A Paleohydrologic and Paleoclimatic Reconstruction for the San Agustin Basin, New Mexico, Based on Oxygen-18 Variation in Ostracode Shells

by
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An Independent Study submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Hydrology

New Mexico Institute of Mining and Technology
May, 1990

ABSTRACT

The Plains of San Agustin form a high-altitude, topographically closed basin in west central New Mexico which held a large, perennial lake during much of the Holocene and Pleistocene. Fluctuations of the paleolake surface area were produced in response to climatic changes (fluctuations in moisture input and temperature), and are a sensitive reflection of changes in the basin water balance (inflow versus evaporative outflow). A history of lake volume fluctuations is recorded in the stable isotope composition of ostracode shell carbonate deposited with lacustrine sediments. A composite stable isotope and biostratigraphic record from the Plains of San Agustin provides the framework for a unique and comprehensive reconstruction of the paleohydrology and paleoclimate of the basin for the period 21-5 ka.

The chronological framework was established by correlation with a ^{14}C-dated ostracode/stratigraphic record developed by previous investigators. Variation in the ^{18}O and ^{13}C content of biogenic carbonate reflects temporal changes in isotopic composition of the lake water and was used to infer changes in paleoclimatic parameters and to quantitatively model lake volume (surface area) fluctuations. The ostracode biostratigraphy formed the basis for inferring changes in paleotemperatures and freshwater inflow and provided a constraint on low lake levels. Correlation between the isotopic and biostratigraphic records was excellent.

Quantitative reconstruction of the paleohydrology of Lake San Agustin based on its isotopic evolution has been facilitated by a numerical model after Phillips and others (1986b). The lumped-parameter model links water mass balance and isotope mass balance equations and incorporates temporally varying inflows, evaporative fluxes, outflows, temperatures, and humidities. Model simulations of lake surface area and inflow correlate well with the biostratigraphic record.

The composite paleoclimate/paleohydrology record from San Agustin is consistent with the following significant climatic events during the late Wisconsin and Holocene: (1) a stable, full glacial climate characterized by cold temperatures and a very favorable water balance from 21.7-19.0 ka; (2) a significant, regional warming event at 19.0 ka; (3) a climatic trend during the late Wisconsin deglacial interval (17.0-12.0 ka) characterized by extreme fluctuations in moisture input and moderate variation in temperature; (4) a cold thermal regime between 12.0 and 11.0 ka which is probably correlative with the Younger Dryas climatic reversal; (5) replacement of a winter, Pacific storm track by a summer monsoonal precipitation regime from the Gulf of Mexico by at least 10.0 ka. A similar mechanism of climatic forcing and hydrologic response probably prevailed throughout the major pluvial basins of the American Southwest.

ACKNOWLEDGEMENTS

Funding for the research presented herein was provided under Federal Water Resources Act grant number 1345662 and New Mexico Water Resources Research Institute grant number 1423687. Appreciation is extended to Sato Lee and family of Datil, New Mexico, for providing access to their land on the San Agustin Plains. I thank my advisor, Fred Phillips, and Andrew Campbell, John Hawley, Dave Johnson and Richard Forester for their knowledge, guidance and support. Special gratitude is expressed to the other members of this research team, Randall Roberts and Cynthia Kruger, for their unconditional support and assistance, and to Annette Schaffer-Perini for her help on the VAX. Julio Betancourt and Richard Madole are graciously acknowledged for their objective review of research results and interpretations.

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1. Geologic and Hydrologic Environment

Site Characteristics. The Plains of San Agustin are located in Catron and Socorro Counties, west central New Mexico (33°45'-34°15'N; 107°25'-108°20'W) (Fig. 1). The region is a high altitude, topographically closed basin which held a large, perennial lake during much of the Holocene and Pleistocene. The San Agustin catchment area, which covers approximately 5,180 square kilometers (2,000 square miles), is bound on the south and west by the Continental Divide. The boundary to the south is formed by the Luera Mountains, Pelona Mountain and O-Bar-O Mountain; to the northeast by the Gallinas Mountains; to the northwest by the Datil Mountains and Mangas Mountains; to the west by the Tulerosa Mountains; and on the east by the San Mateo Mountains. Elevations range from 2,065 meters (6,775 feet) on the southwest portion of the basin floor to 3,083 meters (10,115 feet) on Mt. Withington in the San Mateo Mountains.

The present day climate in the region is semiarid. Annual precipitation ranges from 250-380 millimeters (10-15 inches) in lower elevations to 760 millimeters (30 inches) in the highlands. Modern vegetation (Potter, 1957) consists of saltbrush and greasewood grasslands on the lower elevation flats, pinyon-juniper and ponderosa pine forests on the lower mountain slopes, and douglas fir forest at higher elevations.

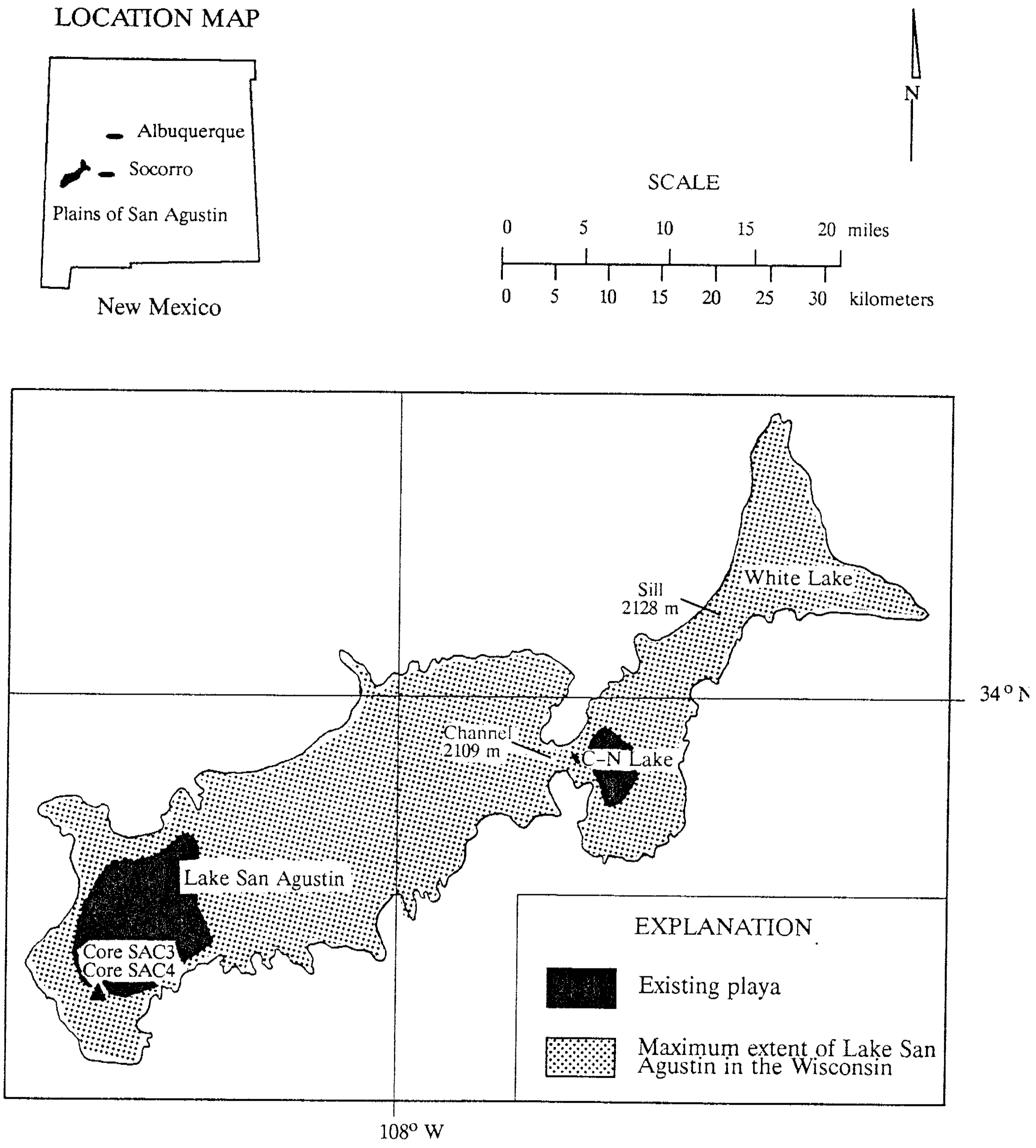


Figure 1: Location and configuration of Lake San Agustin at the 2,135-meter level (after Weber, 1980), and location of sediment cores.

Geologic Environment.

Structure The Plains of San Agustin lie within the Datil-Mogollon volcanic plateau on the boundary between the Basin and Range and Colorado Plateau physiographic provinces. The basin is a graben structure associated with the latest Miocene and/or Pliocene phase of spreading along the Rio Grande rift (Chapin and Seager, 1975), and is bound by faults along the northwest, southeast and southwest margins (Stearns, 1962). Minimum structural relief along the margin-bounding faults is at least 4,000 feet; however, surface expression of the offset has been reduced more than half by Quaternary sedimentation. There is no geologic evidence of tectonic deformation in the basin during post-Wisconsin.

Lithology Lithology in the highlands surrounding the basin consists predominantly of mid-Tertiary (Oligocene-Miocene) volcanics interbedded with sedimentary and volcaniclastic units (Stearns, 1962; Weber, 1980). Pliocene-Pleistocene littoral and lacustrine deposits of extinct Lake San Agustin fill the basin to significant depths. Late Pleistocene to Holocene surficial deposits cover the lower mountain slopes and valleys tributary to the Plains.

Geomorphology Extensive geomorphic evidence of Lake San Agustin exists along the basin margins. Shoreline features in the form of well-developed beaches, spits and bars have been mapped in detail by Powers (1939); this mapping has been refined and modified recently by Weber (1980; oral commun., 1989). The features imply a history of fluctuating lake levels with relatively few stable stages. The highest shoreline recognized by Powers is at 2,115 meters (6,940 feet). Recent work by Weber has further defined traces of pre-Wisconsin shore deposits as high as 2,149 meters (7,050 feet), and a possible Wisconsin shore maximum at 2,135 meters (7,005 feet). A series of wave-cut shorelines and beach deposits, representing lower lake levels, extends to the modern playa boundary at approximately 2,070 meters (6,790 feet).

Three major subbasins occur within the main structural valley of the Plains of San Agustin and include, from southwest to northeast, Lake San Agustin, C-N Lake and White Lake. The subbasins are situated at elevations of 2,065 meters (6,775 feet), 2,101 meters (6,894 feet), and 2,119 meters (6,952 feet), respectively. Lake San Agustin was hydrologically connected to C-N Lake via a channelway at 2,111 meters (6,925 feet). The C-N Lake and White Lake subbasins are separated by a sill at 2,128 meters (6,980 feet). During higher lake levels (above 2,128 meters), the subbasins were interconnected to form one large reservoir. At its 2,149-meter high stage, the lake was 70 meters (230 feet) deep with a surface area of approximately 1,226 square kilometers (473 square miles) (Weber, 1980). During low lake stages (below 2,111 meters) each subbasin was hydrologically isolated, with C-N and White Lakes existing in a playa environment. True lacustrine conditions were maintained most consistently in the Lake San Agustin subbasin.

The current semiarid environment and internal drainage cause playa conditions to dominate the modern basin. No perennial streams discharge into the basin and most precipitation falls during intense storms of short duration in the late summer months. Wet playa conditions are therefore maintained intermittently by runoff during the wet season. Dry playa conditions prevail the remainder of the year.

Hydrologic Environment. The modern regional hydrologic regime in the San Agustin basin is poorly understood. The regional groundwater gradient in the basin subsurface is approximately 0.0054 to the south-southeast with a proposed discharge to the San Francisco River. The water table ranges from 14 to 24 meters below the floor of the San Agustin subbasin (Blodgett & Titus, 1973). The basin fill sediments have not been evaluated for hydraulic properties and values previously used for hydraulic conductivity and specific storage are unfortunately rough estimates at best. Absence of evaporite minerals in subsurface sediments has been interpreted by previous investigators (Blodgett and Titus, 1973) as evidence of a substantial component of groundwater seepage from the lake basin. This position is further supported by estimates of high hydraulic conductivities for the fractured volcanic bedrock and interbedded fluvial-lacustrine sediments underlying the basin floor. In this study, the paleohydrologic environment is conceptualized as involving transient interactions between the lake and a contiguous regional groundwater aquifer; accordingly, fluctuations in lake level are viewed as producing a time-lagged, buffered response in the adjacent aquifer.

Lake level fluctuations are controlled by complex interactions between several mutable factors, both intrinsic and extrinsic to the basin, including climate, hydrologic properties and vegetation. The magnitude of the role played by any one factor has generally been controversial. Identification of synchronous changes in lake level at San Agustin, Searles Lake, and other sites in the western and southwestern United States, may clarify the effects of regional climatic changes; however, climatic change produces interactive feedback responses in vegetation, runoff, and groundwater flow. Further difficulty is encountered with attempts to distinguish which paleoclimatic parameter(s) is the catalyst for a particular hydrologic response. Whereas most investigators agree that changes in lake surface area are probably produced by a combined change in both temperature and precipitation, with the accompanying effects on evaporation rate, humidity, and insolation, there is little accord concerning the relative contribution of any single parameter.

A brief evaluation of the catchment and water balance of the San Agustin basin will provide a qualitative sense of the relative significance of the various parameters controlling lake level. Lake San Agustin has a rather small catchment (lake area to catchment area ratios range from 1:4 for high stages to 1:30 for low stages), and it is unlikely that a high lake stage could be sustained solely from direct runoff and precipitation on the lake surface. Even when the relative contribution of these inflow components is greatly enhanced by reduced temperatures and evaporation rates associated with past glacial climates, it is intuitively improbable that a positive water balance sufficient to maintain a high lake stage would result. A significant contribution to lake inflow was probably provided by local groundwater or interflow, particularly during higher lake stands. Changes in lake level provide estimates of changes in lake volume (dV/dt) which in turn may be assumed to represent a balance between catchment runoff (Q_R), precipitation on the lake surface (Q_P), net evaporation from the lake surface (Q_E), and net exchange with groundwater (Q_{GW}). The water balance for the basin may then be represented by the equation:

$$dV/dt = Q_R + Q_P - Q_E - Q_{GW}$$

In this study, both qualitative interpretations and quantitative numerical modeling of the data group the inflow parameters (runoff, precipitation and groundwater inflow/interflow) into one inflow flux. The outflow parameters (net evaporation and groundwater seepage) are evaluated independently.

2. Stratigraphic Record

Sediments. Subsurface lacustrine sediments from the Plains of San Agustin have previously been described by Clisby and Sears (1956), Foreman and others (1959) and Markgraf, and others (1983). This established sediment record, obtained predominantly from a 600-meter core recovered in the center of the basin, consists of silty clay with alternating layers of sand from 14 to 65 meters and below 290 meters.

The sediment record which forms the basis of this study is a composite of two cores, SAC-4 and SAC-3, funded under this research grant. The cores were recovered at the same site, aproximately 45 meters west of Boss Well in the SW 1/4 of the SE 1/4 of section 21, T6S, R14W, Rael Spring Quadrangle, Catron County, New Mexico, at a surface elevation of 2,071 meters (6,794 feet). The drill site is located along the depositional boundary separating playa and lacustrine conditions, and is situated sufficiently inward from the basin margin so as to avoid thick sequences of littoral and fluvial gravels, and far from regions within the basin center where deflation has removed Holocene sediments. Core SAC-4 was retrieved in one-foot sections with three-inch diameter shelby tubes. This core covers a depth interval from the present surface to 27.4 feet (8.35 meters) with 91% recovery. (The original units of measurement for core SA4 and SA3 were English units of length. Because field logs and notes were completed in units of feet, direct references in the text to depth within the core are in these units and parenthetical references are in metric units.) Core SAC-3 was retrieved with a split-spoon sampler and extends from 26.0 to 63.7 feet (7.92 to 19.48 meters) with 86% recovery.

Cores SA4 and SA3 are correlated along an abrupt contact between two distinctive sand units. This contact occurs at a depth of 26.3 feet (8.02 meters) in SAC-3 and at 26.0 feet (7.92 meters) in SAC-4. Further paleontologic support for correlation is provided by a six-inch interval within the lower sand unit which contains similar and unique specimens of the ostracode Limnocythere ceriotuberosa. In both cores, mature ostracodes from this interval were abnormally small with articulate valves. Similar ostracode specimens were not observed elsewhere in either core. Such lithologic and paleontologic evidence collectively provide a firm basis for correlation between the 26.0-foot (7.92-meter) level of SAC-4 and the 26.3-foot (8.02-meter) level of SAC-3.

A detailed lithologic log of the composite sediment core, SAC-3/4, is attached as Appendix A. The general nature of the sediment record is briefly described here. Deposition in the basin is dominated by clastic sedimentation; no significant intervals of chemical sediments are observed in the record. The upper 25 feet (7.62 meters) of sediment consists of massive and laminated clays and clayey silts which are rich in organic material. The uniform nature of these near-surface sediments suggests that stable deep water conditions prevailed throughout the deposition interval. X-ray diffraction of laminated clay sequences indicates the presence of illite, smectite and mixed-layer clays. This clay assemblage may be suggestive of a variable weathering environment, produced in response to changing climatic conditions, or it may be a product of multiple source areas for the sediments. Sediments recovered from the interval between 25 feet (7.62 meters) and 64 feet (19.51 meters) are dominated by alternating sands and gravels. Field logs of core cuttings from sediment intervals not recovered indicate these sections are dominated by clays and clayey silts. The alternating coarse-fine sediment sequences below 25 feet (7.62 meters) indicate that continually fluctuating lake levels prevailed throughout this deposition interval.

Ostracodes. Ostracodes were found continuously and in large numbers throughout the upper 27 feet (8.23 meters) of sediment. The valves are typically well preserved and always identifiable to species. Only two intervals in the lower section of core -- 33.7 to 34.2 feet (10.27 to 10.42 meters) and 40.4 to 41.6 feet (12.31 to 12.68 meters) -- contain significant numbers of ostracode valves. Five species of Ostracoda were identified from core SAC-3/4: (a) *Limnocythere bradburyi* (Fig. 2a,b), (b) *L. ceriotuberosa* (Fig. 2c,d), (c) *L. platyforma* (Fig. 2e,f), (d) *Candona patzcuaro*, and (e) *Heterocypris* spA. Ostracode biostratigraphy and isotopic data from shell carbonate provide the framework for the paleoenvironmental interpretations presented later in this report.

3. Methods

Lacustrine Ostracoda as a Tool In Paleoenvironmental Reconstructions. Lacustrine Ostracoda have been widely applied in reconstructing continental paleoclimates (Forester, 1985; De Deckker, 1988) and paleohydrochemistry (Forester, 1983; 1986;

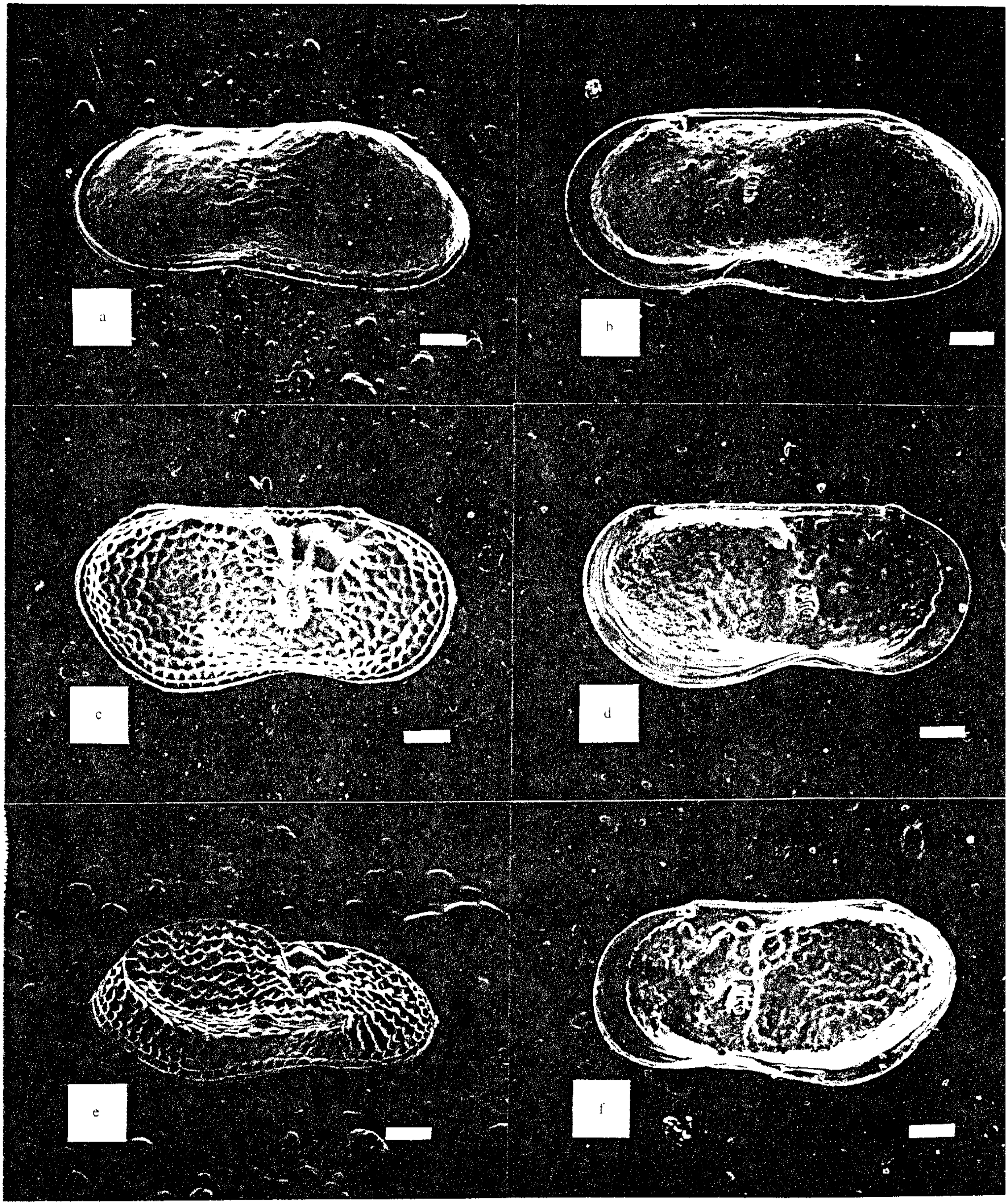


Figure 2: Ostracode specimens from Lake San Agustin. Bar scale is 1 micrometers. (a) *Limnocythere bradburyi*, left valve exterior, male; (*L. bradburyi*, right valve interior, male; (c) *L. ceriotuberosa*, right valve exterior, male; (d) *L. ceriotuberosa*, left valve interior, male; (e) *L. platyforma*, right valve exterior, male; (f) *L. platyforma*, rig valve interior, male.

Chivas and others, 1985; 1986a; 1986b) since Delorme (1969) first recognized that particular ostracode species were so habitat-specific that they could be used as very sensitive indicators of temperature, water depth, salinity and hydrochemistry. When the temporal distribution of these variables is known, they can be used as a proxy record of past climatic conditions. For reviews see Forester (1987), Carbonel and others, (1988), and DeDeckker and Forester (1988).

Use of stable isotope data from lacustrine ostracode shell carbonate to make quantitative paleoenvironmental interpretations has yet to receive such broad application despite the high potential. Ostracodes are typically the most ubiquitous and abundant calcareous microfossil in lacustrine environments, and often the only verifiable source of primary carbonate. Preliminary investigations strongly suggest that freshwater ostracode carapaces are precipitated in isotopic equilibrium with the ambient dissolved carbonate species (Durazzi, 1977; Gasse and others, 1987; Lister, 1988a). In circumstances where ostracode tests precipitate in isotopic equilibrium from a well-mixed reservoir, oxygen isotope variations in biogenic carbonate record temporal changes in ^{18}O composition of the lake water. Such compositional changes may then be related to climatic shifts or hydrologic changes within the basin. The value of ostracode shell carbonate as a source of stable isotope data has been demonstrated in the recent work of Chivas and others, (1986b) and Lister (1988a; 1988b).

The extent to which taxonomic factors influence incorporation of ^{18}O in the ostracode shell is uncertain and should be addressed. Previous studies (Durazzi, 1977) have indicated that different ostracode taxa from the same sample show significant differences in ^{18}O composition. Based on recent studies which support equilibrium isotopic fractionation during shell precipitation, the most likely explanation is that such taxonomic variations reflect different seasonal growth preferences or environmental conditions. In any case, problems resulting from such "vital effects" should be avoided by analyzing samples consisting of a single species or an assemblage of closely related species. The influence of taxonomic factors on ^{18}O composition of ostracode shells in this study is discussed in greater detail later in the report.

Modern Biogeographic Distribution and Occurrence of Ostracode Species. The geographic and ecologic occurrence of *Limnocythere bradburyi* has been well studied by Forester (1985; 1987). Today, *L. bradburyi* lives in large, shallow, ephemeral lakes in the central Mexican Plateau and in southern New Mexico. It has also been identified in Quaternary sediments from localities in Mexico and the southwest United States (Cameron and Lundin, 1977; Forester 1985; 1987). *Limnocythere ceriotuberosa* lives in deep and shallow lakes including ephemeral waters. Its modern distribution extends throughout the central Great Basin and from the central prairies north into the interior plains of Canada (Delorme, 1971; Forester, 1985; 1987). It has been discovered coexisting with L. bradburyi in fossil lake sediments of Lake Cochise in Arizona (Cameron & Lundin, 1977).

Forester (1985; 1987) has also made special interpretations of the co-occurrence of Limnocythere bradburyi and L. ceriotuberosa. Modern geographic distribution of these two species is separated latitudinally along the frost line; L. bradburyi occurs south and L. ceriotuberosa occurs north of the line. It has been proposed that seasonal variation in water temperature is the principal factor controlling geographic occurrence of these two species within suitable compositional and salinity ranges. L. bradburyi requires relatively warm water to hatch, mature and reproduce. The modern temperature constraints for L. bradburyi in central Mexico are roughly 10 to 22 °C; whereas it can probably tolerate winter temperataures colder than 10 °C, it can not tolerate prolonged periods of freezing temperatures. L. ceriotuberosa begins its lifecycle in near freezing winter temperatures and matures through the spring as water temperatures become warmer. It can live in water with a greater seasonal temperature range (0 to 25 °C) than L. bradburyi. Because L. ceriotuberosa lives in regions where summer temperatures are hotter than those of central Mexico, but does not live in Mexico, its occurrence there is apparently precluded by warm winter temperatures. Similarly, absence of L. bradburyi in northern latitudes may be due to cold winter temperatures. Coexistence of L. bradburyi and L. ceriotuberosa at San Agustin therefore implies that winter temperatures were probably warmer than today (above -2 to -4 °C) but not as warm as presently occur in central Mexico (10 °C). Although specie succession is an ecologically complex process affected by numerous parameters (e.g., salinity changes, nutrient distribution, and other biological controls), the modern spatial distribution of L. bradburyi and L. ceriotuberosa appears to be controlled by seasonal temperatures. It is therefore possible to interpret temporal transitions between the two species in the biostratigraphic record in terms of relative temperature changes over time. For example, replacement of L. ceriotuberosa by L. bradburyi indicates a trend toward warmer winter temperatures. Replacement of L. bradburyi by L. ceriotuberosa, on the other hand, suggests significantly colder winters, and possibly cooler summers. Further applications and limitations of such temperature interpretations based on the ostracode biostratigraphy will be discussed in greater detail later in this report.

The modern occurrence of Limnocythere platyforma (Delorme, 1971) is rare. The extant specie has only been documented in a small pond in the central prairies of Canada. L. platyforma is viewed as an ecophenotype of L. ceriotuberosa (R.M. Forester, written commun., 1987) based on a complete gradational series between the two forms. Generation of the morphs is not completely understood, but because L. platyforma is more heavily calcified, one possible explanation calls for it living in waters with a higher Ca^{2+} concentration, i.e., fresh waters. The occurrence of L. platyforma therefore suggests an increase in fresh-water inflow. Its co-occurrence with L. ceriotuberosa could be due to sediment averaging or to seasonal variability in water chemistry.

Candona patzcuaro lives in ditches and ponds throughout the semiarid regions of the North American plains and the southwest central portion of the Canadian prairies (Delorme, 1970). C. patzcuaro and Heterocypris spA, collectively separated from the sediment residue, possess characteristics which specifically adapt them to a fluctuating shoreline environment. Juvenile and adult forms of C. patzcuaro possess the unique ability to form a coating which protects them during long periods of desiccation and, accordingly, are well suited to the environmental variability of shifting shorelines. Heterocypris spA, a new specimen recognized by Richard M. Forester (written commun., 1987) which is believed to have affinities to H. incongruens, is specifically associated with a source of fresh water. Its occurrence at San Agustin is believed to be connected to discharge of relatively fresh, "bank-storage" water during a drop in lake level.

The five species of ostracodes which occur in San Agustin sediments live in chemically similar waters which are carbonate enriched and dominated by Na^+, Mg^{2+}, HCO_3^-, CO_3^{2-}, and/or Cl^- ions. Limnocythere ceriotuberosa lives in fresh to slightly saline waters with a TDS ranging from 500 to 25,000 ppm, with a greater salinity tolerance in Cl^--dominated water (Forester, 1987). L. bradburyi tolerates a narrower salinity range, from 1,000 to 10,000 ppm (Neale, 1988).

Sample Selection, Preparation and Isotopic Analysis.

Sample selection. Determination of sample size was primarily governed by a need to obtain sufficient carbonate from one ostracode specie for isotopic analysis. A second consideration was to select a sample interval with a resolution adequate to define short-term climatic fluctuations, i.e., on the order of 100 years or less. Sample volumes ranged from 90 to 120 cm^3, and sediment samples were processed from one-inch sections of core spaced at two-inch intervals. Based on the chronology discussed below, the average time interval represented in a sample is approximately 105 years.

Sample preparation. The samples were prepared so as to completely disaggregate sediment grains from the ostracode valves, and separate the sand-sized fraction containing mature ostracodes from the silt- and smaller-sized fraction. The preparation technique used was modified from U. S. Geological Survey, Technical Detailed Procedure HP-78, and is briefly discussed below.

Sediment samples were initially sealed in plastic soil bags and frozen. Approximately 30 to 40 cm^3 of frozen sediment was thawed and gently mixed with 500 to 600 ml of boiling, distilled water and one teaspoon sodium bicarbonate. After cooling to room temperature, one teaspoon each of sodium hexametaphosphate (HMP) and sodium triphosphate (TSP) were added as dispersants, and the sample was allowed to stand for 48 hours. The sample was then frozen, thawed, and allowed to stand an additional 48 hours. The disaggregated sediment was gently washed through a 100-mesh (150 micrometer openings) sieve. The size fraction remaining in the sieve was washed with distilled water onto a stack of papertowels, sealed in the towels, and dried at room temperature.

Ostracode extraction and identification. Mature ostracode valves were separated from the sand- and larger-sized sediment for identification and analysis. The dried sediment residue was gently poured and brushed from the papertowel into a nested set of three-inch sieves containing 20-, 40-, 50-, 60-, and 80-mesh sizes, and a receiver pan. Adult specimens were essentially confined to the 40-, 50-, and 60-mesh fractions. These fractions were systematically examined under a binocular microscope with reflected light at 16 to 18X magnification. Adult specimens were removed with a wetted, fine-tip (00) red sable brush and transferred to a standard micropaleontologic slide. The shells were inspected for overgrowths and/or dissolution and separated by specie.

Isotopic analysis. Limnocythere bradburyi, the dominant specie in the core, was preferentially selected for isotopic analysis in order to provide the most consistent data set. Where L. bradburyi was not present in sufficient numbers for analysis, L. ceriotuberosa or a mix of species of the genus Limnocythere was used. Only four samples consisted of some mixture of Heterocypris spA and Candona patzcuaro.

A total of 186 samples from 159 intervals was analyzed for oxygen and carbon isotope ratios. Analyses were performed at the Stable Isotope Laboratory, New Mexico Institute of Mining and Technology, using McCrea's (1950) methods for acid decomposition. About 0.5 to 1.5 mg of shell sample comprised of 40 to 150 individual ostracode valves were reacted under vacuum with 100% phosphoric acid at 25 °C for 10 to 15 hours. The acid reaction produced 2.5 to 15 micromoles of CO_2 gas. $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios of the evolved CO_2 gas were determined using a Finnigan MAT Delta E mass spectrometer.

A special technique was developed for mass spectrometric analysis of the small volumes of CO_2 gas produced. For gas samples less than approximately three micromoles, the gas was first frozen into a coldfinger on the mass spectrometer inlet and then released directly into the ion source. For samples larger than three micromoles, the coldfinger was also used; however, the gas was allowed to expand back into the variable volume to protect the source from excessive pressures. The bellows were then used to equalize sample and standard volumes prior to release of the gas into the source.

Isotopic results are presented using standard (δ) notation (Craig, 1957) as the per mil ($^{o}/_{oo}$) deviation of the sample carbonate from PDB Standard for $^{13}C/^{12}C$, or from SMOW Standard for $^{18}O/^{16}O$.

Reproducibility of the isotopic composition of normal volumes (i.e., 100 micromoles) of duplicate CO_2 samples is

$0.05^\circ/_{oo}$ for both carbon and oxygen. Due to the small volumes of gas sample generated in this study, these specification values could not be verified by duplicate analyses of the same gas sample.

A standard deviation for extraction and isotopic analysis of the CO_2 gas was determined by analyzing six separate samples of _Limnocythere bradburyi_ from the same depth interval. Two different depth intervals where this specie of ostracode was abundant (8.12 feet and 19.54 feet) were used and all samples were of equal size. The standard deviations in ^{18}O were determined to be $\pm 0.425^\circ/_{oo}$ and $\pm 0.504^\circ/_{oo}$ for the upper and lower sample intervals, respectively; deviations in ^{13}C were $\pm 0.160^\circ/_{oo}$ and $\pm 0.264^\circ/_{oo}$.

Chronology. Radiocarbon dating of three samples of organic material and two samples of biogenic carbonate was attempted by accelerator mass spectrometry; however, all five samples yielded anomalous ages. The results are displayed in Table 1 and evaluated below. The plant fragments produced ^{14}C ages ranging from 160 to 410 yr B.P., and are apparently root remains of former vegetation whose root system penetrated to depth from the surface. (At the present time the only vegetation at the drill site is bunch grass, whose roots could not penetrate to depths of 5 meters.) This plant material was common throughout the core from a depth of 4.0 feet (1.22 meters), just below the modern root zone, to 19.0 feet (5.79 meters). The ostracode shell material was retrieved from depths of 9.88 feet (3.01 meters) and

TABLE 1

Results of ^{14}C analysis of organic material and ostracodes from core SAC-3/4 by accelerator mass spectrometry.

Sample No.	Depth (ft)	Depth (m)	Material	^{14}C Age (yr B.P.)
SA4-6-2-3	6.21	1.89	plant fragments	410 ±60
SA4-9-10-11A	9.88	3.01	plant fragments	160 ±65
SA4-9-10-11B	9.88	3.01	ostracodes	22,400 ±210
SA4-18-9-10	18.79	5.73	plant fragments	350 ±55
SA3-40-6-7	40.54	12.34	ostracodes	37,700 ±1100

40.54 feet (12.36 meters). Based on an average sedimentation rate of 0.001 feet/year established in the prior work of Markgraf and others (1984), the expected ages for these samples are approximately 10,000 yr B.P. and 40,000 yr B.P. The most likely explanation for the anomalously old age of 22,400 yr B.P. for sample SA4-9-10-11B is a low $^{14}C/^{12}C$ ratio due to either (1) a source of dissolved old carbonate (the "hard-water effect"), or (2) a supply of old groundwater with a very low content of dissolved carbonate. Although sample SA3-40-6-7 yielded a radiocarbon age (37,700 yr B.P.) in close agreement with its expected age (40,000 yr B.P.), the result must still be questioned in view of the unreliable result produced from biogenic carbonate in sample SA4-9-10-11B.

The chronological framework for core SAC-3/4 was alternatively established by correlation of ostracode stratigraphy with that previously developed by Markgraf and others (1984) and Forester (1987). Three distinctive transitions between _Limnocythere ceriotuberosa_ and _L. bradburyi_ were selected as correlation points between the two biostratigraphic records. At a depth of 24.0 feet (7.32 meters) in SAC-3/4 a dramatic transition occurs wherein _L. ceriotuberosa_ is completely replaced by _L. bradburyi_. This specie succession is also reported in Forester (1987) and corresponds to an age of approximately 19.0 ka. In the upper section of core SAC-3/4, a similar transition occurs at a depth of 7.67 feet (2.34 meters), where _L. bradburyi_ is replaced by _L. ceriotuberosa_, and corresponds to an age of

8.735 ka. Ostracode material is continuous in SAC-3/4 up to a depth of 3.67 feet (1.12 meters); above this point no shell material occurs. This point correlates with an age of approximately 5.2 ka in the core described by Markgraf and others (1984).

The age-depth relationship established for San Agustin sediments is shown in Figure 3. The portion of the curve developed through biostratigraphic correlation is represented by the solid line. The curve was extended to a depth of 40.54 feet (12.34 meters) by correcting ^{14}C dates from ostracode material for inorganic carbon content. The age deviation between the ^{14}C date for sample SA4-9-10-11B and the correlation curve (12,280 years) was applied to sample SA3-40-6-7 to produce an estimated age of 25,420 yr B.P. at 40.54 feet (12.34 meters). This extended portion of the curve is represented by the dashed line in Figure 3.

4. Results

Ostracode Stratigraphy. The relative abundance and stratigraphic distribution of ostracode species in core SAC-3/4 is displayed in Figure 4; the raw data is summarized in Appendix B. Limnocythere bradburyi and L. ceriotuberosa occur in greatest abundance and alternately dominate the core. L. bradburyi dominates intervals from 5.20 to 6.38 ka, 8.74 to 10.83 ka, 12.24 to 16.33 ka, and 17.48 to 18.95 ka. Limnocythere ceriotuberosa dominates a short section from 8.36 to 8.74 ka and intervals

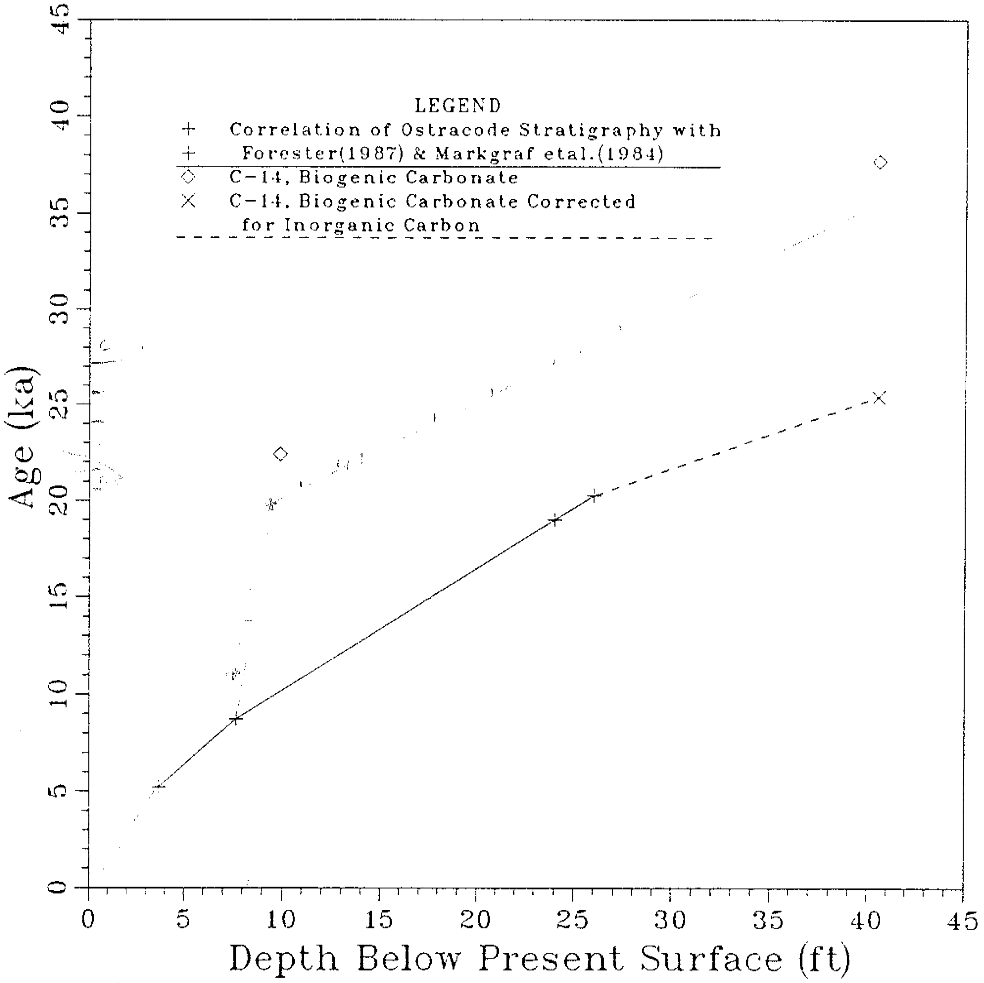


Figure 3: Age-versus-depth plot for core SAC-3/4 from ostracode stratigraphy correlations and carbon-14 dates.

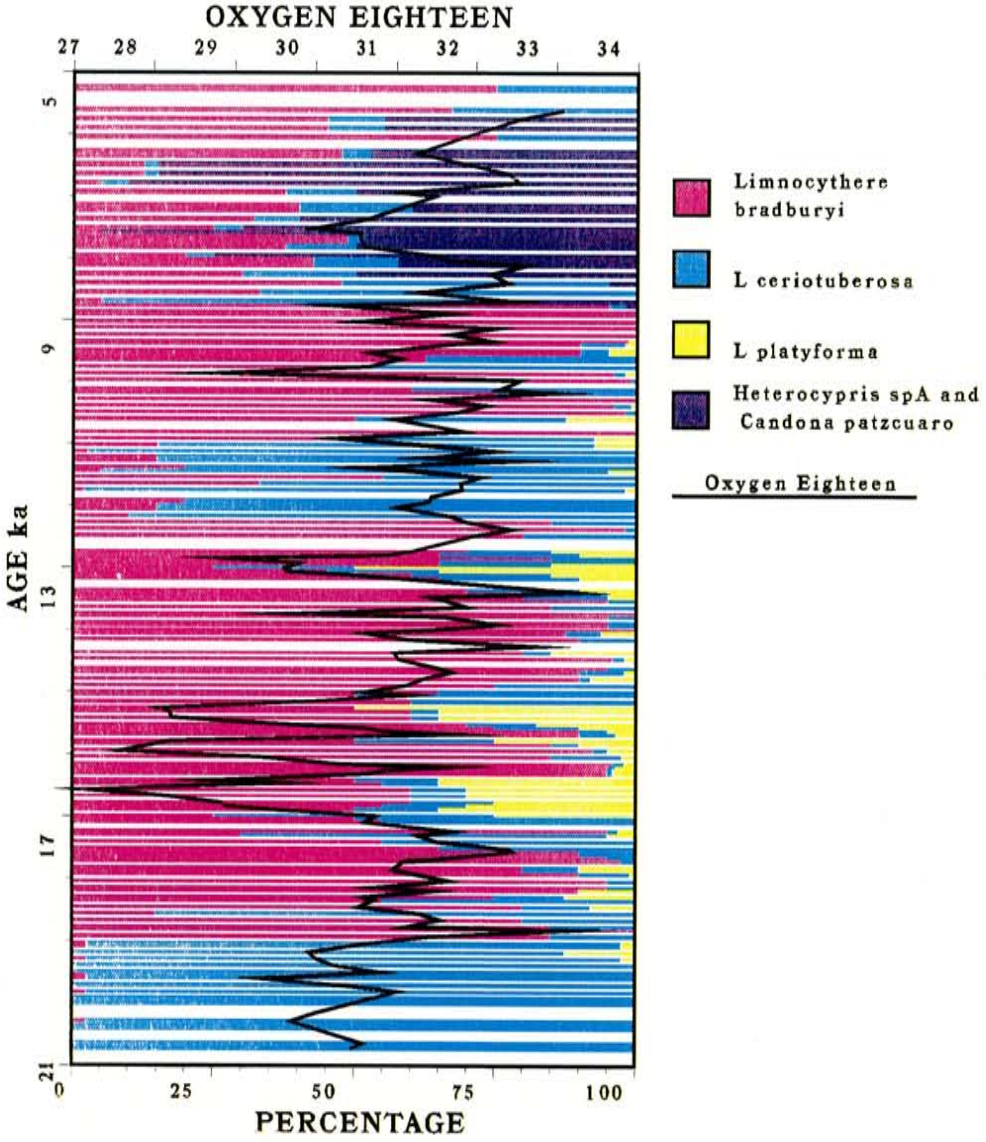


Figure 4: Relative abundance of ostracode species (as percent) and oxygen-18 as a function of age for core SAC-3/4.

10.88 to 12.19 ka, and 19.0 to the end of the stratigraphic section at 20.68 ka. L. bradburyi coexists in equal numbers with L. ceriotuberosa and L. platyforma, collectively, in section 16.38 to 17.43 ka. L. platyforma occurs sporadically in low numbers throughout the stratigraphic column from approximately 9.50 to 19.30 ka, with significant spikes centered at 10.60, 10.96, 13.05, 14.40, 15.40, 15.85, 16.70, 17.87, 18.24, and 19.15 ka. The two species, Candona patzcuaro and Heterocypris spA, are rare and collectively dominate only the interval from 6.45 to 8.29 ka.

Oxygen and Carbon Isotopes. The oxygen- and carbon-isotope curves for Lake San Agustin as determined from ostracode shell carbonate are shown in Figure 5; raw data from isotopic analyses are presented in Appendix C. $\delta^{18}O$ values vary over a range of $6.15^{\circ}/_{oo}$ and $\delta^{13}C$ values over a range of $6.05^{\circ}/_{oo}$. Assuming isotopic equilibrium, negligible interference from taxonomic effects, and a well-mixed reservoir, deviation in ^{18}O and ^{13}C content of the biogenic carbonate will reflect temporal changes in isotopic composition of the lake water and can be used to infer a history of lake level fluctuations.

Nine samples which are included in the raw data shown in Appendix C have been deleted from the isotopic curves. Two samples at the top of core SA4 (LHMX3-1-2 and LB3-8-9.5) appeared to consist of reworked shell material. The ostracode valves in these samples were atypically broken and etched and remained coated with clay and other material even after preparation with

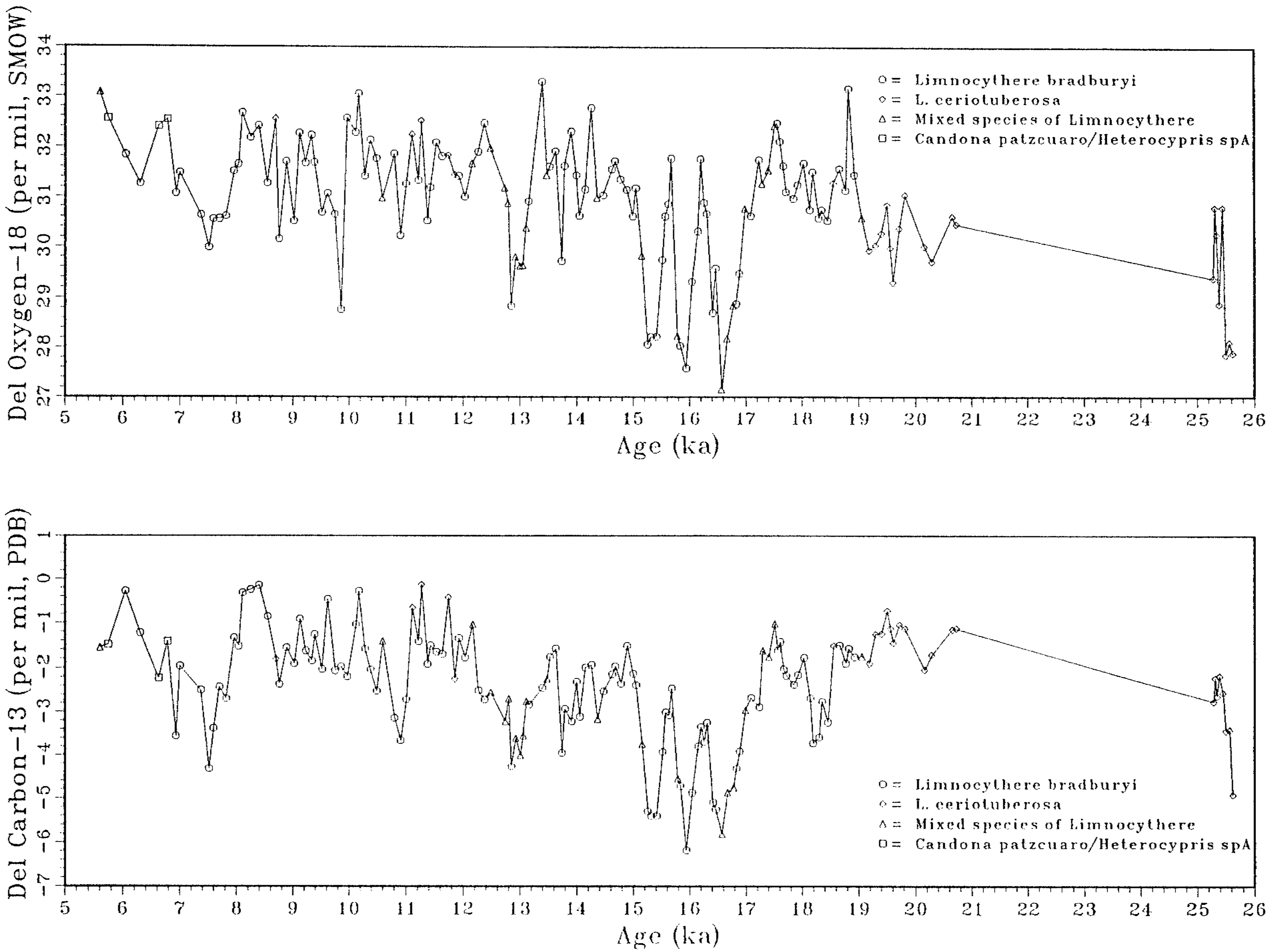


Figure 5: Oxygen-18 and carbon-13 as a function of age for core SAC-3/4.

dispersants. Two samples at the bottom of core SA4 (C-26-0-2 and C-26-2-4) and five samples in core SA3 (C-26-6-8, C-26-8-10, C-26-10-12, C-33-8-10, and C-34-0-2) were further excluded because of alteration. The appearance of these seven samples suggested that the original shell material had been completely replaced. All the valves formed whole carapaces which were opaque and filled with a crystalline carbonate material. In addition, the anomalously enriched ^{13}C content of these samples provides further support for post-depositional alteration.

In order to determine the influence of taxonomic factors on the isotopic composition of shell carbonate, the three species of the genus Limnocythere were evaluated for variability of ^{18}O and ^{13}C content. L. ceriotuberosa and L. platyforma are collectively plotted against L. bradburyi for both ^{18}O and ^{13}C in Figure 6. L. ceriotuberosa and L. platyforma are treated as a single population because the two forms are most likely a response to variation in water chemistry, rather than truely distinct species. Both species apparently occur under similar temperature constraints, and it is therefore appropriate to group them for statistical evaluation of isotopic composition. The sample regression line (solid line) displays good correlation in both plots with a hypothetical one-to-one regression line (dashed line). The hypothetical regression line represents the ideal circumstance in which L. bradburyi incorporates ^{18}O and ^{13}C in the same ratio as the other species of Limnocythere. The correlation between the sample regression line and the ideal is

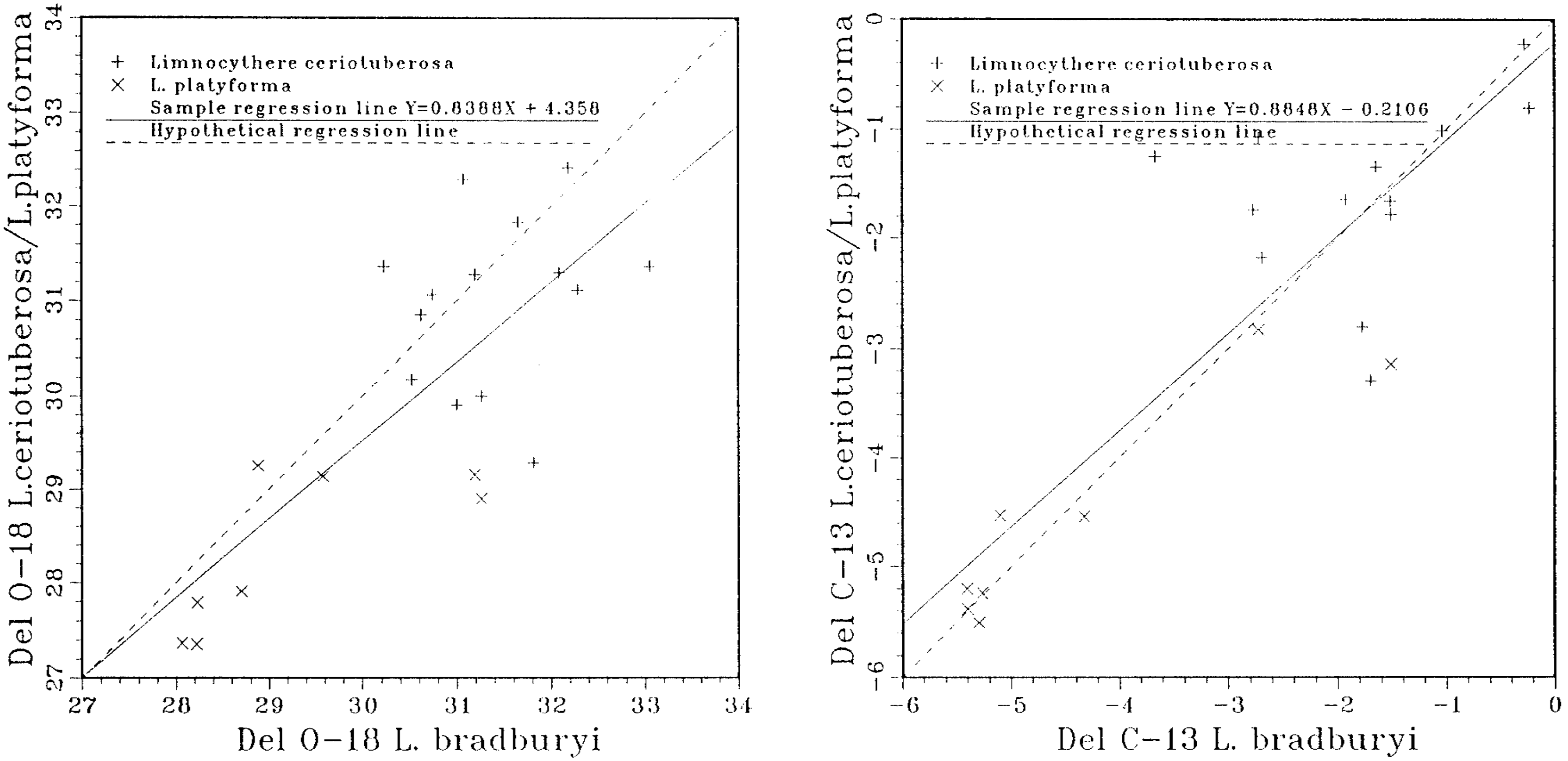


Figure 6: Oxygen-18 and carbon-13 for L. ceriotuberosa and L. platyforma plotted against oxygen-18 and carbon-13 for L. bradburyi.

admittedly not exact; however, it provides sufficient support for disregarding possible taxonomic effects due to different seasonal growth preferences or environmental conditions when interpreting the isotopic data.

All species of the genus Limnocythere which occur in the sediment record are benthic; accordingly, isotopic values obtained from these species will reflect bottom-water conditions. Heterocypris spA and Candona patzcuaro are both characteristic of shoreline facies and will presumably produce isotopic data unique to that environment. If Lake San Agustin did not have a history of stratification, such environmental distinctions are unnecessary. Covariance of the oxygen- and carbon-isotope curves indeed suggests that during the last 25,000 years, stratification did not occur (McKenzie, 1984), and our assumption of a well-mixed reservoir is valid. Further, during most of the lake's history, water levels were likely shallow enough that bottom waters were thermally coupled with the atmosphere, and relative changes in water temperature recorded by ostracode distribution reflect a response to changing air temperature.

Correlation and Interpretation of Ostracode Stratigraphy and Oxygen Isotopes. Oxygen isotope data from biogenic carbonate for the period 5 ka to 21 ka is displayed together with the ostracode stratigraphy in Figure 4. By inferring lake level fluctuations from the ^{18}O curve and correlating this lake level record with the ostracode distribution, a qualitative history of relative changes in temperature, inflow and lake volume can be developed for the San Agustin basin.

A significant event is recorded at 19.0 ka where Limnocythere ceriotuberosa was abruptly replaced by L. bradburyi, and a corresponding sharp positive shift of $3.2°/_{oo}$ in ^{18}O occurred over a time span of approximately 360 years. Prior to 19.0 ka when L. ceriotuberosa was dominant, lake levels were relatively high and stable. Temperatures were either cooler in summer, or significantly colder in winter than present, or both. This interval coincides with the classic period of maximum advance of continental and Pinedale glaciers during late Wisconsin. The species transition was preceded by an increase in inflow, as suggested by the appearance of L. platyforma between 19.3 and 19.0 ka. The sudden dominance of L. bradburyi at 19.0 ka suggests the initiation of an abrupt summer warming trend. The magnitude and abruptness of the ^{18}O shift between 19.2 and 18.8 ka further indicate an increase in both temperature and evaporative enrichment. Subsequent to 19.0 ka, lake levels gradually declined and an interval of low to intermediate lake stage with minor fluctuations was maintained until about 17.3 ka. Temperatures remained relatively stable and equable, with warm summers and temperate winters.

At 17.3 ka Lake San Agustin was apparently at a relatively low level. Spikes of Limnocythere ceriotuberosa which occur from 17.5 to 17.3 ka and 17.1 to 16.9 ka indicate the onset of colder winter temperatures. A broad band of L. platyforma from 17.1 to 16.4 ka, and a negative shift in ^{18}O of $4.59°/_{oo}$ from 17.2 to

16.5 ka, strongly suggest gradual filling in response to a long period of sustained inflow and reduced evaporation. The span between 16.8 and 15.0 ka continued with a series of extreme lake level fluctuations. High stands occurred at 16.5, 15.9 and 15.3 ka in response to the respective intervals of increased inflow from 17.0 to 16.4, 16.0 to 15.75, and 15.6 to 15.25 ka. Inflow intervals are delineated with bands of *L. platyforma* and high stages in lake level are defined by large negative deviations in ^{18}O on the order of 4.2 to $4.6^{\circ}/_{oo}$. Cyclic fluctuations in relative abundance of *L. bradburyi* suggest a variable temperature regime with relatively warm, equable temperatures accompanying low lake levels, and intermediate or seasonally variable temperatures occurring during intervals of increased inflow. This period ended with an interval of effective cooling, defined by an increase in *L. ceriotuberosa* from 15.2 to 14.8 ka, and a reduced lake stage at 15.0 ka.

The interval from 15.0 to 14.4 ka marked a period of relatively stable, intermediate lake levels in the San Agustin basin. Temperatures were similarly stable and quite warm; relative absence of *Limnocythere ceriotuberosa* suggests temperate winters. Formation of a 2,085-meter (6,840-foot) shoreline dated at 14.2 ka (V. Markgraf, written commun., 1989) by radiocarbon methods on surface carbonates most likely occurred during this lake stage.

From 14.3 to 13.7 ka, a period of rapid fluctuations in low to intermediate lake levels occurred with a frequency on the order of 150 to 200 years. Higher stands (defined by low ^{18}O values) correlate with intervals of increased inflow (defined by appearance of Limnocythere platyforma). Temperatures continued to be relatively warm and stable with temperate winters, as reflected by the general dominance of L. bradburyi. The period ended in a very low stand at 13.4 ka, which was immediately followed by an interval of gradual lake level rise, culminating in an intermediate stand at 12.8 ka. This rise in stage was most likely a response to a sustained increase in inflow (defined by occurrence of L. platyforma from 13.4 to 12.7 ka), combined with cooler temperatures (indicated by an increase in L. ceriotuberosa). From 12.8 to 12.4 ka a very rapid reduction in lake stand occurred, most likely induced by a reduction in inflow and rise in temperature. The resultant low stage is well defined by ^{18}O enrichment and a L. bradburyi spike at 12.37 ka.

The interval between 12.4 and 10.2 ka was a period of moderate fluctuations in intermediate lake levels. Cool temperatures occurred from 12.2 to 10.9 ka (indicated by a clear dominance of Limnocythere ceriotuberosa), but were replaced by a relatively warmer, more variable temperature regime beginning 10.9 ka. Several small pulses of inflow, defined by the presence of L. platyforma and negative deviations in ^{18}O, occurred during this period. By 10.2 ka the lake had declined to a very low stage which was maintained until 10.0 ka. Rapid infilling at 10.0 ka caused a very strong, negative deviation in ^{18}O; however, this isotopic response was probably a transient effect from a minor inflow event and lake levels probably remained relatively low. These low to intermediate stages prevailed until 8.7 ka with relatively minor fluctuations. Temperatures during this interval remained quite warm and stable.

A significant transition in the ostracode distribution occurred at 8.7 ka with the appearance and relative dominance of Heterocypris spA and Candona patzcuaro. This faunal transition clearly defines the onset of very low lake levels; however, persistence of species of the genus Limnocythere indicates some degree of lake stablility. Relative absence of species of Limnocythere at 7.6 and 6.8 ka suggest playa rather than lacustrine conditions prevailed at these times. Temperatures after 8.7 ka appear to be characterized by some degree of seasonality as suggested by occurrence of both L. bradburyi and L. ceriotuberosa. This interval also corresponds with the classic Holocene hypsithermal period. Lake San Agustin dropped below playa level by 5.6 ka and subsequently desiccated to its present dry playa.

II. NUMERICAL MODELING

1. Introduction

One goal of this project was to quantitatively reconstruct lake surface-area histories for Lake San Agustin using the stable isotope record. Lake level and stable isotope evolution models generally use solutions to simple analytical equations initially presented by Gonfiantini (1965) to simulate the isotopic and lake level histories. Analytical models are not suitable for reconstructing long lake-level histories because continuous variations in model input parameters can not be readily incorporated into analytical solutions. I have therefore utilized a numerical model constructed by Randall Roberts, New Mexico Institute of Mining and Technology, Department of Hydrology, for this purpose.

The main tool for the lake-level reconstruction is a transient numerical model based on the one described in Phillips and others (1986b). It differs from the previous model by being formulated on a time-derivative, rather than a volume-derivative, basis. The model consists of linked water mass balance and isotope mass balance equations. In order to compute the mass balances the model requires histories of temperature, evaporation rate, humidity, isotopic composition of inflow water, and isotopic composition of atmospheric humidity. The independent parameter that "drives" the model is the inflow flux to the lake. The dependent variables calculated by the model are the surface area of the lake and the isotopic composition of the lake water. The numerical code for the model is presented in Appendix D.

The basic approach used in implementing the transient numerical model was to vary the inflow history so as to match the modeled isotopic history with the measured ^{18}O data. Based on the linked water/isotope mass balance, the model then calculates the lake surface area as a function of time. For a single-lake system such as Lake San Agustin where transient effects play an important role for most of the lake history, the most appropriate modeling approach was to input various inflow functions until the ^{18}O history could be effectively matched over a short time interval.

2. Model Formulation

The model is a transient, numerical, lumped-parameter model which simulates surface area and isotopic evolution of the single-lake system in the San Agustin basin. The water mass balance for the lake is given by:

$$dV_L/dt = Q_I + Q_C - Q_E - Q_{GW} \tag{1}$$

where V_L is the lake volume, Q_I is the inflow flux, Q_C is the back-condensation flux, Q_E is the gross evaporative flux, Q_{GW} is the net groundwater flux , and t is time. The isotopic mass balance is described by:

$$d(V_L\delta_L)/dt = \delta_I Q_I + \delta_C Q_C - \delta_E Q_E - \delta_{GW} Q_{GW} \tag{2}$$

where δ is the relative isotopic enrichment of the fluxes indicated by the subscripts. Applying the chain rule to (2) we have:

$$V_L(d\delta_L/dt) + \delta_L(dV_L/dt) = \delta_I Q_I + \delta_C Q_C - \delta_E Q_E - \delta_{GW} Q_{GW} \qquad (3)$$

Letting $B = \delta_I Q_I + \delta_C Q_C - \delta_E Q_E - \delta_{GW} Q_{GW}$ and solving (3) for $d\delta_L/dt$ gives:

$$d\delta_L/dt = [B - \delta_L(dV_L/dt)]/V_L \qquad (4)$$

Equations (1) and (4) for volume and isotopic composition as functions of time are solved simultaneously for each time step of the numerical simulation using the Runge-Kutta-Fehlberg method of solving multiple differential equations. Because calculations in the modeling involve numbers which differ by many orders of magnitude, all variables in the FORTRAN code were declared as double precision to minimize rounding errors. Accuracy of the numerical solution was verified by comparison with an analytical solution. Bathymetric data for the San Agustin lake basin, developed by computerized digitation of U.S. Geological Survey topographic maps, were used to convert the lake volumes calculated by the model to surface areas. Area/volume/depth relationships developed for the San Agustin basin are graphically illustrated in Figure 7.

The gross evaporative flux is given by:

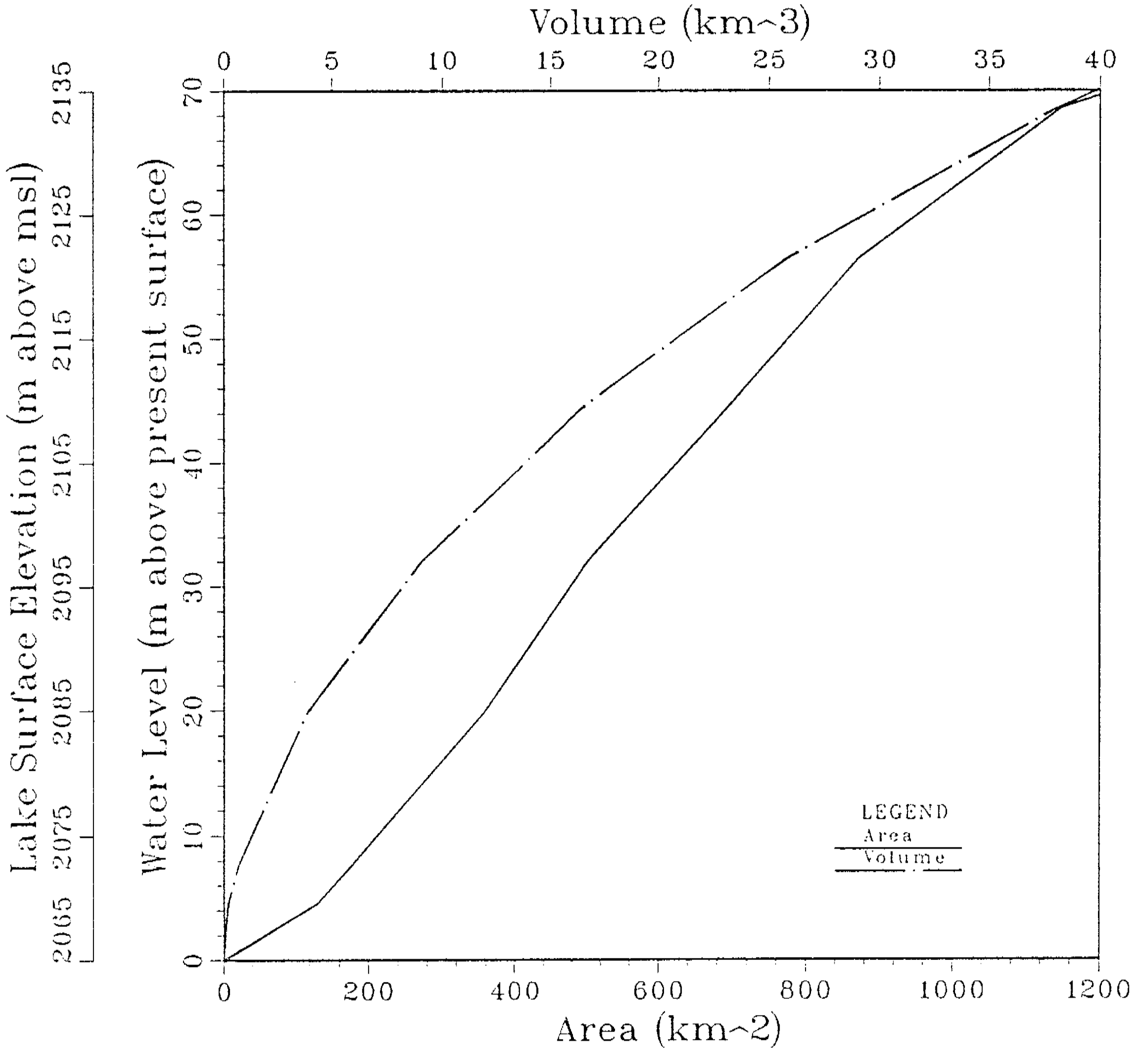


Figure 7: Area/volume/depth relationships for San Agustin basin developed from bathymetric data obtained by computerized digitation of U.S. Geological Survey topographic maps.

$$Q_E = q_E A \tag{5}$$

where q_E is the evaporation rate for pure water (LT^{-1}), and A the lake surface area (L^2). The back-condensation flux, Q_C, can be related to the gross evaporative flux, and the relative humidity, h:

$$Q_C = h Q_E \tag{6}$$

The isotopic composition of the back-condensation flux can be determined from the equilibrium isotopic enrichment factor (ϵ_v) for the liquid/vapor phase change and the isotopic composition of the atmospheric water vapor (δ_a):

$$\delta_C = \epsilon_v(1 + \delta_a/10^3) + \delta_a \tag{7}$$

The equilibrium enrichment factor is a function of temperature alone and was calculated according to Friedman and O'Neil (1977):

$$\epsilon_v = \{\exp [[1.534(10^6T^{-2}) - 3.206(10^3T^{-1}) + 2.644]/10^3] - 1\} 10^3 \tag{8}$$

Because the degree of fractionation during evaporation is determined by the kinetics of vapor diffusion away from the liquid surface, ^{18}O composition of the gross vapor flux (δ_E) is a function of humidity, wind speed, and temperature (Craig and Gordon, 1965).

Modification of an expression from Merlivat and Jouzel (1979) was used in the model to take these factors into account:

$$\delta_E = \{[(1 + \delta_L/10^3)(1 - k)]/[(1 + \epsilon_v/10^3)(1 - kh)] - 1\}10^3 \qquad (9)$$

The variable k accounts for both diffusive and turbulent transport of the isotopic species away from the water surface. For the range of wind speeds expected in most continental settings, k may be treated as a constant having the value 6.8×10^{-3} for $H_2{}^{18}O$ (Merlivat and Jouzel, 1979).

The model first solves the water mass balance equation (1) and then uses the flux values along with the other calculated parameters to solve for the isotopic history (4). It should be noted that $\delta_L = \delta_{GW}$ in the model, based on the assumption that the lake can be treated as a well-mixed system over each time step. The $\delta^{18}O$ value calculated by the model from (4) is the relative isotopic enrichment of the water. Because the isotopic history the model is attempting to match is given as $\delta_{calcite}$, the isotopic values for water are converted to calcite by first calculating the equilibrium isotopic enrichment factor (derived from Friedman and O'Neil, 1977). For water/calcite this is given by:

$$\epsilon_{H_2O,cal} = \{\exp [[(2.78(10^6T^{-2}) - 2.89)/10^3] - 1]\} 10^3 \qquad (10)$$

Then the relative isotopic enrichment of the calcite is given by:

$$\delta_{cal} = \epsilon_{H_2O,cal} + \delta_{H_2O} (\epsilon_{H_2O,cal} / 10^3 + 1) \qquad (11)$$

3. Model Parameterization

In order to calculate lake surface areas, the numerical model requires histories of temperature, evaporation rate, relative humidity, $\delta^{18}O$ of the inflow, and $\delta^{18}O$ of atmospheric humidity. Obviously, there are no independent histories covering the past 25,000 years for each of these parameters for the San Agustin study area. Consequently, histories for the independent parameters must be constructed by correlation to existing paleoclimatic parameter histories that cover a similar time period. No good proxy record for continental paleotemperatures exists for west central New Mexico and, without local corroboration, marine ^{18}O records are so geographically distant from the Plains of San Agustin as to render a good correlation problematical. An internally consistent alternative is provided by the ostracode stratigraphy of San Agustin and the assumption that changes in the proportion of Limnocythere bradburyi to the other species of the genus Limnocythere are a sensitive reflection of relative changes in temperature (Forester, 1985; 1987). Because the modern geographic distribution of L. bradburyi and L. ceriotuberosa appears to be principally controlled by seasonal variations in water temperature (previously discussed in chapter I, section 3), the ostracode biostratigraphy is itself the best available indicator of historic temperature changes.

Development of the temperature history first assumed a temperature reduction estimate of 7 °C at the late Wisconsin glacial maximum at 19.0 ka (Spaulding and others, 1983; Dohrenwend, 1984; and Phillips and others, 1986a). A current mean annual temperature of 9.42 °C was determined using the longest available (9- to 17-year) temperature records compiled by Gabin and Lesperance (1977) for two sites (the Birmingham ranch and the Danley ranch) in the southwest portion of the Lake San Agustin subbasin. By linearly interpolating proportions of <u>L. bradburyi</u> to both <u>L. ceriotuberosa</u> and <u>L. platyforma</u> over the temperature range of 2.42 °C to 9.42 °C (that is, 100% <u>L. bradburyi</u> corresponds to 9.42 °C and 100% <u>L. ceriotuberosa</u> plus <u>L. platyforma</u> to 2.42 °C), a history of estimated mean ostracode life-cycle temperature was created for the lower elevations of the Plains of San Agustin. The complete temperature chronology is presented in Appendix E, together with the other model input parameters for San Agustin, and a 500-year moving average of the temperature data is illustrated in Figure 8. This chronology was principally developed in order to incorporate a temperature-dependent fractionation factor into the numerical model, and is not intended to stand on its own merit as a definitive record of absolute paleotemperature. Although the chronology is a good representation of temperature trends, ambiguities inherent in the data limit its use as an independent proxy for continental paleotemperatures.

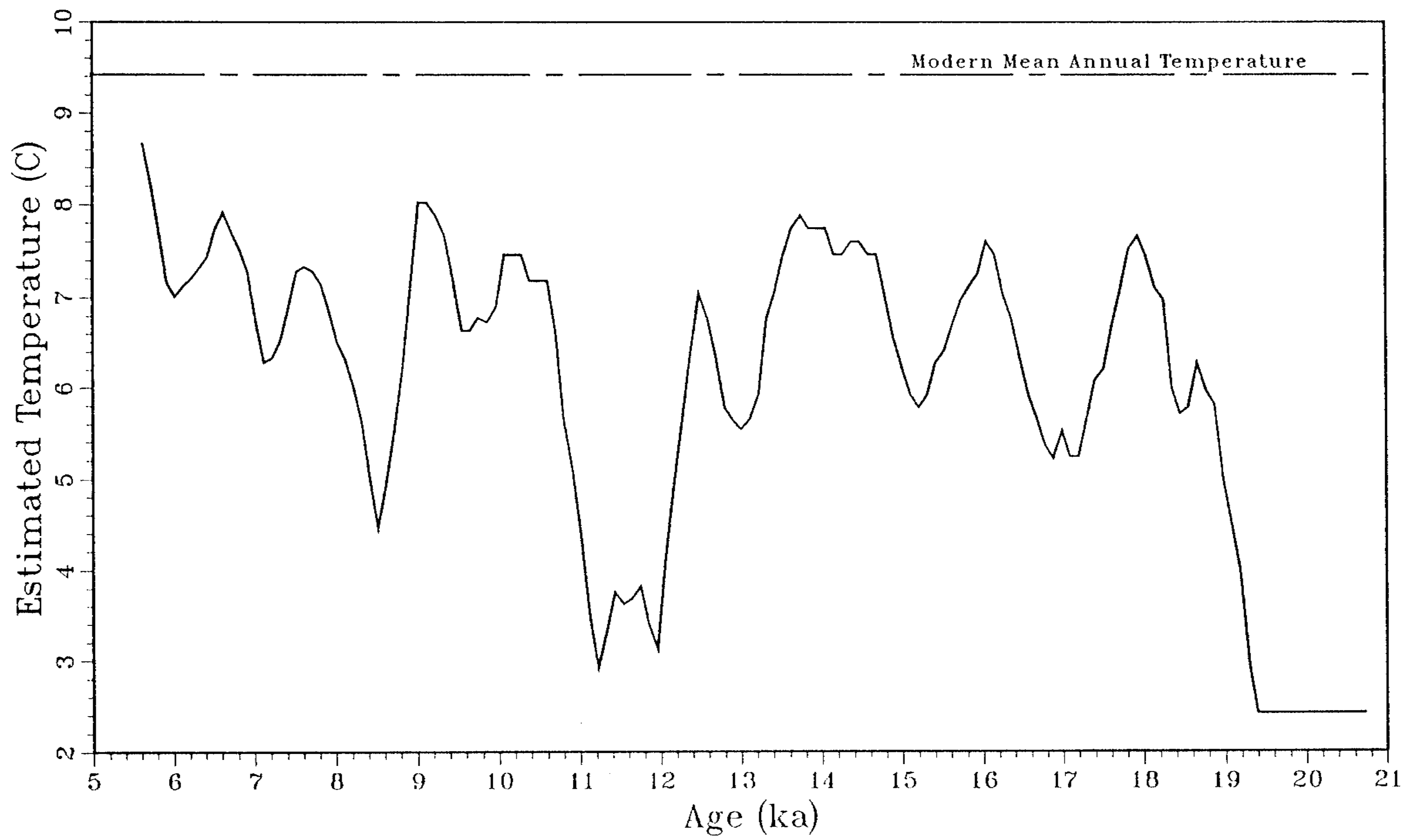


Figure 8: Chronology of estimated mean ostracode-life-cycle temperature for the Plains of San Agustin inferred from the ostracode biostratigraphy and plotted as a 500-year moving average.

In the San Agustin model gross evaporation is linked to the temperature record. A relationship between temperature and evaporation rate was obtained by assuming that a correlation between ancient temperature and evaporation rate with changing climate can be approximated by a modern temperature correlation with changing elevation. By compiling mean annual temperatures and pan evaporation rates for altitudinally-varied sites across western New Mexico, and applying a pan coefficient of 0.70 to convert to lake evaporation, the following regression relationship was established between lake evaporation and temperature:

$$q_E = 0.06567\ T + 0.65924 \tag{12}$$

The equation has a squared correlation coefficient of 0.60458. The regression plot and equation data can be found in Appendix E. The assumption that the ancient relationship of temperature with evaporation, as a function of time, mimics the modern temperature relationship with elevation is obviously at best an approximation. However, it does provide an internally consistent basis for reconstructing the covariation of these climatic parameters.

It was considered that the most accurate reflection of the humidity record in the San Agustin basin was the ^{18}O record itself. By applying a calibration technique of varying the slope and intercept of a humidity/$\delta^{18}O$ regression equation, and substituting the relationship into an analytical steady-state model, it was discovered that both high lake levels (light isotopic episodes) and low lake levels (heavy isotopic episodes) could be matched with the following relation of humidity (in percent) to $\delta^{18}O$:

$$h = 262 - 7\ \delta^{18}O_{cal} \tag{13}$$

This regression relationship yields maximum and minimum humidities of 72% and 30%.

In modeling the water balance for the San Agustin basin all inflow parameters are lumped into one inflow flux which is the independent parameter in the model. Because lake/groundwater interactions are viewed as being a major control on lake level, groundwater inflow is considered to be a significant component of the inflow flux, with precipitation on the lake surface and direct runoff constituting short-term inflow components. Variation of the ^{18}O composition of this inflow water with time is a required input for the model. An estimate of the variation in $\delta^{18}O$ of precipitation and groundwater recharge in northwest New Mexico over the last 35,000 years has been developed by Phillips and others (1986a). This $\delta^{18}O$ history should also be a reasonably accurate representation of the ^{18}O composition of precipitation- and runoff-derived inflow, as well as groundwater inflow, for the San Agustin basin a short distance to the south. The remaining parameter required by the model is the groundwater outflow flux. The paleohydrologic environment in the San Agustin basin, previously discussed in Chapter I, is known to include a substantial component of groundwater seepage from the basin; this component must be incorporated into the model.

First, in order to determine the importance of transient effects in lake/aquifer interactions, the analytical solution to the one-dimensional hydraulic diffusion equation, with a sinusoidally fluctuating boundary condition, was evaluated using aquifer parameters estimated for the regional flow system. Mathematical manipulation of the solution yields an expression for the time lag between a lake level fluctuation and the aquifer response given by:

$$t_L = x\ ((t_o S/4\pi T)^{1/2}) \tag{14}$$

where x is the distance into the aquifer at which the response is evaluated (1 km in this case); t_o is the period of the sinusoidal lake fluctuation in years; S is aquifer storativity; and T is aquifer transmissivity. The time lag for a period of 200 years, a range of storativities of 10^{-1} to 10^{-4}, and a range of hydraulic conductivities of 10^{-4} to 10^{-8} m/s, varies from about 0.045 years to 142 years. The range of estimated values for this "time constant" falls well below or near the average time span of our sampling interval (105 years); accordingly, regional transient effects stemming from lake/groundwater interactions can be considered negligible.

The problem remaining is to develop a steady-state relationship which will describe the groundwater seepage from the lake basin. By using the modern regional hydraulic gradient of 0.0054 (Blodgett and Titus, 1973), assuming this gradient remains constant (i.e., that fluctuations in lake level have a negligible effect on the regional gradient), and applying an estimated hydraulic conductivity of 10^{-6} m/s (an average value for fractured volcanics and silty sand), Darcy's law gives a volumetric outflow flux which is a constant function of lake area: $Q_{GW} = 0.17A$. Although this relationship provided a reasonable "first guess", it was discovered that the model simulations were isotopically heavier than the measured data by an average $1.5^{\circ}/_{oo}$. Considering the level of uncertainty in estimating the aquifer parameters vis-a-vis the climatic parameters, it was reasonable to calibrate the model by varying the groundwater outflow function.

The ^{18}O data point at 19.18 ka was selected as the calibration point. This selection was influenced by two circumstances. First, the shape of the ^{18}O curve immediately preceding this point suggests the system is approaching isotopic equilibrium at 19.18 ka. Second, it is necessary to have some constraint on lake surface area near 19.18 ka by absolute dating of an established shoreline. Such a constraint is provided by a shoreline located at 2,110 m and dated at 21.4 ka (V. Markgraf, written commun., 1989) by radiocarbon methods on surface carbonates. Whereas there is no reason to believe the lake surface area at 19.18 ka corresponds exactly to the 21.4 ka level, evidence from the isotopic and sediment records suggests that for the time interval between 19 ka and at least 21.4 ka the lake maintained high, relatively stable levels; accordingly, the 21.4 ka shoreline provides a reasonable surface-area approximation to govern our model calibration at 19.18 ka.

This calibration technique yielded the following groundwater outflow function:

$$Q_{GW} = 0.32A \tag{15}$$

where Q_{GW} is in units of m^3/s and A is in units of m^2. This relationship was applied in model simulations for the time intervals 20.723 to 18.296 ka, and 17.089 to 15.046 ka, during which high to intermediate lake levels prevailed. The linear groundwater outflow/surface area function is probably a reasonable estimate for regional outflow; however, it does not adequately account for lake/groundwater interactions within the basin. If the lake level declines rapidly, local hydraulic gradients will reverse and groundwater will flow out of "bank storage" and into the lake; the effect is to reduce net groundwater outflow. In order to account for this effect, a lower slope was used during intervals of heavier $\delta^{18}O$. For such cases the groundwater outflow function was modified to:

$$Q_{GW} = 0.22A \tag{16}$$

This relationship was applied over the time intervals 18.296 to 18.032 ka and 15.046 to 5.607 ka.

The actual groundwater outflow flux is clearly a nonlinear function of lake level which cannot be accurately determined without a transient, distributed parameter lake-aquifer model. The approach used here is a simplistic attempt to simulate this nonlinearity and I believe it to be the most reasonable alternative available. The technique cannot, however, fully accommodate local transient effects manifested in bank storage. Storage of water in, and release of water from, sediments peripheral to the shoreline constitute a major component in lake/groundwater interactions. This bank-storage effect further complicates the groundwater outflow flux by making it a function of the rate of change of lake level in addition to absolute lake level; accordingly, solutions obtained by the model for lake surface area and inflow are not unique. The solutions are probably good approximations as the bank-storage effect is significant only during episodes of rapid lake level fluctuation.

4. Model Results

The $\delta^{18}O$ history calculated by the transient model for Lake San Agustin is shown in Figure 9a (solid line), together with the measured ^{18}O data derived from biogenic carbonate (broken line). The established ^{18}O record was successfully simulated with the exception of two time intervals, one between 18.032 and 17.089 ka and a second from 7.958 to 7.003 ka. The ^{18}O data could not be matched over these intervals because the model became insensitive to even large variations in the inflow function. The reason(s)

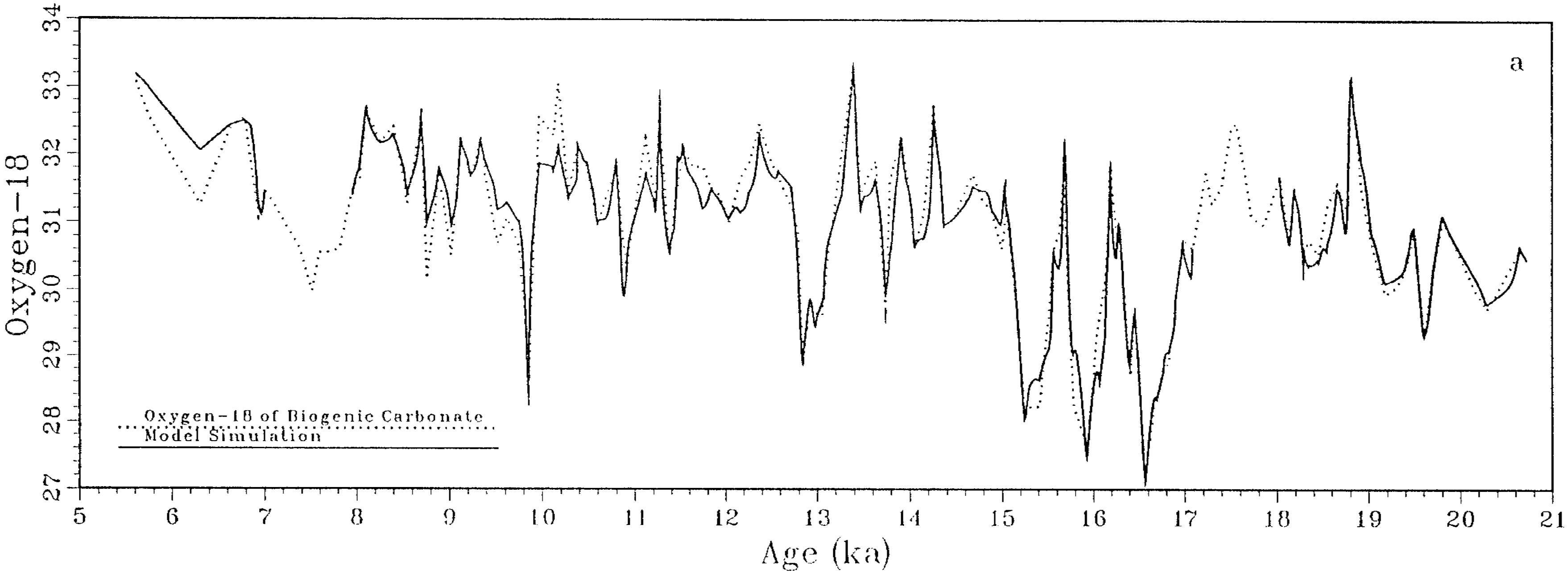
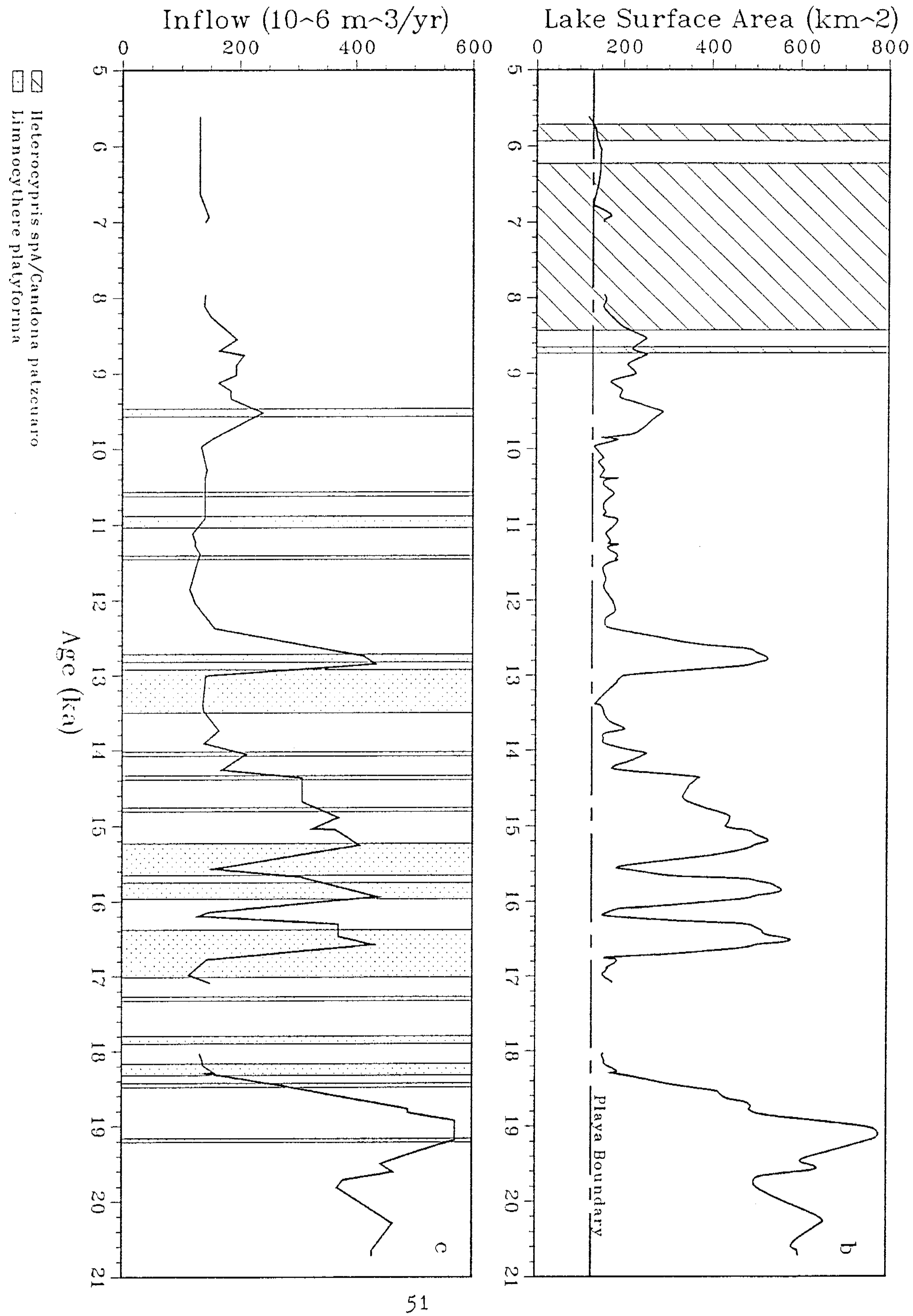


Figure 9: Results of numerical modeling for Lake San Agustin: (a) simulated oxygen-18 history (solid line) and measured oxygen-18 data (broken line); (b) simulated surface area history and *Heterocypris* spA/*C. patzcuaro* biostratigraphy; (c) inflow history and *L. platyforma* biostratigraphy.


Lake Surface Area (km~2)
0
200
400
600
800
b
Playa Boundary
Inflow (10~6 m~3/yr)
0
200
400
600
c
Age (ka)
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Heterocypris spA/Candona patzcuaro
Limnocythere platyforma

for such unresponsiveness in the model is not completely clear, but may be a product of: (1) a discontinuity in the cubic spline function which describes the area/volume relationship; (2) inadequacies inherent in the groundwater outflow function which were described in the preceding section; or (3) an unreasonable combination of climatic and inflow input parameters. The remaining ^{18}O data covering more than 13,000 years of the late Quaternary were simulated by the model with very promising results.

The surface area history calculated by the model, and the inflow record used by the model to produce both the ^{18}O and surface area simulations, are shown in Figures 9b and c respectively. Model output data for Lake San Agustin are presented in Appendix F. As expected, the surface area curve closely mimics the inflow curve with only minor deviations produced by temporal variation in temperature and, accordingly, evaporation. Both inflow and surface area simulations correlate closely with the biostratigraphic succession of Heterocypris spA/Candona patzcuaro and Limnocythere platyforma, shown by patterned boxes in Figures 9b and c. It has been proposed that L. platyforma is principally associated with fresh water lake phases (R.M. Forester, written commun., 1987). This theory is well supported by the excellent correlation between occurrence of L. platyforma and intervals of high or increasing inflow. Heterocypris spA and C. patzcuaro each possess distinct characteristics which specifically adapt them to a fluctuating shoreline. Because this biostratigraphic record is spatially constrained to a point along the playa-lacustrine depositional boundary, occurrence of these shoreline species over the interval 8.3 to 5.6 ka indicates a long period of very low lake levels. The simulated surface area history indeed supports the interpretation of the biostratigraphic record that lake levels were at or slightly above playa levels for most of this time interval. (Surface elevation of the modern playa in the Lake San Agustin subbasin is 2,070 meters (6,790 feet) and corresponds to a lake surface area in Appendix F of about 130 square kilometers.)

The excellent correlation between the biostratigraphy and the model simulations establishes a high level of confidence in the modeling results; however, uncertainties inherent in model input parameters (most significantly temperature, evaporation and humidity) and the problem of the nonunique solution, introduce some uncertainty in the lake surface area simulations and much uncertainty into the inflow simulation. The absolute values of surface area and inflow at any point in time should be considered reasonable approximations. The trends exhibited in the output data are well constrained and can be viewed with a great deal of confidence. Indeed, the lake level chronology developed with the numerical model correlates well with known sediment and shoreline records in addition to the biostratigraphy and, further, is consistent with qualitative lake level reconstructions proposed by Forester (1987) and Markgraf and others (1983).

The surface area simulation for Lake San Agustin indicates that the period from 20.7 to 19.0 ka was characterized by high lake levels with only moderate fluctuations. Inflow was also elevated until about 18.9 ka. The single high stand maintained from roughly 19.2 to 19.0 ka corresponds closely to the highest shoreline recognized by Powers (1939) at the 2,115-meter (6,940-foot) level. This is probably the only time interval in our record during which both Lake San Agustin and C-N Lake subbasins were interconnected in one large reservoir. After 19.0 ka lake levels dropped dramatically, inflow declined, and a low stand (approxmately 2,075 meters (6,805 feet)) was reached at about 18.3 ka. Although no model results were obtained for the interval 18.032 to 17.089 ka, the ^{18}O data suggest that the lake remained at a low stage during this interval. The model simulation after 17.089 ka further indicates that this low stage continued until about 16.7 ka.

Beginning at 16.7 ka Lake San Agustin entered a period of very strong cyclic fluctuations in surface area which continued until about 15.2 ka. Lake stages oscillated between moderately high levels (approximately 2,100 meters (6,890 feet)) at 16.5, 15.9, and 15.2 ka and relatively low levels (approximately 2,070 meters (6,800 feet)) at 16.2 and 15.6 ka. The lake level oscillations occurred at regular frequencies of 650 years, apparently in response to episodic pulses of inflow.

Inflow rates and lake levels gradually declined over the interval from 15.2 to 14.4 ka. Two relatively stable intermediate stages occurred in the transition at 15.0 and 14.6 ka. After 14.4 ka the lake underwent a series of rapid fluctuations over intermediate to low lake levels and ultimately stabilized in a low stage (approximately 2,070 meters (6,800 feet)) at about 13.4 ka.

A gradual lake level rise occurred from 13.4 to 13.0 ka and was followed by an abrupt, dramatic increase to a moderately high level (about 2,100 meters (6,890 feet)) at 12.8 ka. This brief high stage, evidently produced in response to a substantial increase in inflow, declined rapidly to a low lake level at 12.3 ka.

From 12.3 to 9.85 ka lake levels at San Agustin were maintained just above playa level (probably ranging from about 2,070 to 2,075 meters (6,795 to 6,810 feet)), and the inflow approached steady state values for almost 2,500 years. The last substantial lake level rise was initiated at 9.85 ka and culminated in an intermediate stage at 9.5 ka. A distinct series of minor fluctuations accompanied by a gradual reduction in lake level occurred over the next 1,300 years. The final drop in lake level commenced at about 8.55 ka. The terminal stage of Lake San Agustin was one of waning inflow and extremely low lake levels which occasionally dropped below the playa boundary. This period spanned approximately 3,000 years and ended at 5.6 ka when the lake desiccated into an ephemeral playa lake.

III. DISCUSSION AND CONCLUSIONS

1. Implications of the Paleoclimatic Record from Lake San Agustin. The composite stable isotope and biostratigraphic record from Lake San Agustin provides the framework for a unique and comprehensive paleoclimatic reconstruction for west central New Mexico. The ostracode stratigraphy forms the basis for inferring changes in paleotemperatures (Figure 8) and freshwater inflow (Figure 9c) and provides a constraint on low lake levels (Figure 9b). The ^{18}O record establishes a data base for quantitative modeling of the paleolake surface area which is a sensitive expression of changes in the basin water balance (inflow versus evaporative outflow) produced in response to climate change (fluctuations in moisture input and temperature). Radiocarbon dates obtained by previous workers and the sediment record add valuable temporal and geologic constraints. This multitool approach makes it possible to interpret changes in both temperature and moisture balance from the same record that spans 20,000 years of the late Quaternary -- from the late Wisconsin full glacial period to the middle Holocene.

The paleoclimate record suggests that the lacustrine/groundwater system is responding to both regional and global climate variations. Although some aspects of the record are not in agreement with the classical view of late Wisconsin deglaciation obtained from ^{18}O in glacial ice and ocean sediment, thereby signifying a response to regional climate change, other aspects of the San Agustin record appear to indicate a response to climatic events which are more global in nature.

The late Wisconsin full glacial climate is well defined in the San Agustin record as a period of high, relatively stable, lake levels and cold temperatures. A transgressive littoral gravel at a depth of 30.17 feet (9.2 meters) in the sediment record provides a limiting maximum age of roughly 21.7 ka for initiation of this high stage. Because this limiting date was obtained by correlation with another radiocarbon dated chronology and extrapolation through the sediment record, it should be regarded as a rough estimate. A radiocarbon date from shoreline tufa provided by V. Markgraf (written commun., 1989) establishes that lake levels were sufficiently high by 21.4 ka to overflow into the C-N Lake subbasin. This lacustrine maxima continued until about 19.0 ka. Dominance of a cold thermal regime, i.e., cold winters and, most likely, cool summers, during this period is implied by occurrence of _Limnocythere ceriotuberosa_ and absence of _L. bradburyi_; however, the effect of deep water levels on benthic ostracodes is unclear, and may create ambiguities in the paleotemperature/ostracode record.

A dramatic, abrupt climatic event is represented in the San Agustin record at 19.0 ka by replacement of _Limnocythere ceriotuberosa_ by _L. bradburyi_, and a positive shift in ^{18}O of $3.2^{\circ}/_{\infty}$ which is interpreted as a decline in lake level. The exact combination of environmental conditions associated with this abrupt climate change is not completely clear, again because of possible ambiguities in the isotope and ostracode records caused by unknown effects of very deep lake levels on benthic ostracodes. Although statistical analysis has eliminated taxonomic effects as a significant influence on isotopic composition, the possibility remains that different seasonal growth preferences of these two ostracode species may partially account for the isotopic shift. Further, the specie succession itself could theoretically be induced by a change in lake level, independent of a change in air temperature. For example, it may be possible that very deep, cold bottom waters stressed L. bradburyi from the benthic environment and allowed L. ceriotuberosa to dominate, regardless of air temperature. If a drop in lake level then occurred which was induced by a reduction in moisture input rather than a change in temperature, bottom waters could thermally recouple with an existing warm atmosphere and allow L. bradburyi to repopulate in shallow water conditions.

Whereas this ecologic scenario is certainly plausible, it is not fully supported by the evidence. Lake levels declined gradually, taking 800 years to reach a low stage, whereas the specie succession occurred very rapidly -- on the order of 100 years or less -- and at a time (between 19.0 and 18.9 ka) when deep water levels apparently prevailed. The positive isotopic shift progressed over a period of 400 years, from 19.2 to 18.8 ka, and was defined by four ostracode samples. The largest single isotopic deviation occurred between two samples of L. bradburyi, and was not coincident with the specie succession, but rather took place immediately following the specie replacement (between 18.9 and 18.8 ka). Timing of the relevant physical events revealed in the foregoing analysis strongly suggests that: (1) the period prior to 19.0 ka was characterized by a cold thermal regime and a very favorable water balance; (2) the replacement of L. ceriotuberosa by L. bradburyi at 19.0 ka was not induced by a drop in lake level and was probably directly related to a significant warming event; (3) the positive isotopic shift can not be explained by taxonomic effects associated with the specie succession and, accordingly, is most consistent with a dramatic decrease in lake level in response to either an effective warming, reduced precipitation, or both; and (4) the ostracode populations are substantially more sensitive to changes in climatic parameters than the isotopic composition of the lake, which appears to lag behind the faunal response by roughly 100 to 200 years. The ostracode stratigraphy further indicates that temperatures remained substantially warmer than full glacial temperatures until approximately 12.0 ka, although considerable variation occurred. The lake level minima which was reached by 18.2 ka continued until approximately 17.0 ka.

The apparent warming event at 19.0 ka is not in complete agreement with the recognized climate record associated with the late Wisconsin/Pinedale glacial maximum. The temperature transition is supported, however, by groundwater recharge data in New Mexico (Phillips and others, 1986a), and glacial chronologies from the southern Rocky Mountains which, although roughly constrained, indicate that alpine deglaciation occurred substantially earlier than in more northerly glaciated regions. For example, a glacial chronology established by Madsen and Currey (1979) for the Little Cottonwood Canyon in the Wasatch Mountains indicates that the Pinedale maximum occurred there between 20 and 19 ka; major morraines located about 1 km upstream from the maximum are believed to be up to a few thousand years younger (i.e., 16 to 18 ka). Similar chronologies are associated with the San Juan Mountains in southern Colorado, and the southern Park and Front Ranges in central Colorado. In the San Juan Mountains, the higher reaches of glaciated canyons were ice-free by 15.5 ka and the Continental Divide in the southern Park Range was completely deglaciated by 13.7 ka (Carrara and others, 1984). The Front Range in the southern Rockies also provides evidence for a Pinedale maximum at 19.0 ka and was completely deglaciated sometime between 15 and 12 ka (Madole, 1986). Extensive field evidence from the southern Rocky Mountain region indicates that significant oscillations of Pinedale glacial termini began about 19.0 ka and continued until the mid-Pinedale at approximately 16.0 ka (R. Madole, personal commun., 1990). Although the glacial chronologies do not have sufficient temporal constraint to provide conclusive confirmation of the warming event at 19.0 ka, the evidence does suggest that glaciers throughout the region began to retreat from Pinedale-maximum positions at this time and probably oscillated behind Pinedale termini for the next 3,000 to 4,000 years prior to their final retreat. The retreat of alpine glaciers is also consistent with a moderate summer warming, reduced winter precipitation, or both, and glacial oscillations suggest continued fluctuation of these climatic parameters for several thousand years.

The 19.0 ka warming event evidenced in the San Agustin record is also consistent with fossil insect data recently published by Elias (1990). Carbon-14 dating of mixed assemblages of insect fossils from the Lamb Spring site, Colorado, indicated the presence of prairie-associated species at 17.85 ka and tundra-associated species at 14.5 ka. This data is certainly consistent with a trend toward warmer and/or drier conditions as early as 17.85 ka, and further indicates reversal of this warm climatic shift by 14.5 ka. My interpretation of the San Agustin record and supporting regional climatic data is that a significant regional warming event probably occurred at 19.0 ka and was apparently transitory in nature.

Many lake level fluctuations at San Agustin (Figure 9b) are contemporaneous with similar events in other southwestern and western paleolake basins. Refined paleolake chronologies recently proposed for the Wilcox basin in southeastern Arizona (Waters, 1989) and the Estancia basin in central New Mexico (Bachhuber, 1989) show strong correlation with the San Agustin record. The maximum age of the final freshwater phase of Late Lake Estancia, 20.04 ka, is coincident in timing with the high stage at San Agustin prior to 19.0 ka, and is also similar in magnitude. A high stand may also have occurred at paleo-Lake

Cochise in the Wilcox basin at this time, but lack of chronologic constraint limits interpretation to existence of at least two high stands prior to 14.0 ka. The last Pleistocene lake stands in both Wilcox and Estancia basins were roughly synchronous with the 12.8 ka high stand at San Agustin. These stages, both of intermediate magnitude, occurred at Lake Cochise between about 13.75 and 13.4 ka, and at Lake Willard in the Estancia basin approximately 12.5 ka. The early Holocene lacustrine intervals in the Wilcox and San Agustin basins are also coincident; Lake Cochise reoccupied the Wilcox basin about 8.9 ka or before, and increased lake levels are calculated at San Agustin between 10.0 and 8.4 ka.

Timing of paleolake fluctuations in the southwest is not as precisely correlated with changes in the prominent paleolakes of the Great Basin -- Searles Lake, Lake Lahontan and Lake Bonneville -- although a systematic pattern is certainly apparent. These lakes in the southwestern and western United States all show good evidence of a high stand at some time between 20 and 18 ka, followed by a decline between 18 and 15 ka, and a subsequent, and in some cases dramatic, rise between 15 and 12 ka. See Benson and Thompson (1987) for a review of paleolake chronologies in the Great Basin. The general synchroneity of lake stages in the major pluvial basins of the southwest -- San Agustin basin, Wilcox basin, and Estancia basin -- invites the proposal that hydrologic systems in this region of the southwest, south of approximately 35°N latitude, respond to the same mechanism of climatic forcing. The fact that similar hydrologic patterns are observed between paleolakes of the southwest and the Great Basin further suggests that a common climatic mechanism may be influencing the hydrologic response in paleolakes across the entire western midlatitude region; however, absence of direct correlation also indicates that a subregional mechanism must be superimposed upon the regional control.

The time interval from approximately 17.0 to 12.0 ka corresponds to the late Wisconsin deglacial period and is represented in the San Agustin record by dramatic oscillations in inflow and lake surface area, with both parameters varying between near-extreme, full glacial and Holocene values. Temperature similarly appears to have varied at least by several (two to three) degrees Celsius, but remained substantially warmer than during the previous cold thermal regime associated with the full glacial. The complete correlation between L. platyforma, which is associated with large influxes of freshwater, and periods of rising lake level during this deglacial interval is a strong indication that the dominant driving mechanism for these climatic oscillations was increased moisture input and not reduced temperature. By examining all available data -- the surface area simulation, inflow history, and ostracode stratigraphy -- it seems clear that extreme changes in lake surface area were driven more by variation of the inflow fluxes (precipitation, runoff, and groundwater) than by changes in the evaporative outflow flux. This water balance stands in stark contrast to the relatively stable, cold, dry conditions which were apparently maintained during the full glacial interval prior to 19.0 ka. The changes in the water balance which are suggested by the San Agustin data are in complete agreement with late Wisconsin groundwater recharge rates calculated for the central San Juan Basin, New Mexico, by Phillips and others (1986a). The San Juan Basin data indicate that groundwater recharge rates were at a minimum between 20.0 and 19.0 ka, thereafter increased to a maximum at roughly 16.5 ka, and returned to a minimum by 12.0 ka. A further indication of climatic variation during the Wisconsin deglacial is found in the glacial record from the southern Rocky Mountains, which indicates multiple glacial advances and retreats before final and complete deglaciation by or before 12.0 ka (Madsen and Currey, 1979; Carrara and others, 1984; Madole, 1986). Based on the San Agustin record, and solid support from independent, regional, paleoclimatic records, I propose that the prevalent climatic trend during the late Wisconsin deglacial was not one of gradual, unidirectional amelioration, but rather was characterized by extreme fluctuations produced principally by varying moisture input and, to a lesser degree, by fluctuating temperature.

Terrestrial and marine records of climate change from the North Atlantic, Greenland, Europe, and the Gulf of Mexico reveal a deglacial pattern of rapid warming from about 13.0 to 12.6 ka, followed by an abrupt reversal to colder glacial conditions at about 11.0 ka, and a return to warm conditions at about 10.0 ka.

(Rind and others, 1986; Broecker and others, 1988). The Younger-Dryas cooling (11.0 to 10.0 ka) is well documented in paleobotanical, glacial, and ^{18}O/ice core records from the circum-North Atlantic region but other areas, including the western United States, have provided only equivocal evidence for the cooling event. Recently, however, several paleoclimatic investigators have presented evidence of a possible Younger-Dryas signal in paleolake (Oviatt, 1990), paleogroundwater (Haynes, 1990), glacial (Osborn, 1990) and vegetation (Spaulding, 1990) records from the southern Great Basin and the southwest United States. The ostracode record from San Agustin is in very good agreement with these proposals.

Paleotemperature inferences from the ostracode stratigraphy (Figure 8) suggest a warming event from approximately 13.0 to 12.3 ka which was followed by a cold interval from about 12.0 ka to 11.0 ka. During this interval (12.0-11.0 ka) Limnocythere ceriotuberosa comprised 80 to 100% of the ostracodes recovered from the sediment core, suggesting a cold thermal regime of greater magnitude and duration than prevailed at any time since the full glacial. A significant and abrupt warming trend was then initiated at about 11.0 ka and continued to approximately 9.0 ka. The cooling event, together with the bounding warm events inferred from the San Agustin ostracode record, bears a strong correlation, in both duration and chronologic succession, with data recently presented by Fairbanks (1990) on glacial melt-water discharge rates in the Carribean. Using a well-constrained sea level chronology recorded in coral reefs, Fairbanks offered evidence which defines two melt-water pulses -- an initial intense pulse from about 12.6 to 11.6 ka (melt-water pulse IA (mwp-IA)) and a second weaker pulse from 10.3 to 8.6 ka (mwp-IB) -- bounding an interval of low melt-water discharge, presumably correlative with the Younger-Dryas. $\delta^{18}O$ minima in sediment cores from the Gulf of Mexico (Broecker and Denton, 1989) provide additional support for the timing of mwp-IA. Although the temperature variations implicitly associated with fluctuating glacial melt-water discharge rates in the Carribean are not directly synchronous with late Wisconsin paleotemperature inferences from San Agustin, correlation of the succession and duration of the events is sufficient support for the proposal that a Younger-Dryas signal may indeed appear in the San Agustin record. A 400- to 500-year shift in the San Agustin chronology would bring the series of events recorded in the two sets of data into precise agreement; such a temporal shift is within the uncertainty of this chronology. Additionally, lake levels at San Agustin remained low during the period 12.0 to 10.0 ka, which includes the Younger-Dryas (?) interval of substantially reduced temperatures, thus providing further support for the contention that this lacustrine system is predominantly driven by fluctuations in moisture input and not varying temperature.

It has been proposed (Keigwin, 1990) that one effect of cooler summer sea surface temperatures in the Gulf of Mexico produced by pulses of glacial melt water would be westward displacement of the Bermuda High, and a corresponding increase in summer monsoonal precipitation in the American Southwest. The Lake San Agustin high stand from 13.2 to 12.4 ka correlates well with discharge of mwp-IA into the Gulf of Mexico; if the causal relationship between high glacial melt discharge and increased monsoonal precipitation is as Keigwin proposes, then the 12.8 ka high stand at San Agustin may have been a response to transient intensification of summer monsoonal precipitation. Although this mechanism provides a reasonable explanation for lake level rises in southwestern paleolake basins between 13.0 and 12.0 ka, it is not an adequate forcing mechanism for lake level fluctuations in the Great Basin.

It is generally accepted that during the Wisconsin, the southwest was dominated by a winter storm regime brought about by southward displacement of the Aleutian low and associated Pacific storms (e.g., Spaulding and others, 1983; Spaulding and Graumlich, 1986). It is also widely accepted that the transition to a modern climatic regime involved northward retreat of the winter storm track and replacement by enhanced summer monsoonal circulation. There is little agreement, however, concerning the timing of this transition; evidence has been presented to support a transition as early as 12.0 ka (Spaulding and Graumlich 1986) and as late as 8.0 ka (Van Devender and Spaulding, 1979; Van Devender and others, 1987). The proposal that the 12.8 ka high stand at San Agustin may have been a response to an enhanced summer monsoon suggests that a monsoonal precipitation regime could have influenced southwest paleoclimates even earlier than commonly held. The San Agustin record does not support a "permanent" transition to a summer precipitation regime until 10.0 ka, at the earliest, and possibly as late as 9.1 ka, when the last lake level rise occurred. The shift to a mild, seasonal climate typical of middle Holocene appears to be complete by about 8.7 ka. Stable low lake levels and co-occurrence of *Limnocythere bradburyi* and *L. ceriotuberosa* after 8.7 ka are consistent with an interpretation of enhanced summer precipitation combined with freezing winter temperatures. Desiccation of the lake by or shortly after 5.6 ka suggests final transition to a fully-modern, warm and dry, climatic regime.

2. Conclusions. Agreement between the stable isotope data, the biostratigraphic record, and the modeling results, together with support from independent, regional climatic records, lend confidence to the paleoclimatic interpretations discussed above. In summary, the composite paleoclimate record from San Agustin is consistent with occurrence of the following significant climatic events during the late Wisconsin and Holocene:

(1) A stable, full glacial climate, characterized by cold temperatures and a very favorable water balance, extended from roughly 21.7 to 19.0 ka.

(2) A significant, regional, warming event occurred at 19.0 ka, and although considerable variation in temperature occurred,

temperatures remained substantially warmer over the next 7,000 years than during the full glacial thermal regime.

(3) The prevalent climatic trend during the late Wisconsin deglacial interval, from approximately 17.0 to 12.0 ka, was one of extreme fluctuations in moisture influx and only moderate variation in temperature.

(4) A cold thermal regime of greater magnitude and duration than prevailed at any time other than the full glacial period is recorded in the ostracode biostratigraphy at San Agustin between 12.0 and 11.0 ka and is probably correlative with the Younger-Dryas climatic reversal.

(5) Permanent replacement of a winter, Pacific storm track by a summer monsoonal precipitation regime from the Gulf of Mexico probably occurred about 10.0 ka, although the influence of monsoonal precipitation may have been felt as early as 12.8 ka.

(6) A similar mechanism of climatic forcing is controlling the hydrologic systems in the major pluvial basins of the American Southwest from about 32 to 35°N latitude and 106 to 110°W longitude.

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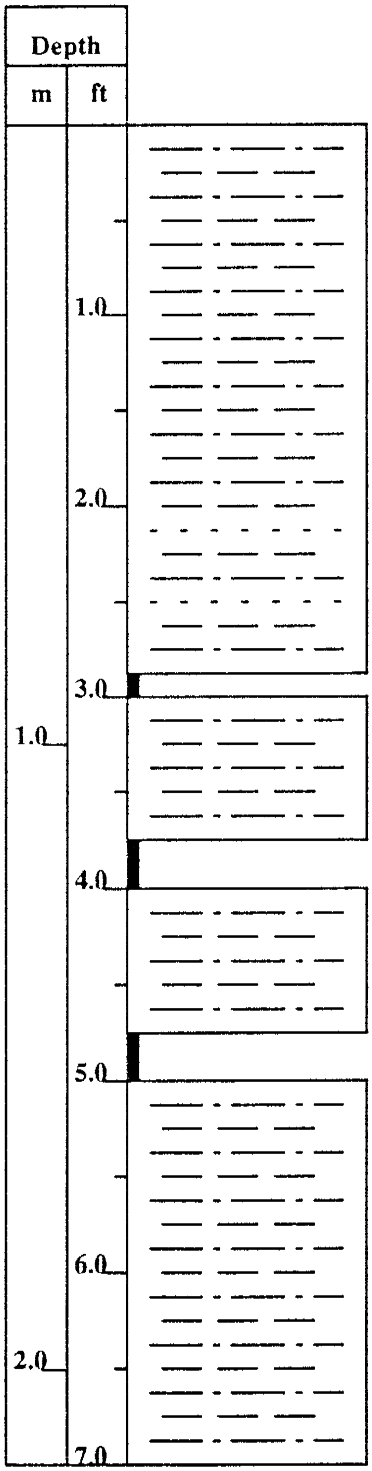
APPENDIX A

Lithologic Log Of San Agustin Core SAC-3/4

Plains of San Agustin, New Mexico
Lithologic Log -- Core SAC-3/4



Lithostratigraphy

0.0–1.0 ft: Clayey and silty surficial sediments with plant and root debris throughout; calcareous below 0.67 ft; light olive gray (5Y6/1).

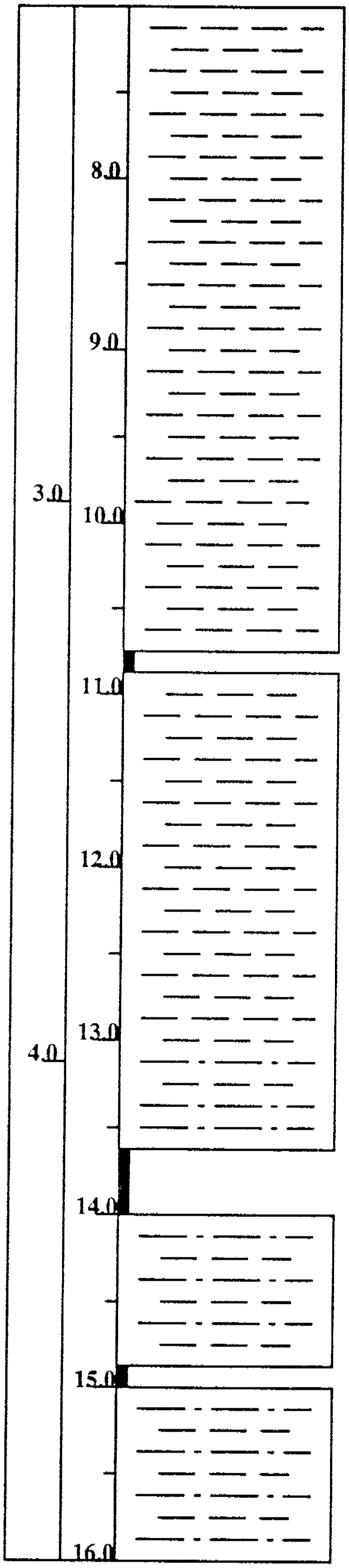
1.0–2.17 ft: Silty clay with plant roots abundant throughout; very calcareous; light olive gray (5Y6/1) to olive gray (5Y4/1).

2.17–2.92 ft: Sandy, silty clay with plant roots common throughout; very calcareous; light olive gray (5Y6/1) to dark yellowish brown (10YR4/2).

3.0–3.83 ft: Silty clay with iron-stained grains; very calcareous; dark yellowish brown (10YR4/2) to dusky yellowish brown (10YR2/2). XRD sample taken at 3.79 ft.

4.0–4.75 ft: Silty clay with organic remains and iron-stained grains; very calcareous; dark yellowish brown (10YR4/2).

5.0–7.0 ft: Silty clay, same as above.



7.0–8.0 ft: Fine clay; very calcareous; dark yellowish brown (10YR4/2). Laminations of yellowish gray (5Y8/1) clay at 7.83 ft. XRD samples taken at: (1) 7.38 ft indicate presence of illite (1/10), smectite (5/10), kaolinite (1/10) and mixed layer illite/smectite (2/10 with illite < 5%) and calcite; and (2) 7.92 ft indicate presence of illite (3/10), smectite (6/10) and kaolinite (1/10) and calcite.

8.0–9.0 ft: Fine calcareous clay, same as above, with yellowish gray laminations at 8.48 and 8.71 ft.

9.0–10.0 ft: Fine calcareous clay, same as above, with organic residue common throughout; yellowish gray lamination at 9.71 ft.

10.0–10.75 ft: Fine calcareous clay, same as above, with abundant organic residue; light olive gray (5Y6/1) and yellowish gray (5Y8/1) varve-like microlaminations from 10.58 to 10.63 ft. XRD sample taken at 10.58 ft indicates presence of illite (2/10), smectite (2/10), kaolinite (1/10) and mixed layer illite/smectite (5/10 with illite < 5%) and calcite.

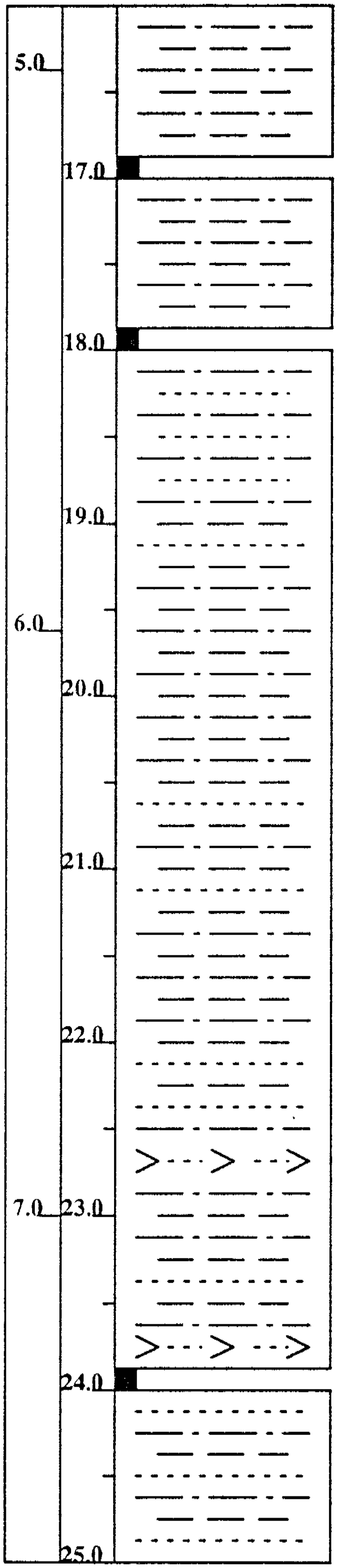
10.92–12.0 ft: Fine calcareous clay, same as above; no organic residue; yellowish gray clay layer at 11.17 ft.

12.0–13.0 ft: Fine clay; moderately calcareous; light olive gray (5Y5/2). Yellowish gray laminations at 12.0 ft.

13.0–13.67 ft: Silty clay, very calcareous; mottled light olive gray (5Y5/2) and moderate brown (5YR4/4). Yellowish gray clay laminations at 13.0 ft, 13.67 ft, and in laminated zones throughout. XRD sample taken at 13.58 ft.

14.0–14.83 ft: Silty clay; calcareous; pale yellowish brown (10YR7/2) to dark yellowish brown (10YR4/2–3/2), with light olive gray (5Y5/2) and pinkish gray (5YR8/1) clay in discontinuous zones throughout. Moderate brown (5YR4/4) iron oxidation zones throughout.

15.0–16.0 ft: Silty clay; very calcareous; dark yellowish brown (10YR4/2) with pinkish gray (5YR7/1) zones and moderate brown oxidized zones throughout.



16.0—16.83 ft: Silty clay; calcareous; interlayered light olive gray (5Y5/2–4/2) and yellowish gray (5Y7/1); minor oxidation.

17.0–17.92 ft: Silty clay with interbedded fine clay; calcareous; yellowish gray (5Y7/1) to light olive gray (5Y5/2–4/2)

18.0–18.83 ft: Silt and very fine sand with iron-coated grains; calcareous.

18.83–20.17 ft: Silty clay; calcareous; dark yellowish brown (10YR4/2) to olive gray (5Y4/1) with yellowish gray (5Y7/1) clay in discontinuous zones to 19.75 ft. Layer of very fine sand from 19.08 to 19.13 ft.

20.17–20.42 ft: Clayey silt with very fine sand (20%), gypsum crystals, and iron-coated grains; calcareous; pale yellowish brown (10YR5/2).

20.42–21.25 ft: Silty clay with very fine sand (10%); calcareous; dark yellowish brown (10YR4/2) with moderate brown (5YR4/4) oxidation zones.

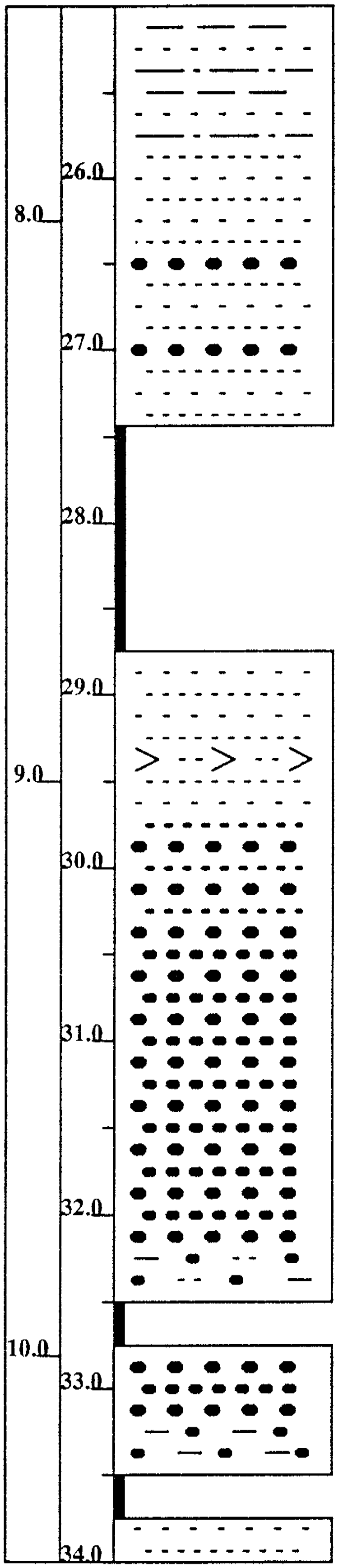
21.25–22.0 ft: Silty clay; calcareous; dark yellowish brown (10YR4/2).

22.0–22.50 ft: Very fine sand with minor clay (20%); light olive gray (5Y6/1).

22.50–22.75 ft: Silty clay with trace of very fine sand; calcareous; dark yellowish brown (10YR3/2); large zone of gypsum at 22.67 to 22.75 ft.

22.75–23.92 ft: Clayey silt and silty clay with very fine sand; light olive gray (5Y6/1) to olive gray (5Y4/1); large zone of gypsum from 23.75 to 23.83 ft; occasional vertebrate bones.

24.0–25.0 ft: Very fine sand and silt, with minor clay; calcareous; light olive gray (5Y6/1).



25.0–26.0 ft: Very fine sand and silt with minor clay; calcareous; light olive gray (5Y6/1).

26.0–26.5 ft: Moderately well sorted, medium to coarse, salt and pepper sand (abrupt contact with overlying very fine sand at 26.0 ft); slightly calcareous; light olive gray (5Y6/1). Sand coarsens downward to gravel layer at 26.5 ft.

26.5–27.0 ft: Poorly sorted, fine to coarse sand with occasional large (to 1 cm diameter) lithic granules. Gravel layer at 27.0 ft.

27.0–27.42 ft: Fine sand with minor coarse sand and occasional large (to 3 mm diameter) lithic granules.

28.75–29.92 ft: Fine to medium, salt and pepper sand with small lithic granules and selenite gypsum crystals; slightly calcareous; yellowish gray (5Y8/1) to light olive gray (5Y5/2). Sand coarsens downward to gravel and sand at 29.92 ft.

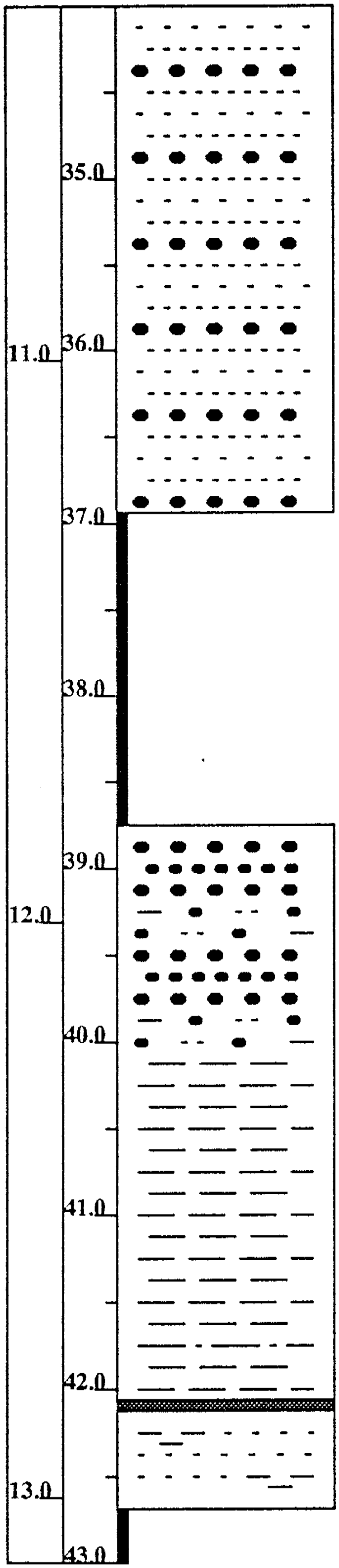
29.92–30.42 ft: Unsorted gravel and sand (granules to 2 cm diameter); noncalcarec

30.42–32.33 ft: Gravel; heavily oxidized; dark reddish brown (10R3/4) pebbles coat with dark yellowish orange (10YR6/6) limonite/geothite.

32.33–32.5 ft: Clayey–gravelly sand; heavily oxidized.

32.75–33.50 ft: Gravel and sand, heavily oxidized, with white and reddish brown zonation as above; locally slightly calcareous. Clay content increases downward to clayey–gravelly sand at 33.5 ft.

33.75–34.0 ft: Fine sand with some coarse sand and lithic granules; strongly oxidized; moderate yellowish brown (10YR5/4) to moderate brown (5YR4/4).

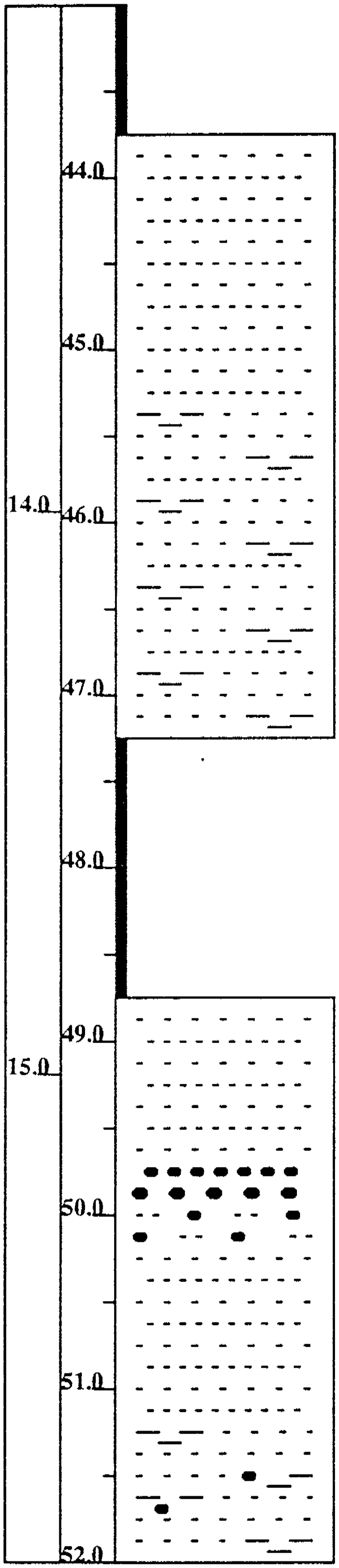


34.0–36.92 ft: Sand and gravel; oxidized; wet; moderate yellowish brown (10YR5/4) to moderate brown (5YR4/4).

38.75–40.0 ft: Gravel with minor sand and clay; large angular clasts to 4 cm length; oxidized.

40.0–42.08 ft: Clay; slightly calcareous in upper portion grading to non-calcareous at base; pale olive (10Y6/2) to light olive gray (5Y5/2) with zones of greenish black (5G2/1) and moderate yellowish brown (10YR5/4). 1 mm lamination of yellowish gray, calcareous silt at 41.75 ft.

42.08–42.67 ft: Abrupt contact at 42.08 ft formed by 1-mm lamination of black organic-rich material; remainder of section is very fine to fine clayey sand; noncalcareous; dark yellowish brown (10YR4/2).



43.75–45.33 ft: Poorly sorted, salt and pepper, medium sand with very coarse sand and occasional small lithic granules; noncalcareous; moderate yellowish brown (10YR5/4) to dark yellowish brown (10YR4/2).

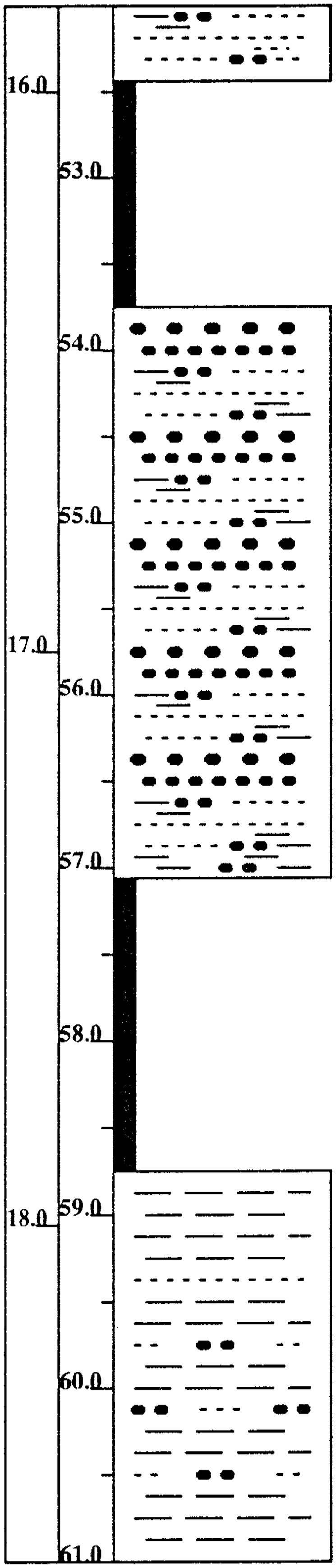
45.33–47.25 ft: (Graded contact, 45.25 to 45.42 ft.) Well sorted very fine clayey sand and sandy clay, with occasional lithic granules; noncalcareous in upper section, and slightly calcareous below 45.75 ft.

48.75–49.75 ft: Poorly sorted, coarse sand with abundant lithic granules, pebbles and some medium–fine sand; noncalcareous and oxidized; dark yellowish brown (10YR4/2) to moderate brown (5YR4/4) coarsens downward to dominantly gravel at 49.75 ft.

49.75–50.58 ft: Poorly sorted, coarse sand, same as above; fines downward to medium sand at 50.58 ft.

50.58–51.25 ft: Medium sand with abundant lithic granules and pebbles; slightly oxidized; pale yellowish brown (10YR6/2).

51.25–51.92 ft: Clay, sand and fine gravel (pebbles to 5mm diameter); oxidized pebbles common; dark yellowish brown (10YR4/2) to dusky yellowish brown (10YR2/2).

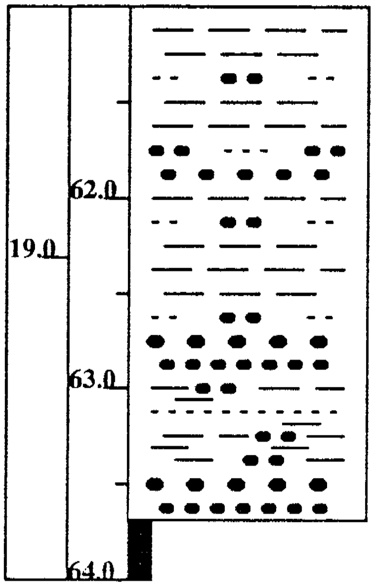


51.92–52.42 ft: Poorly sorted fine to coarse sand with clay and gravel (pebbles to 1.5 mm diameter); clay content decreases downward and disappears at 52.08 ft.

53.75–55.42: Gravel with medium to coarse sand (~15–20%) and minor clay (~5–10%); slightly oxidized; dark yellowish brown (10YR4/2).

55.42–57.08: Oxidized gravel similar to above with increased clay content (~15%) and decreased sand (~10%); high water content.

58.75–62.67 ft: Clay (~85–90%) with some fine sand and lithic granules; slightly calcareous; dark yellowish brown (10YR4/2) to moderate brown (5YR4/4).



61.75 ft: Strongly oxidized gravel layer.

62.67–63.67 ft: Gravel (~50–60%) and clay (~40%) with minor medium to coarse sand; minor oxidation; high water content.

63.67 ft: Gravel (~70%) and clay (~25%).

Explanation

— — —	Clay	— - — ● ●	Clay–Sand–Gravel
— - — -	Silt	> - - > - - >	Gypsum
- - - -	Sand	▨	Organic–Rich Sediment
● ● ●	Gravel	▮	Unrecovered core
— - — — - -	Silty Clay	(10YR5/2)	U.S. National Bureau of Standards Color Designation
— - — - - -	Silty Sandy Clay		

APPENDIX B

Relative Abundance Of Ostracode Species With Depth In San Agustin Core SAC-3/4

		Percent		
Depth Interval	Limnocythere bradburyi	L.ceriotuberosa	L.platyforma	Candona patzcuaro
3.67 - 3.79	75	25	0	0
4.08 - 4.17	67	33	0	0
4.25 - 4.33	45	10	0	45
4.42 - 4.50	45	10	0	45
4.58 - 4.67	75	25	0	0
4.83 - 5.00	47.5	5	0	47.5
5.08 - 5.17	12.5	2.5	0	85
5.25 - 5.33	12.5	2.5	0	85
5.42 - 5.50	5	5	0	90
5.58 - 5.67	37.5	12.5	0	50
5.83 - 6.00	40	20	0	40
6.08 - 6.17	32	8	0	60
6.25 - 6.33	25	5	0	70
6.33 - 6.42	5	0	0	95
6.42 - 6.58	48.5	3	0	48.5
6.58 - 6.67	37.5	12.5	0	50
6.75 - 6.83	20	5	0	75
6.83 - 6.92	42.5	15	0	42.5
6.92 - 7.00	42.5	15	0	42.5
7.08 - 7.17	30	20	0	50
7.25 - 7.33	47.5	47.5	0	5
7.42 - 7.50	33	67	0	0
7.58 - 7.67	5	70	0	25
7.67 - 7.75	95	3	0	2
7.83 - 8.00	100	0	0	0
8.08 - 8.17	100	0	0	0
8.25 - 8.33	100	0	0	0
8.42 - 8.50	100	0	0	0
8.58 - 8.67	98.5	0	1.5	0
8.67 - 8.75	90	8	2	0
8.83 - 9.00	90	5	5	0
9.00 - 9.17	62.5	37.5	0	0
9.25 - 9.33	50	50	0	0
9.42 - 9.50	96	2	2	0
9.58 - 9.67	100	0	0	0
9.83 - 9.92	60	40	0	0
9.92 - 10.0	75	25	0	0
10.08 - 10.17	100	0	0	0
10.25 - 10.33	96	3	1	0
10.42 - 10.50	98	2	0	0
10.58 - 10.67	50	37.5	12.5	0
10.92 - 11.00	100	0	0	0
11.08 - 11.17	46	46	8	0

11.25 - 11.33	15	77.5	7.5	0
11.42 - 11.50	2.5	97.5	0	0
11.58 - 11.67	15	85	0	0
11.67 - 11.75	15	85	0	0
11.83 - 11.92	20	80	0	0
11.92 - 12.00	5	90	5	0
12.08 - 12.17	55	45	0	0
12.25 - 12.33	33	67	0	0
12.42 - 12.50	2	96	2	0
12.67 - 12.83	20	80	0	0
12.83 - 13.00	15	85	0	0
13.08 - 13.17	10	90	0	0
13.25 - 13.33	85	15	0	0
13.42 - 13.50	98	2	0	0
13.58 - 13.67	80	20	0	0
14.00 - 14.08	70	15	15	0
14.08 - 14.17	65	25	10	0
14.17 - 14.25	85	15	0	0
14.25 - 14.33	65	35	0	0
14.33 - 14.42	65	20	15	0
14.42 - 14.50	25	25	50	0
14.50 - 14.58	45	20	35	0
14.58 - 14.67	60	25	15	0
14.67 - 14.75	65	25	10	0
15.00 - 15.08	70	20	10	0
15.08 - 15.17	80	15	5	0
15.17 - 15.25	80	15	5	0
15.25 - 15.33	95	5	0	0
15.42 - 15.50	85	15	0	0
15.58 - 15.67	100	0	0	0
15.67 - 15.75	95	5	0	0
15.83 - 15.96	95	5	0	0
16.00 - 16.08	100	0	0	0
16.08 - 16.17	87.5	6.25	6.25	0
16.25 - 16.33	90	10	0	0
16.58 - 16.67	80	5	15	0
16.75 - 16.83	96	2	2	0
17.00 - 17.08	95	5	0	0
17.08 - 17.17	90	8	2	0
17.25 - 17.33	90	2	8	0
17.42 - 17.50	75	25	0	0
17.58 - 17.67	65	35	0	0
17.67 - 17.75	50	50	0	0
17.83 - 17.92	60	40	0	0
18.00 - 18.08	50	0	50	0
18.08 - 18.17	60	5	35	0
18.25 - 18.33	60	5	35	0
18.42 - 18.50	70	12.5	17.5	0
18.50 - 18.58	75	15	10	0
18.58 - 18.67	90	5	5	0

18.67 - 18.75	90	6.5	3.5	0
18.83 - 18.92	50	25	25	0
18.92 - 19.00	85	5	10	0
19.08 - 19.17	92.5	2.5	5	0
19.25 - 19.33	85	12.5	2.5	0
19.42 - 19.50	96	2	2	0
19.50 - 19.58	95	1.5	3.5	0
19.58 - 19.67	95	1	4	0
19.67 - 19.75	95	1	4	0
19.83 - 19.92	50	15	35	0
19.92 - 20.00	55	10	35	0
20.08 - 20.17	60	10	30	0
20.25 - 20.33	60	10	30	0
20.42 - 20.50	60	15	25	0
20.50 - 20.58	55	15	30	0
20.58 - 20.67	50	15	35	0
20.75 - 20.83	25	50	25	0
20.83 - 20.92	50	50	0	0
20.92 - 21.00	55	45	0	0
21.13 - 21.25	95	2	3	0
21.25 - 21.33	30	65	5	0
21.42 - 21.50	55	45	0	0
21.58 - 21.67	65	35	0	0
21.67 - 21.75	90	10	0	0
21.75 - 21.83	90	10	0	0
21.83 - 21.92	95	5	0	0
21.92 - 22.00	97.5	2.5	0	0
22.08 - 22.25	80	10	10	0
22.25 - 22.33	90	9	1	0
22.42 - 22.50	95	5	0	0
22.58 - 22.67	95	5	0	0
22.67 - 22.75	90	0	10	0
22.83 - 22.92	75	12.5	12.5	0
22.92 - 23.00	55	45	0	0
23.08 - 23.17	80	12	8	0
23.25 - 23.33	15	85	0	0
23.42 - 23.50	80	20	0	0
23.58 - 23.67	85	15	0	0
23.67 - 23.75	100	0	0	0
23.83 - 23.92	85	15	0	0
24.00 - 24.17	2.5	95	2.5	0
24.25 - 24.33	0	87.5	12.5	0
24.42 - 24.50	2.5	95	2.5	0
24.58 - 24.67	9	100	0	0
24.75 - 24.83	0	100	0	0
24.83 - 24.92	2.5	97.5	0	0
24.92 - 25.00	2.5	97.5	0	0
25.08 - 25.17	0	100	0	0
25.25 - 25.33	2.5	97.5	0	0

25.42 - 25.63	0	100	0	0
26.00 - 26.17	2.5	97.5	0	0
26.17 - 26.33	0	100	0	0
26.33 - 26.50	0	100	0	0
27.00 - 27.21	0	100	0	0
27.21 - 27.42	0	100	0	0

APPENDIX C

San Agustin Isotopic Results

Sample No.	Depth (ft)	Age (ka)	Oxygen-18	Carbon-13	Ostracode Species/Assemblage
			CORE SA4		
LHMX3-1-2	3.13	4.43	31.761	-2.246	L.bradburyi/L.ceriotuberosa/C.patzcuaro/H.spA
LB3-8-9.5	3.73	5.25	31.427	-3.091	L.bradburyi
LMX4-1-2	4.13	5.60	33.081	-1.551	L.bradburyi/L.ceriotuberosa
LHMX4-3-4	4.29	5.74	32.556	-1.481	L.bradburyi/L.ceriotuberosa/C.patzcuaro/H.spA
LB4-7-8	4.63	6.04	31.832	-0.270	L.bradburyi
LB4-10-12	4.92	6.30	31.259	-1.221	L.bradburyi
HNS5-3-4	5.29	6.63	32.406	-2.239	C.patzcuaro/H.spA
HNS5-5-6	5.46	6.78	32.540	-1.412	C.patzcuaro/H.spA
LB5-7-8	5.63	6.93	31.071	-3.565	L.bradburyi
LB5-8-9	5.71	7.00	31.478	-1.964	L.bradburyi
LB6-1-2	6.13	7.37	30.632	-2.506	L.bradburyi
LB6-3-4	6.29	7.51	29.986	-4.325	L.bradburyi
LB6-4-5	6.38	7.59	30.555	-3.384	L.bradburyi
LB6-5-7	6.50	7.70	30.558	-2.439	L.bradburyi
LB6-7-8	6.63	7.81	30.612	-2.700	L.bradburyi
LB6-9-10	6.79	7.95	31.506	-1.335	L.bradburyi
LB6-10-11	6.88	8.03	31.647	-1.518	L.bradburyi
LB-6-11-12	6.96	8.10	32.667	-0.307	L.bradburyi
LB7-1-2	7.13	8.25	32.178	-0.234	L.bradburyi
LB7-3-4	7.29	8.39	32.417	-0.141	L.bradburyi
LB7-5-6	7.46	8.54	31.275	-0.853	L.bradburyi
LC-7-7-8	7.63	8.70	32.553	-1.808	L.ceriotuberosa
LB7-8-9	7.71	8.76	30.157	-2.370	L.bradburyi
LB7-10-12	7.92	8.89	31.700	-1.550	L.bradburyi
LB8-1-2	8.13	9.02	30.512	-1.910	L.bradburyi
LB8-3-4	8.29	9.12	32.269	-0.912	L.bradburyi
LB8-5-6	8.46	9.23	31.673	-1.627	L.bradburyi
LB8-7-8	8.63	9.33	32.228	-1.844	L.bradburyi
LB8-8-9	8.71	9.38	31.682	-1.265	L.bradburyi
LB-8-10-12	8.92	9.52	30.684	-2.040	L.bradburyi
LB9-0-2	9.08	9.62	31.066	-0.461	L.bradburyi
LB9-3-4	9.29	9.75	30.649	-2.064	L.bradburyi
LB9-5-6	9.46	9.86	28.764	-1.980	L.bradburyi
LB9-7-8	9.63	9.96	32.571	-2.196	L.bradburyi
LB-9-10-11	9.88	10.12	32.284	-1.037	L.bradburyi

LB-9-11-12	9.96	10.17	33.055	-0.277	L.bradburyi
LB10-1-2	10.13	10.28	31.415	-1.584	L.bradburyi
LB10-3-4	10.29	10.38	32.134	-2.050	L.bradburyi
LB10-5-6	10.46	10.48	31.766	-2.528	L.bradburyi
LMX10-7-8	10.63	10.59	30.970	-1.413	L.bradburyi/L.ceriotuberosa/L.platyforma
LB10-11-12	10.96	10.80	31.855	-3.150	L.bradburyi
LB11-1-2	11.13	10.91	30.228	-3.669	L.bradburyi
LB11-3-4	11.29	11.01	31.260	-2.723	L.bradburyi
LC11-5-6	11.46	11.11	32.247	-0.653	L.ceriotuberosa
LB11-7-8	11.63	11.22	31.332	-1.417	L.bradburyi
LC11-8-9	11.71	11.27	32.516	-0.132	L.ceriotuberosa
LB11-10-11	11.88	11.38	30.525	-1.923	L.bradburyi
LB11-11-12	11.96	11.43	31.189	-1.512	L.bradburyi
LB12-1-2	12.13	11.53	32.083	-1.649	L.bradburyi
LB12-3-4	12.29	11.63	31.811	-1.699	L.bradburyi
LC12-5-6	12.46	11.74	31.828	-0.416	L.ceriotuberosa
LC12-7-8	12.63	11.85	31.443	-2.253	L.ceriotuberosa
LB12-8-10	12.75	11.92	31.421	-1.347	L.bradburyi
LB12-10-12	12.92	12.03	31.001	-1.773	L.bradburyi
LMX13-1-2	13.13	12.16	31.668	-1.036	L.bradburyi/L.ceriotuberosa
LB13-3-4	13.29	12.26	31.903	-2.518	L.bradburyi
LB13-5-6	13.46	12.37	32.468	-2.729	L.bradburyi
LMX13-7-8	13.63	12.48	31.970	-2.568	L.bradburyi/L.ceriotuberosa
LMX14-0-1	14.04	12.73	31.181	-3.231	L.bradburyi/L.ceriotuberosa/L.platyforma
LMX14-1-2	14.13	12.79	30.876	-2.710	L.bradburyi/L.ceriotuberosa/L.platyforma
LB14-2-3	14.21	12.84	28.842	-4.272	L.bradburyi
LMX14-3-5	14.33	12.92	29.803	-3.615	L.bradburyi/L.ceriotuberosa/L.platyforma
LMX14-5-6	14.46	13.00	29.616	-4.021	L.bradburyi/L.ceriotuberosa/L.platyforma
LMX14-6-7	14.54	13.05	29.639	-3.558	L.bradburyi/L.ceriotuberosa/L.platyforma
LMX14-7-8	14.63	13.11	30.380	-2.778	L.bradburyi/L.ceriotuberosa/L.platyforma
LB14-8-9	14.71	13.16	30.913	-2.850	L.bradburyi
LB15-0-2	15.08	13.39	33.308	-2.456	L.bradburyi
LMX15-2-3	15.21	13.47	31.439	-2.255	L.bradburyi/L.ceriotuberosa/L.platyforma
LB15-3-4	15.29	13.52	31.611	-1.761	L.bradburyi
LB15-5-6	15.46	13.63	31.912	-1.579	L.bradburyi
LB15-7-8	15.63	13.73	29.721	-3.965	L.bradburyi
LB15-8-9	15.71	13.78	31.619	-2.943	L.bradburyi
LB15-10-11	15.90	13.90	32.305	-3.229	L.bradburyi
LB16-0-1	16.04	13.99	31.439	-2.321	L.bradburyi

LB16-1-2	16.13	14.05	30.623	-3.120	L.bradburyi
LB16-3-4	16.29	14.15	31.154	-1.997	L.bradburyi
LB16-5-6	16.46	14.26	32.777	-1.945	L.bradburyi
LMX16-7-8	16.63	14.36	30.980	-3.187	L.bradburyi/L.ceriotuberosa/L.platyforma
LB16-9-10	16.79	14.46	31.036	-2.545	L.bradburyi
LB17-0-1	17.04	14.62	31.559	-2.154	L.bradburyi
LB17-1-2	17.13	14.68	31.715	-1.975	L.bradburyi
LB17-3-4	17.29	14.78	31.356	-2.364	L.bradburyi
LB17-5-6	17.46	14.88	31.145	-1.516	L.bradburyi
LB17-7-8	17.63	14.99	30.618	-2.135	L.bradburyi
LB17-8-9	17.71	15.04	31.180	-2.399	L.bradburyi
LMX17-10-11	17.88	15.15	29.825	-3.761	L.bradburyi/L.ceriotuberosa
LB18-0-1	18.04	15.25	28.062	-5.297	L.bradburyi
LB18-1-2	18.13	15.31	28.217	-5.400	L.bradburyi
LB18-3-4	18.29	15.41	28.225	-5.405	L.bradburyi
LB18-5-6	18.46	15.51	29.746	-3.941	L.bradburyi
LB18-6-7	18.54	15.56	30.614	-3.025	L.bradburyi
LB18-7-8	18.63	15.62	30.859	-3.094	L.bradburyi
LB18-8-9	18.71	15.67	31.770	-2.475	L.bradburyi
LMX18-10-11	18.88	15.78	28.233	-4.561	L.bradburyi/L.ceriotuberosa/L.platyforma
LB18-11-12	18.96	15.83	28.036	-4.730	L.bradburyi
LB19-1-2	19.13	15.93	27.583	-6.184	L.bradburyi
LB19-3-4	19.29	16.03	29.313	-4.882	L.bradburyi
LB19-5-6	19.46	16.14	30.313	-3.810	L.bradburyi
LB19-6-7	19.54	16.19	31.760	-3.357	L.bradburyi
LB19-7-8	19.63	16.25	30.891	-3.707	L.bradburyi
LB19-8-9	19.71	16.30	30.670	-3.261	L.bradburyi
LB19-10-11	19.88	16.41	28.701	-5.100	L.bradburyi
LB19-11-12	19.96	16.46	29.580	-5.266	L.bradburyi
LMX20-1-2	20.13	16.56	27.150	-5.819	L.bradburyi/L.platyforma
LMX20-3-4	20.29	16.66	28.182	-4.880	L.bradburyi/L.ceriotuberosa/L.platyforma
LCP20-5-6	20.46	16.77	28.845	-4.764	L.ceriotuberosa/L.platyforma
LB20-6-7	20.54	16.82	28.882	-4.326	L.bradburyi
LB20-7-8	20.63	16.88	29.473	-3.929	L.bradburyi
LMX20-9-10	20.79	16.98	30.768	-2.969	L.bradburyi/L.ceriotuberosa/L.platyforma
LB20-11-12	20.96	17.08	30.620	-2.689	L.bradburyi
LB21-1.5-3	21.19	17.23	31.742	-2.902	L.bradburyi
LMX21-3-4	21.29	17.29	31.272	-1.625	L.bradburyi/L.ceriotuberosa
LMX21-5-6	21.46	17.40	31.535	-1.767	L.bradburyi/L.ceriotuberosa

LMX21-7-8	21.63	17.51	32.419	-1.020	L.bradburyi/ L.ceriotuberosa
LB21-8-9	21.71	17.56	32.478	-1.628	L.bradburyi
LB21-9-10	21.79	17.61	32.114	-1.430	L.bradburyi
LB21-10-11	21.88	17.66	31.627	-2.041	L.bradburyi
LB21-11-12	21.96	17.71	31.107	-2.183	L.bradburyi
LB22-1-3	22.17	17.85	30.973	-2.388	L.bradburyi
LB22-3-4	22.29	17.92	31.248	-2.162	L.bradburyi
LB22-5-6	22.46	18.03	31.678	-1.783	L.bradburyi
LB22-7-8	22.63	18.13	30.749	-2.696	L.bradburyi
LB22-8-9	22.71	18.18	31.505	-3.733	L.bradburyi
LB22-10-11	22.88	18.29	30.586	-3.600	L.bradburyi
LB22-11-12	22.96	18.34	30.744	-2.772	L.bradburyi
LB23-1-2	23.13	18.45	30.532	-3.250	L.bradburyi
LC23-3-4	23.29	18.55	31.287	-1.514	L.ceriotuberosa
LB23-5-6	23.46	18.66	31.569	-1.504	L.bradburyi
LB23-7-8	23.63	18.76	31.136	-1.909	L.bradburyi
LB23-8-9	23.71	18.81	33.173	-1.579	L.bradburyi
LB23-10-11	23.88	18.92	31.450	-1.768	L.bradburyi
LMX24-0-2	24.08	19.05	30.588	-1.750	L.bradburyi/ L.ceriotuberosa
LC24-3-4	24.29	19.18	29.934	-1.912	L.ceriotuberosa
LC24-5-6	24.46	19.28	30.038	-1.259	L.ceriotuberosa
LC24-7-8	24.63	19.39	30.276	-1.244	L.ceriotuberosa
LC24-9-10	24.79	19.49	30.843	-0.732	L.ceriotuberosa
LC24-10-11	24.88	19.55	29.987	-1.130	L.ceriotuberosa
LC24-11-12	24.96	19.60	29.300	-1.452	L.ceriotuberosa
LC25-1-2	25.13	19.71	30.373	-1.047	L.ceriotuberosa
LC25-3-4	25.29	19.81	31.045	-1.136	L.ceriotuberosa
C-26-0-2	26.08	20.28	30.542	1.184	Unknown carbonate
C-26-2-4	26.25	20.34	31.309	1.629	Unknown carbonate
LC27-0-2.5	27.10	20.64	30.611	-1.150	L.ceriotuberosa
LC27-2.5-5	27.31	20.71	30.458	-1.135	L.ceriotuberosa

CORE SA3

LC26-0-4	26.17	20.15	30.009	-2.052	L.ceriotuberosa
LC26-4-6	26.42	20.28	29.709	-1.722	L.ceriotuberosa
C-26-6-8	26.58	20.34	30.746	1.084	Unknown carbonate
C-26-8-10	26.75	20.40	30.782	1.144	Unknown carbonate
C-26-10-12	26.92	20.46	29.860	1.304	Unknown carbonate
C-33-8-10	33.75	22.86	28.130	-1.297	Unknown carbonate
C-34-0-2	34.08	22.98	29.298	-0.933	Unknown carbonate
LC40-5-6	40.46	25.22	29.388	-2.783	L.ceriotuberosa
LC40-6-7	40.54	25.25	30.800	-2.243	L.ceriotuberosa
LC40-7-8	40.63	25.28	30.261	-2.659	L.ceriotuberosa
LC40-8-10	40.75	25.32	28.888	-2.198	L.ceriotuberosa
LC40-10-12	40.92	25.38	30.802	-2.576	L.ceriotuberosa
LC41-0-2	41.08	25.44	27.852	-3.453	L.ceriotuberosa
LC41-2-4	41.25	25.50	28.107	-3.432	L.ceriotuberosa
LC41-4-6	41.42	25.56	27.891	-4.927	L.ceriotuberosa

APPENDIX D

Transient Isotopic Model For Lake San Agustin

```
********************************************************************************
********************************************************************************
* THIS PROGRAM CALCULATES CHANGES IN LAKE VOLUME AND ISOTOPIC COMPOSITION      *
* WITH RESPECT TO TIME.                                                        *
********************************************************************************
********************************************************************************

********************************************************************************
*       A PROGRAM TO CALL THE RUNGE-KUTTA-FEHLBERG ORDER 4 ROUTINE TO SOLVE    *
*       A SYSTEM OF PARTIAL DIFFERENTIAL EQUATION OF THE FORM:  F(T,X)= X'     *
********************************************************************************
        IMPLICIT DOUBLE PRECISION (A-H,O-Z)
        DIMENSION X(3),TOL(3)
        LOGICAL FOUND,GUESS,PASS,GRAF,CPARAM,ONLY1,ZEROVOL,ZEROCHK

        COMMON/FIRST/INCHOICE,A,B,STIME(300),TEMP(300),EVAP(300),
     +  HUM(300),DELA(300),DELI(300),GUESS,C,TEMPC,HUMC,EVAPC,DELAC,
     +  DELIC,CPARAM,TEMPCURV,NPTS,HTIME(300),NHPTS

        COMMON/TRADE1/GRAF,CALTEMP,DELCAL,TDELI,TTEMP
        OPEN(UNIT=98,FILE='SANAG.INP',STATUS='OLD')
        WRITE(6,*)
        WRITE(6,*)'READING ITMAX,N,X(I),DTMAX,DTMIN,TOL(I)'
        READ(98,*)ITMAX,N,(X(I),I=1,N),DTMAX,DTMIN,(TOL(I),I=1,N)

**************************************************************
** THIS VARIABLE IS USED TO "GUESS" AT AN INITIAL INFLOW QI **
**************************************************************
        GUESS=.TRUE.

*****************************************
** A CHANCE TO ADJUST INPUT PARAMETERS **
*****************************************


        WRITE(6,*)
        WRITE(6,*)'THE CURRENT PARAMETERS ARE:'
        WRITE(6,*)'   1 : MAX ITERATIONS =',ITMAX
        WRITE(6,*)'   2 : LAKE VOL =',X(1)
        WRITE(6,*)'   3 : DEL O-18 =',X(2)
        WRITE(6,*)'   4 : MAX TIME STEP =',DTMAX
        WRITE(6,*)'   5 : MIN TIME STEP =',DTMIN
        WRITE(6,*)'   6 : LAKE VOL TOLERANCE=',TOL(1)
        WRITE(6,*)'   7 : O-18 TOLERANCE=',TOL(2)

        WRITE(6,*)
        WRITE(6,*)
        WRITE(6,*)'DO YOU WANT TO CHANGE ANY OF THE STARTING PARAMETERS ?'
        WRITE(6,*)'1=YES    0=NO'
        READ(5,*)ISEE
        WRITE(6,*)
        WRITE(6,*)

        IF(ISEE .EQ. 1)THEN

           WRITE(6,*)
           WRITE(6,*)'HOW MANY PARAMETERS WOULD YOU LIKE TO CHANGE ?'
           READ(5,*)K
           WRITE(6,*)

           DO 250 I = 1,K
              WRITE(6,*)
300           WRITE(6,*)'ENTER THE PARAMETER NUMBER'
              WRITE(6,*)
              WRITE(6,*)'   1 : MAX ITERATIONS ='
              WRITE(6,*)'   2 : LAKE VOL ='
              WRITE(6,*)'   3 : DEL O-18 ='
              WRITE(6,*)'   4 : MAX TIME STEP ='
              WRITE(6,*)'   5 : MIN TIME STEP ='
              WRITE(6,*)'   6 : LAKE VOL TOLERANCE='
              WRITE(6,*)'   7 : O-18 TOLERANCE='
              READ(5,*)NUMP
              IF(NUMP .EQ. 1)THEN
                 WRITE(6,*)
                 WRITE(6,*)'MAX ITERATIONS :',ITMAX
                 WRITE(6,*)'ENTER NEW VALUE'
```

```
                 READ(5,*)ITMAX
              ELSE IF(NUMP .EQ. 2)THEN
                 WRITE(6,*)
                 WRITE(6,'(A,D15.7)')' LAKE VOLUME :',X(1)
                 WRITE(6,*)'NOTE: MAX LAKE VOL IS 39.898D9 (M^3)'
                 WRITE(6,*)'ENTER NEW VALUE'
                 READ(5,*)X(1)
              ELSE IF(NUMP .EQ. 3)THEN
                 WRITE(6,*)
                 WRITE(6,*)'DEL O-18 :',X(2)
                 WRITE(6,*)'ENTER NEW VALUE'
                 READ(5,*)X(2)
              ELSE IF(NUMP .EQ. 4)THEN
                 WRITE(6,*)
                 WRITE(6,*)'MAX TIME STEP :',DTMAX
                 WRITE(6,*)'ENTER NEW VALUE'
                 READ(5,*)DTMAX
              ELSE IF(NUMP .EQ. 5)THEN
                 WRITE(6,*)
                 WRITE(6,*)'MIN TIME STEP :',DTMIN
                 WRITE(6,*)'ENTER NEW VALUE'
                 READ(5,*)DTMIN
              ELSE IF(NUMP .EQ. 6)THEN
                 WRITE(6,*)
                 WRITE(6,*)'LAKE VOL TOLERANCE :',TOL(1)
                 WRITE(6,*)'ENTER NEW VALUE'
                 READ(5,*)TOL(1)
              ELSE IF(NUMP .EQ. 7)THEN
                 WRITE(6,*)
                 WRITE(6,*)'DEL O-18 TOLERANCE :',TOL(2)
                 WRITE(6,*)'ENTER NEW VALUE'
                 READ(5,*)TOL(2)
              ELSE
                 WRITE(6,*)
                 WRITE(6,*)'GET A CLUE BLISTER BRAIN'
                 WRITE(6,*)'PICK A NUMBER BETWEEN 1 AND 8'
                 WRITE(6,*)
                 GO TO 300
              ENDIF
250        CONTINUE

************************************
** WRITE NEW VALUES TO INPUT FILE **
************************************

           REWIND 98
           WRITE(98,*)ITMAX,N,(X(I),I=1,N),DTMAX,DTMIN,(TOL(I),
     +                I=1,N)

        ENDIF

********************************************************************************
*              LET'S CHOOSE AN INFLOW FUNCTION AND TIME INTERVAL               *
********************************************************************************


        WRITE(6,*)
        WRITE(6,*)
115     WRITE(6,*)'WHICH INFLOW FUNCTION WOULD YOU LIKE?'
        WRITE(6,*)'1=LINEAR'
        WRITE(6,*)'2=EXPONENTIAL'
        WRITE(6,*)'3=LOGARITHMIC'
        WRITE(6,*)'4=POWER'
        WRITE(6,*)'5=SINUSOIDAL'
        WRITE(6,*)'6=STEP'
        WRITE(6,*)'7=ZERO INFLOW'
        READ(5,*)INCHOICE

        WRITE(6,*)
        WRITE(6,*)
        IF(INCHOICE .EQ. 1)THEN
           WRITE(6,*)'YOU HAVE CHOSEN f(QI)= A*X+B'
           WRITE(6,*)'ENTER A VALUE FOR ''A'', AND ''B'''
        ELSE IF(INCHOICE .EQ. 2)THEN
           WRITE(6,*)'YOU HAVE CHOSEN f(QI)= B*EXP(A*X)'
           WRITE(6,*)'ENTER A VALUE FOR ''A'', AND ''B'''
```

```
        ELSE IF(INCHOICE .EQ. 3)THEN
           WRITE(6,*)'YOU HAVE CHOSEN f(QI)= B+A*log(X)'
           WRITE(6,*)'ENTER A VALUE FOR ''A'', AND ''B'''
        ELSE IF(INCHOICE .EQ. 4)THEN
           WRITE(6,*)'YOU HAVE CHOSEN f(QI)= B+A*(X**C)'
           WRITE(6,*)'ENTER VALUES FOR ''A'',''B'', AND ''C'''
        ELSE IF(INCHOICE .EQ. 5)THEN
           WRITE(6,*)'YOU HAVE CHOSEN f(QI)= B+A*SIN(C*X)'
           WRITE(6,*)'ENTER VALUES FOR ''A'',''B'', AND ''C'''
        ELSE IF(INCHOICE .EQ. 6)THEN
           WRITE(6,*)'YOU HAVE CHOSEN f(QI)= B+(A*B)'
           WRITE(6,*)'ENTER A VALUE FOR ''A'', AND ''B'''
        ELSE IF(INCHOICE .EQ. 7)THEN
           WRITE(6,*)'YOU HAVE CHOSEN ZERO INFLOW'
           WRITE(6,*)'GRAB YOUR CANTEEN AND HEAD FOR THE SHADE'
        ELSE
           WRITE(6,*)
           WRITE(6,*)
           WRITE(6,*)'NOT A VALID CHOICE MULLET-HEAD'
           WRITE(6,*)
           WRITE(6,*)
           GOTO 115
        ENDIF

        IF(INCHOICE .EQ. 4 .OR. INCHOICE .EQ. 5)THEN
           READ(5,*)A,B,C
        ELSE IF(INCHOICE .NE. 7)THEN
           READ(5,*)A,B
        ENDIF

        WRITE(6,*)
        WRITE(6,*)'ENTER STARTING TIME AND ENDING TIME'
        WRITE(6,*)'0 CORRESPONDS TO PRESENT, 2.0E6 IS 2 MILLION YRS AGO'
        WRITE(6,*)
        WRITE(6,*)
        WRITE(6,*)'MANAGEMENT ACCEPTS NO RESPONSIBILITY FOR PEOPLE WHO'
        WRITE(6,*)'RUN THE MODEL BACKWARD IN TIME'
        WRITE(6,*)
        WRITE(6,*)
        READ(5,*)TBEG, TEND
        WRITE(6,*)

*******************************
** CONSTANT PARAMETER OPTION **
*******************************

        CPARAM=.FALSE.
        WRITE(6,*)
        WRITE(6,*)'DO YOU WANT TO RUN THE PROGRAM WITH CONSTANT PARAMETE
     +RS ?'
        WRITE(6,*)'1=YES   0=NO'
        WRITE(6,*)
        READ(5,*)INPARAM

        IF(INPARAM .EQ. 1)THEN
           CPARAM=.TRUE.
           OPEN(UNIT=68, FILE='CONSTANT.INP', STATUS='OLD')
           READ(68,*) TEMPC,HUMC,EVAPC,DELAC,DELIC
           CLOSE(UNIT=68)

        END IF

********************
** GRAPHICS STUFF **
********************

        GRAF=.FALSE.

        WRITE(6,*)
        WRITE(6,*)'DO YOU WANT TO PLOT THIS RUN ON THE SCREEN'
        WRITE(6,*)'1=YES    0=NO'
        READ(5,*)IGRAF
        WRITE(6,*)

        IF(IGRAF .EQ. 1)THEN
           GRAF=.TRUE.
```

```
        ENDIF


********************************************************************************
*     All we're doing here is reading data files, the good stuff is later     *
********************************************************************************

        IF(.NOT. CPARAM)THEN

           WRITE(6,*)
           WRITE(6,*)
           WRITE(6,*)'READING DATA FILES, GOOD TIME TO GET MUNCHIES'
           WRITE(6,*)
90         WRITE(6,*)'WHICH TEMPERATURE CURVE DO YOU WANT?'
           WRITE(6,*)'1=SHACKLETON OCEAN O-18 CURVE'
           WRITE(6,*)'2=PHILLIPS SAN JUAN BASIN CURVE'
           WRITE(6,*)'3=OSTRACODE STRATIGRAPHY CURVE'
           READ(5,*)TEMPCURV

           IF(TEMPCURV .EQ. 1)THEN
              WRITE(6,*)'YOU HAVE CHOSEN THE SHACKLETON OCEAN CURVE'
              OPEN(UNIT=20,FILE='SHACK_SA.CLIM',STATUS='OLD')
              OPEN(UNIT=25,FILE='SHACK_SA.ISODAT',STATUS='OLD')
              OPEN(UNIT=30,FILE='HUM_SA.DAT',STATUS='OLD')

              DO 101 I=1,300
                 READ(20,*,END=102)STIME(I),TEMP(I),EVAP(I)
101           CONTINUE

102           NPTS = I-1

              DO 103 I=1,NPTS
                 READ(25,*)DELI(I),DELA(I)
103           CONTINUE

              DO 104 I=1,300
                 READ(30,*,END=105) HTIME(I), HUM(I)
104           CONTINUE

105           NHPTS = I-1

              DO 106 I=1,NPTS
                 STIME(I)=STIME(I)*1.0D3
106           CONTINUE

              DO 107 I=1,NHPTS
                 HTIME(I)=HTIME(I)*1.0D3
107           CONTINUE

              CLOSE(UNIT=20)
              CLOSE(UNIT=25)
              CLOSE(UNIT=30)

           ELSE IF(TEMPCURV .EQ. 2)THEN
              WRITE(6,*)'YOU HAVE CHOSEN UNCLE FREDDYS SAN JUAN CURVE'
              OPEN(UNIT=35,FILE='SANJUAN_SA.CLIM',STATUS='OLD')
              OPEN(UNIT=40,FILE='SANJUAN_SA.ISODAT',STATUS='OLD')
              OPEN(UNIT=45,FILE='HUM_SA.DAT',STATUS='OLD')

              DO 120 I=1,300
                 READ(35,*,END=121)STIME(I),TEMP(I),EVAP(I)
120           CONTINUE

121           NPTS = I-1

              DO 122 I=1,NPTS
                 READ(40,*)DELI(I),DELA(I)
122           CONTINUE

              DO 123 I=1,300
                 READ(45,*,END=124)HTIME(I),HUM(I)
123           CONTINUE

124           NHPTS = I-1

              DO 125 I=1,NPTS
```

```
                 STIME(I)=STIME(I)*1.0D3
125           CONTINUE

              DO 126 I=1,NHPTS
                 HTIME(I)=HTIME(I)*1.0D3
126           CONTINUE

              CLOSE(UNIT=35)
              CLOSE(UNIT=40)
              CLOSE(UNIT=45)

           ELSE IF(TEMPCURV .EQ. 3)THEN
              WRITE(6,*)'YOU HAVE CHOSEN THE OSTRACODE CURVE'
              OPEN(UNIT=50,FILE='COD_CLIM_ISO.DAT',STATUS='OLD')
              OPEN(UNIT=55,FILE='HUM_SA.DAT',STATUS='OLD')

              DO 130 I=1,300
                 READ(50,*,END=131)STIME(I),TEMP(I),EVAP(I),DELI(I),
     +           DELA(I)
130           CONTINUE

131           NPTS = I-1

              DO 132 I=1,300
                 READ(55,*,END=133)HTIME(I),HUM(I)
132           CONTINUE

133           NHPTS = I-1

              DO 134 I=1,NPTS
                 STIME(I)=STIME(I)*1.0D3
134           CONTINUE

              DO 135 I=1,NHPTS
                 HTIME(I)=HTIME(I)*1.0D3
135           CONTINUE

              CLOSE(UNIT=50)
              CLOSE(UNIT=55)

           ELSE
              WRITE(6,*)'NOT A VALID CHOICE KNUMB-KNUCKLES, TRY AGAIN!'
           GO TO 90

           ENDIF
        ENDIF

****************************
** START THE BALL ROLLING **
****************************

        CALL RKF(N,X,TBEG,TEND,TOL,DTMAX,DTMIN,ITMAX)

***************************
** FINISH PLOTTING STUFF **
***************************

        IF(GRAF)THEN
           CALL ENDPL(0)
           CALL DONEPL
        ENDIF

        WRITE(99,*)
        WRITE(96,*)
        WRITE(95,*)
        END

        SUBROUTINE RKF(N,X,TBEG,TEND,TOL,DTMAX,DTMIN,ITMAX)
*******************************************************************************
*       SOLVE A SYSTEM OF PARTIAL DIFFERENTIAL EQUATION OF THE FORM:          *
*                          F(T,X)= X'                                         *
*        BETWEEN T1,T2, GIVEN THE INITIAL CONDITION XO(T1)                    *
*******************************************************************************
        IMPLICIT DOUBLE PRECISION (A-H,O-Z)
        COMMON/TRADE1/GRAF,CALTEMP,DELCAL,TDELI,TTEMP
        REAL XMIN,XMAX,YMIN,YMAX,YDEL(300),XPLT(300),YQI(300),
```

```
     +  YAREA(300),YTEMP(300)

        DIMENSION X(3),RK1(3),RK2(3),RK3(3),RK4(3),RK5(3),RK6(3),R(3)
        DIMENSION TERM(3),DEL(3),TOL(3)
        PARAMETER (VOLMAX=39.898D9)
        LOGICAL FOUND,GUESS,PASS,GRAF,CPARAM,ONLY1,ZEROVOL,ZEROCHK
        OPEN(UNIT=99,FILE='DEL.OUT',STATUS='NEW',CARRIAGE CONTROL=
     +       'LIST')
        OPEN(UNIT=97,FILE='DIAG.OUT',STATUS='NEW',CARRIAGE CONTROL=
     +       'LIST')
        OPEN(UNIT=96,FILE='AREA.OUT',STATUS='NEW',CARRIAGE CONTROL=
     +       'LIST')
        OPEN(UNIT=95,FILE='QI.OUT',STATUS='NEW',CARRIAGE CONTROL=
     +       'LIST')
10      FORMAT(A,D12.5)


        XMIN=TBEG
        XMAX=TEND
        TIME=TBEG
        STEP=DTMAX
        KOUNT=1
        ONLY1=.TRUE.
        ZEROVOL=.FALSE.
        ZEROCHK=.FALSE.

*************************************
** THE SOLVING ROUTINE BEGINS HERE **
*************************************

        WRITE(6,*)
        WRITE(6,*)
        WRITE(6,*)'START SOLVING DIFFERENTIAL EQUATIONS'
        WRITE(6,*)
        WRITE(6,*)

        DO 100 ITER=1,ITMAX
           IF(TIME.GT.TEND)THEN
              KNT=1
              T=TIME
              DO 200 I=1,N
                 RK1(I)=STEP*F(I,TIME,X,T,KNT,KOUNT,TBEG)
200           CONTINUE

********************************************
** STORE INITIAL VALUES IN GRAPHICS ARRAY **
********************************************

              IF(ONLY1)THEN
                 YDEL(1)=DELCAL
                 XPLT(1)=TBEG
                 YAREA(1)=SAREA(X(1))
                 YQI(1)=FQI(0.D0)
                 YTEMP(1)=TTEMP
                 ONLY1=.FALSE.
              ENDIF

***********************************************************************
** "TERM" IS AN ARRAY WHICH STORES APPROXIMATIONS OF VOL AND DEL O-18 **
** WHICH WILL BE USED IN FINAL CALCULATIONS IF ERRORS WITHIN THE STEP **
** ARE LESS THAN THE GIVEN TOLERANCES.                                **
***********************************************************************

              T=TIME-STEP/4.D0
              KNT=2
              DO 300 I=1,N
                 TERM(I)=X(I)+ RK1(I)/4.D0
300           CONTINUE
              IF(TERM(1) .LE. 0.D0)THEN
                 IF(STEP .EQ. DTMIN)THEN
                    ZEROVOL=.TRUE.
                    PASS=.TRUE.
                    GOTO 1375
                 ELSE
                    ZEROCHK=.TRUE.
                 ENDIF
```

```
1200          CONTINUE
              IF(TERM(1) .LE. 0.D0)THEN
                 IF(STEP .EQ. DTMIN)THEN
                    ZEROVOL=.TRUE.
                    PASS=.TRUE.
                    GOTO 1375
                 ELSE
                    ZEROCHK=.TRUE.
                 ENDIF
              ENDIF
              PASS=.TRUE.

**********************************************
** CALCULATE ERRORS RESULTING FROM STEP SIZE **
**********************************************

              DO 1300 I=1,N
                 R(I)=DABS(RK1(I)/360.D0 -128.D0*RK3(I)/4275.D0-
     +                  2197.D0*RK4(I)/75240.D0+RK5(I)/50.D0+
     +                  2.D0*RK6(I)/55.D0)/STEP
                 IF(R(I).GT.TOL(I)) PASS=.FALSE.
D                WRITE(97,*)'R(I)',R(I)
D                WRITE(97,*)'TOL(I)',TOL(I)
1300          CONTINUE

D             WRITE(97,10) 'STEP=',STEP
D             WRITE(97,10)'RK1(1)',RK1(1)
D             WRITE(97,10)'RK2(1)',RK2(1)
D             WRITE(97,10)'RK3(1)',RK3(1)
D             WRITE(97,10)'RK4(1)',RK4(1)
D             WRITE(97,10)'RK5(1)',RK5(1)
D             WRITE(97,10)'RK6(1)',RK6(1)
D             WRITE(97,10)'RK1(2)',RK1(2)
D             WRITE(97,10)'RK2(2)',RK2(2)
D             WRITE(97,10)'RK3(2)',RK3(2)
D             WRITE(97,10)'RK4(2)',RK4(2)
D             WRITE(97,10)'RK5(2)',RK5(2)
D             WRITE(97,10)'RK6(2)',RK6(2)

**********************************************************************
** MAKE SURE THE SOLVER ISN''T "STUCK" BECAUSE OF THE ERROR TOLERANCES **
**********************************************************************

              IF(R(1) .EQ. RIPREV)THEN
                 IF(ZEROCHK)THEN
                    PASS=.TRUE.
                    ZEROVOL=.TRUE.
                    GOTO 1375
                 ELSE
                    WRITE(6,*)
                    WRITE(6,*)'THE CURRENT RUN IS "STUCK" BUT WE HAVE
     +FORCED IT TO MOVE ON'
                    WRITE(6,*)'DESPITE THE GIVEN TOLERANCES'
                    WRITE(6,*)
                    PASS=.TRUE.
                    GOTO 1375
                 ENDIF
              ELSE
                 RIPREV=R(1)
              ENDIF

              DO 1310 I=1,N
                 IF(R(I) .EQ. 0.D0)R(I)=.1
1310          CONTINUE
              DELMIN=4.D0

*****************************************************
** 'DEL' IS A VARIABLE USED TO UPDATE THE STEP SIZE **
*****************************************************

              DO 1350 I = 1,N
                 DEL(I)=0.84*(TOL(I)/R(I))**(1.D0/4.D0)
D                WRITE(97,*)' DEL(I)',DEL(I)
                 DELMIN=DMIN1(DEL(I),DELMIN)
1350          CONTINUE
```

```
********************************************************
** IF THE ERROR IS LESS THAN THE GIVEN TOLERANCES ... **
********************************************************

1375          IF(PASS)THEN
                 IF(TIME-STEP.GE.TEND)THEN
                    KOUNT=KOUNT+1
                    TIME=TIME-STEP
                    IF(ZEROVOL)THEN
                       X(1)=0.D0
                       X(2)=TDELI
                       ZEROVOL=.FALSE.
                       ZEROCHK=.FALSE.
                    ELSE

***********************************
** CALCULATE VOLUME AND DEL O-18 **
***********************************

                       DO 1400 I=1,N
                          X(I)=X(I)+25.D0*RK1(I)/216.D0+
     +                         1408.D0*RK3(I)/2565.D0+
     +                         2197.D0*RK4(I)/4104.D0- RK5(I)/5.D0
D                              WRITE(97,*)'X(I)',X(I)
1400                   CONTINUE
                    ENDIF

************************************************
** CALCULATE DEL CALCITE FROM DEL WATER, X(2)**
************************************************

                    DELCAL=FDCAL(CALTEMP,X(2))
D                   WRITE(97,*)'DELCAL',DELCAL

*****************************************************
** STORE VALUES IN ARRAYS FOR THE PLOTTING ROUTINE **
*****************************************************

                    QI=FQI(TBEG-TIME)
                    IF(QI .LE. 0.D0)QI=0.D0

                    IF(GRAF)THEN
                       YQI(KOUNT)=QI
                       YTEMP(KOUNT)=CALTEMP
                       YDEL(KOUNT)=DELCAL
                       YAREA(KOUNT)=SAREA(X(1))
                       XPLT(KOUNT)=TIME
                    ENDIF

***************************
** WRITE RESULTS TO FILE **
***************************

D                   WRITE(97,*)
D                   WRITE(97,*)' TOTAL ELAPSED TIME',TBEG-TIME
D                   WRITE(97,*)

                    AREA=SAREA(X(1))
                    WRITE(96,*)TIME,AREA
                    WRITE(99,*)TIME,DELCAL
                    WRITE(95,*)TIME,QI

D                   WRITE(97,*)KOUNT,TIME,STEP,X(1),DELCAL
                    STEP=DTMAX
                    GOTO 100

**********************************
** MAKE SURE THE SOLVER DOESN'T **
** OVERSTEP DESIGNATED END TIME **
**********************************

                 ELSEIF(TIME-STEP.LT.TEND)THEN
                    DTMAX=TIME-TEND
                    STEP=DTMAX
                    GOTO 100
                 ENDIF
```

```
**************************************
** ADJUST THE SIZE OF THE TIME STEP **
**************************************

              ELSEIF(DELMIN .LE. 0.1)THEN
                 STEP=STEP*1.0D-1
              ELSEIF(DELMIN .GE. 4.D0)THEN
                 STEP=4.D0*STEP
              ELSE
                 STEP=DELMIN*STEP
              ENDIF
              IF(STEP.GT.DTMAX)STEP=DTMAX
              IF(STEP.LT.DTMIN)STEP=DTMIN
           ELSE
              WRITE(6,*)
              WRITE(6,*)'FINAL AREA',AREA
              WRITE(6,*)'FINAL DEL CALCITE',DELCAL
              WRITE(6,*)'FINAL DEL WATER',X(2)
              WRITE(6,*)'FINAL VOLUME',X(1)
              WRITE(6,*)
              IF(GRAF)THEN
                 WRITE(6,*)'CALLING PLOTTING ROUTINE'
                 CALL PLOTEM(XMIN,XMAX,XPLT,YDEL,YAREA,YQI,YTEMP,KOUNT)
              ENDIF
              WRITE(6,*)'FINISHED '
              RETURN
           ENDIF
100     CONTINUE
        IF(ITER .GT. ITMAX)WRITE(6,*)'MAX # OF ITERATIONS EXCEEDED'
        WRITE(6,*)
        WRITE(6,*)'FINAL AREA',AREA
        WRITE(6,*)'FINAL DEL CALCITE',DELCAL
        WRITE(6,*)'FINAL DEL WATER',X(2)
        WRITE(6,*)'FINAL VOLUME',X(1)
        WRITE(6,*)
        IF(GRAF)THEN
           WRITE(6,*)'CALLING PLOTTING ROUTINE'
           CALL PLOTEM(XMIN,XMAX,XPLT,YDEL,YAREA,YQI,YTEMP,KOUNT)
        ENDIF
        END

******************************************************************************
******************************************************************************
*    Below lies a chaotic convolution of esoteric enigmas that hopefully     *
*    accomplish the isotopic and lake level voodoo we set out toodoo.        *
*    Actually this part of the program calculates the derivatives of lake    *
*    volume and isotopic composition with respect to time.                   *
******************************************************************************
******************************************************************************
        DOUBLE PRECISION FUNCTION F(I,TIME,TERM,T,KNT,KOUNT,TBEG)
        IMPLICIT DOUBLE PRECISION (A-H,O-Z)
        LOGICAL FOUND,GUESS,PASS,GRAF,CPARAM,ONLY1,ZEROVOL,ZEROCHK
        COMMON/TRADE1/GRAF,CALTEMP,DELCAL,TDELI,TTEMP
        DIMENSION TERM(3)

        COMMON/FIRST/INCHOICE,A,B,STIME(300),TEMP(300),EVAP(300),
     +  HUM(300),DELA(300),DELI(300),GUESS,C,TEMPC,HUMC,EVAPC,DELAC,
     +  DELIC,CPARAM,TEMPCURV,NPTS,HTIME(300),NHPTS
        PARAMETER(VOLMAX=39.898D9)
        EXTERNAL FQI,FINDT,FINDHT,OINTERP,HUMTERP,SAREA,FEPS,DELE
        INTRINSIC DEXP
        IF(I.EQ.1)THEN

******************************************************************************
******************************************************************************
*   A function subroutine to calculate the lake level history of San Agustin *
*   lake                                                                     *
******************************************************************************
******************************************************************************
*   Check for overflow                                                       *
******************************************************************************

D          WRITE(97,*)
D          WRITE(97,*)
```

```
           VOL = TERM(1)
           IF(VOL .GT. VOLMAX)THEN
           WRITE(6,*)'THE LAKE IS TOO BIG'
           STOP
           ENDIF

10         FORMAT(A,D12.5)

*******************************
** CONSTANT PARAMETER OPTION **
*******************************

           IF(CPARAM)THEN
              TDELI=DELIC
              TTEMP=TEMPC
              TEVAP=EVAPC
              TDELA=DELAC
              THUM=HUMC
           ELSE

**********************************************************************
** DETERMINE VALUES OF NECESSARY PARAMETERS BY ASSIGNING VALUES OR  **
** INTERPOLATING BETWEEN GIVEN VALUES                               **
**********************************************************************

              CALL FINDT(T,INDEX,FOUND,STIME,NPTS)
              CALL FINDHT(NHPTS,T,HINDEX,HTIME)

              IF(FOUND)THEN
                 TDELI = DELI(INDEX)
                 TTEMP = TEMP(INDEX)
                 TEVAP = EVAP(INDEX)
                 TDELA = DELA(INDEX)
                 THUM = HUM(HINDEX)
              ELSE
                 CALL OINTERP(T,INDEX,TDELI,TTEMP,TEVAP,TDELA)
              ENDIF
              CALL HUMTERP(T,HINDEX,THUM)
           ENDIF

******************************************************************
** "REMEMBER" TEMP AT END OF TIMESTEP TO CALCULATE DEL CALCITE **
******************************************************************

           IF(KNT .EQ. 5)CALTEMP=TTEMP

*************************************************
** TRACK TOTAL ELAPSED TIME TO CALCULATE INFLOW**
*************************************************

           ETIME = TBEG-T
D          WRITE(97,*)'TOTAL ELAPSED TIME :',ETIME

******************************************************
** ALSO NEED TO KNOW DEL TIME WITHIN THE TIME-STEP **
******************************************************

           DTIME = TIME-T

****************************
** CALCULATE AREA OF LAKE **
****************************
           AREA = SAREA(VOL)

********************************
** CALCULATE EVAPORATION (QE) **
********************************

           QE = AREA*TEVAP

********************************************
**  CALCULATE BACK-CONDENSATION FLUX (QC) **
********************************************

           QC = THUM*QE
```

```
********************************************
** CALCULATE FLUX TO GROUNDWATER (QGW)    **
********************************************

           QGW = 0.22D0*AREA

*************************************
**  CALCULATE dV/dT IF VOL IS ZERO **
*************************************

           IF(TERM(1) .LE. 0.D0)THEN
              IF(GUESS)THEN
                 WRITE(6,*)
                 WRITE(6,*)'THE INITIAL INFLOW IS :',B
                 WRITE(6,*)
                 WRITE(96,*)TBEG,AREA
                 WRITE(95,*)TBEG,B
                 DELCAL=FDCAL(TTEMP,TERM(2))
                 WRITE(99,*)TBEG,DELCAL
                 GUESS=.FALSE.
              ENDIF

              QI=FQI(ETIME)
              F=QI

              IF(QI .LT. 0.D0)QI=0.D0

              IF(F .LE. 0.D0)THEN
                 DV_DT=0.D0
              ELSE
                 DV_DT=F
              ENDIF

*************************************************
**  CALCULATE dV/dT IF VOL IS LESS THAN VOLMAX **
*************************************************

           ELSE IF(TERM(1)  .LT. VOLMAX)THEN

*************************************************
** PROVIDE AN INITIAL GUESS FOR QI SO THE MODEL**
** STARTS UNDER STABLE CONDITIONS              **
*************************************************

              IF(GUESS)THEN
                 WRITE(6,*)
                 WRITE(6,*)'QI =  ',B
                 WRITE(6,*)'QE = ',QE
                 WRITE(6,*)'QC = ',QC
                 WRITE(6,*)'QGW = ',QGW
                 WRITE(6,*)'dV/dt =',B+QC-QE-QGW
                 WRITE(6,*)
                 WRITE(6,*)'STEADY STATE QI WOULD BE',QE-QC+QGW
                 WRITE(6,*)'WOULD YOU LIKE TO CHANGE B (QI) ?'
                 WRITE(6,*)'1=YES     0=NO'
                 READ(5,*)IQI
                 IF(IQI .EQ. 1)THEN
                    WRITE(6,*)'INPUT NEW VALUE FOR B'
                    READ(5,*)B
                 ENDIF
                 WRITE(96,*)TBEG,AREA
                 WRITE(95,*)TBEG,B
                 DELCAL=FDCAL(TTEMP,TERM(2))
                 WRITE(99,*)TBEG,DELCAL
                 GUESS=.FALSE.
              ENDIF

***************************
** CALCULATE INFLOW (QI) **
***************************

              QI = FQI(ETIME)

**********************
**  CALCULATE dV/dT **
**********************
```

```
              F=QI+QC-QE-QGW
              DV_DT=F
D             WRITE(97,10)' QI=',QI
D             WRITE(97,10)' QC=',QC
D             WRITE(97,10)' QE=',QE
D             WRITE(97,10)' AREA=',AREA
D             WRITE(97,10)' EVAP=',TEVAP
D             WRITE(97,10)'QGW=',QGW
           END IF

D          WRITE(97,10)' dV/dT =',F

*******************************************************************************
* A function subroutine to calculate the isotopic history of San Agustin Lake *
*******************************************************************************

        ELSE IF(I.EQ.2)THEN

        DELL = TERM(2)
D       WRITE(97,10)' THE CURRENT DEL OF THE LAKE IS',DELL
D       WRITE(97,10)' THE CURRENT VOLUME OF THE LAKE IS',VOL

************************
** CALCULATE dDEL/dt  **
************************

        IF(VOL .LE. 10.D0)THEN
           F=0.D0

        ELSE

******************************************
** CALCULATE ISOTOPIC ENRICHMENT FACTOR **
******************************************

           EPS = FEPS(TTEMP)
D          WRITE(97,*)' EPSILON :',EPS

********************************************
** CALCULATE DEL OF THE BACK-CONDENSATION **
********************************************

           DELC =EPS*(1.D0+(TDELA/1.D3))+TDELA
D          WRITE(97,*)'DEL OF THE BACK-COND',DELC

**************************************
** CALCULATE DEL OF THE EVAPORATION **
**************************************

           DDELE = DELE(DELL,EPS,THUM)
D          WRITE(97,*)'DEL OF THE EVAP',DDELE

******************************************************************
** SET DEL OF THE GROUNDWATER OUTFLOW EQUAL TO DEL OF THE LAKE **
******************************************************************

           DELGW = DELL

           F=(QI*TDELI+QC*DELC-QGW*DELGW-QE*DDELE-DELL*DV_DT)/VOL

        ENDIF

D       WRITE(97,10)' dDEL/dt =',F
        END IF
        RETURN
        END

*******************************************************************************
*******************************************************************************
**         A function subprogram to calculate the area of San Agustin Lake   **
*******************************************************************************
*******************************************************************************

        double precision function sarea(vol)
        implicit double precision (a-h,o-z)
```

```
      TVOL=VOL/1.0D9

      if(tvol .ge. 0.0d0 .and. tvol .lt. 0.199d0) then
         sarea = 741.209d0*tvol - 2139.724d0*tvol**3
      else if(tvol .ge. 0.199d0 .and. tvol .lt. 0.667d0) then
         sarea = 130.809d0 + 486.108d0*(tvol-0.199d0) - 1279.662d0*
     +   (tvol-0.199d0)**2 + 964.959d0*(tvol-0.199d0)**3
      else if(tvol .ge. 0.667d0 .and. tvol .lt. 3.861d0) then
         sarea = 176.992d0 - 77.704d0*(tvol-0.667d0) + 73.258d0*
     +   (tvol-0.667d0)**2 - 9.780d0*(tvol-0.667d0)**3
      else if(tvol .ge. 3.861d0 .and. tvol .lt. 9.075d0) then
         sarea = 357.551d0 + 90.925d0*(tvol-3.861d0) - 20.474d0*
     +   (tvol-3.861d0)**2 + 1.600d0*(tvol-3.861d0)**3
      else if(tvol .ge. 9.075d0 .and. tvol .lt. 16.310d0) then
         sarea = 501.798d0 + 7.896d0*(tvol-9.075d0) + 4.549d0*
     +   (tvol-9.075d0)**2 - 0.283d0*(tvol-9.075d0)**3
      else if(tvol .ge. 16.310d0 .and. tvol .lt. 25.810d0)then
         sarea = 689.920d0 + 29.309d0*(tvol-16.310d0) - 1.589d0*
     +   (tvol-16.310d0)**2 + 0.055d0*(tvol-16.310d0)**3
      else if(tvol .ge. 25.810d0 .and. tvol .lt. 38.089d0)then
         sarea = 872.108d0 + 14.010d0*(tvol-25.810d0) - 0.021d0*
     +   (tvol-25.810d0)**2 + 0.058d0*(tvol-25.810d0)**3
      else if(tvol .ge. 38.089d0 .and. tvol .lt. 39.898d0) then
         sarea = 1148.520d0 + 39.772d0*(tvol-38.089d0) + 2.119d0*
     +   (tvol-38.089d0)**2 - 0.391d0*(tvol-38.089d0)**3
      else  if(tvol .eq. 39.898d0)then
         sarea = 1225.064d0

      end if

      sarea=sarea*1.0d6
      return
      end

******************************************************************************
******************************************************************************
*  This is a function subprogram to calculate the isotopic enrichment factor *
******************************************************************************
******************************************************************************

      double precision function feps(temp)
      implicit double precision (a-h, o-z)
      intrinsic dexp

**************************
**CONVERT TEMP TO KELVIN**
**************************

      tempk=temp+273.15d0
      feps =(dexp((1.534d0*(1.0d6/(tempk)**2)-3.206d0*(1.0d3/tempk)+
     +       2.644d0)/1.d3)-1.d0)*1.d3
      return
      end

******************************************************************************
******************************************************************************
*      A subroutine to linearly interpolate between points in data sets      *
*              containing San Agustin Lake parameters                        *
******************************************************************************
******************************************************************************

      subroutine ointerp(time,ndx,tdeli,ttemp,tevap,tdela)

      implicit double precision (a-h,o-z)
      LOGICAL FOUND,GUESS,PASS,GRAF,CPARAM,ONLY1,ZEROVOL,ZEROCHK
      COMMON/FIRST/INCHOICE,A,B,STIME(300),TEMP(300),EVAP(300),
     + HUM(300),DELA(300),DELI(300),GUESS,C,TEMPC,HUMC,EVAPC,DELAC,
     + DELIC,CPARAM,TEMPCURV,NPTS,HTIME(300),NHPTS

      tdeli=(deli(ndx+1)-deli(ndx))/(stime(ndx+1)-stime(ndx))*
     +         (time-stime(ndx))+deli(ndx)

      ttemp=(temp(ndx+1)-temp(ndx))/(stime(ndx+1)-stime(ndx))*
     +         (time-stime(ndx))+temp(ndx)
```

```
      tevap=(evap(ndx+1)-evap(ndx))/(stime(ndx+1)-stime(ndx))*
     +        (time-stime(ndx))+evap(ndx)

      tdela = (dela(ndx+1)-dela(ndx))/(stime(ndx+1)-stime(ndx))*
     +        (time-stime(ndx))+dela(ndx)

      return
      end

********************************************************************************
********************************************************************************
*       A SUBROUTINE TO CALCULATE HUMIDITY FOR LAKE SAN AGUSTIN               **
********************************************************************************
********************************************************************************


      SUBROUTINE HUMTERP(TIME,HINDX,THUM)

      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
      LOGICAL FOUND,GUESS,PASS,GRAF,CPARAM,ONLY1,ZEROVOL,ZEROCHK
      COMMON/FIRST/INCHOICE,A,B,STIME(300),TEMP(300),EVAP(300),
     + HUM(300),DELA(300),DELI(300),GUESS,C,TEMPC,HUMC,EVAPC,DELAC,
     + DELIC,CPARAM,TEMPCURV,NPTS,HTIME(300),NHPTS

      thum=(hum(hindx+1)-hum(hindx))/(htime(hindx+1)-htime(hindx))*
     +       (time-htime(hindx))+hum(hindx)

      RETURN
      END


********************************************************************************
********************************************************************************
**  A function subprogram to calculate the relative isotopic enrichment of    **
**  the evaporating water.                                                    **
********************************************************************************
********************************************************************************

      double precision function dele(dell,eps,hum)
      implicit double precision(a-h,o-z)
      parameter(c=6.8d-3)

      dele=(((1.D0+1.D-3*dell)*(1.D0-c))/((1.D0+1.D-3*eps)*(1.D0-c*
     +     hum))-1.D0)*1.0D3

      return
      end

********************************************************************************
********************************************************************************
**         A function subprogram to calculate the inflow, QI(t)               **
********************************************************************************
********************************************************************************

      DOUBLE PRECISION FUNCTION FQI(X)
      implicit double precision(a-h,o-z)
      LOGICAL FOUND,GUESS,PASS,GRAF,CPARAM,ONLY1,ZEROVOL,ZEROCHK
      COMMON/FIRST/INCHOICE,A,B,STIME(300),TEMP(300),EVAP(300),
     + HUM(300),DELA(300),DELI(300),GUESS,C,TEMPC,HUMC,EVAPC,DELAC,
     + DELIC,CPARAM,TEMPCURV,NPTS,HTIME(300),NHPTS
      INTRINSIC DEXP,DLOG10,DSIN

      IF(INCHOICE .EQ. 1)THEN
         FQI=A*X+B
      ELSE IF(INCHOICE .EQ. 2)THEN
         FQI=B*DEXP(A*X)
      ELSE IF(INCHOICE .EQ. 3)THEN
         IF(X .LT. 1.D0)X=1.D0
         FQI=B+A*DLOG10(X)
      ELSE IF(INCHOICE .EQ. 4)THEN
         FQI=B+A*X**C
      ELSE IF(INCHOICE .EQ. 5)THEN
         FQI=B+A*DSIN(C*X)
      ELSE IF(INCHOICE .EQ. 6)THEN
         IF(X .LT. 1.D0)THEN
```

```
            FQI=B
         ELSE
            FQI=B+A*B
         ENDIF
      ELSE IF(INCHOICE .EQ. 7)THEN
         FQI=0.D0
      ENDIF
      IF(FQI .LT. 0.D0)FQI=0.D0
      RETURN
      END

*******************************************************************************
*******************************************************************************
*             A SUBROUTINE TO FIND THE TIME WITH A BINARY SEARCH              *
*******************************************************************************
*******************************************************************************

      SUBROUTINE FINDT(TM,INDEX,FOUND,STIME,NPTS)
      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
      LOGICAL FOUND,GUESS,PASS,GRAF,CPARAM,ONLY1,ZEROVOL,ZEROCHK
      DIMENSION STIME(300)
      TFIRST=1
      TLAST=NPTS
      FOUND = .FALSE.
      DO 200 I = 1,100
         IF(TLAST .LT. TFIRST) THEN
            INDEX=TLAST
            GOTO 210
         ENDIF
         IF( TFIRST .LE. TLAST .AND. FOUND .EQ. .FALSE.) THEN
            MIDDLE = (TFIRST+TLAST)/2
            TEST = ABS(TM-STIME(MIDDLE))
            IF( TEST .LT. 1.0D-1) THEN
               FOUND = .TRUE.
               INDEX=MIDDLE
               GOTO 210
            ELSE IF(TM .LT. STIME(MIDDLE))THEN
               TLAST = MIDDLE-1
            ELSE
               TFIRST = MIDDLE+1
            END IF
         END IF
200   CONTINUE

210   RETURN
      END


****************************************************************************
**    A SUBROUTINE TO FIND THE HUMIDITY TIME INDEX WITH A BINARY SEARCH **
****************************************************************************

      SUBROUTINE FINDHT(NHPTS,TM,HINDEX,TIME)
      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
      LOGICAL FOUND
      PARAMETER(NUMA=300)
      DIMENSION TIME(NUMA)
      TFIRST=1
      TLAST=NHPTS
      FOUND=.FALSE.
      DO 200 I=1,100
         IF(TLAST .LT. TFIRST) THEN
            HINDEX=TLAST
            GOTO 210
         ENDIF
         IF(TFIRST .LE. TLAST .AND. .NOT. FOUND)THEN
            MIDDLE = (TFIRST+TLAST)/2
            TEST = ABS(TM-TIME(MIDDLE))
            IF(TEST .LT. 1.0D-1) THEN
               FOUND = .TRUE.
               HINDEX = MIDDLE
               GOTO 210
            ELSE IF(TM .LT. TIME(MIDDLE)) THEN
               TLAST = MIDDLE-1
            ELSE
               TFIRST = MIDDLE+1
```

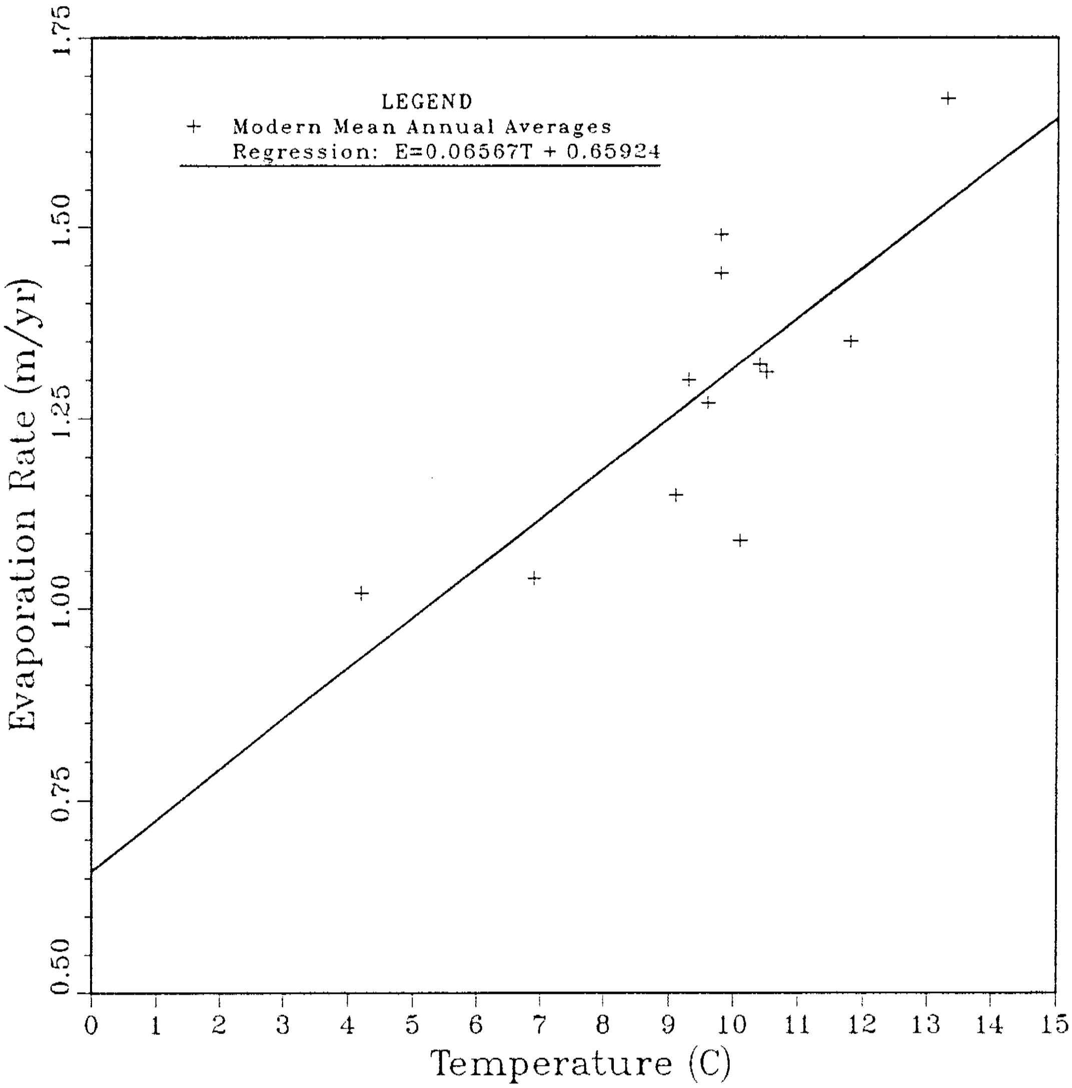
```
              END IF
           END IF
200     CONTINUE

210     RETURN
        END


        SUBROUTINE PLOTEM(XMIN,XMAX,XPLT,YDEL,YAREA,YQI,YTEMP,KOUNT)
****************************************************************************
*       SET UP THE GRAPHICS WINDOW FOR PLOTTING                            *
****************************************************************************
        REAL XMIN,XMAX,YMIN,YMAX,XPLT(300),YAREA(300),YQI(300),
     +       YDEL(300),STIME(300),SAISO(300)

        WRITE(6,*)
        WRITE(6,*)'READING SAN AGUSTIN ISOTOPE DATA'
        WRITE(6,*)

        OPEN(UNIT=60,FILE='OVAGE.DAT',STATUS='OLD')

        DO 100 I=1,300
           READ(60,*,END=101)STIME(I),SAISO(I)
100     CONTINUE

101     NPTS=I-1

        CLOSE(UNIT=60)

        WRITE(6,*)'READ',NPTS,'POINTS FROM SAN AGUSTIN DATA'

        DO 150 I=1,NPTS
           STIME(I)=STIME(I)*1.0E3
150     CONTINUE

        CALL UIS

        CALL PAGE(33.,22.)
        CALL COMPLX
        CALL HEIGHT(.35)

C$$$        FIND THE POSITION TO PUT THE GRAPH
        DO 300 I=1,3
           IF(I .EQ. 1)THEN
              CALL PHYSOR(4.,12.)
           ELSE IF(I .EQ. 2)THEN
              CALL PHYSOR(4.,7.)
           ELSE IF(I .EQ. 3)THEN
              CALL PHYSOR(4.,2.)
           ENDIF

           IF(I .EQ. 1)THEN
              CALL AREA2D (25.,8.)
           ELSE
              CALL AREA2D (25.,3.)
           END IF
           call gapwid(.001)

C$$$   PUT THE HEADING ON THE PLOT

           IF(I .EQ. 1)THEN
              Call YNAME ('DEL O-18$',100)
              Call XNAME ('TIME$',100)
           ELSEIF(I .EQ. 2)THEN
              Call YNAME ('AREA$',100)
              Call XNAME ('TIME$',100)
           ELSEIF(I .EQ. 3)THEN
              Call YNAME ('INFLOW $',100)
              Call XNAME ('TIME$',100)
           ENDIF

*****************************
** CALCULATE YMAX AND YMIN **
*****************************

           IF(I .EQ. 1)THEN
```

```
              YMIN=YDEL(1)
              YMAX=YDEL(1)
              DO 1500 IMM = 2,KOUNT
                 IF(YDEL(IMM) .LT. YMIN)YMIN=YDEL(IMM)
                 IF(YDEL(IMM) .GT. YMAX)YMAX=YDEL(IMM)
1500          CONTINUE
              YMIN=NINT(YMIN)-0.5
              YMAX=NINT(YMAX)+0.5
           ELSE IF(I .EQ. 2)THEN
              YMIN=YAREA(1)
              YMAX=YAREA(1)
              DO 1600 IMM = 2,KOUNT
                 IF(YAREA(IMM) .LT. YMIN)YMIN=YAREA(IMM)
                 IF(YAREA(IMM) .GT. YMAX)YMAX=YAREA(IMM)
1600          CONTINUE
              YMIN=YMIN-0.1D0*YMIN
              YMAX=YMAX+0.1D0*YMAX
           ELSE IF(I .EQ. 3)THEN
              YMIN=YQI(1)
              YMAX=YQI(1)
              DO 1700 IMM = 2,KOUNT
                 IF(YQI(IMM) .LT. YMIN)YMIN=YQI(IMM)
                 IF(YQI(IMM) .GT. YMAX)YMAX=YQI(IMM)
1700          CONTINUE
              YMIN=YMIN-0.1D0*YMIN
              YMAX=YMAX+0.1D0*YMIN
           ENDIF

           CALL GRAF (XMIN,XMIN,XMAX,YMIN,YMAX,YMAX)

           CALL FRAME
           CALL THKCRV(.02)
           CALL MARKER(3)
           CALL SCLPIC(.7)

           IF(I .EQ. 1)THEN
              CALL CURVE(XPLT,YDEL,KOUNT,-1)
              CALL CURVE(STIME,SAISO,NPTS,0)
           ELSE IF(I .EQ. 2)THEN
              CALL CURVE(XPLT,YAREA,KOUNT,-1)
           ELSE IF(I .EQ. 3)THEN
              CALL CURVE(XPLT,YQI,KOUNT,-1)
           ENDIF

           CALL ENDGR(IPLOT)

 300    CONTINUE

        RETURN
        END

********************************************************
********************************************************
**    A function subprogram to  calculate del calcite **
********************************************************
********************************************************

        DOUBLE PRECISION FUNCTION FDCAL(TEMP,DELH2O)
        implicit double precision (a-h,o-z)

***********************************
** CONVERT TEMP TO DEGREES KELVIN **
***********************************

        TEMPK = TEMP+273.15D0

*********************************************
** CALCULATE EPSILON FOR CALCITE AND WATER **
*********************************************

        EPSCAL=(DEXP((2.78D0*(1.D6/TEMPK**2)-2.89D0)/1.D3)-1.D0)*1.D3

D       WRITE(97,*)' EPSCAL',EPSCAL
D       WRITE(97,*)'TEMPK',TEMPK

        FDCAL=EPSCAL+DELH2O*(EPSCAL/1.0D3+1.D0)
```

```
      RETURN
      END
```

APPENDIX E

Model Input Parameters For Lake San Agustin



SAN AGUSTIN LAKE, NEW MEXICO
Evaporation–Temperature Relationship

```
        FOR YOUR CHOICE:  "LINE"   Y=A+B*X
         "A"=       6.5924E-01
         "B" =      6.5671E-02

        THE REGRESSION COEFFICIENT "R" =     0.60458

 THE CALCULATED VALUES:
        X                  Y                     YCALC               % DIFF

     1.3300E+01       1.6700E+00           1.5327E+00              8.22
     1.1800E+01       1.3500E+00           1.4342E+00             -6.23
     1.0500E+01       1.3100E+00           1.3488E+00             -2.96
     1.0400E+01       1.3200E+00           1.3422E+00             -1.68
     1.0100E+01       1.0900E+00           1.3225E+00            -21.33
     9.8000E+00       1.4900E+00           1.3028E+00             12.56
     9.8000E+00       1.4400E+00           1.3028E+00              9.53
     9.6000E+00       1.2700E+00           1.2897E+00             -1.55
     9.3000E+00       1.3000E+00           1.2700E+00              2.31
     9.1000E+00       1.1500E+00           1.2569E+00             -9.29
     6.9000E+00       1.0400E+00           1.1124E+00             -6.96
     4.2000E+00       1.0200E+00           9.3506E-01              8.33


 THE NONLINEAR CORRELATION COEFFICIENT: R**2=  0.60459107
 the ave. % diff=  7.58005667
```

AGE (ka)	TEMPERATURE (Celsius)	EVAPORATION (mm/yr)	OXYGEN-18 OF INFLOW	OXYGEN-18 ATMOSPHERE
5.61000	9.42	1.277851	-12.12212	-22.83470
5.75000	7.32	1.139944	-12.21970	-24.28872
5.90000	7.32	1.139944	-12.32424	-24.28872
6.05000	6.62	1.093975	-12.42879	-24.77442
6.30000	8.02	1.185913	-12.60303	-23.80354
6.49000	7.32	1.139944	-12.73545	-24.28872
6.63000	7.32	1.139944	-12.83303	-24.28872
6.78000	9.42	1.277851	-12.93758	-22.83470
6.93000	6.62	1.093975	-13.04212	-24.77442
7.18000	5.92	1.048006	-13.21636	-25.26062
7.37000	6.62	1.093975	-13.30318	-24.77442
7.52000	7.32	1.139944	-13.31000	-24.28872
7.82000	6.62	1.093975	-13.32364	-24.77442
8.11000	6.62	1.093975	-13.33682	-24.77442
8.26000	5.92	1.048006	-13.34364	-25.26062
8.40000	5.22	1.002037	-13.35000	-25.74733
8.55000	4.52	0.956068	-13.35682	-26.23454
8.70000	2.42	0.818161	-13.36364	-27.69955
8.76000	8.02	1.185913	-13.36636	-23.80354
9.34000	8.02	1.185913	-13.39273	-23.80354
9.39000	7.32	1.139944	-13.39500	-24.28872
9.52000	7.32	1.139944	-13.41200	-24.28872
9.62000	5.92	1.048006	-13.47200	-25.26062
9.75000	5.22	1.002037	-13.55000	-25.74733
9.86000	8.02	1.185913	-13.61600	-23.80354
9.97000	8.02	1.185913	-13.69692	-23.80354
10.12000	5.92	1.048006	-13.71231	-25.26062
10.17000	6.62	1.093975	-13.71744	-24.77442
10.28000	8.02	1.185913	-13.72872	-23.80354
10.49000	8.02	1.185913	-13.75026	-23.80354
10.60000	5.22	1.002037	-13.76154	-25.74733
10.80000	8.02	1.185913	-13.78205	-23.80354
10.91000	5.22	1.002037	-13.79333	-25.74733
11.01000	3.12	0.864130	-13.80359	-27.21071
11.12000	2.42	0.818161	-13.81487	-27.69955
11.22000	3.12	0.864130	-13.82513	-27.21071
11.27000	3.12	0.864130	-13.83026	-27.21071
11.38000	3.82	0.910099	-13.84154	-26.72238
11.43000	2.42	0.818161	-13.84667	-27.69955
11.54000	5.22	1.002037	-13.85795	-25.74733
11.64000	4.52	0.956068	-13.86821	-26.23454
11.75000	2.42	0.818161	-13.87949	-27.69955
11.85000	3.82	0.910099	-13.88974	-26.72238
11.93000	3.12	0.864130	-13.89795	-27.21071

12.17000	3.12	0.864130	-13.92256	-27.21071
12.27000	7.32	1.139944	-13.93282	-24.28872
12.37000	8.02	1.185913	-13.94308	-23.80354
12.48000	6.62	1.093975	-13.95436	-24.77442
12.74000	6.62	1.093975	-13.98103	-24.77442
12.80000	5.92	1.048006	-13.98718	-25.26062
12.85000	7.32	1.139944	-13.99231	-24.28872
12.90000	5.92	1.048006	-13.99744	-25.26062
12.95000	5.92	1.048006	-14.00256	-25.26062
13.00000	3.82	0.910099	-14.00769	-26.72238
13.05000	5.22	1.002037	-14.01282	-25.74733
13.11000	5.92	1.048006	-14.01897	-25.26062
13.16000	5.92	1.048006	-14.02410	-25.26062
13.37000	6.62	1.093975	-14.04564	-24.77442
13.42000	7.32	1.139944	-14.05077	-24.28872
13.48000	7.32	1.139944	-14.05692	-24.28872
13.52000	8.02	1.185913	-14.06103	-23.80354
13.63000	7.32	1.139944	-14.07231	-24.28872
13.74000	8.02	1.185913	-14.08359	-23.80354
14.00000	8.02	1.185913	-14.20000	-23.80354
14.05000	7.32	1.139944	-14.17500	-24.28872
14.15000	7.32	1.139944	-14.12500	-24.28872
14.26000	8.02	1.185913	-14.07000	-23.80354
14.37000	6.62	1.093975	-14.01500	-24.77442
14.47000	8.02	1.185913	-13.96500	-23.80354
14.63000	8.02	1.185913	-13.88500	-23.80354
14.68000	7.32	1.139944	-13.86000	-24.28872
14.78000	7.32	1.139944	-13.81000	-24.28872
14.89000	6.62	1.093975	-13.75500	-24.77442
15.00000	5.92	1.048006	-13.70000	-25.26062
15.05000	5.22	1.002037	-13.74231	-25.74733
15.15000	5.92	1.048006	-13.82692	-25.26062
15.25000	5.22	1.002037	-13.91154	-25.74733
15.31000	5.92	1.048006	-13.96231	-25.26062
15.41000	5.92	1.048006	-14.04692	-25.26062
15.52000	6.62	1.093975	-14.14000	-24.77442
15.57000	6.62	1.093975	-14.18231	-24.77442
15.62000	7.32	1.139944	-14.22462	-24.28872
15.68000	7.32	1.139944	-14.27538	-24.28872
15.78000	5.22	1.002037	-14.36000	-25.74733
15.83000	7.32	1.139944	-14.40231	-24.28872
16.04000	7.32	1.139944	-14.58000	-24.28872
16.15000	8.02	1.185913	-14.67308	-23.80354
16.30000	8.02	1.185913	-14.80000	-23.80354
16.41000	5.22	1.002037	-14.64286	-25.74733
16.46000	5.22	1.002037	-14.57143	-25.74733
16.58000	5.92	1.048006	-14.40000	-25.26062
16.78000	5.92	1.048006	-14.11428	-25.26062
16.83000	5.22	1.002037	-14.04286	-25.74733
16.88000	5.22	1.002037	-13.97143	-25.74733

16.98000	3.82	0.910099	-13.78200	-26.72238
17.09000	5.22	1.002037	-13.88100	-25.74733
17.23000	8.02	1.185913	-14.00700	-23.80354
17.30000	4.52	0.956068	-14.07000	-26.23454
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APPENDIX F

Model Output Data For Lake San Agustin

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