaceous foreland basin on margin of the Western Interior seaway; 22, formation and maintenance of internally drained depositional systems, episodic tectonism resulting in multiple basin-margin unconformities; 23, deposition in numerous shallow lakes; 24, deposition in large lakes dominant; 25, deposition of saline deposits and oil shale in closed lacustrine basins; 26, deposition of alluvial, volcaniclastic, and volcanic rocks in local basins. Late Cretaceous and Paleogene events modified from a similar chart in Franczyk and others (in press). Long-term sea-level curves (curves that do not show high-frequency fluctuations) from Ross and Ross (1988) for the Paleozoic and from Haq and others (1988) for the Mesozoic and Cenozoic, modified to time scale of Harland and others (1990). In compiling sea-level curve, it was assumed that magnitude of long-term changes shown by Haq and others (1988) for the Mesozoic and Cenozoic also applies to the Paleozoic. Paleolatitude compiled from Scotese (1987) and Scotese and McKerrow (1990).

Larson and others (1985) documented Early Ordovician (about 497 Ma) intrusion of a swarm of at least 50 northwest-trending mafic dikes in the southeastern Uinta-Piceance region and suggested that the dikes formed along a zone of Precambrian origin (the Cimarron–Red Rock fault zone of fig. 2). Tweto (1980) noted that Upper Devonian rocks in western Colorado overlie various Ordovician, Cambrian, or Precambrian units, indicating considerable pre–Late Devonian warping. As noted above, Chronic and others (1969) described Devonian kimberlite diatremes from the northern Colorado Front Range.

Summarizing, the Uinta-Piceance region occupied the Cordilleran hingeline and inboard cratonic parts of a passive continental margin from the Cambrian through the Middle



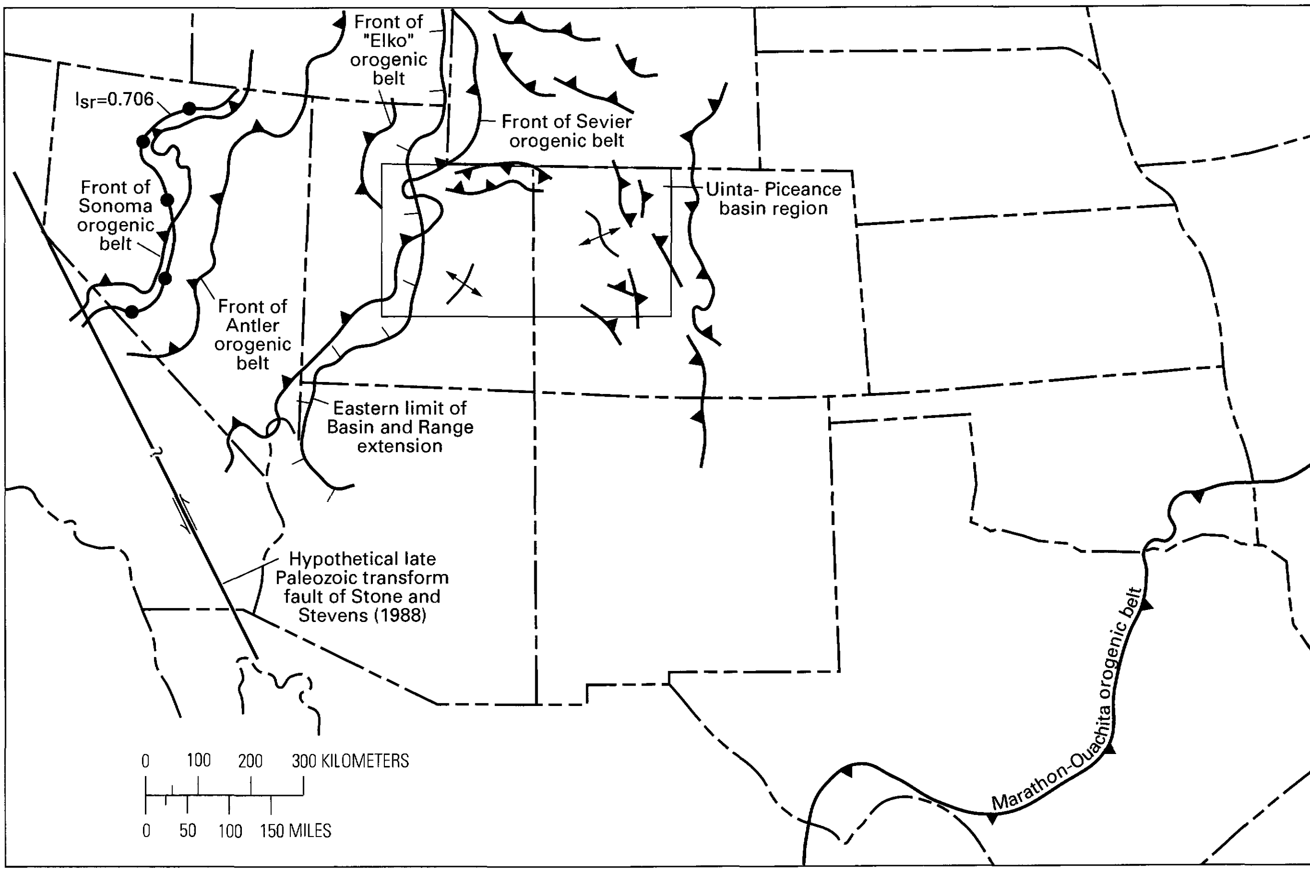


Figure 6. Selected regional tectonic features in the southwestern United States that affected Phanerozoic deposition in Uinta-Piceance basin region. Faults and folds east of front of Sevier orogenic belt are assigned to Laramide orogeny. Front of Middle Jurassic "Elko" thrust belt adapted from Allmendinger and Jordan (1981) and Thorman and others (1991). Compiled from Cross (1986), Hamilton (1988), Poole and Sandberg (1991), and Johnson and others (in press).

Devonian. Strata are thickest along the hingeline, in the westernmost part of the region. Subsidence rates were highest during the synrifting phase of basin evolution in the Early and Middle Cambrian. Regional unconformities probably reflect both (1) transgressions and regressions associated with eustatic fluctuations and (2) epeirogenic movements on the craton. Some of this cratonic epeirogenic movement represents reactivation of Precambrian structural trends.

Late Devonian to Earliest Late Mississippian (phase two)

The passive margin, miogeoclinal phase of evolution of the western United States ended in the Late Devonian with the onset of the Antler orogeny. The nature of the Antler orogeny is somewhat controversial, but the orogeny is commonly thought to involve an arc-continent collision or back-arc thrusting in an overall convergent setting (for example, Nilsen and Stewart, 1980; Speed and Sleep, 1982; Dickinson and others, 1983; Miller and others, 1984; Speed and others, 1988; Burchfiel and Royden, 1991). Eastward emplacement of the Roberts Mountain allochthon thickened the crust and downflexed the pre-existing Paleozoic shelf to the east into a foreland basin (Poole, 1974; Poole and Sandberg, 1977; Speed and Sleep, 1982; Goebel, 1991). Goebel (1991) suggested that the thrust belt of the Antler belt migrated eastward about 250 km during the orogeny. When restored for Neogene extension following Levy and Christie-Blick (1989), the eastern flank of the Antler orogenic highland in northern Nevada was about 240 km west of the western boundary of the Uinta-Piceance region (figs. 1, 6).

The development of the Antler orogenic belt to the west resulted in an increase in subsidence rate and a change in depositional patterns in the westernmost part of the Uinta-Piceance region, and the orogenic belt was coincident with and probably partly controlled a period of submergence and subsidence in the more stable central and eastern parts of the region (fig. 4). Numerous cratonic basins in North America were reactivated at this time, leading Kominz and Bond (1991) to suggest that their subsidence histories were controlled by a pulse of intraplate compressive stress recording the onset of accretion of the Pangea supercontinent.

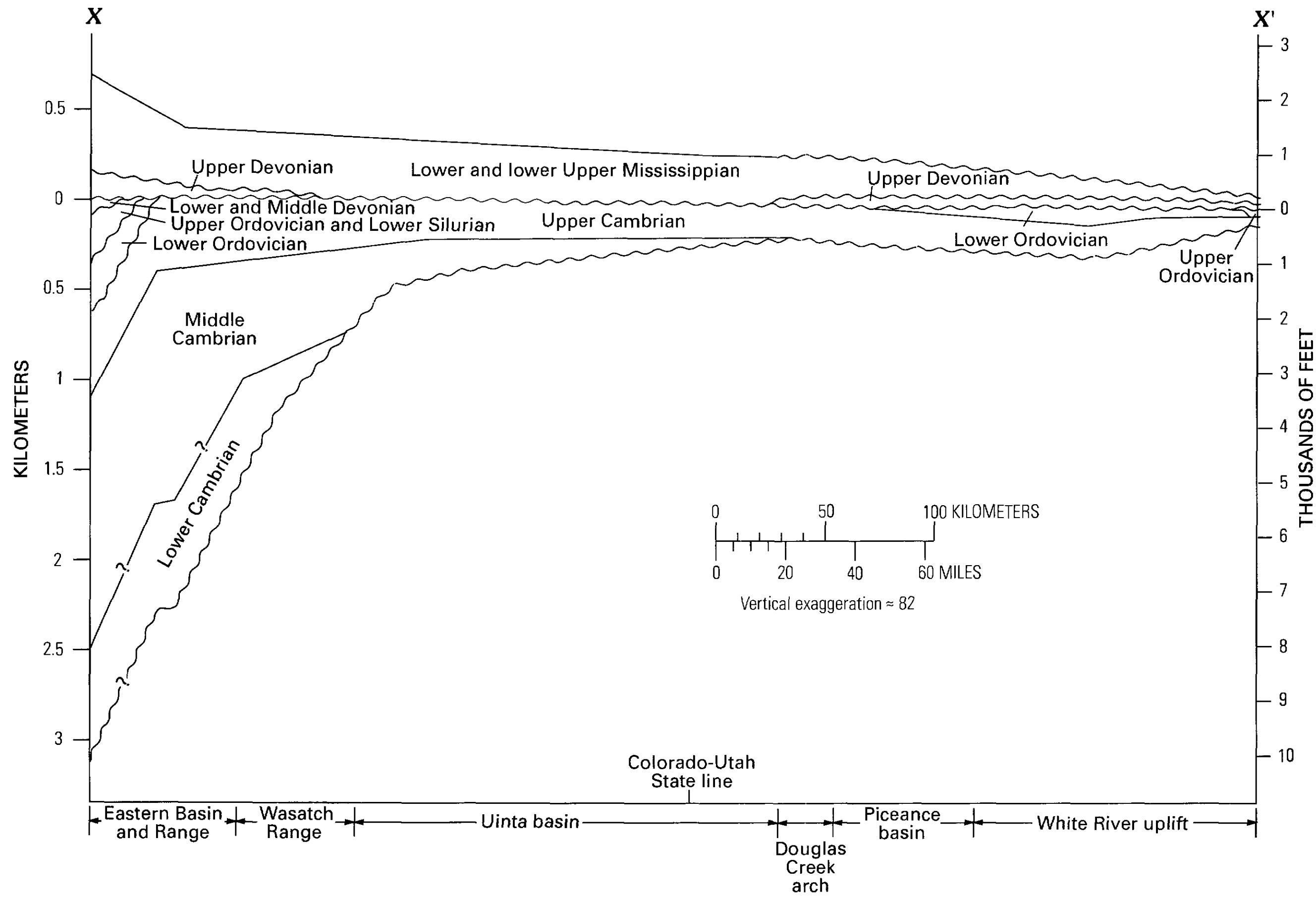


Figure 7. Schematic stratigraphic cross section along line *X–X′* showing Cambrian through lower Upper Mississippian rocks in Uinta-Piceance region. Datum is boundary between rocks deposited during phases one and two of Phanerozoic basin evolution as discussed in the text. About 33 km of Neogene extension was subtracted from eastern Basin and Range area (westernmost part of section) following Levy and Christie-Blick (1989, fig. 3A). Thickness data from compilations of S.Y. Johnson and R.C. Johnson (1991) and R.C. Johnson and S.Y. Johnson (1991). Thickness of Tintic Quartzite in west-central Utah was arbitrarily divided between the Lower and Middle Cambrian. Wavy lines indicate unconformities. Line of section shown in figure 2.

There are many published isopach maps and paleogeographic maps for strata of Late Devonian through earliest Late Mississippian age in all or parts of the Uinta-Piceance region (for example, Baars, 1972; Craig, 1972; Rose, 1976; Poole and others, 1977; Mallory, 1979; Skipp, 1979; Welsh and Bissell, 1979; DeVoto, 1980a; Gutschick and others, 1980; Sandberg and others, 1982). Approximate thicknesses are shown in figure 7. The Uinta-Piceance region migrated northward during this interval from a paleolatitude of about 3° S. to about 4° N. Johnson and others (1985, 1991) showed that sea level in the Late Devonian was rising, relatively high (fig. 5), and characterized by several minor fluctuations. Sea level dropped slightly during the Mississippian and was punctuated by about 20 fluctuations with inferred magnitudes of as much as 100–200 m (Ross and Ross, 1987, 1988).

Antler tectonic activity began in the latest Devonian (Johnson and Pendergast, 1981; Dickinson and others, 1983; Miller and others, 1984; Murphy and others, 1984). Disruption of miogeoclinal depositional patterns in the western part of the Uinta-Piceance region was coincident with this early Antler activity. Uplift led to development of an unconformity that beveled down to Lower Cambrian strata in the Stansbury Mountains (fig. 1) (Rigby, 1959; Morris and Lovering, 1961). Goebel (1991) suggested that this uplift was part of the flexural bulge or "forebulge" of the Antler foreland basin and that it provided the source terrane for local coarse conglomerate and sandstone deposited in the "back-bulge basin" to the east.

Although sea level was generally rising, the central and eastern parts of the Uinta-Piceance region (fig. 1) were emergent during most of the Late Devonian (Sandberg and others, 1982; Johnson and others, 1991). The seas transgressed into the eastern part of the region only during the latest Devonian (late Famennian, event 11 of Sandberg and others, 1982), when shallow-marine siliciclastic and carbonate sediments were deposited in northwestern Colorado (Campbell, 1972; Tweto and Lovering, 1977). Sedimentologic data suggest that the siliciclastic sediments may have had eastern sources in a low-relief highland approximating the present-day location of the Front Range (fig. 1) (Campbell, 1972). Upper Famennian correlatives were probably deposited across the Uinta-Piceance region (Sandberg and others, 1982, fig. 11) but were eroded during a short-term regression at the end of the Devonian (event 12 of Sandberg and others, 1982).

Antler orogenic activity accelerated in the Early Mississippian, when the Roberts Mountain allochthon was emplaced and the adjacent foreland basin deepened (Harbaugh and Dickinson, 1981; Johnson and Pendergast, 1981; Sandberg and others, 1982; Goebel, 1991; Poole and Sandberg, 1991). Coincident with this acceleration, subsidence rates increased in the hingeline area of the Uinta-Piceance region (fig. 4). This area was apparently separated from the deepest part of the foreland basin (to the west) by a submarine rise (Poole, 1974; Sandberg and others, 1982) and did not receive clastic detritus from the Antler highland. Goebel (1991) suggested that this submarine rise was a forebulge and described the effects on depositional patterns of its eastern migration (linked to the advance of the Roberts Mountain allochthon) through Early Mississippian time. Carbonate facies in the hingeline area are predominantly shallow marine, but there is controversy surrounding the origin of interbedded phosphatic rocks and the location of the Early Mississippian shelf margin. Poole and Sandberg (1977), Sandberg and Gutschick (1980), and Sandberg and others (1982, 1991) suggested that the phosphatic rocks were deposited in the "Deseret starved basin" at depths of about 300 m and that the shelf edge at the eastern margin of the basin was near the present-day front of the Sevier thrust belt in west-central Utah (western Uinta-Piceance region) (fig. 6). In contrast, Nichols and Silberling (1990, 1991 a, b) and Silberling and Nichols (1991) contended that the phosphatic rocks were deposited in shallow, anoxic bottom water resulting from incursion far onto the Mississippian shelf of nutrient-rich, organically productive water associated with upwelling in the Antler foreland basin. This interpretation places the Early Mississippian shelf margin well west of the Uinta-Piceance region. Neither analysis includes significant discussion of the effects that repeated eustatic fluctuations (Ross and Ross, 1987, 1988) may have had on depositional patterns.

Increased subsidence in the Early Mississippian in northeastern Utah and northwestern Colorado (fig. 10) led to submergence and deposition of platform carbonate rocks. Deposition was episodic and platform deposits contain numerous disconformities and karst erosion surfaces (DeVoto, 1980a; Gutschick and others, 1980; Poole and Sandberg, 1991) probably related to major, short-term, sea-level fluctuations (Ross and Ross, 1987, 1988). DeVoto (1980a) suggested that minor tectonic activity occurred in the Front Range, Sawatch Mountains, and White River Plateau areas (fig. 1) during the Mississippian, but much of his evidence could also be explained by short-term sea-level fluctuations.

Summarizing, accelerating subsidence rates in the Uinta-Piceance region during the Late Devonian and Early to early Late Mississippian were mainly a response to deformation in the Antler orogenic belt on the continental margin to the west. Most of the Uinta-Piceance region was a periodically emergent carbonate shelf during this interval. Sea-level fluctuations had major effects on patterns of regional deposition and erosion.

Mid-Late Mississippian to Early Early Permian (phase three)

The Late Proterozoic through early Late Mississippian, east to west, shelf to hingeline configuration of the Uinta-Piceance region (figs. 3, 7) was broken apart in the mid-Late Mississippian to Early Permian (mid-Meramecian to mid-Wolfcampian). This segmentation (figs. 8, 9) resulted from a complex mix of contractional, extensional, and strike-slip(?) deformation that was driven by the overlapping influences of interactions along continental margins to the west and southeast (Kluth, 1986; Smith and Miller, 1990; Johnson and others, in press).

West of the Uinta-Piceance region, the convergence associated with the Antler orogeny ended in the early Late Mississippian. The Antler orogenic belt was a highland until the Early Pennsylvanian, but mid-Late Mississippian erosion of this highland and associated filling of the Antler foreland basin is considered postorogenic (Sandberg and others, 1982; Dickinson and others, 1983; Goebel, 1991). Antler shortening in the Great Basin gave way to a complex, heterogeneous (temporally and regionally) tectonic style characterized by local uplift, subsidence, and volcanism (Ketner, 1977; Miller and others, 1984; Stone and Stevens, 1988; Smith and Miller, 1990; Trexler and others, 1991) that is most consistent with a regional strike-slip setting. Ketner (1977) described this late Paleozoic structural style and named the protracted deformational event the "Humboldt orogeny," a designation used here. Ketner (1977) suggested that this period of heterogeneous deformation began in the Middle Pennsylvanian, but more recent work (see above) suggests that the Humboldt-style deformation probably started in the Late Mississippian and peaked in the Middle Pennsylvanian (K.E. Ketner, U.S. Geological Survey, 1991, oral commun.).

During the late Paleozoic, the southeastern margin of the United States was characterized by convergence of North America (part of the Laurasian plate) and South America (part of Gondwana), which resulted in the Marathon and Ouachita fold and thrust belts (see references in Kluth, 1986). Kluth and Coney (1981) and Kluth (1986) argued that this plate collision resulted in deformation that was localized

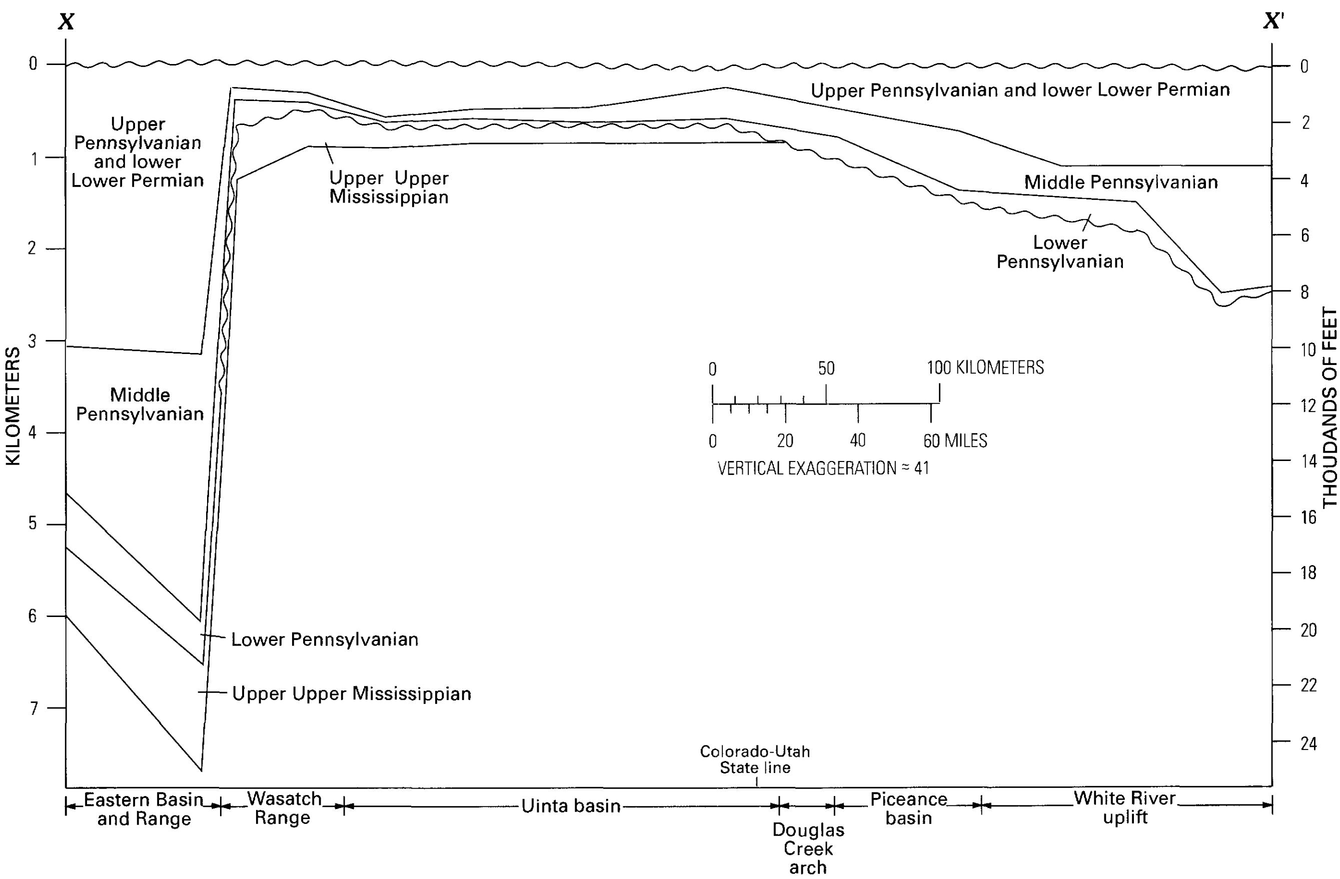


Figure 8. Schematic stratigraphic cross section along line *X–X'* showing upper Upper Mississippian through lower Lower Permian rocks in Uinta-Piceance basin region. About 33 km of Neogene extension was subtracted from eastern Basin and Range area (westernmost part of section) following Levy and Christie-Blick (1989, fig. 3A). Thickness data from compilations of S.Y. Johnson and R.C. Johnson (1991) and R.C. Johnson and S.Y. Johnson (1991). In constructing diagram, (1) half of Manning Canyon Shale in west-central Utah was assigned to the Upper Mississippian and half to the Lower Pennsylvanian, (2) one-third of Weber Sandstone in western Uinta Mountains and Wasatch Mountains was assigned to the Middle Pennsylvanian and two-thirds to the Upper Pennsylvanian and Lower Permian, and (3) half of Morgan Formation in eastern Uinta Mountains was assigned to the Lower Pennsylvanian and half to the Middle Pennsylvanian. Wavy lines indicate unconformities. Line of section shown in figure 2.

on pre-existing zones of structural weakness within the North American interior. Kluth suggested that this foreland deformation is analogous to intraplate deformation in Asia associated with its Cenozoic collision with India (Molnar and Tapponier, 1975).

The late Paleozoic foreland uplifts in the Uinta-Piceance and adjacent regions have been termed the "ancestral Rocky Mountains" (for example, Mallory, 1972; Kluth, 1976). Basement-cored uplifts in this province extend across an area from Oklahoma to Montana. Uplifts in the Uinta-Piceance region include the Front Range, Sawatch, and Uncompahgre (fig. 9). These uplifts had considerable structural and topographic relief and were bounded by narrow fault zones. The Gore fault on the western flank of the Front Range is now locally a reverse fault but could have been either an oblique-slip fault, a normal fault, or a reverse fault in the late Paleozoic (DeVoto and others, 1986; Johnson and others, in press). Numerous intrabasinal faults (with inferred normal, reverse, and oblique-slip displacement) were also active in the Eagle basin during the late Paleozoic (for example, Stone, 1977, 1986; DeVoto, 1980b; Waechter and Johnson, 1985, 1986; DeVoto and others, 1986; Dodge and Bartleson, 1986; Johnson and others, 1988, 1990).

The Uncompahgre uplift is bounded on the north by the Garmesa fault zone on which late Paleozoic oblique-slip or reverse displacement has been postulated (Stone, 1977; Heyman and others, 1986). This uplift is bounded on the south by the Uncompahgre fault, a reverse fault that has at least 9.7 km of late Paleozoic horizontal displacement (Frahme and Vaughan, 1983; White and Jacobson, 1983). The Emery uplift of central Utah (fig. 9) was mostly a neutral area, characterized by minimal positive or negative relief, and may in part represent a flexural forebulge linked to overthrusting of the Uncompahgre uplift (Johnson and others, in press).

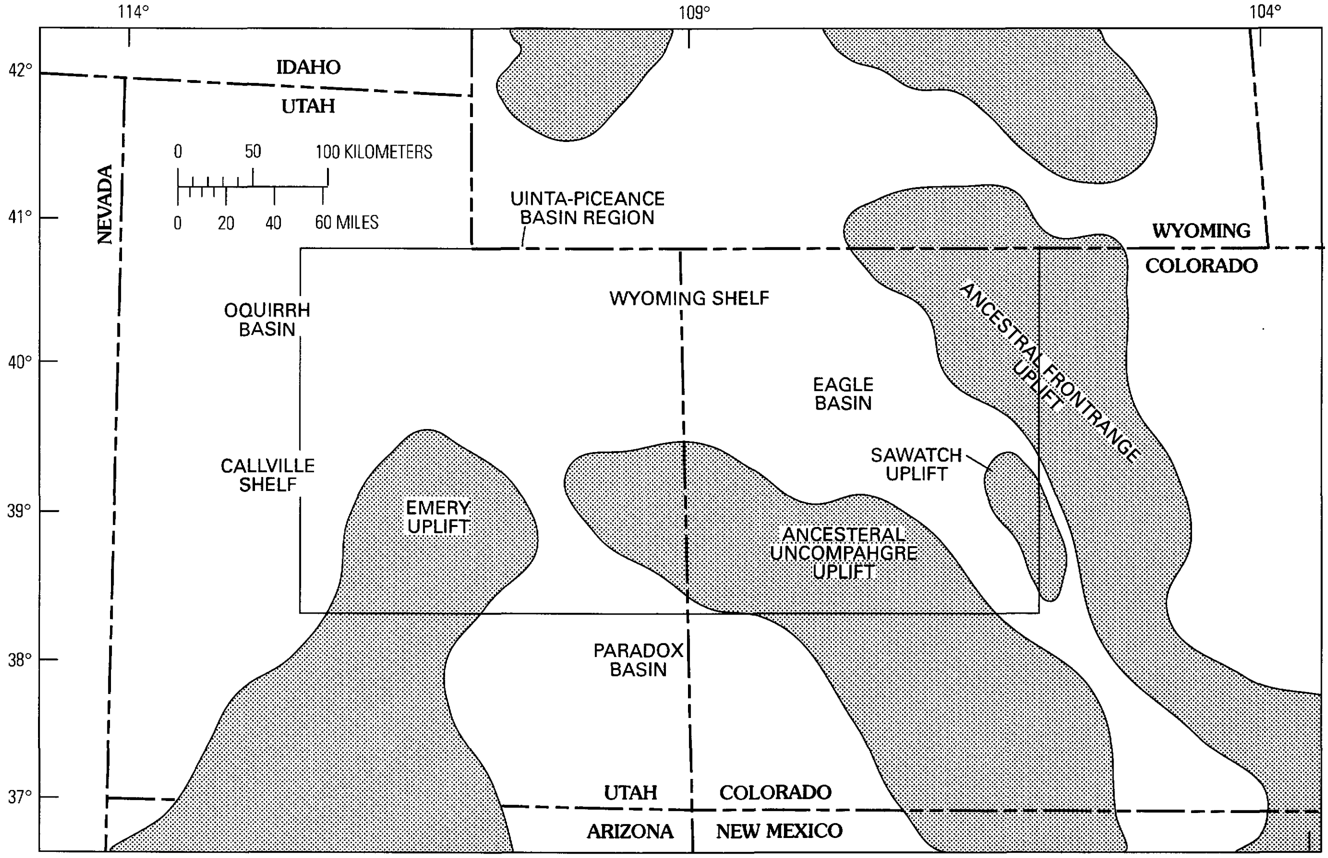


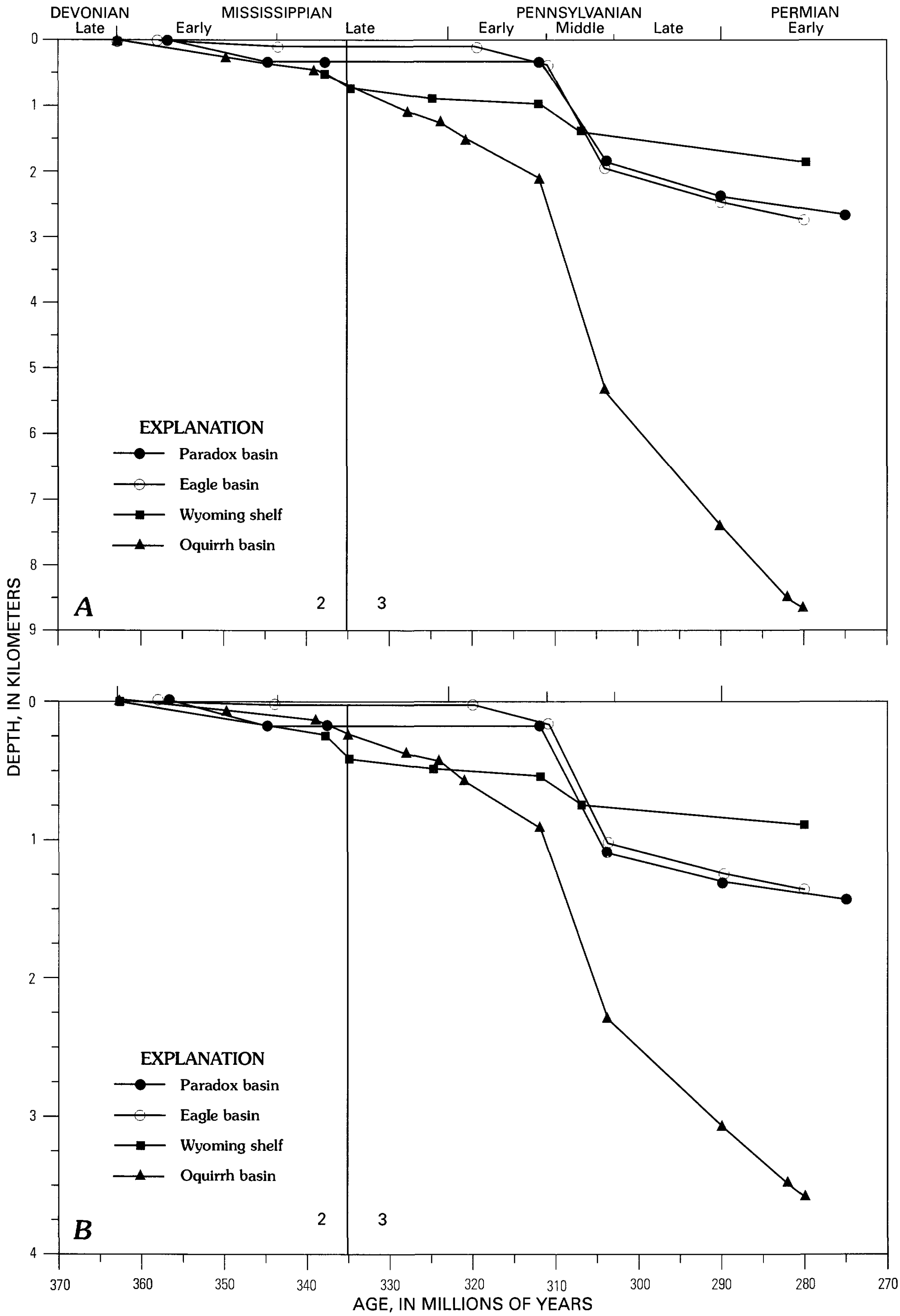
Figure 9. Late Paleozoic uplifts (shaded) and basins of Uinta-Piceance basin region.

Steep, northeast-directed reverse faults on the northeastern flank of the Emery uplift (Potter and others, 1991) are not typical forebulge features and suggest a complex, polygenetic origin for this structural and topographic element. The subsidence history of the northern Paradox basin closely resembles that of the Eagle basin, in that subsidence could reflect crustal loading and flexure, or oblique rifting (Johnson and others, in press).

Late Mississippian to Early Permian subsiding areas in the Uinta-Piceance region include the Eagle, the northern Paradox, and the southeastern Oquirrh basins, the southern Wyoming shelf, and the eastern Callville shelf (fig. 9) (Johnson and others, in press). Isopach maps showing the thickness of Upper Mississippian to Lower Permian deposits in the Uinta-Piceance region are in Brill (1963), Craig (1972), Mallory (1972, 1975), Rascoe and Baars (1972), and DeVoto and others (1 986). Thicknesses on an east-west transect are shown in figure 8. Geohistory diagrams (fig. 10) illustrate basin subsidence histories.

Subsidence rates were highest in the Oquirrh basin, a local feature of probable extensional origin. Faults bounding the Oquirrh basin are apparently masked by younger structural features and sedimentary rocks and have not been positively recognized. Picha (1986) suggested, however, that the Leamington lineament represents the southern boundary of the Oquirrh basin, and Jordan and Douglas (1980) and Bryant and Nichols (1988) noted that the "Oquirrh-Uinta arch" (the western continuation of the Uinta Mountain trend, equivalent to the northern Utah highland of Eardley, 1939) defined the northern margin of the deepest part of the basin. Isopach maps in Poole (1974), Poole and Sandberg (1977), and Skipp (1979) indicate that the Oquirrh basin began to

Figure 10 (facing page). Geohistory diagrams showing subsidence histories of four areas in the Uinta-Piceance basin region for the Mississippian to early Early Permian. Approximate locations of areas shown in figure 9. *A*, Total subsidence corrected for compaction. *B*, Subsidence of basement corrected for load induced by weight of sediment through time and, thus, inferred amount of tectonic subsidence. Corrections for compaction were based on lithology and follow exponential porosity function presented by Sclater and Christie (1980). No corrections were made for bathymetry. Because of uncertainties involving ages of units and their compaction-diagenetic histories, the plots should be regarded as approximations. Thickness data for Oquirrh basin, Wyoming shelf, and Eagle basin are from compilations of S.Y. Johnson and R.C. Johnson (1991) and R.C. Johnson and S.Y. Johnson (1991). Thickness data for Paradox basin are from the Jay Roberts No. 1 Whitecloud borehole (sec. 34, T. 22 S., R. 17 E.; see Johnson and others, in press). Time scale from Harland and others (1990).


DEVONIAN
MISSISSIPPIAN
PENNSYLVANIAN
PERMIAN
Late
Early
Late
Early
Middle
Late
Early
EXPLANATION
Paradox basin
Eagle basin
Wyoming shelf
Oquirrh basin
A
B
2
3
DEPTH, IN KILOMETERS
AGE, IN MILLIONS OF YEARS
370
360
350
340
330
320
310
300
290
280
270

subside as a discrete tectonic element in the mid–Late Mississippian.

Mid- and upper–Upper Mississippian strata were either deposited in or preserved in an east-trending structural trough approximating the Uinta Mountain trend on the Wyoming shelf. Hansen (1986a, fig. 10) documented an east-trending axis of maximum late Paleozoic subsidence on the southern Wyoming shelf that also corresponds with the trend of the Uinta Mountains and reflects reactivation of structures associated with the Precambrian Uinta Mountain trough.

Sedimentation in the Uinta-Piceance region during the mid–Late Mississippian to early Early Permian was strongly affected by short-term cyclic eustatic and climatic changes thought to be synchronous with expansions and contractions of continental ice sheets (Johnson and others, in press). Ross and Ross (1987, 1988) and Ross (1991) suggested that about 68 sea-level fluctuations occurred during this part of the late Paleozoic with amplitudes from a few tens of meters to as much as 200 m. Eustatic fluctuations were superimposed on an overall trend in which sea level fell markedly from the Late Mississippian to the Early Pennsylvanian, rose gradually through the Middle Pennsylvanian, and stayed at high levels in the Late Pennsylvanian and Early Permian (fig. 5). Estimates of cycle periodicity range from about 400,000 years to as much as 1–2 million years (Driese and Dott, 1984; Heckel, 1986; Ross and Ross, 1987, 1988). Johnson and others (in press) documented the cyclic changes in depositional patterns associated with the eustatic and climatic changes in the Uinta-Piceance region. Paleolatitude for the Uinta-Piceance region during this interval ranged from about 4° N. in the Late Mississippian to 15° N. in the Early Permian (fig. 4) (Scotese and McKerrow, 1990). The presence of regionally significant eolianite and evaporite deposits indicates that climate (although variable) was generally arid.

Middle and upper Upper Mississippian (mid-Meramecian to Chesterian) strata in the Uinta-Piceance region include a thick sequence of shallow-water carbonate and minor siliciclastic rocks in the Oquirrh basin and fluvial, deltaic, and marginal-marine siliciclastic and carbonate rocks on the Wyoming shelf in northeastern Utah (the "Humbug deltaic complex" of Sandberg and others, 1982). The Humbug deltaic complex filled a large coastal embayment (the structural trough described above) with locally derived sediment (Mallory, 1979; Sandberg and others, 1982). Strata of this age may have been deposited over a larger area and subsequently eroded during a prolonged period of low sea level in the Early Pennsylvanian (Ross and Ross, 1987, 1988).

Lower to lower Middle Pennsylvanian (Morrowan to lower Atokan) strata in most of the Uinta-Piceance region consist of alternating fine-grained siliciclastic rocks (inferred regressive deposits) and more abundant limestone (transgressive deposits) (Johnson and others, in press). In the Eagle basin, late Morrowan(?) uplift of the ancestral Front Range and Sawatch uplifts created sediment sources for local deltaic deposits (DeVoto and others, 1986). Subsidence in the Paradox basin had not yet begun, and the area including and between the Emery and Uncompahgre uplifts apparently formed a low-relief emergent area, the "Molas platform" of Johnson and others (in press).

Increased tectonic activity during the middle and late Middle Pennsylvanian (late Atokan and Desmoinesian) in the Uinta-Piceance region is reflected in higher rates of basin subsidence in the four main depositional provinces (fig. 10) and in the continued or initial uplift and unroofing of the Front Range, Sawatch, and Uncompahgre uplifts (Johnson and others, in press). The combined effects of tectonic activity and eustatic-climatic fluctuations led to restricted circulation in the Eagle and Paradox basins during regressions, resulting in significant evaporite deposition (for example, Wengerd and Matheny, 1958; Hite and Buckner, 1981; Schenk, 1989). Regressive deposition was also characterized by significant south-southwesterly progradation of eolian sands across the Wyoming shelf into the Oquirrh basin (Konopka and Dott, 1982). Deposition of limestone was dominant during transgressions across the Uinta-Piceance region.

Subsidence rates decreased during the Late Pennsylvanian in all four of the main depositional provinces in the Uinta-Piceance region, but the decrease was least pronounced in the Oquirrh basin (fig. 10) (Johnson and others, in press). The Front Range, Sawatch, and Uncompahgre uplifts continued to serve as major sources of clastic sediment. Evaporite deposition ended in the Eagle and Paradox basins, replaced by fluvial, eolian, sabkha, and (or) shallow-marine deposition. Johnson and others (in press) suggested that termination of evaporite deposition was linked to decreasing subsidence rates (fig. 10), which allowed progradation of clastic sediments into basin interiors. Progradation of eolian sands across the Wyoming shelf and into the Oquirrh basin continued during regressions. Transgressive deposition of limestone was limited to the western part of the Uinta-Piceance region and a small area in the eastern Eagle basin (Johnson and others, in press).

Late Pennsylvanian depositional patterns in the Eagle basin and on the Wyoming shelf continued into the early Wolfcampian (Johnson and others, in press). The Emery uplift became fully or mostly submerged, ending the history of the Paradox basin as a discrete geomorphic element. Deep-water clastic deposition began in the Oquirrh basin (or continued from the latter part of the Late Pennsylvanian) (Jordan and Douglas, 1980). In that subsidence rates in the Oquirrh basin do not appear to have increased from the Middle Pennsylvanian to the Late Pennsylvanian and Early Permian (fig. 10), the transition to deep-water deposition probably represents a decrease in sediment supply (Johnson and others, in press). Transgressive limestone deposition was limited to the southeastern part of the Uinta-Piceance region.

The history of deformation and deposition outlined above provides clues to the driving forces behind regional basin evolution. As described above, Kluth (1986) suggested that continent-continent collision along the southern plate margin provided a driving force for development of the ancestral Rocky Mountains. This deformation should have propagated inland with time as the length of the suture zone and the amount of shortening along the continental margin increased (Kluth, 1986). Accordingly, the earliest deformation attributed to the North America–Gondwana collision in the Uinta-Piceance region should be in the Paradox or Eagle basins, closest to the plate margin. Stratigraphic and subsidence analysis (fig. 10, phase 3) shows, however, that initiation of the Oquirrh basin and Wyoming shelf as discrete structural elements began about 15–25 million years before initial subsidence of the Eagle and Paradox basins. The Oquirrh basin is also distinguished from the Eagle and Paradox basins on the basis of its higher rates and magnitudes of subsidence and on the basis of continuing higher subsidence rates through the Late Pennsylvanian and Early Permian. These contrasts indicate an alternate driving force for basin subsidence, inferred to be Humboldt-style strike-slip(?) extensional tectonism associated with the western continental margin of North America. Late Mississippian deformation on the Wyoming shelf may similarly reflect Humboldt tectonism. In that this extensional deformation was ongoing for 15–25 million years without influencing the eastern parts of the Uinta-Piceance region, it is unlikely that later subsidence in either the Eagle or Paradox basins was greatly influenced by the Humboldt event. The Eagle and Paradox basins are therefore best interpreted as features of the foreland of the Marathon-Ouachita orogenic belt. The effects of the Marathon-Ouachita orogeny may have partly forced rapid subsidence in the Oquirrh basin during the Middle Pennsylvanian, when rates were also highest in the Eagle and northern Paradox basins (fig. 10). Continued high subsidence rates in the Late Pennsylvanian and Early Permian for the Oquirrh basin do not correlate with trends in the Paradox and Eagle basins, indicating domination of the western driving force.

Late Early Permian to Early Jurassic (phase four)

Upper Lower Permian to Lower Jurassic strata in the Uinta-Piceance region form west-thickening wedges (fig. 11), reverting to the geometry that characterized the pre-Late Mississippian history of the region (fig. 7). Thickening is most pronounced in Lower Triassic strata, correlating with the Sonoma orogeny to the west (fig. 6) as discussed below. Tectonic activity on the southeastern margin of North America ended in the late Early Permian (Leonardian) and thereafter had no effect on basin evolution in the Uinta-Piceance region (Kluth, 1986). The ancestral Rocky Mountain highlands were gradually eroded through this interval (Peterson, 1988a) and had progressively diminishing importance as sediment sources and orographic features.

The Uinta-Piceance region migrated northward from about 16° N. to about 20° N. in the Late Permian, migrated southward to about 13° N. in the Middle and Late Triassic, then migrated northward to a high of about 25° N. at the end of the Early Jurassic (fig. 5). The presence of extensive Upper Permian and Lower Triassic evaporites and widespread Lower Jurassic eolianites indicates intervals of arid climate (Peterson, 1988a). Dubiel (1992) suggested that the early Late Triassic climate was tropical monsoonal but became drier toward the latter part of the epoch. In that the paleolatitude in the Late Triassic was almost the same as that of the Late Pennsylvanian when arid conditions prevailed (see previous section), the difference in climate between these two periods must reflect other factors including changes in global circulation patterns due to reconfiguration of continental land masses and melting of polar ice sheets and diminished orographic effects due to erosional beveling of regional highlands.

Sea level fell from the end of the Wolfcampian through the remainder of the Permian (fig. 5) (Ross and Ross, 1987, 1988). Ross and Ross (1987, 1988) inferred 16–18 short-term eustatic fluctuations during this interval, but the magnitude of the inferred changes decreased markedly from about 100 to about 10 m. Haq and others (1988) showed that sea level rose from the late Late Permian to the mid–Late Triassic, reached a low in the early Early Jurassic, then climbed gradually through the Early Jurassic. Haq and others (1988) inferred that small-scale fluctuations superimposed on the Mesozoic sea-level curve have magnitudes generally of a few tens of meters but as much as 100 m.

Late Permian to Early Triassic

Late Early Permian to early Late Permian (late Leonardian to Guadalupian) isopach and (or) paleogeographic and lithofacies maps are in McKee and others (1967), Rascoe and Baars (1972), Stevens (1977, 1991), Maughan (1980), Wardlaw (1980), Peterson (1980), and Hansen (1986a). Isopach maps in McKee and others (1967) and Hansen (1986a) show an eastward deflection in isopachs in the Uinta Mountain area that indicates that structures associated with this Precambrian tectonic feature were active (to a small degree) in the Late Permian.

Upper Lower to lower Upper Permian strata in west-central Colorado are nonmarine to marginal-marine, fine-grained redbeds and minor channel-form sandstone, algal limestone, and gypsum (Freeman, 1971). These strata grade westward to marginal- and shallow-marine carbonate rocks, mudstone, and evaporite; coastal eolian sandstone is present on the western flank of the Uncompahgre uplift in central Utah (Huntoon and Chan, 1987). Phosphatic rock, chert, and carbonaceous shale are interbedded with carbonate shelf

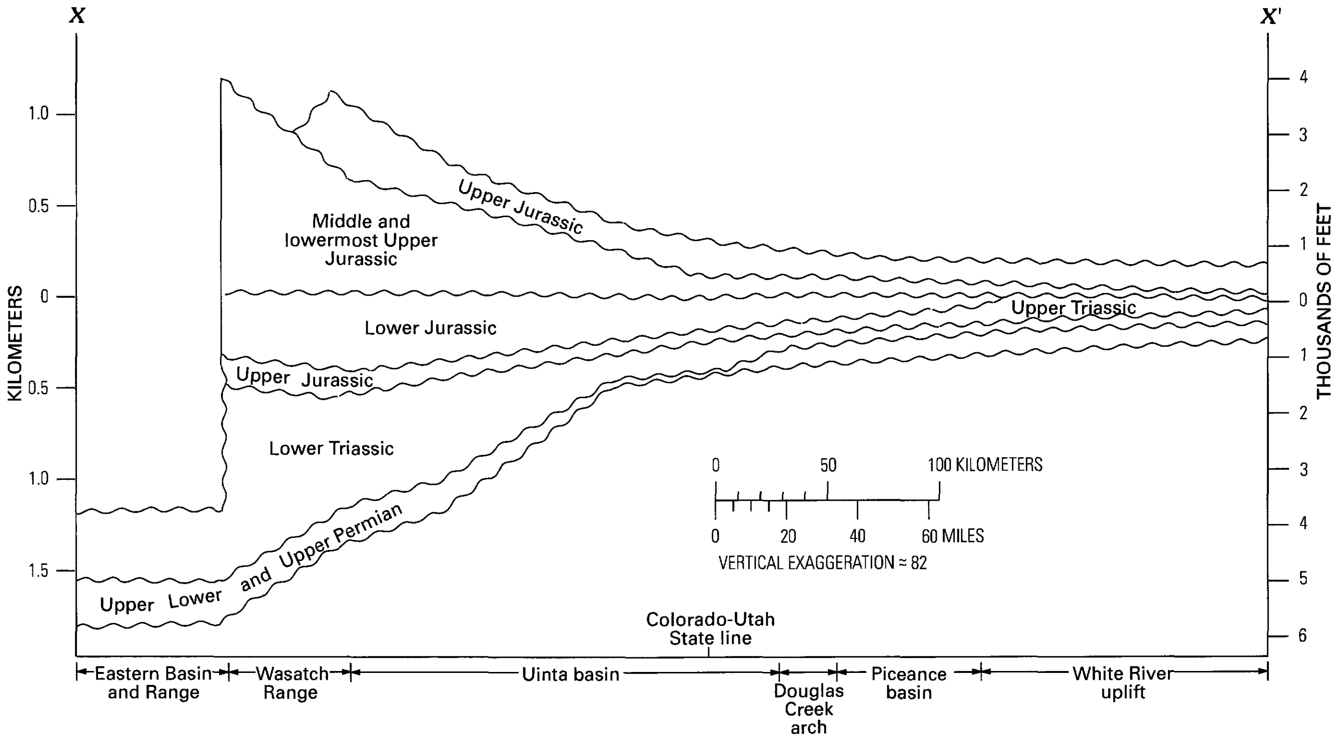


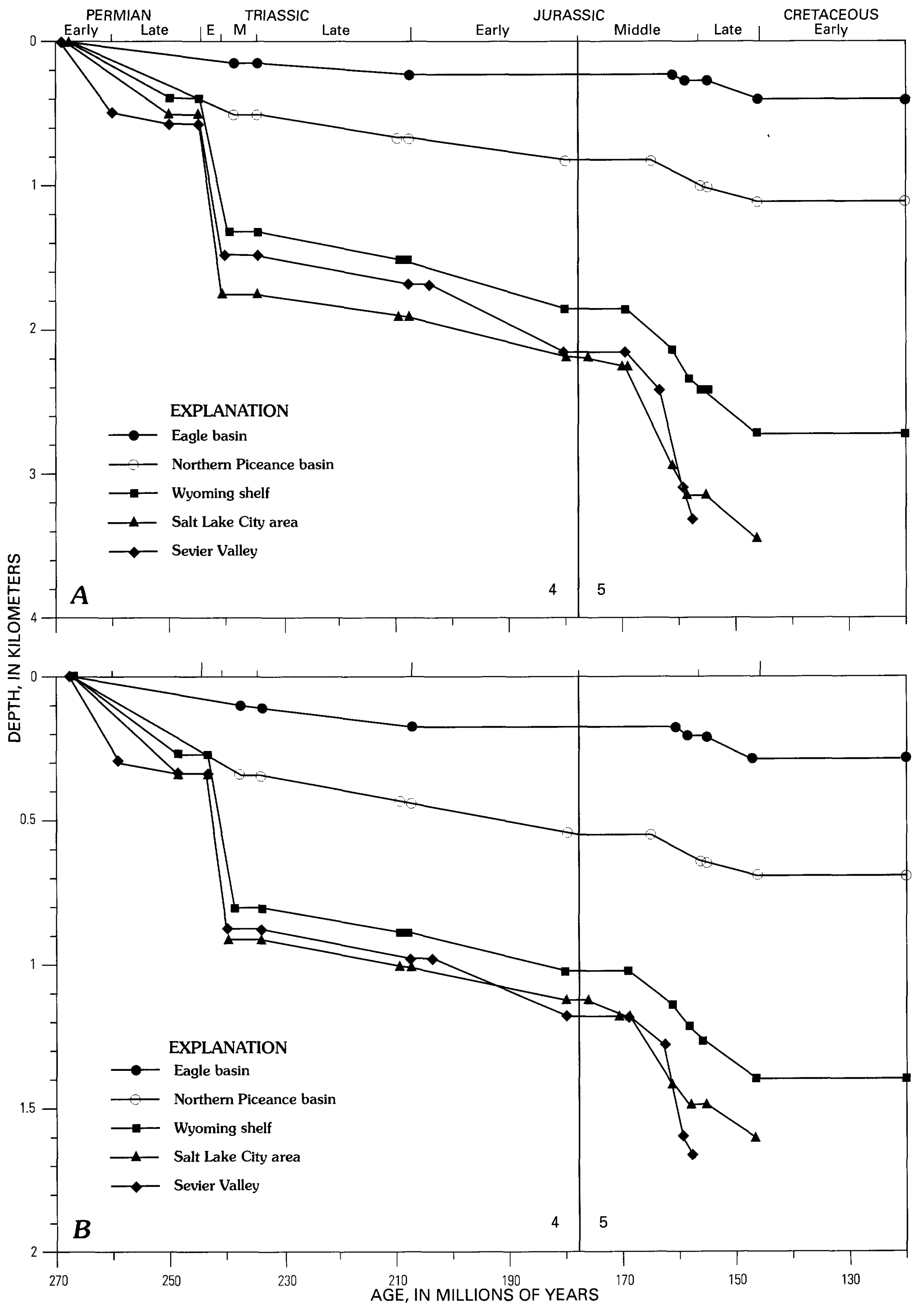
Figure 11. Schematic stratigraphic cross section along line *X–X'* showing upper Lower Permian through lower Lower Cretaceous rocks in Uinta-Piceance region. Datum is the boundary between rocks deposited during phases four and five of Phanerozoic basin evolution as discussed in the text. About 33 km of Neogene extension was subtracted from eastern Basin and Range area (westernmost part of section) following Levy and Christie-Blick (1989, fig. 3A). Thickness data from compilations of S.Y. Johnson and R.C. Johnson (1991) and R.C. Johnson and S.Y. Johnson (1991). In constructing the cross section, two-thirds of State Bridge Formation was assigned to the Permian and one-third to the Early Triassic. Wavy lines indicate unconformities. Line of section shown in figure 2.

deposits in the northwestern part of the Uinta-Piceance region. The upwelling of cool, nutrient-rich waters has been considered necessary for the deposition of these facies, which Wardlaw (1980) and Wardlaw and Collinson (1986) suggested were deposited in a ramp environment during transgressions. There is no record of latest Permian (Ochoan) marine deposition in the western Uinta-Piceance region, suggesting emergence; however, there is no obvious disconformity in nonmarine, nonfossiliferous Upper Permian to Lower Triassic redbeds in northwestern Colorado, and Ochoan deposits could be present in this area.

Early Triassic isopach and (or) paleogeographic maps are in MacLachlan (1972), Collinson and Hasenmueller (1978), and Carr and Paull (1983). Lower Triassic rocks in northwestern Colorado are mainly nonmarine red shale and minor channel-form sandstone. These strata grade progressively westward into (1) mudstone-rich inner-shelf deposits, (2) bioclastic-carbonate-dominated outer-shelf deposits, and (3) calcareous mudstone and siltstone basinal facies (Carr and Paull, 1983). Facies boundaries are transgressive in space and time and variable in orientation. For example, Collinson and Hasenmueller (1978) and Carr and Paul (1983) documented the presence of a large embayment on the shelf in northern Utah and south-central Idaho.

Geohistory plots (fig. 12) indicate that Late Permian and Early Triassic subsidence rates were highest in the western Uinta-Piceance region and decreased substantially to the east, consistent with the noted basin asymmetry (fig. 11). This episode of relatively rapid, asymmetric subsidence

Figure 12 (facing page). Geohistory diagrams showing subsidence histories for five areas in Uinta-Piceance basin region for the late Early Permian to Early Cretaceous. Approximate locations of areas in shown in figures 1 or 9. *A*, Total subsidence corrected for compaction. *B*, Subsidence of the basement corrected for load induced by weight of sediment through time and, thus, inferred amount of tectonic subsidence. Corrections for compaction were based on lithology and follow exponential porosity function presented by Sclater and Christie (1980). No corrections were made for bathymetry. Because of uncertainties involving ages of units and their compaction-diagenetic histories, the plots should be regarded as approximations. Thickness data from compilations of S.Y. Johnson and R.C. Johnson (1991), R.C. Johnson and S.Y. Johnson (1991), and Sprinkel (in press). Because of structural complications, there is uncertainty surrounding primary stratigraphic thickness of Middle Jurassic Arapien Shale in Gunnison Plateau area; thickness estimate used (610 m) may be a minimum (Sprinkel, in press). Time scale from Harland and others (1990).


PERMIAN
Early
Late
TRIASSIC
E
M
Late
JURASSIC
Early
Middle
Late
CRETACEOUS
Early
DEPTH, IN KILOMETERS
EXPLANATION
Eagle basin
Northern Piceance basin
Wyoming shelf
Salt Lake City area
Sevier Valley
A
4
5
B
AGE, IN MILLIONS OF YEARS
270
250
230
210
190
170
150
130

(notably interrupted in the Ochoan) correlates with the Sonoma orogeny (Silberling and Roberts, 1962; Speed, 1979) and associated emplacement of the Golconda allochthon to the west in Nevada (fig. 6). It is tempting to infer that the subsidence to the east in the Uinta-Piceance region was at least partly forced by flexural loading associated with emplacement of this distant allochthon. Ideally, one could test this hypothesis by documenting the proximal portion of a foreland basin east of the Golconda allochthon in eastern Nevada; the axis of this postulated foreland basin must have been between the Golconda allochthon and the west-sloping, Late Permian–Early Triassic shelf of central and western Utah. This postulated proximal foreland basin should be characterized by a thick fill (relative to the section in the western Uinta-Piceance region) of west-derived detritus, or by a significant increase in paleowater depth, or by a combination of the two (Heller and others, 1988). Unfortunately, due to large-scale Mesozoic and Cenozoic structural disruption and erosion, outcrops of uppermost Permian to Lower Triassic rocks are sparse in this region and reliable thickness and facies data are hard to obtain. This disruption and erosion could also mask more easterly thrust faults of Sonoman age; if such structures were present, the postulated correlative foreland basin would be narrower and more consistent with foreland-basin models (for example, Jordan, 1981).

The presence of Upper Permian phosphatic rocks in northwestern Utah indicates upwelling of nutrients from a deep trough west of the shelf edge that was connected with the paleo-Pacific Ocean. In that global sea level was notably low in the Late Permian (fig. 5), the upwelling-required basinal deepening indicates that subsidence in this inferred trough was the result of tectonic activity. The inferred continuity and morphology of this trough is most consistent with emplacement of a regional thrust system such as the Golconda allochthon.

Collinson and Hasenmueller (1978) documented Lower Triassic, west-derived conglomerate in eastern Nevada, indicating a western sediment source; however, Ketner (1984) described east-derived boulder conglomerate and stated that west-derived clastic rocks are rare. Because these east-derived conglomerates could not have been transported across the low-relief Early Triassic shelf, a local intrabasinal uplift on the outer shelf(?) is required. In a foreland-basin setting, this uplift could represent a flexural bulge. The suggested paucity of west-derived detritus could reflect minimal topography in the thrust belt.

As is clear from the discussion above, most important details needed to prove the presence of a Sonoma foreland basin that extended into central Utah are lacking. The most obvious alternative to a foreland-basin setting would invoke regional extension, a continuation of the "Humboldt-style" deformation that characterized the Early Permian. The presence of the Golconda allochthon to the west and the asymmetry, regional extent, and depositional environments of Upper Permian and Lower Triassic strata in Colorado and Utah are more consistent with a foreland-basin setting.

Middle Triassic to Early Jurassic

Middle Triassic strata are absent in the Uinta-Piceance region. Late Triassic to Early Jurassic isopach and (or) paleogeographic maps of parts or all of the Uinta-Piceance region are in MacLachlan (1972), Peterson (1972), Berman and others (1980), Imlay (1980), Kocurek and Dott (1983), Peterson (1988b), and Dubiel (1992). Upper Triassic strata are thin (<200 m) and relatively uniform in thickness across the region. Lower Jurassic strata are thicker (<400 m), have a relatively constant thickness in Utah, and pinch out to the east in northwestern Colorado (fig. 11).

The Middle Triassic to Early Jurassic history of the Uinta-Piceance region reflects relative tectonic quiescence. The region was apparently emergent during the Middle Triassic when sea level was rising (fig. 5) (Haq and others, 1988). The emergence must therefore reflect gentle tectonic upwarping. The contact between Lower and Upper Triassic rocks is generally a disconformity characterized by broad valley fills. On a regional scale and along the southwestern flank of the ancestral Uncompahgre uplift, the contact is slightly angular (Dubiel, 1992).

Upper Triassic strata are nonmarine (fluvial, lacustrine, minor eolian) redbeds (Poole and Stewart, 1964; Dubiel, 1992) across the entire Uinta-Piceance region. The contact between Upper Triassic and Lower Jurassic strata (the J–0 unconformity of Pipiringos and O'Sullivan, 1978) is locally parallel but is angular on a regional scale. This contact may in large part reflect lowering of global sea level in the early Early Jurassic (fig. 5) (Haq and others, 1988). Lower Jurassic rocks are predominantly eolian sandstone (for example, Kocurek and Dott, 1983; Peterson, 1988b). Late Triassic to Early Jurassic depositional patterns apparently extended to the west into eastern Nevada, where Stewart (1980) recognized comparable sequences of rocks. This continuity of facies further supports regional tectonic stability.

Geohistory diagrams (fig. 12) indicate that Late Triassic to Early Jurassic subsidence was slow and almost completely driven by the weight of overlying sediment (fig. 12*B*). The minor component of tectonic subsidence is of the magnitude that could reflect deformation associated with intraplate stress regimes, as described by Cloetingh (1986).

Middle Jurassic to Early Early Cretaceous (phase five)

The Middle Jurassic to early Early Cretaceous phase of basin evolution is similar to the Late Permian to Early Jurassic phase in that it records an initial pulse of rapid, asymmetric subsidence linked to a thrusting event in eastern Nevada followed by a period of slower, more uniform subsidence and relative tectonic quiescence. Middle Jurassic to early Early Cretaceous isopach and (or) paleogeographic maps of the Uinta-Piceance region are in McGookey and others (1972), Peterson (1972), Berman and others (1980), Imlay (1980), Brenner (1983), Kocurek and Dott (1983), and Peterson (1988b). Middle Jurassic rocks thicken markedly to the west (fig. 11). In contrast, Upper Jurassic strata have a relatively uniform thickness over a very broad area and thicken only slightly to the west. Lower Lower Cretaceous rocks (Neocomian to Aptian) are missing in the Uinta-Piceance region. The Uinta-Piceance region migrated from a paleolatitude of about 25° N. to about 36° N. during this interval. Widespread eolianites and evaporites (Middle Jurassic) indicate that the climate was at least periodically arid.

Middle Jurassic rocks are underlain by the J–2 unconformity and overlain by the J–4 unconformity, and they include the J–3 unconformity of Pipiringos and O'Sullivan (1978). These strata were deposited during two major transgressions from the north into an interior seaway (Kocurek and Dott, 1983). Below the J–3 unconformity, facies grade east to west from (1) eolian sandstone in northwestern Colorado, to (2) nearshore marine sandstone and mudstone in northeastern Utah, to (3) limestone in north-central Utah. Facies contacts are transgressive in space and time. Middle Jurassic limestone grades into evaporite and shale in west-central Utah, in the Utah-Idaho trough of Peterson (1988b). The eastern flank of this trough was apparently a fault near the presently active Wasatch fault (Standlee, 1982; Picha, 1986); the western flank was a tectonic highland that, based on sparse lithofacies data (due to poor preservation of Jurassic rocks) and paleoecologic interpretations, probably lay close to the Nevada-Utah State line (Peterson, 1988b). Sprinkel (in press) suggested that the trough was bounded on the north by a submerged barrier coinciding with the western continuation of the Uinta Mountains (the previously discussed "Oquirrh-Uinta arch"). Middle Jurassic strata above the J–3 unconformity consist mainly of shallow-marine sandstone and mudstone.

Upper Jurassic strata are underlain by the J–4 unconformity and overlain by the K–1 unconformity and include the J–5 unconformity of Pipiringos and O'Sullivan (1978). Strata between the J–4 and J–5 unconformities consist mainly of shallow-marine siltstone, mudstone, and limestone and record another transgression (Peterson, 1988b). Upper Jurassic strata above the J–5 unconformity (the Morrison Formation) consist mainly of fluvial sandstone and conglomerate and varicolored mudstone of overbank and lacustrine origin.

Reconstructing the tectonic setting of Middle and Late Jurassic deposition in the Uinta-Piceance region presents problems similar to those encountered when analyzing the Late Permian to Early Jurassic history of the region. Geohistory plots (fig. 12) indicate that subsidence rates increased in the late Middle Jurassic, although rates were not as high as in the Early Triassic. Marked Middle Jurassic asymmetric subsidence is consistent with a flexural load emplaced to the west, but later structural disruption, uplift, and erosion make the proximal parts of a Middle Jurassic foreland basin in westernmost Utah difficult to identify. A westward increase in the coarse clastic component of some of the Middle Jurassic formations indicates a nearby source to the west (Peterson, 1988b). As in the Early Triassic, there is also evidence of synchronous crustal shortening to the west.

Allmendinger and Jordan (1981) described pre-150-Ma thrusting in northwestern Utah, and Thorman and others (1991) documented synchronous thrusting and (or) folding in six different ranges in northeastern Nevada (they also inferred correlative thrusting in four other ranges). Thorman and others designated this event the Elko orogeny and considered it Late Jurassic in age because (1) some of the structures involve Lower Jurassic rocks, (2) some of the structures are intruded by a suite of 150–165-Ma plutons considered by Miller and Allmendinger (1991) to be of rift affinity, and (3) they used the time scale of Palmer (1983), which shows the Middle Jurassic–Early Jurassic boundary at 163 Ma. They considered the Upper Jurassic Morrison Formation to be the fill of the foreland basin paired to this episode of thrusting, a linkage that demands that crustal thickening associated with the episode be confined not only to the latest part of the interval constrained by the dates outlined above but throughout the time when the Morrison was deposited (until about 145 Ma using the time scale of Harland and others, 1990).

This episode of thrusting is here considered Middle Jurassic for two reasons. (1) The updated time scale of Harland and others (1990) shows the Middle Jurassic–Late Jurassic (Callovian-Oxfordian) boundary at 157 Ma. Using this scale, a significant proportion of the post-thrusting intrusive rocks of the "Elko orogeny" are Middle Jurassic in age. (2) The Middle Jurassic timing of accelerated subsidence in the Uinta-Piceance region, the evidence for basin deepening, and the marked basin asymmetry each strongly suggests Middle Jurassic crustal thickening to the west. Formation and deepening of the Utah-Idaho trough (Peterson, 1988b) are considered sensitive indicators of the onset and duration of thrusting to the west. In contrast, the regional sheetlike geometry and the lithology of the Morrison Formation are more consistent with the postorogenic phase of foreland-basin evolution (Heller and others, 1988). Based on different data, Heller and others (1986) and Picha (1986) similarly inferred the presence of a Middle Jurassic foreland basin in the western United States.

The location of the front of the Middle Jurassic thrust belt shown on figure 6 is based on Allmendinger and Jordan (1981). The presence of Middle Jurassic limestone in west-central Utah indicates that the axis of the proposed foreland basin was west of the Wasatch fault and that clastic sediment derived from the inferred thrust belt was not transported across this axis to the east. This relationship suggests minimal relief in the Middle Jurassic thrust belt.

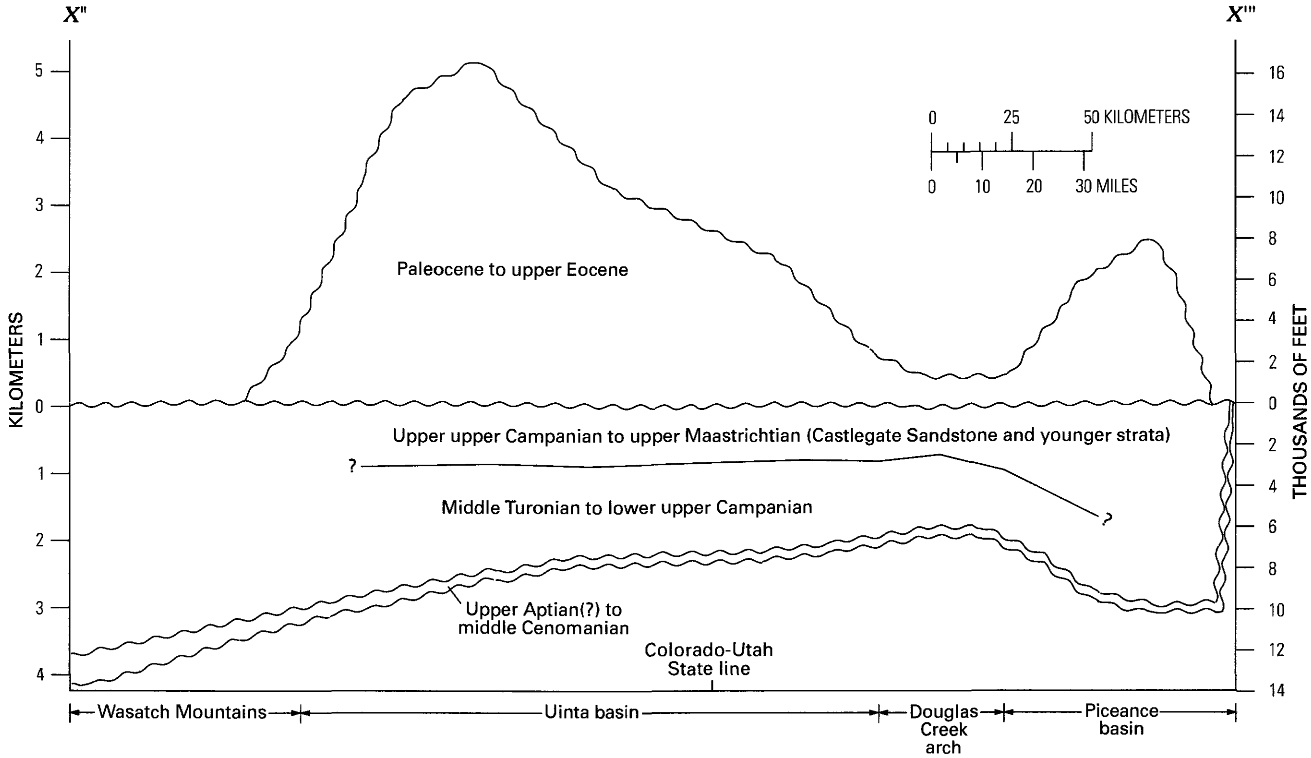


Figure 13. Schematic stratigraphic cross section along line *X''–X'''* showing upper Lower Cretaceous through upper Eocene rocks in Uinta-Piceance basin region (strata of this age do not occur or have not been well described between points *X* and *X''* and points *X'* and *X'''* of fig. 2). Datum is widespread latest Cretaceous unconformity. Thickness data from compilations of S.Y. Johnson and R.C. Johnson (1991) and R.C. Johnson and S.Y. Johnson (1991). In constructing the cross section, (1) all of Kelvin Formation was assumed to be pre-middle Cenomanian (pre-95 Ma) in age, and (2) half of Currant Creek Formation was assigned to the Late Cretaceous and half to the Paleogene. Wavy lines indicate unconformities. Line of section shown in figure 2.

Late Early Cretaceous to Late Eocene (phase six)

Uplift and deposition associated with the Sevier and Laramide orogenies characterized the Uinta-Piceance region during the late Early Cretaceous to late Eocene (fig. 5). These two orogenies are gradational in both space and time (for example, Kulik and Schmidt, 1988) and are therefore considered jointly. Upper Cretaceous nonmarine and marine rocks generally thicken westward (fig. 13) and were deposited in a foreland basin linked to the thin-skinned Sevier orogenic belt. Depositional patterns were strongly influenced by both thrust-belt tectonics and fluctuating eustasy (for example, Fouch and others, 1983; Franczyk and others, in press), which regulated the magnitude and extent of transgressions and regressions of the Western Interior seaway (fig. 14). This seaway retreated from the Uinta-Piceance region during the latest Cretaceous and Paleogene, when sea level fell (fig. 5) and the Cretaceous foreland basin was segmented by basement-cored uplifts into restricted lacustrine basins (fig. 14). There are many published isopach and (or) paleogeographic and lithofacies maps for parts or all of the Uinta-Piceance region during parts or all of late Early Cretaceous to late Eocene time (for example, McGookey and others, 1972; Fouch and others, 1983; Johnson, 1985, 1986; Dickinson and others, 1986; Franczyk and others, in press).

The Uinta-Piceance region migrated northward from a paleolatitude of about 36° N. in the late Early Cretaceous to about 45° N. in the Late Cretaceous, then migrated southward to about 41° N. by the late Eocene (fig. 5). The paleoclimate was subhumid with minimal seasonality in the Late Cretaceous (Wolfe and Upchurch, 1987), humid to moderate in the Paleogene, and relatively dry in the Eocene (Wolfe, 1978). The drying trend might reflect the rain-shadow effect of basin-margin uplifts. Sea level curves (fig. 5) (Haq and others, 1988) show a rise from the Early Cretaceous to the mid-Turonian, a slight drop into the early Campanian, a slight rise in the late Campanian, then a fairly continuous drop through the early Eocene. Short-term fluctuations on this generalized curve range from a few meters to as much as 130 m (Haq and others, 1988).

As in the older Antler, Sonoma, and Middle Jurassic events, east-directed Sevier thrusting occurred mainly within the thick Proterozoic to Jurassic sedimentary section west of the Wasatch fault (fig. 2). Laramide deformation, characterized by thrust- or reverse-fault-bounded, basement-cored

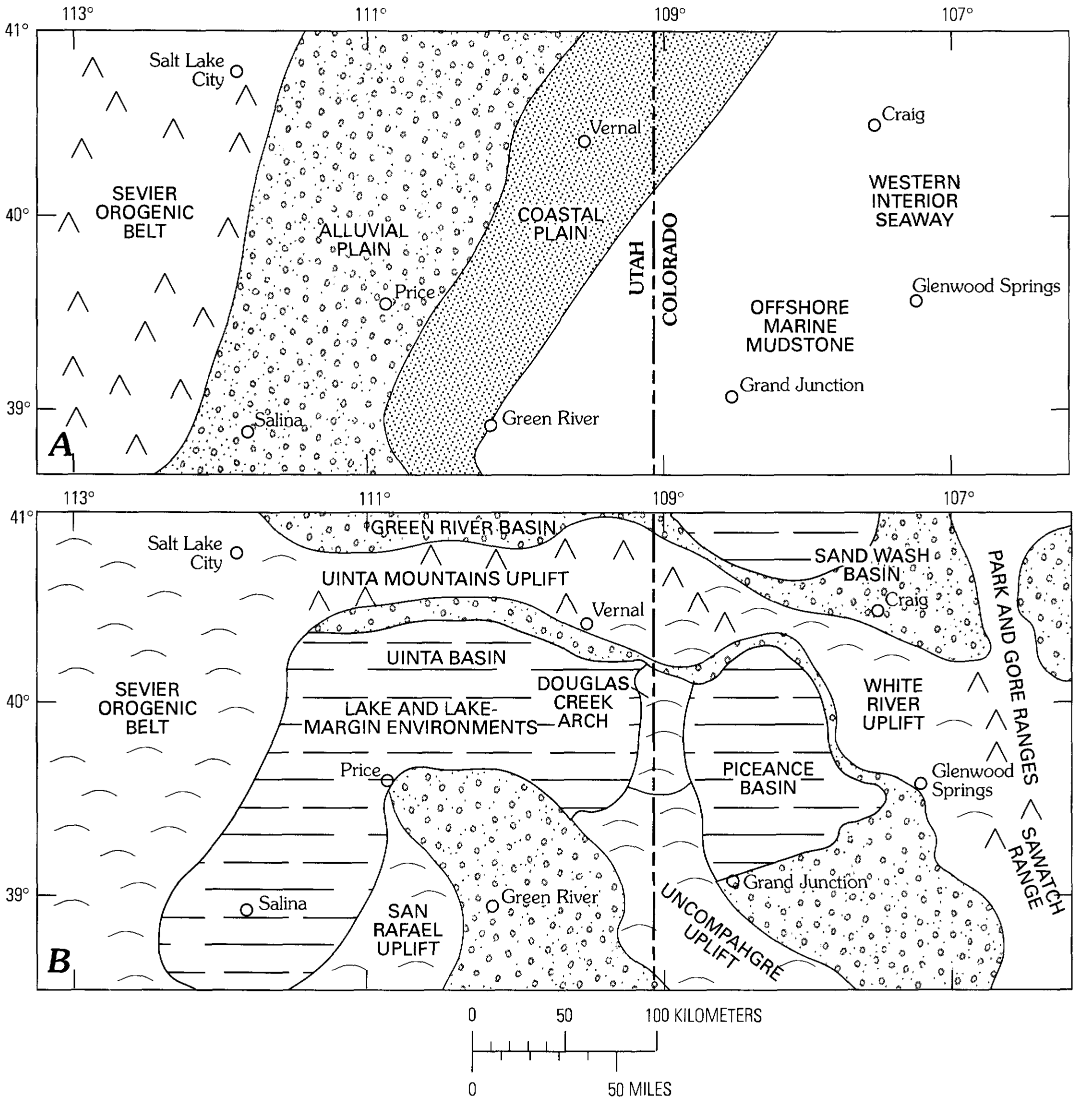


Figure 14. Schematic paleogeographic maps showing tectonic and depositional framework of Uinta-Piceance basin region during the (*A*) early Campanian and (*B*) early Eocene. Simplified from Franczyk and others (in press).

uplifts, occurred east of the Sevier orogenic belt. Laramide uplifts have diverse trends (figs. 6, 14), are commonly flanked by monoclines, and are genetically coupled to adjacent sedimentary basins. In the Uinta-Piceance region, Laramide uplifts include the Uinta Mountains, White River, Front Range, Sawatch, San Rafael, and Uncompahgre uplifts (fig. 14). Tweto (1975, 1980) and others suggested that reactivation of Precambrian and late Paleozoic structural zones was important in determining the geometry and location of Laramide uplifts and basins. Although Hamilton (1988) disputed this contention, evidence for reactivation is strong. For example, the north-flank fault zone of the Laramide Uinta Mountains uplift approximates the southern boundary of the Archean craton (fig. 2) (Bryant and Nichols, 1988). The east trend of the Basin-Mountain boundary fault on the southern flank of the Uinta Mountains parallels the trend of the Precambrian Uinta Mountain trough and could reflect reactivation of structures in or on the southern flanks of this feature. The Front Range, Sawatch, and Uncompahgre uplifts were all positive structural elements in the late Paleozoic, and the San Rafael uplift approximates the position of the late Paleozoic Emery uplift (figs. 9, 14). The White River uplift of west-central Colorado has no obvious earlier history; however, Johnson and others (1988, 1990) discussed evidence for late Paleozoic faults on its flanks, and these structures could have been reactivated in Laramide time.

The driving force for the Sevier and Laramide orogenies is widely attributed to interactions farther west along the western margin of the North American plate (for example, Dickinson and Snyder, 1978; Cross, 1986; Hamilton, 1988).

The Sevier event represents back-arc thrusting during a period of relatively steep subduction. During the Laramide event, subduction accelerated and shallowed, arc magmatism ceased, and contractional deformation moved eastward. Minor clockwise rotation of the Colorado Plateau may have occurred during the Laramide event (Hamilton, 1988). Subsidence of the Sevier foreland basin resulted from crustal loading by thrust sheets. Subsidence of Laramide basins reflects both supracrustal loading from Laramide thrust plates and possibly subcrustal loading from the shallow subducting plate (Cross and Pilger, 1978; Bird, 1984; Cross, 1986). The Precordillera–Sierras Pampeanas region of Argentina provides a Neogene to modern analogue for both the Sevier and Laramide orogenies (Jordan and Allmendinger, 1986; Fielding and Jordan, 1988).

In that there is no preserved record of early Early Cretaceous foreland-basin subsidence in the Uinta-Piceance region (fig. 5), initiation of the Sevier thrust belt and the flanking foreland basin is here regarded (following Heller and others, 1986) as late Early Cretaceous (late Aptian or Albian). Deposition (nonmarine clastic rocks overlain by marine shale) in the juvenile foreland basin was apparently continuous from the time of initiation until the early Cenomanian (about 95 Ma), after which there was a hiatus in much of the region until the late middle Turonian (about 90 Ma) (Molenaar and Wilson, 1990). This hiatus does not coincide with a sea-level lowstand (fig. 5) (Haq and others, 1988) and therefore has a tectonic origin (Molenaar and Wilson, 1990). It could reflect temporary slowing or cessation of thrusting and isostatic rebound of the foreland basin. Stratigraphic cross sections (for example, fig. 13) show that the relatively thin pre-unconformity interval thickens to the west, and geohistory diagrams (fig. 15) show that subsidence was relatively slow during deposition of the interval. These relationships indicate that the inferred thrust-induced crustal load responsible for this subsidence was either relatively small or distant (>100 km?) from the Uinta-Piceance region. For each case, the more proximal, thicker parts of this early foreland basin would have been uplifted and eroded during subsequent Sevier deformation. Bryant and Nichols (1988) suggested that the Canyon Range thrust of western Utah, about 40 km west (present geography) of the Salt Lake City area, was active in the late Albian, synchronous with deposition of the lower interval.

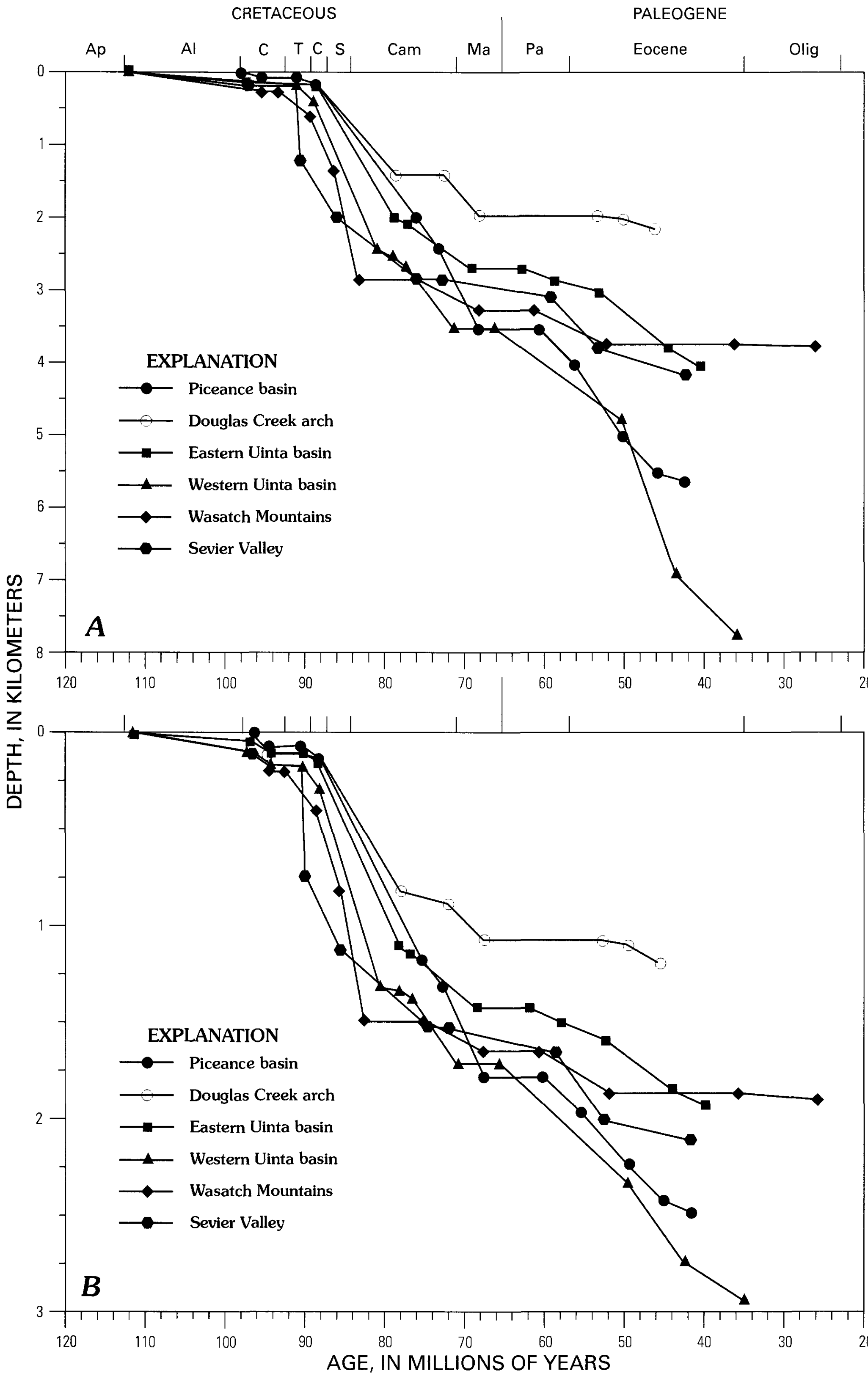
Subsidence and deposition were essentially continuous in the Uinta-Piceance region from the mid-Turonian to the mid-Maastrichtian (figs. 13, 15). Mid-Turonian basin deepening is not associated with a major rise in sea level (fig. 5) and was therefore tectonic in origin, perhaps caused by emplacement of the Nebo and Charleston thrust sheets (Bryant and Nichols, 1988). Subsidence rates were fairly high during this interval and generally increased from east to west (fig. 15). Westward thickening of basinal strata is most pronounced in mid-Turonian to early Campanian (pre-Castlegate Sandstone) time (fig. 13), suggesting crustal loading was more pronounced during this interval.

Sevier uplands and terrane farther west formed source areas that drained into the Western Interior seaway (fig. 14). Shorelines generally moved eastward through successive transgressions and regressions, reflecting filling of the basin (see maps and discussion in Franczyk and others, in press). Nonmarine facies are mainly fluvial sandstone and mudstone; marginal-marine deposits are mainly coastal-plain sandstone and lesser coal; offshore deposits are mainly shale with minor sandstone.

Cross (1986) suggested that a major change in regional subsidence patterns (the initiation of Laramide tectonism, see above) occurred in the early Campanian about 84 Ma. Using similar evidence, Dickinson and others (1988) suggested that Laramide deformation began in the Maastrichtian (71–66 Ma). Franczyk and others (in press) showed Laramide-style deformation in the Uinta-Piceance region beginning about 75 Ma in the mid-Campanian and overlapping with thin-skinned Sevier-style deformation until the late Paleocene (about 57 Ma) (fig. 5). Evidence for the youngest Cretaceous to early Tertiary thin-skinned thrusting comes from small intermontane basins (piggyback basins) on top of the thrust allochthon in central Utah (Fouch and others, 1983; Lawton and Trexler, 1991; Franczyk and others, in press; Lawton and others, in press). The full transition to Laramide-style paleogeography in the Uinta-Piceance region, characterized (in chronologic order) by retreat of the Western Interior seaway, development of an almost regional unconformity, and formation of the large Uinta and Piceance lacustrine basins, occurred in the late Maastrichtian to early Paleocene (Johnson, 1988; Franczyk and others, in press).

The late Maastrichtian to Eocene Uinta and Piceance lacustrine basins are bounded by the Sevier orogenic belt and by the Laramide uplifts described above (fig. 14). Both basins are highly asymmetrical. The structural trough of the

Figure 15 (facing page). Geohistory diagrams showing subsidence histories of six areas in Uinta-Piceance basin region for the late Early Cretaceous to Eocene. Approximate locations of areas shown in figure 1. *A*, Total subsidence corrected for compaction. *B*, Subsidence of the basement corrected for load induced by weight of sediment through time and, thus, inferred amount of tectonic subsidence. Corrections for compaction were based on lithology and follow exponential porosity function presented by Sclater and Christie (1980). No corrections were made for bathymetry. Because of uncertainties involving the ages of units and their compaction-diagenetic histories, the plots should be regarded as approximations. Thickness data from compilations of S.Y. Johnson and R.C. Johnson (1991), R.C. Johnson and S.Y. Johnson (1991), and Sprinkel (in press). Time scale from Harland and others (1990) and J.D. Obradovich (U.S. Geological Survey, written commun., 1991). Time-scale abbreviations as follows: Ap, Aptian; Al, Albian; Ce, Cenomanian; T, Turonian; C, Coniacian; S, Santonian; Cam, Campanian; Ma, Maastrichtian; Pa, Paleocene; Olig, Oligocene.


CRETACEOUS
PALEOGENE
Ap
Al
C
T
C
S
Cam
Ma
Pa
Eocene
Olig
EXPLANATION
Piceance basin
Douglas Creek arch
Eastern Uinta basin
Western Uinta basin
Wasatch Mountains
Sevier Valley
A
B
DEPTH, IN KILOMETERS
AGE, IN MILLIONS OF YEARS

Uinta basin is just south of the Uinta Mountains uplift, and the structural trough of the Piceance basin is along the west flank of the White River uplift (Johnson, 1985, 1988). This basin asymmetry indicates that a large portion of the subsidence in the two basins can be attributed to crustal loading from the north for the Uinta basin and from the east for the Piceance basin. Subsidence rates were high, although generally not as large as rates during the peak of the Sevier orogeny (fig. 15). The two basins were separated during most of the Paleocene and early Eocene by the Douglas Creek arch, a broad north-trending anticline (fig. 14) (Johnson and Finn, 1986; Johnson, 1988).

Latest Paleocene to earliest Eocene deposition in the Uinta and Piceance basins was mainly fluvial to shallow lacustrine; mudstone, limestone and sandstone are common rock types (Johnson, 1988; Franczyk and others, in press). Lacustrine environments expanded greatly at the expense of fluvial environments in the early Eocene. Freshwater lacustrine facies deposited during this interval consist of mollusk- and ostracode-rich sandstone and limestone, gray shale, carbonaceous shale, and mud-rich carbonate rock (Johnson, 1988). The freshwater lakes in both basins expanded during the middle Eocene and were connected across the crest of the Douglas Creek arch to form one continuous lake (Johnson, 1988), Lake Uinta of Bradley (1931). Depositional facies and faunas indicate that Lake Uinta was brackish to saline (Johnson, 1988; Fouch and others, 1989; Franczyk and others, in press). Marginal-lacustrine facies include sandstone, carbonate-rich mudstone, and stromatolitic, ostracodal, and oolitic limestone. Illitic and dolomitic oil shale were deposited in the central parts of the lacustrine basins (Johnson, 1988). Infilling of Lake Uinta near the end of the Eocene marks the cessation of Laramide tectonism and basin evolution.

Oligocene to Holocene

Regional basin development essentially ended in the Uinta-Piceance basin region in the late Eocene or early Oligocene at the end of the Laramide orogeny. Widespread late Eocene or early Oligocene erosion surfaces in northeastern Utah and western Colorado (Bradley, 1936; Epis and others, 1980; Hansen, 1984, 1986b; Johnson, 1986) have proven to be important datums for reconstructing and quantifying Oligocene and younger deformation. Oligocene and younger subsidence was confined to local structural depressions that were mostly filled by siliciclastic and volcaniclastic sediment. Oligocene and early Miocene depocenters on the flanks of the Uinta Mountains contain as much as 300 m of sediment (Hansen, 1986b; Hintze, 1988). Middle Miocene to Holocene depocenters in the western part of the Uinta-Piceance region (the eastern part of the Basin and Range province) contain as much as much as about 2,100 m of sediment (Hintze, 1988).

Deformation during this interval was mainly related to extension and uplift. On a continental scale, extension before about 17 Ma occurred behind the volcanic arc that formed after termination of shallow Laramide subduction (Zoback and others, 1981). The most dramatic manifestation of this early extension was the development of metamorphic core complexes west of the Uinta-Piceance region in western Utah and eastern Nevada. Continuing extension occurred during the time-transgressive development (about 24 Ma to present) of the San Andreas transform fault (Atwater, 1970). The transition to transform faulting on the western continental margin is generally correlated with the 17–15-Ma initiation of the Basin and Range province (see Allmendinger and others, 1987, for a discussion of Basin and Range extensional style). The Wasatch fault (fig. 2) forms the eastern boundary of the Basin and Range. Gans (1987) estimated that about 15 percent extension occurred in the easternmost part of the Basin and Range province (the western part of the Uinta-Piceance region) and 77 percent extension across the entire Basin and Range. This extension was accommodated by crustal thinning. COCORP seismic data show that crustal thickness varies from about 30 km in the Great Basin to about 45 km on the craton east of the hingeline (Allmendinger and others, 1987).

Hansen (1986a, b) suggested that Oligocene and younger deformation in the Uinta Mountains was extensional in origin. Tweto (1977) considered late Tertiary faulting along the Gore fault trend (fig. 2) in north-central Colorado to be extensional, a northern expression of the Rio Grande rift.

Significantly, the Oligocene and Neogene deformation described above was most concentrated along three zones of pre-existing structural weakness: the latest Proterozoic to early Paleozoic hingeline of west-central Utah (Allmendinger and others, 1987), the Uinta Mountain trough (Hansen, 1986b), and the Gore–Park–Front Range area of central Colorado (Tweto, 1977). These three zones of deformation have continued to be active into the Quaternary.

The Oligocene to Holocene history of the Uinta-Piceance region is also characterized by extensive magmatism. Oligocene intrusive and minor volcanic rocks are present in the Elk Mountains (fig. 1) in western Colorado (Tweto, 1977), and granitic intrusive rocks (24–33 Ma) are present in the Salt Lake City area (fig. 1) (Hintze, 1988). Oligocene andesitic and dacitic flows and volcaniclastic rocks (34–35 Ma) are present in the Wasatch Mountains and East Tintic Mountains (fig. 1). Extensive middle Miocene to Holocene volcanic rocks in the eastern Basin and Range province (western Uinta-Piceance region) have bimodal basalt-rhyolite compositions. Miocene (8–24 Ma) basalt and subordinate rhyolitic rocks form several discrete volcanic fields in western Colorado that Tweto (1977) related in a general sense to the Rio Grande rift. Local basaltic centers of Quaternary age are also present in western Colorado.

Regional uplift apparently began in the middle Miocene. Gable and Hatton (1983) suggested that virtually all of the

Uinta-Piceance region was uplifted 2,000–3,000 m in the last 10 million years. Uplift of more than 3,000 m during this interval was inferred for three areas: the Uncompahgre uplift, the Grand Hogback monocline on the western flank of the White River uplift, and a small area in the eastern Uinta Mountains (fig. 1). Hunt (1969) suggested that most of the larger modern drainages, including the Colorado River, were established by about 10 Ma.

CONTROLS ON DEPOSITIONAL FACIES

The Phanerozoic history of the Uinta-Piceance region provides an opportunity to evaluate the role of tectonics, climate, eustasy, and sediment supply in determining depositional patterns in an intraplate setting. The observations made below should be compared with those from other areas in order to develop and refine models of cratonic and craton-margin sedimentation. It should be noted that the rates of total subsidence discussed below are dependent on some imprecise age designations and on accurate calibration of the geologic time scale (Harland and others, 1990) and are thus approximate.

Alluvial Deposits

Narrow belts of alluvial deposits formed adjacent to basin-margin uplifts during phases three and six (see above) of Uinta-Piceance basin evolution. These belts widened as subsidence rates decreased and clastic sediments were no longer trapped in deep troughs adjacent to the uplifts. For example, during phase three, alluvial deposits in the Eagle basin (Maroon Formation) prograded significantly into the basin interior (Johnson and others, in press) only when total subsidence rates (fig. 10) dropped from as much as about 22 to about 3 cm/10^3 years. In the Late Cretaceous seaway, the Campanian transition from marine to nonmarine deposition corresponds to a drop in total subsidence rates (fig. 14) from about 26 to about 15 cm/10^3 years in the eastern Uinta basin area and from about 17 to about 8 cm/10^3 years in the western Uinta basin area. The threshold subsidence rate between marine and nonmarine sedimentation in these two (late Paleozoic and Late Cretaceous) depositional systems primarily reflects sediment supply and (or) eustasy. If sediment supply is high and (or) sea level is dropping, the threshold subsidence rate will be higher than in systems where sediment supply is low and (or) sea level is rising.

Alluvial deposition was most widespread during the tectonically stable Late Triassic (Chinle Formation) and Late Jurassic (Morrison Formation). Total subsidence rates for these intervals ranged from about 0.3 to 1.2 cm/10^3 years and from about 1 to 3 cm/10^3 years, respectively. Moderate (nonarid) climate and relatively low sea level (fig. 5) were important controls on maintaining fluvial deposition during these intervals.

Climate also played a major role in determining the nature and style of fluvial deposition. For example, Middle Pennsylvanian to Lower Permian, arid-climate fluvial deposits of the Eagle basin (Maroon Formation) are sand rich, low in stable floodplain deposits, interbedded with abundant eolianites, and characterized by facies changes typical of terminal fan systems (Johnson, 1987; Johnson and others, 1988). More humid climate, fluvial deposits of the Late Cretaceous foreland basin are more mud rich, were flanked at times by stable floodplains, and are characterized by facies typical of braided and meandering rivers (Franczyk and others, 1990; Franczyk and others, in press).

Eolian Deposits

Widespread eolian deposition (in large sand seas) in the Uinta-Piceance region reflects tectonic stability and arid climate. Total subsidence rates (figs. 10, 12) for the mixed eolian-fluvial parts of the Middle Pennsylvanian to Lower Permian Maroon Formation are about 3 cm/10^3 years; rates for Middle Pennsylvanian to Lower Permian eolianite (Weber Sandstone) are about 1.5 cm/10^3 years; rates for Lower Jurassic eolianite (Nugget Sandstone and Glen Canyon Sandstone) range from about 0.9 to 1.9 cm/10^3 years; rates for eolianite of the Middle Jurassic Entrada Sandstone range from about 1.3 to 2.5 cm/10^3 years. Eolian deposition in these systems was curtailed either by a halt in subsidence leading to emergence and erosion or by submergence resulting from an increase in subsidence and (or) a rise in sea level and (or) a decrease in sediment supply. Eolianite is rare in sequences that formed in rapidly subsiding areas during arid climatic intervals (for example, the Middle Pennsylvanian of the Eagle and Paradox basins) (figs. 9, 10), and alluvial deposits form over a broader range of subsidence rates (see above) than eolianite.

The apparent inability of eolian sand seas to sustain themselves at more than low subsidence rates is consistent with models that relate sediment supply and climate (Langbein and Schumm, 1958; Wilson, 1973; Perlmutter and Matthews, 1990). Rates of weathering, erosion, and sediment supply are lower in arid climates because of the scarcity of water. Other factors that may also contribute to low rates of eolian sediment supply include the increased time needed to rework sediments of noneolian origin in order to form eolian deposits and the limited range of grain sizes (mainly fine grained sand) available from poorly sorted, unconsolidated sediments for deposition in eolian sand seas.

Parrish and Peterson (1988) placed the late Paleozoic to mid-Mesozoic regional climate in the context of global circulation models. Paleolatitude ranged from about 12° N. to 28° N., a belt in which arid climates are expected (for example, Perlmutter and Matthews, 1990) given favorable topographic configurations. Sedimentary facies can be a sensitive indicator of climatic perturbations. Johnson and others (1988, in press) described fluvial-eolian cycles in the upper Paleozoic Maroon Formation that are inferred to reflect repeated high-frequency transitions between more humid and more arid climatic intervals resulting from fluctuations in Gondwana ice sheets.

Marine and Lacustrine Fine-Grained Clastic Deposits

Rates of total subsidence (figs. 4, 10, 12, 15) were relatively high during deposition of each marine or lacustrine, fine-grained sequence in the Uinta-Piceance basin region: (1) about 19 cm/10^3 years during deposition of Middle Pennsylvanian (phase three) black shale interbeds of the Paradox basin; (2) about 23 cm/10^3 years (central Uinta Mountains) to 31 cm/10^3 years (Salt Lake City area) for basinal clastic rocks of the Lower Triassic Moenkopi Formation (phase four); (3) as much as 18 cm/10^3 years during deposition of shale interbeds in the Middle Jurassic Arapien Shale of the Sevier Valley–Gunnison area (phase five); (4) about 26 cm/10^3 years (western Uinta basin) to 17 cm/10^3 years (eastern Uinta basin) for the Upper Cretaceous Mancos Shale (early phase six); and (5) about 30 cm/10^3 years for offshore lacustrine deposits in the Paleocene and Eocene Green River Formation of the Uinta basin (late phase six). In these cases, decreases in subsidence rate led to progradation of more coarse grained subaqueous or subaerial deposits or to emergence. The correlation between deposition of fine-grained marine and lacustrine clastic rocks and high subsidence rates indicates that tectonics was the major control on deposition. During pulses of rapid subsidence, coarse clastic sediments were trapped in troughs near basin-margin uplifts and fine-grained sediments were deposited in more distal parts of basins. The threshold subsidence rate at which coarser clastic sediments prograded was geographically and temporally variable; progradation required less sediment supply in more slowly subsiding basins and more sediment supply in more rapidly subsiding basins. During the arid climatic intervals of phases three, five, and six of basin evolution, evaporites were deposited with the offshore fine-grained clastic rocks in restricted basinal settings.

Marine Carbonate Deposits

There is considerable variability in the rates of total subsidence recorded by marine carbonate deposits in the Uinta-Piceance basin region. Very low subsidence rates (<3 cm/10^3 years) are recorded by (1) phase one uppermost Cambrian and Lower Ordovician rocks (Ajax Dolomite and Garden City Limestone) in west-central Utah; (2) phase two Lower to lower Upper Mississippian rocks (Lodgepole Limestone, Deseret Limestone, Madison Limestone, Leadville Limestone) across the Uinta-Piceance region; and (3) phase three Lower Pennsylvanian rocks (Round Valley Limestone) of the Wyoming shelf province (fig. 9). Moderate total subsidence rates (3–10 cm/10^3 years) are recorded in (1) phase one upper Middle to lower Upper Cambrian rocks (the section extending from the base of the Teutonic Limestone to the top of the Opex Formation) of west-central Utah; (2) phase three Upper Mississippian (Great Blue Limestone) and Lower Pennsylvanian (West Canyon Limestone) rocks of the Oquirrh basin; and (3) phase five Middle Jurassic rocks (Twin Creek Limestone) in the Uinta basin and Gunnison Plateau–Sevier Valley areas. A significant carbonate-rock component is in the Middle Pennsylvanian Butterfield Peaks Formation of the Oquirrh basin, which is characterized by high rates of total subsidence, about 40 cm/10^3 years.

This range in total subsidence rates indicates that limestone deposition in the Uinta-Piceance basin region primarily reflects low clastic sediment supply and was relatively independent of subsidence rate. In other words, given minimal clastic sediment flux, rates of production and accumulation of organic carbonate sediment probably were capable of matching high subsidence rates (see Schlager, 1981, for a thorough discussion of this subject). The role of tectonics is probably most important as an agent for generating uplifts that can serve as sediment-source terranes; when uplifts were distant or of low relief, sediment supply was diminished and carbonate deposition was favored. Thus, carbonate sediments were deposited on the distal, gently west dipping flanks of east-facing foreland basins linked to the Antler, Sonoma, and Middle Jurassic orogenies.

Relatively open marine circulation was another requirement for carbonate deposition. In the late Paleozoic (phase three) Eagle and Paradox basins (fig. 10), for example, evaporites were deposited in settings that otherwise might have favored carbonate deposition had circulation not been restricted. Finally, paleolatitudes within 30° of the Equator (fig. 5) during deposition of carbonate rocks in the Uinta-Piceance region indicate that climate was relatively warm and favorable to production of organic carbonate sediment.

Marine and Lacustrine Evaporite Deposits

Tectonics and climate were the major controls on deposition of evaporitic strata, which occurred in the late Paleozoic Eagle and Paradox basins (phase three), in the foreland of the Middle Jurassic thrust belt (phase five), and in the Laramide Uinta and Piceance basins (phase six). In each case, clastic sediments derived from uplifted basin margins are inferred to have been trapped in proximal basin troughs formed by crustal loading. As a result, rapidly subsiding basin interiors were sediment starved and, given the arid climate, evaporites precipitated. Total subsidence rates during phase three evaporite accumulation were from about 19 cm/10^3 years (Paradox basin) to 22 cm/10^3 years (Eagle basin). During phase five, total subsidence rates during accumulation of Middle Jurassic evaporitic sediments (Arapien Shale) were about 18 cm/10^3 years (fig. 12), given the correlations and the minimum inferred thicknesses of Sprinkel (in press). During phase six, total subsidence rates during evaporite accumulation were about 24 cm/10^3 years in the Uinta basin and 12 cm/10^3 years in the Piceance basin (fig. 15). The requirement of sediment starvation in basin interiors clearly involves a balance between subsidence and sediment supply. For example, basin-margin uplifts surrounding the Piceance basin had much lower relief than those bounding the Uinta basin. Thus, sediment supply to the Piceance basin was probably lower than that to the Uinta basin, and less subsidence was needed to obtain conditions required for evaporite precipitation (R.C. Johnson, U.S. Geological Survey, oral commun., 1991). Rapid subsidence was also needed in phases three and five to allow incursion of cratonic or craton-margin seaways.

Tectonic uplifts or barriers led to drainage restriction during phases three (Johnson and others, in press) and six (Franczyk and others, in press), which in each case was needed for evaporite deposition. Tectonic uplifts also provided orographic effects that contributed to climatic aridity. During phase three, climate was more humid on the eastern flank of the ancestral Front Range uplift (fig. 9), which placed the Eagle and Paradox basins in its rain shadow (Mack and others, 1979). Similarly in the Eocene (late phase six), climate was more humid in Wyoming than in Colorado and Utah (Wolfe, 1978), reflecting the orographic effects of Laramide uplifts. Paleolatitude of the Uinta-Piceance region ranged from about 12° N. to 40° N. from phase three to phase six (fig. 5), a belt in which arid climates are favored (Perlmutter and Matthews, 1990) given suitable topographic configurations. Repetitive eustatic fluctuations were an important control on deposition of upper Paleozoic evaporites (Johnson and others, in press); the eustatic control on Middle Jurassic evaporite deposition is not clear.

Phosphatic Deposits

Tectonic activity was the main control on deposition of phosphatic sediments in the Uinta-Piceance region, which occurred during phase two (Lower and Upper Mississippian Delle Phosphatic Member) and phase four (Lower Permian Phosphoria Formation) of basin evolution. In each case, thrusting and associated crustal loading to the west created a marine trough of sufficient depth to allow upwelling of nutrient-rich waters onto the gently dipping, eastern cratonic flank of a foreland basin (Wardlaw and Collinson, 1986; Sandberg and others, 1991; Silberling and Nichols, 1991). Although both phosphatic units were deposited at low paleolatitudes (fig. 5) under inferred warm climates, phosphate deposition apparently correlates only generally with warm climate and does not bear a close relationship to eustasy (Parrish and Barron, 1986).

Summary

Based on the discussion above, several generalizations can be made regarding the diverse controls on lithofacies distribution and deposition during the Phanerozoic in the Uinta-Piceance region. Periods of tectonic stability (total subsidence rates of less than about 3 cm/10^3 years) were characterized by deposition of widespread alluvial deposits and (or) eolianites and (or) marine carbonate sediments. During these periods, marine carbonate deposition was favored by higher sea levels. In the nonmarine realm, arid climates favored eolian deposition and humid climates favored alluvial deposition. At higher subsidence rates, regional deposition of eolianite is limited by sediment supply.

During periods of tectonic activity (reflected in total subsidence rates of more than about 10 cm/10^3 years), alluvial clastic sediments were generally confined to narrow bands adjacent to tectonic highlands. Distal parts of basins were characterized by deposition of fine-grained clastic rocks. Evaporites were interbedded with basinal clastic rocks when climate was arid and circulation was restricted, conditions that partly resulted from local tectonic controls in each of three cases. Deposition of carbonate sediments occurred in rapidly subsiding basins when the supply of clastic sediment was negligible. Phosphatic deposition on the eastern flanks of two east-facing foreland basins indicates synorogenic basin deepening to the west.

DISCUSSION

Six major phases of Phanerozoic basin evolution are recognized in the cratonic Uinta-Piceance region of northwestern Colorado and northeastern Utah (figs. 4, 5). Each phase is defined by a pulse of accelerated subsidence that in some cases was followed by a period of slower subsidence or emergence and erosion. Each phase can be correlated with a tectonic event driven by interactions along the western margin of North America. The late Paleozoic phase (phase three) is unique in that it reflects overlapping influences of events along both the western and southeastern continental margins. If the effects of Neogene Basin and Range extension and Mesozoic shortening are subtracted (see Cross, 1986; Levy and Christie-Blick, 1989), estimates of the distance between the western boundary of the Uinta-Piceance region and the western continental margin range from about 260 to 415 km during the early Paleozoic (phase one) to more than

800 km during the late Eocene (phase six); the Uinta-Piceance region was about 1,150–1,500 km from the southeastern continental margin during the late Paleozoic. Phanerozoic basin evolution in the Uinta-Piceance region therefore emphasizes the extent to which continental-margin events and processes affect basin evolution in distant, adjacent cratons.

Detailed correlation between Uinta-Piceance basin-evolution phases and plate-motion models (for example, Engebretson and others, 1985; Stock and Molnar, 1988) is difficult. Uncertainties associated with plate reconstructions propagate with increasing age through the Cenozoic and Mesozoic, and there are virtually no specific controls on Paleozoic plate interactions because of the lack of Paleozoic magnetic anomalies in modern ocean basins. This lack of old anomalies also indicates, however, the tremendous volume of oceanic crust consumed at convergent plate margins during the Mesozoic and Cenozoic. For example, the one-sided anomaly pattern of the Pacific Ocean basin (Drummond, 1981) indicates that an area approximately equal to the northern Pacific basin has been subducted below western North America in the last 180 million years. This convergence provided the driving force for the four waves of thrust belts in Nevada and (or) western Utah (fig. 6) that affected basin evolution in the Uinta-Piceance region during the Phanerozoic. Periods of relative tectonic stability characterized by minimal subsidence or slight emergence must primarily reflect slower rates of convergence or periods of transform faulting along the western continental margin. As an example, both Engebretson and others (1985) and Cross (1986) showed marked slowing of Farallon–North America convergence rates between about 145 and 100 Ma, corresponding approximately to the period of relative tectonic stability in the early Early Cretaceous described above.

In examining tectonic style, it is important to note that contractional deformation within the craton itself occurred only during the late Paleozoic ancestral Rocky Mountain orogeny (phase three) and the Late Cretaceous to early Tertiary Laramide orogeny (late phase six). Although in each case the deformation occurred in the foreland of a thin-skinned thrust belt, the driving force for thin-skinned thrusting during the two intervals was apparently different (continent-continent collision versus rapid, shallow subduction of oceanic crust). It may be that there was large-scale shallow subduction of continental or oceanic crust associated with the Gondwana–North America plate collision and that shallow subduction is the connecting thread between the two events. For the Cenozoic continent-continent collision between India and Asia, the analog suggested by Kluth (1986) for the ancestral Rocky Mountain orogeny, there is controversy surrounding the extent to which the Indian continent has been subducted below Tibetan Plateau of the Asian plate (see discussion in Molnar, 1984, 1989).

As discussed in preceding sections, Proterozoic structural grain (fig. 2) was an important yet intermittent control on Phanerozoic deformation and subsidence in the Uinta-Piceance region. Allmendinger and others (1987) described how the latest Proterozoic to early Paleozoic hingeline controlled the location and geometry of ramps in Sevier-age thrust faults and Neogene extensional structures. Hansen (1986a) showed that the Uinta Mountain trough was intermittently active as a depocenter throughout the Paleozoic and Mesozoic; topography was inverted during the Paleogene when the trough formed a major Laramide uplift (fig. 14). The western continuation of the Uinta Mountain axis probably was an active control on subsidence patterns in the late Paleozoic (Jordan and Douglas, 1980; Bryant and Nichols, 1988) and the Middle Jurassic (Sprinkel, in press). Northwest-trending structures associated with the Uncompahgre uplift were active in the Proterozoic, Early Ordovician, late Paleozoic, and Paleogene. North-trending structures associated with the Park–Gore–Front Ranges have a similar multistage history.

CONCLUSIONS

The intraplate Uinta-Piceance region of northwestern Colorado and northeastern Utah is characterized by six main phases of Phanerozoic basin evolution. The onset of each phase is marked by a pulse of rapid subsidence that was forced by a tectonic event driven by interactions on adjacent plate margins. (1) Initiation of the Cambrian to Middle Devonian phase of basin evolution is correlated with rifting on the western margin of North America and subsequent development of a passive margin. (2) Initiation of Late Devonian to early Late Mississippian basin evolution is correlated with the contractional Antler orogeny of east-central Nevada. (3) The entire mid–Late Mississippian to early Early Permian phase is correlated with the transtensional(?) Humboldt orogeny of Nevada. The ancestral Rocky Mountain orogeny, driven by the distant collision of the Gondwana and Laurasian continental plates on the southeast flank of North America, was also a major influence on basin evolution during the late Early Pennsylvanian to early Early Permian. (4) Late Early Permian to Early Jurassic basin evolution is correlated in part with the contractional Sonoma orogeny of central and eastern(?) Nevada. (5) The Middle Jurassic to early Early Cretaceous phase is correlated with a Middle Jurassic episode of thrusting in eastern Nevada and western Utah. (6) Late Early Cretaceous to late Eocene basin evolution is correlated with thin-skinned contractional deformation of the Sevier orogeny of western and central Utah and with thick-skinned contractional deformation of the Laramide orogeny, which occurred west of and in the foreland of the Sevier thrust belt. The latter parts of phases one, two, four, and five were marked by relative tectonic quiescence. The orogenic events inferred to have controlled basin evolution occurred several hundred to more than a thousand kilometers from the Uinta-Piceance region, emphasizing the extent to which intraplate subsidence patterns can be sensitive indicators of plate-margin tectonics.

Within the Uinta-Piceance region, Precambrian structural grain was an important control on Phanerozoic deformation and subsidence. Three ancient structural zones, the latest Proterozoic to early Paleozoic hingeline, the Precambrian Uinta Mountain trough, and the Proterozoic Gore fault zone, were reactivated several times and were particularly important in influencing Phanerozoic deposition and deformation. These zones have continued to be active into the Quaternary.

Because of its long history of basin evolution, the Uinta-Piceance region provides an important opportunity to study the variable controls on cratonic depositional patterns and lithofacies. During periods of tectonic activity, deposition of alluvial clastic sediments was generally confined to narrow bands adjacent to tectonic highlands. Distal parts of basins were characterized by deposition of fine-grained clastic rocks that were interbedded with evaporites when circulation was restricted and climate was arid. Deposition of carbonate sediments also occurred in rapidly subsiding areas when the supply of clastic sediment was negligible. Phosphatic deposits are correlated with synorogenic basin deepening. Periods of tectonic stability were characterized by deposition of widespread alluvial deposits and (or) eolianites and (or) marine carbonate rocks.

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