UCRL-15173

PRECIPITATION AND LAKE-LEVEL CHANGES IN THE WEST AND MIDWEST OVER THE PAST 10,000 TO 24,000 YEARS

S/C 4902009

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MASTER

February 4, 1980

LAWRENCE LIVERMORE LABORATORY
University of California

This work was supported by the United States Nuclear Regulatory Commission under a Memorandum of Understanding with the United States Department of Energy.

Precipitation and Lake-Level Changes in the West and Midwest over the Past 10,000 to 24,000 Years

A Final Report

Prepared for

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ABSTRACT

Geological evidence from the West and Midwest reveals significant variation in precipitation rates and thus in groundwater-recharge rates over the past 10,000 to 20,000 years. Within this time period, the Great Salt Lake has been as large as Lake Michigan, trees have grown in current areas of desert, and the prairie has expanded and contracted in the Midwest. Trends over the past 5000 years show that the West and Midwest have become moister than they were 5000 to 7000 years ago. These trends suggest that long-term increases in average annual precipitation by 20% or more must be allowed for in any hydrological models that estimate possible future groundwater-levels at proposed sites for waste disposal.

The geological evidence examined and summarized in this report includes radiocarbon dates for past lake-levels in the West and pollen data from lakes and bogs in both the West and Midwest. A large map showing the location and maximum extent of past lakes in the West illustrates that many areas in the Great Basin filled with water sometime between 20,000 and 10,000 years ago. A sequence of maps showing the lake-levels for selected 1000-year intervals reveals that lakes on either side of the Sierra Nevada were most extensive about 22,000 and about 12,000 years ago whereas the lakes in Utah, Arizona, New Mexico, and Texas seem to have been highest in the intervening period. Most of the western lakes dried out or were at low levels about 5000 years ago, but since then the water level has increased in four basins with fluctuations in level of over 90 m. Pollen evidence from the West supports the general sequence of hydrological changes. Combining the information from the pollen data and the lake-level data will allow use of computer models for estimating past changes

in precipitation and groundwater-recharge rates at certain western sites.

The geological data in the West indicate several potential hazards for the sites where nuclear wastes might be buried. These hazards include the inundation of many basin floors, including parts of the Nevada Test site; large fluctuations in groundwater levels and spring activity; variations in the degree of integration of surface (and possibly subsurface) drainage; the sudden formation or drainage of lakes situated along active fault systems; and episodes of catastrophic flooding and erosion associated with the complete or partial drainage of large, deep lakes such as Bonneville and Glacial Lake Missoula.

The radiocarbon-dated pollen evidence from the Midwest reveals an eastward expansion of the prairie from South Dakota into eastern Minnesota from 1000 to 7000 years ago and then a gradual westward retreat into central Minnesota. This vegetational change indicates first a decrease and then an increase in annual precipitation by as much as 20 to 30% in the western Midwest. Current trends that began over 4000 years ago indicate a continuing increase in moist climatic conditions in the western and northern Midwest.

FOREWORD

The goal of the research described in this report is to document the climatic variability over the past 10,000 to 20,000 years in areas in which sites may be designated for the burial of nuclear wastes. Three separate data sets were studied, and the results are presented in three chapters.

The first data set consisted of radiocarbon dates documenting past changes in lake levels in lakes and playas in the western United States. We mapped the sites where water levels were higher than the levels today and presented a table telling what evidence is available at each site. We also mapped the lake-level fluctuations for the past 24,000 years at sites in the West and presented time series for these fluctuations at four sites.

The second data set was a selection of the published radiocarbon-dated pollen diagrams from the western United States. These data are a valuable source of climatic information and complement the geological evidence of lake-level fluctuations in the West. A table is presented that gives the location, elevation, and number of radiocarbon dates for each site.

The third data set was a set of fossil pollen data from 20 sites in the upper Midwest. These data were calibrated in terms of precipitation changes over the past 10,000 years, and maps are presented of the estimated precipitation changes between 10,000 and 7000 years ago and between 7000 years ago and today.

ACKNOWLEDGEMENTS

The research presented in this report was funded by Lawrence Livermore Laboratory and is part of a general long-term project funded under the title of COHMAP (Cooperative Mapping of Holocene Climates) by the Program for Climate Dynamics at the National Science Foundation. Technical assistance during the course of the research came from L. Breindel, K. Hui, K. McGown, and R. Mellor.

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CHAPTER 1

LATE QUATERNARY LAKE-LEVEL FLUCTUATIONS IN THE WESTERN UNITED STATES

(F. A. Street)

A) INTRODUCTION

The value of fluctuations in lake level as an indicator of climate has been recognized for more than two centuries (Halley, 1715). Lake depth and area respond to climatic change on time scales ranging from 1 to 10^6 years. This response is most pronounced in the case of closed-basin lakes (lakes without outlets), which often exhibit dramatic fluctuations in size. Past lake-level fluctuations can be reconstructed from a wide variety of evidence, including ancient shorelines and overflow channels, lacustrine sediments and fossils, and lake-side archaeological sites. The large amount of data now available is beginning to provide a highly coherent picture of environmental conditions during the time span covered by ^{14}C dating (approximately the last 30,000 years).

During the last glaciation, ca. 25,000 - 10,000 BP[1], the southwestern United States experienced much wetter conditions than today. The present arid and semi-arid areas were transformed into a network of interconnected lakes and marshes. The largest of these water bodies, Lake Bonneville, covered an area almost the size of the present Lake Michigan, and attained a maximum depth of around 335 m. The accompanying rise in groundwater levels resulted in enhanced spring activity in many low-lying areas. Towards the close of the Late Pleistocene (ca. 10,000 BP), the colonization of the Great Basin lakeland by early man is recorded by the widespread distribution of sites belonging to the Western Pluvial Lakes Tradition (Bedwell, 1973).[2]

1. BP stands for years before present (1950 AD) in radiocarbon time.
2. Bibliography at end of this chapter (pp. 41-53).

This ancient way of life, based largely on fishing and wildfowling, died out during the rapid shrinkage of the lakes after 10,000 BP.

The large changes in water level indicated by the geological and archaeological evidence imply major shifts in water balance over the lake catchments. Two broad approaches have been used to investigate the climatic significance of these fluctuations. The first involves the estimation of past precipitation over individual basins using simple water-budget models (Brakenridge, 1978). The problems encountered by this approach are discussed in section D. The second approach, which will be followed here, treats the spatial and temporal patterns of lake-level maxima and minima as an indicator of the distribution and relative magnitude of past water-balance anomalies, without laying too much emphasis on individual climatic variables such as temperature and precipitation (Street and Grove, 1976, 1979).

The aims of the present report are as follows:

i) To update existing maps showing the distribution and maximum extent of Late Quaternary lakes (including glacial lakes) in the western United States. The area covered includes Washington, Idaho, Montana, Oregon, Wyoming, California, Nevada, Utah, Colorado, Arizona, New Mexico and parts of the Dakotas, Nebraska, Kansas, and Texas (Fig. 1).

ii) To identify the types of lakes which respond most sensitively to climatic fluctuations.

iii) To review briefly the dating problems involved in establishing lacustrine stratigraphic sequences, and to summarize the existing ^{14}C control from the study area. The glacial lakes (other than Glacial Lake Missoula) are not included in this survey.

iv) To identify the spatial and temporal patterns of water-level fluctuations in the closed-basin lakes of the Southwest since 30,000 BP, based on an updated version of the data bank compiled by Street and Grove (1979). This report will no attempt to reconstruct the changes in the atmospheric circulation responsible for the observed patterns.

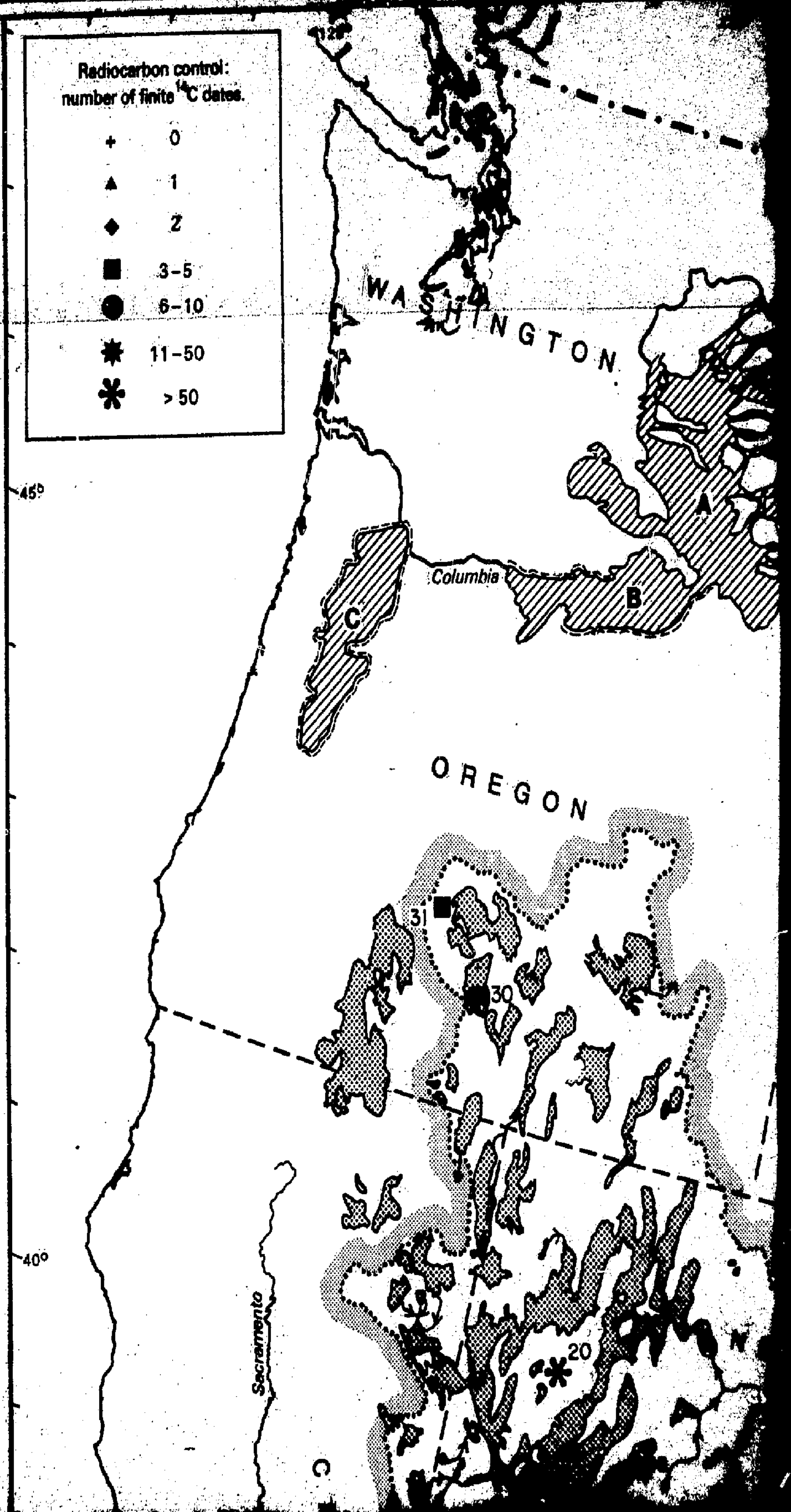
v) To review the problems encountered by previous attempts to derive paleoprecipitation estimates from lake-level curves (each of which is an index of past variations in net water balance integrated over an entire basin area).

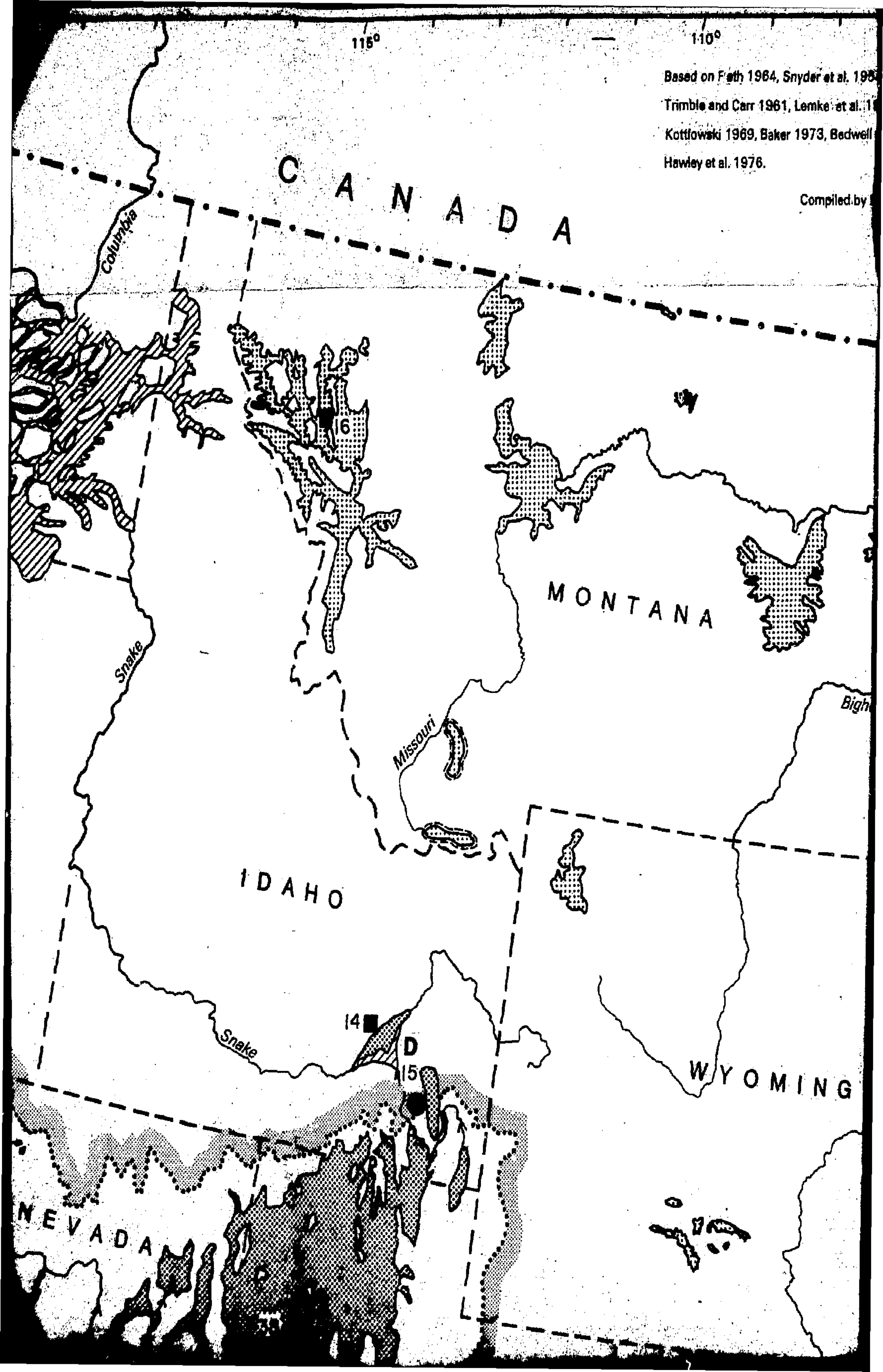
vi) To identify potential hazards associated with lake-level fluctuations on a time-scale of 10^3 to 10^5 years.

B) METHODS USED IN THIS SURVEY

1) Mapping the extent of Late Quaternary lakes

Several previous attempts have been made to map the past extent of Quaternary lakes in the western U.S.A. The most detailed compilations are those by Feth (1964), which covers the entire area of interest, and by Snyder et al. (1964), which is restricted to the Great Basin. The map accompanying this report (Fig. 1) is based largely on these two sources, updated using the references cited in the key, and eliminating lakes now known to be of Early or Middle Quaternary age. The names of the paleolakes (Table 1) follow Hubbs and Miller (1948) and Snyder et al. (1964), and the estimates of lake area and lake depth are derived from the same sources, updated from more recent references wherever possible. Figure 1 and Table 1 also summarize the distribution of radiocarbon dates from non-glacial lakes and from Glacial Lake Missoula. Information on the other glacial lakes can be found in standard texts such as Wright and Frey (1965) and Mahaney (1976).

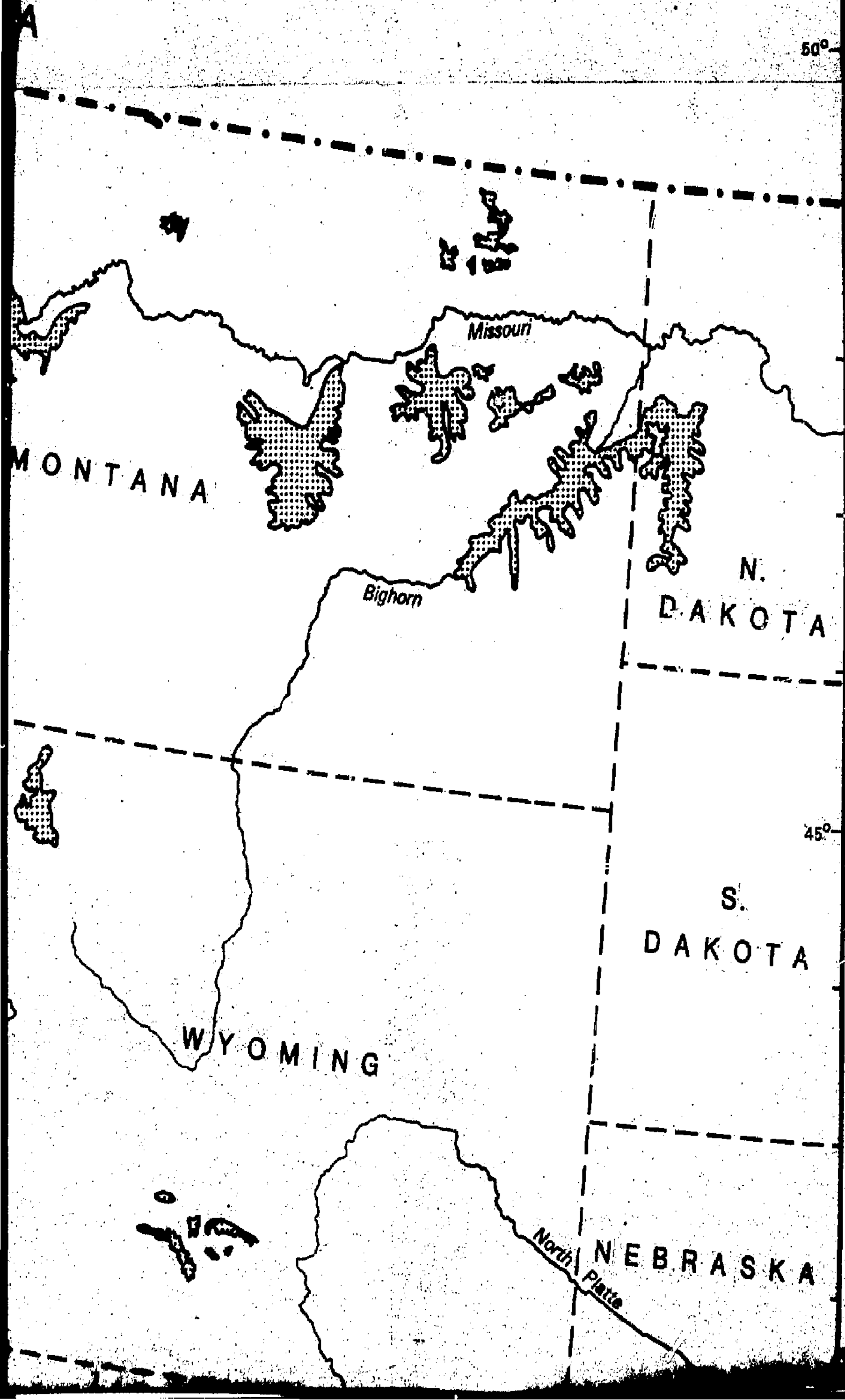

Radiocarbon control: number of finite ¹⁴C dates.
0
1
2
3–5
6–10
11–50
> 50
WASHINGTON
OREGON
Columbia
Sacramento
A
B
C
31
30
20
45°
40°

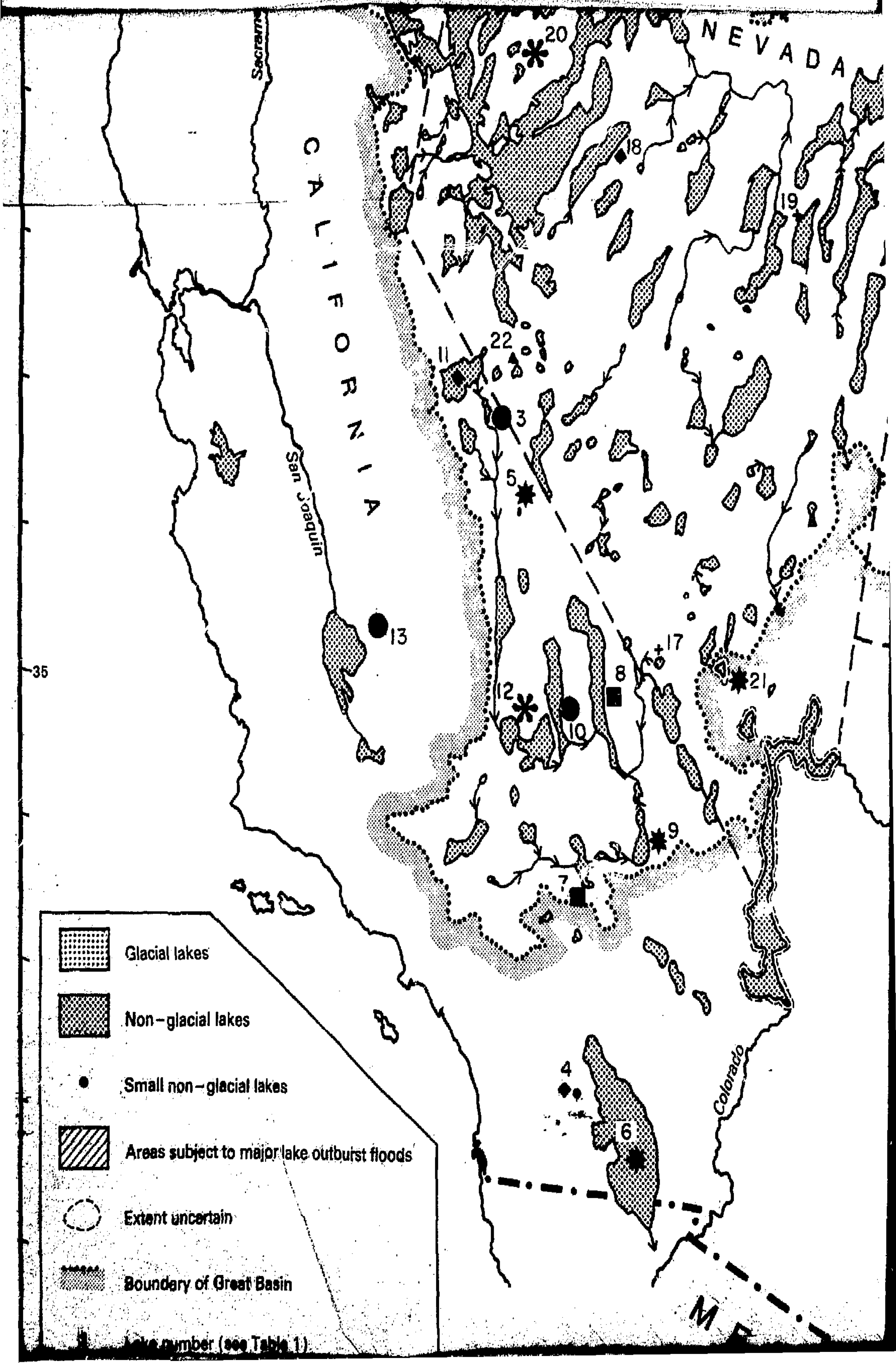

115°
110°
Based on Feth 1964, Snyder et al. 195
Trimble and Carr 1961, Lemke et al. 1
Kottlowski 1969, Baker 1973, Bedwell
Hawley et al. 1976.
Compiled by
CANADA
Columbia
16
MONTANA
Snake
Missouri
IDAHO
14
D
15
Snake
NEVADA
WYOMING

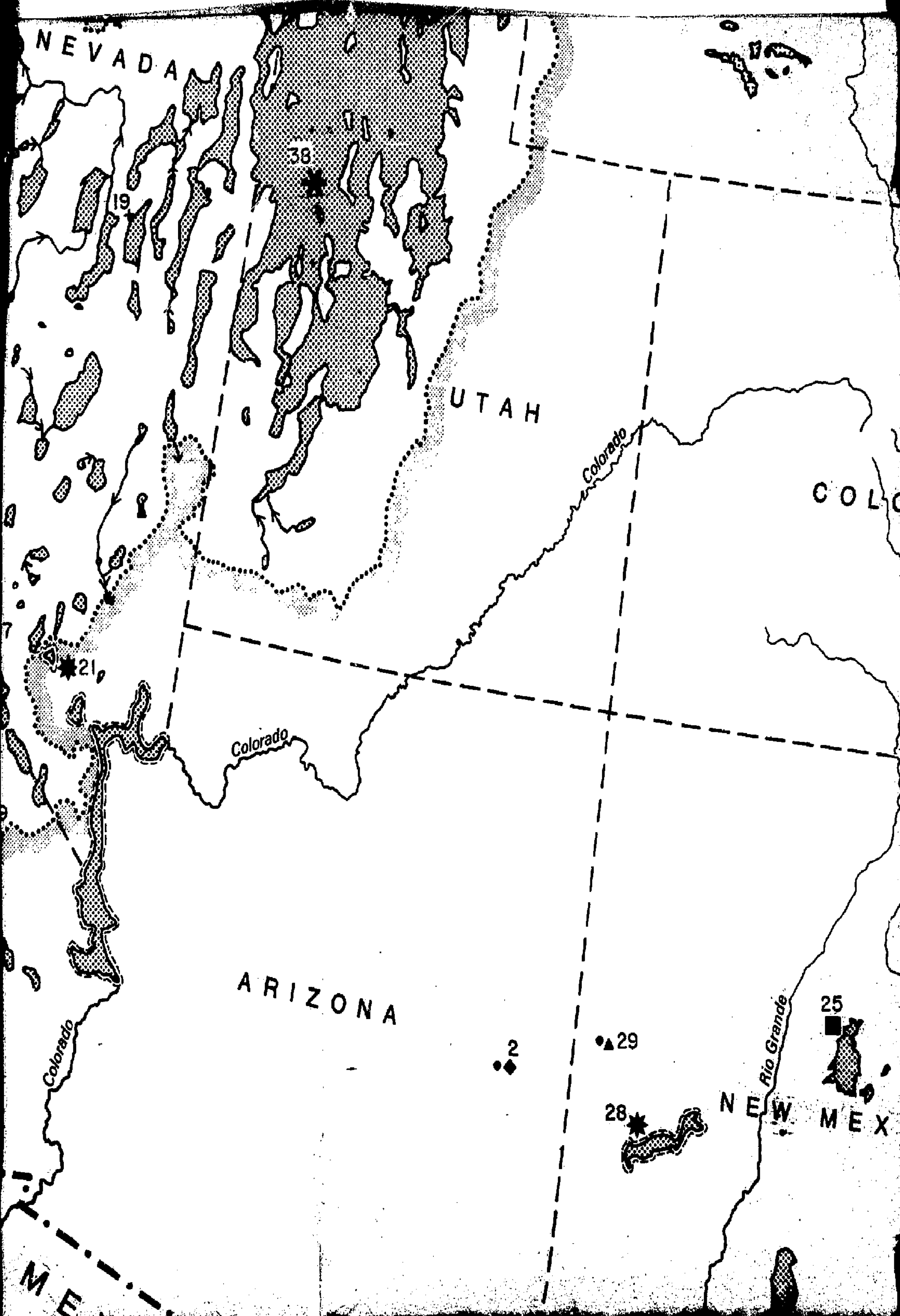
110°   108°

Based on Feth 1964, Snyder et al. 1964 and Morrison 1965, with emendations from Davis et al. 1959, Trimble and Carr 1961, Lemke et al. 1965, Reeves 1966, Bright 1967, Haynes 1967, Hawley and Kottlowski 1969, Baker 1973, Bedwell 1973, Jenkins 1973, Van de Kamp 1973, Van Denburgh 1975, Hawley et al. 1976.

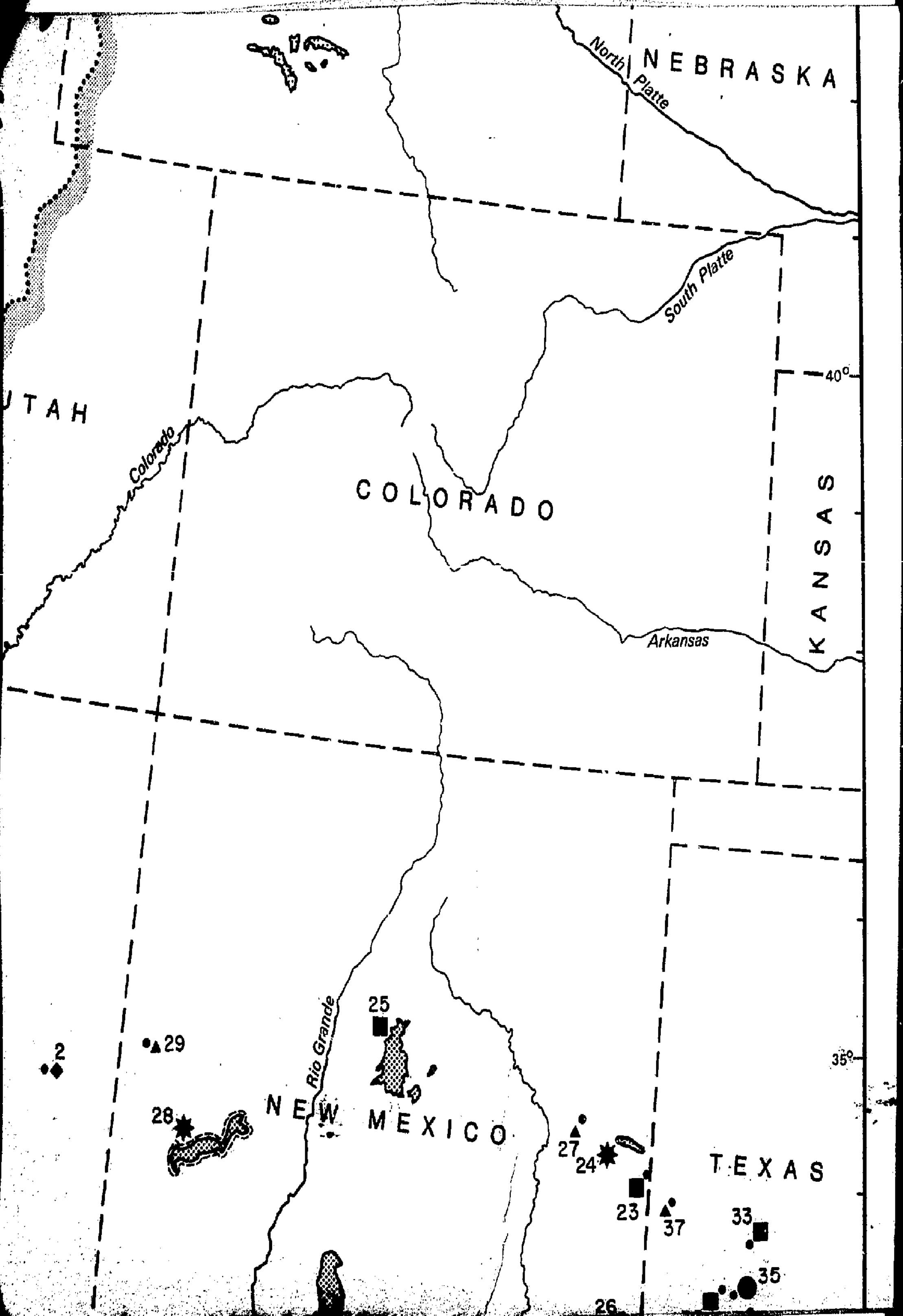
Compiled by F. A. Street and drawn by M. L. Loveless.

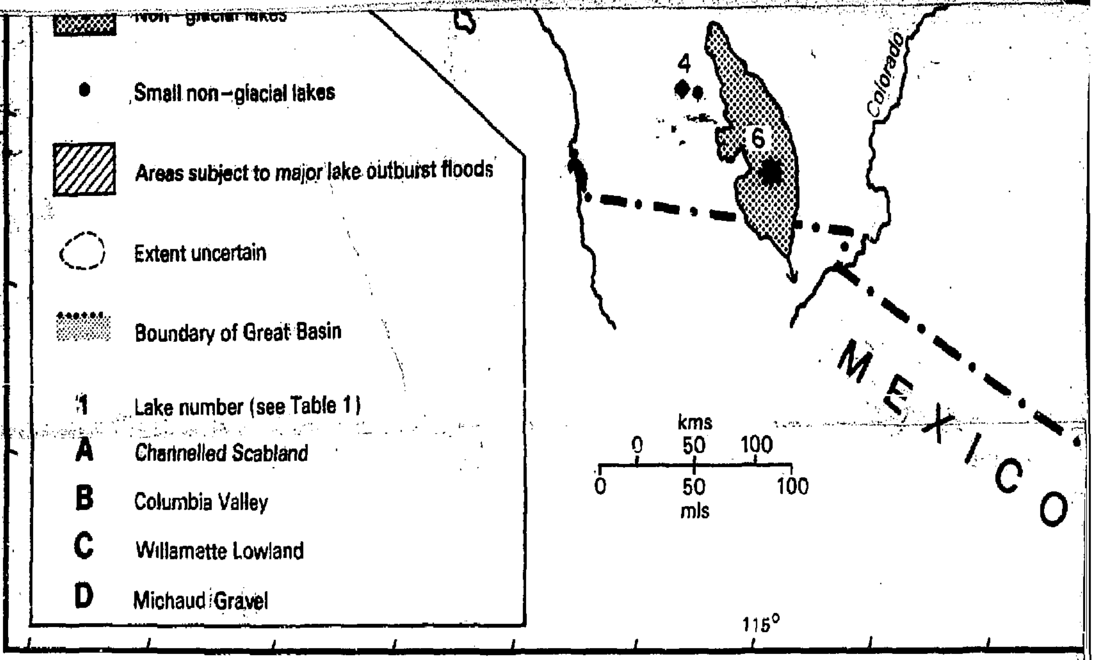



NEVADA
CALIFORNIA
Sacram
San Joaquin
Colorado
20
18
19
22
11
3
5
13
35
17
8
21
12
10
9
7
4
6
M
Glacial lakes
Non-glacial lakes
Small non-glacial lakes
Areas subject to major lake outburst floods
Extent uncertain
Boundary of Great Basin
Lake number (see Table 1)

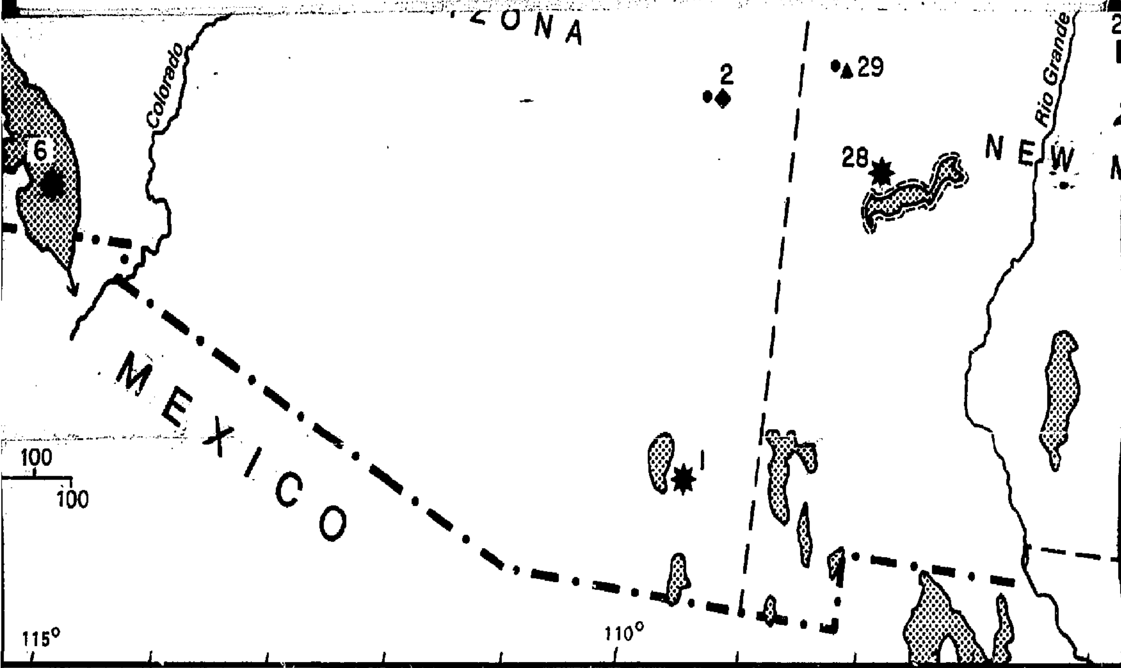


NEVADA
UTAH
COLO
ARIZONA
NEW MEX
ME
Colorado
Colorado
Colorado
Rio Grande
38
19
21
2
29
28
25

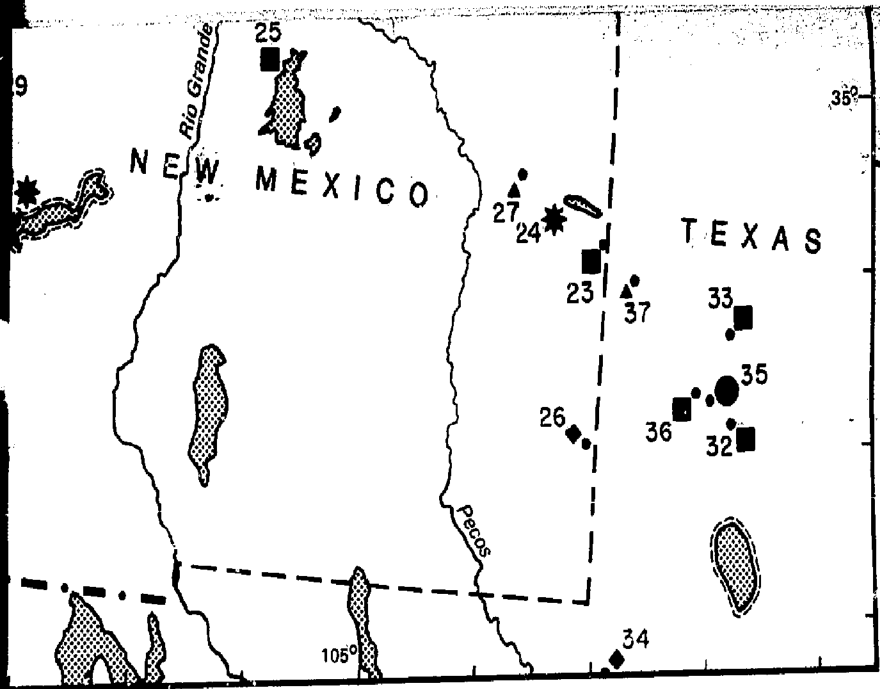

NEBRASKA
North Platte
South Platte
40°
UTAH
Colorado
COLORADO
KANSAS
Arkansas
Rio Grande
25
29
2
35°
28
NEW MEXICO
27
24
TEXAS
23
37
33
35
26



MAXIMUM EXTENT OF LATE PLEIS



TENT OF LATE PLEISTOCENE LAKES IN THE WESTERN UNITED ST



ERN UNITED STATES

FIG. 1. Maximum extent of Late Pleistocene lakes in the western United States.

Table 1: Data on lakes in the western United States which have radiocarbon-dated chronologies.

Lake no.	Name (modern lake or playa)	Lat. (°N)	Long. (°W)	Finite ^{14}C dates	Oldest ^{14}C date (yrs B.P.)	Maximum area (km^2)	Maximum increase in depth relative to present (m)	References (most useful references underlined)
ARIZONA								
1	Cochise (Willcox playa)	32°08'	109°51'	33	>30,000	363	12	Schreiber et al., 1972 Damon et al., 1963 Long and Mielke, 1966 Damon et al., 1964 Haynes et al., 1967 Mielke and Long 1969 Long, 1965 Schultz and Smith, 1965
2	Laguna Salada [illegible]	34°21'	110°17'	2	7250 ± 170	ca. 8	ca. 27	Hevly, 1962 Cooley and Hevly, 1962 Damon et al., 1963
CALIFORNIA								
3	Adobe (Black Lake)	37°55'	118°36'	7	11,350 ± 350	52	24	Batchelder, pers. comm., 1978 Snyder et. al., 1964 Hubbs and Miller, 1948
4	Clark (Clark Dry Lake)	33°20'	116°18	2	700 ± 150	ca. 24	ca. 14	Hubbs and Miller 1948 Hubbs et al., 1960
5	Deep Spring	37°17'	118°02'	47[1]	10,000 ± 1000	ca. 44	unknown[2]	Miller, 1928 Snyder et al., 1964 Jones, 1965 Peterson et al., 1963 Hubbs et al., 1963, 1965 Hubbs and Bien, 1967
6	Le Conte (Salton Sea)	33°20'	116°00'	48	>50,000	ca. 4600	≥85[3]	Hubbs and Miller, 1948 Hubbs et al., 1960 Hubbs et al., 1963 Hubbs and Bien (1967) Crane and Griffin, 1958 Fergusson and Libby, 1962, 1963 Bien and Pandorfi, 1972 Van de Kamp, 1973 Spiker et al., 1977 Clark et al., 1972 Stanley, 1966
7	Manix (Troy Lake - Coyote Lake)	35°03'	116°42'	5	30,950 ± 1000	407	116	Hubbs and Miller, 1948 Snyder et al., 1964 Hubbs et al., 1962 Fergusson and Libby, 1962 Hubbs et al., 1965 Berger and Libby, 1967
8	Manly (Death Valley) Salt Pan	36°00'	116°48'	4	21,500 ± 700	1601	183	Hooke, 1972 Snyder et al., 1964
9	Mohave (Soda Lake - Silver Lake)	35°22'	116°08'	24	15,350 ± 240	ca. 200	≥12	Ore and Warren, 1971 Snyder et al., 1964 Hubbs et al., 1965 Stuiver, 1969
10	Panamint (Panamint dry lake)	36°18'	117°18'	10	32,900 ± 1700	722	283[4]	Snyder et al., 1964 Hubbs et al., 1965 Berger and Libby, 1966 Smith, 1977

11	Russell (Mono Lake)	38°03'	118°46'	2[5]	21,900 ± 600[6]	692	238	Lajoie, 1968 (abstr.), 1969 and pers. comm., 1978 Hubbs et al., 1965 Fergusson and Libby, 1962 Snyder et al., 1964
12	Searles (China Lake - Searles Lake)	35°36'	117°42'	110	46,350 ± 1500[7]	1000	200	Smith, 1968, 1977, 1979 Stuiver, 1964 Flint and Gale, 1958 Rubin and Berthold, 1961 Ives et al., 1964 Levin et al., 1965 Ives et al., 1967 Robinson, 1977 Marsters et al., 1969 Peng et al., 1978 Damon et al., 1964
13	Tulare (Kern-Buena Vista-Tulare Lake Beds)	36°00	119°40'	8	26,780 ± 600[8]	ca. 4110	BVL 4[9] TL 9	Croft, 1968 Davis et al., 1959 Janda and Croft, 1967 Ives et al., 1967 Hubbs and Bien, 1967 Buckley et al., 1968
IDAHO								
14	American Falls	42°54'	112°49'	4	>42,000	unknown	unknown	Trimble and Carr, 1961 Marde, 1960, 1965 Rubin and Alexander, 1958, 1960 Ives et al., 1964 Strawn, 1965
15	Thatcher[10]	42°35'	111°41'	6	34,000 ± 1600	ca. 625	unknown	Bright, 1967 Rubin and Alexander, 1960 Rubin and Berthold, 1961 Ives et al., 1964
MONTANA								
16	Glacial Lake - Missoula (Pend Oreille Lake - Coeur D'Alene Lake)	47°30'	114°30'	3	32,700 ± 900[11]	ca. 7500	ca. 610	Pardee, 1942 Baker, 1973 Baker and Nummedal, 1978 Easterbrook, 1976 Mullineaux et al., 1978 Richmond, 1976
NEVADA								
17	Ash Meadow	36°21'33"	116°16'51"	0	>29,000	16[12]	unknown	Snyder et al., 1964 Hubbs and Bien, 1967
18	Dixie (Humboldt Salt Marsh)	39°54'45"	117°59'45"	2	11,700 ± 180	1088	72	Buckley and Willis, 1970 Snyder et al., 1964 Hubbs and Miller, 1948
19	Hubbs	39°38'	115°22'	0	>30,000	531	76	Hubbs and Miller, 1948 Snyder et al., 1964 Hubbs and Bien, 1967
20	Lahontan (Pyramid Lake - Walker Lake, etc.)	40°00'	119°30'	166	>40,000[13]	22,440	160[14]	Benson, 1978 Broecker and Orr, 1958 Olson and Broecker, 1961 Broecker and Kaufman, 1965 Born, 1972 Fergusson and Libby, 1964 Rubin and Alexander, 1960 Levin et al., 1965 Morrison and Frye, 1965 Libby, 1955 Kaufman and Broecker, 1965
21	Las Vegas	36°19'	115°11'	3[15]	31,300 ± 2500	unknown	unknown	Haynes, 1967
22	Teel (Teels Marsh)	38°12'30"	118°20'20"	1	10,760 ± 400	47	unknown, probably shallow	Hubbs and Miller, 1948 Snyder et al., 1964 Crane and Griffin, 1965 Hay, 1966

NEW MEXICO								
23	Arch (= Big Salt Lake, *Laguna Salada*)	34°04'30"	103°07'30"	5	22,300 ± 700	ca. 130	≤12	Reeves, 1966a Glass et al., 1973 Leonard and Frye, 1975 Hester, 1975 Harbour, 1975 Olson and Broecker (1961)
24	Blackwater Draw	34°15'	103°20'	17	15,770 ± 440	*unknown*[16]	*unknown*[16]	Haynes and Agogino, 1966 Wendorf, 1970 Hester, 1972 Haynes, 1975
25	Estancia (Laguna del Perro, Salina Lake, etc.)	34°45'	106°00'	4	>33,000	2,860[17]	90	Bachhuber, 1971 Bachhuber and McLellan, 1977
26	Lea County	33°27'	103°09'30"	2	16,010 ± 180	uncertain (small)	uncertain (small)	Leonard and Frye, 1975 Coleman, 1974 Glass et al., 1973
27	Portales Valley	34°26'30"	103°49'30"	1	15,280 ± 210	unknown (small)	unknown (small)	Coleman, 1974 Glass et al., 1973 Leonard and Frye, 1975
28	San Augustin (San Augustin playa)	33°50'	108°10'	16	$27,000^{+5000}_{-3200}$	660	50[18]	Powers, 1939 Stearns, 1962 Stuiver and Deevey, 1962 Clisby and Sears, 1956 Damon et al., 1964 Long and Mielke, 1966 Schultz and Smith, 1965 Foreman et al., 1959
29	Zuni (Zuni Salt Lake)	34°27'	108°46'	1	23,000 ± 1500	5	15	Schultz and Smith, 1965 Haynes et al., 1967 Darton, 1905 Cummings, 1968
OREGON								
30	Chevaucan	42°40'	120°30'	6	$30,700^{+2500}_{-1900}$	1,240	115	Allison, 1966 Buckley et al., 1968 Allison, 1945, 1954 Phillips and van Denburgh, 1971 Van Denburgh, 1975 Levin et al., 1965 Ives et al., 1967 Sullivan et al., 1970
31	Fort Rock (Silver Lake - Christmas Lake - Fossil Lake)	43°10'	120°45'	4	$29,000^{+2000}_{-1600}$	3,885	49	Bedwell, 1970, 1973 Allison, 1966
TEXAS								
32	Guthrie	ca.33°06'	ca.101°48'	4	34,400 ± 3450	unknown (small)	unknown (small)	Reeves and Parry, 1965 Reeves, 1966
33	Lubbock	33°38'	101°54'	3	12,650 ± 250	unknown (small)	unknown (small)	Green, 1962 Wendorf, 1970 Black, 1974 Hester, 1975 Broecker and Kulp, 1957
34	Monahans Dunes	ca.31°36'	ca.102°53'	2	19,200 ± 500	unknown	unknown	Haynes, 1975 (citing Green, 1961) Broecker and Kulp, 1957 Olson and Broecker, 1961
35	Mound	33°05'	102°05'	8	>37,000	<20	<15	Reeves and Parry, 1965 Reeves, 1966 Oates et al., 1970 Hester, 1975 Harbour, 1975

36	Rich	33°17'	102°12'	4	32,525 ± 2400	unknown (small)	615	Reeves and Parry, 1965 Reeves, 1966 Hester, 1975 Haynes, 1975 Olson and Broecker, 1961
37	White	ca. 33°58'	102°44'	1	19,275 ± 560	unknown (small)	unknown (small)	Reeves and Parry, 1965 Hester, 1975 Harbow, 1975
UTAH								
38	Bonneville (Great Salt Lake - Utah Lake - Sevier Lake, etc.)	40°30'	113°00'	109	>37,000[19]	51,640	ca. 335	Broecker and Orr, 1958 Broecker and Kaufman, 1965 Rubin and Alexander, 1958, 1960 Rubin and Berthold, 1961 Ives et al., 1964, 1967 Levin et al., 1965 Jennings, 1957 Karlstrom, 1961 Eardley, 1962 Morrison and Frye, 1965 Marsters et al., 1969 Stuiver, 1969 Morrison, 1966 Kaufman and Broecker, 1965 Eardley et al., 1973 Crittenden, 1963

Footnotes:

1. With one exception, these ages were measured on diagenetic dolomite in lacustrine muds, and should not therefore be regarded as an accurate measure of the time of sedimentation. Peterson et al. (1963) suggest that the dolomite began to nucleate after the close of the last pluvial period, estimated to be 10,000 B.P.

2. Former lake depth is impossible to reconstruct due to active faulting.

3. Lake basin has been strongly affected by faulting and tilting, so that the Late Pleistocene configuration is hard to reconstruct.

4. Highest shoreline remnants dated suggest maximum depth 298 m.

5. Lajoie dates not published.

6. Basin has been continuously occupied by a lake since 150,000 B.P. (est.).

7. Major fluctuations in lake level have occurred throughout the last 150,000 yrs (est.).

8. Lacustrine clay units within the Quaternary sediments of the San Joaquin Valley indicate at least 9 major lake expansions, beginning well before 600,000 B.P.

9. Depth and extent of much larger Late Pleistocene and early Holocene lakes are uncertain, owing to structural downwarping and changes in the height of the alluvial-fan barriers separating the present lake basins.

10. Lake created by lava flows which dammed Bear R., which used to flow northwards into the Snake R; and drained by downcutting of its outlet southwards into the Bonneville Basin (modern course of Bear R.).

11. Stratigraphic information suggests that Lake Missoula drained catastrophically through the Channeled Scabland at least four, and possibly six, times. One, possibly two, events occurred before the Bull Lake Glaciation (60,000 - 120,000 B.P. or even earlier: Richmond, 1977).

12. Lake area given is underestimate according to Hubbs and Bien (1967). Impoundment of lake no longer possible due to tectonic deformation related to Death Valley sump (see Lake Manly).

13. Oldest ^{230}Th age: 250,000 y

14. Measured from natural (pre-irrigation) level of Pyramid Lake (1180 m).

15. Three from lacustrine beds, numerous others from nonlacustrine beds.

16. Several closed, or at times interconnected, ponds or shallow lakes of varying extent existed in this area.

17. Maximum area includes satellite Pinos Wells and Encino Basins.

18. Highest shoreline remnants dated suggest maximum depth 69 m.

19. Oldest ^{230}Th age: >105,000 y. Major fluctuations of lakes in Bonneville Basin began before deposition of Bishop ash (K/Ar dated at 730,000 y) (Eardley et al., 1973).

2) <u>Compiling lake-level information</u>

Several categories of lake-level evidence are widely available throughout the Southwest. The past extent and depth of any lake can be determined most accurately by dating its strandlines by ^{14}C. Most of the shoreline dates obtained so far have come from calcareous tufas deposited on rocky outcrops. Tufa is often very porous and easily contaminated by younger carbonate (Broecker and Orr, 1958; Broecker and Kaufman, 1965; Benson, 1978). Ages measured on shell from nearshore sands and gravels, or on charcoal from lakeside archaeological sites, tend to be more consistent and reliable. In many areas, however, the older shorelines are poorly preserved, and past variations in lake level have been deduced from the sequence of lacustrine and non-lacustrine deposits in cores or sedimentary exposures from the basin floors. More detailed information is usually obtained by studying the sedimentology, mineralogy and paleontology of the lake sediments themselves. In such situations, the dating framework often consists largely of ages measured on disseminated organic matter or carbonate precipitates (aragonite, calcite, dolomite, etc.) from the lacustrine units. These ages are supplemented by dates on wood, charcoal, bone or caliche from the interbedded colluvial, alluvial or aeolian units. There is considerable debate about the reliability of carbonate dates, particularly those derived from caliche and highly soluble Na-carbonates such as trona (Stuiver, 1964; Broecker and Kaufman, 1965; Morrison and Frye, 1965; Thurber, 1972; Smith, 1979).

In basins where tectonic deformation has been negligible, and where good altimetric, stratigraphic and radiometric control is available, it is possible to draw up curves showing the variation in lake levels through time. Only four basins -- Mohave, Lahontan, Searles, and Russell -- have so far yielded reliable curves, and unfortunately all these lakes are situated close together on the eastern side of the Sierra Nevada. The often quoted water-level curve for Lake Bonneville by Broecker and Kaufman (1965, Fig. 6) is based largely on tufa dates and disagrees seriously with the curve published by Morrison and Frye (1965).

In Figure 2, the curves for Mohave, Lahontan and Searles are plotted at the same scale. This reveals not only the rapidity and large amplitude of the major Late Quaternary fluctuations, but also the amount of variation during the last 5000 years: up to 90 m in the case of Walker Lake. Lake Mohave has not undergone such dramatic fluctuations because it possesses an outlet at a relatively low level above the present basin floor.

Even where the drawing-up of detailed curves is not justified, due to lack of data, it is often possible to make reliable statements about the water level during at least part of the history of any given lake. By pooling all the available evidence, and assessing the validity of the radiocarbon control in each area, it is possible to extend the spatial coverage of the data set.

This report is based on a careful search of the literature, following the procedures established by Street and Grove (1976, 1979). Attention has once again been concentrated on closed basins which have yielded radiocarbon dates (Fig. 1). The present survey has increased the number of mappable data points from 17 to 33 (including the Salton Sea), and the entire compilation has been thoroughly revised and checked. The resulting data set is summarized in Figure 1 and Table 1. A simple standardization procedure has been used to express the available evidence in a semi-quantitative form (Street and Grove, 1979, pp. 84-87).

The water-level information for each lake was classified on

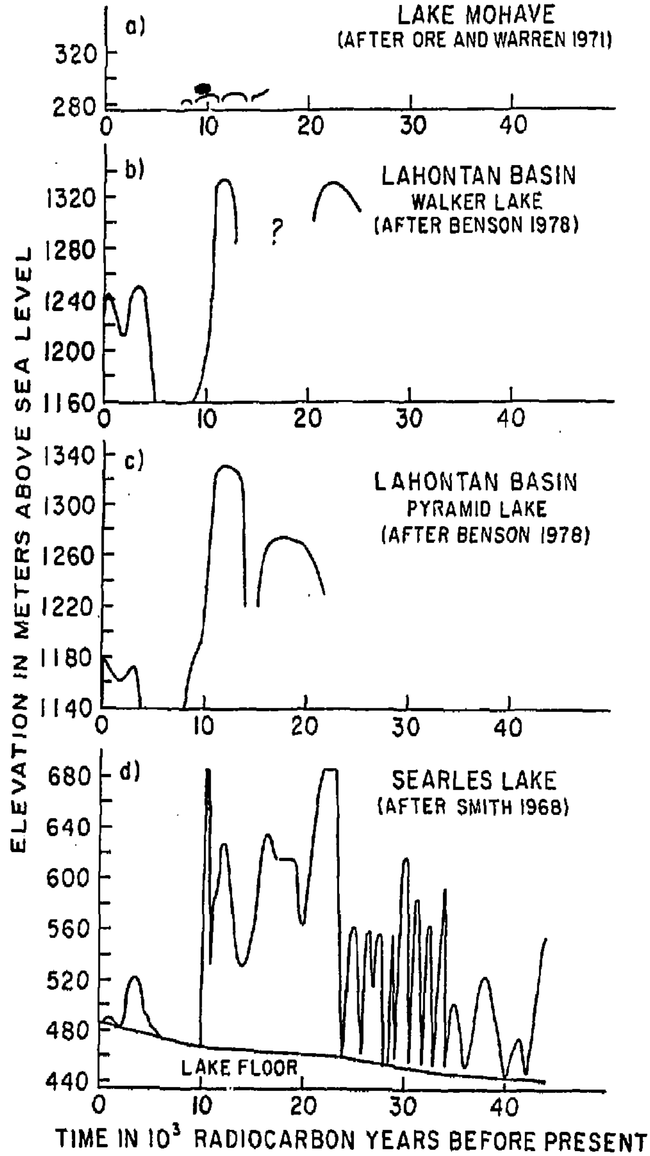


FIG. 2. Fluctuations of the water levels in Lakes Mohave, Lahontan and Searles since 44,000 BP. All lakes plotted to the same vertical scale.

Time series of water levels in 4 lakes.

a simple ordinal scale:

low	0-15% of the total altitude range
intermediate	15-70%
high	>70%

Each basin was considered relative to its own internal range of variation rather than to its level at the present day. This scheme works well in practice and permits some flexibility at the upper limit, to allow for downcutting of outlets or uncertainties in dating the highest shorelines.

The radiocarbon dates for each lake have been stored in a computer data bank in Oxford, together with the lake-level status of each lake during each 1000-year time frame from 0 to 30,000 BP. The status of each lake was determined as follows:

Status 0	No data
Status 1	Lake was high during all or part of this time period
Status 2	Lake was intermediate, but not high, during all or part of this time period
Status 3	No high or intermediate levels occurred during this time period

This method underemphasizes arid periods of less than 1000 years duration, but makes best use of single ^{14}C dates, which tend to come from lacustrine rather than from non-lacustrine deposits. The 1000 year mapping interval was chosen to allow for the effective resolution of the radiocarbon dating framework, without obscuring the rapidity of the major fluctuations. Where there is serious conflict between ^{14}C dates on carbonate and non-carbonate materials, for example in the Bonneville and Lahontan Basins (No. 38 and 20), the interpretation used is based on the following assumed order of reliability: i) charcoal and wood in basin sediments or cave sequences; ii) peat or organic carbon in lake sediments; iii) disseminated inorganic carbonate, calcareous algae, ostracods and mollusca in lake sediments; iv) tufa; v) dolomite and Na-carbonates. Dates on bone and soil humus or carbonate have been treated throughout with caution. No adjustment has been made for the initial $^{14}C/^{12}C$ ratio of the lake waters, because few laboratories have attempted to apply this correction, and there is no consensus about its magnitude (Thurber, 1972; Benson, 1978; Peng et al., 1978).

3) Reconstructing the spatial and temporal patterns in the lake-level data

The lake-level information contained in the data bank has been summarized in two different ways. In Figure 3, the broad history of lake levels over the entire Southwest is shown in the form of a histogram of lake status against time. Figures 4 - 10 display the same information on maps for selected 1000 year time periods. The maps reveal smaller-scale, spatial organization in the data which may reflect regional climatic anomalies. The patterns selected are the most distinctive ones, representing the climatic extremes experienced in the southwestern states during the last 30,000 years.

D) *ANALYSIS ANL INTERPRETATION*

1) Distribution of Late Quaternary lakes in the western U.S.A.

Late Quaternary lakes were very unevenly distributed across the western States (Fig. 1). The largest group (about 120) were situated within the Great Basin; the enormous area of internal drainage which lies between the Sierra Nevada and the Wasatch Mountains. There was a second concentration in the Basin and Range country of southern Arizona and New Mexico, extending into

Mexico, and a third along the southern margin of the former Laurentide and Cordilleran ice sheets. Large numbers of smaller lakes and ponds occur in all the glaciated areas and on the Llano Estacado (Staked Plains) of Texas and New Mexico. The distribution of radiocarbon dates from closed-basin lakes is also very clustered: 75 percent of those in the West come from the Great Basin.

The origin and geological setting of the palaeolakes are important to an understanding of their sensitivity to climatic fluctuations. These geological factors have also exerted a profound influence on the length and continuity of the sedimentary record. If we consider the factors leading to the initial impoundment of a lake, five common categories of basins can be identified in the western U.S.A.: fault-bounded depressions, volcanic and meteoric craters, basins scoured out by glacial erosion, blocked drainage systems, and deflation hollows. These various types have differed markedly in terms of their size, permanence, and susceptibility to water-level fluctuations.

a) Fault-bounded depressions

This category includes most of the lakes in the Basin and Range Province of Oregon, southern Idaho, Utah, Nevada, California, Arizona, and New Mexico (Hubbs et al., 1948; Morrison, 1965; Hawley et al., 1976). In this area Late Cenozoic faulting has created several hundred steep-sided, often isolated basins, separated by mountain ranges. Many of the paleolakes became large and attained considerable depths before overflowing. For example, 33 of the lakes in the Great Basin exceeded 500 km^2 in maximum area, and at least 27 experienced fluctuations with a vertical amplitude of ≥ 50 m (Snyder et al., 1964) (Table 1). At maximum, many of the lakes were linked by overflows from one basin into another (Fig. 1), forming complex systems such as the Owens - Death Valley chain (Morrison, 1965, Fig. 5).

Due to prolonged subsidence of the graben floors, lakes have existed in many of the larger fault-bounded basins since the Middle Quaternary or even earlier (Eardley et al., 1973; Janda and Croft, 1967; G. I. Smith, pers. comm.), and have experienced a long history of fluctuations in both water-surface area and salinity. Although these fluctuations may be partly attributable to drainage disruption by faulting or volcanism, it is impossible to explain the frequent and large-scale shifts in environmental conditions -- from freshwater lakes to salt pans and back again -- without invoking climatic change. Recent tectonic activity has, however, significantly affected lake levels in certain areas; notably in the area between Death Valley and the Nevada Test Site (Greene and Hunt, 1960; Hubbs and Bien, 1967; Hooke, 1972) and along the San Andreas and related fault systems in California (Hubbs and Miller, 1948; Clark et al., 1972; Jenkins, 1973).

b) Crater lakes

Although a number of large volcanic and meteoric craters have contained lakes, only the uppermost shoreline around Zuni Salt Lake (a volcanic caldera in New Mexico) has so far been dated by ^{14}C. In other parts of the world, steep-sided crater lakes have often yielded long and detailed records of water-level fluctuations, which are particularly valuable because they can be attributed to climatic changes over a very restricted and well-defined catchment (Talbot and Delibrias, 1977; Kershaw, 1978).

c) Lakes created by glacial erosion

Although numerous ice-scoured basins exist in the Western Cordillera, most of the lakes created in this way have remained small and are unresponsive to climatic fluctuations because they possess outlets. They will not be discussed further in this report.

d) Blocked drainage systems

Lakes have formed in many areas through the temporary ponding of drainage systems by ice, lava, or sediments. The first category includes a number of extensive glacial lakes which developed along the southern margins of the Cordilleran and Laurentide ice sheets (Lemke et al., 1965; Richmond et al., 1965; Moran et al., 1976; Easterbrook, 1976). Ice-dammed lakes have a tendency to drain suddenly and catastrophically, due to changes in the configuration of the ice margin or to the accumulation of meltwater beyond a critical depth, resulting in discharge through tunnels under the ice (Whalley, 1971). The largest ice-dammed lake in the western U.S. was Glacial Lake Missoula, which was formed by ponding of the Clark Fork River during advances of the Cordilleran ice into northern Montana and Idaho. It covered an area of about 7500 km^2 and contained an estimated 2.0×10^{12} m^3 of water (Pardee, 1942). Lake Missoula drained catastrophically at least four, and possibly six times (Table 1), inundating an enormous area of eastern Washington known as the Channeled Scablands, and causing extensive downstream flooding and sedimentation in the Columbia River Valley and the Willamette Lowland (Fig. 1). The ponding and subsequent discharge of Lake Missoula is only indirectly related to climate, through the fluctuations of the Cordilleran ice lobes; this is also true of the other glacial lakes further east, which did not, as far as is known, display such dramatic behavior. The latter, and the innumerable smaller moraine-dammed lakes scattered throughout the glaciated area, will not be discussed further in this report.

Like ice- and moraine-dammed lakes, lakes created by the blockage of drainage systems by lava, alluvium or aeolian sand tend to be geologically short-lived. Lava-dammed lakes have formed at various times in the volcanic terrains of Idaho and adjacent states, and also in southern Arizona and New Mexico (Feth, 1964; Hawley et al., 1976). These lakes were seldom very deep, and in humid areas, have tended to drain naturally as a result of fluvial erosion, or have been filled in by lava or sediments. Lakes Thatcher and American Falls (No. 15 and 14) are good examples. In arid and semi-arid areas, closed basins may be formed. The resulting lakes or playas (such as Laguna Salada in Arizona) are much more responsive to fluctuations in water balance, for reasons discussed below.

The deposition of alluvium has played an important role in isolating lakes in two of the larger fault troughs of the Southwest: the Imperial Valley and the Central Valley of California. The present Salton Sea is the remnant of the much larger Lake Leconte (No. 6) which was fed by distributaries of the Colorado River. During its recent high stage the level of the lake was limited by overflow across the lowest part of the Colorado Delta. Although the topography of the basin floor has also been greatly affected by subsidence and tilting (Stanley, 1963, 1966; Clarke et al., 1972; Van de Kamp, 1973), which have rendered it impossible to reconstruct the Late Pleistocene outlet, the history of the lake shows many parallels with basins less subject to tectonic disturbance. This fact suggests that the overriding control on its water level has been climate. This is also true of the chain of lakes in the southern part of the Central Valley (No. 13). These were created by partial blocking of the San Joaquin and its tributaries by large outwash fans derived from glaciated headwaters in the Sierra Nevada (Davis et al., 1959; Janda and Croft, 1967). Once again, the repeated development of lakes was made possible by long-continued subsidence of the valley axis. Despite the complications introduced by channel migration and changing patterns of sedimentation, the sequence of Late Quaternary fluctuations so closely matches the history of the lakes on the east side of the range that climatic control seems the most likely explanation (Croft, 1968).

Basins formed as a result of the blockage of stream systems by moving sand are most common in the western Llano Estacado (Hawley et al., 1976). Good examples are the former ponds along Blackwater Draw (No. 24). The lakes thus formed have generally been small and relatively short-lived. Drier conditions have resulted in desiccation, renewed dune movement and partial deflation of the lake sediments; whereas wetter conditions have led to the integration of the drainage network and the erosion of the former barriers (Haynes, 1975). In these areas, maximal wetness may be reflected in the reestablishment of a functioning stream network rather than in the maximal development of lakes.

e) Deflation basins

The final category, wind-eroded lake basins, are common today throughout the southern High Plains and in the desert and semi-desert areas further west, wherever unconsolidated sediments are exposed to wind action (Reeves, 1966a; Wendorf and Hester, 1975; Leonard and Frye, 1975). This is the predominant type of lake basin found in the Llano Estacado, where most are small and reflect multiple episodes of deflation and flooding (Reeves, 1976). During wet phases in this area, shoreline erosion under the influence of the prevailing winds also helped to erode the older lake deposits and yielded a sedimentary record that is often incomplete and highly variable from site to site (Reeves, 1966a; Harbour, 1975). To add to the difficulties of interpretation, the levels of these lakes appear to reflect fluctuations in the regional water table rather than the water balance over their restricted surface catchments (Brakenridge, 1978).

f) Areas without lake basins

Large areas of the Southwest never contained extensive Late Quaternary lakes because they were drained by large, integrated river systems such as the Colorado, the Pecos and the Rio Grande (Fig. 1). This fact does not mean, however, that these areas have not undergone major environmental changes as a result of climatic fluctuations. The latter are clearly demonstrated by pollen, macrofossil and archaeological evidence (e.g., Hall, 1977; Van Devender, 1977), and are also expressed in the time and space distribution of fluvial deposits, aeolian sands and palaeosols (Leonard and Frye, 1975; Hawley et al. 1976; Reeves, 1976; Baker and Penteado-Orellana, 1977).

2) Hydrological considerations

Before discussing the lake-level evidence in detail, the hydrological and hydrogeological factors must be considered which control the sensitivity of lakes to climatic change. These have been examined in detail by Langbein (1961), Szestay (1974), and Street (in press). Their main conclusions can be summarized as follows.

The water balance of a lake at equilibrium can be expressed by the general equation

$$P_L + R + G_I = E + O + G_O \qquad (1)$$

where P_L is the precipitation falling directly on the lake

R is the runoff from the catchment

G_I is the groundwater inflow into the lake

O is the surface outflow from the lake

E is the evaporation from the lake surface

G_O is the subsurface outflow

The inputs and outputs are of three different types: atmospheric, surface, and subsurface. There is a crucial distinction between closed lakes, which lose water entirely by evaporation, and open lakes, which also undergo losses by outflow and/or subsurface seepage. The former are only found in areas in which $E/P_L > 1$ (Langbein, 1961). They undergo much larger fluctuations in depth and extent than open lakes. This sensitivity results from changes in input being balanced by changes in the area of evaporating surface alone rather than in evaporation and outflow combined. Topography permitting, the closed lakes that experience the largest fluctuations in depth are those that are fed predominantly by rivers rather than by direct rainfall or groundwater inflows (Szestay, 1974), and for which dA/dD (the rate of change of evaporating surface with water depth) is small. Steep-sided basins like Searles, Russell and Panamint, with average values of dA/dD less than 5 km^2/m, are likely to show the greatest vertical range in lake levels. Although extensive shallow lakes such as Estancia exhibit a more dramatic response of lake area to fluctuations in water balance than the deeper lakes, this response is often offset by desiccation, which gives rise to deflation and gullying of the sediments. The most detailed paleoclimatic record is therefore to be expected in deep, fault-bounded troughs adjacent to well-watered mountain ranges such as the Sierra Nevada.

Lakes receiving a large proportion of groundwater are unlikely to fluctuate as sensitively as those with predominantly surface inflows, unless the flow path through the aquifer is very short. Fossil spring conduits in the Ash Meadow, Las Vegas and Blackwater Draw Basins (No. 17, 21 and 24) indicate that these lakes received significant amounts of groundwater. The situation in the Llano Estacado has already been mentioned. Because many of the former lake basins in the Basin and Range Province are linked by ground-water transfers beneath surface divides (Hunt and Robinson, 1960; Eakin, 1966; Phillips and Van Denburgh, 1971; Van Denburgh, 1975; Winograd and Thordarson, 1975), the hydrogeology of the Late Quaternary lakes deserves further investigation. Not only was the network of surface drainage more highly integrated, due to overflows from one basin into the next (Fig. 1); but the groundwater flow pattern must also have been rather different from today because of changes in the hydraulic gradient between adjacent basins.

3) Temporal and spatial patterns of lake-level fluctuation

The broad pattern of lake-level fluctuations through time (Fig. 3) is very similar to the earlier diagram by Street and Grove (1979, Fig. 12a), which was compiled from a much smaller number of data points. The period since 30,000 BP can conveniently be divided into five time intervals: 30,000 - 24,000 BP, 24,000 - 14,000 BP, 14,000 - 10,000 BP, 10,000 - 5000 BP, and 5000 - 0 BP.

a) 30,000 - 24,000 BP

Only cautious conclusions can be drawn for this interval, because of the uncertainties attached to the radiocarbon dating framework. In general, lake levels were moderately high but fluctuating. No spatial pattern is evident. Studies of continuous cores from the Searles, Tulare, and Bonneville Basins (No. 12, 13 and 38) demonstrate that a major rise in lake level took place around 25,000 BP (Eardley et al., 1957; Croft, 1968; Peng et al., 1978; Smith, 1979). Maximum levels were reached about 24,000 BP.

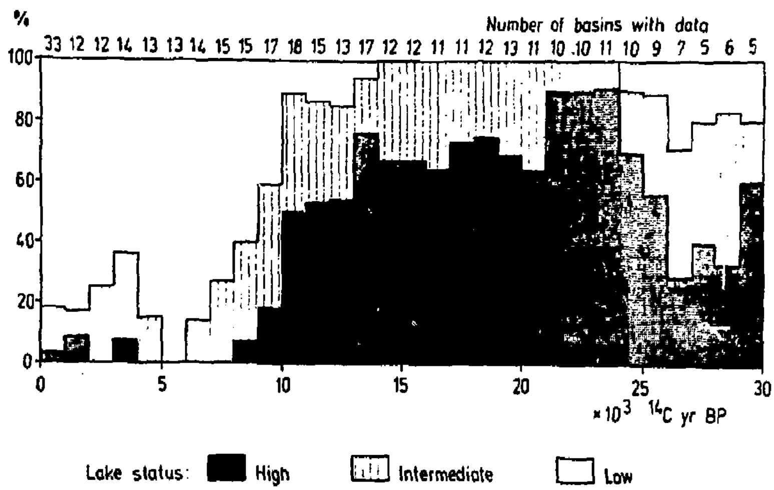


FIG. 3. Histogram of lake status (high, intermediate, or low) during 100-yr time periods from 30,000 BP to present for the closed-basin lakes of the Southwest.

Histogram of lake status.

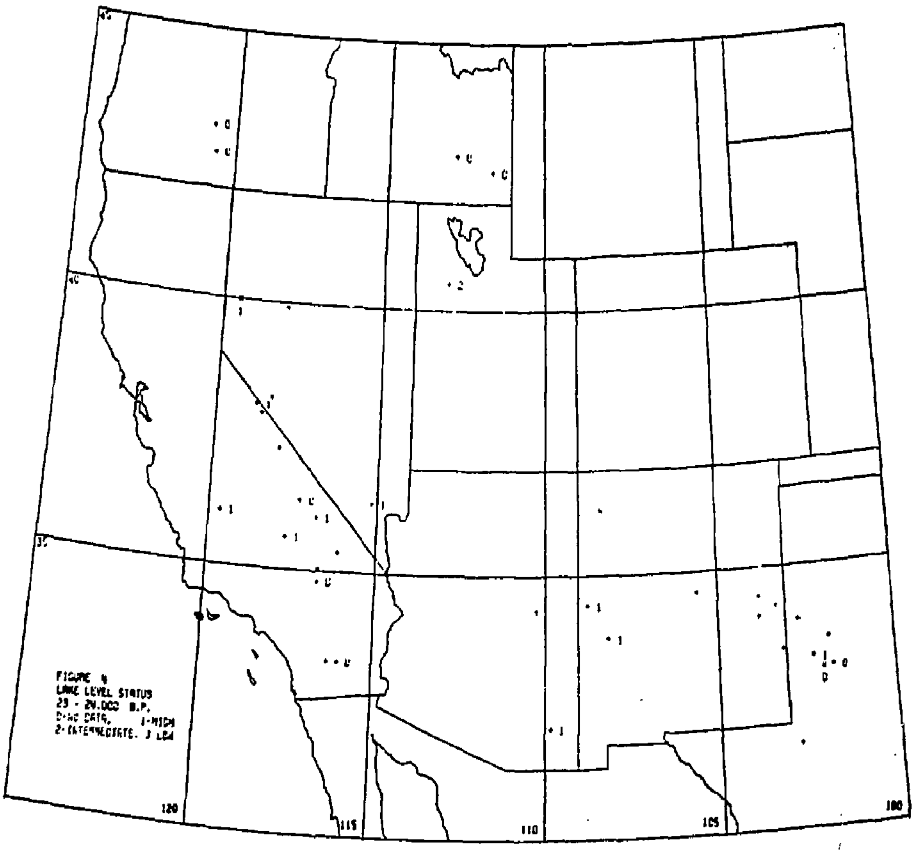


FIG. 4. Lake-level status (Blank or 0: no data; 1: high; 2: intermediate; 3: low) at sites in the Southwest 24,000 - 23,000 BP.

Lake-level status: 24,000 - 23,000 BP.

b) 24,000 - 14,000 BP

During this period all the lakes for which information is available were either high or intermediate. High levels were most widespread from 24,000 to 21,000 BP (Fig. 4), when only Bonneville (No. 38) remained intermediate. This interval seems to be the last during which Lake Russell (No. 11) overflowed through the Adobe (No. 3), Owens and Searles (No. 12) Lakes into the Panamint Basin (No. 10) (Figs. 1 and 2). The evidence for a further overflow from Lake Panamint into Death Valley (No. 8) is inconclusive (G. I. Smith, pers. comm.).

Between 21,000 and 14,000 BP only about 65-75 percent of the data points record high levels. The intermediate lakes tend to cluster in the northwest of the map area, particularly adjacent to the Sierra Nevada (Fig. 5); although there was considerable fluctuation (Fig. 2). No information is available from Oregon to determine whether the region of intermediate levels extended into the far northwest of the Great Basin. A brief episode of partial desiccation in the Llano Estacado is recorded by the widespread but thin Vigo Park dolomite (Reeves and Parry, 1965; Reeves, 1976). The radiocarbon dates from this unit, which are probably not very reliable, scatter widely between 15,240 and 20,500 BP (Bates et al., 1970).

c) 14,000 - 10,000 BP

The period between 14,000 and 10,000 BP was characterized by rapid, large-amplitude fluctuations that were not synchronous across the region and resulted in rather complex map patterns (Fig. 6). In part, this apparent lack of synchroneity may result from the uncertainties inherent in the radiocarbon method when applied to a wide variety of materials from quite different geological settings; but it also seems to reflect genuine spatial

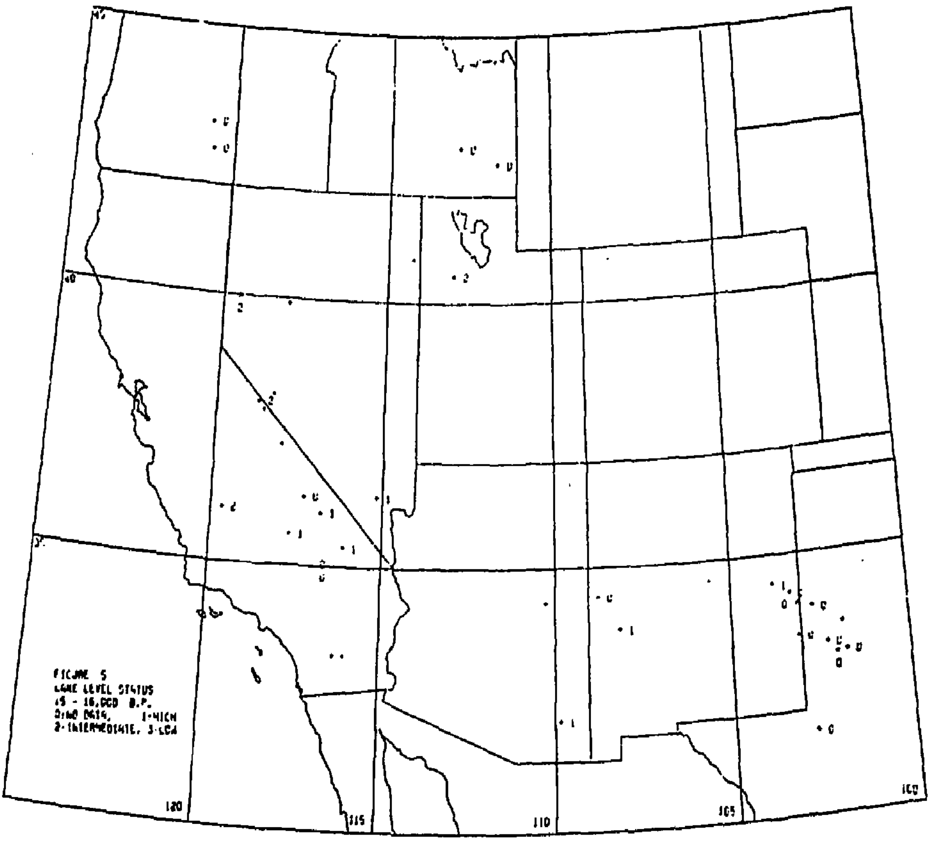


FIG. 5. Lake-level status (Blank or 0: no data; 1: high; 2: intermediate; 3: low) at sites in the Southwest 16,000 - 15,000 BP.

Lake-level status: 16,000 - 15,000 BP.

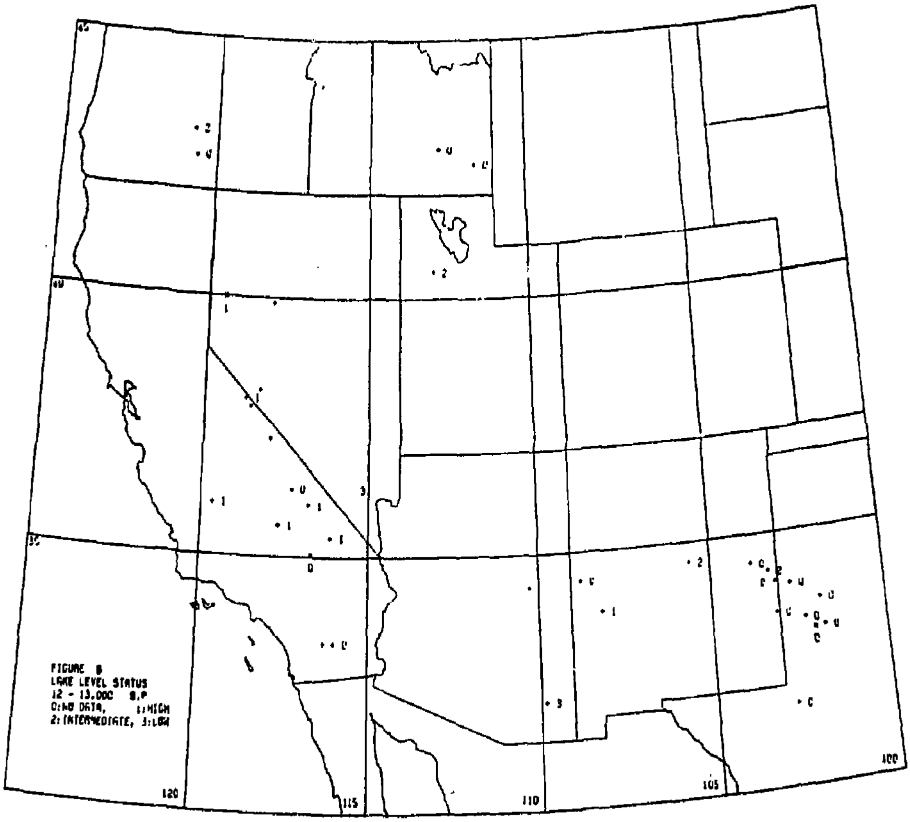


FIG. 6. Lake-level status (Blank or 0: no data; 1: high; 2: intermediate; 3: low) at sites in the Southwest 13,000 - 12,000 BP.

Lake-level status: 13,000 - 12,000 BP.

variations in behavior.

Many lakes experienced a drop in levels centered on 14,000 - 13,000 BP (Fig. 2). In most cases this event was too short to appear on Fig. 3. However, in Arizona, New Mexico, and Texas, 13,000 BP seems to mark the end of the main lacustral phase (basins 1, 21, 26, 27, 32, 34) (see also Haynes, 1967). Lake Bonneville (No. 38) ceased to overflow at about this time (Bright, 1966). This conclusion is based on a date on peaty lake sediments from the overflow channel, which is almost certainly more reliable than the inconsistent tufa dates on which Broecker and Kaufman (1965, Fig. 6) based their water-level curve (Morrison and Frye, 1965; Benson, 1978).

The pattern of fluctuations during the concluding millennia of the Late Pleistocene is particularly complex. A major highstand occurred in the lakes situated on both sides of the Sierra Nevada (Fig. 6) (No. 7, 9, 11-13, 18, 20) and culminated between 13,500 and 11,000 BP. A second distinct peak was experienced by two of the southerly lakes in this group, Searles (No. 12) and Mohave (No. 9), between 11,000 and 10,000 BP (Fig. 2). In contrast, widespread evidence exists for desiccation, lowered water tables and deflation in Arizona, New Mexico, and Texas between 13,000 and 11,000 BP (basins 1, 24, 25, 34, 36) (Haynes, 1975). This arid episode was followed by a brief lacustrine recovery from 11,000 to 10,000 BP, which has been christened the Lubbock subpluvial (Wendorf, 1970).

d) <u>10,000 - 5000 BP</u>

From 10,000 BP onwards, drought set in in many areas (Fig. 7) and culminated between 6000 and 5000 BP (Fig. 3, 8), when not a single lake is known to have been high. In some basins the fall in water levels was sudden and monotonic (Fig. 2), but in

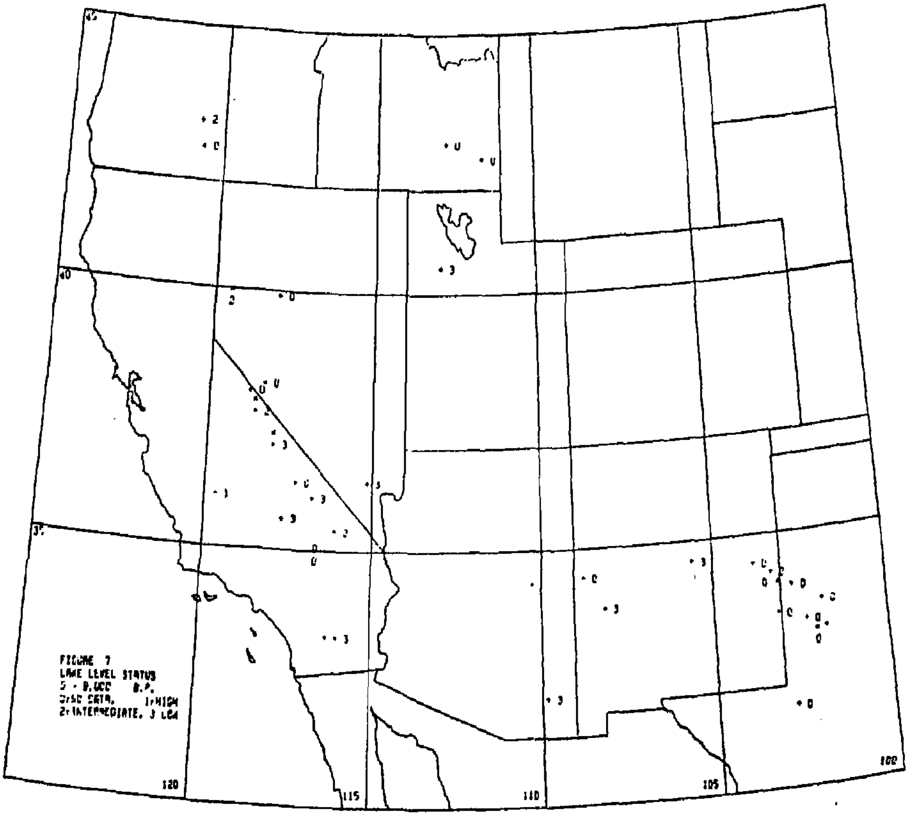


FIG. 7. Lake-level status (Blank or 0: no data; 1: high; 2: intermediate; 3: low) at sites in the Southwest 9,000 - 8,000 BP.

Lake-level status: 9,000 - 8,000 BP.

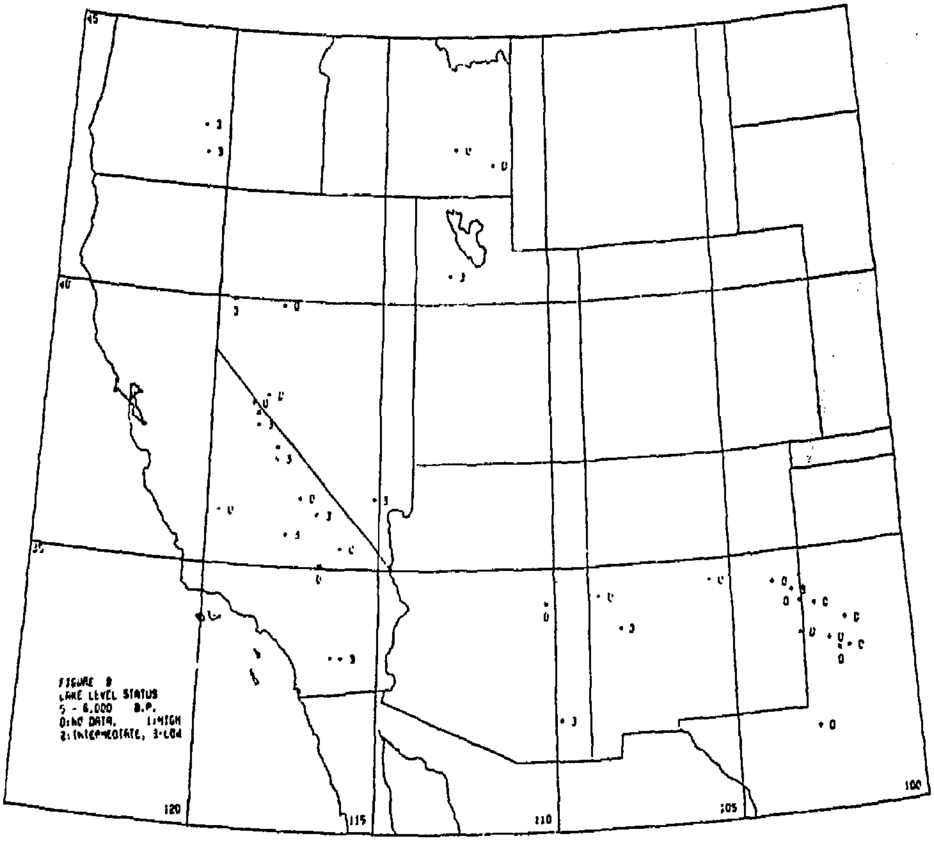


FIG. 8. Lake-level status (Blank or 0: no data; 1: high; 2: intermediate; 3: low) at sites in the Southwest 6,000 - 5,000 BP.

Lake-level status: 6,000 - 5,000 BP.

others there seems to have been a certain amount of fluctuation. The final desiccation is often difficult to date (Karlstrom, 1961; Hester, 1972; Wendorf and Hester, 1975; Smith, 1979). Datable materials are usually scarce and the results on different samples frequently conflicting.

e) 5000 - 0 BP

This period has seen significant reexpansions of the lakes, notably on the western margins of the Great Basin and in California (No. 3-5, 12, 20, 32) (Fig. 9, 10, 11). The vertical amplitude of these fluctuations is surprisingly large: up to 90 m in the Walker Lake area (Fig. 2) and 85 m around the Salton Sea. The levels were much higher before the start of irrigation agriculture in the late 19th century, and therefore present conditions in many areas are highly unrepresentative of the average for the last few centuries or millennia (Harding, 1965; Benson, 1978).

D) PALEOCLIMATIC ESTIMATES DERIVED FROM LAKE-LEVEL DATA

Lake-level fluctuations are potentially the best source of quantitative paleoclimatic data in desert areas where pollen data are sparse or unreliable. This applies particularly to the American Southwest, where few continuous pollen records exist. However, attempts to derive paleoprecipitation estimates from lake-level information have so far met with severe setbacks, due principally to the difficulties of estimating paleo-evaporation rates. The problems encountered are described in a useful and thought-provoking paper by Brakenridge (1978), which is summarized below.

The surface area of a closed lake fluctuates in order to balance its water budget, as given by the following equation:

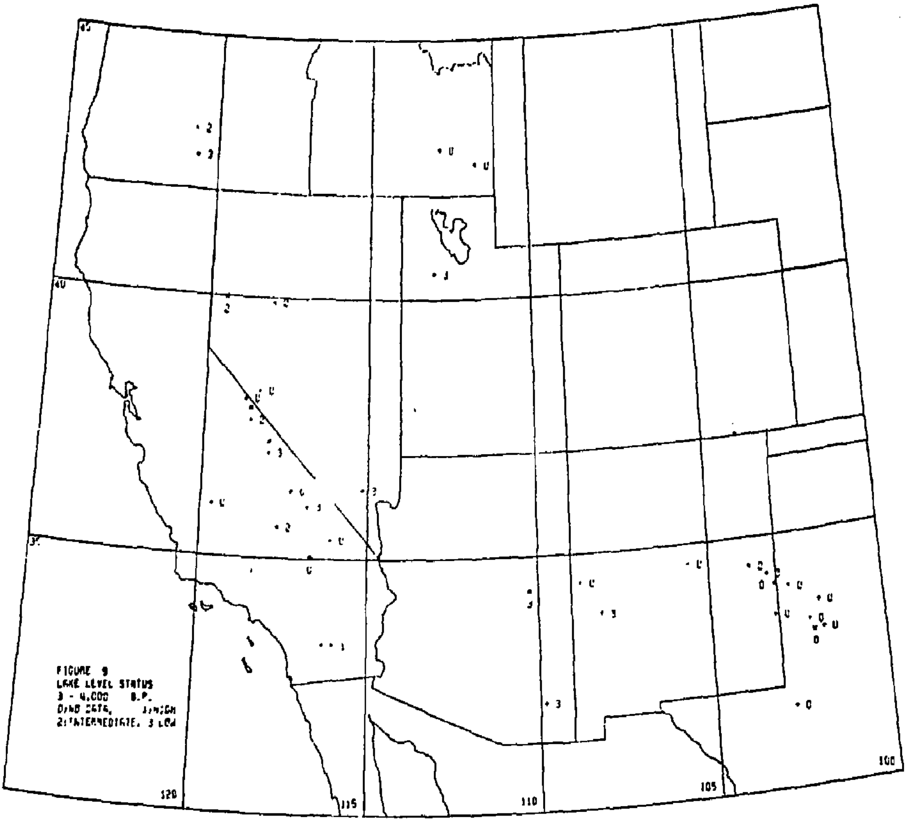


FIG. 9. Lake-level status (Blank or 0: no data; 1: high; 2: intermediate; 3: low) at sites in the Southwest 4,000 - 3,000 BP.

Lake-level status: 4,000 - 3,000 BP.

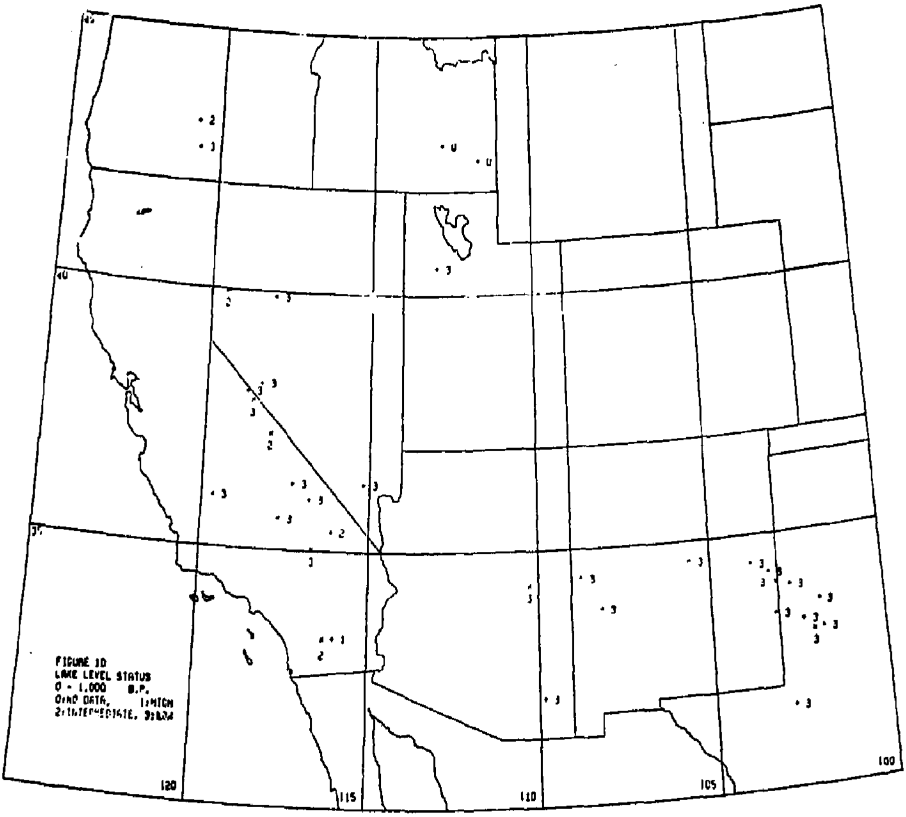


FIG. 10. Lake-level status (Blank or 0: no data; 1: high; 2: intermediate; 3: low) at sites in the Southwest 1,000 - 0 BP.

Lake-level status: 1,000 - 0 BP.

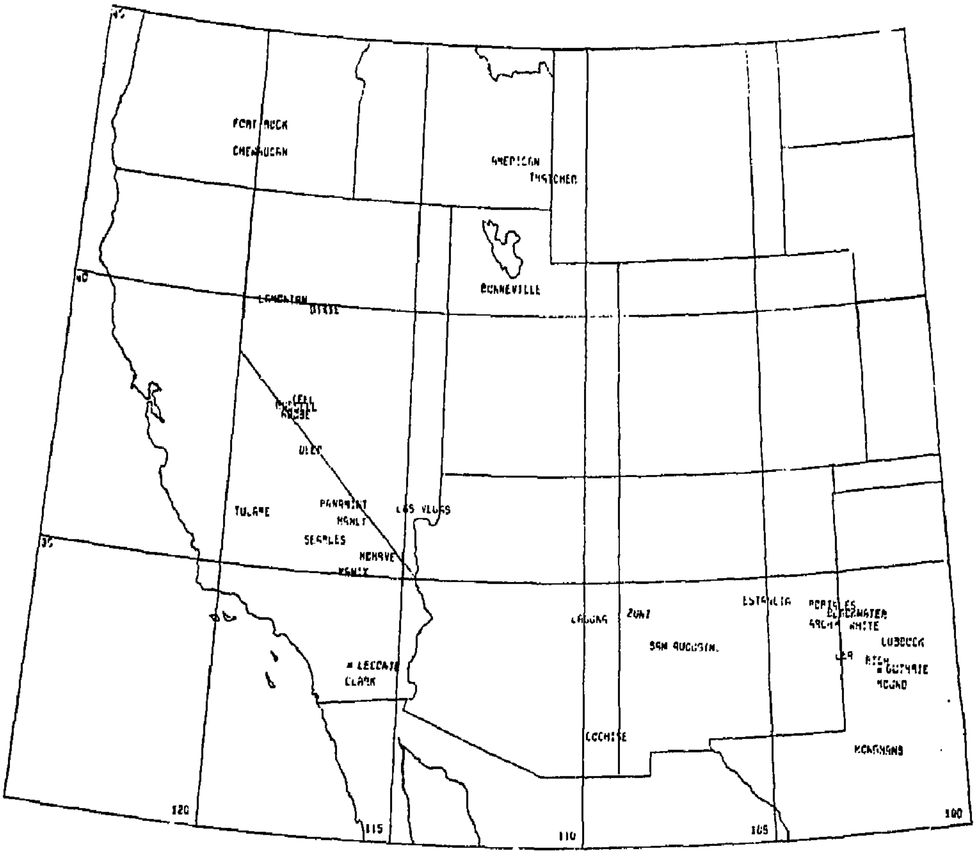


FIG. 11. Location of sites contributing data to Figures 4 to 10. First letter in the site name is plotted at the site location except where asterisks mark the site because two sites were too close together.

Location of sites with lake-level status.

$$A_L P_L + A_B P_B k = A_L E \qquad (2)$$

where A_B is the catchment area, A_L is the lake area,

P_L is the precipitation falling over the lake,

P_B is mean annual precipitation over the catchment,

k is the runoff coefficient (the proportion of rain falling on the catchment which eventually reaches the lake),

E is mean annual evaporation from the lake.

Equation (2) is equivalent to equation (1) when O, G_I, and G_O are all negligibly small. It can be used to calculate past values of P_L provided that:

(i) The basin has been topographically and hydrographically stable

(ii) A_L and A_B are known from geological information

(iii) P_L is a known and constant function of P_B

(iv) E and k can be reliably estimated.

All studies to date, including Brakenridge (1978) have been forced to make the assumption that E can be satisfactorily estimated from modern empirical relationships between lake evaporation and mean monthly, seasonal, or annual mean temperatures. This will be referred to as the hydrological approach. The greatest difficulty lies in the selection of appropriate paleotemperature values for the time-period being modelled, which is usually loosely defined as "the last glacial maximum". Temperature estimates have been variously derived from data on snowline lowering, periglacial slope mantles, and timberline lowering. All of these methods are subject to a variety of pitfalls, but the most crucial assumptions concern i) the stability of the environmental lapse rate through time and ii) the magnitude of the full-glacial temperature depression and its seasonal variability (Brakenridge, 1978).

Unfortunately, the results obtained by various authors have proved to be highly sensitive to the exact paleotemperature values adopted (Table 2). The assumption of a constant lapse rate and year-round cooling leads to the conclusion that full-glacial conditions were drier than today (Galloway, 1970; Brakenridge, 1978). *If, however, the temperature lowering was significantly* less in winter, or at lower elevations, a large increase in precipitation must be invoked in order to explain the expansion of the lakes. A further problem, not discussed by Brakenridge, emerges from Figures 4 - 10. This is the extent to which the timing of the lake-level maxima varied from one basin to another, and therefore may not have corresponded with the maximum displacement of snowlines and timberlines. Other, potential sources of error include the effects of past changes in wind speed, precipitation intensity and frequency, runoff, and groundwater levels.

Brakenridge (1978) concluded that:

(i) There is very little agreement among published lake-budget results;

(ii) Recomputation of several lake budgets using a uniform cooling of 8^{o}C produces comparable results from apparently divergent studies and indicates the precipitation was about equal to that of today (Table 2);

(iii) The neglect of groundwater in the traditional paleolake reconstructions casts doubt on the resulting conclusions and especially those from the Llano Estacado lakes; and

(iv) The paleolakes do not provide convincing evidence for a "pluvial" or rainier climate in the full-glacial Southwest.

The spatial and temporal variability in lake levels during the interval 24,000 - 10,000 BP (Fig. 4-10) seems to conflict with Brakenridge's conclusions. The pattern of water-level maxima is not nearly as uniform as might be expected if lowered temperatures were solely responsible. Precipitation anomalies, and long-term changes in glacier and groundwater storage, seem to have played a significant role in determining the response of different basins through time. A breakthrough in techniques of water-balance modelling is therefore required in order to resolve the present controversy. The way forward seems to lie in the combined energy- and water-balance models currently being developed by J. E. Kutzbach of the Climatic Research Unit at the University of Wisconsin-Madison, which handle evaporation as a function of net radiation balance rather than of temperature (Kutzbach, pers. comm.). A logical extension of this approach would be the development of combined models which consider the response of the glacier and lake storages within a single catchment to the same climatic event.

E) HAZARDS ASSOCIATED WITH LAKES

Apart from the hazards associated with the rapid rise or fall of lake levels and the accompanying adjustment of groundwater levels, which have been discussed in previous sections, certain lakes exhibit catastrophic behavior which may have severe consequences if repeated in the future.

The outburst floods from Glacial Lake Missoula are the largest hydrological events known to occur on Earth (Baker, 1973, 1978; Baker and Nummedal, 1978). Maximum discharges of as much as 21.3 x 10^6 m^3/sec are thought to have occurred in the Spokane area of Washington. The last two outbursts apparently took place just before and just after the last maximum of the Cordilleran ice, ca.

18,000 and 13,000 BP (Baker and Nummedal, 1978). There is some disagreement about the relative magnitude of the two events.

The impact of Lake Missoula flooding was greatest in the Channeled Scabland (Fig. 1), an enormous area (ca. 40,000 km^2) of anastomosing channels and rock-cut basins. Some of the most significant geomorphic features created by the flooding are listed in Table 3. From the viewpoint of nuclear waste disposal, the most significant point to note is the dramatic erosion of the strongly jointed Scabland basalts during floods. The peak flows were capable of moving boulders up to 11 m in diameter. They created numerous abandoned cataracts in excess of 100 m in height and rock basins as much as 60 m deep. The 32 km-long upper Grand Coulee was formed by the upstream recession of a cataract 250 m high.

Similar, though much smaller, erosional and depositional features were produced by a catastrophic Late Pleistocene overflow from Lake Bonneville into the Snake River via Red Rock Pass (Malde, 1960; Trimble and Carr, 1961; Strawn, 1965; Morrison, 1966). The flood peak is estimated to have attained 1.3×10^5 m^3/sec. The floodwaters entered the American Falls Lake, causing a dramatic overspill, and depositing a delta of coarse gravel up to 15 m thick (Fig. 1). Below the lake there is a strip of basalt scabland eroded by the flood. This is 16 miles long and 1 - 6 km broad, and is bounded by abandoned cataracts up to 30 m high (Malde, 1960). The date of the Bonneville flood remains controversial (Morrison, 1966). An age of 30,000 BP has been suggested on the basis of the available radiocarbon dates, but these lie close to the limits of reliability. The catastrophic nature of this flood has also not been adequately explained. It was once thought to have resulted from the overflow of Lake Thatcher (No. 15) into the Bonneville Basin (Rubin and Alexander, 1960), but this hypothesis can no longer be substantiated (Morrison, 1966).

Floods of smaller magnitude are to be expected from lakes which form along the San Andreas and related fault systems in California. Strike-slip motions of the San Andreas fault have repeatedly created lakes by triggering landslides which block small rivers and streams (Jenkins, 1973). One example, Pleistocene Lake Benito, covered about 570 km^2. The sudden release of water from a lake of this size during an earthquake could greatly compound the resulting damage.

F) CONCLUSIONS

1) The distribution of Late Quaternary lakes in the western United States is highly clustered. The largest group of about 120 lakes was situated within the Great Basin. Other concentrations of lakes occurred just north of the Mexican border, in the Llano Estacado, and along the southern margins of the ice sheets.

2) The lakes which respond most sensitively to climatic change are the closed-basin lakes of the Southwest, particularly the deeper, river-fed lakes in the Basin and Range Province. Fluctuations of the ice-marginal lakes were essentially controlled by ice-sheet dynamics.

3) 33 of the palaeolakes in the Great Basin exceeded 500 km^2 in maximum area, and at least 27 experienced fluctuations with a vertical amplitude of $\geq$50 m. The largest and deepest was Lake Bonneville (51,640 km^2, 335 m). At maximum, many of the present closed basins were linked by overflows. The most complex system thus created was the Owens-Death Valley chain in western Nevada and California, which may have included as many as 15 individual lakes. There is evidence of increased spring activity during the lake maxima, particularly in southeastern Nevada and the Llano Estacado.

4) Fluctuations in the lakes of the Southwest have occurred throughout at least the last 700,000 years, and appear to reflect climatic changes as well as faulting and volcanism.

5) The radiocarbon chronology from the lakes of the Southwest is based on a wide range of materials subject to varying degrees of contamination. This report is based on the following assumed order of reliability: 1) charcoal and wood in basin and cave sediments; 2) peat or organic matter in lake sediments; 3) disseminated inorganic carbonate, calcareous algae, ostracods and mollusca in lake sediments; 4) tufa; and 5) dolomite and Na-carbonates.

6) The Southwest experienced a major lacustral phase which was broadly coincident with the last glacial maximum, ca. 25,000 - 10,000 BP. During this interval, however, lake levels varied significantly from region to region. Probably at no time were all the lakes simultaneously high. The lakes on either side of the Sierra Nevada appear to have been most extensive during the intervals 24,000 - 21,000 BP and 13,500 - 10,000 BP, whereas the less complete information from Utah, Arizona, New Mexico, and western Texas suggests that many of the lakes there were highest in the intervening period, with a minor recovery from 11,000 to 10,000 BP.

7) This study provides strong support for the concept of an arid Altithermal period in the Southwest during the mid-Holocene. Conditions were most severe between 5000 and 6000 BP, when surface water supplies became so restricted that the Palaeo-Indians were forced to move up into the wetter mountain areas (Benedict and Olson, 1978).

8) Conditions have fluctuated widely during the last 5000 years. Many of the lakes have experienced fluctuations of quite

large amplitude (≤90 m). The present day is highly unrepresentative of the long-term average for this interval because of the reduction in runoff and groundwater levels resulting from irrigation.

9) Previous attempts to estimate paleoprecipitation from the former extent of closed-basin lakes, using simple water-budget models, have yielded highly ambiguous results. This problem is due largely to the difficulties of estimating paleo-evaporation rates. *New, combined water- and energy-balance models are currently being developed.*

10) The spatial patterns of fluctuation in the closed-basin lakes suggest that precipitation and runoff anomalies were at least as important as changing evaporation rates. Glacial meltwater may have played a role in the history of lakes adjacent to the Sierra Nevada and Wasatch Mountains.

11) Potential hazards for the sites with nuclear wastes include: the inundation of many basin floors, including parts of the Nevada Test site; large fluctuations in groundwater levels and spring activity; variations in the degree of integration of surface (and possibly subsurface) drainage; the sudden formation or drainage of lakes situated along active fault systems; and episodes of catastrophic flooding and erosion associated with the complete or partial drainage of large, deep lakes such as Bonneville and Glacial Lake Missoula.

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CHAPTER 2

AN ANNOTATED LIST OF SELECTED POLLEN DIAGRAMS FROM THE WESTERN UNITED STATES

(Thompson Webb III)

INTRODUCTION

In future work to gain quantitative estimates of past changes in the rates of ground-water recharge in the West, knowledge of the past vegetation cover will be essential. This information is needed in models such as the one recently introduced by Kutzbach (in press) for transforming lake-level data into estimates of past precipitation and temperature. (See p. 21 in Chapter 1 for a discussion of the potential uses of this model.) I have therefore summarized some of the information available from a selected set of published pollen diagrams from sites in the West, because well-dated pollen diagrams provide the best continuous records with quantitative information about the vegetational changes over the past 20,000 years.

As illustrated in Chapter 3, pollen diagrams are also an excellent source of paleoclimatic information. A brief review of the major pollen changes during the past 20,000 years shows that climatic conditions during the past 2500 years have been generally cooler and moister over much of the West than the conditions from 7000 to 4000 years ago. This pattern agrees with the trend toward higher lake levels in several of the basins in the West (see Fig. 2 in Chapter 1). Were this trend to continue for the next 100 to 1000 years, and evidence exists that it may, then higher water tables and faster rates of ground-water recharge can be expected over many areas in the West.

THE SITES

Table 1 presents the main information contained in this chapter. This table was designed to provide a short summary of the

Table 1. Western U.S. Pollen Diagrams: Notes on a Representative Group.

Site Name and Locality	Site Location and Elevation	Chronostratigraphic Information	The Site and Present Conditions	The Pollen Record and Interpreted Vegetation	Climatic Interpretation
C. Texas					
Hershop Bog	29°35'N 97°37'W 124 m	2002 ± 80 6006 ± 100 10,574 ± 160 from a 540 cm core. Max. age is ca. 11,000 B.P.	Domed-quaking peat bog. 155 m diameter, 5.4 m deep. Depends on seepage from Carrizo Fm.	Shift from 25% AP to 10% AP at 10.5K. AP = Oak and Birch. Change from Oak parkland to Oak savanna.	Drier conditions after 10.5K than before.
Larson, D.A., Bryant, V.M., Jr., and Patty, T.S. (1972). Pollen analysis of a central Texas bog. American Midland Naturalist 88, 358-367.					
Boriack Bog	ca. 30°30'N ca. 97°05'W ca. 100 m	3770 ± 80 9930 ± 160 14,115 ± 210 15,460 ± 250 from 540 cm core. Max. age is ca. 16,000 B.P.	1.4 hectare bog in Post oak savanna. Seepage from Carrizo sandstone Fm.	AP(Alnus) 70% from 16K to 8K, then Grass dominant. "Altithermal" period not well defined in pollen record.	Drier after 8K than before.
Bryant, V.M., Jr. (1977). A 16,000 year pollen record of vegetational change in central Texas. Palynology 1, 143-156.					
Gause Bog	ca. 30°50'N ca. 96°40'W ca. 90 m	No C-14 dates. Estimated to be older than 10,000 B.P. at base of 170 cm core.	3 ha. Bog formed in Corrizo Sands aquifer. Sphagnum on surface today. Located on western edge of Post Oak Savanna.	40% Alnus pollen up to 110 cm in core. Grass pollen dominates with 20% oak and 20% Composite pollen to surface.	Drier after 10K than before.
Bryant, V.M., Jr. (1977). A 16,000 year pollen record of vegetational change in central Texas. Palynology 1, 143-156.					
W. Texas					
Llano Estacado a) Rich Lake b) Crane Lake	a) 33°17'N 102°12'W 1000 m b) ca. 31°30'N ca. 20°40'W ca. 600 m	a) 17,400 ± 600 26,500 ± 800 at 125 cm and 350 cm levels in a 560 cm core. Max. age is possibly 33,000 B.P. Min. age (at top) may be no later than 15,000 B.P. b) No dates in 300 cm core of gypsum mud.	Llano Estacado is southern most extension of high plains with grassland and desert vegetation. a) Playa (dried up lake) today. No pollen in upper 40 cm. Llano Estacado Climate: Jan. Temp. = 2-7°C July Temp. = 25-28°C Ann. Precip. = 400-500 mm 8 surface samples	a) 26K - 33K: 15% Pinus pollen, 80% NAP. 26K - 17K: Gradual rise in % of Pinus pollen to 90% with 5% Picea after 17K to ca. 15K. Change from herb grassland to woodland. b) 3m - 2m = 90% Pinus pollen. 1.5 m to surface: 15% Pinus and 80% NAP.	26K - 15K: became wetter and colder than today. Postglacial time: dry like today. Some oscillations.
Wafsten, U. (1964). A standard pollen diagram for the southern high plains, USA, covering the period back to the early Wisconsin Glaciation. Report of VI INQUA, Warsaw, Vol. II: Paleobotanical Section, Lodz, 407-420.					

N. E. Oklahoma

Little Caney Alluvial Valley Copan area	36°56'N 95°56'W 218 m	69 ± 55 1981 ± 75 from a composite set of samples from archeological sites, eolian and alluvial deposits. Max. age is 1981 B.P.	Samples from several sections in valley where Little Caney R. has incised 6 m into its flood plain. Includes the Copan paleosol dated at 1330 ± 100 B.P. Located at transition from Cross Timbers post oak-blackjack oak (<u>Q. stellata</u> - <u>Q. marilandica</u>) forest to the west into the tall grass prairie to the east.	2K to 1K: 25% grass pollen, 20% <u>Ambrosia</u> 5% oak pollen. 1K - 69 B.P.: 20% Chenopod., 20% <u>Ambrosia</u>, 3% grass, 10% oak pollen. Modern: 30% oak, 10% hickory, 15% <u>Ambrosia</u> pollen. Interpreted that fewer oak trees in area at 1K to 2K than there today.	No interpretation given.

Hall, S.A. (1977). Geology and palynology of archeological sites and associated sediments. <u>In</u> "The Prehistory of the *Little Caney River, 1976 Field Season*." (D.O. Henry, Ed.) pp. 13-42, Laboratory of Archeology, Univ. of Tulsa, Tulsa OK, 141 p.

Birch Creek Valley Painted Shelter	36°32'N 96°08'W 212 m	1450 ± 80 at 55 cm in a 70 cm section from an archeological site. Max. age is ca. 1600 B.P. Age at top of section is ca. 600 B.P.	70 cm section from a rock shelter along a small stream in Cross Timbers postoak-blackjack oak forest. Tall grass prairie to the west and mixed prairie and oaks to the east.	Oak pollen dominates at 40 to 55%. 10% Ambrosia and 5% grass pollen. Slight rise in pine pollen %'s (2 to 6%) in upper 20 cm. Oak forest like today.	Climate like todays from 1600 to 600 B.P.

Hall, S.A. (1977). Geological and paleoenvironmental studies. <u>In</u> "The Prehistory and Paleoenvironment of Birch Creek Valley." (D.O. Henry, Ed.), pp. 11-31, Laboratory of Archeology, Univ. of Tulsa, Tulsa, OK, 134 p.

New Mexico

San Augustin Plains	33°50'N 108°00'W 2300 m	19,700 ± 1600 27,000 ± 4000 in upper part of 100 m core. 18,000 B.P. at about 600 cm. Max. age perhaps over 100K.	Core from playa in alkaline semidesert grassland. Ann. Temp. = 11.7°C Ann. Precip. = 407 mm	Very general pollen diagram. Last 10K = about 1.5 m. 20% <u>Picea</u> pollen 12 - 20% NAP. 60 - 70% <u>Pinus</u> pollen at 18K (ca. 6 m in core), 20% <u>Picea</u> pollen continues to 1.5 m when replaced by 20 - 30% semidesert scrub and grass pollen.	18K: Colder than present

Clisby, K.H. and Sears, P.B. (1956). San Augustin Plains -- Pleistocene climatic changes. <u>Science</u> 124, 537-539.

N. W. New Mexico

Chaco Canyon a) Gallo Wash b) Chaco Wash III c) Chaco Wash II d) Chaco Wash IV	36°01'N 107°53'W 1908 m	a) 2900 ± 330 5680 ± 120 6725 ± 110 5860 ± 700 Only bottom date from 635 cm section with pollen diagram. Other dates fitted in by correlation. b) No dates on 460 cm section. c) 1010 ± 90 at 75 cm in 410 cm section. d) 1025 ± 85 2170 ± 110 1655 ± 85 Top date fitted in by correlation in 240 section.	Sections of alluvial sediments in a modern arroyo that began eroding in 1860 A.D. 4 main alluvial units. Oldest dated at 5.6 to 6.7K. Pueblo Bonito excavations at Chaco.	7K - 6K: Pine zone with 60% pine pollen 6K - 1K: Chenopod. zone with 10% pine pollen, 50% Chenopod. pollen. 500K - 0: Pine- henop. zone with 40% pine pollen. Pinyon pine woodland today.	Climate arid from 5.8K to 2.4K and drier than today till 500 B.P.

Hall, S.A. (1977). Late Quaternary sedimentation and paleoecologic history of Chaco Canyon, New Mexico. Geological Society of America Bulletin 88, 1593-1618.

Chuska Mts. Dead Man Lake (3 other lakes studied but no dates for them)	36°15'N 108°55'W 2780 m	Three cores: 1) 3900 ± 300 date at 20 cm in 35 cm core that has younger sediments than the top of the long core. 2) 4 C-14 dates 19,400 to 28K in 810 cm core with 19.4K date at 160 cm.	12 hectare, 11 m deep lake at crest of mountains. Open Ponderosa pine forest around lake and down to 2250 m. Pinyon/juniper/sage to 1900 m, and steppe below that. Spruce/fir forest not in mts. today except in canyons above 2400 m; replaces p. pine in San Juan Mts. at 2900 m today. 6 surface samples. Ann. Temp. = 11°C Jan. Temp. = 1°C July Temp. = 25°C Ann. Precip. = 142 mm (at the nearest met. station).	5 pollen zones Core 1): before 4K: Picea and NAP decline. After 4K: Pinus pollen to 70%. 20% Chenop., 10% Artemisia pollen, 2% Quercus pollen. Evidence for compression and lowering of vegetation zones in glacial times. The alpine zone decreased in elevation more than the lower vegetation zones. Core 2): 65% NAP with 45% Artemisia, 10% Picea pollen from top to 28K. Alpine vegetation or spruce parkland Treeline depression of 8000 to 1000 m.	20K: Ann. Temp. 4 to 7°C lower than today. Climatic gradient up mountains was steeper than today. Postglacial: warmer than in glacial times.

Wright, H.E., Jr., Bent, A.M., Hansen, B.S., and Maher, L.J., Jr. (1973). Present and past vegetation of the Chuska Mountains, northwestern New Mexico. Geological Society of America Bulletin 84, 1155-1180.

Colorado

La Plata Mts. Twin Lakes	37°28'N 108°06'W 3290 m	11 radiocarbon dates from 2545 to 9765 B.P. in a 395 cm core. Max. date ca. 10,000 B.P.	Core from edge of small, 1 m deep pond. Open Engelmann spruce-subalpine fir forest at site which is 250 m below treeline. 4 surface samples. July Temp. = 11.4°C Jan. Temp. = 8.5 Ann. Precip. ≈ 1063 mm Maximum precipitation in July and August. Lapse rate in July is 7°C/km.	Picea and Pinus dominance throughout, (60 to 80%). Use ratios of pollen types to estimate treeline fluctuations. 9.8 - 8.6 K: tree line lower than today. Several changes since then.	Tree line changes imply a fluctuating climate over last 10,000 years.

Petersen, K.L. and Mehringer, P.J., Jr. (1976). Postglacial timberline fluctuations, La Plata Mountains, southwestern Colorado. Arctic and Alpine Research 8, 275-288.

Front Range Redrock Lake	40°05'N 105°32'W 3095 m	7 radiocarbon dates from 1640 to 9760 B.P. in a 180 cm core. Max. date of ca. 10,000 B.P.	2.1 hectare, 1 m deep lake. Limber pine, Engelmann spruce, subalpine fir, and other trees and shrubs on the slopes about the site. Timberline at 3300 m.	10K - 9.7K: 60% Artemisia pollen 9.7K - 8K: 40% Pinus pollen. Peak in Picea pollen. 8K - 0: 50% Pinus pollen with a rise in Betula pollen after 2.5K: Picea/Pinus ratio used to plot elevation changes of vegetation.	Evidence for early warming and later cooling. Changing throughout last 10K years.

Maher, L.J., Jr. (1972). Absolute pollen diagram of Redrock Lake, Boulder County, Colorado. Quaternary Research 2, 531-553.

Arizona

Montezuma Castle National Monument Montezuma Well	34°39'N 111°48'W 1120 m	8 C-14 dates, 7 on modern material, 3 of these are 17K to 24.7K dates and date ancient carbonates.	1 hectare water-containing limestone-sinkhole fed by artesian spring waters. 10 m deep. 300 cm core from sedge-peat mat less than 1 m under water at edge of sink. 56 cm core from center of lake. In lower Sonoran vegetation zone with some Juniper and abundant grass.	56 cm core shows increase in NAP and deep water pollen types at 21 cm level.	Nature of change not clear.

Hevly, R.H. (1974). Recent paleoenvironments and geological history at Montezuma Well. Journal of the Arizona Academy of Science 9, 66-75.

E. Arizona

White Mts - Mogollon Rim Laguna Salada	34°21'N 110°17'W 1900 m	3500 ± 60 at base of 190 cm core from center of lake and 7250 ± 170 at 110 cm level of 290 cm section exposed in arroyo to west of present lake. Max. age is not well fixed. Could be as much as 14K.	Spring and arroyo-fed lake in 2 km² basins. Seasonally dry lake. Pollen samples from center of lake; exposed lake sediments in arroyo west of the present basin. Pinyon pine - Juniper grassland region (Savanna - woodland). Ann. Temp. = 8°C Jan. Temp. = 1°C July Temp. = 17°C Ann. Precip. = 637 mm Some surface samples.	Today: 25% Juniperus 20% Pinus, and 50% NAP. 4 pollen zones. 7K and earlier: 60 - 70% Pinus pollen. 7K - 5K: Grass peak of 1%. After 7K: increase in Chenopod. pollen to 50% at top of arroyo section.	Drier climate after 7K.

Hevly, R.H. (1964). Paleoecology of Laguna Salada. Chicago Natural History Museum Fieldiana (Anthropology) 55, 171-187.

W. Arizona

Hualapai Mts. Boulder Springs *Shelter*	35°06'N 114°08'W 976 m	No C-14 dates. Dating from pollen and ceramic analysis. 800 to 1050 B.P. for 100 cm of sediments. Max. age estimated at 1050 B.P.	Archeological site, rock shelter. Desert vegetation. Semiarid climate. Ann. Precip. = 270 mm	NAP dominated spectra with 15 to 20% <u>Ephedra</u> pollen.	May indicate climatic fluctuations from summer dominate biseasonal rainfall to winter-dominated regime.

Hevly, R.H., Heuett, M.L., and Olsen, S.J. (1978). Paleoecological reconstruction from an upland Patayan rock shelter, Arizona. <u>Journal of the Arizona - Nevada Academy of Science</u> 13, 67-78.

S. E. Arizona

Willcox Playa *Lake Cochise*	31°50'N 109°50'W 1290 m	20,000 B.P. 22,000 ± 500 23,200 ± 500 in 42 m core. All dates from 150 to 210 cm. Max. age is between 70K and 210K.	Desert grassland and shrubs in Willcox Basin today (<u>Hilaria</u>, <u>Bouteloua</u>, <u>Aristida</u>, <u>Sporobolus</u>, and mesquite). No plants on playa -- too salty. Ann. Temp. = 32°C (?) Ann. Precip. = 469 mm Ann. Evap. = 1550 mm	No pollen counted above 200 cm, except at surface. No postglacial record. 20K: 90 to 100% <u>Pinus</u> pollen.	20K: colder and moister than today.

Martin, P.S. (1963). Geochronology of pluvial Lake Cochise, Southern Arizona. II Pollen analysis of a 42-meter core. <u>Ecology</u> 44, 436-444.

Cochise County Double Adobe Sulphur Springs Site	31°28'N 109°42'W 1234 m	9 C-14 dates between 7756 and 9350 B.P. from a 380 cm and a 100 cm section. Max. age is ca. 9000 B.P.	Pollen diagrams from north and south wall of an archeological site. Pollen spectra from a mammoth tooth are included. Desert grassland today.	3 of 6 pollen zones are illustrated. NAP dominates with Compositae highest in zone IV before 8K and Chenopod. pollen up to 50% after 8K in zone I and III.	Martin argued that the "Altithermal" (8 - 4K) may have been moister than today. Final proof not in hand.

Martin, P.S. (1963). Early man in Arizona; the pollen evidence. <u>American Antiquity</u> 29, 67-73.

San Pedro Valley *Murray Springs*	31°35'N 110°10'W 1292 m	7 radiocarbon dates from 1550 (unit E) to 8270 (unit A) in 115 cm section. Max. age ca. 8270 B.P. or younger since date on eroded peat.	Stratigraphic section from a tributary arroyo to the San Pedro River. In desert scrub vegetation. 8 stratigraphic units from basal A to upper H.	Chenopod pollen dominates at base in units A to D and units F to H and short-spine Compositae pollen dominates in the 95 cm of unit E. Unit B deposited in 500 years between 4000 and 5000 years ago. Vegetation zones lower by 300 m.	Authors argued that higher pine pollen (up to 10%) in unit B (4 - 5K) imply moisture conditions.

Mehringer, P.J., Martin, P.S., Haynes, C.V., Jr. (1966). Murray Springs, a mid-postglacial pollen profile from southern Arizona. Interim Research Report No. 13, Geochronology Laboratories, Univ. of Arizona, Tucson, 16 pp.

Utah

Wasatch Mts. Little Cottonwood Canyon Showbird Bog	40°34'N 111°45'W 2470 m	5 C-14 dates from from 1870 to 12,300 B.P. in a composite profile of 2 profiles. Max. age of ca. 13,000 B.P.	375 to 450 cm thick bog over 1 - 3 m of Hegum Fork till (13 to 14K old). Bog section includes 7 forest-floor mats with spruce and fir needles and roots and 6 clay-loam units. Engelmann spruce and subalpine fir at site with Douglas fir, aspen, willow, and alder nearby.	Sediment stratigraphy suggests several bog-meadow/forest replacements. Local sequence, not seen in regional pollen. 13K - 8K: 40% sage and NAP, up to 30% alder pollen. 8K - 5K: 60% spruce and 20% pine pollen. 5K - 0: 15% sage, up to 40% alder with peaks in spruce.	Uses spruce/pine ratio and conifer/other pollen ratio to trace temp. and moisture changes. 13K - 8K: cool, dry 8K - 5K: warm, wet 3K - 0: cool, dry.

Madsen, D.B. and Currey, D.R. (1979) Late Quaternary glacial and vegetation changes, Little Cottonwood Canyon area, Wasatch Mountains, Utah. Quaternary Research 12, 254-270.

Zion National Park Beatty Lake, Paris Lake, Sentinal Slide Lake, Trail Canyon lava Lake, Coalpits lava Lake	ca. 37°10'N ca. 113°W 1280 - 19?? m		Preliminary report of some potentially interesting sites. Pollen records also preliminary.		

Hevly, R.H. (1978). Paleoecology of Holocene and Pleistocene lacustrine sediments from Zion National Park, Utah. First Annual Conference of Research in National Parks, A.I.B.S. Publication, 151-158.

S. E. Idaho

N. E. Great Basin Red Rock Pass Swan Lake	42°17'N 112°01'W 1450 m	1850 ± 200 10,.90 ± 250 12,090 ± 300 In a 805 cm core (with pollen). Max. age is oldest date.	10 ha lake in outlet of Lake Bonneville when at its highest (1430 m). In Artemisia steppe. Pollen and plant macrofossil date 6 surface samples. Jan. Temp. = 6°C July Temp. = 21°C Ann. Precip. = 400 m Snowfall = 1250 mm	7 pollen zones 12K - 10K: 65% Pinus pollen with 20% P. flexilis type, 10 - 25% Artemisia pollen. 10K - 0: 15% (5 - 30%) Pinus pollen and 20 to 50% Artemisia, 5% Ambrosia, 10% Gramineae pollen. 8.4K - 0: 20% Chenopod. pollen. 3.1K - 1.8K: 30% Pinus pollen, with ! % P. flexilis, rest is P. contorta type. L. Bonneville lower than 1430 m by 12K and possibly by 13K.	12K - 10K: colder than today. 10K - 0: like today or warmer except from 3.1 to 1.8K when colder.

Bright, R.C. (1966). Pollen and seed stratigraphy of Swan Lake, southeastern Idaho: its relation to regional vegetational history and to Lake Bonneville History. Tebiwa, The Journal of the Idaho State University Museum 9, 1-47.

Montana/Idaho

Bitterroot Mts. Lost Trail Pass Bog	45°43'N 113°56'W 2152 m	16 radiocarbon dates from 60 to 585 cm and 125 to 11,200 B.P. in 625 cm core. Max. age ca. 12,000 B.P.	2 hectare bog and meadow. In subalpine fir zone (1900 - 2900 m).	Artemisia zone to 11,500 B.P. Pinus pollen dominates since then (80%). Peaks in Artemisia pollen about 600 years ago.	11.5K - 7K cooler than today. 7K - 4K: warmer. 4K - 0: cooler with perhaps more moist interval 3.7 to 3.4K.

Mehringer, P.J., Jr., Arno, S.F., and Petersen, K.L. (1977). Postglacial history of Lost Trail Pass Bog, Bitterroot Mountains, Montana. Arctic and Alpine Research 9, 345-368.

N. W. Wyoming

Yellowstone Park Cub Creek Pond	44°28'N 110°14'W 2523 m	11,630 ± 180 14,360 ± 400 in 840 cm core with Mazama ash layer. Max. age is ca. 14,360 B.P. in an ash horizon.	Lodge pole pine dominates with some spruce and fir.	14K - 11.6K: Tree-line lower by 500 m with 30 - 40% Artemisia pollen and 10% Betula. 11.6K - 0: 80% Pinus mostly P. contorta type. 4.5K - 0: 5% more Picea pollen.	14K - 11.6K: Cooler climate. 11.6K - 4.5K: warmer and/or drier climate. 4.5K - 0: perhaps a little cooler.

Waddington, J.C.B. and Wright, H.E., Jr. (1974). Late Quaternary vegetational changes on the east side of Yellowstone Park, Wyoming. Quaternary Research 4, 175-184.

Yellowstone National Park Abandoned lagoon above Yellowstone Lake	44°30'N 110°20'W 2384 m	2,470 ± 250 5,390 ± 250 9,240 ± 300 11,550 ± 350 on a 950 cm core. Max. age is ca. 13,000 B.P. or older.	Vegetation today: Pinus contorta about site with Picea engelmannii, Abies lasiocarpa, and Pinus albicaulis on slopes just 30 m above the site. Treeline at 3015 m.	2 main pollen zones. Upper one with 3 subzones. ca. 13K - 11.6K: 30% Artemisia pollen with some Juniperus and Picea pollen and 40% Pinus pollen implies alpine vegetation. More trees in upper part of zone. 11.6K - 0: Pinus contorta zone. 70 - 80% Pine pollen. P. albicaulis pollen high till 10K. 10K - 5K: mainly P. contorta pollen. Hiatus in sediments possible. 5K - 0: more Picea and Abies pollen (5%).	13K-11.6K: Colder than today. 11.6K - 10K: Cooler and drier than today. Annual temp. of -1°C or 1.5°C colder than today. 10K - 15K: warmest and driest. 5K and 2.8K: Cooler pulses perhaps tied to neoglaciation.

Baker, R.G. (1970). Pollen sequence from late Quaternary sediments in Yellowstone Park. Science 168, 1449-1450.

Nevada

Guano Cave Fishbone Cave	ca. 40°00'N ca. 119°30'W 1350 m	8 C-14 dates from 3200 to 15,760 B.P. in two series of samples from both caves. Max. age is dated by oldest date in 10 cm of lake silts at Level 6 of Fishbone Cave	Sections of cave deposits from caves in the desert. The caves were cut by a high stand of L. Lahontan. Ann. Temp. = 10.6°C Jan. Temp. = 0°C July Temp. = 23°C Ann. Precip. = 166 mm	Composite diagram made from different samples. Pollen stratigraphy is rough. 15K: 1 level with high Pinus pollen, rest high NAP. 7K to 2K or 0: Desert pollen types dominate, some rise in AP near top.	15K: mostly dry 7K - 2K or 0: Dry or drier than today.

Sears, P.B. and Roosma, A. (1961). A climatic sequence from two Nevada caves. American Journal of Science 259, 669-678.

S. Nevada

Mohave Desert Tule Springs	36°19'N 115°11'W 555 m	7480 ± 120 9000 ± 1000 12,400 ± 350 in 3 separate sections comprising a composite postglacial profile with some overlap from 12.4K to ca. 6.5K. Hiatus at site from ca. 12.4K to 22K, then 2 dates of 22.6K and 31.2K for the max. age at the site.	Pollen data from lake sediments. Some work associated with archeological sites. In Mohave Desert today with creosote bush and bursage. Ann. Temp. = 17.8°C Jan. Temp. = 6.4°C July Temp. = 30.6°C Ann. Precip. = 101 mm	12.5K: Dominance of Artemisia and Juniperus as occurs in N. Nevada today. 30% pine pollen, 15% Artemisia pollen. 12K: Gradual change to sagebrush and shadscale (Atriplex) as Chenopod. pollen rose to 60% and pine pollen decreased 15%. ca. 6.5K: 2% Pinus, 15% Chenopod., and 70% Compositae pollen; conditions like today.	12.5K: colder than today. 12K - 7.5K: trend toward warmer drier conditions with some short intervals that may have been wetter and cooler. ca. 6.5K: climate similar to todays.

Mehringer, P.J., Jr. (1967). The environment of extinction of the late-Pleistocene megafauna in the arid southwestern United States. In "Pleistocene Extinctions." (P.S. Martin and H.E. Wright, Jr., Eds.), pp. 247-266, Yale University Press, New Haven, CT.

Martin, P.S. and Mehringer, P.J., Jr. (1965). Pleistocene pollen analysis and biogeography of the Southwest. In "The Quaternary of the United States." (H.E. Wright, Jr. and D.G. Frey, Eds.), pp. 433-451, Princeton University Press, NJ.

California

Yosemite and L. Tahoe Areas a) Hodgdon Ranch b) Crane Flat c) Soda Springs d) Osgood Swamp	a) 37°45'N 119°52'W 1400 m b) 37°45'N 119°45'W 1850 m c) 37°50'N 119°20'W 2750 m d) 38°50'N 120°00'W 1900 m	a) No dates in 685 cm of stratigraphic section. b) 950 ± 70 1500 ± 80 2040 ± 160 in 275 cm section from an archeological midden. Max. age of 4000 B.P. possible. c) No dates in 138 cm core. d) 2830 ± 200 9900 ± 800 in 440 cm core. Max. age of 12,000 B.P. possible	Sites near Mono Lake. a-c) Sections from archeological sites. d) 300 m diameter lake,1 m deep water before artificially drained in 1961. 33 surface samples from 2 altitudinal transects.	d) 12K - 10K: 40% *Artemisia* pollen till 10K. 10K - 0: 70% *Pinus* pollen 2.8K - 0: Higher *Abies* and *Ericaceae* pollen.	End of glacial climatic conditions by 10K. Cooler after ?.8K.

Adam, D.P. (1967). Late-Pleistocene and recent palynology in the central Sierra Nevada, California. In "Quaternary *Paleoecology*", (E.J. Cushing and H.E. Wright, Jr., eds.), pp. 275-301, Yale University Press, New Haven, CT.

near L. Tahoe Ralston Ridge Bog	38°51'N 120°07'W 2580 m	1145 ± 90 1345 ± 95 2595 ± 85 Last date at base of 102 cm core. Max. age = 2595 B.P.	Bog is 250 m from crest of Sierra Nevada. Several small springs account for peat growth at site. Near Osgood Swamp (Adam, 1967).	Complacent pollen record with 60% Diplox. pine, 15% Haplox. pine, 25% *Tsuga*. 4 root horizons from 35 to 75 cm may indicate periods of relative dryness and decreased spring discharge. Two of these are dated by the 2 younger C-14 dates.	Drier at 1100 to 1300 B.P. than today or at 2500 B.P.

Sercelj, A. and Adam, D.P. (1975). A late Holocene pollen diagram from near Lake Tahoe, ElDorado County, California Journal Research U.S. Geological Survey 3, 737-745.

San Francisco Peninsula Weeks Creek Pearson's Pond	37°21'N 122°15'W 365 m	1545 ± 85 2190 ± 85 3040 ± 95 in 210 cm core. Max. age is 3400 B.P.	Small pond in grassland and chaparral with redwood and mixed evergreen forests in stream valleys. Some marl in sediments. Ann. Precip. = 900 mm	20 to 40% TCT pollen (probably from *Sequoia*) in core. 3.4 - 3.0K: 10 - 20% *Pinus* and *Corylus* pollen but none from 3K to 0. Active record with Chenopod., *Quercus*, Gramineae, and TCT pollen. Human disturbance indicated by rise in % of Grass pollen in upper 30 cm.	Two wet intervals from 2.3 to 1.9K and from 1.3 to 1K.

Adam, D.P. (1975). A late Holocene pollen record from Pearson's Pond, Weeks Creek Landslide, San Francisco Peninsula, California. Journal of Research, U.S. Geological Survey 3, 721-731.

S. California

Searles Lake	35°17'N 117°20'W ca. 530 m	Well-dated from 12,730 to 21,200 in parting mud of organic lake sediments.	Pollen data from Upper Salt and Parting Mud in core L-31. Dried up lake bed located in SW corner of Basin Range province. Was part of a chain of lakes, those upstream in the high Sierras (e.g., Mono L., Adobe L.) connected by the Owens R. Desert scrub, bare areas and phreatophytes in basin today. Desert scrub to 1300 m on mt. slopes. Some Ceanothus, Juniperus, pinyon-juniper woodland above 2120 m in Panamint Mts. Ann. Temp. = 19.1°C Jan. Temp. = 8°C July Temp. = 30°C Ann. Precip. = 97 mm	Modern pollen: 35% woodland pollen (pine, oak, sage, juniper). 20% Compositae, 30% Chenopod. pollen. 23K - 10K: 75% woodland pollen types. 10K to top of Upper Salt unit: 50% woodland pollen types. Increased amounts of Chenopod., Compositae pollen. Oscillations in amounts of these pollen types.	Climate drier and warmer after 10K. Oscillations in climate in last 10K.

Leopold, E.B. (1967). Summary of palynological data from Searles Lake. In "Pleistocene Geology and Palynology of Searles Valley, California." Guidebook for Friends of the Pleistocene, Pacific Coast Section, 52-60.

Roosma, A. (1958). A climatic record from Searles Lake, California. Science 128, 716.

N. Idaho

Selkirk Range Hager Pond	48°36'N 117°58'W 860 m	12 C-14 dates from 2670 to 9510 B.P. for a 970 cm core with Mazama ash. Max. age is ca. 10,000 B.P.	Hemlock/Pachistima vegetation type 7°C in January 17°C in July 800 mm Ann. Precip. Peat since 2700 B.P. over lake sediment.	5 pollen zones. 50 to 80% pine pollen. Highest pine 10K to 8K and 6K to 0. 10% fir and hemlock since 2.5K.	10K - 8.3K: cooler, moister. 8.3K - 3K: warmer, drier 3K - 0: cooler, moister

Mack, R.N., Rutter, N.W., Bryant, V.M., Jr., Valastro, S. (1978). Reexamination of postglacial vegetation history in northern Idaho: Hager Pond, Bonner Co. Quaternary Research 10, 241-255.

N. E. Washington

Colville R. Valley Waits Lake	48°12'N 117°46'W 610 m	8 C-14 dates from 3530 to 11,950 B.P. in a 1060 cm core of calcareous sediments. Dates corrected using Mazama and Glacier Peak ashes. Mazama ash dated at 8K and 11.9K date 50 cm above 11.3K G.P. ash. Max. age is ca. 12,500 B.P.	180 hectare lake, core from its shore. Peat over gyttja and marl in upper 100 cm. Douglas fir/Physocarpus vegetation type.	50 to 75% Pine pollen throughout core. 15 to 20% Artemisia pollen until 5K. 75% Pine after 5K. Alnus, grass pollen also decrease at 5K. 4 major pollen zones. Modern climax forest of Douglas fir since 2.3K.	10K - 12.5K: cool, moist 6.7K - 10K: warmer 5K - 6.7K: drier 5K - 0: like today

Mack, R.N., Rutter, N.W., Valastro, S., and Bryant, V.M., Jr. (1978). Late Quaternary vegetation history at Waits Lake, Colville River Valley, Washington. Botanical Gazette 139, 499-506.

Selkirk Mts. Big Meadow	48°43'N 117°33'W 1040 m	8 C-14 dates from 1170 to 10,460 B.P. with Mazama ash in 1030 cm core. Max. age is earlier than 11,000 B.P., ca. 12,500 B.P.	Fen in glacially eroded trough, 55 km north of late Pindale limit. In hemlock (T. heterophylla) series or Abies grandis zone. Jan. Temp. = 5°C (1975) July Temp. = 21°C (1975) Ann. Precip. = 700 mm	5 pollen zones. Base to 10K: 25% sage pollen, 40% pine pollen. 6.5K - 0: 75% pine pollen. 2.4K - 0: Climatic climax of Tsuga heterophylla. (Tsuga pollen continuously above 2% after 3K).	9.7 - 3.3K: warmer than today.

Mack, R.N., Rutter, N.W., Bryant, V.M., Jr., and Valastro, S. (1978). Late Quaternary pollen record from Big Meadow, Pend Oreille County, Washington. Quaternary Research 59, 956-966.

Sanpoil R. Simpson's Flats	48°25'N 118°45'W 535 m	11 C-14 dates from 1970 to 10,010 B.P. in a 850 cm core with Mazama ash. Max. age is dated at 10,010 B.P.	A mire with 250 cm peat over gyttja with Mazama ash over marl. Within area of Fraser glaciation (19K to 10K). Pinus ponderosa/Festuca vegetation around site with Pseudotsuga menziesii in the valley. Jan. Temp. = 13°C July Temp. = 20°C Ann. Precip. = 400 m (at Republic, WA, 800 m)	4 pollen zones. NAP (Artemisia + Grass) 35% till Mazama ash. Diplox. Pinus pollen from 50 to 80% at 6.7K.	Climate warmer than today after 6.7K to 4K. Other climate changes possible but subtle

Mack, R.N., Rutter, N.W., and Valastro, S. (1978). Late Quaternary pollen record from the Sanpoil River Valley, Washington. Canadian Journal of Botany 56, 1642-1650.

Okanogan R. Valley a) Mud Lake b) Bonaparte Meadows	a) 48°37'N 119°31'W 655 m b) 48°46'N 119°04'W 1021 m	a) 5 C-14 dates from 8030 to 11,490 B.P. in a 500 cm core with Mazama and St. Helens Wn ashes. b) 14 C-14 dates from 1480 to 10,000 B.P. in a 633 cm core with Mazama (2 units) and St. Helens Wn ashes.	a) small pond, 890 cm of sediment with pollen analyzed in upper 500 cm. b) 112 hectare fen with 490 cm of peat over 143 cm of gyttja. Detailed study of Mazama ash shows two distinct ash falls (6.8 to 7K).	4 pollen zones. 11.5K - 10K: Haplox. pines and Artemisia dominant. 10K - 5K: Diplox. pines and Artemisia dominant. 5K - 0: Modern vegetation dominated by Douglas fir.	11.5K - 10K: cool 10K - 5K: warmer and drier. 5K - 0: less warm and dry.

Mack, R.N., Rutter, N.W., and Valastro, S. (1979). Holocene vegetation history of the Okanogan Valley, Washington. Quaternary Research 12, 212-225.

Mack, R.N., Okazaki, R., and Valastro, S. (1979). Bracketing dates for two ash falls from Mount Mazama. Nature 279, 228-229.

E. Washington

Columbia R. Valley Fen near Creston (Wilbur Bog)	47°45'N 118°32'W 763 m	9390 ± 400 Mazama ash and Glacier Peak ash in 245 cm core. Max. age is ca. 11,000 B.P.	Fen formed in depression left by "scabland" flood waters of glacial Lake Missoula (15 to 20,000 B.P.) Sage-grass (Artemisia-Festuca) vegetation type with ponderosa pine and aspen at the site.	2 pollen zones. Decrease in haplox. pine, spruce, fir, and Artemisia pollen at ca. 10K. Mainly treeless vegetation to 10K. Notes 10K date for frost polygon at Marmes Rockshelter, 140 km south of Creston.	Climate interpreted to be drier and warmer after 10K.

Mack, R.N., Bryant, V.M., Jr., and Fryxell, R. (1976). Pollen sequence from the Columbia Basin, Washington: reappraisal of postglacial vegetation. American Midland Naturalist 95, 390-397.

S. E. Washington

Snake R. System Wildcat Lake	46°48'N 118°10'W 340 m	400 ± 60 900 ± 70 in a 400 cm core with Mt. St. Helens W ash of 450 B.P.	1-3 ha., 1-3 m deep lake in channeled scablands. In grass steepe (Agropyron-Festuca) vegetation type. Ann. Precip. = 400 mm. 2/3 falls Nov. to April.	Pollen complacent from 1.1K to 40 cm level when pigweed pollen increases 5 to 30% and pine pollen decreases 60 to 20%.	No major climatic change in last 1000 years.

Davis, O.K., Kolva, D.A., and Mehringer, P.J., Jr. (1977). Pollen analysis of Wildcat Lake, Whitman County, Washington: the last 1000 years. Northwest Science 51, 13-30.

N. W. Washington

Olympic Peninsula 1) Hoh R. Valley a) Bog-Site 1 b) Bog-Site 6 2) Sea Cliff Peats near Kalaloch	1) 47°50'N 124°15'W a) 146 m b) 195 m 2) 47°35'N 124°20'W 3 to 35 m	1 a) 14 C-14 dates from 250 to 15,600 B.P. in a 580 cm core. Max. age is oldest date. b) 18,000 ± 800. 2) 14 C-14 dates from 16,700 to >47,000 B.P. in 26 m section.	1 a) 21 hectare bog near forest of western hemlock (Tsuga heterophylla) and western red cedar (Thuja plicata), with some Douglas fir (Pseudotsuga menziesii) and Sitka spruce (Picea sitchensis). Some 6 m high lodgepole pine on the bog. Several surface-sample sites. 1) Ann. Temp. = 9°C Jan. Temp. = 3-7°C July Temp. = 16°C Ann. Precip. = 2600 to 3200 mm. Measured lapse ratio of 6°C/km. 2) Exposed peats in sea cliffs in region of Pacific coastal forest.	1 a) 13K - 9K Pinus Picea, Tsuga pollen increase to replace NAP. 9K - 7K: Alnus pollen increase to replace Pinus. Pseudotsuga broad peak (10%) from 10K to 3K. 7K - 0: Tsuga pollen increase to replace Alnus. 3K - 0: Thuja, Tsuga pollen highest, Picea pollen lower. 2) 18K - 20K: 75% NAP. Tundra, treeline 1300 m lower.	18 - 20K: colder by 7°C or more than today. 8K - 6K: warmer than today by 2°C. 1K-100 years ago: colder than today.

Heusser, C.J. (1977). Quaternary palynology of the Pacific slope of Washington. Quaternary Research 8, 282-306.

Olympic Peninsula Bogachiel R. area	47°53'N 124°16'W ca. 200 m	20,100 ± 750 30,000 ± 800 in 275 cm bog section. Max. age is ca. 31,000 B.P.	Section from a bog just outside a moraine and the glaciated area. In cloud forest today with some tree flora as in nearby Hoh Valley. July Temp. = 15.4°C Jan. Temp. = 3.7°C Ann. Precip. = 2974 mm but only 120 mm falls in July and August.	Pollen stratigraphy for past 10K years much like that in Hoh Valley.	Climate changes similar to those in Hoh Valley.

Heusser, C.J. (1978). Palynology of Quaternary deposits of the lower Bogachiel River area, Olympic Peninsula, Washington. Canadian Journal of Earth Sciences 15, 1568-1578.

pertinent information available at each pollen site. For each location from which I have summarized the pollen data, Table 1 lists 1) the name of the site and the state in which it is located; 2) its latitude, longitude, and elevation; 3) the chronostratigraphic information such as radiocarbon dates and volcanic-ash horizons; 4) the present condition of the site, of the regional vegetation, and of the climate (when information is available); 5) the main features of the pollen record and interpreted changes in the past vegetation; and 6) the interpreted changes in past climates.

The network of well-dated sites is best in Washington and Idaho (Fig. 1), where R. N. Mack has recently published data from a series of sites to complement the work of Heusser, Mehringer, and Bright (Table 1). Outside of this region, the location of sites is uneven, and the dating is generally not as thorough at each of the sites.

Of this set of over 42 sites with pollen evidence, nine occur in or near the lake basins described by F. A. Street in Chapter 1. These include Rich and Crane Lakes in the Llano Estacado; cores from Searles Lake, the San Augustine Plains, Lake Cochise, and Tule Springs in pluvial Lake Las Vegas; Guano and Fishbone caves that were cut by pluvial Lake Lahontan; and Swan Lake in a spillway of pluvial Lake Bonneville. The pollen records from all of these sites will help in estimating the vegetation about the pluvial lakes and thus aid the use of computer models to simulate past climatic and hydrological conditions at these sites. Such work will be an important follow-up to work reported in the first chapter of this report.

THE INFERRED PALEOCLIMATIC RECORD

All of the pollen diagrams show a certain degree of climatic variation over the past 10,000 to 20,000 years. The general pat-

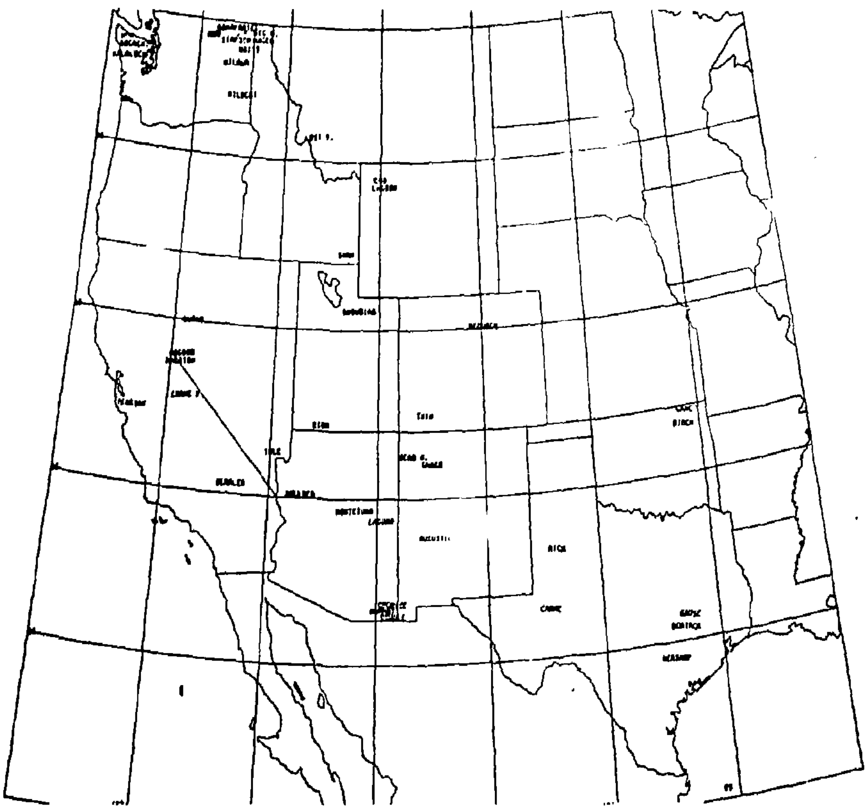

FIG. 1. Location of the sites with pollen data in the western United States. Only the data at Zion, Gause, and Boulder are not directly dated by radiocarbon dates. The first letter of each name is plotted at the sample location except where +'s mark the location for Ralston, Lagoon, Big M. (Big Meadow), Simpson, and Hoh.

Location of sites with pollen diagrams.

tern includes colder conditions by 3 to 10^{o}C about 18,000 years ago, warming from 15,000 to 9000 or 7000 years ago, a period of relatively high temperatures from 9000 or 7000 to 4000 or 2500 years ago, and a recent period of cooling and of lower temperatures associated with glacial advance among certain alpine glaciers.

Between 18,000 and 20,000 years ago, the pollen data are consistent in showing that the vegetation shifted to lower elevations on the mountains and in the basins and valleys. The amount of lowering varied from 600 to 1300 m (Peterson et al., 1979).[1] These values agree well with the estimate for the 900 m lowering of the glaciation threshold in the southern North Cascade Range between 18,000 and 22,000 B.P. (S.C. Porter, unpublished ms.). Botanical data from radiocarbon-dated pack-rat middens yield similar estimates for the amount of downward displacement of vegetational regions (Peterson et al., 1979).

From 15,000 to 13,000 years ago until 2500 to 4000 years ago, the pollen record shows evidence first of a climatic warming and then of climates often warmer and perhaps drier than those today. This warm period called the Altithermal or Hypsithermal seems to have lasted from 7000 or 9000 years ago until 2500 or 4000 years ago. Detailed mapping and more intense study of the data are needed to show what sorts of climatic patterns existed in the West during the period from 9000 to 2500 years ago.

Since about 2500 years ago, evidence from studies of alpine glaciers exists for neoglaciation (i.e., extension of certain of the glaciers) in the Rocky Mountains and the Cascades, and the term Neoglaciation is sometimes used for this recent time period (Heusser, 1977). Some but not all of the pollen diagrams show evidence for lower temperatures during this time period. In a study of tree rings and the upper treeline in the White Mountains of

1. References are given at the end of this chapter (p. 71).

California, LaMarche (1973) has used his records, which are temporally more sensitive than most pollen records, to document some of the high-frequency climatic oscillations during this time period (Fig. 2). The overall trend in his data during the past 1000 years is toward colder conditions than those during the previous 5000 years.

In summary, the pollen record complements the lake-level and other geological records in the West by showing colder, moister conditions 18,000 years ago, a period of general warm and dryness from 7000 to 4000 years ago, and a recent period of cooler, moister conditions relative to those from 7000 to 4000 years ago. Figure 2 of Chapter 1 shows that the water-level in at least three basins has increased dramatically in the recent 2500 year period. The hydrological effect of this recent climatic change is thus manifest, and the evidence for cooling in this area during the past 700 years (Fig. 2) suggests that a further increase in water levels is likely over the next 100 to 1000 years. Such changes could affect the suitability of any sites in the Great Basin that might be chosen as repositories of radioactive wastes.

PLANNED FUTURE WORK

The pollen data listed in Table 1 will help in the next step in interpreting the lake-level data summarized in Chapter 1. Our plans call for using a combined hydrological and energy-budget model developed by Kutzbach (in press) in order to estimate the precipitation changes associated with the lake-level fluctuations and in order to estimate the changes in the rates of groundwater recharge in a selected set of the basins. The model uses values of surface albedo (reflectivity) in its calculations of the basin heat-budgets. By indicating the nature of the past vegetation, the pollen data will improve the accuracy of the surface-albedo estimates and thus of the model simulations.

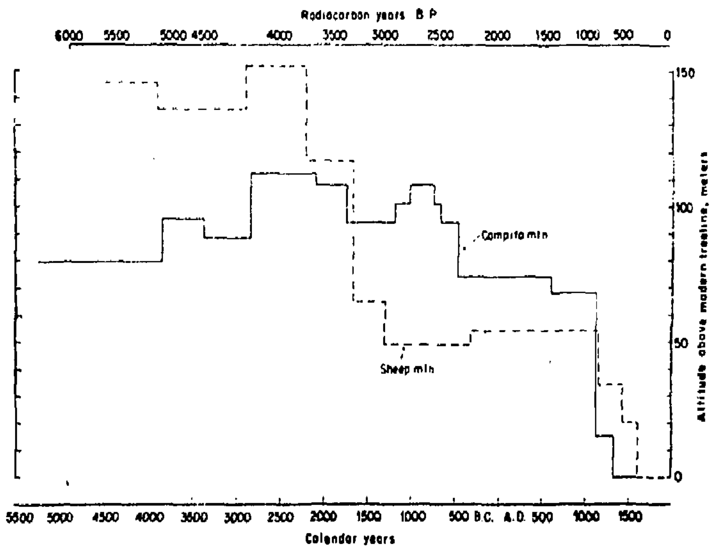

FIG. 2. Minimum levels of past treeline in the White Mountains of east-central California as reconstructed by LaMarche (1973). Estimates assembled from the evidence in wood of living and dead bristlecone pines (*Pinus longaeva*).

Treeline elevation changes in the White Mts.

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Heusser, C.J. (1977). Quaternary palynology of the Pacific Slope of Washington. Quaternary Research 8, 282-306.

Kutzbach, J.E. Estimates of past climate at Paleolake Chad, North Africa based on a hydrological and energy balance model. Quaternary Research (in press).

La Marche, V.C., Jr. (1973). Holocene climatic variations inferred from treeline fluctuations in the White Mountains, California. Quaternary Research 3, 632-660.

Peterson, G.M., Webb, T. III, Kutzbach, J.E., van der Hammen, T., Wijmstra, T.A., and Street, F.A. (1979). The continental record of environmental conditions at 18,000 yr B.P.: an initial evaluation. Quaternary Research 12, 47-82.

Porter, S.C. (1979). Present and past glaciation threshold in the Cascade Range, Washington: topographic and climatic controls, and paleoclimatic implications. Unpublished ms., Quaternary Research Center, Univ. of Washington, Seattle, 26 pp.

CHAPTER 3

CLIMATIC CHANGE IN THE NORTHERN MIDWEST DURING THE PAST 10,000 YEARS

(Thompson Webb III and Sally Howe)

INTRODUCTION

The possible burial of nuclear wastes in either Upper Michigan or other Midwestern localities requires an examination of the 10,000-year climatic variability within the northern Midwest. Of particular interest for estimating possible changes in groundwater recharge is the record of precipitation changes during this time interval. This record provides evidence for the past range of long-term (100 to 1000 year) changes in precipitation, and these changes can be used as a guide for estimating the potential range in precipitation that may occur over comparable time-periods in the future. The past record also indicates the trends in recent long-term changes in climate, and these trends can be used as first-order guesses for estimating future long-term changes in climate. Paleoclimatic evidence from tree-rings (Fritts, 1976) and from historical records should be used when estimates of the short-term (10 to 300 year) trends are needed.

Fossil pollen data by monitoring past changes in the vegetation provide the main stratigraphic evidence for the long-term climatic changes in the Midwest. The data are quantitative and can be calibrated in terms of climatic changes over the past 10,000 years. Not only do the data and methods exist for deriving quantitative estimates of past precipitation from pollen data, but enough radiocarbon-dated sites with fossil pollen exist that both the pollen data and the precipitation estimates can be mapped for certain 1000-year intervals within the past 10,000 years. In the second section of this chapter, we have illustrated some of this potential by briefly describing pollen analysis and then reviewing some of the previous paleoclimatic studies from the northern Midwest. In the third section, we describe the methods used in estimating the climatic values from pollen data; and in the fourth section, we present the latest set of past-precipitation maps derived from pollen data and discuss their relevance to the possible burial of nuclear wastes in the Midwest.

POLLEN ANALYSIS AND PREVIOUS MIDWESTERN POLLEN STUDIES

Brief Description of Pollen Analysis

Ever since the technique of pollen analysis was first introduced in 1916, pollen data have been the main source of climatic information on the time scale of 5000 to 15,000 years. The technique depends upon the steady accumulation of sediments in lakes and bogs to form organically rich deposits that can be collected by hand-driven corers and can be dated by radiocarbon methods. These sediments incorporate a variety of materials including microscopic (20 to 100 μm) pollen grains that have a resistant outer wall. Conifers and flowering plants produce this outer wall to protect the inner sperm-producing cell during sexual reproduction, and wind-pollinated plants release millions of grains for each one that reaches a receptive stigma. Pollen is both blown and washed into lakes and bogs where the durable walls are well preserved in the accumulating sediments.

In the American Midwest and Northeast, lakes contain 2 to 10 m of sediment that has accumulated in the last 10,000 to 15,000 years since the continental Laurentide ice sheet retreated. Cores of these sediments are subsampled at 5 to 10 cm intervals, and 1 ml samples are processed in the laboratory by a variety of concentrated acids and bases that dissolve away most of the unwanted sediment and leave a residue rich in pollen. Examination of the residue under a microscope at magnifications of 400 to 100 x permits identification of different types of pollen from the genus to even the species level based on the wall-sculpturing and the shapes of the grains. For each sample, the numbers of grains of each pollen type are tallied.

Pollen diagrams produced from the tallies show the changing relative abundances of pollen through time at individual coring sites (Fig. 1). The information from several diagrams can then be linked by mapping the different pollen types in similar-age sediments from different lakes (Fig. 2). Patterns in maps of the relative abundances of recently deposited pollen not only resemble the spatial patterns in the plants currently producing the pollen but also are often comparable to the modern-day patterns of climatic variables. In eastern North America, for example, both oak and spruce pollen have north-south distributions that resemble the north-south gradient in temperature (Fig. 2), and herb pollen (excluding ragweed) increases westward with decreasing annual rainfall (Fig. 3). These similar patterns between pollen and climatic variables are the basis for calibrating pollen data in climatic terms and for interpreting what the past changes in pollen imply about past climatic changes.

Midwestern Pollen Studies

After the introduction of radiocarbon-dating, the study of Wright et al. (1963)[1] at Kirchner Marsh (Fig. 1) was one of the first in the Midwest to illustrate a major increase in the percentages of herb pollen (Fig. 2) and thus indicate the eastward movement of the prairie during the period from 8000 to 4000 years ago (Wright, 1968). Subsequent studies by McAndrews (1966), Watts and Bright (1968), and Ritchie (1969) added further radiocarbon-

1. References appear at the end of this chapter (pp. 101-102).

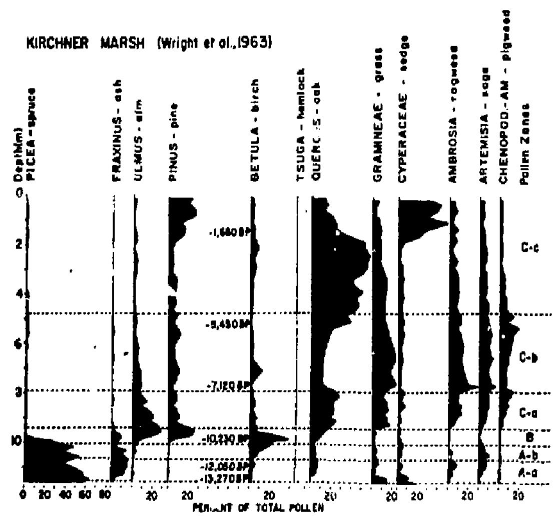


FIG. 1. Pollen diagram from Kirchner Marsh (Wright <u>et</u> <u>al</u>., 1963) showing how the percentages of the different pollen types change with depth and/or time. Six radiocarbon dates indicate the age increase with depth.

Pollen diagram from Kirchner Marsh, MN.

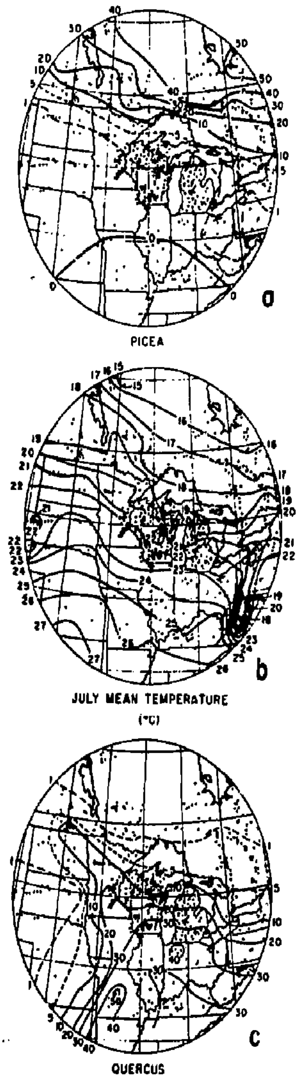
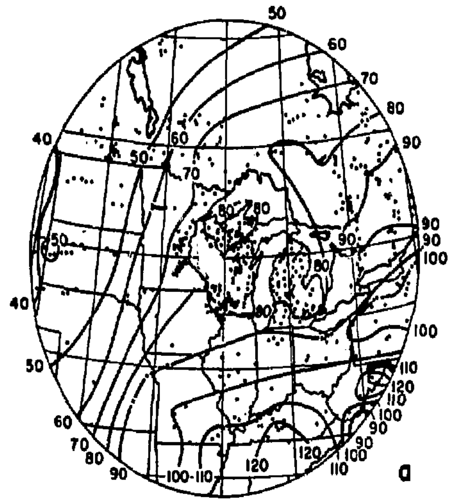
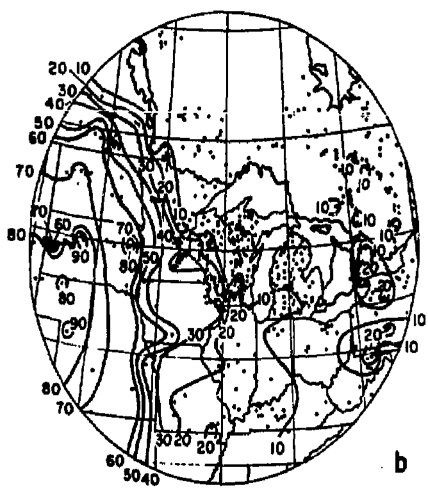


FIG. 2. Maps a and c show the contemporary patterns in the percentages of spruce (Picea) and oak (Quercus) pollen in surface lake-sediments and peats. The percentages are based on a sum of total pollen excluding aquatic pollen and spores. Map b shows the July mean temperatures for the period 1941 to 1970 A.D.

Maps of spruce pollen, oak pollen, and temperature today.



ANNUAL PRECIPITATION
(cm)



HERB POLLEN

FIG. 3. Map (a) shows the average annual amount of precipitation for 1941 to 1970 A.D. Values are in centimeters. Map (b) shows the contemporary pattern in the percentages of herb pollen-types (pigweed + grass + types of the daisy family excluding ragweed).

Maps of precipitation and herb pollen today.

dated evidence for this prairie expansion; and the detailed study of pollen and plant-macrofossils at Kirchner Marsh by Watts and Winter (1966) showed that the water level in the basin had decreased during the time when the percentages of herb pollen were highest at this site. The main climatic interpretation of these pollen and inferred vegetation changes was that precipitation had decreased along the prairie/forest border from Minnesota into Illinois and perhaps Ohio. This evidence fitted in neatly with previous botanical studies in which the current-day growth of relic communities of prairie plants into Pennsylvania and Michigan was used to postulate the existence of a dry "prairie period" at some time during the past 10,000 years (Transeau, 1935).

Bryson and Wendland (1967) were the first to estimate and map the circulation changes associated with the prairie advance and retreat. Webb and Bryson (1972) then quantified some of these estimates by deriving temperature, precipitation, and air-mass-duration values from the pollen data at Kirchner Marsh in Minnesota and Disterhaft Farm Bog and Lake Mary in Wisconsin (Figs. 4 - 7). This study showed that dry western air replaced the moist southern air in Minnesota 4000 to 8000 years ago, but this circulation change did not extend into eastern Wisconsin. These results suggested that conditions in the Midwest 4000 to 8000 years ago were in some ways analogous to the short-term climatic changes during the "dust-bowl" years in the 1930's. Since this initial calibration study, we have improved the calibration methods (Webb and Clark, 1977; Howe and Webb, 1977), and we have expanded our data base by adding new sites with modern and fossil pollen data to our computer files.

Our first study (Bernabo and Webb, 1977) after adding the new data was to map the pollen data in order to illustrate the patterns and magnitudes of past changes in pollen for four major pollen

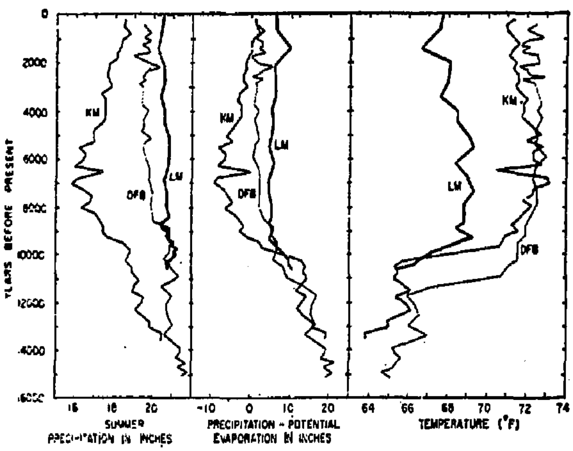


FIG. 4. The values for summer precipitation (April to September), precipitation minus evaporation, and July mean temperature estimated from the pollen records at Kirchner Marsh (KM), Disterhaft Farm Bog (DFB), and Lake Mary (LM). Originally published in Webb and Bryson (1972).

Paleoclimatic estimates for Kirchner Marsh, MN.

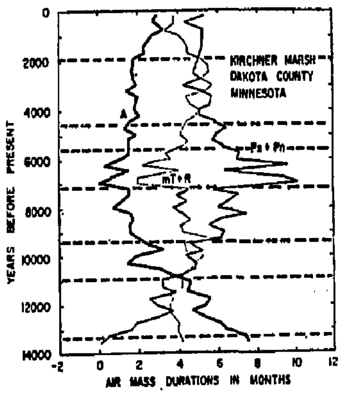


FIG. 5. The duration of air masses estimated from the pollen data from Kirchner Marsh over the last 13,000 years. A = arctic air from the north, mT = maritime tropical air from the south, R = return polar air from the south, Ps = Pacific southern air from the west, Pn = Pacific northern air from the west. From Webb and Bryson (1972).

Air-mass durations for Kirchner Marsh, MN.

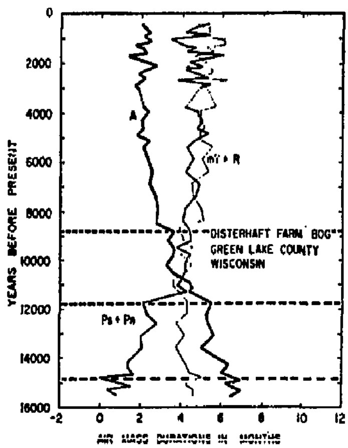


FIG. 6. The duration of air masses estimated from the pollen data from Disterhaft Farm Bog. See Figure 5 for a key to A, mT, R, Ps, and Pn. From Webb and Bryson (1972).

Air-mass durations for Disterhaft Farm Bog, WI.

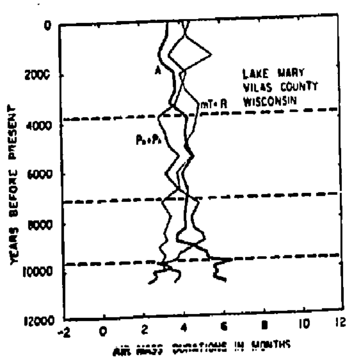


FIG. 7. The duration of air masses estimated from pollen data from Lake Mary. See Figure 5 for a key to A, mT, R, Ps, and Pn. From Webb and Bryson (1972).

Air-mass durations for Lake Mary, WI.

types (spruce, pine, oak, and prairie-herbs). These maps showed that not only had spruce migrated northwards from 11,500 to 8,000 years ago but that the prairie/forest border had moved first eastward 500 km and then retreated westward 100 to 200 km (Fig. 8). This study also showed that spruce trees have become more plentiful along the southern border of the boreal forest, thus indicating a southward movement of this border over the past 4000 years. At the same time, a group of mesic forest trees (birch, maple, beech, and hemlock) increased in abundance eastward from New York and New England (Fig. 9).

These final pollen changes imply that the climate of the Midwest became cooler and moister than it had been prior to 4000 B.P. This long-term trend toward moister conditions in the Midwest is one that may continue over the next 1000 or more years and is a trend that warrants concern if nuclear wastes are to be buried in the Midwest. Such an increase in moisture would significantly affect the rates and amount of ground-water recharge occurring in this region.

METHODS

General Procedure

At about the time that Imbrie and Kipp (1971) and Fritts et al. (1971) developed quantitative methods for calibrating marine plankton and tree rings, respectively, into climatic estimates, Webb and Bryson (1972) used canonical correlation analyses to calibrate pollen data in climatic terms. Since then, Webb and Clark (1977) have compared several numerical methods that can be used for calibrating fossil data and concluded that multiple regression analysis is the simplest, most straight-forward technique to use.

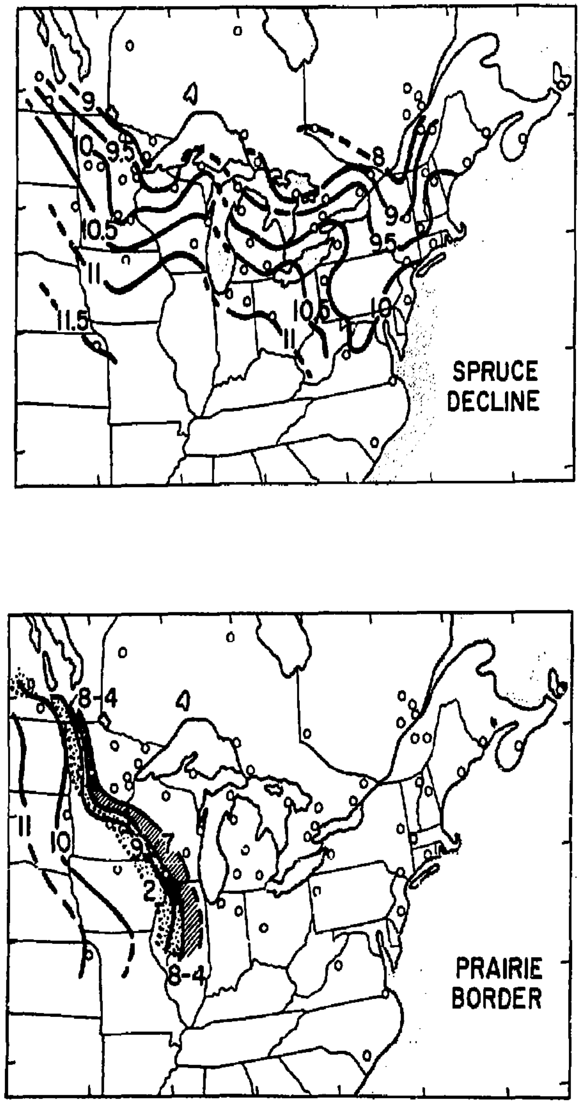


FIG. 8. Top map: Isochrones in 10^3 years for the time when spruce pollen decreased below 15% in the pollen diagrams from the sites indicated by open circles. These isochrones trace the movement of the inferred position of the southern border of the boreal forest. Bottom map: Isochrones in 10^3 years for the time when herb pollen increased above and/or decreased below 30% in the pollen diagrams from the sites indicated by the open circles. These isochrones show the inferred position of the prairie/forest border.

Maps of spruce decline and prairie migration.

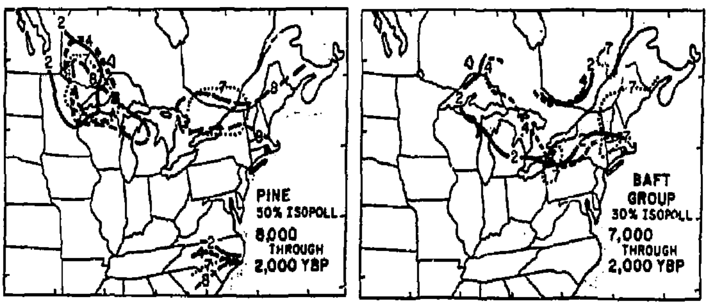


FIG. 9. Left map: Isochrones in 10^3 years showing the position of the 50% isofrequency contour for pine pollen. Note that the 50% contour occurs only in the west at 4000 and 2000 years ago. After 7000 years ago, pine dominance was replaced by the dominance of birch, maple, beech, and hemlock in the New England and the eastern Great Lakes region. Right map: Isochrones in 10^3 years showing the position of the 30% isofrequency contour for pollen from birch, maple, beech, and hemlock pollen. Note the westward movement of the 30% contour indicating the westward increase in abundance of these trees.

Maps of pine pollen and northern hardwood pollen.

The climatic calibration of pollen data begins with a set of modern pollen and climatic data. Maps of these data (Figs. 2 and 3) indicate the close correspondence between the distributions of certain pollen types and the distribution of standard climatic variables. When July-mean temperature and the percentages of oak pollen are plotted on a graph (Fig. 10), a strong positive relationship is evident. Existence of such a relationship makes it possible to calibrate the changing relative abundance of oak pollen in terms of numerical changes in temperature. Other pollen types can also be included in this calibration that then can be used to transform past changes in oak and other pollen types into past changes in climatic variables. These calibrations are most accurate for those situations in which the samples of past pollen resemble the samples of modern pollen used in the calibration.

The basic calibration-method involves finding a set of weighting factors B that rescale the pollen values P in terms of the climatic value C. The model for this procedure can be written as PB = C and represents in symbols the general process used in interpreting pollen data in terms of climate. Such an interpretation results in a transformation of changes scaled in pollen terms (i.e., a 30% increase in oak, elm, hickory, and ash pollen) into changes scaled either qualitatively (e.g., warmer and wetter) or quantitatively (e.g., higher by $2^{o}C$) in terms of climatic variables. In the situation illustrated in Figures 2, 3, and 10, regression analysis estimates the weighting coefficients B directly from the known values of modern pollen (P_m) and modern climate (C_m), i.e., the B's are calculated from the equation $P_m B = C_m$. Estimates of past climate (C_p) are then calculated by rescaling the values of previously deposited pollen (P_p) by B, i.e., $P_p B = C_p$, where B and C_p are estimates of B and C_p.

The major advantages of this procedure are that it produces

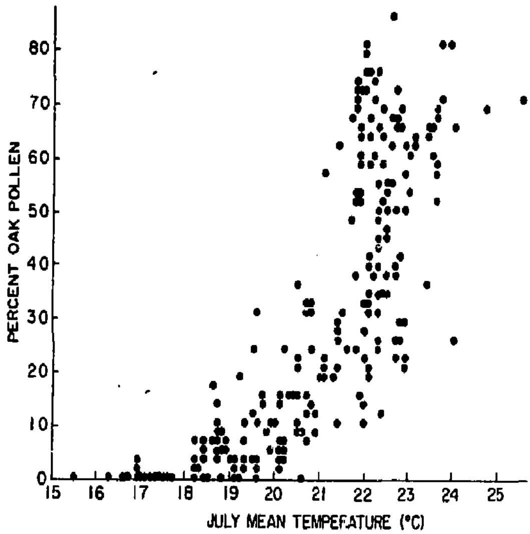


FIG. 10. Scatter diagram showing the relationship between July-mean temperature (°C) and the percentages of oak pollen today in the surfical lake-sediments.

Scatter diagram for oak pollen and temperature.

quantitative results for which confidence intervals can be calculated (Howe and Webb, 1977). The data and procedures are clearly defined and available to all investigators for use, criticism, and refinement.

The assumptions underlying this method of climatic interpretation are also clearly defined and available for criticism (Webb and Clark, 1977). Three of the assumptions are

1. that no significant changes have occurred to the biological factors in species or genera that affect their competition with other species or genera, i.e., evolution at the species or generic level is insignificant during the time period studied;

2. that modern data provide sufficient information for interpreting past data and further that a snapshot of modern spatial patterns is a sufficient basis for interpreting temporal changes; and

3. that the biological responses (i.e., changes in adaptations, growth rates, or abundances) are and have been related to physical attributes of the biotic environment, in particular to climatic variables.

The main criticisms of the procedure just described have focused on how well the latter two assumptions hold. The concern is that application of the regression coefficients, B, can yield climatic estimates for pollen changes unrelated to climate or can produce incorrect estimates when spatial variations in modern pollen are not good analogues for past temporal changes. In order to overcome the first of these criticisms, an investigator must establish that climatic changes are the likely cause for the observed changes in pollen.

One way to demonstrate this fact is to produce maps showing the spatial patterns of the temporal changes in the pollen record. Because broad-scale geographical patterns are generally associated with changes in the broad-scale climate, the pollen changes that show similar trends over large areas are probably caused by climatic changes. In contrast, those pollen changes at particular sites that do not occur at nearby sites probably result from one of several non-climatic factors that influence vegetation. These factors include soil changes, forest fires, human disturbance, local infilling of the site, and invasions by new species.

A second concern with the calibration procedure is that it is empirical and statistical rather than deductive and deterministic. When biologists produce a deterministic model for long-term plant-population changes and base the model on equations derived deductively from well known physical laws that can be assumed to hold constant throughout geological time, then the empirical procedures and their associated short-comings can be avoided. Because no such deterministic models are available, we have been forced to proceed with empirical methods. In the course of our research, we hope that we can aid the biologists who are developing the deterministic models.

Calibration Functions for Estimating Annual Precipitation

Two calibration equations were used in this study in estimating past precipitation values from the 26 sites with fossil pollen data. The first calibration function is based on data from 282 sites from 40 to 47^{o}N (Table 1) and was used at all fossil sites except for Glenboro and Grand Rapids (Table 3). The second calibration function is based on data from 120 sites from 47 to 60^{o}N (Table 2) and was used at these two northern sites (Table 3). The first equation shows the importance of herb pollen in estimating

TABLE 1: Calibration Function Used at 24 Midwestern Sites to Estimate Annual Precipitation (in cm).

Pollen Type	Correlation with Annual Precipitation	Multiple Regression Coefficients
$(\text{Pigweed Family})^{1/2}$	-.71	-0.6733
$(\text{Sage})^{1/2}$	-.71	-4.1835
Pigweed Family	-.70	-0.3592
Juniper/Cedar	.20	+0.9683
$(\text{Hickory})^{1/2}$	.38	+2.0152
Daisy Family	-.36	-0.4798
Willow	.22	+0.6244
Constant		80.9053
Variance (%)		78
Standard Error		5.4 cm
Area of Samples		40-47°N 85-105°W
Number of Samples		282

TABLE 2: Calibration Function Used at 2 Sites in Manitoba to Estimate Annual Precipitation (in cm).

Pollen Type	Correlation with Annual Precipitation	Multiple Regression Coefficients
$(\text{Oak})^{1/2}$	.50	2.0973
Pine	.20	0.2658
Birch	.21	0.2204
Grass Family	.10	0.2359
Pigweed Family	-.15	-0.5256
$(\text{Pigweed Family})^{1/2}$	-.01	1.4950
Willow	.00	0.4836
Daisy Family	.05	0.5274
Constant		28.8001
Variance Explained (%)		65
Standard Error		3.3 cm
Area of Samples		47-60°N 95-105°W
Number of Samples		120

TABLE 3: ESTIMATES OF ANNUAL PRECIPITATION IN C.M. A... PRECIPITATION DIFFERENCES IN % OF TODAYS VALUE.

SITE	ANNUAL PRECIPITATION 10,000 B.P.	7,000 B.P.	TODAY	PRECIP. DIFFERENCES 7,000 -10,000 B.P.	TODAY -7,000 B.P.	DATING INFORMATION NO. OF C-14 DATES	EARLIEST DATE B.P.
GRAND RAPIDS	--	41	48	----	14.6	3	7220
GLENBORO LAKE	47	46	48	-2.1	4.2	5	12800
LAKE OF THE CLOUDS	73	72	68	-1.5	-5.9	+	10000
BOG D POND	72	60	69	-17.4	13.0	4	11000
TERHELL POND	75	62	69	-18.8	10.1	1	4270
WEBER LAKE	73	71	71	-2.8	0.0	5	14600
PORTAGE LAKE	75	62	70	-18.6	11.4	3	9780
RUTZ LAKE	71	60	72	-15.3	16.7	7	12000
KIRSCHNER MARSH	76	64	72	-16.7	11.1	6	13270
PICKEREL LAKE	71	51	57	-35.1	10.5	4	10670
W. OKOBOJI LAKE	76	66	70	-14.3	5.7	10	13990
JACOBSON CORE 1	74	70	74	-5.4	5.4	2	10400
JACOBSON CORE 2	--	71	74	----	4.1	2	7210
DEVILS LAKE	--	39	52	----	25.0	1	6120
LAKE MARY	75	77	77	2.6	0.0	3	9460
CAMP 11 LAKE	76	78	80	2.5	2.5	+	10000
STEWART'S DARK L.	77	74	74	-4.1	0.0	6	10570
DISTERHAFT	78	75	75	-4.0	0.0	6	15560
ALFIES LAKE	72	80	81	9.9	1.2	3	9210
GREEN LAKE	74	75	80	1.2	6.3	3	15215
DEMONT LAKE	79	78	76	-1.3	-2.6	5	11410
VESTABURG BOG	80	82	75	2.7	-9.3	3	10330
WINTERGREEN LAKE	80	80	82	0.0	2.4	8	13195
FRAINS LAKE	81	81	78	0.0	-3.8	7	12570
HUDSON LAKE	81	81	95	0.0	14.7	6	11500
PRETTY LAKE	81	85	90	4.4	5.6	15	13265
SILVER LAKE	85	87	96	2.1	9.4	8	10800

annual precipitation (Fig. 3). Explaining 79% and 65% of the variance and having standard errors of 5.3 and 3.3 cm, these two equations provide the best calibrations that we have gained so far. One major achievement of the research for this project was to reduce the standard error from 8.3 cm to 5.3 cm in the main equation used (Table 1).

RESULTS AND DISCUSSION

The calibration functions (Tables 1 and 2) were applied to pollen data from 26 sites in the Midwest and Canada (Fig. 11). Twenty-one of the sites have more than two radiocarbon dates (Table 3), and ten sites are well-dated with six or more dates. One site (Lake of the Clouds) possesses both multiple radiocarbon dates and annually laminated sediments that can be used for establishing a chronology for the past 9500 years. Pollen data are available at all sites for 7000 years ago, but no data exist at either Devil's Lake or Grand Rapids for 10,000 years ago.

The sequence of maps of precipitation estimated for 10,000 (Fig. 12) and 7000 (Fig. 13) years ago and observed for today (Fig. 14) shows a decrease in precipitation from 10,000 to 7000 years ago in the western Midwest (Fig. 15) followed by an increase in precipitation in this area from 7000 to today (Fig. 16). In the eastern Midwest, the changes are smaller, but the data indicate an increase in precipitation in Ohio and Indiana from 10,000 to 7000 years ago and a decrease from 7000 to today in central Michigan. All sites show some change over the last 10,000 years with the highest percentage changes (of 15 to 30%) located in the west.

These results reflect the vegetational changes described in the POLLEN ANALYSIS section and are consistent with the previous estimates of Webb and Bryson (1972). The maps showing decreasing

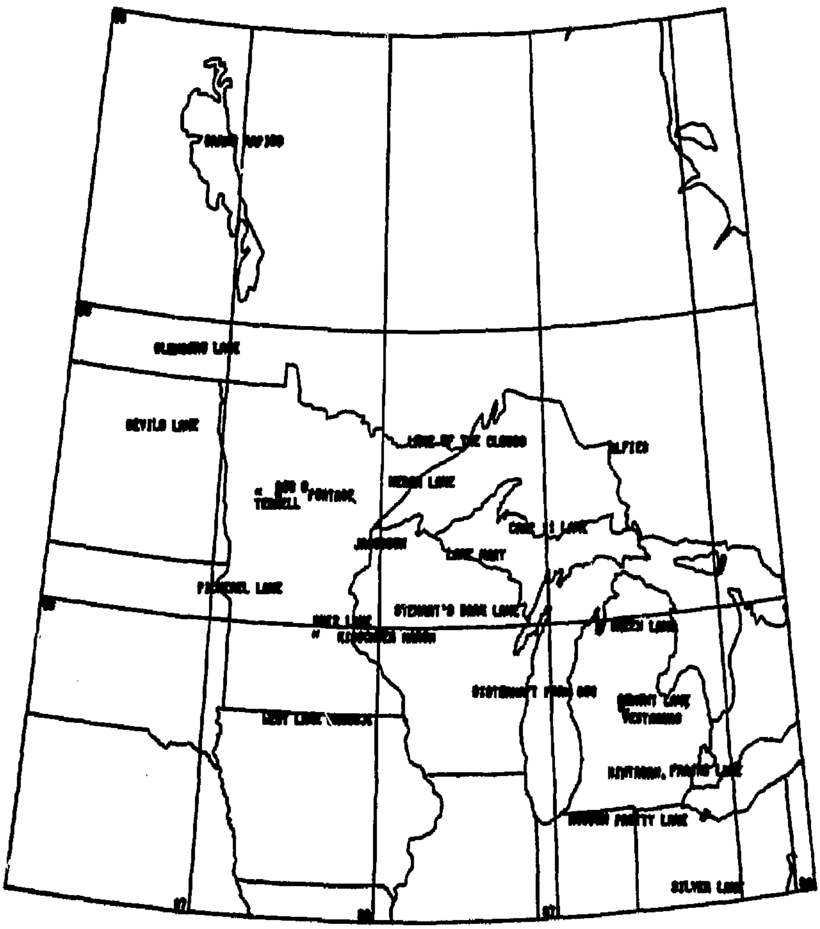


FIG. 11. Location of the 26 sites with radiocarbon-dated pollen data used in estimating annual precipitation at 7000 and 10,000 years ago.

Location of 26 sites with pollen.

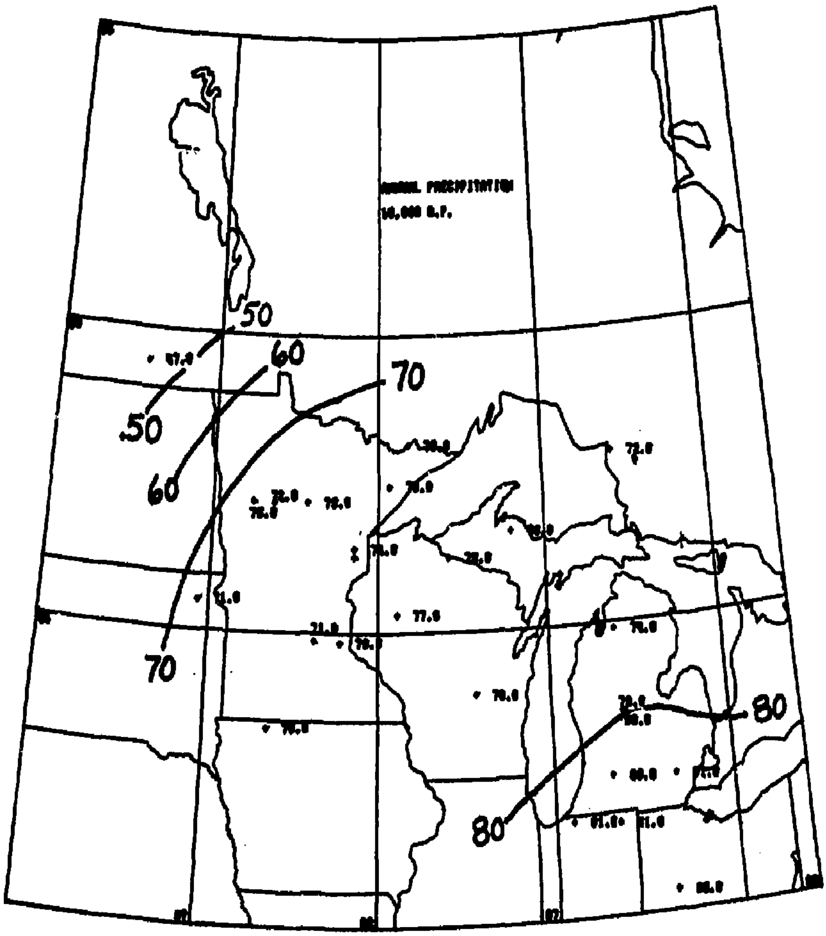


FIG. 12. The estimates of annual precipitation in cm for 10,000 years ago.

Precipitation estimates for 10,000 years ago.

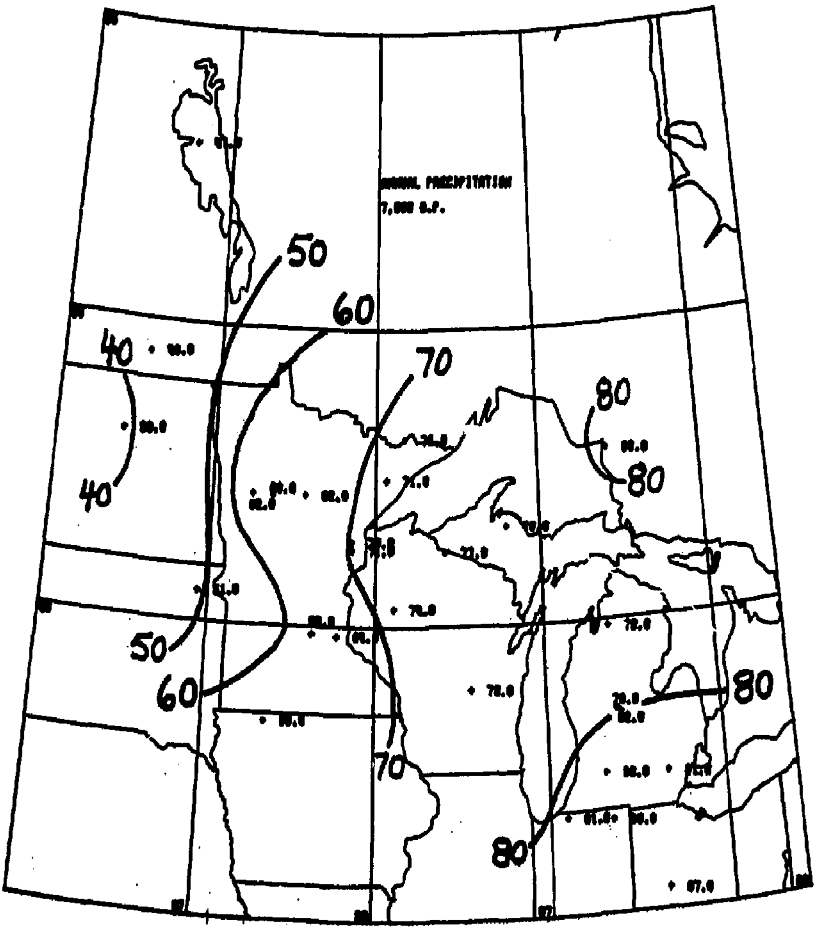


FIG. 13. The estimates of annual precipitation in cm for 7000 years ago.

Precipitation estimates for 7000 years ago.

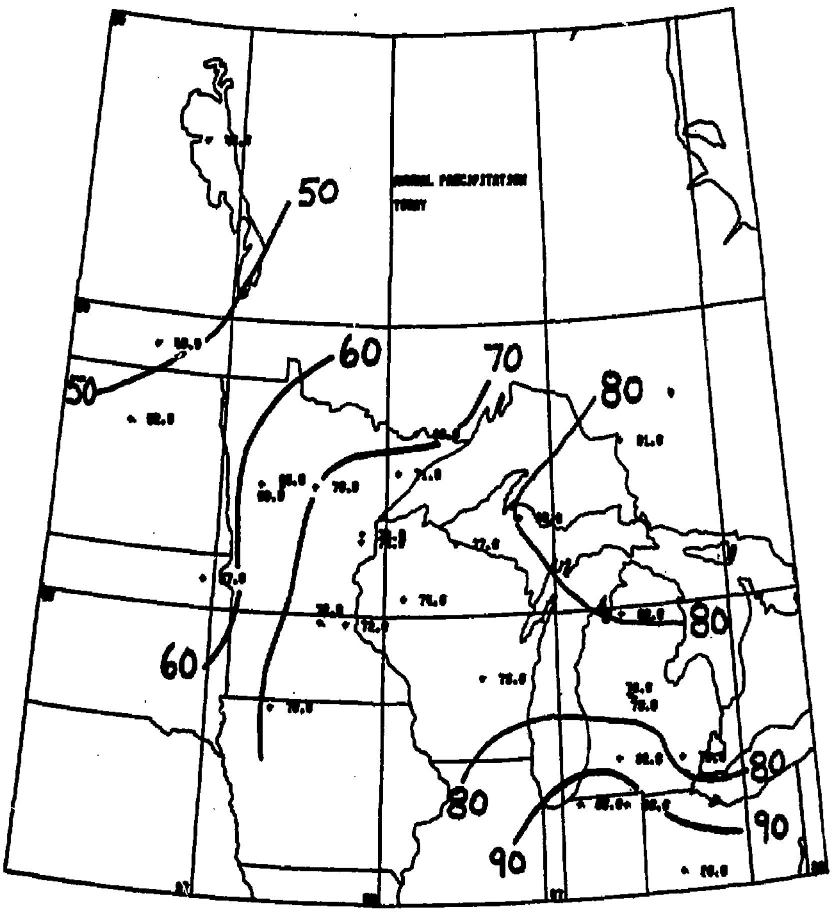


FIG. 14. The observed values for mean annual precipitation in cm for 1941 to 1970.

Observed precipitation today.

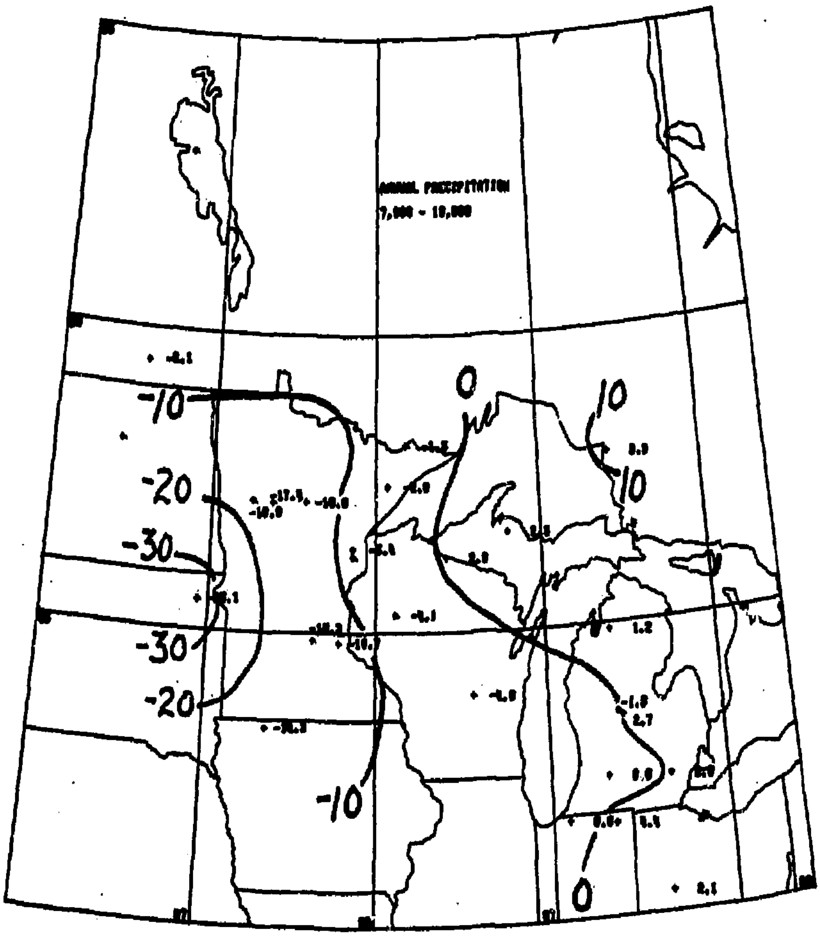


FIG. 15. The changes in annual precipitation between 10,000 and 7000 years ago in % of today's value at each site. Negative values indicate sites with less precipitation at 7000 years ago than at 10,000 years ago.

Percent changes in precipitation 10,000 to 7000 BP.

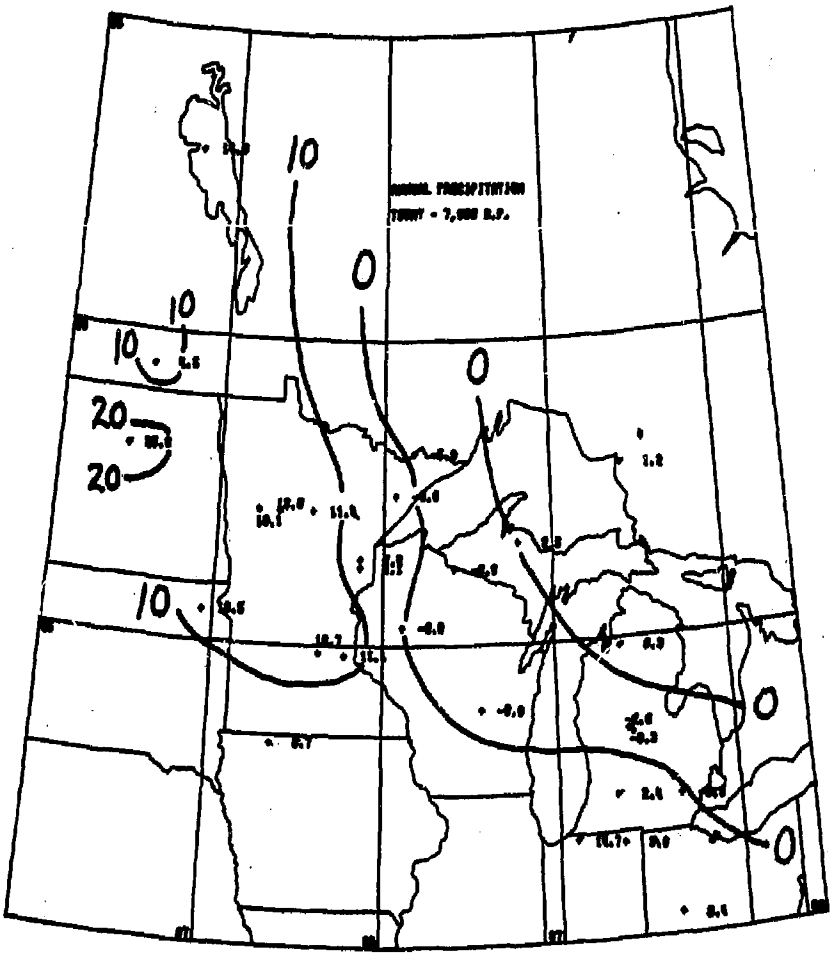


FIG. 16. The changes in annual precipitation between 7000 years ago and today in % of today's value at each site. Positive values indicate sites with more precipitation today than at 7000 years ago.

Percent changes in precipitation 7000 BP to today.

and then increasing precipitation in the western Midwest reflect the pollen evidence for the eastward and then westward movement of the prairie/forest border (Fig. 8). The increase in precipitation in northern Michigan and Ontario reflects an increasing abundance of mesic forest trees over the past 7000 years (Fig. 9). A decrease in temperature of 1 to 2°C over the past 7000 years is also estimated for these sites and the other northern sites, thus indicating an increase in moist conditions throughout the northern Midwest during this time period.

The hydrological conditions in the Midwest have therefore been in a constant state of flux over the past 10,000 years. Recent trends indicate that increasingly moist conditions are likely in this area over the next 1000 or more years. Because such conditions imply more rapid rates of groundwater recharge than those observed today, these trends should be allowed for in any hydrological calculations that are made for proposed sites for waste storage.

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