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FUTURE CLIMATIC AND ENVIRONMENTAL CONDITIONS IN THE TEXAS PANHANDLE -- A GEOLOGICAL PERSPECTIVE

by

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INTRODUCTION

Among the many factors to be considered in planning a high-level nuclear waste repository in northwestern Texas are: future climatic conditions and their role in effecting environmental change. In future millenia the regional climate will almost certainly undergo episodic variations comparable to those inferred from the paleoclimatic record of the late Quaternary Period. In addition, local and perhaps global weather patterns may change in ways not previously sustained, as a consequence of inadvertent and possibly deliberate human activities. If the scope and duration of these natural and induced climatic changes were significant they would appreciably influence geomorphic and geohydrologic processes in the Texas Panhandle.

NEED FOR LONG-TERM CLIMATIC ASSESSMENTS

Plans for terminal disposal of nuclear waste depend on resolution of many complex problems not routinely encountered in other fields of technology. Strategies for isolating these materials are constrained by the large initial quantities, extreme radioactivity, and long half-lives of the principal radionuclides and their decay products ("daughters"). Approximately ten half-lives are required to reduce to one thousandth (10^{-3}) the residual amount of a radiogenic species. Twenty half-lives reduce the nuclides to about one millionth (10^{-6}) their original levels. Of course, nuclear waste is a complex combination of radioactive isotopes, some of which are also daughters of other radionuclides present in the initial mixture of wastes. Therefore, the actual concentration of a given isotope may not decline through smooth geometric progression. In addition, the rates at which various radionuclides decay may differ by several orders of magnitude.

Most of the materials in a high-level waste repository have half-lives of several thousand (10^3) years (Board on Radioactive Waste Management, 1983, tables 4-4 and 4-6). Given these slow decay rates, estimates of the composition and quantity of waste to be stored, and the hazardous nature of many of the daughter products, the interior of the repository will be designed for waste containment for 10,000 yr or more (Office of Nuclear Waste Isolation, 1981, p. 3). The tens or possibly hundreds of millenia (Bredehoeft and others, 1978, p. 9) that the wastes must be sequestered from the biosphere are periods over which substantial climatic variations can be expected if the geologic record is a reliable indicator. Thus, in order to predict the climate 10,000 yr hence we must extrapolate the inferred climatic cycles of the past. We must also consider whether other factors, such as incidental and purposeful manipulation of weather, will be significant during this period and determine probable net effects.

Major climatic changes could affect the kinds, rates, and interactions of geomorphic processes in a prospective disposal area. Over an extended period erosion, deposition, and ground-water movement could in turn affect the integrity of a disposal facility in almost any geologic medium. How will geomorphic and geohydrologic systems respond to climatic changes that may obtain in the future? The purpose of this discussion is to summarize the most pertinent results of previous paleoclimatic reconstructions and studies of weather modification, and present a reasonable projection of climatic conditions during the next 100,000 yr. This period exceeds by one order of magnitude the required minimum tenure (10^4 yr) of wastes in storage (Office of Nuclear Waste Isolation, 1981, p. 3). Climatic projections provide a partial basis for estimating the range of environmental conditions during that period.

PALEOCLIMATOLOGY OF THE TEXAS HIGH PLAINS

Reconstruction of past climates is not a new subject. Leonardo da Vinci noted variations in the widths of tree rings and from these inferred the "nature of past seasons" in Italy in the late Fifteenth Century (Hitch, 1982, p. 300). Widespread acceptance of the principles of Huttonian Uniformitarianism in the early and middle 1800's inevitably led to recognition of major climatic variations of the geologic past. By 1840, Agassiz had successfully demonstrated the existence of Quaternary subalpine glaciers in Europe (see excerpt in Mather and Mason, 1939, p. 329-335). With the advent of techniques for absolute dating, particularly radiocarbon analysis (Libby, 1955), the primary basis for systematic investigation of paleoclimate was complete. Considerable attention has been devoted to this topic in the past 30 years.

Several paleoclimatic studies pertain specifically to the Texas High Plains region. But of those reports that have appeared some are flawed by erroneous interpretations of the general Quaternary stratigraphy and by the absence of a detailed, well-established chronostratigraphy. These problems continue to hamper paleoclimatic investigations in the area. The most useful local sources of information on past climates are recent studies of vertebrate and molluscan paleoecology, geomorphic investigations, and descriptions of paleosols. A synthesis of many of the relevant works on these subjects was presented by Caran and McGookey (1983). Since that time further studies in the High Plains, notably those of Holliday (1983), have supplemented the record of the very late Quaternary. Work in the contiguous Rolling Plains (Caran, 1984; Caran and Neck, 1984), to the east has furnished additional details. Modern investigations in the region are well-constrained by radiocarbon dating (Holliday and others, 1983; Caran and Baumgardner, 1985). These and other studies have sought to reconstruct the Quaternary climate of the High Plains, based on inferences from the most reliable paleoclimatic indicators. Investigations currently underway may provide further information and a better overall summary of the regional paleoclimate than is now attainable.

Long-Term Worldwide Climatic Cycles

In recent years several important studies of global climate in the geologic past have been reported. Much of the significant literature appearing before 1978 was reviewed or at least cited by Frakes (1979) who has reconstructed climatic conditions throughout Earth history. Pre-Quaternary continental glaciation has been treated in detail by Hambrey and Harland (1981). The interpretation of sea-level fluctuations throughout Phanerozoic time by Vail and others (1977) can be regarded as a surrogate climatic history in part although other processes such as continental drift, tectonic evolution of the continental and oceanic plates, and eustatic adjustments of the crust have affected sea level, as well. Basinal marine sedimentary deposits provide a very complete high-resolution record of post-Jurassic history. This stratigraphic sequence incorporates a variety of paleontologic, geochemical, tephrachronologic, and sedimentologic indicators of paleoclimate, many of which have been described in detail (for example, see Cline and Hays, 1976). However, these are really paleoceanographic indicators. The circulation (vertical and horizontal) and chemistry of ocean waters can affect the record in ways not solely or directly related to paleoclimate (see discussion by Rea and others, 1985, p. 721). Several excellent paleoceanographic reconstructions (for example, that of McIntyre and Kipp, 1976) have been derived from global oceanic data. But although the marine record is important it is not the ideal source of paleoclimatic data, particularly for the continental interior.

The cause of worldwide climatic changes has been the subject of considerable discussion and controversy. However, Budyko (1977, p. 100) noted that two important causal factors have been identified very clearly: (1) changes in insolation, or the amount of solar radiation reaching Earth's atmosphere at a given latitude and season, owing to secular variations of the planet's axis and orbit relative to the sun; and (2) changes in the transparency of the atmosphere with respect to incident solar energy. Equally significant are changes in the atmosphere's insulation value in terms of absorption of emitted and reflected energy. The amount of atmospheric dust, volcanic ash, and cloud cover controls the flux of incoming solar energy; whereas the concentration of water vapor and carbon dioxide, in particular, governs the retention of part of the outgoing heat and light within the atmosphere ("greenhouse effect"). Effects of cyclical changes in Earth's orbit are discussed by Milankovitch (1941), Hays and others (1976), Denton and Hughes (1983), and Kutzbach and Guetter (1984), although others including Moore and others (1982) have shown that this relation may be more complex and variable than many have supposed.

Properties of the atmosphere combine with planetary orbital parameters ("forcing functions") to regulate the distribution of heat and moisture. This in turn influences "secondary" climatic controls such as the areal extent of high-albedo ice cover, which is inversely proportional to that of climate-moderating ocean waters. These and many other factors interact to influence atmospheric circulation, seasonality, and the position of climatic zones. There are several orbital cycles that have been shown to affect climate, of which those of 0.4, 0.1, 0.04, and 0.02 million years have been most significant during the late Cenozoic Era (Moore and others, 1982). Denton and Hughes (1983, p. 132, 133) have explained the roughly 100,000-yr late Pleistocene full-glacial/interglacial cycle in terms of a combination of orbital parameters that periodically reinforce one another. If this relation persists the next full-glacial episode would be expected in 80,000 yr, or approximately 100,000 yr after the Wisconsinan glacial maximium 18,000 yr b.p. (McIntyre and Kipp, 1976). Several intermediate glacial advances during relatively cool periods are likely to occur within those 80,000 yr (Denton and Hughes, 1983).

Regional Paleoclimatic Summary

The paleoclimate of the Southern High Plains and adjacent areas has undergone marked changes since late Pleistocene time (Caran and McGookey, 1983). Even within the past 100,000 yr, the period with which we are particularly concerned, there have been several moderate and major climatic fluctuations (fig. 1). Beginning approximately 70,000 yr b.p (end of the Sangamonian interglacial stage), temperatures in the Northern Hemisphere decreased rapidly and dramatically with the onset of the Wisconsinan glacial stage (Beard and others, 1982, fig. 1). Direct evidence of this change in northwestern Texas is uncertain because the regional chronostratigraphic record of this period has not been defined in sufficient detail. The so-called "Cover sands" and superimposed "Sangamon" soil of the Southern High Plains (Frye and Leonard, 1957, p. 38) are pedogenically modified eolian deposits that Reeves (1976, p. 213) renamed the Blackwater Draw Formation. This thick, laterally extensive body of fine sediment is now known to comprise a suite of stacked buried soils, the oldest of which is perhaps 1.4 million years old or slightly older (Holliday, 1984; Machenberg and others, 1985). The Blackwater Draw Formation may be actively forming and if so spans most of the middle and late Quaternary Period. There is, however, surprisingly little variation within the unit itself, and its relation to paleoclimate has not yet been interpreted.

Three or more stratigraphically distinct lacustrine deposits are at least partly contemporaneous with the Blackwater Draw. The lacustrine strata fill discrete paleobasins. The youngest of these units is being deposited today in numerous small, ephemeral playa lakes distributed over most of the Southern High Plains. The oldest of the Quaternary lake deposits, the Tule Formation, ranges from 1.3 to 0.6 million years in age (Schultz, in press) and either underlies (predates) or interfingers with the Blackwater Draw Formation (Holliday, 1984). Clearly, considerable moisture was available during most of the period when the Tule Formation was deposited. A number of large lakes had existed on the High Plains of Texas during the Pliocene Epoch, as well. The Blanco and Rita Blanca Formations embody the stratigraphic record of these lakes which were similar in many respects to the lacustrine environment of the Tule Formation (Evans and Meade, 1945; Anderson and Kirkland, 1969).

Regional conditions near the end of the Pleistocene Epoch are not well understood. Pierce (1975) has defined a molluscan fauna that may date from the Sangamonian interval immediately prior to the Wisconsinan climatic shift. This fauna is indicative of a warm, dry climate, an interpretation that is consistent with the marine record of Beard and others (1982) and data from many other parts of North America (for example, Follmer, 1978).

The history of early Wisconsinan time in the Texas Panhandle is no better known than that of the previous, interglacial period. The Blackwater Draw Formation and some of the lacustrine units record part or all of this interval but again, there is inadequate data from which to develop a detailed reliable paleoclimatic reconstruction. The age and stratigraphic affinity of these deposits remain uncertain and the strata may lack suitable diagnostic climatic indicators. Some authors (for example, Wendorf, 1961; and Reeves, 1965, 1966, 1973) have proposed environmental summaries covering early to late Wisconsinan time. But these attempts were fraught with difficulties owing to the problems noted above. Data from contiguous areas, particularly the Desert Southwest, give an indirect indication of conditions in northwestern Texas. Perhaps the most representative evidence is that from packrat middens at several sites in New Mexico, the Trans-Pecos Region of West Texas, and adjacent areas (Van Devender and Spaulding, 1979; Lanner and Van Devender, 1981), and vertebrate paleofaunas from a few nearby localities (see Kurten and Anderson, 1980, map 4). The early Wisconsinan record cannot be dated by radiocarbon analyses, and materials suitable for other forms of absolute dating generally are not available, so that this interval is known imperfectly. However, assessment of both marine data (Beard and others, 1982) and available terrestrial indicators suggests a much cooler and wetter climate than had existed previously (fig. 1).

The late Wisconsinan and Holocene histories of the region are comparatively well understood. Evidence from the Southern High Plains (Holliday and others, 1983) and the western Rolling Plains (Caran, 1984; Caran and Neck, 1984) is in reasonably close agreement and is consistent with data from many other areas (Lanner and Van Devender, 1981). Limited evidence from vertebrate faunas, especially that of Dalquest (1964), Johnson and others (1982), and Hughes (1977), is compatible with molluscan data (Pierce, 1975; Neck, 1978; Caran, 1984). Cool, wet conditions in the late Pleistocene gave way rapidly to a warm, dry climate in Holocene time. The transition to a warm, dry climate evidently was accomplished in two stages. The area had become almost as warm as it is today by 5,000 yr b.p., culminating a trend that began about 10,000 to 12,000 yr b.p. By about 3,000 yr b.p., the climate was nearly as dry as at present; desiccation commenced at about the same time as the rise in temperature but intensified more gradually (Caran, 1984; Caran and Neck, 1984) (fig. 1). Holliday and others (1983, fig. 6) see much the same trend overall but infer a wider range of variation throughout the Holocene and envision conditions drier and warmer than today during the Hypsithermal interval (fig. 1). Most authors agree that the climate was at least as warm as in the post-Neoglacial Holocene (fig. 1). Whether conditions were even warmer and whether relatively wet or dry are at issue; yet the reconstruction shown in fig. 1 seems to fit the preponderance of evidence, when a close accounting of environments of deposition, absolute chronology, and paleo-environmental indicators is taken. In the Texas Panhandle other variations in Holocene climate were relatively minor.

ANTHROPOGENIC CLIMATIC VARIATIONS

Incidental Effects

Numerous investigators have discussed individual examples of human impact on climate. Notable among these effects is the demonstrated increase in atmospheric carbon dioxide that results from combustion of fossil fuels and certain industrial and agricultural processes (Liss and Crane, 1983, p. 9). Carbon dioxide, along with water vapor and ozone, selectively absorbs infrared energy emitted from the ground. This causes an increase in atmospheric heat, the "greenhouse effect." Through a complex system of feedbacks these gases and vapors are able to retain within the atmosphere an ever increasing percentage of the solar energy absorbed by the ground, as well as vagrant heat from manufacturing and other activities. Whether this effect is partly offset by the increase in reflective atmospheric dust that too results from these operations is unclear. For a thorough treatment of these relations and their possible consequences <u>see</u> Bach and others (1983).

Humans appear to have unintentionally affected climate in many different ways, although there remains considerable controversy surrounding some of these issues. A particularly spirited exchange followed the announcement of purported increases in precipitation linked to massive irrigation projects in the Columbia River Basin (Stidd, Fowler, and Helvey, 1975). In the final analysis there does appear to have been a marked rise in local seasonal rainfall attributable to the heightened moisture from evaporation of of irrigation waters. Intensified land use, especially urbanization, cultivation, deforestation, and overgrazing, changes the surface albedo over vast areas and generally increases atmospheric dust. These factors also may affect atmospheric temperatures but in ways not well understood. Other effects are now clearly demonstrated. As early as 1852, investigators had detected increased air temperatures from combustion within the "urban heat island" of London relative to the surrounding countryside (Griffiths, 1976, p. 127). Lyons (1974) used satellite imagery to reveal intensified cloud cover downwind from Midwestern industrial areas contributing atmospheric moisture and aerosols. Some urban centers habitually receive 10 to 15 percent more precipitation than do otherwise comparable rural areas (Weather Modification Board, 1978, p. 7) owing to similar occurrences. Additional effects are described by Flohn and Fantechi (1984, p. 176-197).

Intentional Weather Modification

Incidental effects of human activities have intentional counterparts in the growing field of weather modification. For example, snow and ice can be increased by 10 to 30 percent in selected areas by intensive cloud seeding with hygroscopic aerosols (Weather Modification Board, 1978, p. 3). The literature pertaining to weather modification, particularly for increased rainfall, is extensive. An annotated bibliography on this subject was assembled by the Water Resources Scientific Information Center (1973), and includes numerous references dealing with precipitation enhancement in many parts of the world. One of the areas where such programs have been especially active is the Panhandle Region of Texas. Between 1971 and 1980, rainfall was increased 28 percent in an area just southeast of the Southern High Plains (Girdzus, 1980, p. 3, 28). This and other efforts are still largely experimental and results to date have been mixed. However, weather modification is likely to assume an increasingly important role in agriculture and other activities in the future. Should natural and induced climatic changes eventually pose a significant problem, new techniques of climatic manipulation may be developed to combat adverse conditions. Strategies for dealing with even a single problem, increased concentrations of atmospheric carbon dioxide, could consume a substantial percentage of an industrial nation's gross national product (Laurmann, 1983). Yet the alternative could be gradual desiccation of much of the planet including more than half of North America as far south as the Southern High Plains (Kellogg, 1983, fig. 10).

RANDOM FACTORS

Regional and even global climate may occasionally be affected by essentially random yet profound disturbances. Major volcanic eruptions (or a series of moderate eruptions) and impacts of very large extraterrestrial objects may be sufficient to alter weather patterns over a large area for extended periods. The role of increased high-altitude atmospheric aerosols from volcanoes has been discussed by Pollack and others (1976), Bray (1977), and Rampino and Self (1982). Clearly, volcanic ash can permeate the troposphere and even the stratosphere and remain in suspension for years. Incident solar radiation is backscattered by these particles. If the concentration of ash is sufficient radiation may be reduced significantly over a large part of the planet. Flohn and Fantechi (1984, p. 230) concluded that during the "Little Ice Age" (Neoglacial climatic interval) of the present millenium (1350-1850), intense volcanic activity was responsible for much of the appreciable cooling felt throughout the Northern Hemisphere. An even more extensive series of eruptions could have greater effects, but these presumably would be relatively temporary (from 10^2 to 10^3 yr). Volcanic eruptions are essentially random events in time. Their effect on climate is to reduce radiative heating, causing parts of the planet to cool. Impact of a large meteorite or other body would have the same effect if debris were thrown into the atmosphere. Some recent discussions of this topic have linked such rare events to major extinctions (for example see Silver and Schultz, 1982), but this relation is by no means free of controversy (Kerr, 1985). Large eruptions and impacts must be considered random occurrences. Their effects are not differentiated from other natural climatic variations in this discussion.

FUTURE CLIMATIC CONDITIONS

The previous discussion of paleoclimate and anthropogenic effects on the atmosphere emphasized the multivariate controls on weather conditions, the long history and wide range of climatic variations, and uncertainties regarding man's present and future roles. The geologic record leaves little reason to doubt that climate will continue to vary in the future, but in what ways and to what degree, and when might significant changes be felt? Will the weather change rapidly or gradually? Will there be wide fluctuations prior to establishment of a new equilibrium, or will the transition be smooth? Will effects be global, with compression or elimination of some existing climatic zones? Or will changes be confined to certain latitudes, leaving other areas largely unaffected?

In addition to natural variations there may be appreciable changes attributable to man. These changes are not well understood. We can only guess that increasingly intensive land use, combustion of fossil fuels, redistribution of surface water, and other actions may have an unintended impact on climate. Apart from these endeavors there will likely be deliberate efforts to manipulate weather conditions to a far greater extent than has been attempted to date. Future interaction of natural and anthropogenic factors affecting climate may have unexpected results. The pattern of weather conditions across the Southern High Plains in the next several thousand years is extremely uncertain and must be considered in terms of (1) trends perceived in the distant to recent past and projected into the future, and (2) effects, both intentional and inadvertent, of man's wide-ranging activities (to include many that are as yet unanticipated).

Net Effects on Climate and Environment

Cool and Wet

The Southern High Plains of Texas may be as warm and dry today as at any time in the Quaternary Period. Short-term drought like that of the 1930's in the Midcontinent is one extreme of the range of normal variation in the region's modern climate (Warrick, 1975, fig. I-6) and probably that of the entire Holocene Epoch. It is possible that relatively dry, warm conditions could become more persistent but this probably would require unmitigated anthropogenic effects such as a marked increase in atmospheric carbon dioxide. Predicted solely on the basis of the late Quaternary paleoclimatic record the regional climate is likely to grow wetter and cooler in coming millenia, with substantial but temporary reversals in this overall trend. Just when this might occur has been widely debated (Kukla and others, 1972; Mitchell, 1972) but no firm conclusions have been reached.

An absolute increase in precipitation, coupled with reduced evaporation as a result of cooler temperatures, would increase 1) discharge through drainages and 2) impondment in poorly drained areas on the High Plains themselves. At the same time, erosion-retarding vegetative cover would increase in areas not otherwise disturbed. Finley (1979, p. 66) has stated that erosion by running water at present may approach a maximum theoretical rate. This determination is based on the mean precipitation and the inverse relation between ground cover and runoff in terms of an area's susceptibility to erosion (Langbein and Schumm, 1958; Schumm, 1965, fig. 2). If the regional climate were to become wetter and cooler this relation would be disturbed and erosion (including deflation) could decrease from present high levels.

However, most of the erosion in the Panhandle region occurs at the margins of the Southern High Plains, along steep escarpments where recessive-weathering Permian gypsum and clastic deposits are exposed. Soils are absent from most of the interfluves in this terrain or are thin and saline because of the gypsum. The runoff entering some drainages may be only slightly saline but it combines with discharge from moderately to extremely saline (NaCl and $CaSO_4$) springs. Salts in the alluvium and upland soils inhibit or reduce vegetative ground cover, particularly along the major streams and steepest Permian outcrops. These effects are confined to a narrow but important zone near the base of the escarpment. There, Schumm's (1965) relation may not apply because precipitation is not the principal factor limiting vegetation. A long-term increase in precipitation might not result in greater density of soil-stabilizing plants. As a result erosion in these areas might increase steadily in response to increased precipitation.

Moreover, this added moisture probably would enhance recharge and underground dissolution of evaporites beneath the High Plains margins. Additional saline water would discharge and, even more important, subsidence likely would increase. Regional subsidence probably promotes erosion along the escarpments, by rapidly lowering local base levels. This would accelerate escarpment retreat and headward extension of drainages toward the High Plains interior. Flow between playas on the High Plains also would increase which too would enhance incision and extension of the drainage network. Increased precipitation would reduce dependence on ground-water withdrawals and directly supplement recharge of the Ogallala Formation on the High Plains. These effects would enhance spring flow and sapping, further accelerating escarpment retreat (Gustavson, 1983).

Warm and Dry

An essentially permanent climatic shift to warm, dry conditions could only occur if anthropogenic effects, especially augmentation of atmospheric carbon dioxide, were to continue unabated. Both natural processes and human endeavors probably could prevent, delay, or partly offset a permanent occurrence of this kind if the change were gradual (Laurmann, 1983; Liss and Crane, 1983). But should the regional climate in fact stabilize with conditions as dry and warm as those of today, or even slightly drier and warmer, geomorphic processes probably would be little changed. Denudation, incision, and mass wasting would continue to be important, particularly during intermittent, if perhaps less frequent periods of intense rainfall (Finley and Gustavson, 1980). Deflation would continue on disturbed (cultivated and overgrazed) uplands at the fairly rapid modern rates (Machenberg and Caran, 1984). Spring sapping along the Caprock Escarpment would essentially terminate but the importance of this process already has declined from historic levels because of overpumping of the Ogallala aquifer (Gustavson, 1983). Thus, modern erosional rates probably represent effective maxima for estimating future conditions. Such estimates would remain appropriate even if the climatic changes were pronounced, producing weather conditions that were substantially drier and/or warmer yet. Changes of this magnitude might accentuate deflation relative to erosion by water under ordinary circumstances but extreme events might not differ from those under existing conditions. This assertion is based on interpretation of the findings of Finley and Gustavson (1980) and Machenberg and Caran (1984). Recharge to deep aquifers probably would be reduced as would dissolution of Permian evaporites in consequence.

SUMMARY AND CONCLUSIONS

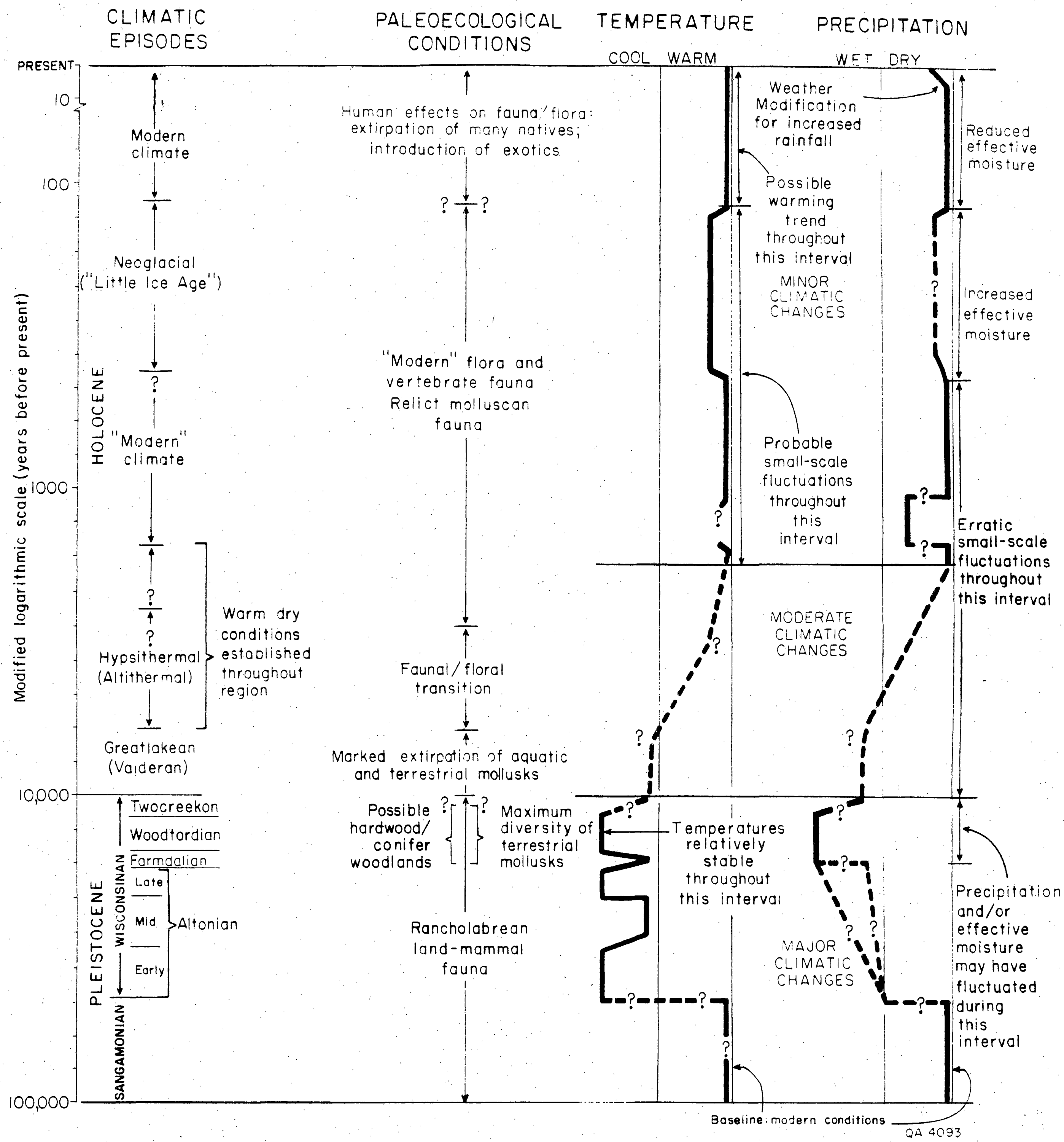
Although the exact course of climatic fluctuations in the geologic future (10^4 to 10^5 yr) cannot be charted with certainty we can project the two most likely conditions, one based on natural episodic variations alone, the other based solely on anthropogenic effects like those occurring at present. The two projections are diametrically opposed and neither can be accepted or rejected with confidence. The real answer may lie between these extremes, or perhaps in another direction entirely, but the evidence at hand favors the alternate conclusions stated here. If climate follows the pattern of the late Pleistocene cool, wet conditions will develop, probably within 80,000 yr. Dissolution-subsidence, spring sapping, and erosion by running water possibly would increase; therefore, direct effects on a geologic repository for nuclear waste might be expected given sufficient time.

If, instead, the climate were to stabilize at or near existing temperature and moisture levels geomorphic processes would be largely unaffected. The repository appears less likely to be disturbed under these circumstances (warm, dry climate) although this appraisal too is uncertain. Anthropogenic effects probably would be needed to cause very long-term (10^4 yr or longer) warm, dry conditions beyond the present interglacial stage. The adverse global consequences of induced atmospheric warming probably would trigger deliberate efforts to control emissions of carbon dioxide, or other remedial measures (Lamb, 1971). The results of such efforts cannot be predicted. Possible societal adjustments to future global climatic changes are discussed by Butzer (1983). Reactions of various societies (prehistoric and historic) to climatic variations of the past have been described by Malde (1964), Livingstone (1971), Warrick (1975, p. 40-58), and Flohn and Fantechi (1984, p. 269-312).

Siting and design of a high-level nuclear waste repository must account for conditions over ten or more millenia. Because the magnitude, but not the direction of future climatic changes can be estimated from geologic and anthropogenic effects, a reasonable, conservative response is to plan for the "worst-case scenario" in the long term. Erosion, subsidence, and deep infiltration of unsaturated (with respect to NaCl and $CaSO_4$) ground water could exceed conditions now existing in the Southern High Plains within the time frame necessary for appreciable decay of the waste.

CAPTION

Figure 1. Paleoclimatic reconstruction of the late Pleistocene and Holocene Epochs, northwestern Texas (modified from Caran and McGookey, 1983, fig. 90; and Caran and Baumgardner, 1984, fig. 3). Pleistocene climatic episodes essentially correspond to the "conceptual Pleistocene stages" of Beard and others (1982, fig. 1). Note that the vertical scale is logarithmic overall but linear between orders of magnitude.



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