Palynology and Its Relationship to Climatically Induced Depositional Cycles in the Middle Pennsylvanian (Desmoinesian) Paradox Formation of Southeastern Utah

U.S. GEOLOGICAL SURVEY BULLETIN 2000–K

Cover. View south toward the La Sal Mountains along the Colorado River between Cisco and Moab, Utah. Fisher Towers in center is composed of Permian Cutler Formation and capped by Triassic Moenkopi Formation. The prominent mesa at left center is capped by Jurassic Kayenta Formation and Wingate Sandstone and underlain by slope-forming Triassic Chinle and Moenkopi Formations. The Chinle-Moenkopi contact is marked by a thin white ledge-forming gritstone. The valley between Fisher Towers and Fisher Mesa in the background is part of Richardson Amphitheater, part of Professor Valley. Photograph by Omer B. Raup, U.S. Geological Survey.

Palynology and Its Relationship to Climatically Induced Depositional Cycles in the Middle Pennsylvanian (Desmoinesian) Paradox Formation of Southeastern Utah

By Bruce F. Rueger

EVOLUTION OF SEDIMENTARY BASINS—PARADOX BASIN
A.C. Huffman, Jr., Project Coordinator

U.S. GEOLOGICAL SURVEY BULLETIN 2000–K

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

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Palynology and Its Relationship to Climatically Induced Depositional Cycles in the Middle Pennsylvanian (Desmoinesian) Paradox Formation of Southeastern Utah

By Bruce F. Rueger[1]

ABSTRACT

The Middle Pennsylvanian (Desmoinesian) Paradox Formation of the Hermosa Group consists of a thick sedimentary wedge of strongly cyclical predominantly evaporitic rocks and minor siliciclastic units that define the areal extent of the Paradox Basin. Palynomorphs are abundant throughout the formation and provide a tool to aid in the evaluation of the climatic factors influencing cyclicity. Analysis of the palynomorph assemblage of the Paradox Formation allows construction of four distinct biofacies, from base to top, zones of *Vesicaspora*, *Striatites*, *Potonieisporites*, and *Striatites-Potonieisporites*. Analysis of a single evaporite cycle provides data significant to understanding the mechanisms influencing cyclicity. Rocks of the carbonate-siliciclastic interbeds between halite units contain palynomorphs typically associated with Desmoinesian coal beds and indicate relatively moist conditions. No palynomorphs of this type were collected from the halites of the Paradox Formation, but those collected from the interbeds indicate conditions more xeric in nature. These changes in palynomorph assemblage composition reflect an oscillation between warm, wet and cool, dry conditions. This climatic oscillation corresponds with the rock types within each cycle. Sedimentation rates for the rock types in each cycle provide a periodicity of approximately 100,000 years, which is attributable to perturbations in the eccentricity of the Earth's orbit. Palynomorph assemblages in the Paradox Formation reflect this periodicity and indicate expansion and contraction of equatorial desert or arid regions caused by the impact of continental glaciation on the global climatic regime. As Gondwanan glaciers built up, cool and dry climatic conditions developed in equatorial regions, initiating evaporite deposition. When glacial conditions relaxed, the climate became warmer and wetter and carbonate-siliciclastic strata were deposited. Vegetation in the Paradox Basin region may have responded to this climatic variability by becoming specialized, and by evolving rapidly, and may represent a source area for plants of gymnospermous and pteridospermous affinity and a plant province distinct from the Midcontinent region of the United States.

INTRODUCTION

The Paradox Formation of the Hermosa Group consists of a thick sedimentary wedge of primarily marine rocks dominated by evaporites in the Paradox Basin, a major structural and depositional basin in southeastern Utah and southwestern Colorado. It was deposited during the Middle Pennsylvanian (Desmoinesian) and has been related to a period of major worldwide eustatic sea-level rise and epicontinental transgression. The rocks of the formation are strongly cyclical in nature and are characterized by the classic vertical and lateral succession of facies associated with evaporite deposits. Each cycle is composed of chemical and clastic rocks deposited in the sequence anhydrite, silty dolomite, black shale, silty dolomite, anhydrite, and halite and terminates with an unconformity. Many theories have been advanced that address possible mechanisms controlling such cyclicity, including changes in sedimentation rate, tectonic pulses, climate fluctuations, and eustatic rise and fall of sea level, but none except those having climatic influences adequately explain the characteristics of the cycles.

A paucity of invertebrate fossils is in the evaporite facies of Paradox Formation. The high salinity of the brines that formed the Paradox Formation probably was very inhospitable to most organisms that would have existed

[1]Department of Geology, Colby College, Waterville, Maine 04901, and Department of Geological Sciences, Campus Box 250, University of Colorado, Boulder, Colorado 80309.

under normal marine conditions and is the most probable explanation for the noticeable lack of fossils. Because of high salinities, the brines were anoxic. This lack of oxygen was, however, favorable for the preservation of organic matter, and palynomorph fossils are well preserved in sediments of the Paradox Formation. These palynomorphs allow definitive dating for the Rocky Mountain region, biozonation, and regional biostratigraphic correlation and can aid in ascertaining the mechanisms inducing cyclicity.

During an investigation of water-insoluble residues collected from halite samples of the Paradox Formation, abundant diverse and exquisitely preserved palynomorphs were encountered in the organic fraction. The samples were obtained from complete, unaltered core recovered from the U.S. Department of Energy Gibson Dome No. 1 borehole, sec. 21, T. 30 S., R. 21 E., San Juan County, southeastern Utah (fig. 1). This fortuitous discovery led to further investigation, and palynomorphs were subsequently recovered in varying amounts from every halite sample, as well as from rocks of most of the other chemical and clastic facies, throughout the Paradox Formation in the borehole. These palynomorphs were the first widespread fossils to be discovered in the evaporite facies of the Paradox Formation, and they have considerable potential for biostratigraphic zonation and regional biostratigraphic correlation. Because the lithofacies and palynomorph record of the Paradox Formation is so complete and well preserved in the borehole, possibilities are afforded for biostratigraphic and paleoenvironmental studies that hopefully will add significantly to the interpretation of these evaporite deposits.

In this report I evaluate the use of the Paradox palynomorphs for precise dating, biostratigraphic zonation, and regional to intercontinental correlation at a level previously not possible from sparse foraminifera (fusilinid) data. I also analyze the palynomorph biofacies and biostratigraphic zones within the context of large- and small-scale depositional cycles of the Paradox Formation and present interpretations of environmental, climatic, and other factors that may have produced these cycles.

Acknowledgments.—I am indebted to the support and friendship offered by Robert J. Hite and Dr. Robert M. Kosanke, without whose help this project would not have reached fruition. I am also grateful for their careful and critical review of this manuscript, which has greatly improved its quality. I also acknowledge the support of Dr. Erle G. Kauffman, chairman of my M.S. thesis committee at the University of Colorado, Boulder, whose faith in me has made me a much better geologist. I am also grateful to Dr. Susan K. Short, who with Dr. Kosanke, served on my M.S. thesis committee. My wife Donna provided moral support throughout this endeavor. Alice Ridky typed the original draft of this manuscript and assisted in the development of the figures. The majority of the research presented in this investigation was completed while I held a Student Appointment with the U.S. Geological Survey.

REGIONAL GEOLOGY AND STRATIGRAPHIC SETTING

LOCATION AND CONFIGURATION OF THE PARADOX BASIN

The Paradox Basin in the east-central part of the Colorado Plateaus province extends from southeastern Utah into the Four Corners area (fig. 1). It is both a structural and sedimentary basin, the boundaries of which are delineated by the areal extent of salt deposits in the Middle Pennsylvanian (Desmoinesian) Paradox Formation of the Hermosa Group. The Paradox Basin is bounded at its northeastern margin by the Uncompahgre uplift, along its southern margin by the Defiance uplift, and along its western margin by the Monument uplift and the San Rafael Swell (fig. 1). The northeastern half of the basin is characterized by a deep trough, designated the Uncompahgre trough by Hite (1968), that contains very thick accumulations of salt (>450 m) and a series of northwest-trending salt anticlines. The southwestern half of the basin was the site of a shallow shelf and is characterized by relatively undeformed and considerably thinner salt deposits (<450 m).

LATE PALEOZOIC TECTONICS AND STRATIGRAPHY

Tectonic activity associated with elevation of the Uncompahgre uplift began to break up the stable Cordilleran shelf in the Early Pennsylvanian (Ohlen and McIntyre, 1965). This tectonic activity was accompanied by regional sagging, especially in southeastern Utah, that initiated development of the Paradox Basin. Associated with this subsidence, areas of relatively low relief evolved that surrounded the subsiding basin and delineated the areal extent of the Paradox Basin (Kelley, 1958). During the early periods of subsidence in the Middle Pennsylvanian (Atokan), marine waters invaded the area from accessways on the southeastern and western margins of the basin (Peterson and Hite, 1969). This invasion of marine waters is associated with a major rise in sea level that continued throughout the Pennsylvanian (Vail and others, 1978). As relative sea level rose, filling the newly formed basin, the soil and regolith overlying the Mississippian Leadville Limestone was reworked and redeposited as red shale of the lower part of the Molas Formation (fig. 2). This

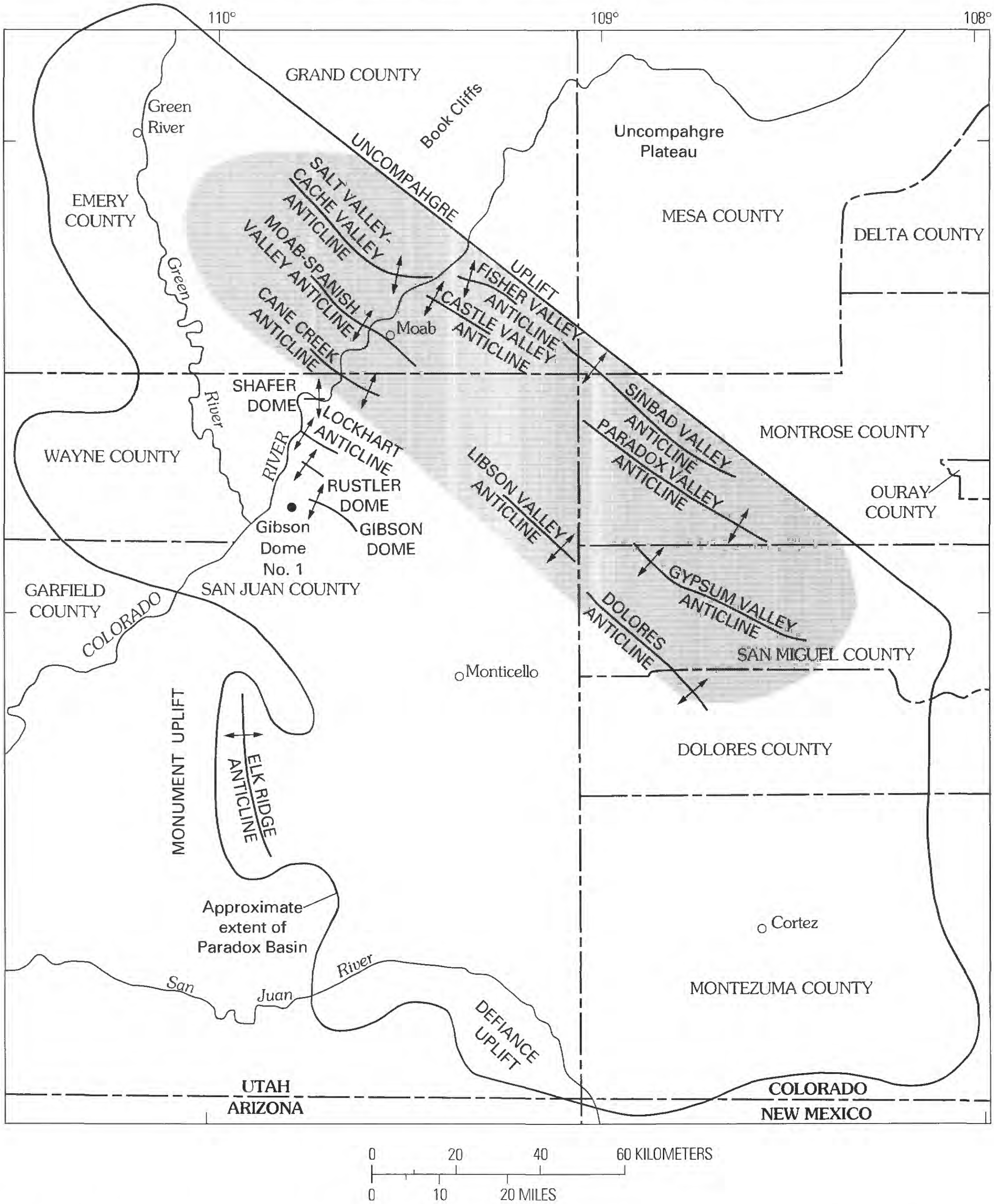


Figure 1. Map of Paradox Basin showing approximate limits of halite in the Middle Pennsylvanian Paradox Formation (heavy line) and location of Uncompahgre trough (shaded area) and uplift and Gibson Dome No. 1 borehole. Modified from Friedman and others (1994).

transgression began in the late Morrowan (Early Pennsylvanian), and by the end of Atokan time marine waters covered all but the northwestern part of the basin (Herman and Sharps, 1956). Stabilization of the basin during this time allowed deposition of shallow-water marine limestone that forms the upper part of the Molas Formation.

During Desmoinesian time, the Uncompahgre uplift once again became active, rising slowly and gently to become a dominant structure in the Paradox Basin region. Coincident with this renewed uplift, basinal sagging west of the rising Uncompahgre rapidly accelerated, especially in a major foredeep area, the Uncompahgre trough, that developed along the southwestern flank of the Uncompahgre uplift. This tectonic activity, coupled with the development of broad shelf areas and low-lying land masses on the western and southern basin margins, acted to significantly restrict marine circulation with the developing Paradox Basin (Peterson and Hite, 1969). Also

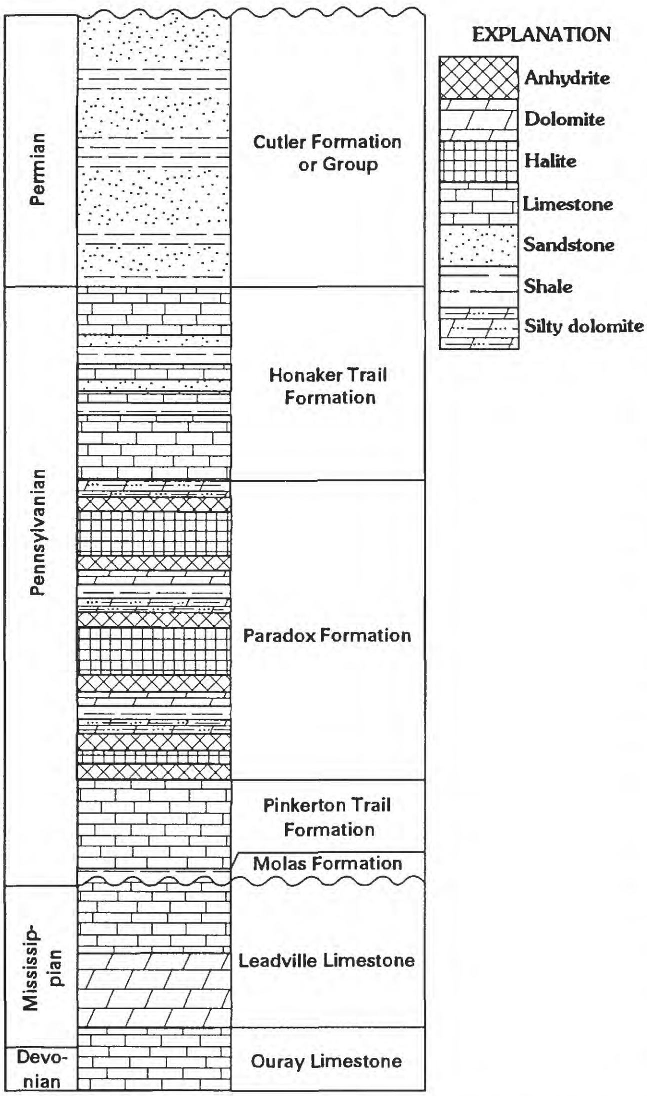


Figure 2. Generalized Late Paleozoic stratigraphy for the Paradox Basin, southeastern Utah.

during the Early Pennsylvanian, the climate changed from the warm humid environment of the Late Mississippian to a much more arid environment (Herman and Barkell, 1957).

As the Uncompahgre uplift rose, fine-grained continental sediments were shed into the Paradox Basin along its northeastern margin, and conditions suitable for carbonate deposition continued at the basin's center and along its western and southwestern margins. In the central and western part of the basin, the underlying Molas Formation grades upward into marine carbonate rocks of the Pinkerton Trail Formation of the Hermosa Group. The Pinkerton Trail Formation represents the transition from open-marine conditions of the Molas Formation to the hypersaline environment of the Paradox Formation (Bodine and Rueger, 1984).

As a result of restriction of circulation caused by continued uplift along the basin margins, and under the arid conditions prevalent during Desmoinesian time, deposition of the cyclic evaporite sequences that characterize the Paradox Formation of the Hermosa Group began. The cyclicity of the Paradox Formation is attributed to the fact that the Paradox Basin was never completely isolated tectonically; thus, evaporite deposition was controlled by small-scale sea-level oscillation related to fluctuations in continental ice volume in the Southern Hemisphere (Wanless and Shepard, 1936). As sea level fell during regressive phases and the quantity of seawater available to replace losses by evaporation was diminished, prime conditions for deposition of anhydrite, halite, and occasionally potash salts developed. Each transgressive phase began when a fresh influx of seawater lowered salinity to near-normal conditions and carbonate rocks and shale were deposited. In the Paradox Formation penetrated by the Gibson Dome No. 1 borehole, 33 of these transgressive-regressive sequences have been reported, and results from this and other boreholes show that each cycle has its own areal extent (R.J. Hite, oral commun., 1992). Deposition of these cycles initially was restricted to the foredeep area of the Uncompahgre trough and includes cycles 20–29 (fig. 3); as this foredeep area was filled, evaporite deposition began to take place across the broad southwestern shelf area continuing through cycles 1–19 (fig. 3), reaching maximum areal extent in cycles 6 and 9 (Hite, 1970).

The development of shoaling in the Late Pennsylvanian eliminated any barriers to circulation that previously had existed. Shoaling, caused by the infilling of the basin with evaporites, prevented the trapping of evaporite brines and caused reflux. Near-normal marine conditions resulted, and marine carbonate deposition resumed throughout the Paradox Basin. This carbonate facies constitutes the Honaker Trail Formation of the Hermosa Group (fig. 2) and represents the transition from hypersaline to normal marine conditions (Bodine and Rueger, 1984).

During deposition of the Hermosa Group, the Uncompahgre uplift was also shedding fine-grained clastic sediments into the basin along its northeastern margin. Deposition of these fine-grained sediments was generally confined to the northeastern side of the basin because sediment-carrying currents were unable to mix with the higher density brines of the basin (Hite, 1970). As salinity decreased during deposition of the Honaker Trail Formation of the Hermosa Group and a major tectonic pulse exposed the granitic core of the Uncompahgre uplift at the close of the Pennsylvanian Period, coarse arkosic marginal-marine and continental clastic sediments, which constitute the Lower Permian Cutler Group (fig. 2), filled the

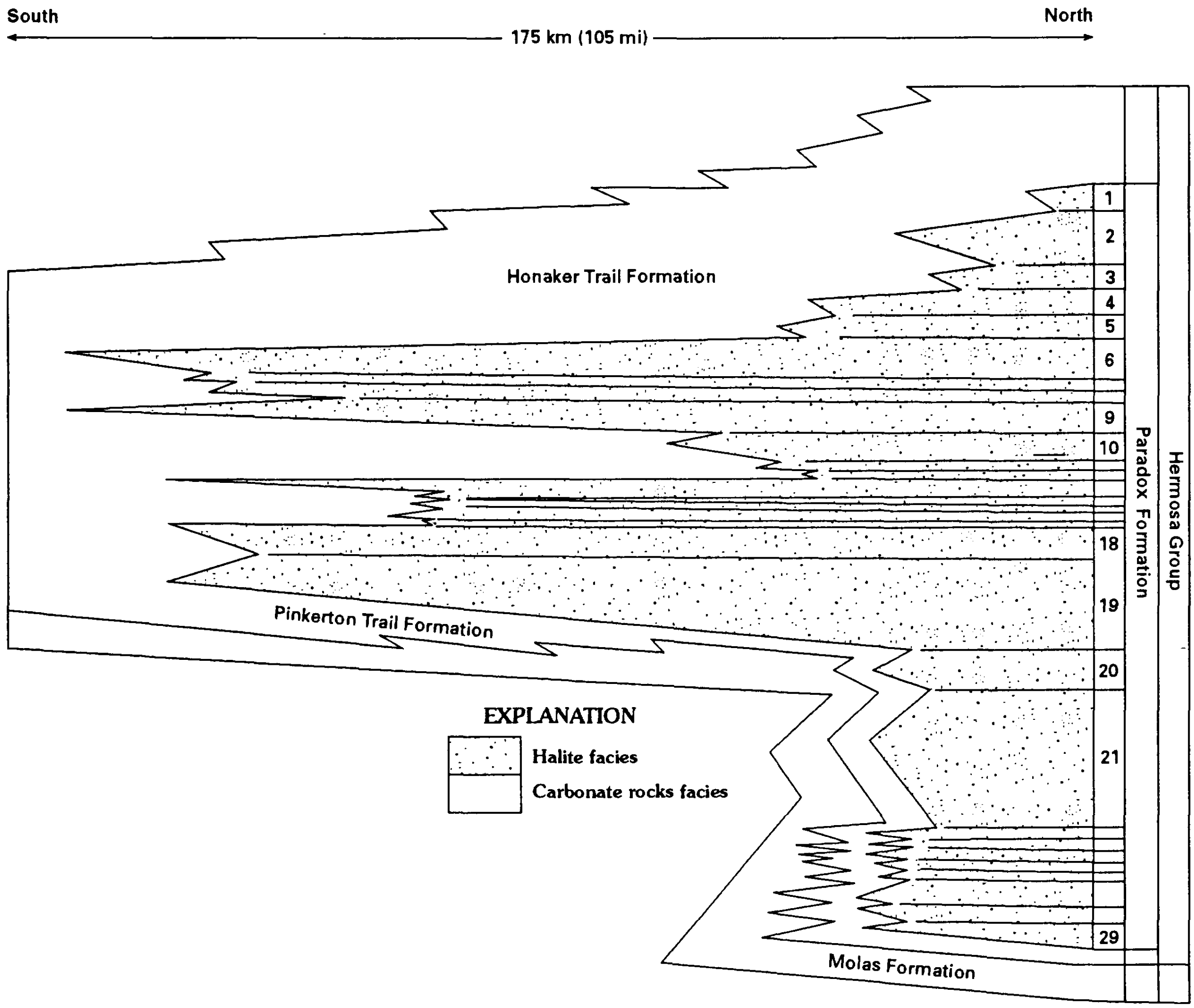


Figure 3. Diagrammatic north-south stratigraphic section showing the stratigraphic nomenclature of the Middle and Upper Pennsylvanian Hermosa Group. This relationship is similar to that toward the basin margins in all other directions. Numbered units are evaporite cycles of the Paradox Formation, which are predominantly halite. Maximum extent of evaporite deposition was during cycles 6, 9, 13, and 18. Modified from Hite and Buckner (1981).

basin. The Cutler Group represents the final episode of Paleozoic deposition in the Paradox Basin.

PREVIOUS INVESTIGATIONS CONCERNING PALYNOLOGY OF SALT DEPOSITS

Although salt deposits are present on every continent (Zharkov, 1981), only in Europe and North America has the palynology of salts of any age been investigated to any large degree. Studies in Europe are directly attributed to the pioneering work of Dr. Wilhelm Klaus, whose palynological research on the Permian Zechstein salts in the German and Austrian Alps (1953a, b, 1955, 1963, 1964, 1965, 1970, 1972, 1974) set the precedent for future study. Subsequently, Potonié and Klaus (1954), Leschik (1956), Grebe (1957), and Grebe and Schweitzer (1962) added much to the knowledge of the palynology of German Zechstein salts. Palynomorphs from Zechstein equivalents have been reported in Hungary by Déak (1959) and Stuhl (1962) and in Poland by Orlowska-Zwolinska (1962) and Dybová-Jachowicz (1974, 1978).

Since the discovery of palynomorphs in the salts of the Zechstein, other salt deposits have come under scrutiny. Palynomorphs have been reported in Mississippian deposits in the former Soviet Union by Varencov and others (1964), in Permian and Triassic deposits of the Hengelo salts of the Netherlands by Freudenthal (1964) and Visscher (1966), in Triassic salts of France by Geisler and others (1978), and in the Tertiary salt deposits of Romania by Costea and Baltes (1962) and Baltes (1967).

Palynological investigations of salt deposits in North America have been primarily directed toward the Mesozoic salt in the domes developed in the Gulf Coast region. Jux (1961), in an effort to date the formation of these salt domes, recovered Triassic and Jurassic palynomorphs from subsurface deposits in Louisiana. Later, as part of the Deep Sea Drilling Project, Kirkland (1969) recovered and described Jurassic palynomorphs from core material taken from the Challenger Knoll salt dome in the Gulf of Mexico. In a followup to this investigation, Kirkland and Gerhard (1971) also reported the occurrence of palynomorphs collected from a single sample taken from the salts of the Paradox Basin. Cousminer (1978) collected and described Jurassic palynomorphs from salt cores from the Isthmus of Tehuantepec of Mexico. Shaffer (1964), however, provided the most extensive data concerning the palynology of salt deposits of North America in his investigation of the salts within the Lower Permian Wellington Formation of Kansas. He collected samples at 1-foot intervals from two salt beds and attempted correlation between the two mines from which he obtained samples; he also determined relative abundances of important and diagnostic palynomorph genera.

My investigation adds a new dimension to the study of the palynology of salt deposits in several ways. First, it offers a technique that allows the extraction of palynomorphs from evaporite rocks in quantity and without any apparent damage to the palynomorphs. Prior to this investigation, no successful mechanism for the digestion of bulk evaporite samples had been developed. Second, core samples obtained from the Gibson Dome No. 1 borehole in the Paradox Basin yielded abundant palynomorphs throughout and thus provide the first opportunity to evaluate Carboniferous palynomorphs preserved in salt in North America. Finally, this research provides the first refined biostratigraphy for use within the Paradox Basin and for regional biostratigraphic correlation of the Paradox Formation with rocks of similar age in other basins. With the discovery of abundant palynomorphs in the salts of the Paradox Formation it was hoped that the Desmoinesian age based on fusilinids could be substantiated; however, the composition of the palynomorph assemblages extracted from the Paradox Formation presents a further problem of correlation because these palynomorphs represent a complex and unusual palynoflora that is not typically associated with the Middle Pennsylvanian but rather is associated with the Upper Pennsylvanian (Virgilian) and the Lower Permian (Wolfcampian) in the Midcontinent of the United States (Jizba, 1962; Peppers, 1964; Tschudy and Kosanke, 1966), Europe (Leschik, 1956; Klaus, 1963), and Asia (Bharadwaj and Sulujha, 1963; Bharadwaj, 1966). The relative abundance of *Striatites*, *Vesicaspora*, and *Potonieisporites* within the overall assemblage is atypical of floras obtained from Pennsylvanian coals of the world, which have been extensively studied.

EVAPORITE CYCLES OF THE PARADOX FORMATION

The evaporite cycles preserved within the Paradox Formation of the Hermosa Group are unique in that they provide a record of sedimentation that is unequaled by other known evaporite sequences, both in number and completeness. Superimposed upon a major worldwide eustatic event (Sloss, 1963; Vail and others, 1978) that reached a maximum during the Atokan and Desmoinesian Series, the 33 cycles of the Paradox Formation, because of their predominantly chemical nature, preserve a sensitive record of salinity fluctuation. As extensive coal swamps of the eastern United States developed in the more humid climate of what were then slightly northerly paleolatitudes during the Middle Pennsylvanian, evaporites of the Paradox Basin accumulated in the arid climate of the equatorial regions (Wray, 1983).

IDEALIZED EVAPORITE CYCLE

Hite (1960) observed that the depositional pattern of chemical and clastic constituents of the cycles in the Paradox Formation is very similar to the sequence of salt precipitation from seawater defined by Usiglio (1849). In Usiglio's model, as salinity is increased due to continued evaporation, more and more soluble salts are precipitated. Recognizing the similarities between Usiglio's model and the evaporites of the Paradox Formation, Hite (1970) hypothesized that the depositional cycles preserved were induced by variations in relative sea level that caused major changes in salinity. Applying the barred basin model of Ochsenius (1877), which implies restricted circulation within a basin by topographic barriers, Hite (1970) also concluded that changes in relative sea level caused a significant variation in the influx and reflux of dissolved salt into and out of the basin. When sea level is at its highest, or maximum transgressive stage, waters of a basin freely reflux with influxing waters of the open ocean. If sea level is high enough, salt load reflux equals salt load influx, and salinity increase is prohibited and normal marine sedimentation occurs. As sea level falls with regression, the barrier restricts circulation and salt load influx remains constant at the expense of reflux. As sea level continues to fall, reflux is inhibited causing a surplus of salts, and evaporites are precipitated. On the basis of this scenario, the evaporite-clastic cycles of the Paradox Formation were defined in terms of a chemical sequence that reflects a rapid decrease, followed by a gradual increase, in salinity (Hite, 1970).

The model of Hite (1970) explains the sedimentary sequence preserved in the Paradox salt cycles as follows. As marine waters of the Paradox Basin attained a point of maximum sea-level highstand, normal marine sedimentation resulted in deposition of silty, calcareous, dolomitic, organic-rich black shale (fig. 4). As sea level began to fall

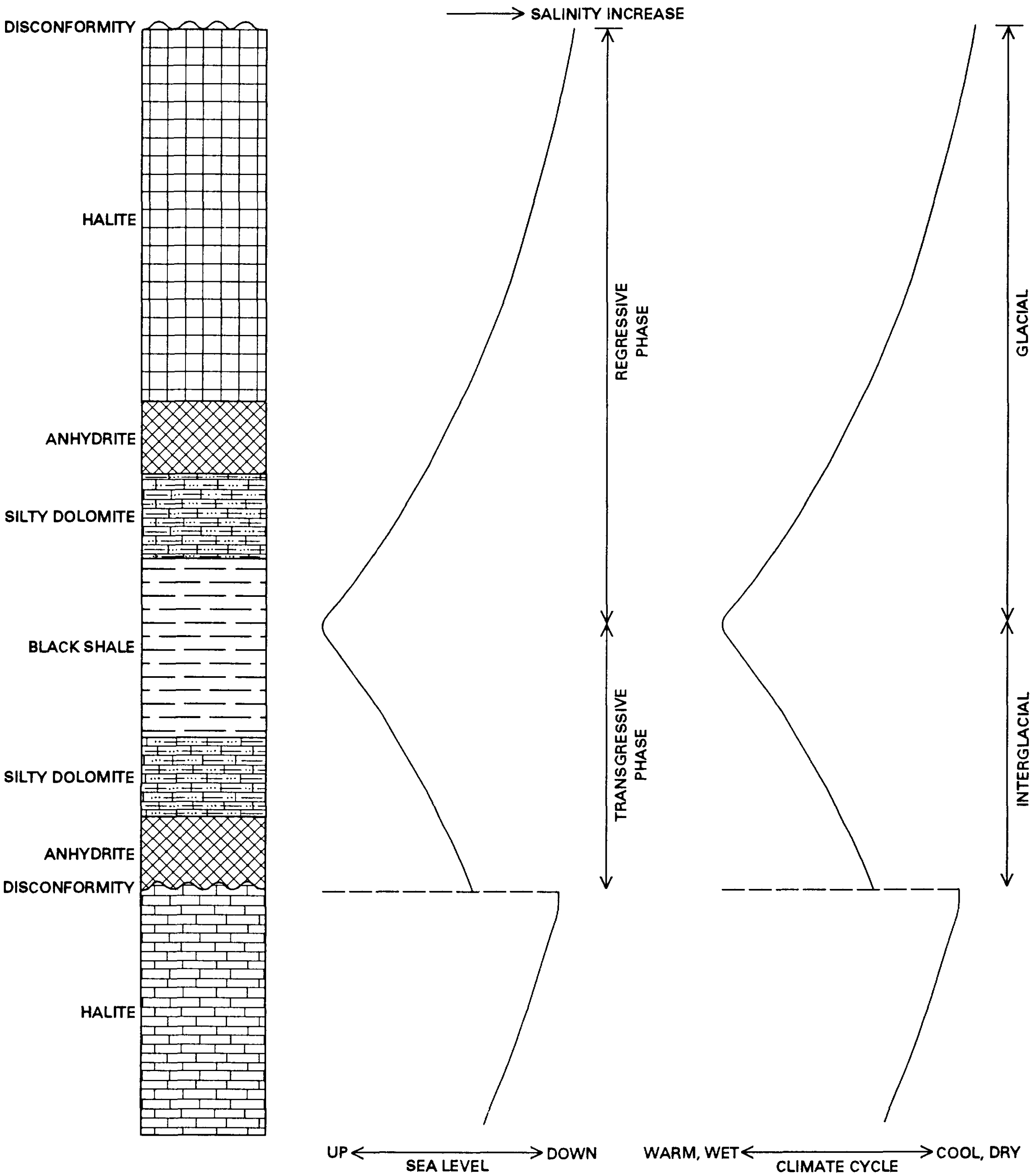


Figure 4. Idealized evaporite cycle of the Middle Pennsylvanian Paradox Formation. Relative sea-level, salinity, and climatic conditions during deposition of each facies are also shown. Rock types are shown in figure 2. Modified from Hite (1970).

and reflux was limited, evaporation exceeded mixing of normal seawater causing an increase in salinity and precipitation of silty dolomite (fig. 4). In this facies, most of the clastic material was derived from terrestrial sources (Hite and others, 1984). Continued salinity increase, sea level lowering, and less frequent mixing led to the deposition of more soluble nodular and laminar anhydrite (fig. 4), which overlies the silty dolomite facies of the cycle. When conditions of maximum salinity were attained during peak sea-level lowstand, halite, with or without potash salts, was deposited (fig. 4). Halite deposition was continuous except for occasional seasonal spurts of thin, single or multiple laminations of anhydrite or shale. These laminations are thought to represent seasonal or annual fluctuations in salinity, temperature, and clastic supply caused by variations in runoff (Hite, 1970). Halite deposition ceased when relative sea level once again began to rise and increased inflow of normal marine waters during the transgression increased reflux; salinity began to drop, initiating first deposition of anhydrite as in the regressive phase and subsequently very silty dolomite followed by black shale, as before (fig. 4).

Although this discussion suggests that the transgressive and regressive phases of the Paradox evaporite cycles are symmetrical, strong asymmetry is present. In the regressive marine phase, each of the units, black shale, silty dolomite, anhydrite, and halite, was deposited in response to gradually increasing salinity, and there is a gradual transition from one rock type to the next. Ideally, the point of maximum regression should occur at the midpoint of the halite unit; however, it can be shown, based on bromine content, that salinity continued to increase to near the top of most halite units and that there is no gradual transition with the overlying anhydrite (Hite, 1970). Potash salts, which, when present, represent conditions of highest salinity, are near the top rather than in the middle of the halite unit. The contact between the halite and the overlying anhydrite represents a sharp break in the record of sedimentation caused by rapid incursion of marine waters that redissolved some of the halite at the sediment-water interface, producing a disconformity (fig. 4). Asymmetry of the cycle is primarily the result of abrupt cessation of halite deposition, but asymmetry is also observed in the thicknesses of the transgressive and regressive hemicyclothems (fig. 4). The transgressive phase is very similar to the regressive phase in terms of lithology but represents a much more condensed section.

In developing an idealized model for the cycles in the Paradox Formation, Hite (1970) and Hite and Buckner (1981) suggested the use of the prominent disconformities at the top of each halite unit as a much more workable system of cycle boundaries than individual rock units (fig. 4). Therefore, when using the disconformities, the sequence of lithologic units in the idealized model is anhydrite, silty dolomite, black shale, silty dolomite, anhydrite, and finally halite, and the entire sequence is bounded above and below by a disconformity (fig. 4). The change from transgressive to regressive conditions occurs at the midpoint of the black shale and therefore represents the change from decreasing to increasing salinity (fig. 4).

The cycles of the Paradox Formation, because of their relative completeness, afford an excellent opportunity to evaluate the effects of climate, both direct local influences and indirect global factors, on the oscillating salinity conditions in the waters of the Paradox Basin and on the vegetation of the region. In analyzing the variations in palynomorph flora throughout the various lithologies of the cycles, the numerous theories, such as tectonism, changes in sedimentation rate and climate, proposed as possible mechanisms causing cyclicity can be evaluated. To accomplish this, palynomorph assemblages were analyzed in two ways, first by looking at changes throughout the entire Paradox Formation and then by studying a single evaporite-clastic cycle. It was hoped that a complete cycle within the Paradox Formation could be analyzed as a continuous sequence, but restrictions on sampling and previous bulk sampling precluded this opportunity, leaving the halites of salt cycle 7 and the transitional interbeds between the halites of cycles 8 and 9 as the only alternatives (fig. 3).

EVAPORITE CYCLE 7

The halite facies of evaporite cycle 7 (fig. 3) represents microvariations of hypersalinity during deposition. This facies is composed of numerous anhydrite-halite couplets in which halite is the dominant lithology and anhydrite is present as thin bands separating the halite units. Precipitation of the evaporites in cycle 7 was induced by a continued increase in salinity. As salinity continued to rise, minor episodes of potash salt deposition occurred as the result of saturation of the brines of the basin with respect to potash minerals. Sylvite is present in cycle 7 only as small isolated crystals in the upper part of the salt unit. Precipitation of halite and sylvite in cycle 7 and in all halite beds of the Gibson Dome No. 1 core was also contemporaneous with precipitation of thin sulfate laminae, each averaging 0.80 mm in thickness, that are thought to represent periods of annual replenishing of SO_4 ions in the basin by marine influx (Hite, 1983a). It is not known whether these laminae were anhydrite or gypsum when precipitated.

The halite facies of cycle 7 is 20.4 m thick, and the base of this deposit is transitional with the anhydrite below. Above the transitional contact, the halite facies of cycle 7 is a massive halite deposit containing regularly spaced (4.0-cm intervals) bands of anhydrite. Near the top of cycle 7, halite is intercalated with scattered crystals of potash salts. Precipitation of halite was dominant within cycle 7 until its deposition was terminated by a rapid influx of much lower salinity waters that dissolved the upper part of the halite of cycle 7 and produced a disconformity between cycle 7 and the carbonate-siliciclastic facies of cycle 6.

INTERBED 8–9

The carbonate-siliciclastic facies that separates the halite facies of cycles 8 and 9, herein designated interbed 8–9, represents deposition under conditions of changing salinity and sea level. In interbed 8–9 anhydrite was deposited first, followed by silty dolomite and black shale. At the end of black shale deposition the sequence was reversed, and silty dolomite followed by anhydrite were deposited. Interbed 8–9 represents an imperfect Hite cycle because minor salinity fluctuations are apparent. These minor salinity fluctuations are preserved as duplication of black shale and

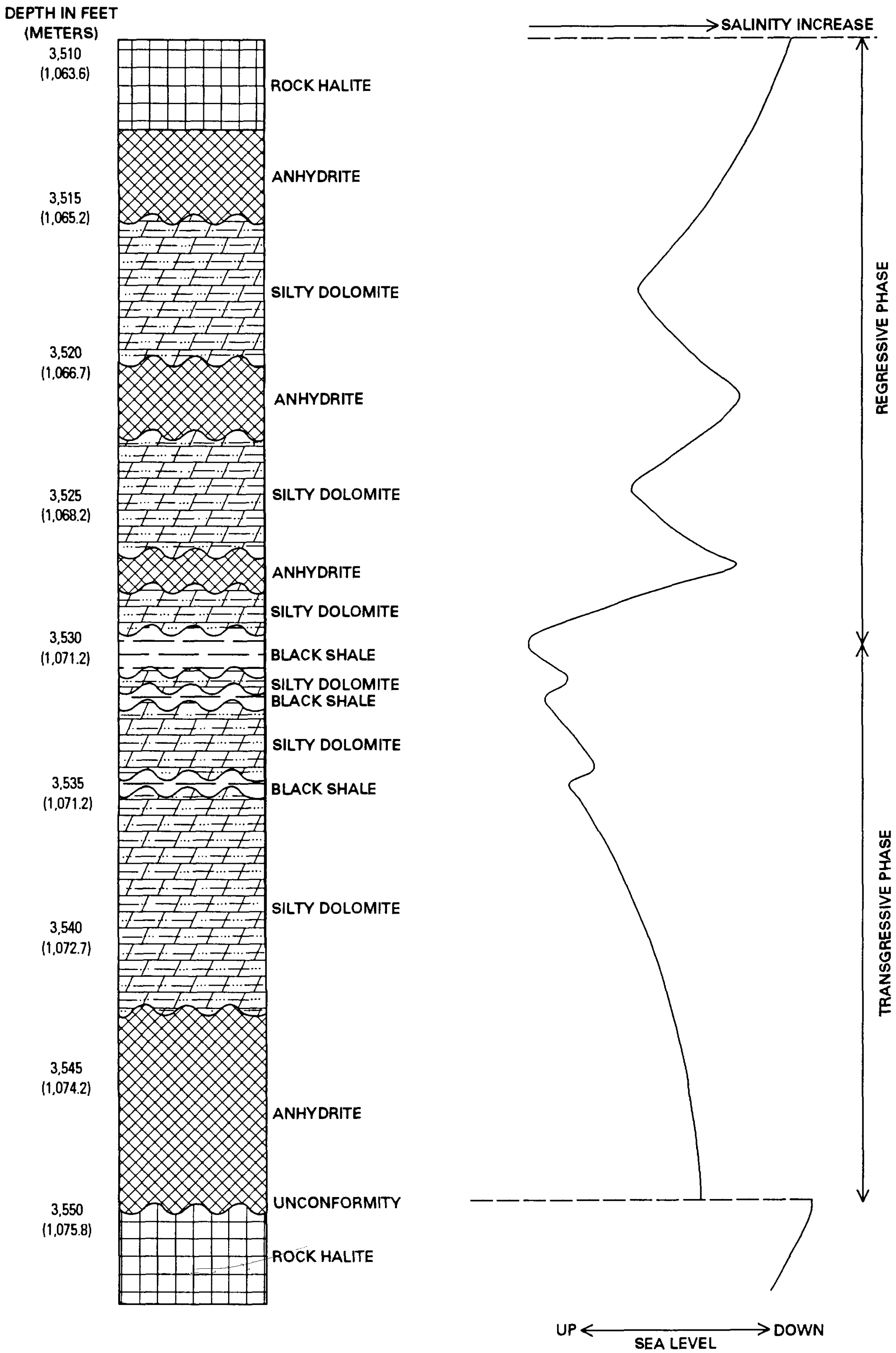


Figure 5. Generalized lithologic section of interbed 8–9 of the Middle Pennsylvanian Paradox Formation showing relative sea-level and salinity conditions during deposition of each facies. Modified from Hite (1970).

anhydrite units within the carbonate-siliciclastic facies designated interbed 8–9 (fig. 5). Deposition of interbed 8–9 was initiated by a rapid decrease in salinity associated with a sudden influx of normal marine water during transgression. These conditions produced the bedding sequence of anhydrite through black shale (fig. 5). They were followed by a gradual increase in salinity and a corresponding drop in sea level and associated marine regression. As salinity increased after the clastic sedimentation of black shale, the lithologies of silty dolomite and anhydrite in interbed 8–9 (fig. 5) reflect the succession of salt precipitation described by Usiglio (1849).

The deposits of interbed 8–9 are 11.1 m thick, and the base of these carbonate-siliciclastic facies is marked by a disconformity that has been used to designate the boundary with cycle 9 (Hite, 1970) and also represents initiation of the transgressive phase of deposition (fig. 5). The decrease in salinity as a result of this transgression resulted in deposition of 1.9 m of sulfate mineral, preserved as nodular and laminar anhydrite. This period of sulfate precipitation was followed by the deposition of 3.6 m of very silty dolomite in response to a further decrease in salinity (fig. 5). Many of the beds in this silty dolomite unit were disturbed by fluid-release phenomena that are preserved as sedimentary structures. The high silt content of the silty dolomite reflects significant terrigenous clastic influx attributed to runoff (R.J. Hite, written commun., 1994). Deposition of this very silty dolomite unit was interrupted twice by deposition of black, carbonaceous shale beds, each approximately 0.1 m thick, that represent minor sea-level oscillations during transgression (fig. 5). A 0.3-m-thick bed of black carbonaceous shale caps this sequence (fig. 5); this bed is the thickest accumulation of shale in this cycle and represents the point of maximum transgression, free mixing of normal marine waters, and the period of minimum salinity.

As conditions of salinity began to reverse and increase with the onset of regression, black shale deposition continued but gradually changed to deposition of a very thin (0.33 m) bed of silty dolomite that has a significantly lower silt content than the silty dolomite deposited during the transgressive phase (fig. 5) (Hite, 1970). This thin silty dolomite grades into a much thicker (3.1 m) anhydrite unit reflecting further increase in salinity (fig. 5). The anhydrite unit is predominantly nodular at its base and laminar and massive toward its top. Precipitation of the anhydrite unit was also interrupted by two major periods of silty dolomite deposition—deposition of a lower bed 1.2 m thick and deposition of a bed 1.5 m thick—that again represents sea-level oscillation (fig. 5). The uppermost part of the anhydrite unit is transitional into the overlying halite of cycle 8, and many halite laminae and inclusions are present within the upper 1.0 m of anhydrite.

COMPARISON WITH IDEALIZED CYCLE OF HITE

In comparing the observed depositional sequence of evaporites in cycle 7 with that described in the model proposed by Hite (1970), the similarities are striking. At the base, both salt units are transitional with the underlying anhydrite and both rapidly become massive halite deposits. Each salt unit is characterized by anhydrite laminae of varying thickness. As in the model, potash salts, which are present in cycle 7 as minor constituents, are near the top of the salt unit. Due to their stratigraphic position, the potash salts give the cycle a lithologic asymmetry that is also consistent with the model.

Complementing the lithologic asymmetry of the potash salts, a profile of bromine distribution in cycle 7 derived by X-ray fluorescence (fig. 6) reflects changes in salinity based on changes in bromine concentration in the salts precipitated from the basin brines and documents the chemical asymmetry that is called for by the model. The bromine profile indicates a period of relatively stable salinity during early deposition of halite near the base of cycle 7. The sudden increase in bromine concentration indicates an increase in salinity, which resulted in potash precipitation further into the basin. This increase in salinity continued until salt precipitation ended, marked by a disconformity.

Sediments of the transitional rocks of interbed 8–9 reflect, on the other hand, several minor deviations from the model of Hite, although, in general, deposition occurred as described. Deposition was initiated by an abrupt decrease in salinity associated with the rapid influx of normal marine waters into the basin. This event is preserved as a sharp contact between the salt of cycle 9 and the lowermost anhydrite of interbed 8–9 (fig. 5). This anhydrite grades into a silty dolomite, thought to correspond with a rise in sea level and decreasing salinity (Hite, 1970) (fig. 5).

It is at this point that the depositional sequence of interbed 8–9 begins to deviate from that of the model. Silty dolomite is overlain by a thin black shale bed that immediately grades back into silty dolomite reflecting a minor oscillation of salinity and, possibly, sea level. A second oscillation caused repetition of the sedimentary sequence before conditions of minimum salinity were achieved, and conditions ultimately reversed, initiating regression (fig. 5).

Black shale deposition ended suddenly, and precipitation of silty dolomite was initiated with continued regression (fig. 5). Adhering to the model of Usiglio (1849), silty dolomite deposition should have been followed by precipitation of anhydrite. Again, the depositional model does not precisely match the sequence of facies in this example: anhydrite, which should be overlain by halite, actually grades into silty dolomite, indicating a brief reversal in environmental conditions that control the cycles (fig. 5). This type of reversal is present twice before the uppermost anhydrite grades

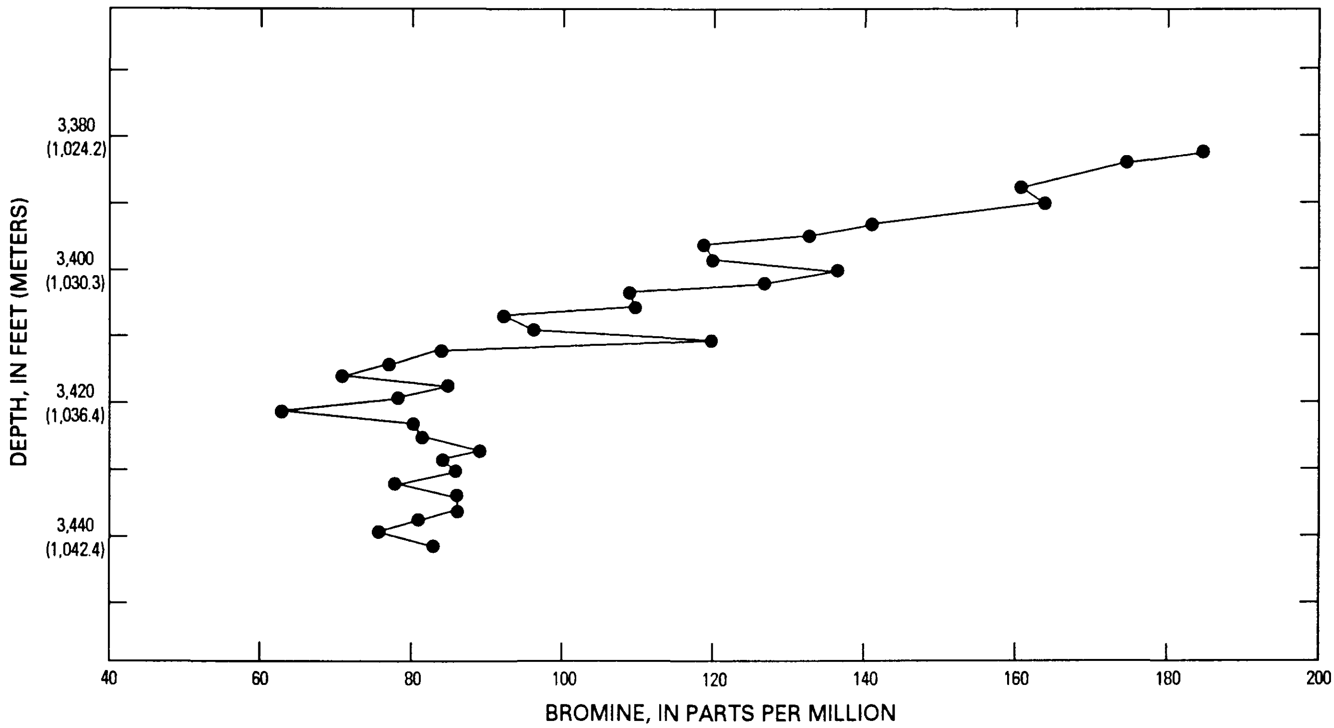


Figure 6. Bromine distribution in evaporite cycle 7 of the Middle Pennsylvanian Paradox Formation, Gibson Dome No. 1 borehole. Analysis by X-ray fluorescence (Hite, 1983b, fig. 7). Location of borehole is shown in figure 1.

into halite, indicating development of maximum salinity in the basin (fig. 5).

Although the deposits of interbed 8–9 may vary in regards to the model, all the elements defined by Hite (1970) are evident. Only minor fluctuations of sea level, climate, or subsidence history are required to explain the repetition of some of the units within the cycle. The observed differences in the depositional sequences do not surpass the expected limitations inherent in a generalized model such as this, and hence the model of Hite (1970) is used in subsequent discussions of the cycles within the Paradox Formation.

CLIMATIC FACTORS INFLUENCING CYCLIC SEDIMENTATION

As a result of the definition of numerous cyclothems in the Middle Pennsylvanian sequence of the Eastern Interior Basin of the United States by Weller (1930, 1931), Pennsylvanian cyclicity has attracted considerable interest due to recognition of its correlative worldwide scale. Since the time of the recognition of Pennsylvanian cyclothems, considerable debate has developed, however, regarding possible mechanisms controlling the cyclic sedimentation inherent to those deposits. Fortuitously, the Paradox Formation of southeastern Utah, with the unusual preservation of 33 halite-bearing evaporite-clastic cycles and the presence of abundant, well-preserved palynomorphs, provides an excellent opportunity to investigate the driving mechanisms controlling cyclicity in such deposits and, especially, to test the role of climatic variability.

Shortly after Weller (1930) defined the Pennsylvanian cyclothems of the Eastern Interior Basin and proposed tectonism as the dominant control influencing cyclicity, Wanless and Shepard (1936) presented a convincing argument documenting the existence of Gondwanan continental glaciation throughout much of the late Paleozoic. Using this evidence, they offered a hypothesis that sea-level fluctuation, strongly influenced by glacial accumulation and ablation, provided a mechanism for cyclic deposition of epeiric facies during the Pennsylvanian Period. In their hypothesis, decrease and increase of ice mass volume were associated with cyclic changes in the worldwide climate system and, in addition, caused alternate episodes of transgression and regression in the Eastern Interior Basin. This mechanism was considered to be responsible for the lithologic variations noted within each of these cyclothems. Accumulation of large continental ice masses would have caused dramatic changes in relative humidity on a worldwide basis, which in turn would strongly influence amounts of precipitation, even in regions far removed from glaciated areas. As the volume of glacial ice grew, humidity would drop in equatorial regions and sea level would fall, restricting marine connections with inland seas. These conditions would allow the precipitation of evaporites such as those in the Paradox Basin, and ablation of glacial ice would cause a reverse situation to occur. Wanless and Shepard (1936) cited the combined effects of periodic perturbations of the Earth's eccentricity, inclination of the Earth's axis, and the migration of perihelion—all related to the 100,000-, 42,000-, and 21,000-year cycles defined by Milankovitch—as the regulating mechanism for climatic changes that may have controlled glacial cycles and induced the development of the Pennsylvanian cyclothems of the United States and elsewhere. In a subsequent investigation, Wanless and Patterson (1951) extended this study of cyclic sedimentation in the Eastern Interior Basin (Wanless and Shepard, 1936) to Pennsylvanian rocks of the southwestern United States. They attributed the cyclic deposition of evaporites in the Paradox Basin to an increase in aridity caused by the same global climatic fluctuations described earlier.

In a more recent investigation, Hite and Buckner (1981) applied relative sedimentation rates for halite (4.0 cm/year), anhydrite (0.08 cm/year), dolomite (0.017 cm/year), and shale (0.21 cm/year) to these rock types within the cycles of the Paradox Formation and documented the approximate 100,000-year nature of these cycles. In an attempt to determine a possible mechanism for the Paradox cycles, Hite and Buckner (1981) also relied on global climatic factors induced by changes in ice volume that directly influenced eustatic changes in sea level and indirectly modified regional climatic regimes. Together these factors caused the development of cyclicity observed in the Paradox Formation. The glacio-eustatic hypothesis of Hite and Buckner (1981) proposes that changes in water volume in the Paradox Basin during the Pennsylvanian Period were directly related to changes in ice volume in the Southern Hemisphere.

In the Milankovitch theory, three types of orbital perturbations act to influence the Earth's climate on a global scale (Covey, 1984). The dominant influence on the global climate regime is attributed to fluctuations in the Earth's eccentricity as it travels about the Sun. These fluctuations occur in cycles of approximately 100,000 years. Perturbation of 42,000 years, due to changes in the tilt of the Earth's axis (obliquity), and 21,000 years, caused by variations in precession of the North Pole, also act to influence the Earth's global climate system. It should be noted, however, that, although the shorter cycles should potentially have a much greater influence on the amount of solar insolation received by the Earth and hence a greater effect on the Earth's climate, it is the perturbations of the eccentricity with a periodicity of 100,000 years that appear to dominate global climate regimes, at least during the Pennsylvanian. The influence of changes in orbital eccentricity may have a much greater effect on world climate because these perturbations occur at a frequency near the natural frequency of the world's climate system and thereby force the effects of the 100,000-year periodicity over those of the 42,000- and 21,000-year cycles (Covey, 1984).

Because of the location of the Paradox Basin at 10° N. paleolatitude (Wray, 1983), there are two potential ways in which the climate could have been modified in response to the orbital perturbations described by the Milankovitch theory and subsequently could have acted to influence the cyclicity observed in the Paradox Formation (E.J. Barron, oral commun., 1984). Of these factors, the most obvious climatic influence on the deposits of the Paradox Formation is the changes in orbital variation that modify the climate by altering the amounts of solar insolation received by the Earth at different latitudes and seasons. Effects of varying amounts of solar insolation are greatest in the northern latitudes and influence the development of polar ice masses. These ice masses increase and decrease in response to changes in the eccentricity of the Earth's orbit around the Sun. Accumulation and melting of ice masses would have a major influence on the water volume of inland seas such as the Paradox Basin. Changes in ice volume would have global implications on climate.

Due to the equatorial location of the Paradox Basin, the Milankovitch periodicity could have modified the climate of the region on a 100,000-year basis. The first of these modifiers is very appealing to the understanding of cyclic sedimentation of the Paradox Formation in that it documents the development of desert areas in equatorial regions of the world during Pleistocene glacial periods (Sarnthein, 1978). Development of extensive sand dunes during Pleistocene glaciation indicated an arid climatic optimum during the glacial maximum. This arid situation was enhanced because, even though temperatures were lower due to accumulation of ice masses, decreases in precipitation and increased wind intensity increased total evaporation (Sarnthein, 1978). Similar conditions of high aridity have been observed in the tropical regions during Gondwanan glaciation during the late Paleozoic (Wanless and Patterson, 1951), and this mechanism could have greatly influenced the climate of the Paradox Basin.

The second of the two regional climatic factors that potentially could have developed in response to Milankovitch periodicity, and could have influenced the deposition of the Paradox Formation, involves the circulation of air masses in the tropics and the relationship of land masses to ocean basins (Manabe and Hahn, 1977). The climate model of Manabe and Hahn illustrates a situation in which the climate of the tropics during maximum glaciation is considerably drier than during periods of glacial minimum. This tropical aridity can be ascribed to air circulation phenomenon whereby surface outflow from the continents is greater than surface inflow from the oceans and thus precludes precipitation (Manabe and Hahn, 1977). Stronger outflow enhances sinking and reduces precipitation over tropical continents. This effect could have possible implications in the Paradox Basin region, but, because of the proximity of the continents, separated only by a narrow oceanic belt at the equator (Parrish, 1982), the surface inflow-outflow circulation pattern would be weak, at least during the Pennsylvanian.

It is hypothesized that changes in climate should influence the distribution of vegetation in the Paradox Basin and that these changes should be reflected in the abundant palynomorph assemblages discovered in the Paradox Formation. If changes in the palynoflora indeed are observed, a major question is which of two climatic factors—both attributable to Milankovitch periodicity—was dominant in the Paradox Basin.

PALYNOLOGY OF THE PARADOX FORMATION

SAMPLES AND LOCATION

As part of an investigation to evaluate the suitability of salt in the Paradox Formation of the Hermosa Group for underground disposal of nuclear waste, the U.S. Department of Energy contracted Woodward-Clyde Consultants to drill and core the Gibson Dome No. 1 borehole in sec. 21, T. 30 S., R. 21 E., San Juan County, Utah (fig. 1). This borehole, on the southeast-plunging nose of Gibson Dome, a small salt anticline in the Paradox Basin, was drilled to a depth of 1,946.4 m with the coring beginning 127 m below Kelly bushing. This yielded 1,819 m of 4-inch-diameter core (Bodine and Rueger, 1984). Drilling began in the Lower Permian Cutler Group, with coring starting at a depth of 127 m, and passed through the Pennsylvanian Hermosa Group and the Molas Formation as well as the Mississippian Leadville Limestone and was completed 9.8 m below the Mississippian-Devonian contact in the Upper Devonian Ouray Limestone (fig. 2).

All samples used in this investigation were collected from the Paradox Formation penetrated by the borehole and are listed in table 1. The intervals given in table 1 represent the depth of the sample below Kelly bushing, which was 5.2 m above ground surface.

SAMPLE PREPARATION

Because many of the samples used in this investigation were collected from an evaporite sequence, modifications of standard palynomorph extraction techniques were necessary. Samples collected from halite and anhydrite were first washed in distilled water to remove any readily water soluble minerals, namely halite, sylvite, and carnallite. Most of the palynomorphs were still held within the resulting water-insoluble residue composed primarily of sulfate, carbonate, and silicate minerals. These residues presented a major problem in preparation. Although carbonate and silicate minerals can be easily removed by conventional techniques utilizing hydrochloric and hydrofluoric acids, respectively, sulfate minerals are generally unaffected by these acids.

In an attempt to alleviate this problem, many alternative techniques were considered and tried, including modifications of the standard acid technique for evaporite rocks by Sittler (1955), Freudenthal (1964), and Visscher (1966) and the use of potassium hydroxide as suggested by Déak (1959), but none of these methods proved satisfactory. However, while working on an investigation of the clay mineralogy of the Paradox evaporites, I made use of a very simple, yet highly effective technique that was developed by Bodine and Fernalld (1973) for the separation of clay minerals from evaporite host rocks. This same technique was modified slightly for the extraction of palynomorphs from evaporite rocks (Rueger, 1986) and allows the complete removal of both sulfate and carbonate minerals from the water-insoluble residue by the use of an EDTA (ethylenedinitrilotetraacetic acid) solution.

After removal of the evaporite minerals, the remaining silicate-dominated residue was removed by treatment with hydrofluoric acid, and the palynomorphs were concentrated using heavy liquid separation as described by Doher (1980).

Samples collected in shale, dolomitic siltstone, and silty dolostone were processed using standard palynomorph extraction techniques also described by Doher (1980).

Slides were prepared from the organic residue using canada balsam as a mounting medium. Slides were labeled giving sample designation and slide number for future reference. A complete set of slides including type and all illustrated specimens will be deposited in the type collections of the Department of Paleobiology, U.S. National Museum, Washington, D.C.

PRESERVATION OF PALYNOMORPHS

Typically, preservation of palynomorphs in evaporite deposits is extraordinary and is directly influenced by the geochemical nature of the evaporite environment. Because most evaporites are precipitated directly from seawater, palynomorphs suspended in the water column are readily incorporated into the evaporite rock as it forms, and little or no abrasive or corrosive damage is done to the palynomorph once it reaches the depositional surface of the evaporite basin (Klaus, 1970). The degree of preservation observed in the palynomorphs recovered from the evaporite-clastic rocks of the Paradox Formation is extremely variable, ranging from exquisite to very poor.

A substantial number of the samples collected from the Paradox evaporites yielded palynomorphs in an extraordinary state of preservation. These well-preserved specimens, which were collected from the halites, are unbroken and undeformed and show little or no evidence of corrosion or abrasion. However, these exceptional palynomorphs were also found in association with a much larger number of

Table 1. Lithology and location of palynological samples collected from the Gibson Dome No. 1 borehole, San Juan County, Utah, sec. 21, T. 30 S., R. 21 E.
[Salt cycles are from Hite (1960)]

Sample No.	Salt cycle	Depth below Kelly bushing (feet)	Depth below Kelly bushing (meters)	Lithology
GD1–472	5	2,981.8–2,983.7	903.6–904.2	Rock halite with anhydrite laminae.
GD1–237	6	3,242.9–3,243.3	982.7–982.8	Rock halite with anhydrite laminae.
GD1–239	6	3,312.2–3,312.6	1,003.7–1,003.8	Rock halite with anhydrite laminae.
GD1–240	6	3,324.1–3,324.5	1,007.3–1,007.4	Rock halite with anhydrite laminae.
GD1–325	7	3,377.5–3,377.9	1,023.5–1,023.6	Rock halite with anhydrite laminae.
GD1–326	7	3,399.7–3,400.1	1,030.2–1,030.3	Rock halite with anhydrite laminae.
GD1–327	7	3,421.3–3,421.7	1,036.8–1,036.9	Rock halite with anhydrite laminae.
GD1–328	7	3,435.2–3,435.6	1,041.0–1,041.1	Rock halite with anhydrite laminae.
HR–3	8	3,515.4–3,515.6	1,065.27–1,065.33	Anhydrite with silt stringers and halite inclusions.
HR–4	8	3,518.8–3,519.0	1,066.3–1,066.4	Dark-gray dolomitic siltstone.
HR–5	8	3,525.0–3,525.1	1,068.18–1,068.21	Gray dolomitic siltstone.
HR–6	8	3,530.5–3,530.8	1,069.8–1,069.9	Black carbonaceous shale.
HR–7	8	3,545.4–3,545.5	1,074.36–1,074.39	Black silty dolostone.
GD1–319	13	3,924.5–3,925.0	1,189.2–1,189.4	Rock halite with anhydrite laminae.
GD1–596	15	4,147.8–4,149.7	1,256.9–1,257.5	Rock halite with anhydrite laminae.
GD1–624	18	4,716.3–4,716.7	1,429.2–1,429.3	Rock halite with anhydrite laminae.
GD1–625	19	4,856.3–4,856.7	1,471.6–1,471.7	Rock halite with anhydrite laminae.
GD1–626	19	4,954.2–4,954.6	1,501.3–1,501.4	Rock halite with anhydrite laminae.
GD1–597	21	5,113.8–5,116.1	1,549.6–1,550.3	Rock halite with anhydrite laminae.
GD1–627	21	5,138.3–5,138.7	1,557.1–1,557.2	Rock halite with anhydrite laminae.
GD1–628	21	5,211.3–5,211.7	1,579.2–1,579.3	Rock halite with anhydrite laminae.
GD1–629	24	5,313.3–5,313.7	1,610.1–1,610.2	Rock halite with anhydrite laminae.
GD1–598	24	5,314.2–5,316.0	1,610.4–1,610.9	Rock halite with anhydrite laminae.
GD1–630	24	5,380.3–5,380.7	1,630.4–1,630.5	Rock halite with anhydrite laminae.
GD1–631	25	5,462.3–5,462.7	1,655.2–1,655.4	Rock halite with anhydrite laminae.
GD1–632	25	5,485.3–5,485.7	1,662.2–1,662.3	Rock halite with anhydrite laminae.
GD1–599	26	5,503.2–5,504.5	1,667.6–1,668.0	Rock halite with anhydrite laminae.

grains that are crumpled, folded, corroded, and abraded and have been rendered unidentifiable. This high degree of variance in preservation can be attributed to the processes by which the palynomorphs were transported into the basin. It is highly likely that those grains exhibiting the best preservation were carried into the basin by wind, a mechanism to which many of the bisaccate and monosaccate palynomorphs are extremely well adapted. The poor preservation of the remaining palynomorphs can be attributed to transport into the Paradox Basin by streams or by marine reflux during transgression. These grains were probably subjected to much more abrasion, and possibly corrosion, than those carried by wind. The presence of many well-preserved grains probably introduces a degree of bias in terms of evaluating the degree of preservation of the palynomorphs recovered from the Paradox Formation.

Preservation of specimens extracted from the interbed deposits of the Paradox Formation is generally of lesser overall quality than that of those recovered from halites. The interbed samples yielded a much greater quantity of broken, abraded, and corroded palynomorphs than the halite samples, and identification was difficult. No palynomorphs were recovered from sample HR–3 (table 1), which was collected from anhydrite, probably because the anhydrite of the interbeds was likely precipitated as gypsum that was subsequently dehydrated to form anhydrite. Most likely any palynomorphs in the gypsum were destroyed in the process of dehydration. Samples HR–4, HR–5, and HR–6 (table 1), collected from dolomitic siltstone and black shale, yielded a large quantity of palynomorphs and organic matter, but, because of the geochemical nature of these rocks, most grains were highly corroded, and identification was difficult if not impossible in some cases. One unusual sample, HR–7 (table 1), collected from dolomitic siltstone, yielded extremely well preserved palynomorphs on a par with those obtained from the halite samples. This occurrence of well-preserved palynomorphs may indicate the development in the water column of primary dolomite that was later precipitated as sedimentary particles along with the palynomorphs rather than by recrystallization of calcium carbonate.

Another peculiar aspect of the palynomorphs extracted from the rocks of the Paradox Formation is the inability of the palynomorphs to take and hold an organic stain, even after the palynomorphs were subjected to stain over a long period of time (as long as 1 hour). This characteristic may be attributed to the modification of organic compounds by the evaporite brines and has been noted by other palynologists studying specimens collected from salts (Klaus, 1955; Baltes, 1967; Kirkland and Gerhard, 1971).

LITHOLOGIC OCCURRENCE OF PALYNOMORPHS

Palynomorph distribution was generally widespread and abundant, regardless of host lithology. Palynomorphs were recovered from all rock types sampled in the Gibson Dome No. 1 drillhole (table 1) except those taken from the anhydrite of interbed 8–9. Although barren in terms of identifiable palynomorphs, very minute organic particles were abundant in this anhydrite sample and tiny fragments of palynomorphs were recovered. The fragmented state of these palynomorphs is attributed to dehydration of gypsum to form anhydrite, as described earlier. Samples collected from halite containing numerous anhydrite laminae invariably yielded more palynomorphs than any other rock type analyzed. Samples of halite having a greater spacing of anhydrite laminae also yielded palynomorphs but in fewer numbers. This observation can be directly related to sedimentation rate in that halite is precipitated much more rapidly than anhydrite so there is greater rock volume per unit time accumulated and hence palynomorph concentration is not as great as it is in the anhydrite laminae. It has also affected the number of countable grains per sample, and consequently some samples did not have an adequate number of grains (minimum 300) for statistical analysis. Samples collected from the interbed material, excluding anhydrite, also yielded palynomorphs in significant numbers, but many were poorly preserved. Sample HR–7 (table 1) had the greatest abundance of palynomorphs of all the interbed samples.

STRATIGRAPHIC OCCURRENCE OF PALYNOMORPHS

The stratigraphic distribution of palynomorphs obtained from samples collected in the Paradox Formation was evaluated at three levels. First, the palynoflora of the Paradox Formation is dominated by monosaccate and bisaccate palynomorphs, and the initial level of evaluation determined the relative abundance of monosaccate, bisaccate, and cryptogamic and other palynomorphs.

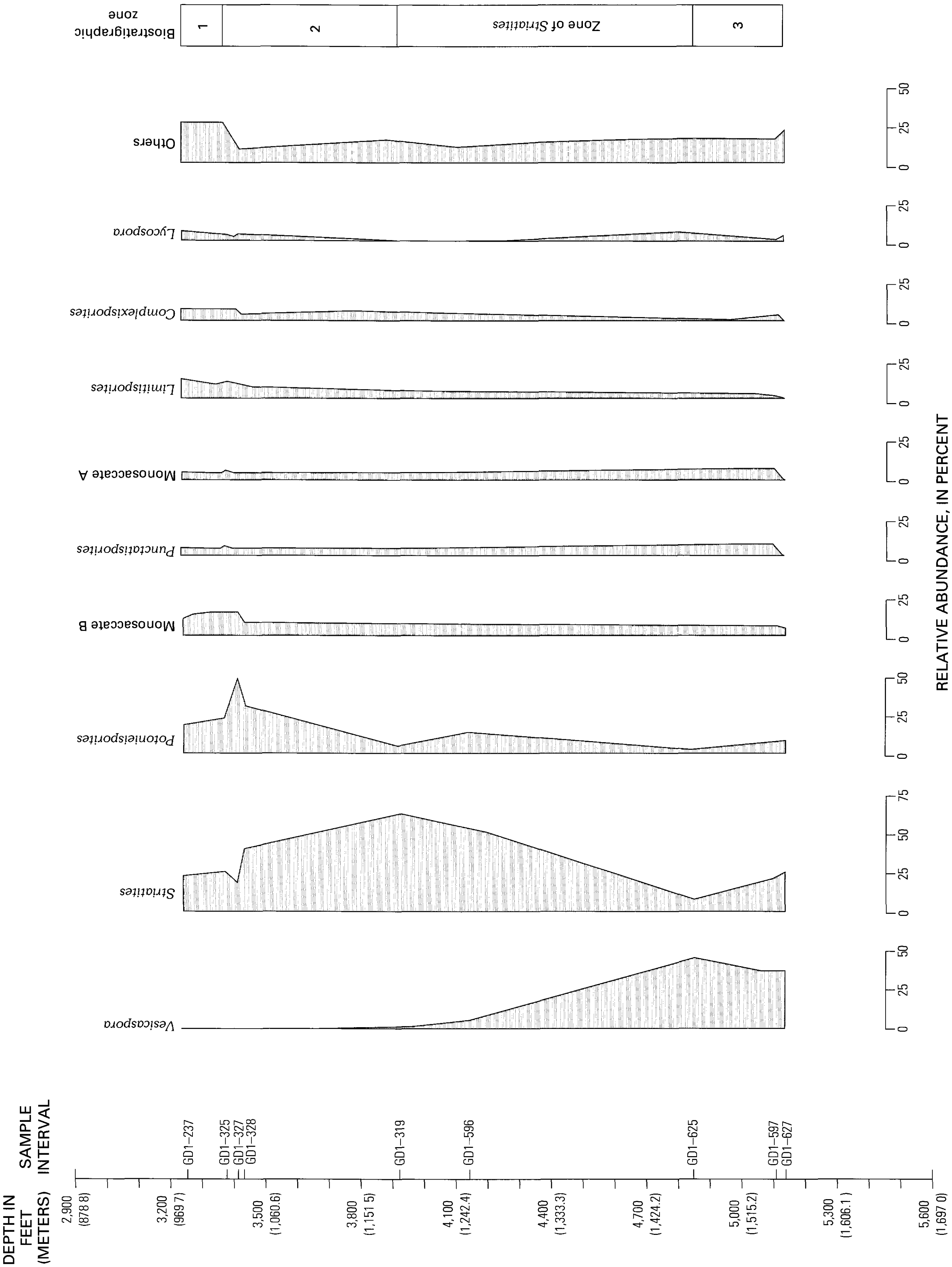
A second and higher level of evaluation involved determination of the relative abundances of striated monosaccate and bisaccate palynomorphs versus nonstriated monosaccates and bisaccates. Striated palynomorphs include those forms that have few to many well-defined grooves on the surface of the body (see, for example, figs. 5–7 of plate 1 and figs. 1–4 of plate 2). An increase in abundance of striated palynomorphs in the late Paleozoic may indicate a separate line of development for the plants that produced the palynomorphs recovered from the Paradox Formation. These first two levels of analysis were discussed in detail in a previous publication (Rueger, 1984), and the results are reflected in the third level of analysis.

The third and most advanced level of analysis determined the stratigraphic distribution of palynomorph genera. This determination was done to evaluate changes in generic abundance throughout the formation and to provide the finest detail possible in terms of palynofloral changes that may reflect climatic fluctuation. The generic analysis of palynomorphs within the Paradox Formation also provides an excellent opportunity for the development of a useful biostratigraphic zonation.

All of the analyses described above were performed at two scales to provide the optimal amount of data in terms of palynoflora variation. Initially, these analyses were performed on the entire Paradox Formation to evaluate any large-scale changes in the palynoflora. Subsequently, these analyses were done on samples collected from cycle 7 and interbed 8–9 to evaluate changes in the palynoflora during the deposition of a complete cycle. These data were then used to evaluate the minor changes in the palynoflora and to determine the possible mechanism that may have influenced cyclic sedimentation in the Paradox Basin.

STRATIGRAPHIC DISTRIBUTION OF PALYNOMORPH GENERA IN THE PARADOX FORMATION

The third and most detailed phase of the investigation was carried out at the generic level due to the complexity of the palynomorph suite obtained from the Paradox Formation and the number of species that presently remain undescribed. At this level it was still possible, however, to detect small changes in the palynoflora that may have been induced by variations in climatic regime. This phase of investigation was also undertaken to provide a detailed biostratigraphy available for use within the Paradox Formation. Samples illustrated in figure 7 comprise those samples containing a minimum of 300 identifiable palynomorphs, which afforded statistical credibility to the samples. Continued taxonomic differentiation of the palynomorph specimens recovered



Biostratigraphic zone
1
2
Zone of Striatites
3
Others
Lycospora
Complexisporites
Limitisporites
Monosaccate A
Punctatisporites
Monosaccate B
Potonieisporites
Striatites
Vesicaspora
RELATIVE ABUNDANCE, IN PERCENT
0
25
50
75
SAMPLE INTERVAL
GD1-237
GD1-325
GD1-327
GD1-328
GD1-319
GD1-596
GD1-625
GD1-597
GD1-627
DEPTH IN FEET (METERS)
2,900 (878.8)
3,200 (969.7)
3,500 (1,060.6)
3,800 (1,151.5)
4,100 (1,242.4)
4,400 (1,333.3)
4,700 (1,424.2)
5,000 (1,515.2)
5,300 (1,606.1)
5,600 (1,697.0)

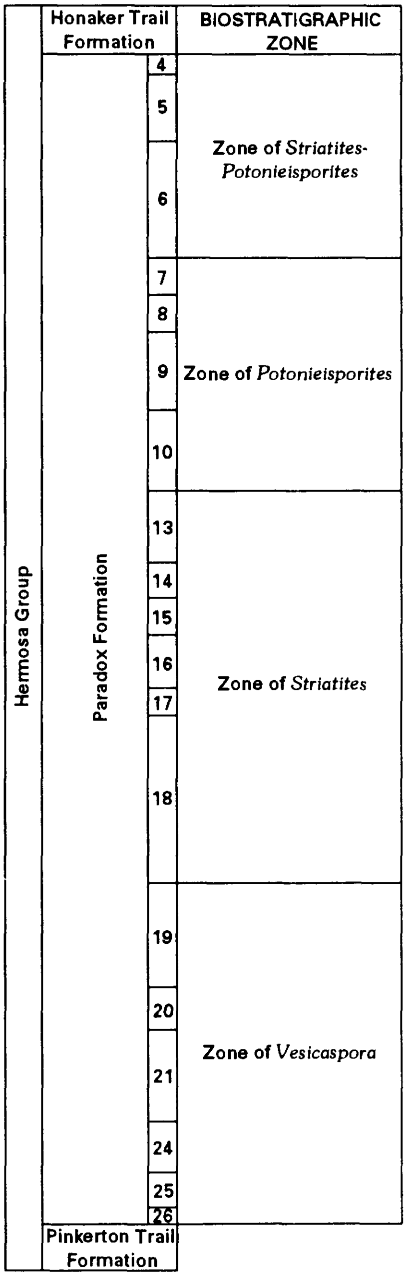


Figure 8. Biostratigraphic zonation of palynomorph genera recovered from the Middle Pennsylvanian Paradox Formation penetrated by the Gibson Dome No. 1 borehole. Numbers indicate cycles. Location of borehole is shown in figure 1.

Figure 7 (facing page). Stratigraphic distribution of palynomorph genera recovered from the Middle Pennsylvanian Paradox Formation penetrated by the Gibson Dome No. 1 borehole. Numbers refer to biostratigraphic zones: 1, *Striatites-Potonieisporites*; 2, *Potonieisporites*; 3, *Vesicaspora*. Location of borehole is shown in figure 1.

from the Paradox Formation, as well as the addition of larger samples at closer spacing, should ultimately produce a refinement of the biostratigraphic zonation developed in this investigation.

In analyzing the stratigraphic distribution of palynomorph genera, only dominant genera were considered and illustrated in the accompanying plates. Dominant genera include those genera that were present in the samples with a relative abundance of at least 5 percent.

Three distinct biostratigraphic zones became apparent during evaluation of the stratigraphic distribution of palynomorph genera (fig. 7). A fourth but less obvious zone was also noted. The basal zone is dominated by *Vesicaspora* spp. (plate 1, figs. 1–4), which is a nonstriated, monosaccate palynomorph, and the zone ranges from the bottom of the Paradox Formation to sample GD1–625 (fig. 7). *Vesicaspora* spp. (36–46 percent) by far outranks the other genera of this zone, which include *Striatites* spp. (plate 1, figs. 5–7), *Potonieisporites* spp. (plate 2, fig. 7; plate 3, figs. 1–4), Monosaccate sp. A (plate 1, fig. 8), *Punctatisporites* spp., and Monosaccate sp. B (plate 2, figs. 1–3) in terms of relative abundance. Stratigraphically, cycles 19–26 in the Gibson Dome No. 1 borehole are included in the zone of *Vesicaspora* (fig. 8).

Stratigraphically above the zone of *Vesicaspora* is the zone of *Striatites* (fig. 7), a striated bisaccate palynomorph. The zone of *Striatites* extends from sample GD1–319 to sample GD1–625 and includes sample GD1–596 (fig. 7). This zone is dominated by species of *Striatites* (52–61 percent) but also includes species of *Potonieisporites*, *Punctatisporites*, Monosaccate sp. B, *Limitisporites* (plate 4, fig. 2), and *Complexisporites* (plate 4, figs. 3, 4) as other important components of this assemblage in terms of relative abundance. The zone of *Striatites* stratigraphically includes cycles 13–18 in the Gibson Dome No. 1 borehole (fig. 8).

Continuing upward, the third zone in the Gibson Dome No. 1 borehole is the zone of *Potonieisporites* spp., which is also a nonstriated monosaccate palynomorph but is distinct from *Vesicaspora*. This zone extends from sample GD1–325 to sample GD1–319 and includes samples GD1–327 and GD1–328 (fig. 7). Other significant taxa within the zone of *Potonieisporites* are *Striatites*, Monosaccate sp. B, *Limitisporites*, and *Punctatisporites*. Cycles 7–10 penetrated by the Gibson Dome No. 1 borehole are stratigraphically within the zone of *Potonieisporites* (fig. 8).

The fourth and uppermost palynomorph zone of the Paradox Formation was not easily recognized until this particular phase of the investigation, during which genera were considered. In this zone *Striatites* spp. are co-dominant with *Potonieisporites* spp. The zone of *Striatites-Potonieisporites* begins at sample GD1–325 and continues upward to the top of the Paradox Formation (fig. 7). Other genera significant to this zone are *Limitisporites*, Monosaccate sp. B, *Complexisporites*, *Punctatisporites*, and *Ricaspora* (plate 4, fig. 1). Another significant taxon that is present within the zone of *Striatites-Potonieisporites* is *Costapollenites ellipticus* (plate 4, figs. 5, 6). The stratigraphic range of this species therefore is extended into much older rocks because it previously was not reported in strata older than the Wolfcampian (Tschudy and Kosanke, 1966). The zone of *Striatites-Potonieisporites* stratigraphically encompasses cycles 4–6 (fig. 8).

DISTRIBUTION OF PALYNOMORPH GENERA IN A SINGLE SALT CYCLE

Parts of two adjacent cycles were used for cycle analysis because samples were unavailable from a complete cycle in the Paradox Formation. The closest available sampling to illustrate the distribution of palynomorph genera in a single cycle was from the halite facies of cycle 7 and the carbonate-siliciclastic facies of cycle 8 (interbed 8–9).

Both the halite of cycle 7 and interbed 8–9 are completely included within the zone of *Potonieisporites* and contain the same dominant genera (figs. 7, 8). The stratigraphic distribution of palynomorph genera within interbed 8–9 is of extreme importance in the understanding of the climatic influence on the Paradox Formation. Within the rocks of interbed 8–9 is the unprecedented occurrence of Middle Pennsylvanian palynomorphs that are commonly extracted from coals of the Midcontinent region. Although the abundances of these palynomorphs, which include *Calamospora, Densosporites, Lycospora* (plate 2, figs. 5, 6), *Acanthotriletes, Convolutispora, Cyclogranisporites, Knoxisporites, Dictyotriletes, Leiotriletes,* and *Triquitrites*, are low in terms of relative abundance and they are not all included within the genera illustrated in figure 9, they are extremely important because they indicate that changes in climate took place during the deposition of a single Paradox cycle.

CONCLUSIONS

As a result of evaluating palynomorph taxa and their abundances in the Paradox Formation penetrated by the coring of the Gibson Dome No. 1 borehole, significant interpretations regarding climatic variations were made. Although the palynomorph suite recovered from the entire Paradox Formation tends to represent, to a large degree, the regional composition of the vegetation surrounding the Paradox Basin (fig. 7), very subtle changes were detected during the analysis of the palynoflora of a single salt cycle that, although masked by regional components of the palynoflora, are of major significance. The presence of palynomorphs typically associated with Middle Pennsylvanian coal deposits, including such genera as *Densosporites, Acanthotriletes, Convolutispora, Cyclogranisporites, Dictyotriletes, Leiotriletes, Triquitrites,* and *Lycospora*, indicates that when sea level was at maximum highstand the environment of the Uncompahgre highlands bordering the Paradox Basin on the east had been modified sufficiently to support large, arborescent plants normally associated with a coal-swamp environment. In support of this conclusion, the occurrence of *Lepidodendron johnsonii* from central Colorado may represent the remains of an in situ forest (Arnold, 1940). These data do not imply development of extensive coal swamps during sea-level highstand, but they indicate that moisture availability was sufficiently high in the region to support some of the plants commonly associated with the coal-swamp environment. These plants could also have existed throughout deposition of the Paradox Formation, but, because sea level was at a highstand, their palynomorphs were more readily transported into the basin simply because transport distance was shortened. In support of the preceding it should be noted that, although these plants did exist, conditions were never optimum for the development of coal swamps, as indicated by the absence of Middle Pennsylvanian coals in the Rocky Mountain region. The occurrence of these palynomorph genera does, however, have implications in terms of climatic variability during each of the cycles within the Paradox Formation and tends to support the hypothesis of expanding and contracting equatorial desert regions proposed by Sarnthein (1978). Applying this hypothesis to the Pennsylvanian Period the following scenario is suggested. As continental glaciation increased in the Southern Hemisphere, deserts or at least very arid conditions developed in the equatorial regions, which then included the Paradox Basin. The climate of the Paradox Basin during the glacial periods was cool and dry, and sea level was at a minimum, allowing the development of restricted inland seas and inducing the precipitation of evaporites. At the opposite extreme of the cycle, when glacial melting was greater than accumulation, large amounts of water were free to once again become part of the hydrologic cycle during the interglacial period. This event influenced the volume of water in the ocean basins on a worldwide scale, causing a rise in sea level and associated changes in the global climate regime. In the Paradox Basin the climate became warmer and wetter. Terrestrial runoff was at a maximum during the interglacial periods, as documented by the increased amounts of terrestrial organic matter incorporated within the rocks of the interbeds (Hite and others, 1984). In this manner, the cyclic nature of the Paradox Formation can be attributed to the 100,000-year perturbations of the Earth's eccentricity defined in the Milankovitch theory that control the development of continental glaciation.

By adding this climatic information to the idealized Paradox evaporite cycle of Hite (1970), an interesting relationship between climate and cyclic sedimentation is

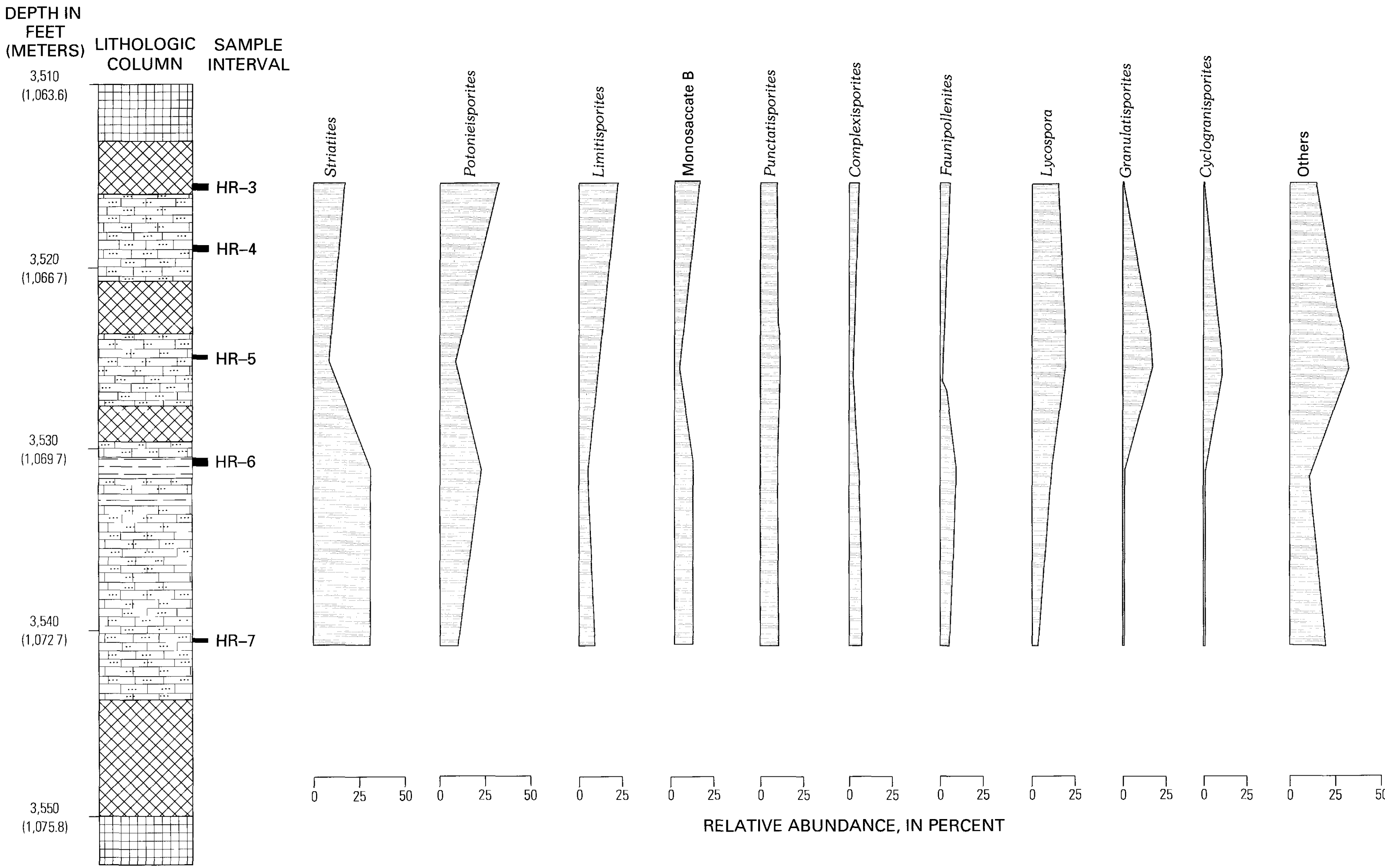


Figure 9. Stratigraphic distribution of palynomorph genera recovered from interbed 8–9 of the Middle Pennsylvanian Paradox Formation penetrated by the Gibson Dome No. 1 borehole. Conodonts also were collected from sample locations HR–4 and HR–6. Relative sea-level and salinity conditions during deposition of each facies are also shown. Rock types are shown in figure 2; location of borehole is shown in figure 1.

apparent (fig. 4). The climatic-cycle and sea-level curves are identical in nature. Deposition of black shale corresponds with the warm, wet (humid) climatic phase and precipitation of halite with the cooler, drier phase of the climate cycle. In this climatic model, the interglacial period corresponds with the transgressive phase of Hite (1970), and the glacial period is equivalent to the regressive phase of Hite (fig. 4). During the cool, dry glacial period the drop in temperature was not great enough to compensate the decreased precipitation and increased wind that allowed precipitation of evaporites. The dominance of saccate palynomorphs in the salts indicates that the source of these palynomorphs was nearby, and the anemophilous nature of the saccate palynomorphs allowed easy transport by winds that were active during the glacial periods. The increased abundance of nonsaccate palynomorphs in the interbeds is favored by the increase in runoff associated with the interglacial periods, and these palynomorphs are preserved because they are small enough to withstand the effects of abrasion.

The dominance of saccate palynomorphs has long been accepted as a sudden event associated with the advent of Permian time (Wilson, 1962), and this is the nature of the assemblage recovered from the Paradox Formation. Although common components of the Middle Pennsylvanian Desmoinesian Series of the Midcontinent and eastern United States, such as *Schopfites*, *Laevigatosporites*, *Thymospora*, or *Alatisporites* (Kosanke, 1969), are not present in any of the samples examined from the Paradox Formation, neither are any true Permian guide fossils such as *Nuskoisporites* (Hart, 1969). Also, the distribution of palynomorph genera in the Paradox Formation is quite different from the genera collected by Shaffer (1964) in Permian salts of Kansas, from which a much more typical Permian assemblage was recovered. In very small amounts, however, specimens of *Calamospora*, *Densosporites*, *Acanthotriletes*, *Convolutisporites*, *Cyclogranisporites*, *Leiotriletes*, *Triquitrites*, *Knoxisporites*, *Dictyotriletes*, and particularly *Lycospora*, where it is present with its highest abundance, have been recovered from the Paradox Formation. The presence of *Lycospora*, although low in abundance in the Paradox Formation, is significant because it is not known to be present naturally above the Desmoinesian coals of the Midcontinent region, and where it is present it is only in non-coals in very small amounts, probably as reworked grains (Peppers, 1964).

It can be stated that the dominance of saccate palynomorphs is attributable to climate, particularly the aridity associated with the Paradox Basin region and the central Rocky Mountains during the Middle Pennsylvanian. In addition, the high abundances of saccate grains may indicate that the Paradox Basin region represents the area in which the gymnosperms and pteridosperms underwent evolution and radiation. Fossil evidence from central Colorado (Arnold, 1941) substantiates this conclusion. The presence of abundant saccate grains in the palynoflora of the Paradox Formation also indicates the development of a separate and distinct Lower-Middle Pennsylvanian palynomorph province previously unrecognized in North America. The climate of the Paradox Basin provided an environment to which the vegetation of the region was forced to adapt or perish, resulting in the rapid evolution of these plants, while at the same time this stress had little effect on organisms of the marine realm.

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PLATES

Contact prints of the plates in this report are available, at cost, from U.S. Geological Survey Photograph Library, Federal Center, Denver, Colorado 80225

PLATE 1

[All photographs were taken using ordinary light microscopy. Slide coordinates established using Leitz Ortholux microscope 569349]

Figure 1. *Vesicaspora* sp. A. Distal view, sample GD1–597, slide 2, negative number 4365; location 104.6 × 13.4, length 63 microns, width 49 microns, USNM 382729.

2. *Vesicaspora* sp. A. Proximal view, sample GD1–625, slide 2, negative number 4704; location 99.3 × 6.4, length 60 microns, width 46 microns, USNM 382730.

3. *Vesicaspora wilsonii* (Schemel) Wilson and Venkatachala, 1963. Proximal view, sample GD1–597, slide 1, negative number 4190; location 116.2 × 17.8, length 53 microns, width 33 microns, USNM 382731.

4. *Vesicaspora wilsonii* (Schemel) Wilson and Venkatachala, 1963. Proximal view, sample GD1–597, slide 2, negative number 4242; location 109.3 × 18.1, length 53 microns, width 34 microns, USNM 382732.

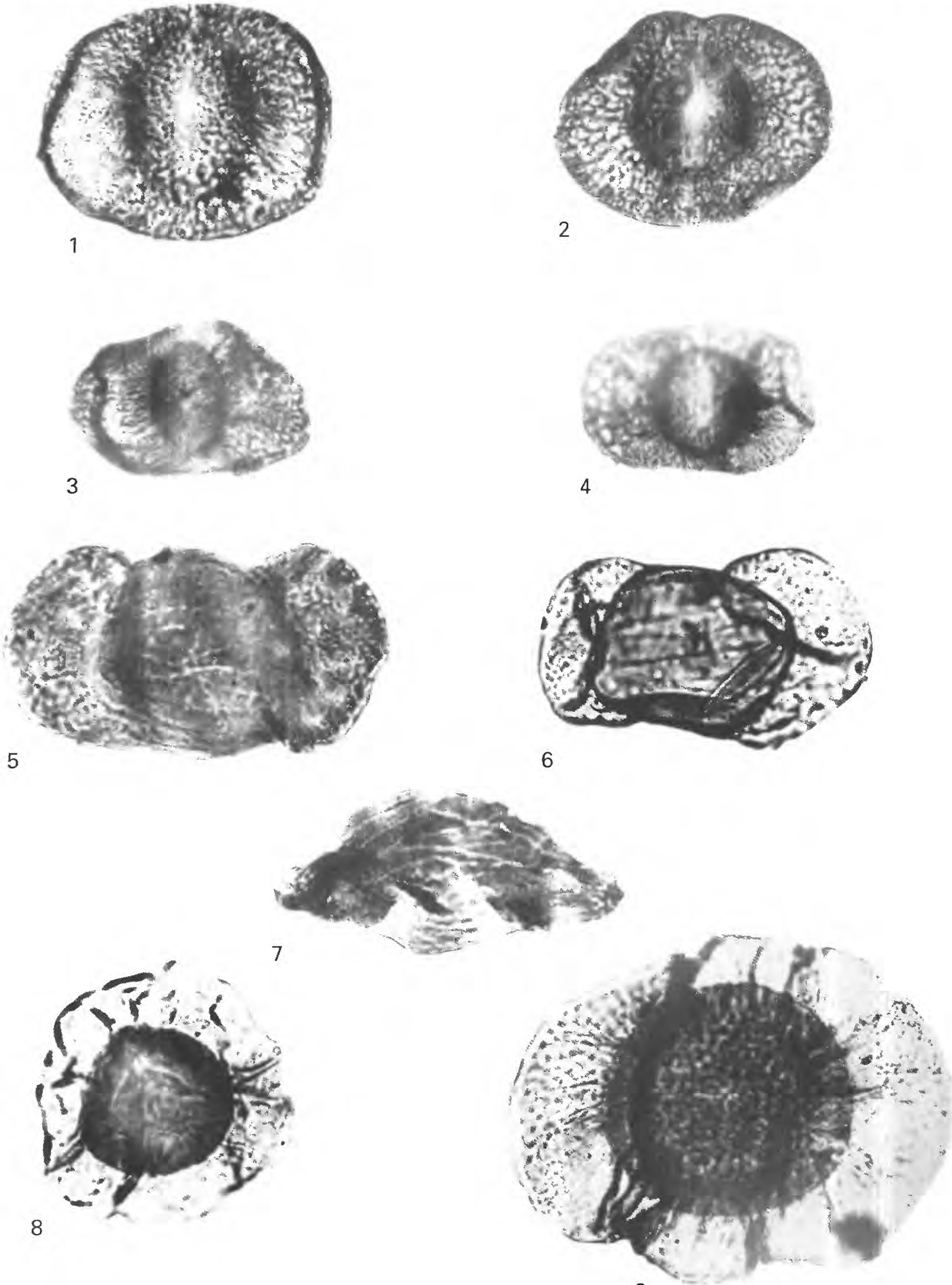
5. *Striatites splendens* (Jizba) Tschudy and Kosanke, 1966. Proximal view, sample GD1–319, slide 3, negative number 3920; location 98.3 × 3.9, length 84 microns, width 50 microns, USNM 382733.

6. *Striatites splendens* (Jizba) Tschudy and Kosanke, 1966. Proximal view, sample GD1–237, slide 5, negative number 3903; location 117.1 × 8.9, length 80 microns, width 42 microns, USNM 382734.

7. *Striatites splendens* (Jizba) Tschudy and Kosanke, 1966. Equatorial view, sample GD1–319, slide 3, negative number 3952; location 107.3 × 15.1, length 78 microns, USNM 382735.

8. Monosaccate sp. A. Proximal view, sample GD1–237, slide 1, negative number 4834; location 123.6 × 6.6, length 58 microns, USNM 382736.

9. Monosaccate sp. Proximal view, sample GD1–319, slide 2, negative number 4701; location 114.9 × 23.1, slide label at right side of stage, length 102 microns, width 55 microns, USNM 382737.



SELECTED PALYNOMORPHS FROM THE
MIDDLE PENNSYLVANIAN PARADOX FORMATION

PLATE 2

[All photographs were taken using ordinary light microscopy. Slide coordinates established using Leitz Ortholux microscope 569349]

Figure 1. Monosaccate sp. B. Proximal view, sample GD1–237, slide 1, negative number 4657; location 120.5 × 13.2, length 100 microns, width 66 microns, USNM 382738.

2. Monosaccate sp. B. Proximal view, sample GD1–319, slide 3, negative number 3956; location 118.4 × 17.1, length 84 microns, width 60 microns, USNM 382739.

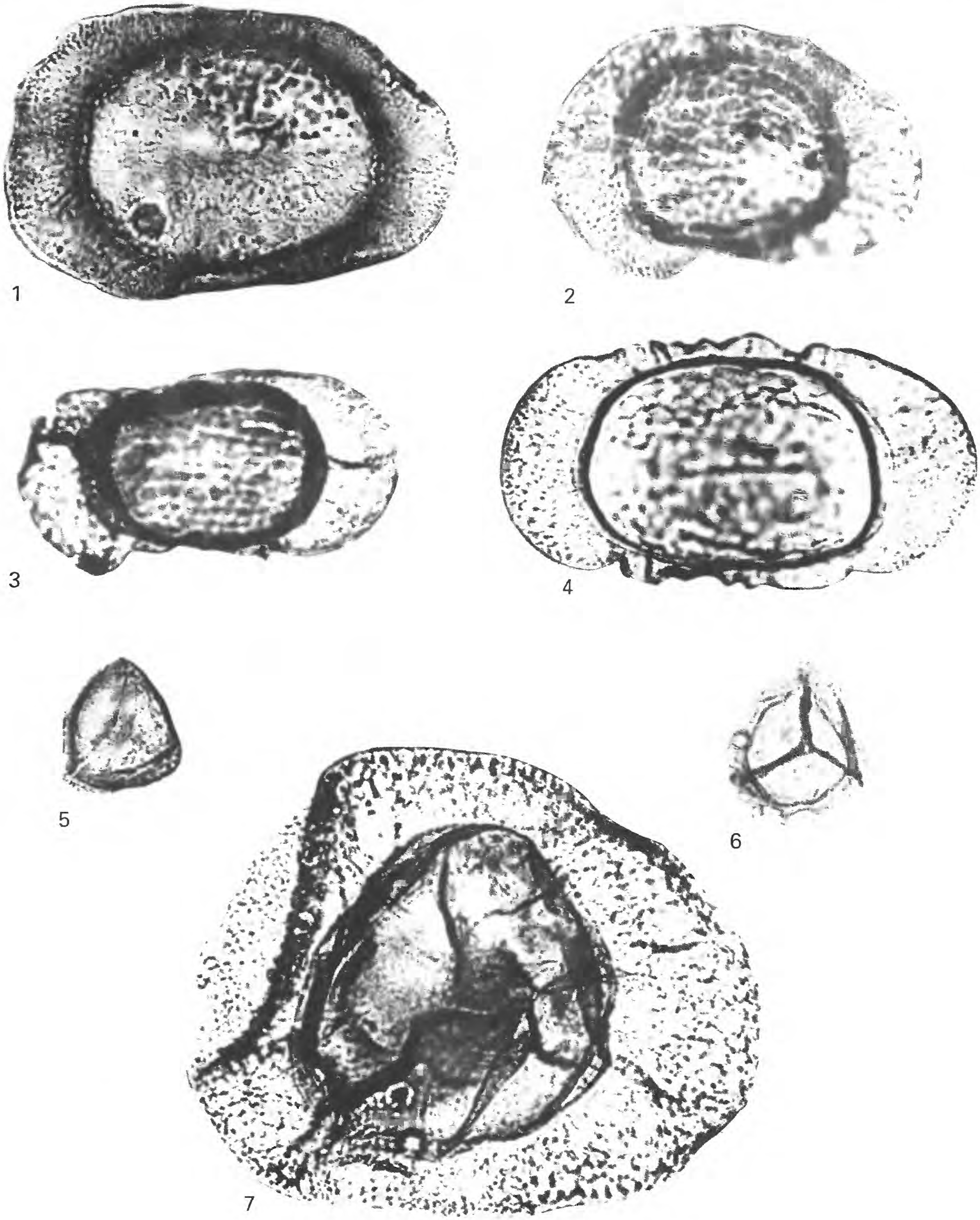
3. Monosaccate sp. B. Proximal view, sample GD1–597, slide 1, negative number 4478; location 105.0 × 21.1, length 87 microns, width 44 microns, USNM 382740.

4. Monosaccate sp. C. Proximal view, sample GD1–328, slide 3, negative number 4675; location 107.0 × 13.4, length 102 microns, width 55 microns, USNM 382741.

5. *Lycospora pellucida* (Wicker) Schopf, Wilson, and Bentall, 1944. Proximal view, sample GD1–597, slide 2, negative number 4483, location 108.9 × 21.9, length 33 microns, USNM 382742.

6. *Lycospora* sp. Proximal view, sample GD1–237, slide 5, negative number 3904; location 103.7 × 11.6, length 34 microns, USNM 382743.

7. *Potonieisporites simplex* Wilson, 1962. Proximal view, sample GD1–325, slide 1, negative number 4665, location 114.8 × 3.4, length 126 microns, width 94 microns, USNM 382744.



SELECTED PALYNOMORPHS FROM THE
MIDDLE PENNSYLVANIAN PARADOX FORMATION

PLATE 3

[All photographs were taken using ordinary light microscopy. Slide coordinates established using Leitz Ortholux microscope 569349]

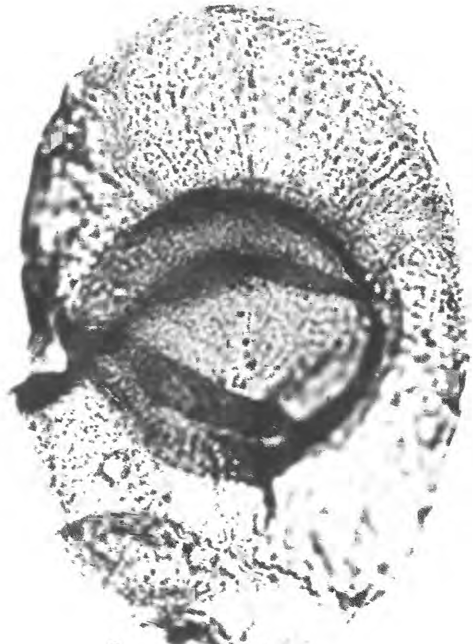
Figure 1. *Potonieisporites simplex* Wilson, 1962. Proximal view, sample GD1–237, slide 5, negative number 3900; location 113.8 × 8.1, length 131 microns, width 105 microns, USNM 382745.

2. *Potonieisporites grandis* Tschudy and Kosanke, 1966. Proximal view, sample GD1–237, slide 6, negative number 4728; location 123.4 × 13.8, length 109 microns, width 59 microns, USNM 382746.

3. *Potonieisporites* cf. *P. novicus* Bharadwaj, 1954. Proximal view, sample GD1–328, slide 3, negative number 4672, location 117.4 × 4.1, length 113 microns, width 81 microns, USNM 382747.

4. *Potonieisporites* (?) sp. Proximal view, sample GD1–237, slide 6, negative number 4726; location 107.0 × 3.2, length 99 microns, width 58 microns, USNM 382748.

1



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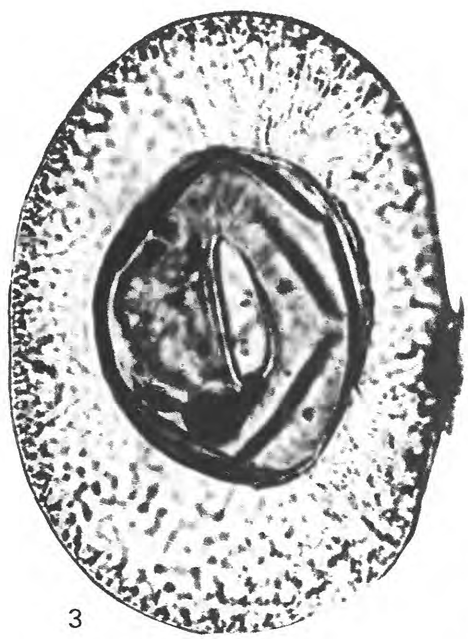

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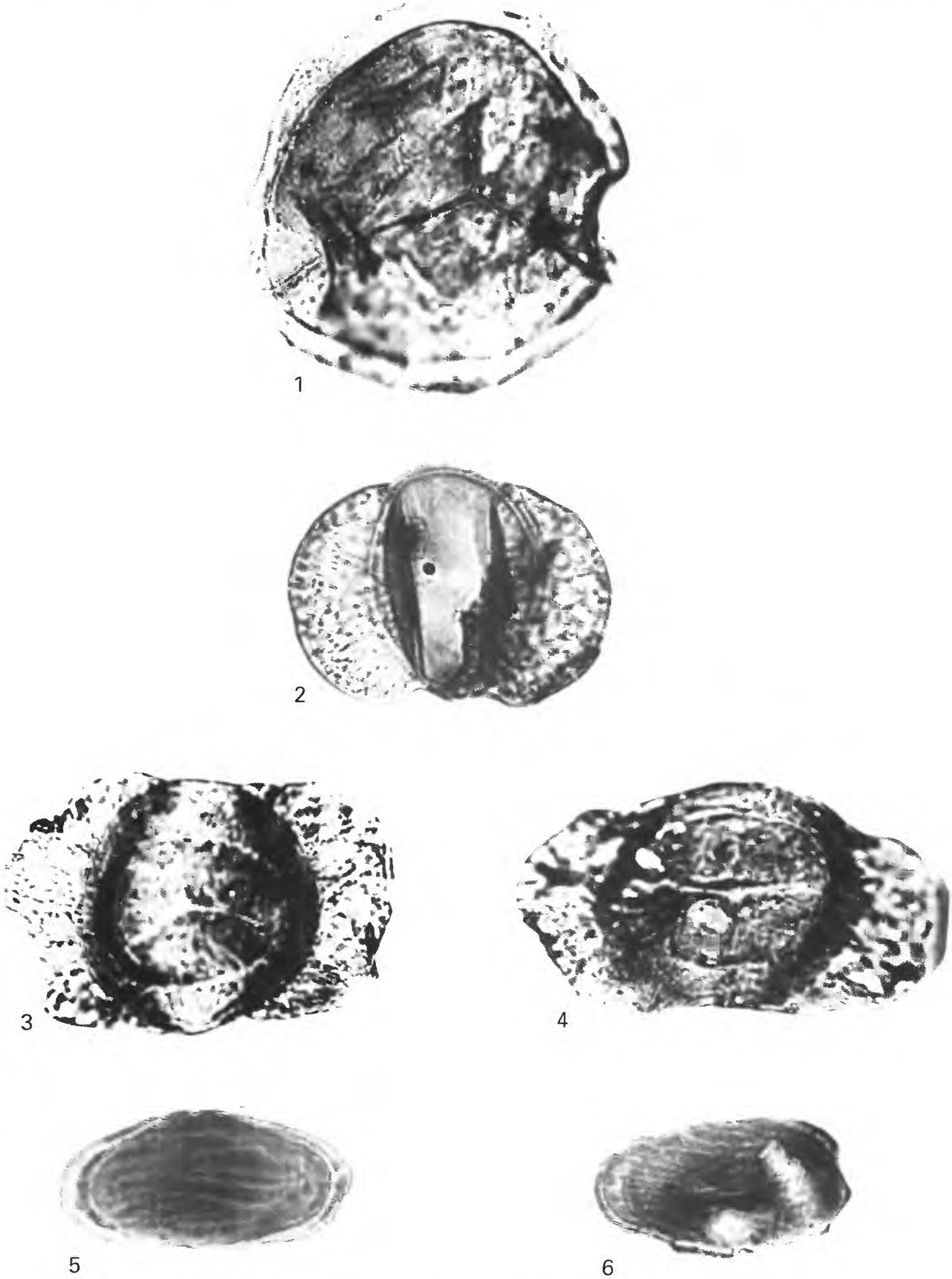
SELECTED PALYNOMORPHS FROM THE
MIDDLE PENNSYLVANIAN PARADOX FORMATION

PLATE 4

[All photographs were taken using ordinary light microscopy. Slide coordinates established using Leitz Ortholux microscope 569349]

Figure

1. *Ricaspora grandis* Bharadwaj and Salujha, 1963. Proximal view, sample GD1–325, slide 2, negative number 4839; location 107.6 × 21.3, length 84 microns, USNM 382749.
2. *Limitisporites* cf. *L. rectus* Leschik, 1956. Proximal view, sample GD1–327, slide 1, negative number 4706; location 111.9 × 18.3, length 68 microns, width 51 microns, USNM 382750.
3. *Complexisporites polymorphus* Jizba, 1962. Proximal view, sample GD1–319, slide 2, negative number 4844; location 118.4 × 8.4, length 87 microns, width 57 microns, USNM 382751.
4. *Complexisporites polymorphus* Jizba, 1962. Proximal view, sample GD1–319, slide 3, negative number 3958; location 100.1 × 18.7, length 92 microns, width 49 microns, USNM 382752.
5. *Costapollenites ellipticus* Tschudy and Kosanke, 1966. Proximal view, sample GD1–237, slide 3, negative number 4723; location 111.4 × 11.6, length 63 microns, width 30 microns, USNM 382753.
6. *Costapollenites ellipticus* Tschudy and Kosanke, 1966. Proximal view of incomplete specimen, sample GD1–240, slide 1, negative number 3948; location 97.7 × 12.6, length 66 microns, width 34 microns, USNM 382754.



SELECTED PALYNOMORPHS FROM THE
MIDDLE PENNSYLVANIAN PARADOX FORMATION

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