Title 40 CFR Part 191
Compliance Certification Application
for the
Waste Isolation Pilot Plant

Appendix CLI

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Area Office
Carlsbad, New Mexico

Long-Term Climate Variability at the Waste Isolation Pilot Plant

CONTRACTOR REPORT

SAND91–7055
Unlimited Release
UC–721

Long-Term Climate Variability at the Waste Isolation Pilot Plant, Southeastern New Mexico, USA

Peter N. Swift
Tech Reps, Inc.
5000 Marble Avenue NE
Albuquerque, NM 87110

Prepared by Sandia National Laboratories Albuquerque, New Mexico 87185 and Livermore, California 94550 for the United States Department of Energy under Contract DE-AC04-76DP00789

Printed November 1992

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
Office of Scientific and Technical Information
PO Box 62
Oak Ridge, TN 37831

Prices available from (615) 576-8401, FTS 626-8401

Available to the public from
National Technical Information Service
US Department of Commerce
5285 Port Royal Rd
Springfield, VA 22161

NTIS price codes
Printed copy: A04
Microfiche copy: A01

SAND91-7055
Unlimited Release
Printed November 1992

Distribution
Category UC-721

Long-Term Climate Variability at the Waste Isolation Pilot Plant, Southeastern New Mexico, USA*

Peter N. Swift
Tech Reps, Inc.
5000 Marble Avenue NE
Albuquerque, NM 87110, USA

ABSTRACT

The United States Department of Energy is developing the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico for the disposal of transuranic wastes generated by defense programs. Because changes in climate during the next 10,000 years (10 ka) may affect performance of the repository, an understanding of long-term climate variability is essential for evaluating regulatory compliance.

Fluctuations in global climate corresponding to glaciation and deglaciation of the northern hemisphere have been regular in both frequency and amplitude for at least 780 ka. Coolest and wettest conditions in the past have occurred at the WIPP during glacial maxima, when the North American ice sheet reached its southern limit roughly 1200 km north of the WIPP and deflected the jet stream southward. Average precipitation in southeastern New Mexico during the last glacial maximum 22 to 18 ka before present (BP) was approximately twice that of the present. Driest conditions (precipitation approximately 90% of present) occurred 6.5 to 4.5 ka BP, after the ice sheet had retreated to its present location. Wet periods of unknown duration have occurred since the retreat of the ice sheet, but none have exceeded glacial conditions. Global climate models suggest that anthropogenic climate changes (i.e., warming caused by an increased greenhouse effect) will not result in an increase in precipitation at the WIPP. The climate of the last glacial maximum is therefore suitable for use as a cooler and wetter limit for variability during the next 10 ka.

*Also published in *Environmental Management*, Vol. 17, No. 1, p. 83-97 (1993)

ACKNOWLEDGMENTS

This work was performed for the WIPP Performance Assessment Department (6342) of Sandia National Laboratories and the United States Department of Energy under contracts 27-3504 and DE-AC04-76DP00789. Portions of the material presented here have also been reported by Bertram-Howery and others (1990) and Swift (1991).

The author thanks R. Y. Anderson, S. H. Conrad, R. V. Guzowski, G. R. Heath, R. L. Jones, G. J. Kukla, M. G. Marietta, W. D. McCoy, C. L. Northrop-Salazar, T. R. Van Devender, and W. D. Weart for reviews of this work at various stages. Comments from these reviewers greatly improved the organization and content of the manuscript; however, the author accepts full responsibility for the interpretations and conclusions presented here. The author also thanks D. A. Marchand and the illustration department at Tech Reps, Inc., Albuquerque, NM, for assistance with the figures.

CONTENTS

Figures

1. Introduction

The Waste Isolation Pilot Plant (WIPP), located 42 km east of Carlsbad, New Mexico (Figure 1), is being evaluated by the United States Department of Energy (DOE) for disposal of transuranic wastes generated since 1970 by defense programs. The repository is excavated approximately 655 m below the ground surface in bedded halite of the Late Permian Salado Formation, deposited approximately 255 million years before the present (255 Ma BP).

Before the WIPP can be used for long-term disposal of transuranic waste, the DOE must demonstrate compliance with the United States Environmental Protection Agency's (EPA) *Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Waste* (40 CFR 191) (U.S. EPA, 1985), hereafter referred to as the standard. Although the standard was vacated by a Federal Court of Appeals in 1987 and is undergoing revision, by agreement with the State of New Mexico, the DOE is continuing to evaluate repository performance with respect to the regulation as first promulgated until a new version is available (U.S. DOE and the State of New Mexico, 1981, as modified in 1984 and 1987).

The standard requires that the DOE consider "all significant processes and events that may affect the disposal system" during the 10,000 years (10 ka) following decommissioning. The performance assessment being conducted for the DOE by Sandia National Laboratories is therefore examining, among other things, the likelihood and consequences of long-term changes in climate. Climatic changes have the potential to affect repository performance directly, by altering groundwater recharge and flow in the region, and indirectly, by changing human land-use patterns in the region. Increases in precipitation are of primary concern because they may result in increased groundwater flow and, in the event of a breach of the repository, increased transport of radionuclides to the accessible environment.

2. Modern Climate at the WIPP

At present, the climate at the WIPP is arid to semiarid. Mean annual precipitation at the WIPP has been estimated to be between 28 and 34 cm/yr (Hunter, 1985). At Carlsbad, 100 m lower than the WIPP, 53-yr (1931-1983) annual means for precipitation and temperature are 32 cm/yr and 17.1°C (University of New Mexico, 1989). Short-term variation about the annual means can be considerable, and historic weather data cannot be used to predict long-term climatic shifts. For example, the 105-yr (1878 to 1982) precipitation record from Roswell, 135 km northwest of the WIPP and 60 m

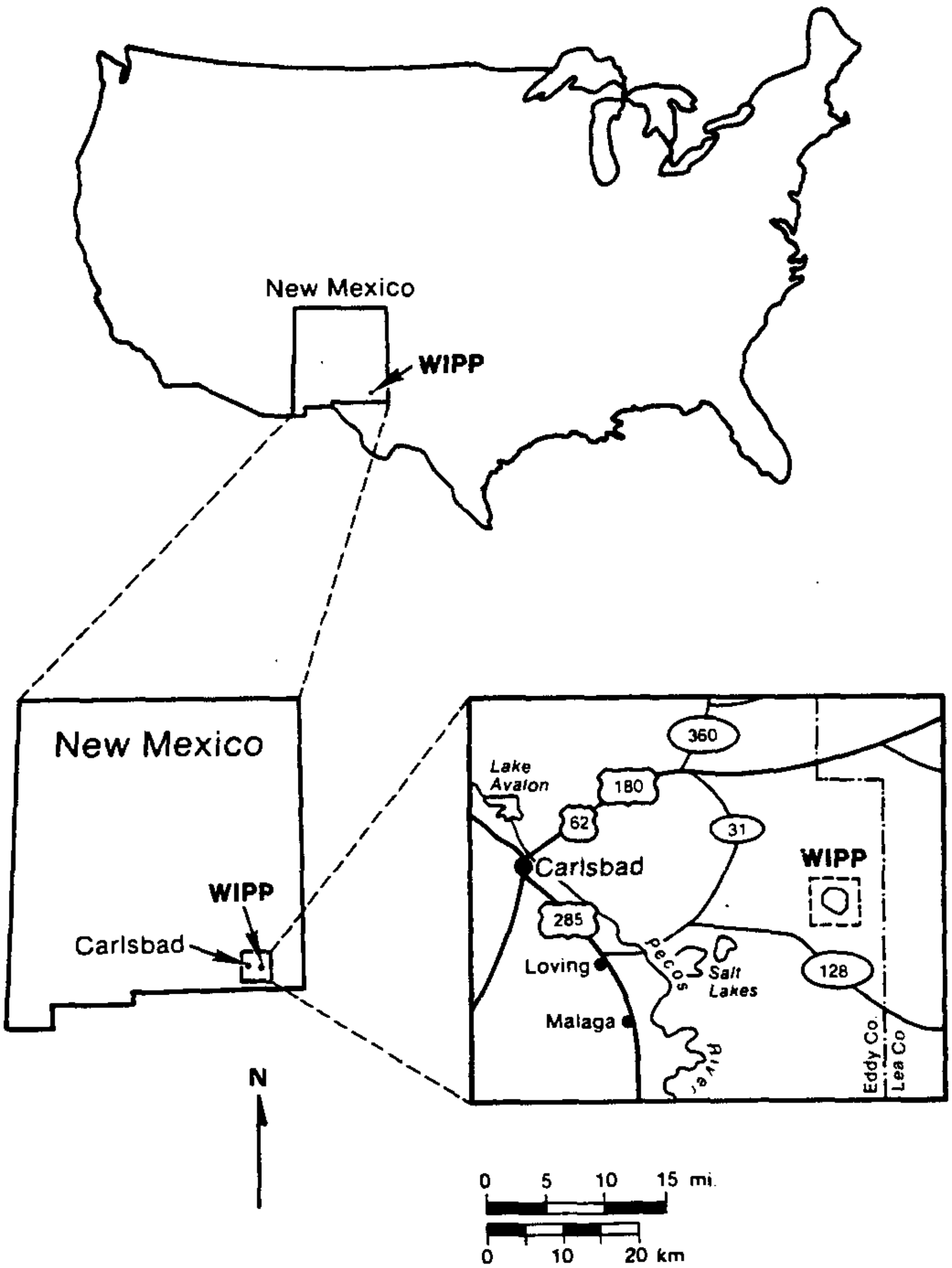


Figure 1. Location of the WIPP (after Bertram-Howery and Hunter, 1989).

higher, shows an annual mean of 27 cm/yr with a high of 84 cm/yr and a low of 11 cm/yr (Hunter, 1985).

The climate of southeastern New Mexico is monsoonal: most of the precipitation falls in late summer, when solar warming of the continent creates an atmospheric pressure gradient that draws moist air inland from the Gulf of Mexico (Cole, 1975). The coincidence of precipitation and temperature maxima is typical of a monsoonal climate (Figure 2). Much of the rain falls during localized and often intense summer thunderstorms, and winters are cool and generally dry. Both temperature and precipitation are dependent on elevation, and local climates vary with topography. At lower elevations throughout the region, including the vicinity of the WIPP, potential evaporation greatly exceeds precipitation. Freshwater pan evaporation in the region is estimated to exceed 274 cm/yr (Hunter, 1985). Surface runoff and infiltration of rainwater into the subsurface are limited. Hunter (1985) concluded from a literature review that within the vicinity of the WIPP an average of 96 percent of precipitation is lost to evapotranspiration. Evapotranspiration values may be significantly higher or lower locally.

3. Climatic Change

Presently available long-term climate models are incapable of resolution on the spatial scales required (e.g., Hansen and others, 1988; Mitchell, 1989; Houghton and others, 1990), and it is not realistic to predict the climate of southeastern New Mexico for the next 10 ka. Instead, this report reviews evidence of past climatic changes in the region, and establishes limits on future precipitation based on known and modeled past extremes. Much of the available paleoclimatic data only record long-term average levels of precipitation, and these limits do not reflect the high variability apparent in the modern short-term data. The precipitation record presented here primarily reflects gradual shifts in long-term mean values.

A fundamental assumption, analogous to that made by Spaulding (1985) in a study of climatic variability at the Nevada Test Site, is that climatic extremes of the next 10 ka will not exceed those associated with glaciations and deglaciations that have recurred repeatedly in the northern hemisphere since the late Pliocene (2.5 Ma BP). The possibility that human-induced changes in the composition of the earth's atmosphere may influence future climates complicates projections of this cyclic pattern into the future, but, as presently modeled (e.g., Mitchell, 1989; Houghton and others, 1990), such changes do not appear likely to have a negative effect on the performance of the WIPP. The highest past precipitation levels in southeastern New Mexico,

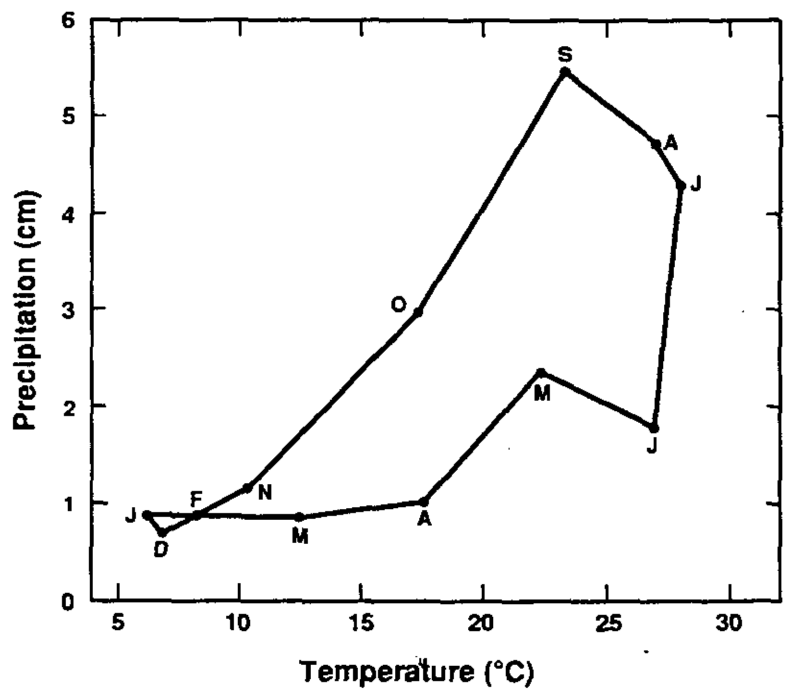


Figure 2. Climatograph showing 30-yr (1951-1980) monthly precipitation and temperature means recorded at the Carlsbad, New Mexico airport, approximately 45 km west of the WIPP and 50 m lower (data from NOAA, 1989).

up to twice those of the present, occurred during full-glacial conditions associated with global cooling (e.g., Van Devender and others, 1987; other sources cited below). Presently available greenhouse models, however, predict average equilibrium global warming of 1.8 to 5.2°C for carbon dioxide concentrations twice present levels (Mitchell, 1989; Houghton and other, 1990), a condition that could delay the start of renewed glaciation. Published model predictions of precipitation trends accompanying greenhouse warming are less consistent and less reliable than temperature predictions, but none suggest significantly higher levels of precipitation in southern New Mexico than those of the present (Washington and Meehl, 1984; Wilson and Mitchell, 1987; Schlesinger and Mitchell, 1987; Houghton and others, 1990). Because long-term increases in recharge are improbable without increases in precipitation, the highest-risk climatic change that will be considered here is, therefore, a return to the glacial extremes of the past.

Data that can be used to interpret paleoclimates in southeastern New Mexico and the surrounding region come from a variety of sources, and indicate an alternation of arid and subarid to subhumid climates throughout the Pleistocene. Prior to 18 ka BP, radiometric dates are relatively scarce, and the record is incomplete. From 18 ka BP to the present, however, the climatic record is relatively complete and temporally well constrained by radiocarbon dates. This report cites extensive floral, faunal, and lacustrine data from the region that permit reconstructions of precipitation and temperature during the late Pleistocene and Holocene. These data span the transition from the last full-glacial maximum to the present interglacial period, and, given the global consistency of glacial fluctuations as described below, they can be taken to be broadly representative of extremes for the entire Pleistocene.

4. Variability in Global Climate Over the Last 2.5 Million Years

Core samples of datable marine sediments provide a continuous record that reveals as many as 50 glaciation/deglaciation events in the last 2.5 Ma. Specifically, correlations have been made between major glacial events and variables such as the ratio of $^{18}O/^{16}O$ measured in the remains of calcareous foraminifera and past sea-surface temperatures determined from planktonic assemblages (Ruddiman and Wright, 1987). In addition, glacial cycles have been observed in the past composition of the earth's atmosphere preserved in polar glacial ice (Langway and others, 1985; Jouzel and others, 1987; Barnola and others, 1987) and in a $^{18}O/^{16}O$ record from calcite vein fillings in Nevada (Winograd and others, 1988).

Oxygen isotope ratios from oceanic foraminifera provide the most direct evidence, because they reflect past volumes of glacial ice (Imbrie and others, 1984). Evaporation fractionates ^{18}O and ^{16}O isotopes in water, producing a vapor relatively enriched in ^{16}O and residual seawater relatively enriched in ^{18}O. Glacial ice sheets store large volumes of ^{16}O-enriched meteoric water, thereby preventing the remixing of the two isotope fractions and significantly altering $\delta^{18}O$ values in the world's oceans.* Foraminifera preserve samples of past $\delta^{18}O$ values when they extract oxygen from seawater and incorporate it into calcareous body parts. Abundant fossil remains permit the construction of detailed records such as that shown in Figure 3, covering the last 780 ka. High positive values of $\delta^{18}O$ reflect glacial maxima, and negative values reflect warm interglacial periods. Because the largest volumes of glacial ice were incorporated in the North American sheet, $\delta^{18}O$ fluctuations can be interpreted directly as a first order record of North American glaciation and deglaciation (Mix, 1987; Ruddiman and Wright, 1987). Because the correlation is quantitative, the isotopic record indicates that the most recent glacial event was as severe as any within the last 780 ka. It also indicates that the present value is at or near that of a glacial minimum.

Sea-surface temperature records, although not as closely tied to glacial events, show the same alternating pattern. Temperatures at the surface of northern hemisphere oceans, as determined from the fossil assemblages of planktonic foraminiferal species, were measurably colder during glaciation and warmer during interglacial periods (Ruddiman, 1987).

Samples from the ice sheets of Greenland and Antarctica and calcite vein fillings in Nevada provide independent confirmation of the oceanic data (Langway and others, 1985; Jouzel and others, 1987; Barnola and others, 1987; Winograd and others, 1988). Glacial ice preserves $\delta^{18}O$ and δD values of the precipitation that formed the ice, and, because fractionation of the isotopes is temperature dependent, fluctuations can be interpreted quantitatively as changes in local mean temperature. Bubbles of air trapped within the ice can also be sampled to give a measure of past CO_2 concentrations in the atmosphere, which, because of the importance of CO_2 in the earth's greenhouse effect, correlate well with the isotopic temperature record. Figure 4 shows

---

* By convention, $^{18}O/^{16}O$ ratios are reported as:

$$\delta^{18}O = 1000 \times \frac{(^{18}O/^{16}O_{sample} - {}^{18}O/^{16}O_{reference})}{^{18}O/^{16}O_{reference}}$$

Deuterium/hydrogen ratios (D/H) are similarly reported as δD values.

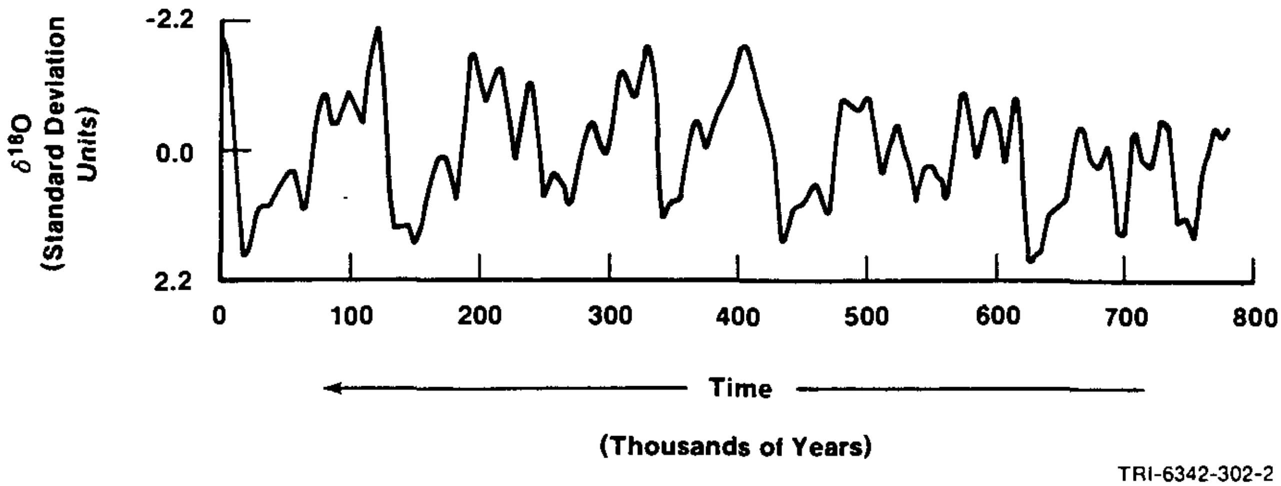


Figure 3. Foraminiferal $\delta^{18}O$ record of the last 780,000 years. Curve reflects $\delta^{18}O$ variations from five deep-sea core samples. Data have been normalized, stacked, and smoothed with a nine-point Gaussian filter (Imbrie, and others, 1984).

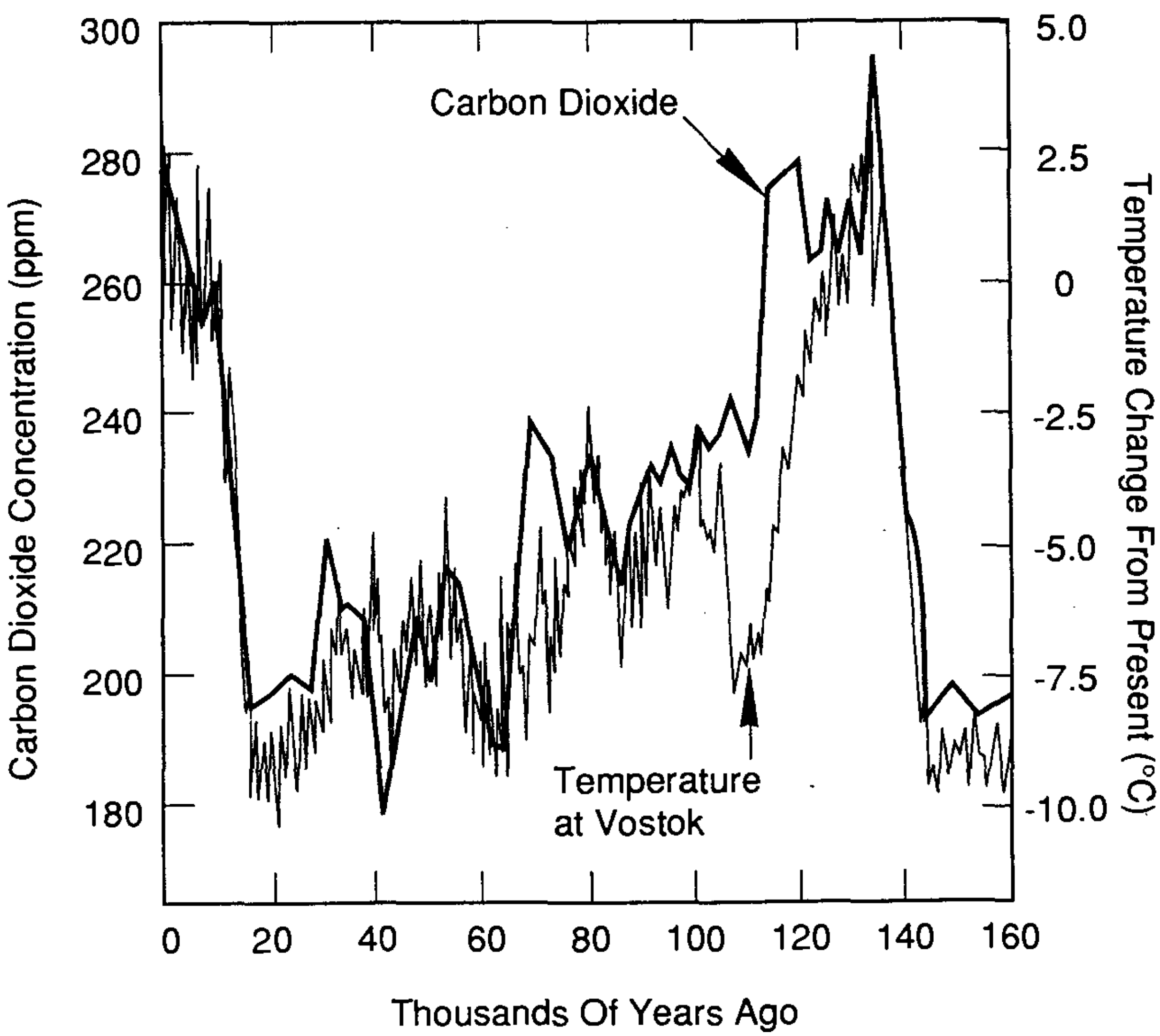


Figure 4. Atmospheric CO_2 concentration and δD temperature record from the Vostok, Antartica, ice core for the last 160 ka (modified from Schneider, 1990; after Barnola and others, 1987).

the 160-ka record of CO_2 concentration and temperature as determined from the D/H ratio at Vostok in East Antarctica. With some minor discrepancies, the two curves reveal the same basic glacial chronology visible in the last 160 ka of the oceanic $\delta^{18}O$ record shown in Figure 3. The $\delta^{18}O$ record from 50 ka to 310 ka BP from calcite vein fillings in Devils Hole, Nevada, reflects changes in local surface temperature as well as other, less well quantified, factors, including groundwater travel time. This record also shows a chronology similar to that of Figure 3, although peaks in the calcite curve are shifted toward increasingly older times earlier in the record relative to the oceanic curve. The reason for this phase shift, which reaches 28 ka at 272 ka BP, is not known (Winograd and others, 1988).

5. Stability of Glacial Cycles

The causes of glaciation and deglaciation are complex and not fully understood (Ruddiman and Wright, 1987), but the strong periodicity of the isotopic record indicates that climatic alternations have been systematic in the past. Spectral analysis of the foraminiferal $\delta^{18}O$ curve for the last 780 ka shows that within that time the primary control on the periodicity of glacial events has been variation in global insolation caused by irregularities in the earth's orbit (Figure 5). Observed periods of 19, 23, 41, and 100 ka in the oceanic $\delta^{18}O$ curve correspond to calculated periods of northern hemisphere summer insolation minima of 19 and 23 ka related to the precession of the earth's axis, 41 ka related to the tilt of earth's axis, and 94, 125, and 413 ka related to the eccentricity of the earth's orbit (Milankovitch, 1941; Hays and others, 1976; Imbrie and others, 1984; Imbrie, 1985). Calculations based on astronomical observations indicate that orbital parameters have not changed significantly in the last 5 Ma (Berger, 1984), and geological evidence suggests they may have been stable for as long as 300 Ma (Anderson, 1984; Heckel, 1986).

Longer-term global climatic changes, such as the beginning of the present pattern of glaciation and deglaciation 2.5 Ma BP, have been attributed to changes in the configuration of the earth's continents, which in turn controls both the potential distribution of ice sheets and global circulation patterns (e.g., Crowell and Frakes, 1970; Caputo and Crowell, 1985; Crowley and others, 1986; Hyde and others, 1990). Continental masses move at plate-tectonic rates of centimeters per year, several orders of magnitude too low to affect glacial processes within the next 10 ka. Vertical uplift or subsidence of large continental regions may also affect global climate by changing circulation patterns (e.g., Ruddiman and Kutzbach, 1989), but, again, maximum uplift rates are at least an order of magnitude too low to change present circulation patterns within the next 10 ka.

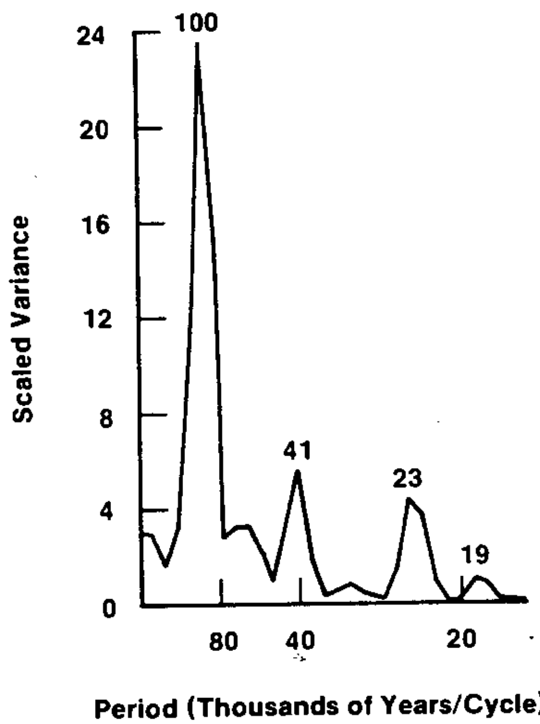
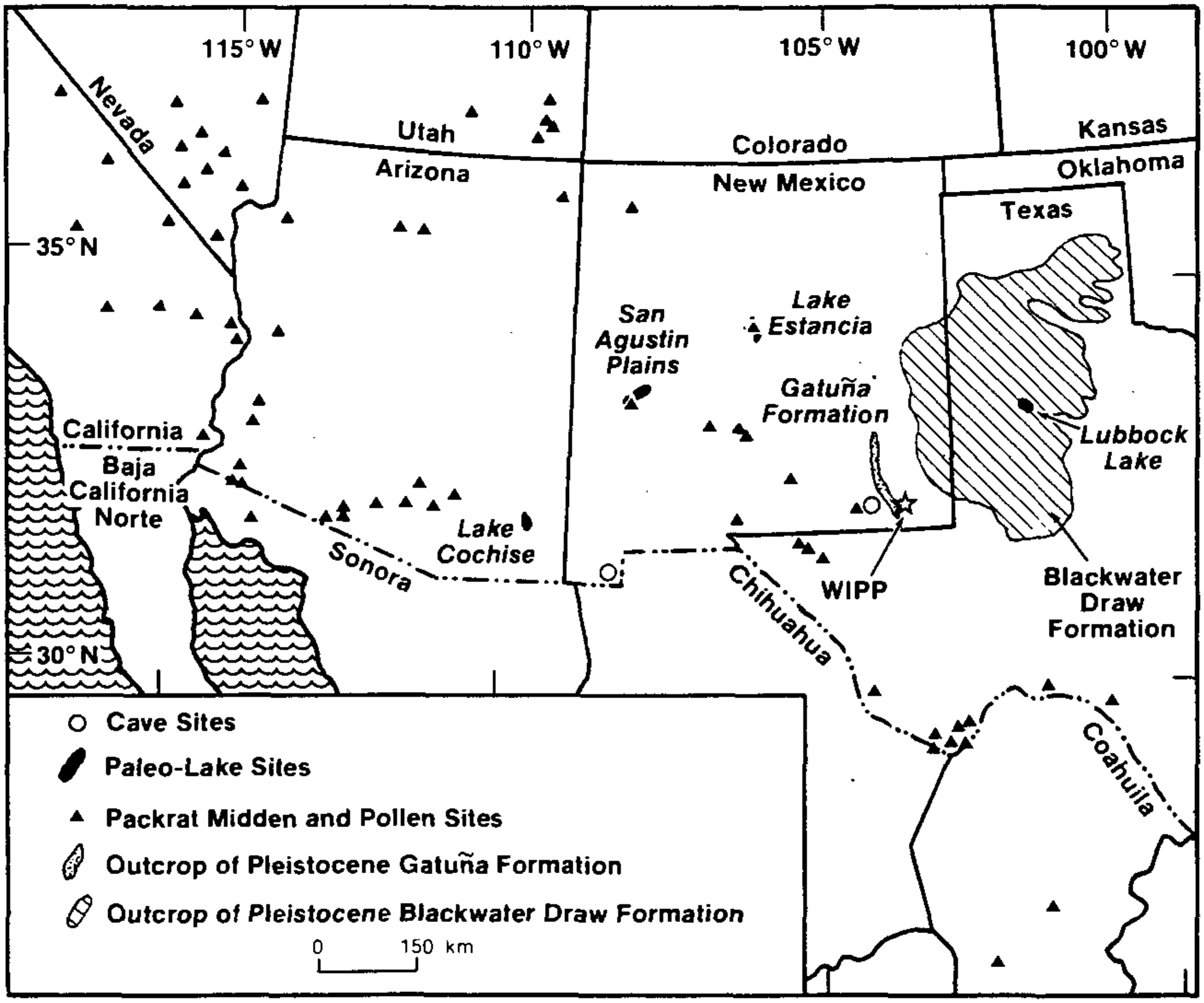


Figure 5. Spectral analysis of the foraminiferal $\delta^{18}O$ record presented in Figure 3, showing periodicity of glaciation and deglaciation (after Imbrie, 1985).

The long-term pattern of the cycles of glaciation and deglaciation provides the basis for concluding that climatic extremes of the next 10 ka will remain within past limits. The relative amplitudes of past glacial cycles (Figure 3) imply that future glaciations will be no more severe than the last one. The periodicity of the pattern indicates that although glacial minima such as that of the present are relatively brief, glacial advances are, in general, slow and the next full maximum will not occur for many tens of thousands of years. Predictions about the precise timing of future glacial events are not straightforward, however. Higher resolution records, such as those available from polar ice cores, show that some glacial advances can occur relatively rapidly. Modeling of glacial processes is complicated by uncertainties about feedback processes involved in the growth of ice sheets, but extrapolation of the isotopic curve of Figure 3 using a relatively simple model for nonlinear climate response to insolation change suggests that, in the absence of anthropogenic effects, the next full glacial maximum could occur in approximately 60 ka (Imbrie and Imbrie, 1980). These observations, combined with the climatic data discussed below, justify the choice of the late Pleistocene full-glacial climate as a conservative upper limit for precipitation during the next 10 ka.

6. Pleistocene and Holocene Climates of Southeastern New Mexico

Early and middle Pleistocene paleoclimatic data for southeastern New Mexico and the surrounding region are incomplete, and permit neither continuous reconstructions of paleoclimates nor direct correlations between climate and glaciation prior to the last glacial maximum 22 to 18 ka BP. Stratigraphic and pedologic data from several locations (Figure 6), however, indicate that cyclical alternation of wetter and drier climates in southeastern New Mexico had begun by the early Pleistocene. Fluvial gravels in the Gatuña Formation exposed in the Pecos River Valley of eastern New Mexico suggest relatively wetter conditions 1.4 Ma BP and again 600 ka BP (Bachman, 1987). The Mescalero caliche, exposed locally over much of southeastern New Mexico, has been interpreted as indicating relatively drier conditions 510 ka BP (Lambert and Carter, 1987), and loosely dated spring deposits in Nash Draw west of the WIPP imply wetter conditions again later in the Pleistocene (Bachman, 1981, 1987). The Blackwater Draw Formation of the southern High Plains of eastern New Mexico and western Texas, time-correlative to both the Gatuña Formation and the Mescalero caliche, contains alternating soil and eolian sand horizons that show at least six climatic cycles beginning more than 1.4 Ma BP and continuing to the present (Holliday, 1989a). The duration, frequency, and total number of Pleistocene climatic cycles in southeastern New Mexico have not been established.



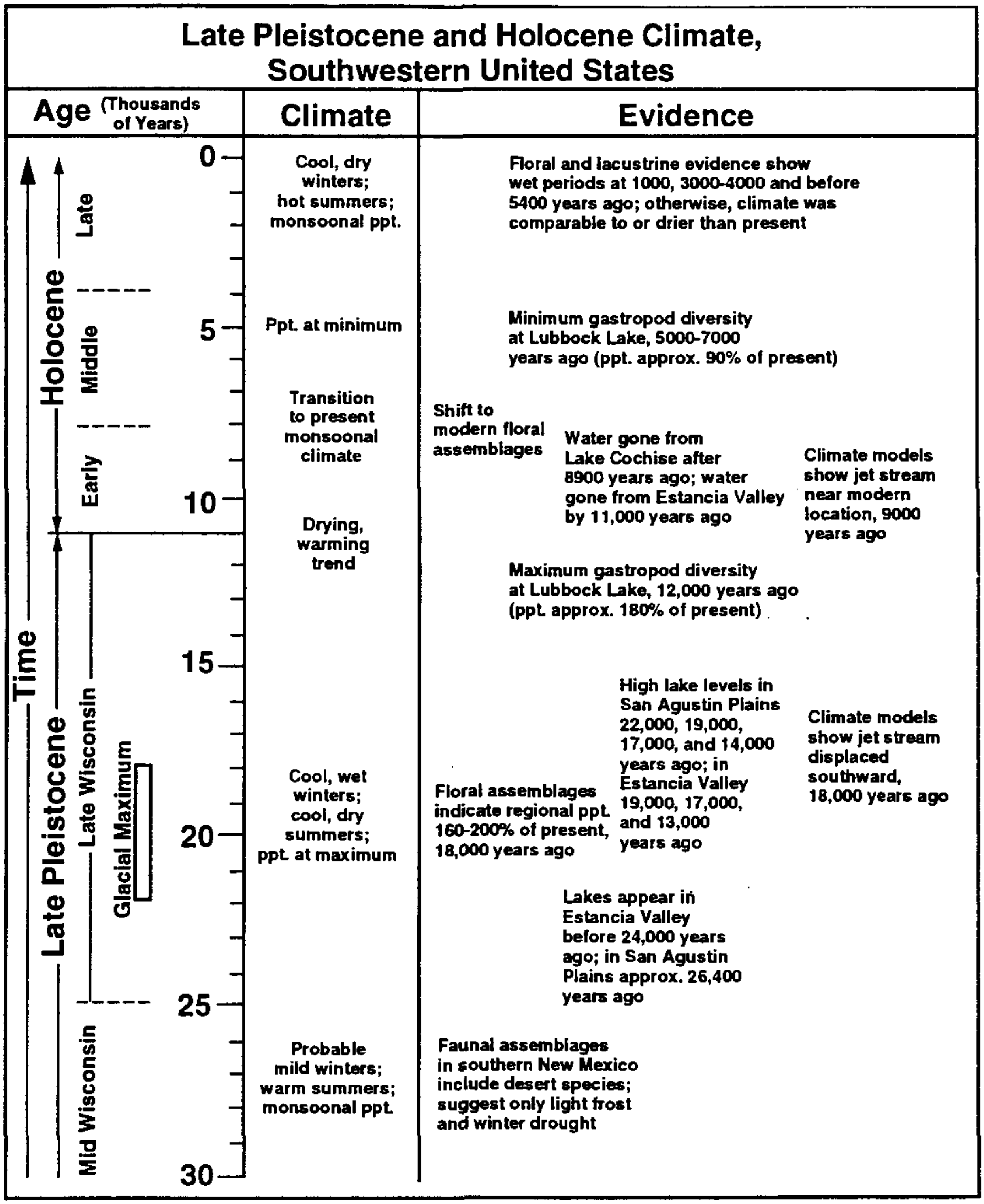
TRI-6342-301-1

Figure 6. Location map for paleoclimate data. Data from Bachman (1981); Markgraf and others (1983); Harris (1987); Pierce (1987); Van Devender and others (1987); Waters (1989); Bachhuber (1989); Holliday (1989a); Van Devender (1990); Allen (1991); Phillips and others (1992).

Data used to construct the more detailed climatic record for the latest Pleistocene and Holocene come from multiple lines of evidence dated primarily using carbon-14 techniques. Packrat middens examined at sites throughout the southwestern United States, including locations in southeastern New Mexico, preserve local plant communities and, in some cases, insect remains (Van Devender, 1980, 1990; Van Devender and others, 1984, 1987; Elias, 1987; Elias and Van Devender, 1990). Pollen assemblages have been analyzed from lacustrine deposits in western New Mexico, western Texas, and other locations in the southwestern United States (Martin and Mehringer, 1965; Markgraf and others, 1984; Bryant and Holloway, 1985; Van Devender and others, 1987). Faunal data come from gastropod assemblages from western Texas (Pierce, 1987), ostracode assemblages from western New Mexico (Markgraf and others, 1984; Forester, 1987; Phillips and others, 1992), and vertebrate remains from caves in southern New Mexico (Harris, 1987, 1988). Stable-isotope data are available from ostracodes in western New Mexico (Phillips and others, 1992) and groundwater samples in northwestern New Mexico (Phillips and others, 1986). Paleo-lake level data are available from sites throughout the southwestern United States (Reeves, 1973; Smith and Anderson, 1982; Markgraf and others, 1983, 1984; Benson and Thompson, 1987; Holliday and Allen, 1987; Bachhuber, 1989; Waters, 1989; Wells and others, 1989; Enzel and others, 1989; Benson and others, 1990; Allen, 1991). Figure 6 shows the locations of key sites discussed here and in the references cited.

Because decreases in temperature and increases in precipitation produce similar environmental changes, not all data cited uniquely require the paleoclimatic interpretation presented in this report (Figure 7). For example, lake-level increases can, in theory, result solely from decreased evaporation at lower temperatures. Interpretations drawn individually from each of the data sets are consistent with the overall trends shown in Figure 7, however, and the pattern of change is confirmed by global general circulation climate models (Kutzbach and Guetter, 1986; COHMAP Members, 1988). Furthermore, specific floral and faunal assemblages are sufficiently sensitive to precipitation and temperature effects to distinguish between the two (e.g., Van Devender and others, 1987; Pierce, 1987; Van Devender; 1990). The paleoclimates described here are those that best explain data from all sources.

Prior to the last glacial maximum 22 to 18 ka BP, evidence from mid-Wisconsin faunal assemblages in caves in southern New Mexico, including the presence of extralimital species such as the desert tortoise that are now restricted to warmer climates, suggests warm summers and mild, relatively dry winters (Harris, 1987, 1988). Lacustrine evidence confirms the interpretation that conditions prior to and during the glacial advance that



TRI-6342-300-4

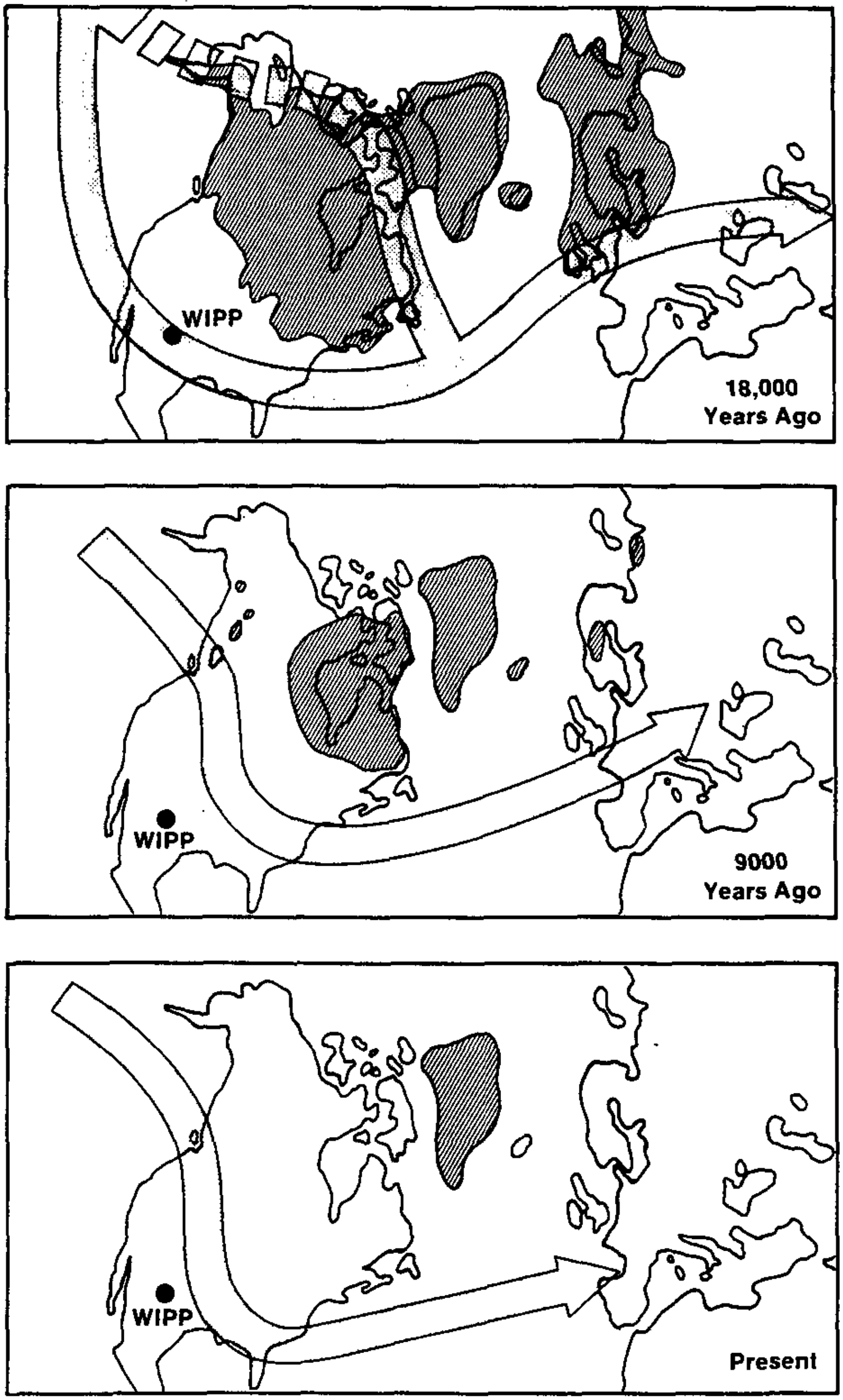
Figure 7. Late Pleistocene and Holocene climate, southwestern United States. Time scale after Van Devender and others (1987). Climate references cited in text.

were generally drier than those at the glacial maximum. Permanent water did not appear in what was later to be a major lake in the Estancia Valley in central New Mexico until sometime before 24 ka BP (Bachhuber, 1989). Late-Pleistocene lake levels in the San Agustin Plains in western New Mexico remained low until approximately 26.4 ka BP, and the $\delta^{18}O$ record from ostracode shells suggests that mean annual temperatures at that location did not decrease significantly until approximately 22 ka BP (Phillips and others, 1992).

Ample floral and lacustrine evidence documents cooler and wetter conditions in southeastern New Mexico and the surrounding region during the glacial peak (Van Devender and others, 1987; Pierce, 1987; Bachhuber, 1989; Allen, 1991; Phillips and others, 1992). These changes were not caused by the immediate proximity of glacial ice. None of the Pleistocene continental glaciations advanced farther southwest than northeastern Kansas, and the most recent, late Wisconsin, ice sheet reached its limit in South Dakota, roughly 1200 km from the WIPP (Andrews, 1987). Discontinuous alpine glaciers formed at the highest elevations throughout the Rocky Mountains, but these isolated ice masses were symptoms, rather than causes, of cooler and wetter conditions, and had little influence on regional climate at lower elevations. The closest such glacier to the WIPP was on the northeast face of Sierra Blanca Peak in the Sacramento Mountains, 220 km to the northwest (Richmond, 1962).

Global climate models indicate that the dominant glacial effect in southeastern New Mexico was the disruption and southward displacement of the westerly jet stream by the physical mass of the ice sheet to the north (Figure 8) (Manabe and Broccoli, 1985; Kutzbach and Guetter, 1986; COHMAP members, 1988). At the glacial peak, climate models show that major Pacific storm systems followed the jet stream across New Mexico and the southern Rocky Mountains, and winters were wetter and longer than either at the present or during the previous interglacial period.

Field evidence does not support the suggestion (Galloway, 1970, 1983; Brakenridge, 1978) that higher lake levels and changed faunal and floral assemblages at the glacial maximum could have resulted solely from lowered temperatures. Plant communities indicate that, regionally, the decrease in mean annual temperatures below present values was significantly less than the 7 to 12°C required by cold and dry climate models (Van Devender and others, 1987; Van Devender, 1990). Interpretation of stable-isotope data from groundwater samples from northwestern New Mexico suggest mean annual temperatures were 5 to 7°C colder than at present at that location (Phillips and others, 1986). Isotopic data from ostracode shells in the San Agustin Plains suggest mean annual temperatures there may have been 8.3°C colder than



TRI-6342-315-2

Figure 8. Distribution of northern hemisphere ice sheets and modeled position of jet stream at 18 ka BP, and present (from COHMAP Members, 1988). Ice shown with dark pattern, jet stream shown with arrow (broken where disrupted or weak).

at present at approximately 21 ka BP, but hydrologic modeling of the basin indicates lake levels were controlled by precipitation rather than evaporation throughout the glacial advance and retreat (Phillips and others, 1992). Gastropod assemblages at Lubbock Lake in western Texas suggest mean annual temperatures 5°C below present values (Pierce, 1987). High water levels in playas in western Texas reflect an increase in runoff best explained by substantially higher levels of precipitation (Reeves, 1973).

Floral and faunal evidence taken together indicate that mean annual precipitation throughout the region at the last glacial maximum was 60 to 100 percent more than today (Spaulding and Graumlich, 1986; Pierce, 1987; Van Devender and others, 1987). Floral evidence also suggests that winters may have continued to be relatively mild, perhaps because the glacial mass blocked the southward movement of arctic air. Summers at the glacial maximum were cooler and drier than at present, without a strongly developed monsoon (Van Devender and others, 1987). Piñons, oaks, and junipers grew at lower elevations throughout southern New Mexico (Van Devender and others, 1987; Van Devender, 1990), probably including the vicinity of the WIPP.

According to climatic modeling, the jet stream shifted northward following the gradual retreat of the ice sheet after 18 ka BP (Figure 8), and the climate responded accordingly. By the Pleistocene/Holocene boundary approximately 11 ka BP, conditions were significantly warmer and drier than previously, although still dominated by winter storms and still wetter than today (Van Devender and others, 1987). Major decreases in total precipitation and the shift toward the modern monsoonal climate did not occur until the margins of the ice sheet had retreated into northeastern Canada in the early Holocene.

Evidence for the late Pleistocene and early Holocene drying trend comes from several sources. In contrast to the northern Great Basin, where lake levels continued to rise until between 15 and 13.5 ka BP (Benson and others, 1990), lake levels in southern New Mexico and the surrounding region decreased following the glacial maximum. Permanent water disappeared from late-Pleistocene lakes in the Estancia Valley between 12 and 11 ka BP, following a series of fluctuations in lake levels with progressively lower high stands at approximately 19, 17, and 13 ka BP (Allen, 1991). Lake Cochise (the modern Willcox Playa) in southeastern Arizona was dry after 8.5 ka BP, following two high stands prior to 14 ka BP and a third between 14 and 13 ka BP (Waters, 1989). Modeling of lake levels in the San Agustin Plains shows high stands at progressively lower elevations at approximately 22, 19, 17, and 14 ka BP (Phillips and others, 1992). Water remained in lakes in the San Agustin Plains until 5 ka BP, but ostracode assemblages suggest an increase in salinity by 8 ka BP, and the pollen record shows a gradual shift at that location from a spruce-pine forest 18 to 15 ka BP to a juniper-pine forest by 10 ka BP (Markgraf and others, 1984). Packrat middens in Eddy County, New Mexico, indicate that desert-grassland and desert-scrub communities predominated at lower elevations between 10.5 and 10 ka BP (Van Devender, 1980). Soil studies indicate drier conditions at Lubbock Lake after 10 ka BP, although marshes and small lakes persisted at the site until the construction of a dam and reservoir in 1936 (Holliday and Allen, 1987). Based on a decrease in diversity of both terrestrial and aquatic gastropod species, Pierce (1987) estimated a drop in annual precipitation at Lubbock Lake from a high of 80 cm/yr (nearly twice the modern level at that location of 45 cm/yr) at 12 ka BP to 40 cm/yr by 7 ka BP.

Coincident with this decrease in precipitation, evidence from vole remains recovered from caves in southern New Mexico (Harris, 1988) and from plant communities throughout the southwestern United States (Van Devender and others, 1987) indicates a rise in summer temperatures. Mean annual temperatures interpreted from the isotopic composition of groundwater samples from northwestern New Mexico also show a sharp rise in the early Holocene (Phillips and others, 1986).

By middle-Holocene time, the climate was similar to that of the present, with hot, monsoon-dominated summers and cold, dry winters. The pattern has persisted to the present, but not without significant local variations. Soil studies show the southern High Plains were drier from 6.5 to 4.5 ka BP (Holliday, 1989b) than before or since. Gastropod data from Lubbock Lake indicate the driest conditions from 7 to 5 ka BP (precipitation approximately 90 percent of present, mean annual temperature 2.5°C higher than present), with a cooler and wetter period at 1 ka BP (precipitation approximately 145 percent of present, mean annual temperature 2.5°C lower than present) (Pierce, 1987). Plant assemblages from southwestern Arizona suggest steadily decreasing precipitation from the middle Holocene to the present, except for a brief wet period around 990 years ago (Van Devender and others, 1987). Stratigraphic work at Lake Cochise shows two mid-Holocene lake stands, one near or before 5.4 ka BP and one between or before 3 to 4 ka BP, but both were relatively short-lived, and neither reached the maximum depths of the late-Pleistocene high stand that existed before 14 ka BP (Waters, 1989).

Precipitation maxima during these Holocene wet periods were less in both magnitude and duration than those of the late Pleistocene. Enzel and others (1989) observed comparable Holocene wet periods recorded in playa deposits in the Mojave Desert 3620 ± 70 and 390 ± 90 years ago, and related them to short-term changes in global circulation patterns that resulted in increased winter storm activity in the region. Historical records over the last several hundred years indicate numerous lower intensity climatic fluctuations, some too short in duration to affect floral and faunal assemblages, which may also be the result of temporary changes in global circulation (Neilson, 1986). Sunspot cycles and the related changes in the amount of energy emitted by the sun have been linked to historical climatic changes elsewhere in the world (e.g., Lamb, 1972), but the validity of the correlation is uncertain (Robock, 1979; Stuiver, 1980). Correlations also have been proposed between volcanic activity and climatic change (Robock, 1979; Palais and Sigurdsson, 1989; Bryson, 1989). In general, however, causes for past short-term changes are unknown, and it is impossible at present to predict the amplitude or frequency of recurrence. Despite this uncertainty, the past record does support the conclusion that future short-term fluctuations in southeastern New Mexico will not be as severe as the long-term climatic changes created by major ice sheets in the northern hemisphere. Full-glacial conditions remain a conservative upper limit for mean annual precipitation at the WIPP during the next 10 ka.

7. Climatic Implications of Data from WIPP Groundwater Samples

Isotopic data from groundwater samples collected in the vicinity of the WIPP from the Late Permian Rustler and Dewey Lake Formations that overlie the Salado Formation are generally consistent with the climatic changes described above. Lambert (1986) and Lambert and Harvey (1987) concluded that although deuterium/hydrogen and $^{18}O/^{16}O$ ratios indicate a meteoric origin for water in the confined aquifers, they are sufficiently distinct from modern surface water values to suggest that the contribution of modern recharge to the system is slight. Chapman (1986) disagreed with this interpretation, noting similar ratios in the presumably young waters of the Roswell Artesian Basin immediately to the north, and she concluded that stable-isotope data from the WIPP area do not permit definitive interpretations about the age of the groundwater. Tritium data are less ambiguous. Low tritium levels in all WIPP-area samples indicate minimal contributions from the atmosphere since 1950 (Lambert, 1987; Lambert and Harvey, 1987). The four internally consistent radiocarbon analyses currently available for water samples from the Rustler and Dewey Lake Formations support this interpretation. Modeled minimum ages in each case are between 12 and 16 ka, suggesting that both units have had little recharge since the period immediately following the late Pleistocene glacial maximum (Lambert and Harvey, 1987). Lambert and Carter (1987) presented uranium isotope data that also support this interpretation: observed high $^{234}U/^{238}U$ activity ratios require a conservative minimum residence time in the Culebra Dolomite of several thousands of years and more probably reflect minimum ages of 10 to 30 ka. Chapman (1988) questioned the validity of equating isotope residence times with groundwater age, but agreed that high $^{234}U/^{238}U$ activity ratios occur in regions of low transmissivity, where flow is presumably slower and residence times are longer.

Lambert (1991) used groundwater isotope data, along with supporting evidence from $^{87}Sr/^{86}Sr$ ratios in vein fillings, to argue that the Rustler Formation has been essentially a closed hydrologic system for the last 12 ka. In his interpretation, significant recharge last occurred during the late Pleistocene, and the present flow field reflects the slow draining of the aquifer. If this interpretation is correct, recharge may not occur again until precipitation levels are substantially higher than at present.

Other data suggest that, isotopic evidence notwithstanding, some recharge may be occurring at the present. Anomalous increases in water levels have been observed at seven WIPP-area wells since 1988 (Beauheim, 1989). Recharge from the surface cannot be ruled out as a cause for these rises, although no specific link to precipitation events has been demonstrated. Other possible causes include decreases in discharge, changes in reservoir volume related to incomplete recovery from the transient pressure changes associated with the pumping test itself, changes in reservoir volume related to external changes in the regional stress field, or undetected recharge from other aquifers or from the surface through existing boreholes (Beauheim, 1989). Numerical modeling of groundwater flow in the WIPP area indicates that, although it is hydraulically possible for present flow to reflect late Pleistocene recharge (Davies, 1989), some component of modern vertical recharge is also compatible with observed conditions (Haug and others, 1987; Davies, 1989). Major ion chemical analyses of groundwater samples support the interpretation of vertical recharge south of the WIPP, where low salinities may be the result of mixing with fresh surface water (Chapman, 1988). Lambert (1991) suggests instead that water chemistry has remained essentially unchanged from the late Pleistocene and is a function of host rock composition, noting that groundwater salinity correlates well with the distribution of halite in the Rustler Formation.

Questions about recharge to the Rustler Formation and the true age of WIPP-area groundwater remain unanswered. In the absence of definitive data, this report makes no assumptions about groundwater age.

8. Discussion and Conclusions

Speculation about future climate variability must be based on observed past fluctuations. The largest global climatic changes in the last 2.5 Ma have been those associated with glaciation and deglaciation in the northern hemisphere. The high degree of consistency in both frequency and intensity displayed in the glacial record indicates that an accurate interpretation of past climatic cycles does provide a useful guide for estimating future changes.

Geologic data from southeastern New Mexico and the surrounding region show repeated alternations of wetter and drier climates throughout the Pleistocene. Floral, faunal, and lacustrine data permit detailed and quantitative reconstructions of precipitation that can be linked directly to glacial events of the late Pleistocene and Holocene. Figure 9 shows estimated mean annual precipitation for the WIPP for the last 30 ka, interpolated from the composite regional data cited above and based on present average precipitation at the site of 30 cm/yr (Brinster, 1991). This plot should be interpreted with caution, because its resolution and accuracy are limited by the nature of the data used to construct it. Floral and faunal assemblages may change gradually and show only a limited response to climatic fluctuations that occur at frequencies higher than the typical life span of the organisms in question. For long-lived species such as trees, resolution may be limited to hundreds or even thousands of years (Neilson, 1986). Sedimentation in lakes and playas has the potential to record higher frequency fluctuations, including single-storm events, but only under a limited range of circumstances. Once water levels reach a spill point, for example, lakes show only a limited response to further increases in precipitation. Dry playas generally show little response to decreases in precipitation. A more complete record of precipitation would almost certainly show far more variability than that implied by the plot presented here. Specifically, Figure 9 may fail to record abnormal precipitation lows during the Holocene, it may underestimate the number of high-precipitation peaks during the same period, and it may underestimate the magnitude of relatively brief precipitation maxima during the late Pleistocene. Although the magnitude of the long-term shift in precipitation is adequately documented by the data reviewed here, the amplitude of the higher-frequency fluctuations in both the late Pleistocene and the Holocene is not well constrained, and the climate may have been wetter or drier than shown for some intervals.

With these observations in mind, three significant conclusions can be drawn from the climatic record of southeastern New Mexico and the surrounding region. First, maximum precipitation in southeastern New Mexico in the past coincided with the maximum advance of the North American ice sheet. Minimum precipitation occurred after the ice sheet had retreated to its present limits. Second, past maximum long-term average precipitation levels were roughly twice present levels. Minimum levels may have been 90 percent of present levels. Third, short-term fluctuations in precipitation have occurred during both the glacial maximum and the present, relatively dry, interglacial period, but fluctuations during the present interglacial period have not exceeded the upper limits of the glacial maximum.

It would be unrealistic to attempt a direct extrapolation of the precipitation curve of Figure 9 into the future. Too little is known about the relatively short-term behavior of global circulation patterns, and it is at present impossible to predict the probability of a recurrence of a wetter climate such as that of approximately 1000 years ago. The long-term stability of patterns of glaciation and deglaciation, however, do permit the conclusion that future climatic extremes are unlikely to exceed those of the late Pleistocene. Furthermore, the periodicity of glacial events suggests that a return to full glacial conditions is highly unlikely within the next 10,000 years.

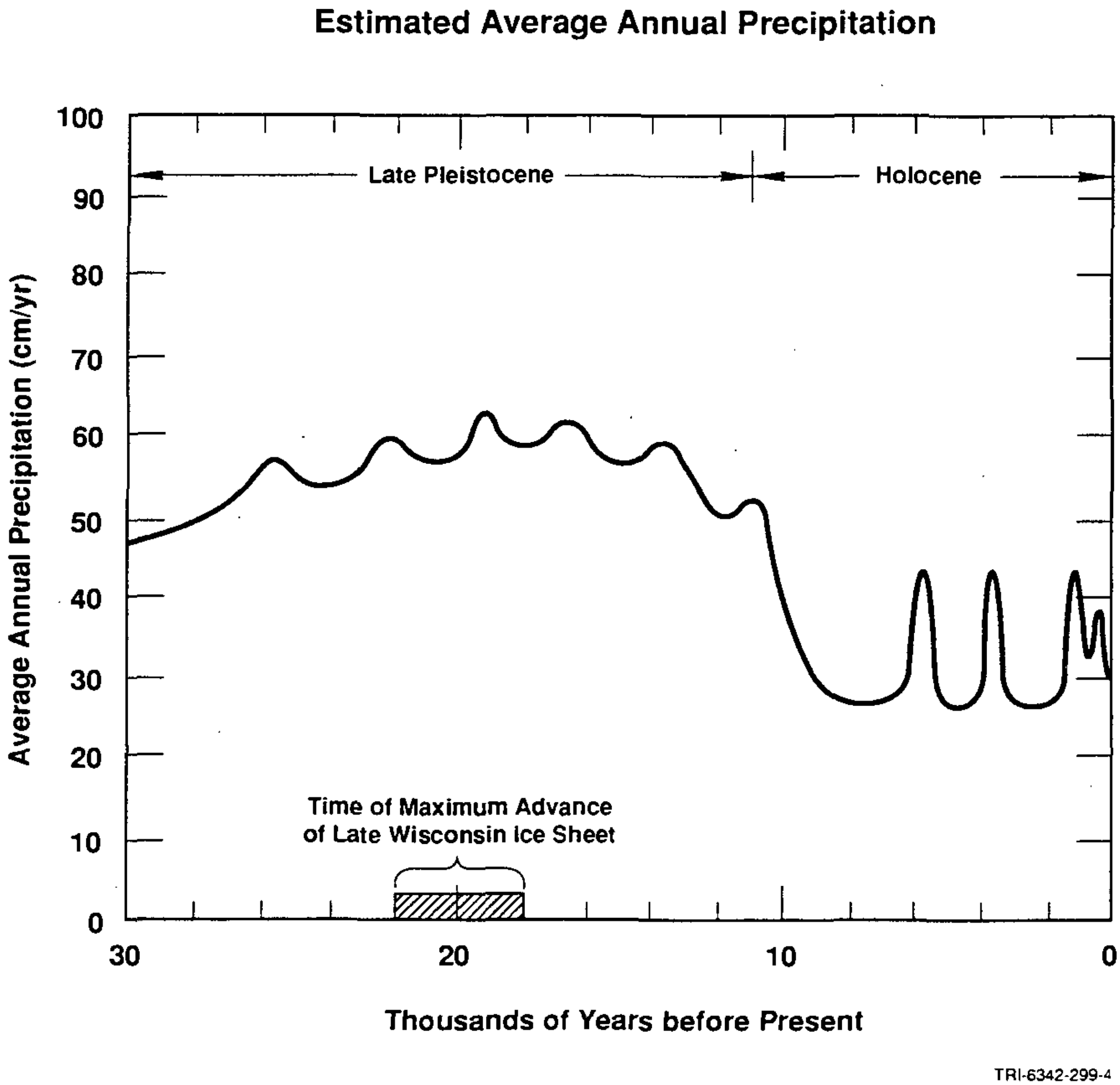


Figure 9. Estimated mean annual precipitation at the WIPP during the late Pleistocene and Holocene. Amplitudes of relatively high-frequency fluctuations are less well constrained than the amplitude of the shift from glacial conditions of the Pleistocene to interglacial conditions of the Holocene. Data from Van Devender and others (1987); Pierce (1987); Waters (1989); Allen (1991); Phillips and others (1992); and other sources cited in text.

9. LITERATURE CITED

Allen, B.D. 1991. "Effect of Climatic Change on Estancia Valley, New Mexico: Sedimentation and Landscape Evolution in a Closed-Drainage Basin," *Field Guide to Geologic Excursions in New Mexico and Adjacent Areas of Texas and Colorado.* Eds. B. Julian and J. Zidek. New Mexico Bureau of Mines and Mineral Resources Bulletin 137. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources. 166-171.

Anderson, R.Y. 1984. "Orbital Forcing of Evaporite Sedimentation," *Milankovitch and Climate: Understanding the Response to Astronomical Forcing, Proceedings of the NATO Advanced Research Workshop on Milankovitch and Climate, Palisades, NY, November 30-December 4, 1982.* Eds. A Berger, J. Imbrie, J. Hays, G. Kukla, and B. Saltzman. Boston, MA: D. Reidel Publishing Company, Pt. 1, 147-162.

Andrews, J.T. 1987. "The Late Wisconsin Glaciation and Deglaciation of the Laurentide Ice Sheet," *North America and Adjacent Oceans During the Last Deglaciation.* Eds. W.F. Ruddimen and H.E. Wright, Jr. The Geology of North America Volume K-3. Boulder, CO: Geological Society of America, Inc. 13-37.

Bachhuber, F.W. 1989. "The Occurrence and Paleolimnologic Significance of Cutthroat Trout (Oncorhynchus clarki) in Pluvial Lakes of the Estancia Valley, Central New Mexico," *Geological Society of America Bulletin.* Vol. 101 in no. 12, 1543-1551.

Bachman, G.O. 1981. *Geology of the Nash Draw, Eddy County, New Mexico*, U.S. Geological Survey. Open-File Report 81-31. Denver, CO: U.S. Geological Survey.

Bachman, G.O. 1987. *Karst in Evaporites in Southeastern New Mexico.* SAND86-7078. Albuquerque, NM: Sandia National Laboratories.

Barnola, J.M., D. Raynaud, Y.S. Korotkevich, and C. Lorius. 1987. "Vostok Ice Core Provides 160,000-year Record of Atmospheric CO_2," *Nature.* Vol. 329, no. 6138, 408-414.

Beauheim, R.L. 1989. *Interpretation of H-11b4 Hydraulic Tests and the H-11 Multipad Pumping Test of the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) site.* SAND89-0536. Albuquerque, NM: Sandia National Laboratories.

Benson, L. [V.], and R.S. Thompson. 1987. "The Physical Record of Lakes in the Great Basin," *North America and Adjacent Oceans During the Last Deglaciation*. Eds. W.F. Ruddiman and H.E. Wright, Jr. The Geology of North America Volume K-3. Boulder, CO: Geological Society of America, Inc. 241-260.

Benson, L.V., D.R. Currey, R.I. Dorn, K.R. Lajoie, C.G. Oviatt, S.W. Robinson, G.I. Smith, and S. Stine. 1990. "Chronology of Expansion and Contraction of Four Great Basin Lake Systems During the Past 35,000 Years," *Palaeogeography, Palaeoclimatology, Palaeoecology*. Vol. 78, no. 214, 241-286.

Berger, A.L. 1984. "Accuracy and Frequency Stability of the Earth's Orbital Elements During the Quaternary," *Milankovitch and Climate: Understanding the Response to Astronomical Forcing, Proceedings of the NATO Advanced Research Workshop on Milankovitch and Climate, Palisades, NY, November 30-December 4, 1982*. Eds. A. Berger, J. Imbrie, J. Hays, G. Kukla, and B. Saltzman. Boston, MA: D. Reidel Publishing Company. Pt. 1, 3-39.

Bertram-Howery, S.G., and R.L. Hunter. 1989. *Plans for Evaluation of the Waste Isolation Pilot Plant's Compliance with EPA Standards for Radioactive Waste Management and Disposal*. SAND88-2871. Albuquerque, NM: Sandia National Laboratories.

Bertram-Howery, S.G., M.G. Marietta, R.P. Rechard, P.N. Swift, D.R. Anderson, B.L. Baker, J.E. Bean, Jr., W. Beyeler, K.F. Brinster, R.V. Guzowski, J.C. Helton, R.D. McCurley, D.K. Rudeen, J.D. Schreiber, and P. Vaughn. 1990. *Preliminary Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant, December 1990*. SAND90-2347. Albuquerque, NM: Sandia National Laboratories.

Brakenridge, G.R. 1978. "Evidence for a Cold, Dry Full-Glacial Climate in the American Southwest," *Quaternary Research*. Vol. 9, no. 1, 22-40/

Brinster, K.F. 1991. *Preliminary Geohydrologic Conceptual Model of the Los Medaños Region Near the Waste Isolation Pilot Plant for the Purpose of Performance Assessment*. SAND89-7147. Albuquerque, NM: Sandia National Laboratories.

Bryant, V.M., Jr., and R. G. Holloway. 1985. "A Late-Quaternary Paleoenvironmental Record of Texas: An Overview of the Pollen Evidence," *Pollen Records of Late-Quaternary North American Sediments*. Eds. R.G. Holloway and V.M. Bryant, Jr., Dallas, TX: American Association of Stratigraphic Palynologists Foundation. 39-70.

Bryson, R.A. 1989. "Late Quaternary Volcanic Modulation of Milankovitch Climate Forcing," *Theoretical and Applied Climatology*. Vol. 39, no. 3, 115-125.

Caputo, M.V., and J.C. Crowell. 1985. "Migration of Glacial Centers Across Gondwana During Paleozoic Era," *Geological Society of America Bulletin*. Vol. 96, no. 8, 1020-1036.

Chapman, J.B. 1986. *Stable Isotopes in Southeastern New Mexico Groundwater: Implications for Dating Recharge in the WIPP Area*. EEG-35. Santa Fe, NM: Environmental Evaluation Group, State of New Mexico.

Chapman, J.B. 1988. *Chemical and Radiochemical Characteristics of Groundwater in the Culebra Dolomite, Southeastern New Mexico*. EEG-39. Santa Fe, NM: Environmental Evaluation Group, State of New Mexico.

COHMAP Evaluation Group, [Cooperative Holocene Mapping Project] Members. 1988. "Climatic Changes of the Last 18,000 Years: Observations and Model Simulations," *Science*. Vol. 241, no. 4869, 1043-1052.

Cole, F.W. 1975. *Introduction to Meteorology*. 2nd ed. New York, NY: John Wiley and Sons, Inc.

Crowell, J.C., and L.A. Frakes. 1970. "Phanerozoic Glaciation and the Causes of Ice Ages," *American Journal of Science*. Vol. 268, no. 3, 193-224.

Crowley, T.J., D.A. Short, J.G. Mengel, and G.R. North. 1986. "Role of Seasonality in the Evolution of Climate During the Last 100 Million Years," *Science*. Vol. 231, no. 4738, 579-584.

Davies, P.B. 1989. *Variable-Density Ground-Water Flow and Paleohydrology in the Waste Isolation Pilot Plant (WIPP) Region, Southeastern New Mexico*. United States Geological Survey Open-File Report 88-490. Albuquerque, NM: U.S. Geological Survey.

Elias, S.A. 1987. "Paleoenvironmental Significance of Late Quaternary Inspect Fossils from Packrat Middens in South-Central New Mexico," *The Southwestern Naturalist*. Vol. 32, no. 3, 383-390.

Elias, S.A., and T.R. Van Devender. 1990. "Fossil Insect Evidence for Late Quaternary Climatic Change in the Big Bend Region, Chihauhuan Desert. Texas," *Quaternary Research*. Vol. 34, no. 2, 249-261.

Enzel, Y., D.R. Cayan, R.Y. Anderson, and S.G. Wells. 1989. "Atmospheric Circulation During Holocene Lake Stands in the Mojave Desert: Evidence of Regional Climate Change," *Nature*. Vol. 341, no. 6237, 44-47.

Forester, R.M. 1987. "Late Quaternary Paleoclimate Records from Lacustrine Ostracodes," *North America and Adjacent Oceans During the Last Deglaciation*. Eds. W.F. Ruddiman and H.E. Wright, Jr. The Geology of North America Volume K-3. Boulder, CO: Geological Society of America, Inc. 261-276.

Galloway, R.W. 1970. "The Full-Glacial Climate in the Southwestern United States," *Annals of the Association of American Geographers*. Vol. 60, no. 2, 245-256.

Galloway, R.W. 1983. "Full-Glacial Southwestern United States: Mild and Wet or Cold and Dry?" *Quaternary Research*. Vol. 19, no. 1, 236-248.

Hansen, J., I. Fung, A. Lacis, D. Rind, S. Lebedeff, R. Ruedy, and G. Russel. 1988. "Global Climate Changes as Forecast by Goddard Institute for Space Studies Three-Dimensional Model," *Journal of Geophysical Research*. Vol. 93, no. D8, 9341-9364.

Harris, A.H. 1987. "Reconstruction of Mid-Wisconsin Environments in Southern New Mexico," *National Geographic Research*. Vol. 3, no. 2, 142-151.

Harris, A.H. 1988. "Late Pleistocene and Holocene Microtus (Pitymys) (Rodentia: Cricetidae) in New Mexico," *Journal of Vertebrate Paleontology*. Vol. 8, no. 3, 307-313.

Haug, A., V.A. Kelley, A.M. LaVenue, and J.F. Pickens. 1987. *Modeling of Ground-Water Flow in the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site*: Interim Report. SAND86-7167. Albuquerque, NM: Sandia National Laboratories.

Hays, J.D., J. Imbrie, and N.J. Shackleton. 1976. "Variations in the Earth's Orbit: pacemaker of the Ice Ages," *Science*. Vol. 194, no. 4270, 1121-1132.

Heckel, P.H. 1986. "Sea-Level Curve for Pennsylvanian Eustatic Marine Transgressive-Regressive Depositional Cycles Along Midcontinent Outcrop Belt, North America," *Geology*. Vol. 14, no. 4, 330-334.

Holliday, V.T. 1989a. "The Blackwater Draw Formation (Quaternary): A 1.4-plus-m.y. Record of Eolian Sedimentation and Soil Formation on the Southern High Plains," *Geological Society of America Bulletin* Vol. 101, no. 12, 1598-1607.

Holliday, V.T. 1989b. "Middle Holocene Drought on the Southern High Plains," *Quaternary Research.* Vol. 31, no. 1, 74-82.

Holliday, V.T., and B.L. Allen. 1987. "Geology and Soils," *Lubbock Lake: Late Quaternary Studies on the Southern High Plains.* Ed. E. Johnson College Station, TX: Texas A&M University Press. 14-21.

Houghton, J.T., G.J. Jenkins, and J.J. Ephraums. 1990. *Climate Change: The IPCC Scientific Assessment.* New York, NY: Cambridge University Press.

Hunter, R.L. 1985. *A Regional Water Balance for the Waste Isolation Pilot Plant (WIPP) Site and Surrounding Area.* SAND84-2233. Albuquerque, NM: Sandia National Laboratories.

Hyde, W.T., K-Y. Kim, T.J. Crowley, and G.R. North. 1990. "On the Relation Between Polar Continentality and Climate: Studies With a Nonlinear Seasonal Energy Balance Model," *Journal of Geophysical Research.* Vol. 95, no. D11, 18653-18668.

Imbrie, J. 1985. "A theoretical Framework for the Pleistocene Ice Ages," *Journal of the Geological Society.* Vol. 142, pt. 3, 417-432.

Imbrie, J., and J.Z. Imbrie. 1980. "Modeling the Climatic Response to Orbital Variations," *Science.* Vol. 207, no. 4434, 943-953.

Imbrie, J., J.D. Hays, D.G. Martinson, A. McIntyre, A.C. Mix, J.J. Morley, N.G. Pisias, W.L. Prell, and N.J. Shackleton. 1984. "The Orbital Theory of Pleistocene Climate: Support from a Revised Chronology of the Marine $\delta^{18}O$ Record," *Understanding the Response to Astronomical Forcing Proceedings of the NATO Advanced Research Workshop on Milankovitch and Climate, Palisades, NY, November 30-December 4, 1982.* Eds. A. Berger, J. Imbrie, J. Hays, G. Kukla, and B. Saltzman. Boston, MA: D. Reidel Publishing Company. Pt. 1, 269-305.

Jouzel, J., C. Lorius, J.R. Petit, C. Genthon, N.I. Barkov, V.M. Kotlyakov, and V.M. Petrov. 1987. "Vostok Ice Core: A Continuous Isotope Temperature Record Over the Last Climatic Cycle (160,000 Years)," *Nature.* Vol. 329, no. 6138, 403-418.

Kutzbach, J.E., and P.J. Guetter. 1986. "The Influence of Changing Orbital Parameters and Surface Boundary Conditions on Climate Simulations for the Past 18,000 Years," *Journal of the Atmosphere Sciences*. Vol. 43, no. 16, 1726-1759.

Lamb, H.H. 1972. *Climate: Present, Past and Future*. London: Methuen and Co. Vol. 1.

Lambert, S.J. 1986. "Stable-Isotope Studies of Groundwaters in Southeastern New Mexico," *The Rustler Formation at the WIPP Site*. EEG-34; SAND85-1978C. Santa Fe, NM: Environmental Evaluation Group, State of New Mexico.

Lambert, S.J. 1987. *Feasibility Study: Applicability of Geochronologic Methods Involving Radiocarbon and Other Nuclides to the Groundwater Hydrology of the Rustler Formation, Southeastern New Mexico*. SAND86-1054. Albuquerque, NM: Sandia National Laboratories.

Lambert, S.J. 1991. "Isotopic Constraints on the Rustler and Dewey Lake Groundwater Systems," *Hydrogeochemical Studies of the Rustler Formation and Related Rocks in the Waste Isolation Pilot Plant Area, Southeastern New Mexico*. Eds. M.D. Siegel, S.J. Lambert, and K.L. Robinson. SAND88-1096. Albuquerque, NM: Sandia National Laboratories.

Lambert, S.J., and J.A. Carter. 1987. *Uranium-Isotope Systematics in Groundwaters of the Rustler Formation, Northern Delaware Basin, Southeastern New Mexico. I: Principles and Methods*. SAND87-0388. Albuquerque, NM: Sandia National Laboratories.

Lambert, S.J., and D.M. Harvey. 1987. *Stable-Isotope Geochemistry of Groundwaters in the Delaware Basin of Southeastern New Mexico*. SAND87-0138. Albuquerque, NM: Sandia National Laboratories.

Langway, C.C., Jr., H. Oeschger, and W. Dansgaard, eds. 1985. *Greenland Ice Core: Geophysics, Geochemistry, and the Environment*. Geophysical Monograph 33. Washington, D.C: American Geophysical Union.

Manabe, S., and A.J. Broccoli. 1985. "The Influence of Continental Ice Sheets on the Climate of an Ice Age," *Journal of Geophysical Research*. Vol. 90, no. D1, 2167-2190.

Markgraf, V., J.P. Bradbury, R.M. Forester, W. McCoy, G. Singh, and R. [S]. Sternberg. 1983. "Paleoenvironmental Reassessment of the 1.6-million-year-old record from San Agustin Basin, New Mexico," *in Socorro Region*

II, New Mexico Geological Society Thirty-Fourth Annual Field Conference, Socorro, NM, October 13-15, 1983. Ed. C.E. Chapin. New Mexico Geological Society Guidebook. Volume 34. Roswell, NM: New Mexico Geological Society. 291-297.

Markgraf, V., J.P. Bradbury, R.M. Forester, G. Singh, and R.S. Sternberg. 1984. "San Agustin Plains, New Mexico: Age and Paleoenvironmental Potential Reassessed," *Quaternary Research*. Vol. 22, no. 3, 336-343.

Martin, P.S., and P.J. Mehringer, Jr. 1965. "Pleistocene Pollen Analysis and Biogeography of the Southwest," *The Quaternary of the United States*. Eds. H.E. Wright, Jr. and D.G. Frey. Princeton, NJ. Princeton University Press. 433-451.

Milankovitch, M.M. 1941. *Canon of Insolation and the Ice-Age Problem*. Koniglich Serbische Akademie, Beograd. (English translation by the Israel Program for Scientific Translations). U.S. Department of Commerce and National Science Foundation. (Available from National Technical Information Service, Springfield, VA).

Mitchell, J.F.B. 1989. "The 'Greenhouse' Effect and Climate Change," *Reviews of Geophysics*. Vol. 27, no. 1, 115-139.

Mix, A.C. 1987. "The Oxygen-Isotope Record of Glaciation," *North America and Adjacent Oceans During the Last Deglaciation*. Eds. W.F. Ruddiman and H.E. Wright, Jr. The Geology of North America Volume K-3. Boulder, CO: Geological Society of America, Inc. 111-135.

Neilson, R.P. 1986. "High-Resolution Climatic Analysis and Southwest Biogeography," *Science*. Vol. 232, no. 4746, 27-34.

NOAA (National Oceanic and Atmospheric Administration). 1989. *Climatological Data, New Mexico*. Vol. 93.

Palais, J.M., and H. Sigurdsson. 1989. "Petrologic Evidence of Volatile Emissions from Major Historic and Pre-Historic Volcanic Eruptions," *Understanding Climate Change*. Eds. A. Berger, R.E. Dickinson, and J.W. Kidson. Geophysical Monograph 52, IUGG Volume 7. Washington, D.C: American Geophysical Union. 31-53.

Phillips, F.M., L.A. Peeters, M.K. Tansey, and S.N. Davis. 1986. "Paleoclimatic Inferences from an Isotopic Investigation of Groundwater in the Central San Juan Basin, New Mexico," *Quaternary Research*. Vol. 26, no. 2, 179-193.

Phillips, F.M., A.R. Campbell, C. Kruger, P.S. Johnson, R. Roberts, and E. Keyes. 1992. A reconstruction of the water balance in Western United States lake basins in response to climate change. New Mexico Water Resources Research Institute Report 269. Las Cruces, New Mexico.

Pierce, H.G. 1987. "The Gastropods, with Notes on Other Invertebrates," *lubbock Lake: Late Quaternary Studies on the Southern High Plains*. Ed. E. Johnson. College Station, TX: Texas A&M University Press. 41-48.

Reeves, C.C., Jr. 1973. "The Full-Glacial Climate of the Southern High Plains, West Texas," *Journal of Geology*. Vol. 81, no. 4, 693-704.

Richmond, G.M. 1962. *Correlation of Some Glacial Deposits in New Mexico*. U.S. Geological Survey Professional Paper 450E. E121-E125.

Robock, A. 1979. "The 'Little Ice Age': Northern Hemisphere Average Observations and Model Calculations," *Science*. Vol. 206, no. 4425, 1402-1404.

Ruddiman, W.F. 1987. "Northern Oceans," *North America and Adjacent Oceans During the Last Deglaciation. Eds. W.F. Ruddiman and H.E. Wright, Jr. The Geology of North America Volume K-3. Boulder, CO: Geological Society of America, Inc. 137-154.*

Ruddiman, W.F., and J.E. Kutzbach. 1989. "Forcing of Late Cenozoic Northern Hemisphere Climate by Plateau Uplift in Southern Asia and the American West," Journal of Geophysical Research. Vol. 94, no. D15, 18409-18427.

Ruddiman, W.F., and H.E. Wright, Jr. 1987. "Introduction," *North America and Adjacent Oceans During the Last Deglaciation*. Eds. W.F. Ruddiman and H.E. Wright, Jr. The Geology of North America Volume K-3. Boulder, CO: Geological Society of America, Inc. 1-12.

Schlesinger, M.E., and J.F.B. Mitchell. 1987. "Climate Model Simulations of the Equilibrium Climatic Response to Increased Carbon Dioxide," *Reviews of Geophysics*. Vol. 25, no. 4, 760-798.

Schneider, S.H. 1990. "The Global Warming Debate Heats Up: An Analysis and Perspective," *Bulletin of the American Meteorological Society*. Vol. 71, no. 9, 1292-1304.

Smith, L.N., and R.Y. Anderson. 1982. "Pleistocene-Holocene Climate of the Estancia Basin, Central New Mexico," *Albuquerque Country II, New Mexico*

Geological Society, 33rd Annual Field Conference, Albuquerque, NM, November 4-6, 1982. Eds. J.F. Callender, J.A. Grambling, and S.G. Wells. New Mexico Geological Society Guidebook Vol. 33. Roswell, NM: New Mexico Geological Society. 347-350.

Spaulding, W.G. 1986. *Vegetation and Climates of the Last 45,000 Years in the Vicinity of the Nevada Test Site, South-Central Nevada.* United States Geological Survey Professional Paper 1329. [Reston, VA]: U.S. Department of the Interior, Geological Survey.

Spaulding, W.G., and L.J. Graumlich. 1986. "The Last Pluvial Climatic Episodes in the Deserts of Southwestern North America," *Nature.* Vol. 320, no. 6061, 441-444.

Stuiver, M. 1980. "Solar Variability and Climatic Change During the Current Millenium," *Nature.* Vol. 286, no. 5776, 868-871.

Swift, P.N. 1991. "Long-Term Climate Variability at the Waste Isolation Pilot Plant, Background Information Presented to the Expert Panel on Inadvertent Human Intrusion into the Waste Isolation Pilot Plant." Eds. R.V. Guzowski and M.M. Gruebel. SAND91-0928. Albuquerque, NM: Sandia National Laboratories.

U.S. DOE (Department of Energy) and State of New Mexico. 1981, as modified. *Agreement for Consultation and Cooperation" on WIPP by the State of New Mexico and U.S. Department of Energy*, modified 11/30/84 and 8/4/87.

U.S. EPA (Environmental Protection Agency). 1985. *40 CFR 191*: "Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Waste: Final Rule," *Federal Register.* Vol. 50, no. 182, 38066-38099.

University of New Mexico. 1989. *New Mexico Statistical Abstract 1989.* Albuquerque, NM: University of New Mexico, Bureau of Business and Economic Research.

Van Devender, T.R. 1980. "Holocene Plant Remains from Rocky Arroyo and Last Chance Canyon, Eddy County, New Mexico," *The Southwestern Naturalist.* Vol. 25, no. 3, 261-372.

Van Devender, T.R. 1990. "Late Quaternary Vegetation and Climate of the Chihuahuan Desert, United States and Mexico," Eds. J.L. Betancourt, T.R. Van Devender, and P.S. Martin. Tucson, AZ: University of Arizona Press. 104-133.

Van Devender, T.R., J.L. Betancourt, and M. Wimberly. 1984. "Biogeographic Implications of a Packrat Midden Sequence from the Sacramento Mountains, South-Central New Mexico," *Quaternary Research*. Vol. 22, no. 3, 344-360.

Van Devender, T.R., R.S. Thompson, and J.L. Betancourt. 1987. "Vegetation History of the Deserts of Southwestern North America; The Nature and Timing of the Late Wisconsin-Holocene Transition," North America and Adjacent Oceans During the Last Deglaciation. Eds. W.F. Ruddiman and H.E. Wright, Jr. The Geology of North America. Volume K-3. Boulder, CO: Geological Society of America, Inc. 323-352.

Washington, W.M., and G.A. Meehl. 1984. "Seasonal Cycle Experiment on the Climate Sensitivity Due to D doubling of CO_2 With an Atmospheric General Circulation Model Coupled to a Simple Mixed-Layer Ocean Model," *Journal of Geophysical Research*. Vol. 89, no. D6, 9475-9503.

Waters, M.R. 1989. "Late Quaternary Lacustrine History and Paleoclimatic Significance of Pluvial Lake Cochise, Southeastern Arizona," *Quaternary Research*. Vol. 32, no. 1, 1-11.

Wells, S.G., R.Y. Anderson, L.D. McFadden, W.J. Brown, Y. Enzel, and J-L. Miossec. 1989. *Late Quaternary Paleohydrology of the Eastern Mojave River Drainage, Southern California: Quantitative Assessment of the Late Quaternary Hydrologic Cycle in Large Arid Watersheds*. WRRI Report No. 242. Las Cruces, NM: New Mexico Water Resources Research Institute..

Wilson, C.A., and J.F.B. Mitchell. 1987. "A Doubled CO_2 Climate Sensitivity Experiment With a Global Climate Model Including a Simple Ocean, *Journal of Geophysical Research*. Vol. 92, no. D11, 13,315-13,343.

Winograd, I.J., B.J. Szabo, T.B. Coplen, and A.C. Riggs. 1988. "A 250,000-Year Climatic Record from Great Basin Vein Calcite: Implications for Milankovitch Theory," *Science*. Vol. 242, no. 4883, 1275-1280.

PERFORMANCE ASSESSMENT DISTRIBUTION LIST

Federal Agencies

US Department of Energy (2)
Office of Environmental Restoration
and Waste Management
Attn: L.P. Duffy, EM-1
C. Frank, EM-50
Washington, DC 20585

US Department of Energy (3)
Office of Environmental Restoration
and Waste Management
Attn: M. Frei, EM-34 (Trevion II)
Director, Waste Management Projects
Washington, DC 20585-0002

US Department of Energy
Office of Environmental Restoration
and Waste Management
Attn: J. Lytle, EM-30 (Trevion II)
Washington, DC 20585-0002

US Department of Energy
Office of Environmental Restoration
and Waste Management
Attn: S. Schneider, EM-342
(Trevion II)
Washington, DC 20585-0002

US Department of Energy (3)
WIPP Task Force
Attn: G.H. Daly
S. Fucigna
J. Rhoderick
12800 Middlebrook Rd.
Suite 400
Germantown, MD 20874

US Department of Energy (4)
Office of Environment, Safety and
Health
Attn: R.P. Berube, EH-20
C. Borgstrum, EH-25
R. Pelletier, EH-231
K. Taimi, EH-232
Washington, DC 20585

US Department of Energy (4)
WIPP Project Integration Office
Attn: W.J. Arthur III
L.W. Gage
P.J. Higgins
D.A. Olona
PO Box 5400
Albuquerque, NM 87115-5400

US Department of Energy (11)
WIPP Project Site Office (Carlsbad)
Attn: A. Hunt (4)
V. Daub (4)
J. Lippis
K. Hunter
R. Becker
PO Box 3090
Carlsbad, NM 88221-3090

US Department of Energy, (5)
Office of Civilian Radioactive Waste
Management
Attn: Deputy Director, RW-2
Associate Director, RW-10
Office of Program
Administration and
Resources Management
Associate Director, RW-20
Office of Facilities
Siting and Development
Associate Director, RW-30
Office of Systems
Integration and
Regulations
Associate Director, RW-40
Office of External
Relations and Policy
Office of Geologic Repositories
Forrestal Building
Washington, DC 20585

US Department of Energy
Attn: National Atomic Museum Library
Albuquerque Operations Office
PO Box 5400
Albuquerque, NM 87185

US Department of Energy
Research & Waste Management Division
Attn: Director
PO Box E
Oak Ridge, TN 37831

US Department of Energy (2)
Idaho Operations Office
Fuel Processing and Waste
Management Division
785 DOE Place
Idaho Falls, ID 83402

US Department of Energy
Savannah River Operations Office
Defense Waste Processing
Facility Project Office
Attn: W.D. Pearson
PO Box A
Aiken, SC 29802

US Department of Energy (2)
Richland Operations Office
Nuclear Fuel Cycle & Production
Division
Attn: R.E. Gerton
825 Jadwin Ave.
PO Box 500
Richland, WA 99352

US Department of Energy (3)
Nevada Operations Office
Attn: J.R. Boland
D. Livingston
P.K. Fitzsimmons
2753 S. Highland Drive
Las Vegas, NV 87183-8518

US Department of Energy (2)
Technical Information Center
PO Box 62
Oak Ridge, TN 37831

US Department of Energy (2)
Chicago Operations Office
Attn: J.C. Haugen
9800 South Cass Avenue
Argonne, IL 60439

US Department of Energy
Los Alamos Area Office
528 35th Street
Los Alamos, NM 87544

US Department of Energy (3)
Rocky Flats Area Office
Attn: W.C. Rask
G. Huffman
T. Lukow
PO Box 928
Golden, CO 80402-0928

US Department of Energy
Dayton Area Office
Attn: R. Grandfield
PO Box 66
Miamisburg, OH 45343-0066

US Department of Energy
Attn: E. Young
Room E-178
GAO/RCED/GTN
Washington, DC 20545

US Bureau of Land Management
101 E. Mermod
Carlsbad, NM 88220

US Bureau of Land Management
New Mexico State Office
PO Box 1449
Santa Fe, NM 87507

US Environmental Protection
Agency (2)
Office of Radiation Protection
Programs (ANR-460)
Attn: R. Guimond (2)
Washington, DC 20460

US Nuclear Regulatory Commission
Division of Waste Management
Attn: H. Marson
Mail Stop 4-H-3
Washington, DC 20555

US Nuclear Regulatory Commission (4)
Advisory Committee on Nuclear Waste
Attn: D. Moeller
M.J. Steindler
P.W. Pomeroy
W.J. Hinze
7920 Norfolk Avenue
Bethesda, MD 20814

Defense Nuclear Facilities Safety Board
Attn: D. Winters
625 Indiana Avenue, NW
Suite 700
Washington, DC 20004

Nuclear Waste Technical Review Board (2)
Attn: D.A. Deere
S.J.S. Parry
Suite 910
1100 Wilson Blvd.
Arlington, VA 22209-2297

Energy and Science Division
Office of Management and Budget
Attn: K. Yuracko
725 17th Street NW
Washington, DC 20503

US Geological Survey (2)
Water Resources Division
Attn: C. Peters
Suite 200
4501 Indian School, NE
Albuquerque, NM 87110

State Agencies

Environmental Evaluation Group (5)
Attn: R. Neill
Suite F-2
7007 Wyoming Blvd., NE
Albuquerque, NM 87109

New Mexico Bureau of Mines and Mineral Resources
Socorro, NM 87801

New Mexico Energy, Minerals and Natural Resources Department
Attn: Librarian
2040 South Pacheco
Santa Fe, NM 87505

New Mexico Energy, Minerals and Natural Resources Department
New Mexico Radioactive Task Force (2)
(Governor's WIPP Task Force)
Attn: A. Lockwood, Chairman
C. Wentz, Coordinator/Policy Analyst
2040 South Pacheco
Santa Fe, NM 87505

Bob Forrest
Mayor, City of Carlsbad
PO Box 1569
Carlsbad, NM 88221

Executive Director
Carlsbad Department of Development
Attn: C. Bernard
PO Box 1090
Carlsbad, NM 88221

New Mexico Environment Department
Secretary of the Environment
Attn: J. Espinosa (3)
PO Box 968
1190 St. Francis Drive
Santa Fe, NM 87503-0968

New Mexico Environment Department
Attn: P. McCasland
WIPP Project Site Office
PO Box 3090
Carlsbad, NM 88221-3090

New Mexico State Engineer's Office
Attn: M. Chudnoff
PO Box 25102
Santa Fe, NM 87504-5102

Advisory Committee on Nuclear Facility Safety

John F. Ahearne
Executive Director, Sigma Xi
99 Alexander Drive
Research Triangle Park, NC 27709

James E. Martin
109 Observatory Road
Ann Arbor, MI 48109

WIPP Panel of National Research Council's Board on Radioactive Waste Management

Charles Fairhurst, Chairman
Department of Civil and
Mineral Engineering
University of Minnesota
500 Pillsbury Dr., SE
Minneapolis, MN 55455-0220

John O. Blomeke
3833 Sandy Shore Drive
Lenoir City, TN 37771-9803

John D. Bredehoeft
Western Region Hydrologist
Water Resources Division
US Geological Survey (M/S 439)
345 Middlefield Road
Menlo Park, CA 94025

Fred M. Ernsberger
1325 NW 10th Avenue
Gainsville, FL 32601

Rodney C. Ewing
Department of Geology
University of New Mexico
200 Yale, NE
Albuquerque, NM 87131

B. John Garrick
PLG, Inc.
Suite 400
4590 MacArthur Blvd.
Newport Beach, CA 92660-2027

Leonard F. Konikow
US Geological Survey
431 National Center
Reston, VA 22092

Jeremiah O'Driscoll
505 Valley Hill Drive
Atlanta, GA 30350

Christopher Whipple
Clement International Corp.
160 Spear St.
Suite 1380
San Francisco, CA 94105-1535

National Research Council (3)
Board on Radioactive
Waste Management
RM HA456
Attn: P.B. Myers,
Staff Director (2)
G.J. Grube
2101 Constitution Avenue
Washington, DC 20418

Performance Assessment Peer Review Panel

G. Ross Heath
College of Ocean and
Fishery Sciences HN-15
583 Henderson Hall
University of Washington
Seattle, WA 98195

Thomas H. Pigford
Department of Nuclear Engineering
4159 Etcheverry Hall
University of California
Berkeley, CA 94720

Thomas A. Cotton
JK Research Associates, Inc.
4429 Butterworth Place, NW
Washington, DC 20016

Robert J. Budnitz
President, Future Resources
Associates, Inc.
2000 Center Street
Suite 418
Berkeley, CA 94704

C. John Mann
Department of Geology
245 Natural History Bldg.
1301 West Green Street
University of Illinois
Urbana, IL 61801

Frank W. Schwartz
Department of Geology and Mineralogy
The Ohio State University
Scott Hall
1090 Carmack Rd.
Columbus, OH 43210

National Laboratories

Argonne National Laboratory (2)
Attn: A. Smith
D. Tomasko
9700 South Cass, Bldg. 201
Argonne, IL 60439

Battelle Pacific Northwest Laboratory (3)
Attn: R.E. Westerman
S. Bates
H.C. Burkholder
Battelle Boulevard
Richland, WA 99352

Los Alamos National Laboratory
Attn: B. Erdal, CNC-11
PO Box 1663
Los Alamos, NM 87545

Los Alamos National Laboratory
Attn: A. Meijer
Mail Stop J514
PO Box 1663
Los Alamos, NM 87545

Los Alamos National Laboratory (3)
HSE-8
Attn: M. Enoris
L. Soholt
J. Wenzel
PO Box 1663
Los Alamos, NM 87545

Los Alamos National Laboratory
EM-7
Attn: S. Kosiewicz
Mail Stop J595
PO Box 1663
Los Alamos, NM 87545

Oak Ridge National Laboratory
Martin Marietta Systems, Inc.
Attn: J. Setaro
PO Box 2008, Bldg. 3047
Oak Ridge, TN 37831-6019

Savannah River Laboratory (3)
Attn: N. Bibler
M.J. Plodinec
G.G. Wicks
Aiken, SC 29801

Savannah River Plant (2)
Attn: R.G. Baxter
Building 704-S
K.W. Wierzbicki
Building 703-H
Aiken, SC 29808-0001

Corporations/Members of the Public

Benchmark Environmental Corp. (3)
Attn: C. Frederickson
K. Lickliter
4501 Indian School, NE
Suite 105
Albuquerque, NM 87110

Deuel and Associates, Inc.
Attn: R.W. Prindle
7208 Jefferson, NE
Albuquerque, NM 87109

Disposal Safety, Inc.
Attn: B. Ross
Suite 314
1660 L Street, NW
Washington, DC 20006

Ecodynamics Research Associates (2)
Attn: P. Roache
R. Blaine
PO Box 9229
Albuquerque, NM 87119-9229

EG & G Idaho (3)
1955 Fremont Street
Attn: C. Atwood
C. Hertzler
T.I. Clements
Idaho Falls, ID 83415

Geomatrix
Attn: K. Coppersmith
100 Pine Street #1000
San Francisco, CA 94111

Golder Associates, Inc. (3)
Attn: M. Cunnane
R. Kossik
I. Miller
4104 148th Avenue, NE
Redmond, WA 98052

In-Situ, Inc. (2)
Attn: S.C. Way
C. McKee
209 Grand Avenue
Laramie, WY 82070

INTERA, Inc.
Attn: A.M. LaVenue
8100 Mountain Road, NE
Suite 213
Albuquerque, NM 87110

INTERA, Inc.
Attn: J.F. Pickens
Suite #300
6850 Austin Center Blvd.
Austin, TX 78731

INTERA, Inc.
Attn: W. Stensrud
PO Box 2123
Carlsbad, NM 88221

INTERA, Inc.
Attn: W. Nelson
101 Convention Center Drive
Suite 54[illegible]
Las Vegas, NV 89109

IT Corporation (2)
Attn: R.F. McKinney
J. Myers
Regional Office - Suite 700
5301 Central Avenue, NE
Albuquerque, NM 87108

MACTEC (2)
Attn: J.A. Thies
D.K. Duncan
8418 Zuni Road, SE
Suite 200
Albuquerque, NM 87108

Pacific Northwest Laboratory
Attn: B. Kennedy
Battelle Blvd.
PO Box 999
Richland, WA 99352

RE/SPEC, Inc. (2)
Attn: W. Coons
Suite 300
4775 Indian School, NE
Albuquerque, NM 87110

RE/SPEC, Inc.
Attn: J.L. Ratigan
PO Box 725
Rapid City, SD 57709

Reynolds Elect/Engr. Co., Inc.
Building 790, Warehouse Row
Attn: E.W. Kendall
PO Box 98521
Las Vegas, NV 89193-8521

Roy F. Weston, Inc.
CRWM Tech. Supp. Team
Attn: C.J. Noronha
955 L'Enfant Plaza, SW
North Building, Eighth Floor
Washington, DC 20024

Science Applications International Corporation (SAIC)
Attn: H.R. Pratt,
10260 Campus Point Drive
San Diego, CA 92121

Science Applications International Corporation (2)
Attn: G. Dymmel
C.G. Pflum
101 Convention Center Dr.
Las Vegas, NV 89109

Science Applications International Corporation (2)
Attn: M. Davis
J. Tollison
2109 Air Park Road, SE
Albuquerque, NM 87106

Science Applications International Corporation (2)
Attn: J. Young
D. Lester
18706 North Creek Parkway
Suite 110
Bothell, WA 98011

Southwest Research Institute
Center for Nuclear Waste Regulatory
Analysis (2)
Attn: P.K. Nair
6220 Culebra Road
San Antonio, TX 78228-0510

City of Albuquerque
Public Works Department
Utility Planning Division
Attn: W.K. Summers
PO Box 1293
Albuquerque, NM 87103

Systems, Science, and Software (2)
Attn: E. Peterson
P. Lagus
Box 1620
La Jolla, CA 92038

TASC
Attn: S.G. Oston
55 Walkers Brook Drive
Reading, MA 01867

Tech Reps, Inc. (6)
Attn: J. Chapman
V. Gilliland
D. Marchand
J. Stikar
P. Oliver
D. Scott
5000 Marble, NE
Suite 222
Albuquerque, NM 87110

Tolan, Beeson, & Associates
Attn: T.L. Tolan
2320 W. 15th Avenue
Kennewick, WA 99337

TRW Environmental Safety Systems
(TESS)
Attn: I. Saks
10306 Eaton Place
Suite 300
Fairfax, VA 22030

Westinghouse Electric Corporation (5)
Attn: Library
L. Trego
C. Cox
L. Fitch
R.F. Kehrman
PO Box 2078
Carlsbad, NM 88221

Westinghouse Hanford Company
Attn: D. Wood
PO Box 1970
Richland, WA 99352

Western Water Consultants
Attn: D. Fritz
1949 Sugarland Drive #134
Sheridan, WY 82801-5720

Western Water Consultants
Attn: P.A. Rechard
PO Box 4128
Laramie, WY 82071

Neville Cook
Rock Mechanics Engineering
Mine Engineering Dept.
University of California
Berkeley, CA 94720

P. Drez
8816 Cherry Hills Road, NE
Albuquerque, NM 87111

D.W. Powers
Star Route Box 87
Anthony, TX 79821

Shirley Thieda
PO Box 2109, RR1
Bernalillo, NM 87004

Jack Urich
c/o CARD
144 Harvard, SE
Albuquerque, NM 87106

Universities

University of California
Mechanical, Aerospace, and
Nuclear Engineering Department (2)
Attn: W. Kastenberg
D. Browne
5532 Boelter Hall
Los Angeles, CA 90024

University of Hawaii at Hilo
Attn: S. Hora
Business Administration
Hilo, HI 96720-4091

University of New Mexico
Geology Department
Attn: Library
Albuquerque, NM 87131

University of New Mexico
Research Administration
Attn: H. Schreyer
102 Scholes Hall
Albuquerque, NM 87131

University of Wyoming
Department of Civil Engineering
Attn: V.R. Hasfurther
Laramie, WY 82071

University of Wyoming
Department of Geology
Attn: J.I. Drever
Laramie, WY 82071

University of Wyoming
Department of Mathematics
Attn: R.E. Ewing
Laramie, WY 82071

Libraries

Thomas Brannigan Library
Attn: D. Dresp
106 W. Hadley St.
Las Cruces, NM 88001

Hobbs Public Library
Attn: M. Lewis
509 N. Ship Street
Hobbs, NM 88248

New Mexico State Library
Attn: N. McCallan
325 Don Gaspar
Santa Fe, NM 87503

New Mexico Tech
Martin Speere Memorial Library
Campus Street
Socorro, NM 87810

New Mexico Junior College
Pannell Library
Attn: R. Hill
Lovington Highway
Hobbs, NM 88240

Carlsbad Municipal Library
WIPP Public Reading Room
Attn: L. Hubbard
101 S. Halagueno St.
Carlsbad, NM 88220

University of New Mexico
General Library
Government Publications Department
Albuquerque, NM 87131

NEA/Performance Assessment Advisory Group (PAAC)

P. Duerden
ANSTO
Lucas Heights Research Laboratories
Private Mail Bag No. 1
Menai, NSW 2234, AUSTRALIA

Gordon S. Linsley
Division of Nuclear Fuel Cycle and
Waste Management
International Atomic Energy Agency
PO Box 100
A-1400 Vienna, AUSTRIA

Nicolo Cadelli
Commission of the European Communities
200, Rue de la Loi
B-1049 Brussels, BELGIUM

R. Heremans
Organisme Nationale des Déchets
Radioactifs et des Matiéres
Fissiles
ONDRAF
Place Madou 1, Boitec 24/25
B-1030 Brussels, BELGIUM

J. Marivoet
Centre d'Etudes de l'Energie Nucléaire
CEN/SCK
Boeretang 200
B-2400 Mol, BELGIUM

P. Conlon
Waste Management Division
Atomic Energy Control Board (AECB)
PO Box 1046
Ottawa, Canada KIP 559, CANADA

A.G. Wikjord
Manager, Environmental and Safety
Assessment Branch
Atomic Energy of Canada Limited
Whiteshell Nuclear Research
Establishment
Pinewa, Manitoba ROE 1LO, CANADA

Jukka-Pekka Salo
Teollisuuden Voima Oy (TVO)
Fredrikinkatu 51-53 B
SF-00100 Helsinki, FINLAND

Timo Vieno
Technical Research Centre of Finland
(VTT)
Nuclear Energy Laboratory
PO Box 208
SF-02151 Espoo, FINLAND

Timo Äikäs
Teollisuuden Voima Oy (TVO)
Fredrikinkatu 51-53 B
SF-00100 Helsinki, FINLAND

M. Claude Ringeard
Division de la Sécurité et de la
Protection de l'Environment (DSPE)
Commissariat á l'Energie Atomique
Agence Nationale pour la Gestion des
Déchets Radioactifs (ANDRA)
Route du Panorama Robert Schuman
B. P. No. 38
F-92266 Fontenay-aux-Roses Cedex
FRANCE

Gérald Ouzounian
Agence Nationale pour la Gestion des
Déchets Radioactifs (ANDRA)
Route du Panorama Robert Schuman
B. P. No. 38
F-92266 Fontenay-aux-Roses Cedex
FRANCE

Claudio Pescatore
Division of Radiation Protection and
Waste Management
OECD Nuclear Energy Agency
38, Boulevard Suchet
F-75016 Paris, FRANCE

M. Dominique Greneche
Commissariat á l'Energie Atomique
IPSN/DAS/SASICC/SAED
B. P. No. 6
F-92265 Fontenay-aux-Roses Cedex,
FRANCE

Robert Fabriol
Bureau de Recherches Géologiques et
Miniéres (BRGM)
B. P. 6009
45060 Orléans Cedex 2, FRANCE

P. Bogorinski
Gesellschaft für Reaktorsicherheit
(GRS) mbH
Schwertnergasse 1
D-5000 Köln 1, GERMANY

R. Storck
GSF - Institut für Tieflagerung
Theodor-Heuss-Strabe 4
D-3300 Braunschweig, GERMANY

Ferrucio Gera
ISMES S.p.A
Via del Crociferi 44
I-00187 Rome, ITALY

Hiroyuki Umeki
Isolation System Research Program
Radioactive Waste Management Project
Power Reactor and Nuclear Fuel
Development Corporation (PNC)
1-9-13, Akasaka
Minato-ku
Tokyo 107, JAPAN

P. Carboneras Martinez
ENRESA
Calle Emilio Vargas 7
R-28043 Madrid, SPAIN

Tönis Papp
Swedish Nuclear Fuel and Waste
Management Co.
Box 5864
S 102 48 Stockholm, SWEDEN

Conny Hägg
Swedish Radiation Protection Institute
(SSI)
Box 60204
S-104 01 Stockholm, SWEDEN

J. Hadermann
Paul Scherrer Institute
Waste Management Programme
CH-5232 Villigen PSI, SWITZERLAND

J. Vigfusson
USK- Swiss Nuclear Safety Inspectorate
Federal Office of Energy
CH-5303 Würenlingen, SWITZERLAND

D.E. Billington
Departmental Manager - Assessment
Studies
Radwaste Disposal R&D Division
AEA Decommissioning & Radwaste
Harwell Laboratory, B60
Didcot Oxfordshire OX11 ORA
UNITED KINGDOM

. Grimwood
Waste Management Unit
BNFL
Sellafield
Seascale, Cumbria CA20 1PG
UNITED KINGDOM

Alan J. Hooper
UK Nirex Ltd
Curie Avenue
Harwell, Didcot
Oxfordshire, OX11 ORH
UNITED KINGDOM

Jerry M. Boak
Yucca Mountain Project Office
US Department of Energy
PO Box 98608
Las Vegas, NV 89193

Seth M. Coplan (Chairman)
US Nuclear Regulatory Commission
Division of High-Level Waste
Management
Mail Stop 4-H-3
Washington, DC 20555

A.E. Van Luik
INTERA/M&O
The Valley Bank Center
101 Convention Center Dr.
Las Vegas, NV 89109

NEA/PSAG User's Group

Shaheed Hossain
Division of Nuclear Fuel Cycle and
Waste Management
International Atomic Energy Agency
Wagramerstrasse 5
PO Box 100
A-1400 Vienna, AUSTRIA

Alexander Nies (PSAC Chairman)
Gesellschaft für Strahlen- und
Institut für Tieflagerung
Abteilung für Endlagersicherheit
Theodor-Heuss-Strasse 4
D-3300 Braunschweig, GERMANY

Eduard Hofer
Gesellschaft für Reaktorsicherheit
(GRS) MBH
Forschungsgelände
D-8046 Garching, GERMANY

Andrea Saltelli
Commission of the European Communities
Joint Resarch Centre of Ispra
I-21020 Ispra (Varese), ITALY

Alejandro Alonso
Cátedra de Tecnología Nuclear
E.T.S. de Ingenieros Industriales
José Gutiérrez Abascal, 2
E-28006 Madrid, SPAIN

Pedro Prado
CIEMAT
Instituto de Tecnología Nuclear
Avenida Complutense, 22
E-28040 Madrid, SPAIN

Miguel Angel Cuñado
ENRESA
Emilio Vargas, 7
E-28043 Madrid, SPAIN

Francisco Javier Elorza
ENRESA
Emilio Vargas, 7
E-28043 Madrid, SPAIN

Nils A. Kjellbert
Swedish Nuclear Fuel and Waste
Management Company (SKB)
Box 5864
S-102 48 Stockholm, SWEDEN

Björn Cronhjort
Swedish National Board for Spent
Nuclear Fuel (SKN)
Sehlsedtsgatan 9
S-115 28 Stockholm, SWEDEN

Richard A. Klos
Paul-Scherrer Institute (PSI)
CH-5232 Villingen PSI
SWITZERLAND

NAGRA (2)
Attn: C. McCombie
F. Van Dorp
Parkstrasse 23
CH-5401 Baden, SWITZERLAND

Daniel A. Galson
INTERA Information Technologies
Park View House, 14B Burton Street
Melton Mowbray
Leicestershire, LEI3, 1AE
UNITED KINGDOM

Brian G.J. Thompson
Department of the Environment
Her Majesty's Inspectorate of
Pollution
Room A5.33, Romney House
43 Marsham Street
London SW1P 2PY, UNITED KINGDOM

INTERA/ECL
Attn: T.J. Sumerling
Chiltern House
45 Station Road
Henley-on-Thames
Oxfordshire RG9 1AT, UNITED KINGDOM

US Nuclear Regulatory Commission (2)
Attn: R. Codell
N. Eisenberg
Mail Stop 4-H-3
Washington, DC 20555

Battelle Pacific Northwest
Laboratories (PNL)
Attn: P.W. Eslinger
PO Box 999, MS K2-32
Richland, WA 99352

Center for Nuclear Waste Regulatory
Analysis (CNWRA)
Southwest Research Institute
Attn: B. Sagar
PO Drawer 28510
6220 Culebra Road
San Antonio, TX 78284

Geostatistics Expert Working Group (GXG)

Rafael L. Bras
R.L. Bras Consulting Engineers
44 Percy Road
Lexington, MA 02173

Jesus Carrera
Universidad Politécnica de Cataluña
E.T.S.I. Caminos
Jordi, Girona 31
E-08034 Barcelona, SPAIN

Gedeon Dagan
Department of Fluid Mechanics and Heat Transfer
Tel Aviv University
PO Box 39040
Ramat Aviv, Tel Aviv 69978, ISRAEL

Ghislain de Marsily (GXG Chairman)
University Pierre et Marie Curie
Laboratorie de Geologie Applique
4, Place Jussieu - T.26 - 5e etage
75252 Paris Cedex 05, FRANCE

Alain Galli
Centre de Geostatistique
Ecole des Mines de Paris
35 Rue St. Honore
77035 Fontainebleau, FRANCE

Steve Gorelick
Department of Applied Earth Sciences
Stanford University
Stanford, CA 94305-2225

Peter Grindrod
INTERA Information Technologies Ltd.
Chiltern House, 45 Station Road
Henley-on-Thames
Oxfordshire, RG9 1AT, UNITED KINGDOM

Alan Gutjahr
Department of Mathematics
New Mexico Institute of Mining and Technology
Socorro, NM 87801

C. Peter Jackson
Harwell Laboratory
Theoretical Studies Department
Radwaste Disposal Division
Bldg. 424.4
Oxfordshire Didcot Oxon OX11 ORA
UNITED KINDGOM

Peter Kitanidis
60 Peter Coutts Circle
Stanford, CA 94305

Ray Mackay
Department of Civil Engineering
University of Newcastle Upon Tyne
Newcastle Upon Tyne NE1 7RU
UNITED KINGDOM

Dennis McLaughlin
Parsons Laboratory
Room 48-209
Department of Civil Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

Shlomo P. Neuman
College of Engineering and Mines
Department of Hydrology and Water Resources
University of Arizona
Tucson, AZ 85721

Christian Ravenne
Geology and Geochemistry Division
Institut Francais du Pétrole
1 & 4, av. de Bois-Préau BP311
92506 Rueil Malmaison Cedex, FRANCE

Yoram Rubin
Department of Civil Engineering
University of California
Berkeley, CA 94720

Foreign Addresses

Studiecentrum Voor Kernenergie
Centre D'Energie Nucleaire
Attn: A. Bonne
SCK/CEN
Boeretang 200
B-2400 Mol, BELGIUM

Atomic Energy of Canada, Ltd. (3)
Whiteshell Research Estab.
Attn: M.E. Stevens
B.W. Goodwin
D. Wushke
Pinewa, Manitoba
ROE 1L0, CANADA

Esko Peltonen
Industrial Power Company Ltd.
TVO
Fredrikinkatu 51-53
SF-00100 Helsinki 10, FINLAND

Jean-Pierre Olivier
OECD Nuclear Energy Agency (2)
38, Boulevard Suchet
F-75016 Paris, FRANCE

D. Alexandre, Deputy Director
ANDRA
31 Rue de la Federation
75015 Paris, FRANCE

Claude Sombret
Centre D'Etudes Nucleaires
De La Vallee Rhone
CEN/VALRHO
S.D.H.A. BP 171
30205 Bagnols-Sur-Ceze, FRANCE

Bundesministerium fur Forschung und Technologie
Postfach 200 706
5300 Bonn 2, GERMANY

Bundesanstalt fur Geowissenschaften und Rohstoffe
Attn: M. Langer
Postfach 510 153
3000 Hanover 51, GERMANY

Gesellschaft fur Reaktorsicherheit (GRS) (2)
Attn: B. Baltes
W. Muller
Schwertnergasse 1
D-5000 Cologne, GERMANY

Hahn-Mietner-Institut fur Kernforschung
Attn: W. Lutze
Glienicker Strasse 100
100 Berlin 39, GERMANY

Institut fur Tieflagerung (2)
Attn: K. Kuhn
Theodor-Heuss-Strasse 4
D-3300 Braunschweig, GERMANY

Physikalisch-Technische Bundesanstalt
Attn: P. Brenneke
Postfach 33 45
D-3300 Braunschweig, GERMANY

Shingo Tashiro
Japan Atomic Energy Research Institute
Tokai-Mura, Ibaraki-Ken
319-11, JAPAN

Netherlands Energy Research Foundation (ECN)
Attn: L.H. Vons
3 Westerduinweg
PO Box 1
1755 ZG Petten, THE NETHERLANDS

Johan Andersson
Swedish Nuclear Power Inspectorate
Statens Kärnkraftinspektion (SKI)
Box 27106
S-102 52 Stockholm, SWEDEN

Fred Karlsson
Svensk Karnbransleforsorjning AB
SKB
Box 5864
S-102 48 Stockholm, SWEDEN

Nationale Genossenschaft fur die Lagerung Radioaktiver Abfalle (NAGRA) (2)
Attn: S. Vomvoris
P. Zuidema
Hardstrasse 73
CH-5430 Wettingen, SWITZERLAND

D.R. Knowles
British Nuclear Fuels, plc
Risley, Warrington, Cheshire WA3 6AS
1002607, UNITED KINGDOM

AEA Technology
Attn: J.H. Rees
D5W/29 Culham Laboratory
Abington
Oxfordshire OX14 3DB, UNITED KINGDOM

AEA Technology
Attn: W.R. Rodwell
044/A31 Winfrith Technical Centre
Dorchester
Dorset DT2 8DH, UNITED KINGDOM

AEA Technology
Attn: J.E. Tinson
B4244 Harwell Laboratory
Didcot, Oxfordshire OX11 ORA
UNITED KINGDOM

Internal

1	A. Narath
20	O.E. Jones
1502	J.C. Cummings
1511	D.K. Gartling
6000	D.L. Hartley
6119	E.D. Gorham
6119	Staff (14)
6121	J.R. Tillerson
6121	Staff (7)
6233	J.C. Eichelberger
6300	D.E. Miller
6301	E. Bonano
6302	T.E. Blejwas, Acting
6303	W.D. Weart
6303	S.Y. Pickering
6312	F.W. Bingham
6313	Supervisor
6313	L.S. Costin
6315	Supervisor
6316	R.P. Sandoval
6320	R.E. Luna, Acting
6341	A.L. Stevens
6341	Staff (6)
6341	Sandia WIPP Central Files (100)
6342	D.R. Anderson
6342	P.N. Swift (10)
6342	Staff (30)
6343	T.M. Schultheis
6343	Staff (3)
6345	R.C. Lincoln
6345	Staff (9)
6347	D.R. Schafer
6400	D.J. McCloskey
6400	N.R. Ortiz
6613	R.M. Cranwell
6613	R.L. Iman
6613	C. Leigh
6622	M.S.Y. Chu
7141	S.A. Landenberger (5)
7151	G.C. Claycomb
7613-2	Doc. Processing (10) DOE/OSTI
8523-2	Central Technical Files
9300	J.E. Powell
9310	J.D. Plimpton
9330	J.D. Kennedy

☆ U.S. GOVERNMENT PRINTING OFFICE 1992—774-122/80050