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PLATE TECTONICS, SPACE, GEOLOGIC TIME, AND THE GREAT PLAINS

A PRIMER FOR NON-GEOLOGISTS

R. F. DIFFENDAL, JR.

For most Americans, "The Great Plains" evokes images of grasslands, dust storms, prairie fires, Indians on horseback, cowboys and wheat lands, and perhaps flat valleys crossed by braided rivers carrying a heavy load of sand and gravel, extremes of weather, and a climate typified by an alternation of droughts and wetter periods. Geologists picture such general images, too, but they also see radical changes in the landscape over periods expressed in millions rather than hundreds of years. Geologically speaking, human activities on the Great Plains are too recent to have much of a place in the broad geologic history of the region, but they have certainly influenced both the use and the appearance of the region today and hence the terms in which we understand it. Fire was one

of the first human technologies to affect the Plains, and it favored the development of some types of vegetation, particularly grasses, over others, such as woody plants. Farming and ranching have had vast impacts on the vegetative cover, on the soils, and on wildlife distribution. And dams, built across rivers to control flooding, to produce hydroelectric power, or to divert water for irrigation or other uses, have produced major changes in the behavior of the rivers.

While historians look at the past on a human time scale, for geologists human time is simply the most recent frame in an unfinished movie. Each frame is composed of a mosaic of worldwide snapshots. Pieces of the film are missing, but what is left is usually in a chronological sequence. What geologists seek to do is to trace their way back through time as it is recorded on this broken film to explain the development of a particular place, a region, or even the entire earth. The geologic history of any region is tied up with the history of earth as a whole, because events happening far away can leave an indelible impression on the region under consideration. Recent volcanic eruptions, for example, have injected into the atmosphere dust particles that have altered the weather or that have been

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deposited as ash for great distances downwind *from their sources*. *The geologist's holistic view* of the earth should include the overall consequences of evolving life as well as purely geological forces. Beginning in 1972, J. E. Lovelock hypothesized that all life makes up "a single living entity, capable of manipulating the Earth's atmosphere to suit its overall needs and endowed with faculties and powers far beyond those of its constituent parts." Lovelock suggested that living organisms might influence not only climate change but also volcanism, mountain formation, and the movement of the earth's lithospheric plates. Climate change is also at least partly attributable to the solar cycle of variations in the earth's orbital eccentricity, axial tilt, and precession of the equinoxes due to variation in the earth's motion and position relative to other planets.¹ J. E. Oliver linked these plate movements, differences in the amount of radiation coming from the sun, and other factors to make a "compromise theory" of climatic change.²

My purpose in this paper is to explain for the non-geologist what some of these factors are, to give a history of how geologists have come to understand them, and then to go beyond Oliver's general model to focus on the relationship between climate change and the geological development of the Great Plains as it has been influenced by major geological events both outside and within the region. These events include movements of the earth's rigid lithosphere plates with attendant mountain formation and volcanism, cyclic changes in sea level and glaciation, broad uplifts and downwarps of the continents, the evolution of new environment-changing organisms, and meteorite impacts. While most of these affect an area far greater than just the Great Plains, local events also produce regional change. For example, the altitude of the Plains was once considerably lower than it is at present. Folding, faulting, and igneous activity have thrust up mountains in parts of the region. Rivers have cut valleys and then filled them back in, wholly or partially, with sediments. The climate has been wetter and dryer, hotter and colder, than it is now. Natural

weathering rates of rocks and sediments have changed in response to the actions of wind and rain and also of plants, and thus the elements have laid down various kinds of soils in places and thicknesses that changed over time. Organisms have evolved, emigrated or immigrated, and changed in abundance. Yet for the past 66.5 million years, since the uplift of the Rocky Mountains and the withdrawal of the shallow seas from the North American mid-continent, this region has maintained the basic identity that we associate with the Great Plains.

HISTORY OF GEOLOGY

In order to understand what it is that geologists know about the Great Plains, it is necessary to understand a little bit about the history of the science of geology and of how geologists understand what it is that they are doing. In the 1700s geologists began describing a chronological sequence of layers of rock, upsetting earlier ideas of a relatively stable and recently created world. Geologists recognized that the layers at the bottom of the sequence were the oldest and that the layers were usually deposited horizontally. A third idea, that any feature cutting across or deforming several strata had to be younger than any of the affected strata, also helped in constructing a time frame. When similar types of fossils appeared in rocks great distances apart, they served as indexes to match up or correlate the strata. By the latter part of the nineteenth century, when the concept of evolution was sweeping the biological sciences, evolutionary succession of organisms allowed geologists to establish a fairly precise worldwide chronological sequence of rock strata. In the twentieth century, with the discovery of the principles of radioactive dating, geologists tentatively established time spans for formation of rock sequences and increasingly refined these dates to the point that many correlations are now excellent.³

Precambrian rocks are older than 570 million years before present (mybp); the oldest of these contain no known fossils, while somewhat younger Precambrian rocks have been found so

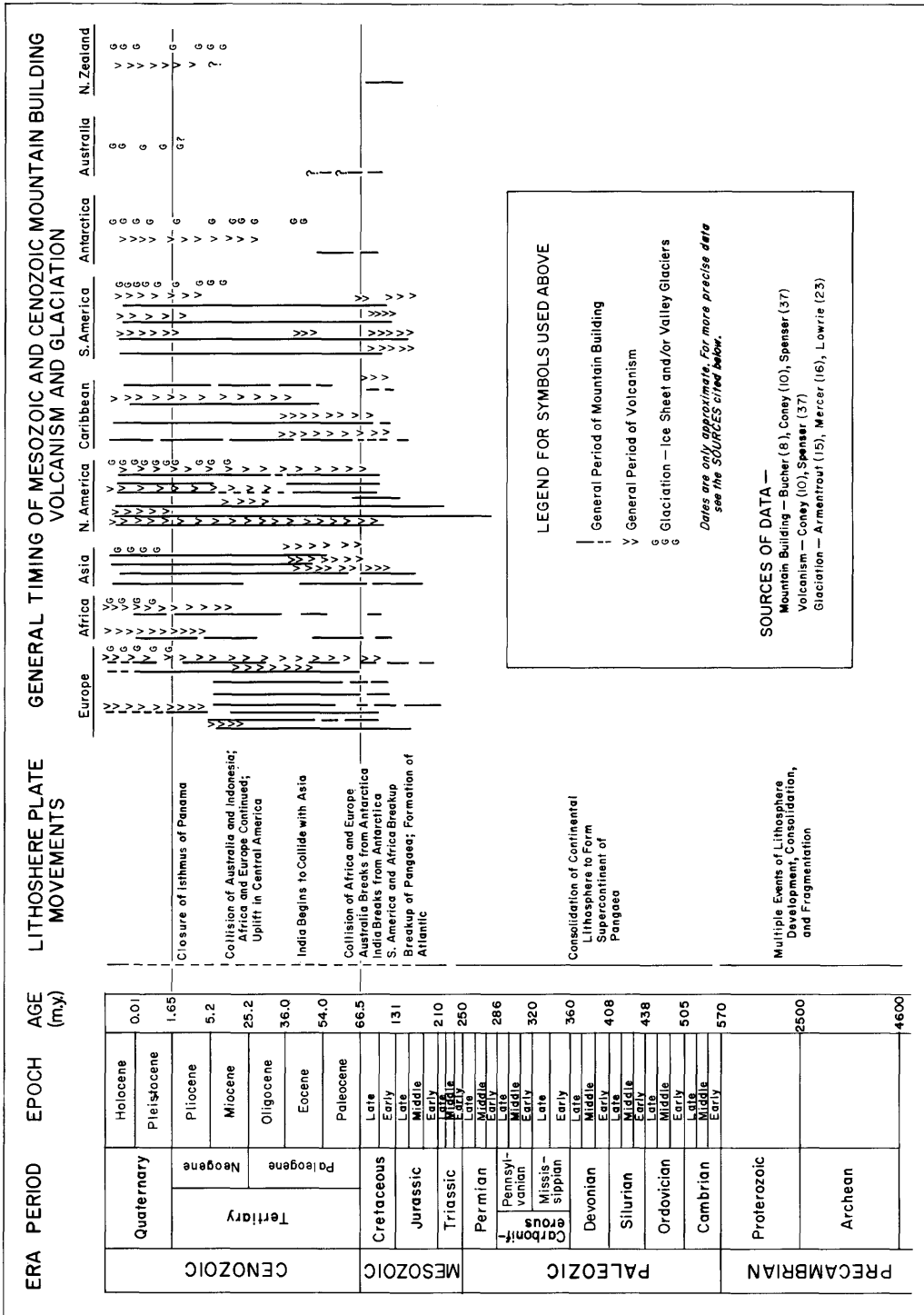


FIG. 1. Geologic Time Scale and General Correlations with major geologic events including lithosphere plate movement, mountain building, volcanism, and glaciation. No geographic position implied by placement of symbols for latter three events.

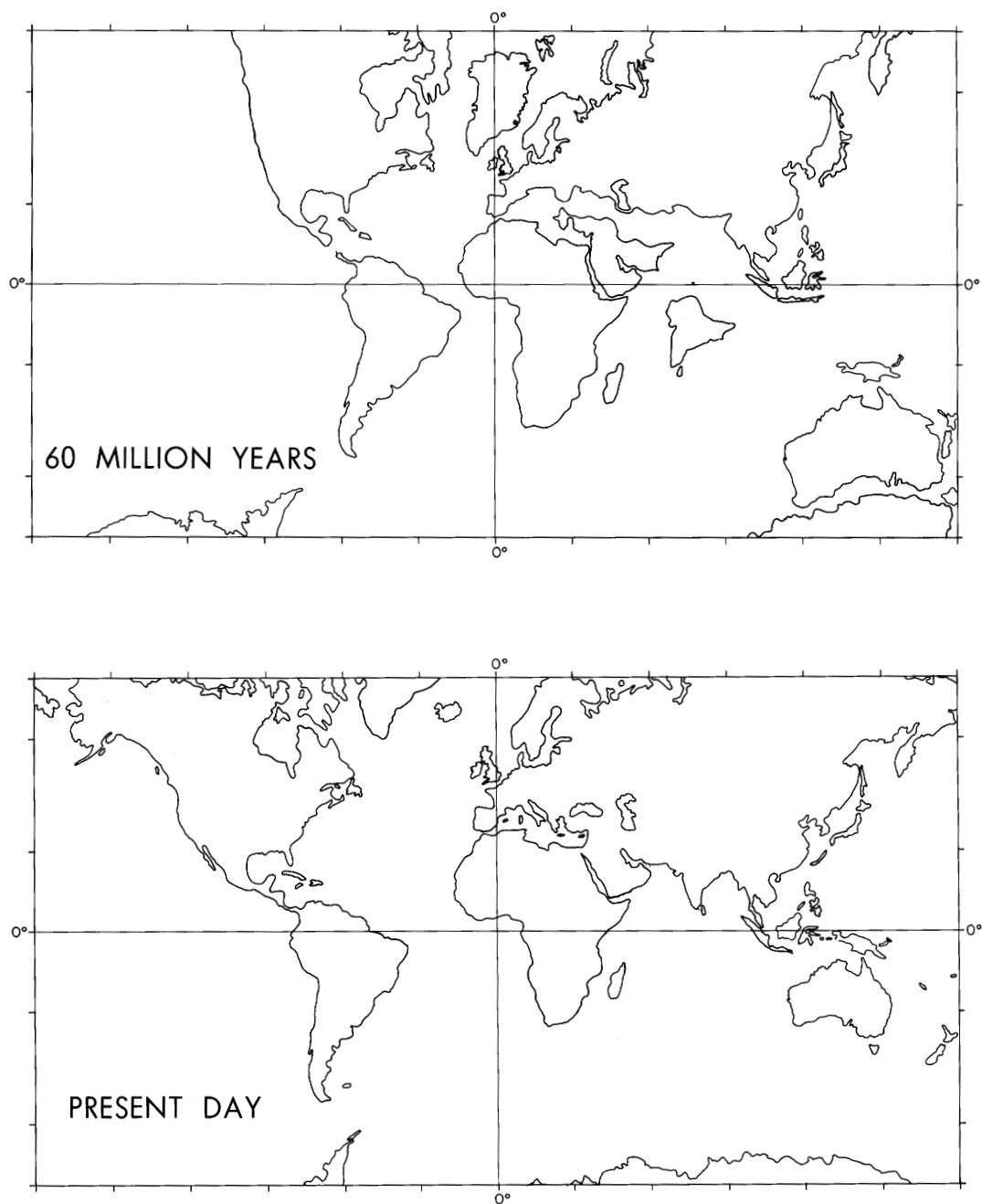


FIG. 2. Changes in the positions of land masses over the last 60 my. (Modified after Smith and Briden, note 7, courtesy of Cambridge University Press.)

far to contain only primitive invertebrate animals, algae, bacteria, and viruses (Fig. 1). The remaining younger rocks, including those that contain more advanced fossils, were formed during parts of three major time spans or eras, the Paleozoic (570-250 mybp), Mesozoic (250-66.5 mybp), and Cenozoic (66.5 mybp to present). The fossils from the rocks formed during these eras are the preserved remains of life that more and more resembles the organisms alive today as one progresses from the oldest to the youngest rocks in the sequence. Geologists define the systems of rocks formed during periods by major changes in the types of fossils and types of rock strata. Subdivisions are made according to definite but less dramatic changes in the rock formations and their fossils. In this paper I will deal primarily with the geologic history of the Great Plains during the part of the Cenozoic era from 37 mybp, when perhaps the oldest Cenozoic rocks in western Nebraska were deposited, to 1.65 mybp, the time of the deposition of the youngest Pliocene sediments. I have avoided discussing times closer to the present because the geologic record is still too complex for the type of analysis I am performing here. I will begin by discussing those events that had an impact on most of the earth and then consider those that were more regional in scale.

LITHOSPHERE PLATE MOVEMENTS

Plate tectonics has now been so widely described in the popular media that the concept is familiar to any school child, but I well remember that in the late 1950s, when I was an undergraduate majoring in geology, some of my professors were extremely scornful of the idea, already several decades old, that the continents had not stayed fixed in their places throughout time but had moved or drifted in respect to one another. German meteorologist and geophysicist Alfred Wegener was the foremost proponent of the drift idea, which so elegantly explained such geological phenomena as the amazing jigsaw-like fit of the eastern coastline of the Americas with the western coastlines of Europe and Africa, the striking similarities of

the geology and paleontology along this fit, and the evidence of past climate changes that seemed explicable only in terms of continental drift.⁴ Other geophysicists, however, insisted that the continents could not float about like rafts on the seas of a denser mass of solid rock. Geologists studied spinoffs of Wegener's ideas or proposed other explanations for the similarities, such as the development and later disappearance of land bridges across the oceans, to avoid the problems involved in the drift concept.⁵

By the early 1960s, however, oceanographers and other earth scientists produced data that showed that the entire crust of the earth is broken into larger and smaller pieces that move with respect to each other.⁶ New crustal material is generated along submarine oceanic ridges and consumed under oceanic trenches. Within a decade of the production of these new data that satisfactorily explained the basic mechanics, the idea of sea floor spreading and plate tectonics had produced the major conceptual revolution in geological sciences in the twentieth century. Not only did the concept explain the jigsaw puzzle, but it allowed geologists to develop a coherent theoretical framework that linked the fit with the origins of mountains, metamorphism, and earthquakes, as well as other phenomena.

The theory describes a giant supercontinent, Pangaea, that had formed by the end of the Permian Period (250 mybp) and that broke apart as new plates formed and carried continental fragments to their present positions. Figure 2 shows the many changes in land/ocean relationships that have taken place over the last sixty million years.⁷ These changes in the positions of continents and changes in the shapes and connections of seas and oceans had profound effects on climate and atmospheric/oceanic circulation patterns, and they also triggered other events, such as the formation of mountains. Earlier theories had held that mountain formation had occurred at regular intervals worldwide, but plate tectonics theory suggests that mountain building has been going on more or less continuously in one part of the earth or other throughout geologic time.⁸ Most

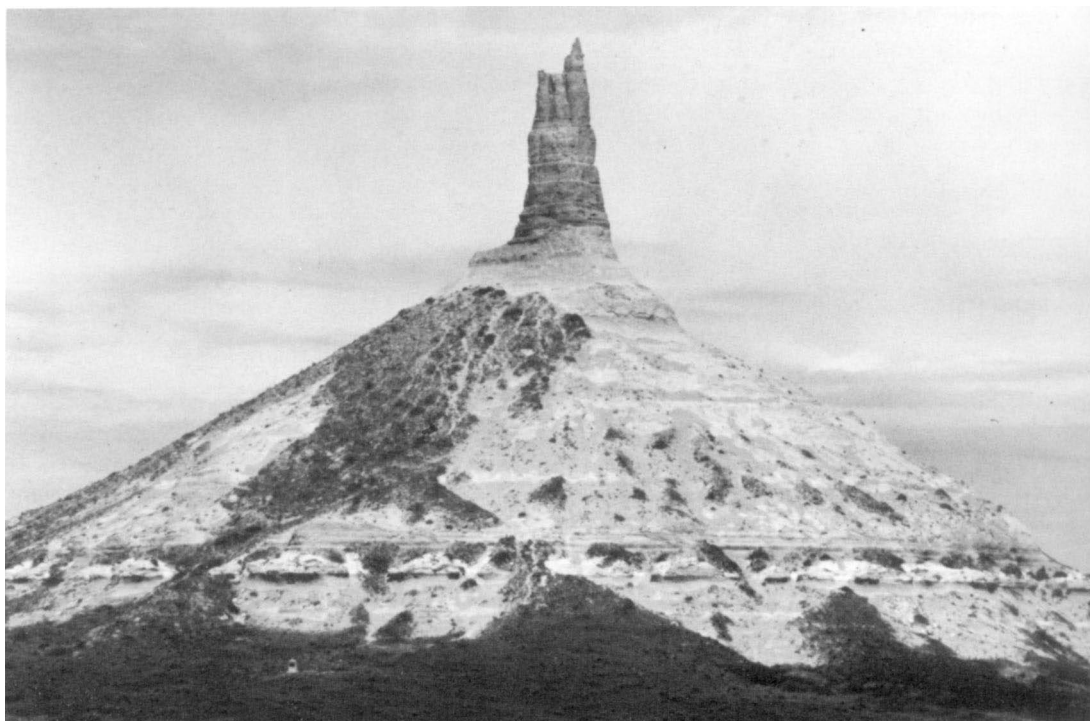


PHOTO 1. Chimney Rock, Morrill County, Nebraska. The white layer near the base of the rock is Lower Whitney volcanic ash. The darker rock above it is Whitney Member of Brule Formation, while the spire is basal Arikaree Group. Photograph courtesy of R. F. Diffendal, Jr.

studies of plate tectonics have focused on the areas where plates have broken apart or ground together, but these forces have also had a great impact on regions like the Great Plains, floating seemingly untouched in the middle of the plate.

MOUNTAIN FORMATION

When the leading margins of moving plates collide, the rocks crumple and fault (break with displacement). Deeper down, rocks melt and flow upward, forming intrusive masses beneath the surface of the land or erupting in volcanoes with flowing lava. Mesozoic (250-66.5 mybp) and Cenozoic (66.5 mybp to present) deformation resulted in the formation of most of the

major mountain belts on land today (Figs. 1, 3). Mountain ranges affect atmospheric circulation and precipitation.⁹ Clearly the tremendous mountain uplift of the last 66.5 million years has played a major part in changes in world climate, as recent computer simulations have confirmed.

VOLCANISM

Volcanism has been widespread along and adjacent to plate boundaries (Fig. 1).¹⁰ Volcanic activity has been particularly important to the Great Plains during two time spans (Figs. 4, 5). Eruptions to the south and west from sixty-five to about seventeen million years ago produced

huge volumes of volcanic ash (particles less than two mm in diameter) that were carried into the atmosphere and deposited in thick accumulations to the east in intermontane basins and on parts of the Great Plains.¹¹ In the last seventeen million years, lesser episodes of volcanism have also sent ash onto the Great Plains.

Volcanism plays an important role in climate change. The fine cloud of ash an erupting volcano injects into the atmosphere reduces the solar radiation reaching the earth's surface. Major episodes of volcanism during the last 66.5 million years correlate with periods of sharply lowered temperature.¹² R. S. White hypothesized from this that massive volcanism would cause major worldwide cooling, reduction in photosynthesis, huge wildfires, and, because erupted gases contain carbon dioxide, sulfates, and chloride which combine with water vapor to form acids, a decrease in the alkalinity of the surface waters of the oceans.¹³

GLACIATION

Glaciation has been part of earth's history on and off since the earliest geological era (Fig. 1).¹⁴ Evidence for multiple glaciations during the Pleistocene Epoch (c. 1.65 mybp to present) includes glacial deposits and other landforms on land and on continental shelves and, on the deep sea floors, both ice rafted deposits and variations in fossil marine shells that indicate changing sea temperatures.

Similar evidence indicates that glaciations occurred several times back to the beginning of the Oligocene Epoch (36 mybp) in the northern hemisphere.¹⁵ Pre-Pleistocene glacial deposits and landforms also have been found in the southern hemisphere (Fig. 1).¹⁶ Geologists differ about the placing of the boundary between the Pliocene/Pleistocene epochs (Fig. 1). While most would date it at about 1.65 mybp, others

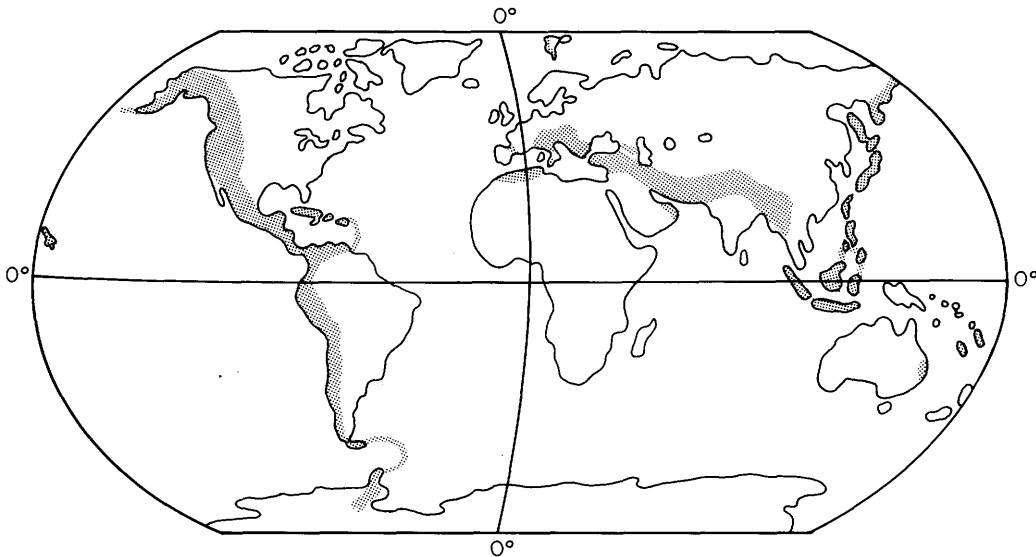


FIG. 3. Positions of Cenozoic Mountain Belts. (Modified after Umbgrove, note 8.)

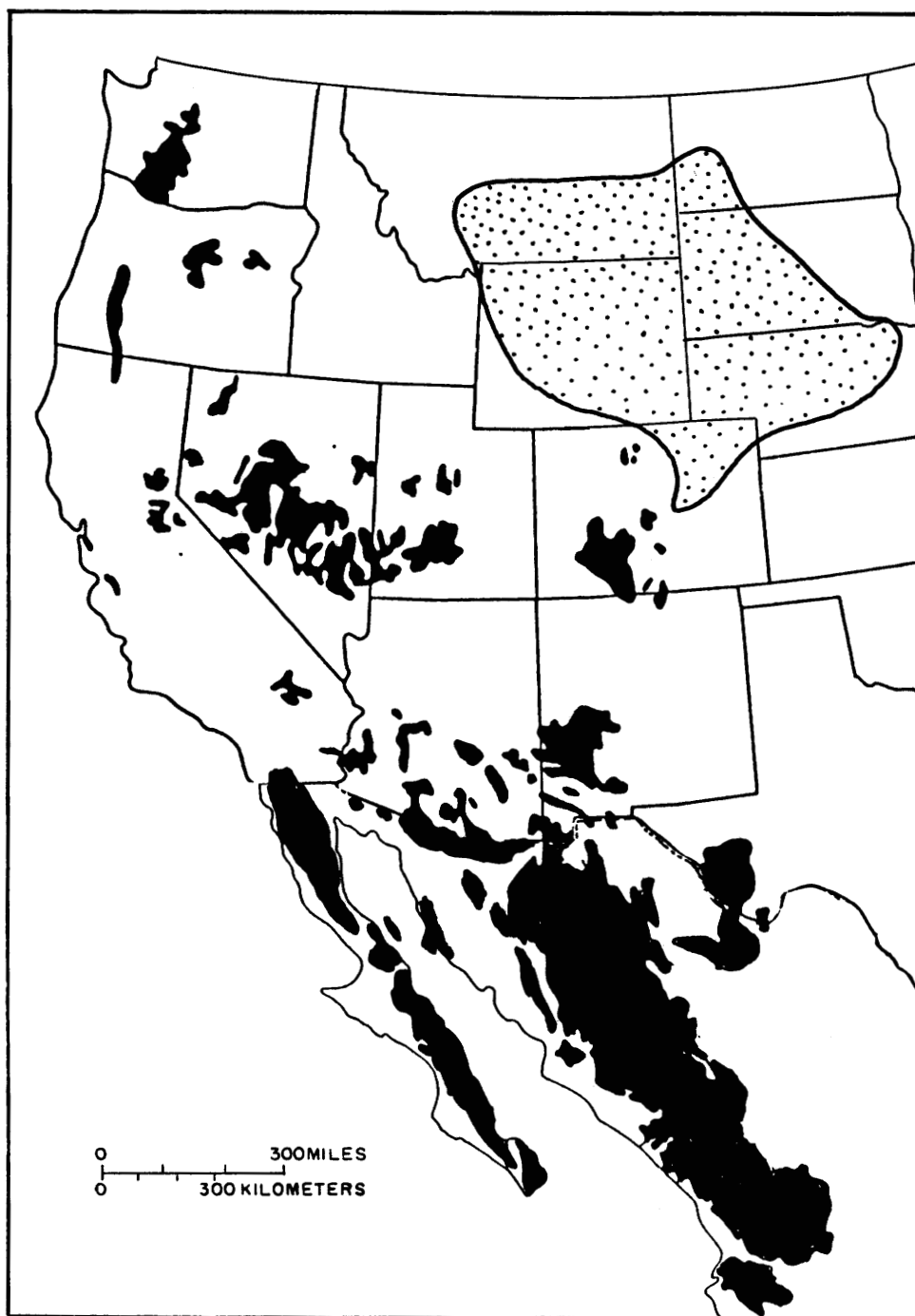


FIG. 4. Acidic volcanic sites in the western United States and northern Mexico, 65 to 17 million years ago. Minimum former extent of Arikaree Group stippled. (Modified after Stewart and Carlson, note 10 [Plate 11-1]; Swinehart, Souders, DeGraw, and Diffendal, note 11; and McDowell and Clabaugh, note 38.)

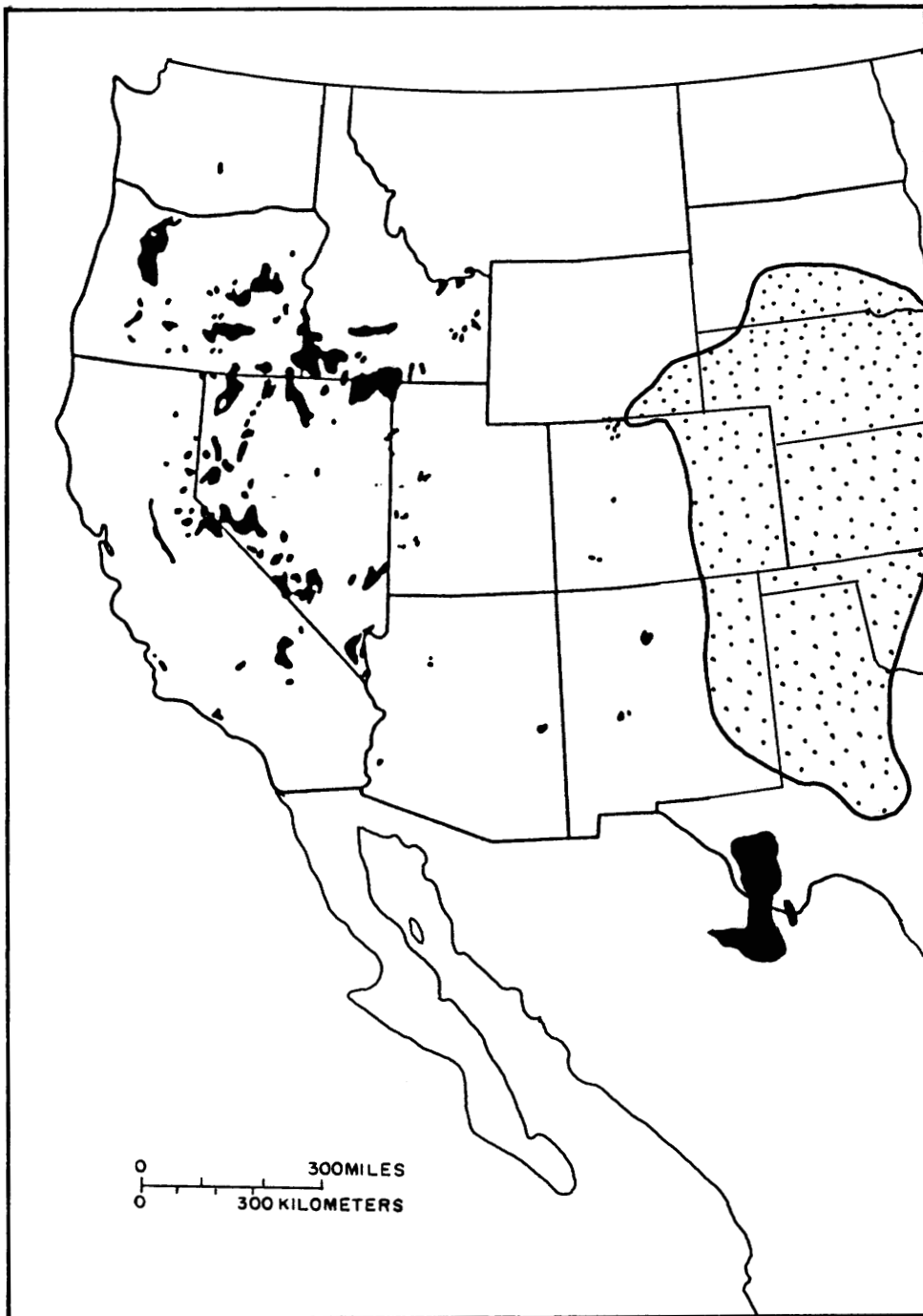


FIG. 5. Acidic volcanic sites in the western United States and northern Mexico, 17 million years to present. Minimum former extent of Ogallala Group stippled. (Modified after Stewart and Carlson, note 10 [Plate 11-2]; Swinehart, Souders, DeGraw, and Diffendal, note 11; and McDowell and Clabaugh, note 38.)

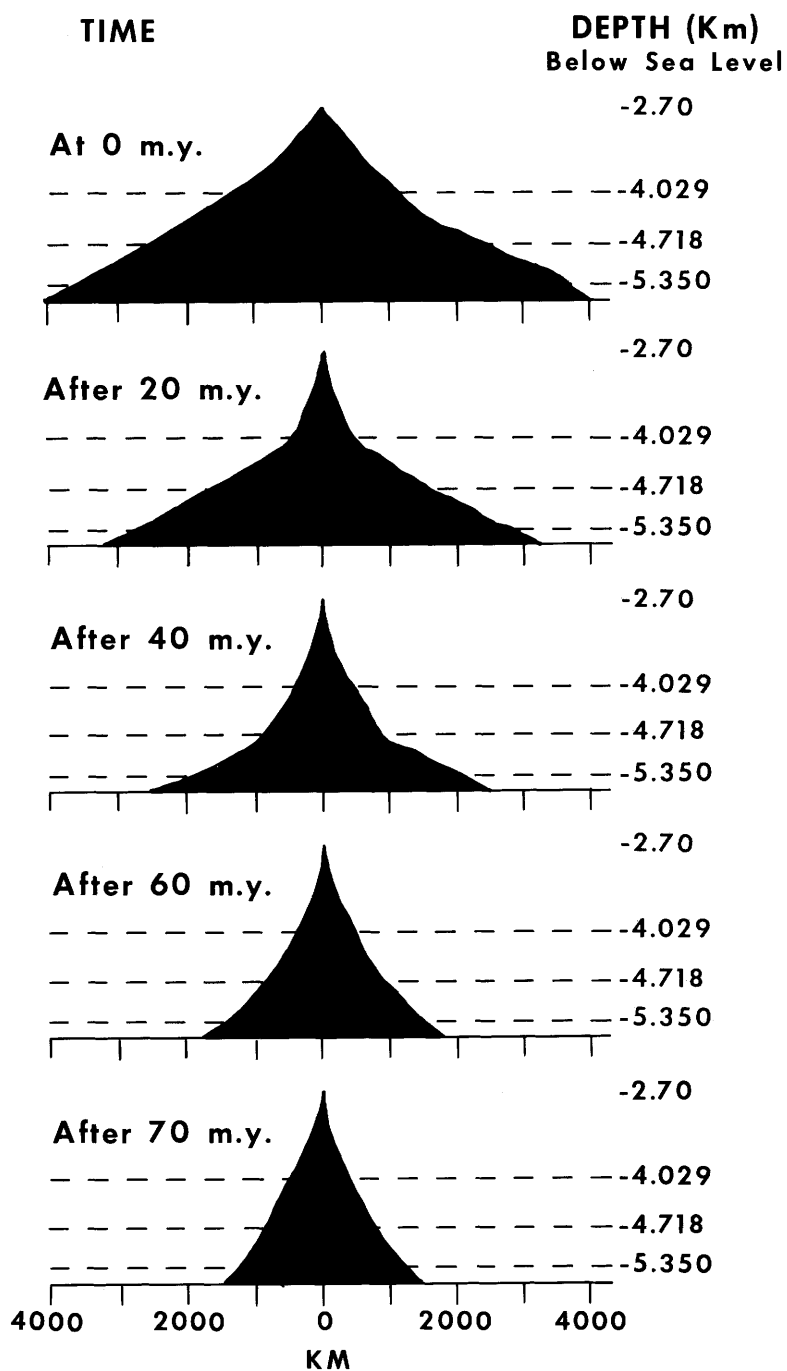


FIG. 6. Change in oceanic ridge profile when spreading rate at ridge is reduced from 6 cm/yr to 2 cm/yr at 0 million years. Top of ridge is about 2.70 km below sea level. (Modified after Pittman, note 18 [Figure 2].)

place it back at 2.8 million years ago.¹⁷ No glacial deposits older than this disputed time period have been found on or adjacent to the Great Plains, but the older Cenozoic glaciations noted above also affected the Great Plains because they were implicated in coincident climate changes, and their effect on sea level worldwide would have affected erosion and river entrenchment on the Plains.

SEA LEVEL CHANGES

Scientists have known for centuries that sea levels have not remained constant. Using seismic techniques that allow them to pick out changes in sediments and to define the presence of erosion surfaces between major masses of strata, geologists have worked out a sea-level curve showing the changes, their frequencies, and their magnitudes. In the 1970s Peter Vail and his colleagues at Exxon used these techniques to work out a sea level change curve back through geologic time, a curve that continues to be refined as new data are found. W. C. Pittman related some major rises and falls to changes in the size and number of submarine ridges, the plate-generating areas of the lithosphere (Fig. 6).¹⁸ Undersea ridges, underlain by hot rock that erupts into volcanic activity, are the places where heat expands the lithosphere. When a ridge ceases to be active, the rocks beneath it cool and contract, displacing less sea water and producing a fall in sea level. When such ridges cover more of the sea floor, the opposite sequence takes place. These effects are geologically very slow and account for long-term rises and falls in sea level on the order of tens to hundreds of millions of years. Vail and his colleagues called the various long and slow changes in sea level first and second order cycles. The much more rapid third order cycles of rises and falls they discovered are probably the result of glaciation and deglaciation, possibly combined with tectonics.

Sea level rises and falls, whatever their causes and magnitudes, have had major impacts on other aspects of earth's geologic history. Falls have caused major river valley erosion on land

and on newly emergent continental shelves. Rises seem to correlate to major periods of deposition in these valleys. Far as they were from an ocean, the rivers and streams of the Great Plains responded thus to changes in sea levels.

FLORAL CHANGES

Plants may also have had an important impact on climate change. Although scientists have not yet been able to date the advent of angiosperms (flowering plants) with certainty, deciduous angiosperms are among the fossil floras of the Early Cretaceous Period (131-98 mybp), and these angiosperms have become more and more abundant up to the present.¹⁹ Vascular plants (the majority of visible terrestrial plants), which have well-developed conductive systems from roots to leaves, and their root-associated fungi, increase the breakdown of soil minerals. The deciduous angiosperms have higher net nutrient losses than do gymnosperm (coniferous) ecosystems, which makes for overall increased weathering rates where angiosperms dominate. T. Volk has associated this plant-caused increase in the decomposition of rocks and soil over the past 131 million years with the increased losses of potassium, calcium, and magnesium ions from the soil and the capture of the ions by marine organisms in which oxides of the ions combine with carbon dioxide to form carbonate skeletons. If this relationship between soil decomposition and marine organisms has been correctly hypothesized, then the growth and diversification of the angiosperms, including the grasses of the Great Plains, has been a factor in the systematic removal of carbon dioxide from the atmosphere over the past 66.5 million years and may have been an important contribution to overall global cooling throughout this time period.²⁰

Studies of the distribution of fossil floras during the Tertiary (66.5-1.65 mybp) in the northern hemisphere support the idea that substantial cooling occurred at the Eocene/Oligocene boundary (36 mybp) and that climates have continued to be cool since then. Vastly accelerated erosion of the continents during the last

fifteen million years may also be the result, at least in part, of floral evolution.²¹

METEORITE IMPACTS

A number of researchers have suggested that comets or meteorites strike the earth at regular intervals. One theory is that these extraterrestrial objects are brought into the solar system when "Nemesis," a hypothetical companion star to our sun with a very eccentric orbit, approaches our solar system. If such objects are large enough, their collision with the earth would inject huge dust clouds into the atmosphere and cause worldwide climate changes, extinctions, and other major geologic events.²²

ATTEMPTS AT SYNTHESIS

The idea of constructing a coherent geologic record of all these simultaneous events is daunting, but at least two scientists have attempted such syntheses. In 1966 J. F. Simpson tried to link mountain formation, sea level change, climate change, change in the earth's magnetism, and extinction and origination of organisms into one interrelated whole. More recently A. Lowrie has related major geologic events, including the effects of meteorite impacts, to one another over the past twenty-five million years.²³ Lowrie is continuing this work and has helped me in attempting to associate climatic cycles with the geologic record of the Great Plains.

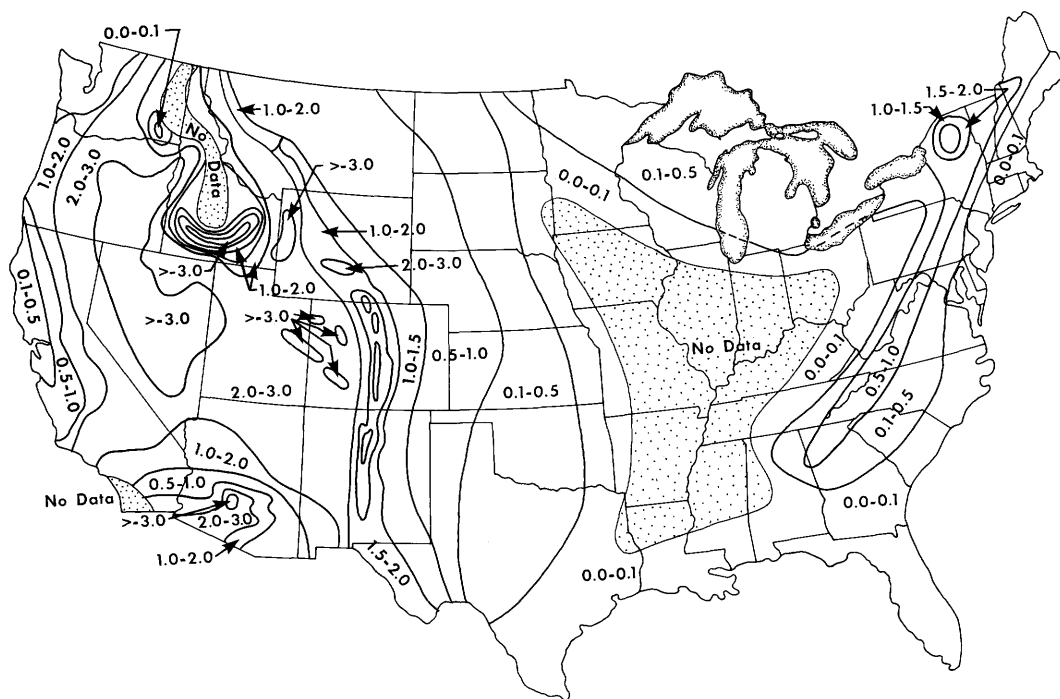


FIG. 7. Magnitude of vertical movement in thousands of meters in the conterminous United States over the last 10 million years. (Figure modified after Gable and Hatton, note 27.)

REGIONAL EROSION AND FILL

Thus far I have been discussing geologic events on a worldwide scale. Now it is time to look specifically at the geologic history of the Great Plains. The Laramide Orogeny, the mountain-building episode that produced the Rocky Mountains and hence defined the Great Plains in contrast, began in the Cretaceous (131-66.5 mybp) and culminated in the Eocene (54-36 mybp). Throughout the late Eocene, streams eroded the mountains down to a plain of low relief. The period of perhaps fifteen million years, from fifty to about thirty-five million years ago, was thus marked by widespread erosion followed by soil formation across this broad area. Deep and extensive weathering of minerals in areas with warm, humid climates leaves behind bright red and yellow iron oxide and clay-rich ancient soils (paleosols) indicative of such environmental conditions. Parts of the erosion surface and paleosols are preserved in both the Rocky Mountains and in the adjacent Great Plains.²⁴

Deposition during the Paleocene and Eocene (66.5-36 mybp) took place in basins between mountain uplifts and on parts of the adjacent Great Plains region, presumably up to the general level of the erosion surface.²⁵ Little evidence of deposition during this time span has been found in Nebraska, either because the sediments were eroded away at most sites after their deposition or because they are buried beneath younger beds. The oldest part of Nebraska's Chadron Formation is very Late Eocene, while one site in northeastern Nebraska has yielded Early Eocene fossils from river deposits, both circumstances suggesting that this phase of the depositional record has for the most part been worn away.²⁶

REGIONAL UPLIFTS

Uplifts have affected both the Rocky Mountains and the adjacent Great Plains for the last thirty-six million years, although they do not seem to have affected the whole area simultaneously.²⁷ Thus as certain areas were pushed up,

the sediments produced by their erosion were deposited by rivers in valleys radiating out from the mountains, while when other areas were later uplifted an overlay of sediments of different composition was deposited over the older beds. During the last ten million years,²⁸ parts of the Rocky Mountains were elevated as much as three thousand meters or more, while parts of the adjacent plains were uplifted up to fifteen hundred meters during the same time (Fig. 7). The rain shadow effects produced by such increases in altitude changed the climate from humid to semiarid.

As deeply buried blocks of Precambrian rocks broke and shifted with periodic differential movement, the overlying rocks were draped in folds or faulted. Subsequent erosion smoothed off the sharp edges of these surface inequalities, creating hills and valleys.²⁹ At least some of this movement has continued into the present. Geologists have also found faulting, or breaks across strata, in rocks of the Tertiary (66.5-1.65 mybp) in parts of eastern Wyoming, northwestern Nebraska, and southwestern South Dakota.³⁰

GEOLOGIC HISTORY OF NEBRASKA AND ADJACENT AREAS, 37-1.65 MYBP

In order to correlate geologic events in Nebraska to the larger picture described in the first half of this article, it is necessary to establish a precise and accurate dating system for the period in question. The classification of the Tertiary System of rock formations (three-dimensional mappable masses of rock having some distinctive features) in Nebraska was initially worked out in some detail by N. H. Darton in 1899 and was refined nearly fifty years ago by A. L. Lugin and others. Scholars have subsequently published many works that add details to the classification or revise it to a greater or lesser degree.³¹ T. M. Stout's work is of particular importance, because in it he addresses questions of origins of the Tertiary sediments and causes of their deposition and of the erosional surfaces separating them one from another. According to Stout, deposition and erosion are cyclic, with erosion occurring during cold, dry periods on

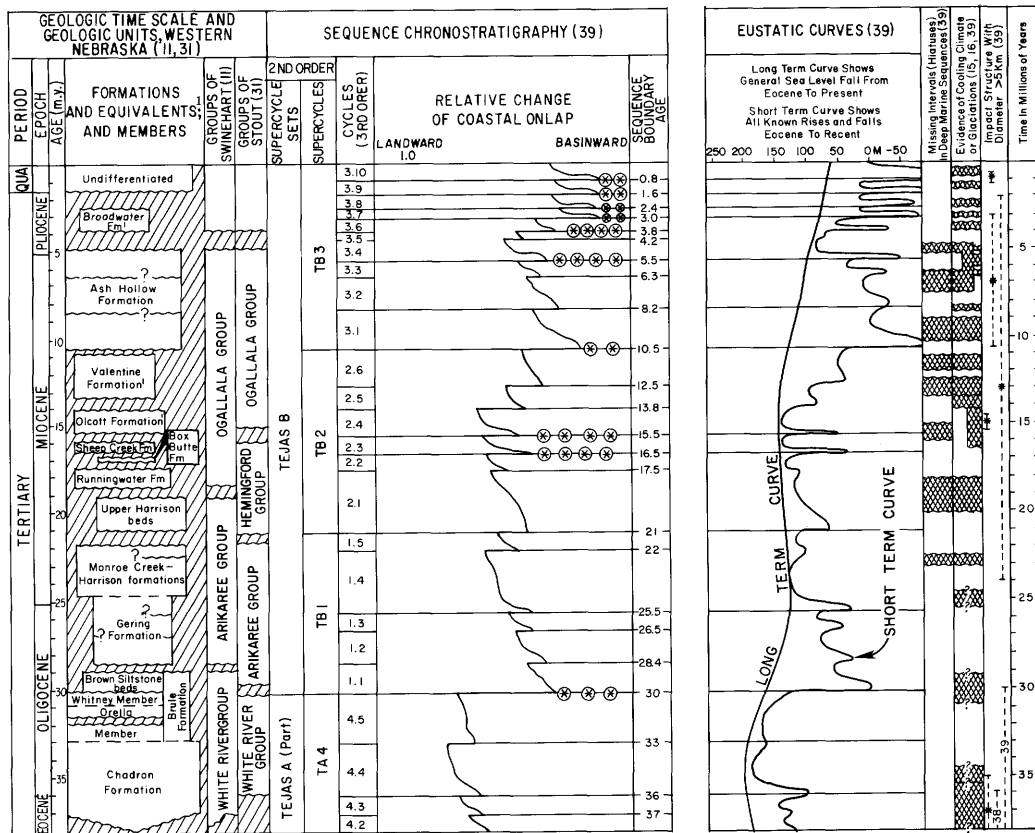


FIG. 8. Distributions of Tertiary geologic groups, formations, and members in western Nebraska compared to coastal onlap curve, eustatic curve, meteorite ages, and known glacial and cold climate episodes. (Scale of geologic units after Swinehart, Souders, DeGraw, and Diffendal, note 11, and Stout, note 31.) Width of box indicates general amount of western Nebraska covered by unit. Wavy lines show erosion surfaces. Diagonal lines denote no deposits recognized. (Cycles, onlap curve and eustatic curve after Haq and others, note 39; Deep sea hiatuses [crosshatched] after Keller and Barron, note 39; Glacial episodes [crosshatched] after Armentrout, note 15, Mercer, note 15, Lowrie, note 23; overlap of episodes indicates differences in reports of authors. Crater [*] ages after Alvarez and Muller, note 39.) Lines of onlap curve noted by circled stars are major sea level declines.

the Great Plains that coincide with major glaciation and lowered sea levels in other parts of the world. Deposition would then occur when the glaciers melted and sea levels rose.

Refinement of radiometric and other dating techniques over the last two decades have enabled scientists to determine the geologic ages of key beds in formations and soils quite precisely, sometimes with a standard deviation of less than half a million years on multiple sam-

ples. New data from field studies have allowed my colleague J. B. Swinehart to revise the classification of the Tertiary rocks in Nebraska (Fig. 8). More recent work by Swisher and Prothero has resulted in some slight changes in dates for older units.³²

Swinehart and others have recently discussed in some detail the basic nature of the Cenozoic deposits in western Nebraska (Fig. 8). The White River and Arikaree groups (a group is two or

more consecutive formations) are mainly composed of valley fills of wind-borne volcanic debris carried into Nebraska from the west and southwest. Some stream-transported sediments also occur in these fills, particularly but not exclusively at the bases of the groups and formations. On the other hand the Ogallala Group and Broadwater Formation deposits are principally stream-transported sediments with minor volcanic ash contribution. Paleosols occur in all of the groups and formations.

The boundaries between most of the various formations and groups seem to coincide quite precisely with the worldwide events chronicled earlier in this article. The volcanic debris comprising much of the White River and Arikaree groups is the right age to have come from the explosive volcanism in the western United States and northern Mexico (Figs. 4, 5). Late Oligocene-Early Miocene (29-19 mybp) strata on the Texas coastal plain, approximately the same age as the Arikaree Group, also have significant air fall volcanic debris as well as stream-transported volcanic rock fragments preserved in major valley fills.³³ Stream sediments begin to predominate in the Ogallala Group at an age that coincides with the period of quiescence of volcanism in the west about seventeen million years ago, which was followed by generally less explosive volcanism.

Most of the major erosional breaks representing gaps in time between formations and groups fit points of greatest relative sea level decline on the curve developed by Vail and his co-workers (Fig. 8). These correlations are remarkable, as are the fits of many of the rock formation boundaries with the least generalized cycles of the curve of sea level rise and fall. The incidences in which these third order cycles do not appear to match our geologic formations may simply reflect a lack of subdivision of the formation rather than a lack of correlation. For example Swinehart and his colleagues have not as yet divided the Ash Hollow Formation into named subdivisions, but I recognize that at least three cut and fill sequences are present in the formation. These seem to fit the changes on the curve. A major cycle break occurring about

10.5 million years ago appears to coincide with the erosion surface between the Valentine and Ash Hollow formations. The Ash Hollow sediments are different in texture, geometry, and prominence of paleosols when compared to older beds, so this formation break may be made more prominent in future classifications. On the other hand, some formations may have been eroded away during a later cycle of erosion and deposition, thus producing gaps in the correlations.

Gravels derived from the erosion of the Rocky Mountains occur in the basal Chadron Formation, in some Whitney Member fills, in the Gering Formation, and in the Runningwater and younger formations of the Ogallala Group (Fig. 8). They are particularly abundant in the Ash Hollow Formation and the younger Pliocene Broadwater Formation. These pulses of coarser sediment correlate well with periods of renewed uplift in the Rocky Mountains and especially well with times that Vail and others have identified with relative sea level rises, that is, times which sediment is being deposited largely in river valleys rather than being transported out to sea.

The glacial model proposed by Stout and generally accepted by this author must also be compared to the Nebraska Tertiary sequence if we are to claim an overall correlation of events on the Great Plains with those of the rest of the globe.³⁴ According to Vail and his co-workers, their generalized first and second order sea level cycles are related to such plate tectonics phenomena as increase or decrease in oceanic ridge volume with consequent changes in sizes of ocean basins, but some or all of the more rapid third order cycles result from glaciation and deglaciation. Known onsets of glaciation correlate with the beginnings of third order sea level cycles and with erosional formation boundaries in some places, but the currently recognized match in timing between these events is not nearly so good as that between relative sea level changes and erosional formation boundaries (Fig. 8). As scientists acquire more data the correlation between glacial cycles and geologic formations may improve, but perhaps, as Vail and his colleagues have claimed, short-

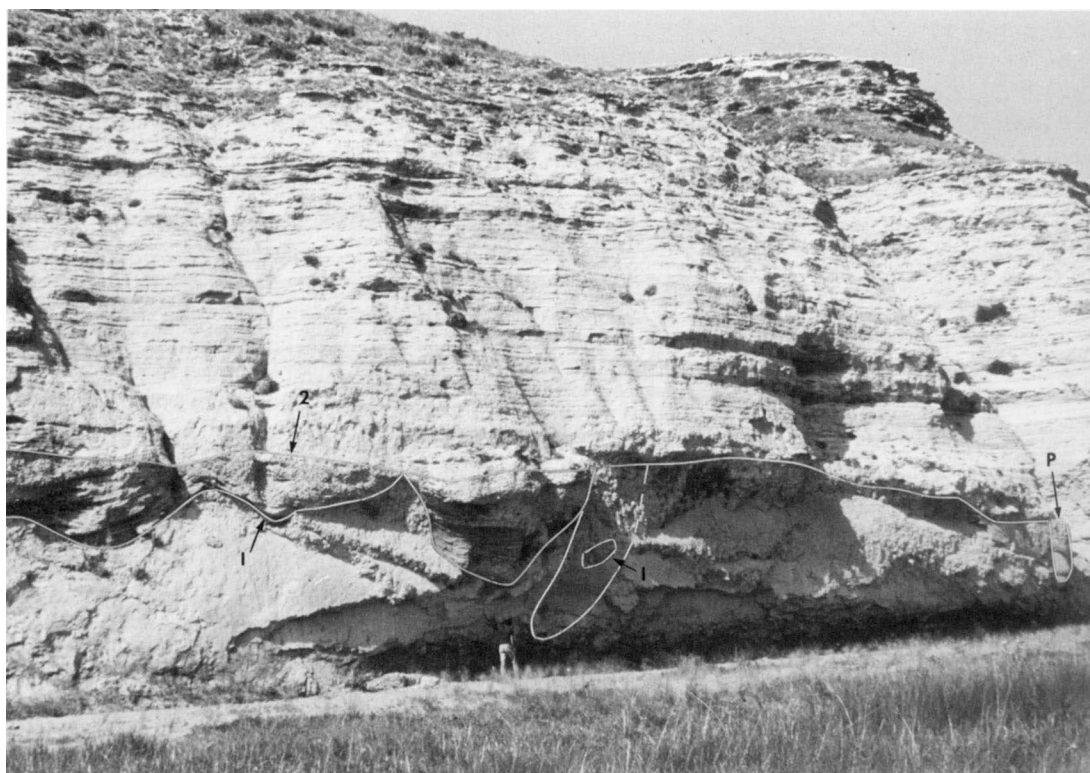


PHOTO 2. Banner County, Nebraska. An older river bed (1), including scour holes and potholes (P), has been eroded into Brule Formation. The younger river bed (2) has been carved into Brule and overlying Gering Formation. Photograph courtesy of R. F. Diffendal, Jr.

term mountain building may be related to some third order cycles, rather than glaciation/deglaciation.

SOILS

As several researchers have noted, paleosols seem to reflect a general trend of increasing aridity throughout the 37 to 1.65 million-year span of geologic history I am considering.³⁵ One anomalous finding that seems to argue against the increasing aridity is the existence of abundant and widespread fossil hackberry pits and casts of these trees in even the youngest Ash Hollow deposits. If it was really so very arid near the end of Ash Hollow Formation deposition, why were all of those trees alive and

flourishing in places where they do not live today? Furthermore, the paleosols of the Ogallala Group do not give evidence of having been deposited during increasingly arid times. There should be more evidence of aridity than simply calcium carbonate enriched paleosols whose origins do not always reflect aridity. Wind transported sediments that do indicate aridity have been recognized in parts of the Ogallala in Texas, but no such deposits have been discovered in Nebraska and adjacent areas.³⁶ In fact rivers deposited almost all of the strata of the Ash Hollow Formation. A small, older loess-like unit below the Ash Hollow Formation, which may or may not be part of Ash Hollow, is at the base, the wrong place to indicate increasing aridity, since aridity increases wind erosion and

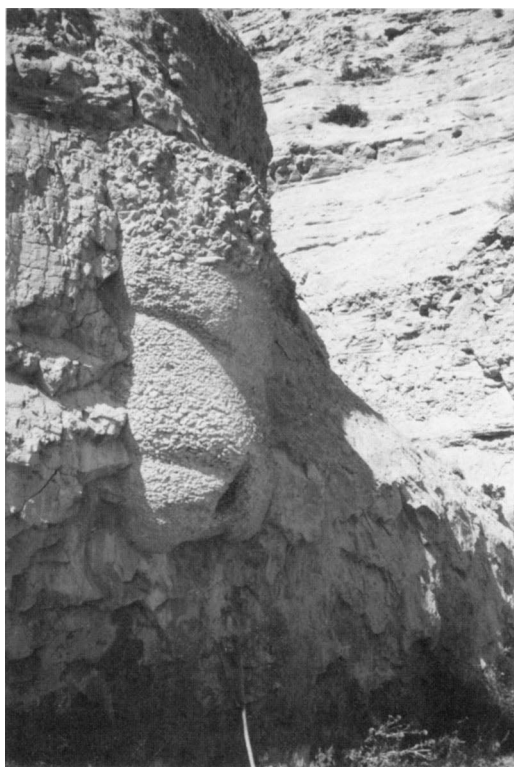


PHOTO 3. Close up of pothole in Photo 2. Basal Gering Formation gravel fill (left center) of the river pothole eroded into Brule Formation siltstones. Photograph courtesy of R. F. Diffendal, Jr.

therefore wind deposits indicate a period of relatively high aridity, higher than that at the time streams were depositing sediments. Evidently many questions about the geologic history of the Great Plains remain unanswered, but we can draw some conclusions.

CONCLUSION

A study of the geologic history of Nebraska and adjacent parts of the Great Plains during the Cenozoic era reveals that the area developed according to the geologic rhythms of the region and the rest of the world. The events that shaped the Plains were synergistic and reflect the idea of a dynamic living planet, the Gaia hypothesis expressed so well by Lovelock. Movement of

tectonic plates with resultant mountain formation,³⁷ igneous activity,³⁸ and changes in ocean circulation and ocean basin sizes and shapes interacts with variations in the earth's solar cycle and possibly collisions with meteors throughout geologic time. Climate changes and evolution of flowering plants and of animals may be driven by these events or, according to Lovelock, may be driving some of them.

On the Great Plains, rivers rising in the Rocky Mountains eroded sediments from upstream and deposited them on the Plains along with air-fall volcanic debris. Volcanic ash from the south and west blanketed much of the Plains between thirty-seven and seventeen million years ago. Renewed uplift of the mountains over the last nineteen million years provided a continuing source of sediment for the rivers to lay down upon the Plains. Throughout the whole period discussed in this article the sea level of the planet repeatedly rose and fell in response to changes in plate tectonic activity and to the waxing and waning of glaciers. Sea level falls are probably related to the erosion of river valleys, while rises probably are related to sediment deposition in those valleys. Riding on the center of a lithospheric plate, the Great Plains nonetheless responded to the multiple geologic events that defined the geologic transformation of the world.³⁹

NOTES

A. Diffendal, V. Souders, and two anonymous reviewers offered helpful suggestions that greatly improved this article.

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