Comparative Paleoclimatic Interpretations from Nonmarine Ostracodes Using Faunal Assemblages, Trace Elements Shell Chemistry and Stable Isotope Data

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Lacustrine ostracodes (microcrustaceans) are powerful tools for reconstructing paleoclimates. Western North American Pleistocene pluvial lakes are ideal environments to study ostracode paleoecologic and geochemical attributes since many of them have proven to be responsive to climatic changes. The purpose of this paper is to illustrate how faunal assemblages, stable isotopes and trace elements present in ostracode carapaces, correlate in one Pleistocene lake basin in south-central Oregon, pluvial Lake Chewaucan, by comparing their response signals throughout the lake's history. The combined analysis of paleoecologic and geochemical profiles indicate that pluvial Lake Chewaucan underwent broad limnologic fluctuations during the late Pleistocene. Ostracode assemblages clearly demonstrate periods of increasing salinity and temperature alternating with cooler and less saline conditions. Covariant $\delta^{18}O$ and $\delta^{13}C$ values indicate that this lake remained a closed basin throughout its history. Trace elements (Mg/Ca and Sr/Ca molar ratios) indicate that salinity excursions were a major factor affecting pluvial Lake Chewaucan. Fluctuations in the $\delta^{18}O$ values during this interval suggest that temperature and humidity changed profoundly between the latest interglacial and the full glacial. Hydroclimate changes in Lake Chewaucan during the Pleistocene probably occurred in response to the greater influence of the jet stream south-branch as it shifted position during this period of time. As a result, greater and more frequent storms occurred in south-central Oregon.

INTRODUCTION

The reconstruction of ancient lake histories allows paleolimnologists to understand both local and regional processes of environmental and climatic change. Water temperature and the chemistry of lakes are sensitive to regional climate parameters (i.e. air-temperature, precipitation and evaporation). In the short-term (i.e. decade, yearly) other non-climatic factors or those factors which are indirectly related to climate, such as basin morphometry or input/output balance, influence seasonal limnologic processes [Forester, 1991a]. But in the long-term (i.e. hundreds to thousands of years) these effects are eclipsed by a climate signal which is likely to reflect regional processes. Some lacustrine organisms, like ostracodes, are highly responsive to environmental perturbations and may be used for paleohydrochemical and paleoclimatic interpretations.

The occurrence of lacustrine ostracodes appears to be primarily controlled by both water chemistry (both major dissolved ion content and total dissolved solids: TDS) and temperature. Ostracodes respond to environmental variations in several ways: biogeographic distribution [Forester, 1987; De Deckker & Forester, 1988], shell morphology [Delorme, 1969, and 1989] and shell chemistry [stable isotopes: Lister, 1988 and trace elements: Chivas et al., 1983]. As fossils these organisms provide a proxy record for interpreting paleoclimate [Forester, 1991a]. The purpose of this paper is to illustrate how these different signals correlate in one Pleistocene lake basin in south-central Oregon, pluvial Lake Chewaucan, by comparing three lines of evidence: faunal assemblages, shell chemistry and stable isotopes.

OSTRACODE/ENVIRONMENT RELATIONSHIP

Ostracode occurrence patterns and associations provide important tools for paleoenvironmental reconstructions. Delorme [1969 and 1989], Forester [1983, 1986, 1987, and 1991a,b] and Chivas et al. [1983, 1986] described a relationship between ostracodes and their environment and suggested that ostracode species distribution is defined primarily by thermal and chemical parameters. Forester [1991a] indicated that ostracode life-cycles are coupled to those parameters and that growth, maturation and

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reproduction can only be completed if specific conditions are satisfied for each species.

During growth ostracodes moult up to nine times to reach maturity. The calcification of a new carapace from ions in solution is thought to occur in thermal and chemical equilibrium with the host water [Chivas et al., 1983] . Water temperature, water chemistry and seasonal variability control the presence of many taxa [Forester, 1991b].

Limnocythere ceriotuberosa (the most common fossil species present in Lake Chewaucan sediments) today is a euryhaline (wide salinity tolerance range) organism, whereas *Limnocythere sappaensis* is a halobiontic (restricted salinity tolerance range) species. The co-occurrence of these two species brackets a specific environment; an evaporative basin. *Limnocythere bradburyi*, a species known only in the fossil record has been suggested to be a warm water indicator distributed from Lake Texcoco, central Mexico to Lake Estancia, New Mexico, and Silver (Mojave) Lake, California [Forester, 1987; Wells et al., 1989].

Candona caudata is also a common species in the Lake Chewaucan sediments. Today this species lives in freshwater to low salinity conditions and streams, within a wide temperature range (Forester, pers. comm. 1992). It appears to be associated with fairly deep waters (greater than 10m). In contrast, *Candona patzcuaro* a member of the *C. rawsoni* group lives in prairie lakes and pondsthat are permanent or ephemeral. Eventually these two species overlap within the Lake Chewaucan record. Another significant species, *Cypridopsis vidua*, is a eurythermic organism which prefers to live in warm wetlands (10-25°C: Palacios-Fest, unpublished data from Magdalena, Sonora and Agua Caliente Spring, Tucson, Arizona).

The replacement of any of these species by the cold/freshwater species *Cytherissa lacustris* (an occasional species present in the Lake Chewaucan sediments; with a present maximum temperature tolerance of 19°C and maximum salinity tolerance of 215 mg/l Na), indicates cooler conditions and a more positive water budget for the basin (increasing inflow and precipitation-evaporation) [Delorme, 1989]. Thus, species appearance/ disappearance trends are critical for determining the paleohydroenvironmental history of a lake.

Shell morphology also provides valuable information for interpreting lake paleoenvironments. Delorme [1989] indicates that changes in carapace growth may be controlled by environmental factors, such as salinity, solute composition, pH, and depth of water. Some eurytopic species may develop unusual ornamentations in response to water temperature, water chemistry and possibly seasonal variation. For example, *Cyprideis torosa,* a well-known brackish water species, generates a heavily ornamented carapace in freshwater but a smoother carapace as salinity increases [Teeter and Quick, 1990]. Ornamental changes within a species provide another useful criterion to understand paleohydroenvironmental fluctuations.

Ostracode shell chemistry is also sensitive to lake hydrochemistry. In 1971, Turpen and Angell demonstrated that calcium in solution is the exclusive source of Ca^{2+} for the calcification of ostracode valves. Later, Chivas et al. [1983] showed that some trace elements like magnesium and strontium are similarly extracted from ambient water during shell formation. They defined a relationship between water temperature, hydrochemistry and ostracode shell chemistry. Based upon these results Chivas and colleagues [1986a, b] discussed the applications of magnesium and strontium contents in ostracode carapaces as paleohydrochemical indicators. More recently, De Deccker and co-workers [1988a, b] have presented examples of the application of Mg and Sr trace element data for interpreting ostracodes from the Miocene of the Mediterranean and the late Pleistocene of the Gulf of Carpentaria (Australia). Ostracode trace-element geochemistry is becoming a major tool for paleohydrochemical reconstructions which in turn may be used for paleoclimatic interpretations.

Lister [1988] and Eyles and Schwarcz [1991] have pursued the utility of stable isotope (oxygen and carbon) geochemistry as another approach to paleoclimatic reconstructions from ostracode shells. In 1988, Lister reconstructed the latest Pleistocene-Holocene paleohydroenvironmental history of Lake Zurich, Switzerland (a deep, peri-alpine, open basin). The isotopic record from ostracode carapaces allowed him to establish the rate and timing of the latest Pleistocene Alpine deglaciation, Holocene climatic changes, and changing lacustrine productivity. Lake Turkana, Kenya (in a low latitude, closed basin) provides another important example of ostracode stable- isotope analysis; preliminary isotopic studies of specimens from the uppermost 12 m of annually laminated basinal sediments indicate a probable correlation with Holocene lake level changes [Lister, 1988]. Eyles and Schwarcz [1991] have recently analyzed the stable isotopic ($\delta^{18}O$ and $\delta^{13}C$) composition of two candonid ostracodes (*Candona subtriangulata* and *Candona caudata*). Using this method they determined the glaciolacustrine evolution of Lake Ontario during the last glacial cycle (Wisconsin).

HYDROLOGIC AND GEOLOGIC SETTING OF PLUVIAL LAKE CHEWAUCAN AND MODERN SUMMER LAKE

Allison [1982] has previously described the geomorphology and Pleistocene geology of Pluvial Lake Chewaucan. It is located in the northwest corner of the Great Basin. The basin contains two small relict lakes, Lake Abert and Summer Lake. Today Summer Lake is a topographically closed lake in the northwest corner of the Chewaucan Basin. Pluvial Lake Chewaucan consisted of a four-lobed body of water which reached a maximum area of about 1250 km^2 in the confluent structural basins of modern Summer Lake, Upper Chewaucan Marsh, Lower Chewaucan Marsh and Lake Abert in Lake County, south-central Oregon (Fig. 1). During the Pleistocene, shoreline terraces indicate a maximum recorded depth of 115 m, with lake

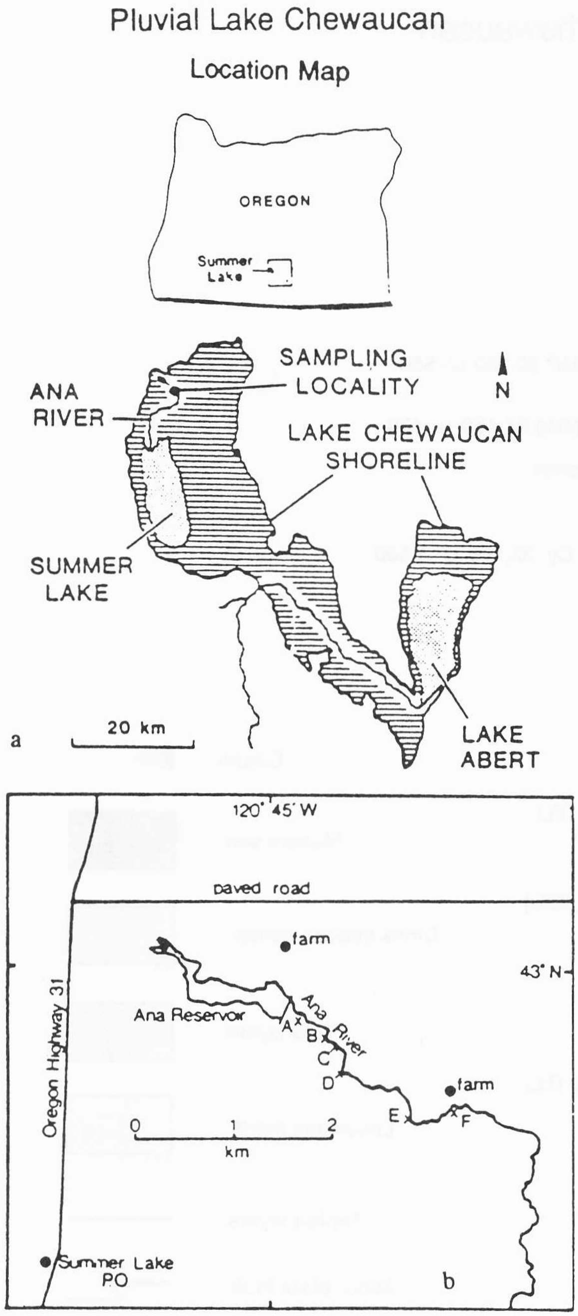

Fig. 1. Location map of the Pleistocene pluvial Lake Chewaucan Basin showing a) Holocene relicts: Summer Lake to the northwest and Lake Abert to the southeast, and b) R. Negrini's sampling localities along the Ana River canyon cut. Samples used for this study are from sections C and E. After Negrini et al. [1988].

levels reaching to about 1380 m above sea level (masl). Summer Lake is a playa lake with an area of ~180 km^2 and an elevation averaging 1264 masl. Its present average depth is less than 2 m.

Stream input has changed through time. At present, Summer Lake receives most of its inflow from small streams from the surrounding highlands and from the Ana Spring, located in the northwest margin of the basin [Davis, 1985]. The Ana Spring drains southward via the Ana River to the lake. However, during the Pleistocene pluvial Lake Chewaucan was fed by the Chewaucan River which drained northward from the Lower Chewaucan Marsh. Davis [1985] have proposed that Summer Lake had a much higher lake level before the Holocene due to the continuous inflow from the Chewaucan River.

Van Denburgh [1975] presents the most complete study of present-day Summer Lake and Lake Abert (the remnants of pluvial Lake Chewaucan) water chemistry. Summer Lake is characterized by a large volume of solutes primarily derived from the groundwater supply through Ana Spring. The spring flow contains about 160 ppm of dissolved solids (mostly silica, sodium and bicarbonate). The influence of peripheral groundwater input is marked by brines with high salinity values (80,000-100,000 ppm). Measured salinities in the lake at 0.65 and 1.5 m depth are between 40,000 and 50,000 ppm. The lake brine is dominated by Na^+, Cl^- HCO_3^-, $CO_3^=$, K^+ and $SO_4^=$, and depleted in Ca^{2+}, Mg^{2+}, and Si^{4+}. The modern dissolved-solids content of Summer Lake varies significantly on both a seasonal and long-term basis.

Banfield et al. [1991a, b] have discussed the weathering and diagenetic processes affecting adjacent Lake Abert, which are probably similar to those of Summer Lake. These authors suggest that not only evapotranspiration but fractionation processes involving surrounding springs are significant in determining the composition of the lake water. Reactions between meteoric water and rocks in the vicinity of the lake also contribute to the lake water composition. Banfield et al. [1991a] indicate that the lithology of clay sediments (at Lake Abert) produced by weathering reflect their sources: pumice, ash, pyroclasts and felsic volcanics. The weathering alteration of olivine probably facilitated the redistribution of alkali and alkali-earth elements that enriched the lake water [Banfield et al., 1991a].

During the Holocene the lake level has dropped dramatically; the Ana River has cut a canyon, exposing a thick sedimentary sequence. A 20 m sequence of Pleistocene silty clays intercalated with tephra layers and fine ostracode-bearing sands are revealed along the canyon. Figure 2 presents a composite stratigraphic column of sections C, and E sampled by R.M. Negrini in 1987. Most of the sequence outcrops in section C but the youngest portion occurs at section E [Davis, 1985].

The upper 8 m of the sequence includes 21 tephra layers interspersed between marls. Fine laminae are rarely present, lacustrine marls are generally organized in beds a few centimeters thick. Ostracodes occur in high to very high concentrations throughout most of the lacustrine sediments. Several planar unconformities occur through the section, in part marked by degraded ostracode sands, tufa breccias and *in situ* carbonate cementation (R.M. Negrini, unpubl. manuscript). Others are marked by fine gravel lag or simple weathered horizons.

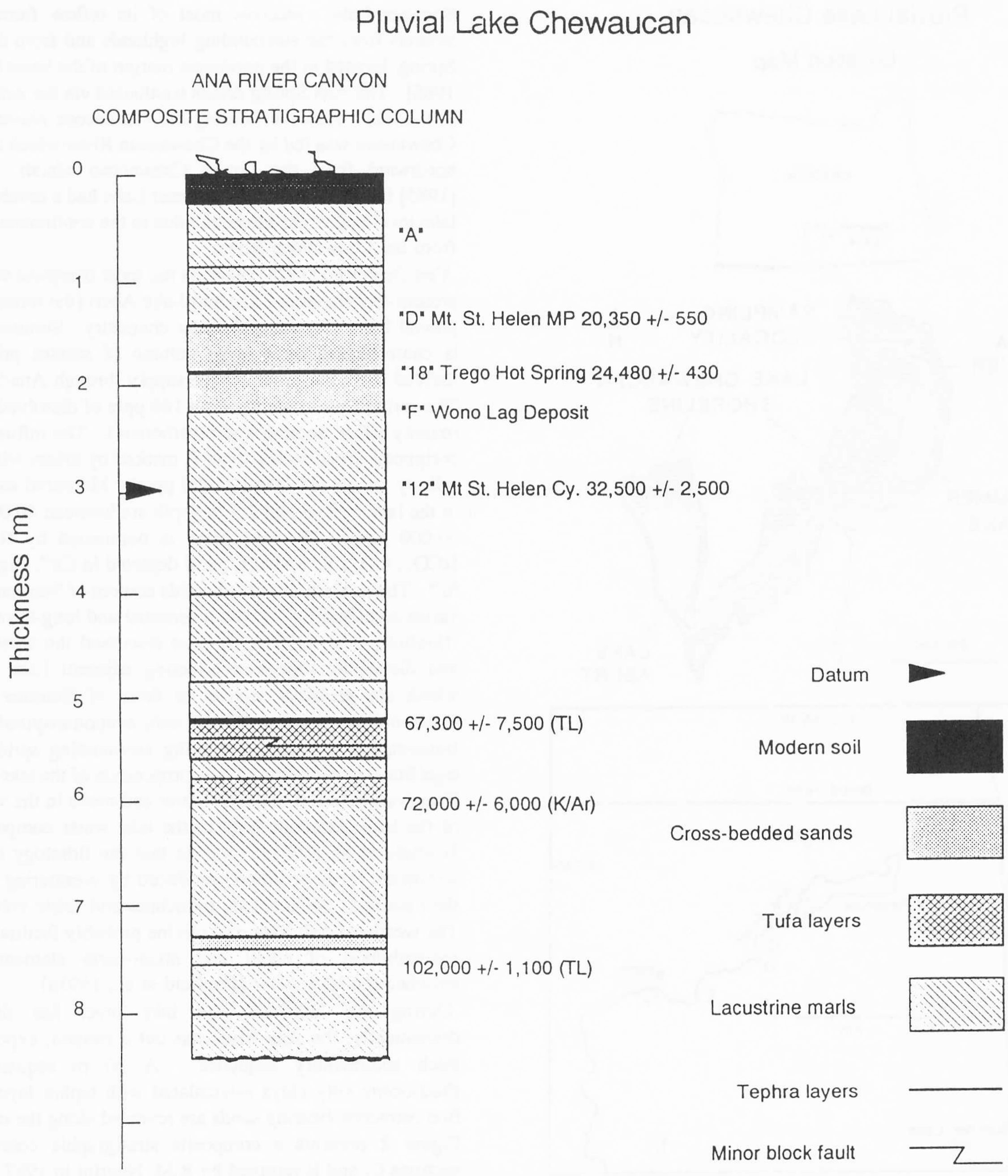

Fig. 2. Composite stratigraphic column of Pleistocene pluvial Lake Chewaucan deposits along the Ana River canyon cut. Sections C and E are integrated in this schematics. Section C includes the longest record and section E contains the youngest sediments. Note the unconformity at the base of the column which indicates a period of deflation of the Chewaucan Basin during isotope stage 5. No lake sediments were preserved around the Ana River during probably the last ~16,000 years (latest Pleistocene to Holocene).

GEOCHRONOLOGIC RECORD

A geochronologic framework has been defined for the Ana River section investigated in this study [Davis, 1985; Berger et al., 1990; Negrini and Davis, in press]. Tephra correlations and thermoluminescence age estimates were determined from tephra samples collected at sections C and E. Tephra 12 (Mt. St. Helens Cy), yielding an age of 32,500 +/- 2,500 yrs. B.P. provides the primary datum for this work. Other tephras like Mt. St. Helens Mp (20,350 +/- 550 yrs. B.P.), Wono and Trego Hot Spring (24,800 +/- 430 yrs. B.P.) provide additional constraints to establish the chronology of the upper pluvial Lake Chewaucan stratigraphic sequence [Negrini et al., 1988]. The correlation of the paleomagnetic record from Summer Lake with data from Lake Russell in east-central California, also provides excellent dating control for the interval between 30,000 and 16,000 years [Negrini and Davis, in press]. Four TL ages on the associated tephra also contribute to the age control of this interval; with ages of 24,300 +/- 2,700, 50,200 +/- 3,400, 67,300 +/- 7,500, and 102,000 +/- 1,100 yrs. B.P. [Berger et al., 1990]. Finally, a K/Ar age of 72,000 +/- 6,000 yrs. B.P. for tephra 1 [Negrini et al., 1988] constrains one of the oldest intervals considered for this study. Ages for all sampled intervals were estimated by linear interpolation from adjacent dated horizons.

METHODS

The samples used for this study were collected at 10 cm intervals from the upper 8 m of the high resolution record from the Ana River canyon exposed at sections C, and E (Fig. 1b). Paleomagnetic sampling cubes containing about 6 cm^3 (2 cm X 2 cm X 1.5 cm) of lacustrine sediments collected by R.M. Negrini in 1987 (sampling procedure and sample description in Negrini et al., 1988), were processed to recover ostracodes.

Seventy seven samples were prepared according to a slightly modified version of Forester's [1991b] freeze and thaw procedure. Residuals were analyzed under a low power stereoscopic microscope. Routine paleontological study of all fossiliferous samples was performed to determine fossil content and faunal composition. Between 100 and 35,000 ostracode valves per gram of sample were recorded. Ostracode relative abundance and assemblages were defined by counting 300 specimens per sample. A qualitative "salinity index" was used to estimate salinity trends based on weighted average species proportions. This index is:

$$SI = 3(\%\ L.\ sappaensis) + 2(\%\ L.\ bradburyi) + \%\ L.\ ceriotuberosa - (\%\ C.\ patzcuaro + 2(\%\ C.\ caudata) + 3(\%\ C.\ lacustris)) \quad (1)$$

The index positively weights species with incrementally higher salinity tolerances and negatively weights species with incrementally lower salinity tolerances.

Species identification, adult/juvenile and carapace/valve ratios were determined for all samples. Taphonomic features including fragmentation, encrustation, abrasion, oxidation and coating were also recorded to distinguish autochthonous from allochthonous individuals. These allowed us to select the ideal specimens for shell chemistry analysis. Eleven intervals did not contain any fossils; they consisted entirely of tephra. Of the remaining 66 samples 16 were selected for chemical analysis since they were associated with the best geochronologically controlled intervals. Individuals from the cleanest horizons were separated for shell chemistry analysis. Specimens from the other 50 beds were either coated or encrusted with $CaCO_3$ or the samples had no significant number of adult individuals for analysis.

Fifteen pristine valves of *Limnocythere ceriotuberosa*, the most common species present at Pluvial Lake Chewaucan, were removed from each of the 16 stratigraphic horizons selected for spectrometric analysis. The specimens were thoroughly cleaned with ultra (4 times) distilled water and a fine (000) brush. Valves were weighed in a Cahn 29 electronic balance and then cut into two halves with a microsurgery scalpel. One half of each specimen was mounted into a micropaleon-tological slide per sample and sent to the Stable Isotope Research Laboratory at the University of Michigan for stable isotope ($\delta^{18}O$ and $\delta^{13}C$) analysis, using a Finnigan Mat 251 mass spectrometer. The other half of each specimen was kept at the Department of Geosciences of the University of Arizona for trace metal (Mg and Sr) study, using a VG inductively-coupled plasma mass spectrometer (ICP-MS). In an attempt to compare and correlate isotopic information, trace element analysis was performed only on the correlative shell fragments analyzed for stable isotopes. As a result of size and weight limitations a total of about 7 specimens per sample were jointly analyzed in this fashion. Calcium content in ostracode valves was determined stoichiometrically as a result of the instrument sensitivity to major elements like calcium. For purposes of consistency only those horizons from which both stable isotope and trace element data were secured were incorporated in the geochemistry portion of this analysis.

RESULTS

PALEOECOLOGIC DATA

Figure 3 summarizes the paleontologic and paleoecologic records for Pluvial Lake Chewaucan ostracodes. All fossiliferous samples are characterized by a relatively low diversity fauna comprising a variety of North American species. A total of eight species occur throughout the stratigraphic sequence. Figure 3 (a-i) synthesizes the total and relative abundance profiles for each species present. The ostracode abundance diagram (Fig. 3a) indicates the concentration of ostracodes of all species through the section. The relative abundance diagrams per species (Figs. 3b-i) are arranged according to decreasing tolerance to salinity, with the highest salinity tolerant species to the left and the more freshwater species to the right.

Based upon the relative abundance diagrams, six paleoecologic intervals are recognized. *Limnocythere ceriotuberosa* (the most common species) alternates with other species throughout the stratigraphic sequence. Interval 1, between 525 cm and 455 cm below datum (~110,000 to ~102,000 years B.P.), is characterized by the co-occurrence of *L. ceriotuberosa, C. caudata*, and *C. patzcuaro*. Interval 2, between 455-295 cm below datum (~102,000 to ~89,000 years B.P.), comprises almost entirely *L. ceriotuberosa* and *L. sappaensis* with minor occurrence

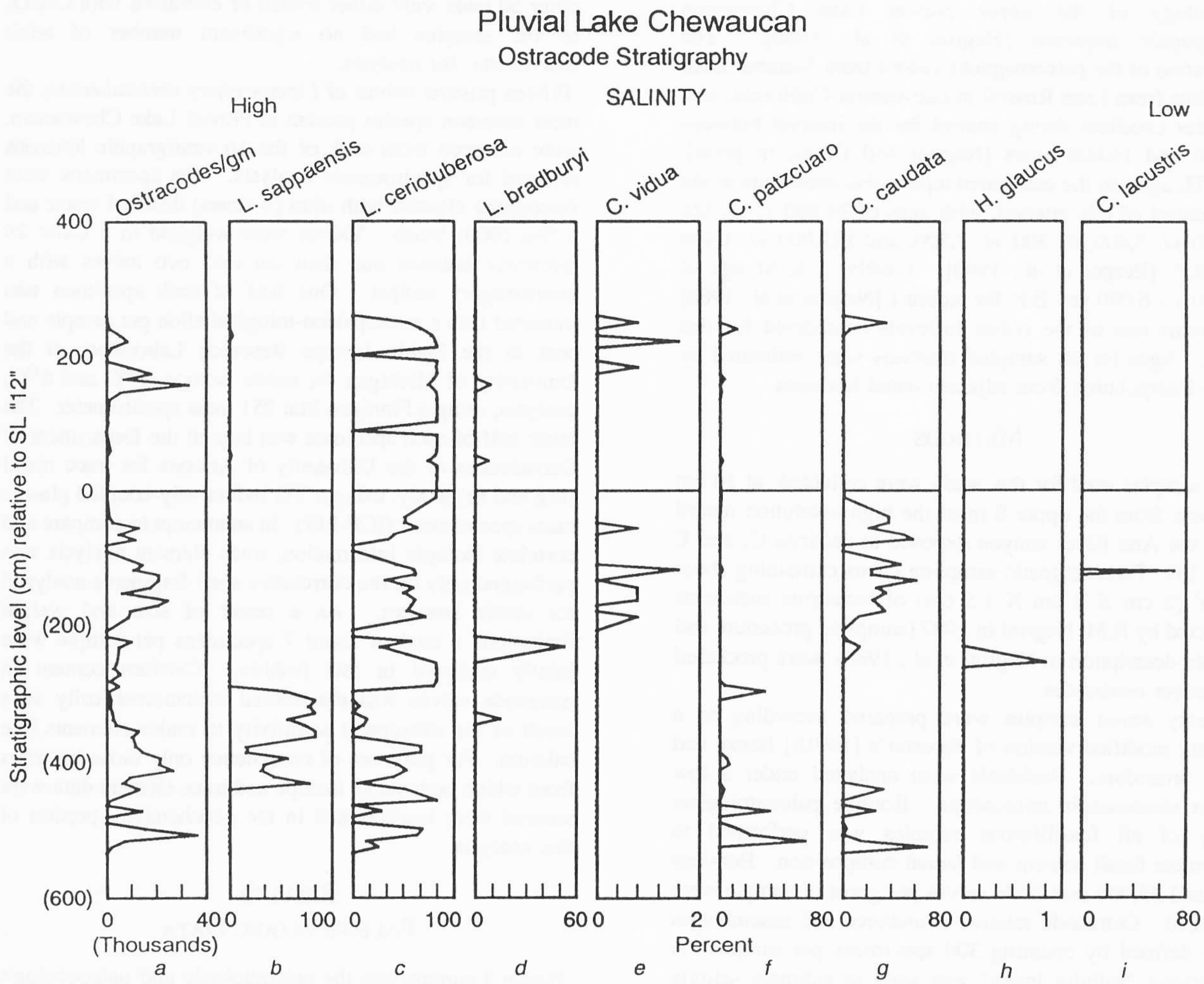

Fig. 3. Total (diagram a) and relative abundance (diagrams b-i) of ostracode species present at pluvial Lake Chewaucan during the Wisconsin. Note the strong dominance of *Limnocythere ceriotuberosa* and the ocassional occurrence of *Cytherissa lacustris* through the stratigraphic sequence. See text for explanation.

of *L. bradburyi* and *C. patzcuaro*. Interval 3, between 295 and 125 cm below datum (~89,000 to ~76,000 years B.P.), is dominated by *L. ceriotuberosa* and *C. caudata* with occasional occurrences of *Cypridopsis vidua*.

Interval 4, between 125-120 cm below datum and only ~2,000 years in duration (~76,000 to ~74,000 years B.P.) is defined by the presence of *Cytherissa lacustris*. Interval 5, between 120 cm below datum and 185 cm above datum (~74,000 to ~22,000 years B.P.) almost entirely consists of *L. ceriotuberosa* with minor occurrences of *L. bradburyi* and *C. patzcuaro*. Interval 6, between 185 to 261 cm above datum (~22,000 to 16,000 years B.P.), is characterized by a nearly monospecific assemblage of *L. ceriotuberosa* with erratic occurrences of *L. sappaensis, C. caudata* and *Cypridopsis vidua*.

Based upon the relative abundances shown in figure 3, a paleoenvironmental interpretation was generated (Fig. 4a). Interval 1 assemblage suggests low to moderate but increasing salinity. Interval 2 assemblage dominated by *L. ceriotuberosa* and *L. sappaensis* (both eurythermic) suggests moderate to high salinity conditions. Interval 3 assemblage, characterized by *L. ceriotuberosa, C. caudata* and *Cypridopsis vidua*, strongly suggests low to moderate salinity conditions and increasing precipitation. The interval 4 assemblage, marked by the occurrence of *C. lacustris*, indicates the rapid development and disappearance of cold-, freshwater conditions. In interval 5 the occurrence of *L. ceriotuberosa* and the occasional appearance of *Cypridopsis vidua* and *L. bradburyi* suggests that salinity increased beyond *C. lacustris*'s maximum tolerance after ~74,000 years B. P. These conditions prevailed until ~22,000 B.P.; from this horizon (interval 6) to the end of the record an erratic pattern of ostracode species (*L. ceriotuberosa, C. vidua*, and occasional *C. caudata, C.*

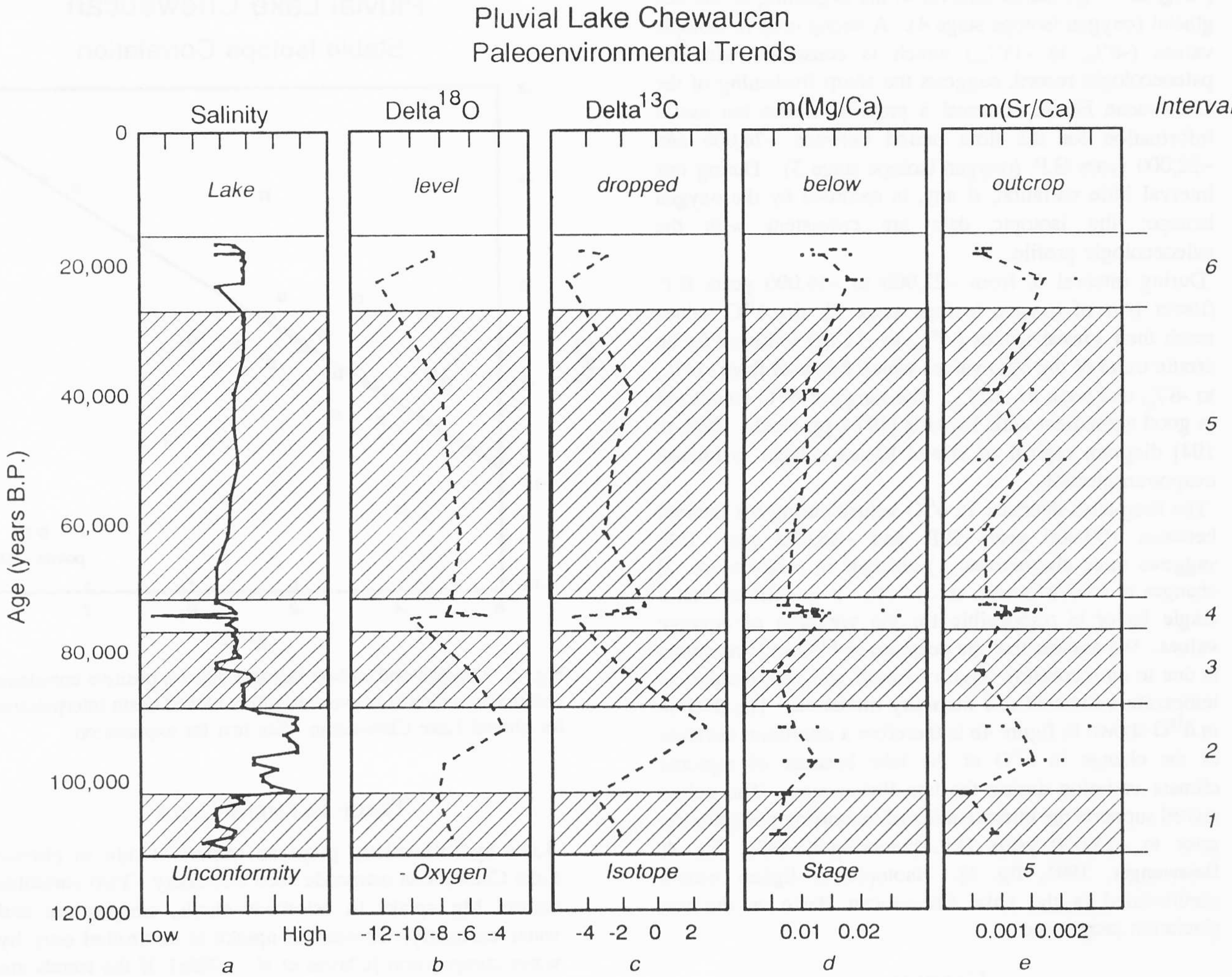

Fig. 4. Comparative trends from paleoecologic and geochemical profiles; a) salinity index generated from the appearance/disappearance pattern and the weigh average of the five most significant species; b) oxygen isotope trend; c) carbon isotope trend; d) Mg/Ca molar ratio trend; and e) Sr/Ca molar ratio trend of *Limnocythere ceriotuberosa* (the most common species present throughout the stratigraphic sequence). See text for explanation.

patzcuaro and *L. sappaensis*) suggests more unstable conditions which concluded with the lake level dropping below the Ana River section.

Stable Isotope Data

Stable isotope values from *L. ceriotuberosa* are plotted in figures 4b and 4c. The six intervals recognized from the paleoecologic data are also evident from the isotope data. A covariant trend is evident through most of the sequence, except for a horizon at ~75,000 years B.P. and between ~22,000 and ~16,000 years B.P. where the trends are opposite. A secular isotopic trend for both the $\delta^{18}O$ and $\delta^{13}C$ values is discernible toward lower values (Fig. 4b).

Oxygen

The $\delta^{18}O$ values during interval 1 remain stable within a one per mil range (-6‰ to -7‰) between ~110,000 and ~102,000 years B.P. (oxygen isotope stage 5d), suggesting stable temperatures and/or humidity through this term. Interval 2 between ~102,000 and 89,000 years B.P. (oxygen isotope stage 5c) is characterized by higher $\delta^{18}O$ values increasing from -7‰ to -4‰; this interval's pattern is consistent with the marine oxygen isotope stage 5 record [Martinson et al, 1987].

Interval 3 (~89,000 to ~76,000 years B.P.) marked by a decline towards more negative $\delta^{18}O$ values (-4‰ to -6‰) supports the conclusion of interglacial climate (oxygen isotope stage 5b and a). A minor reduction of $\delta^{18}O$ values

($-6^{\circ}/_{oo}$ to $-7^{\circ}/_{oo}$) marks interval 4, the beginning of the last glacial (oxygen isotope stage 4). A strong drop in isotopic values ($-6^{\circ}/_{oo}$ to $-11^{\circ}/_{oo}$) which is consistent with the paleoecologic record, suggests the sharp freshening of the Chewaucan Basin. Interval 5 provides scarce but useful information for the time period between ~74,000 and ~22,000 years B.P. (oxygen isotope stage 3). During this interval little variation, if any, is recorded by the oxygen isotope; the isotopic data are consistent with the paleoecologic profile.

During interval 6, from ~22,000 to ~16,000 years B.P. (lower part of oxygen isotope stage 2), the $\delta^{18}O$ values reach their lowest values ($-7^{\circ}/_{oo}$ to $-11^{\circ}/_{oo}$) followed by an erratic trend of the $\delta^{18}O$ values which fluctuate from $-11^{\circ}/_{oo}$ to $-8^{\circ}/_{oo}$ and back to $-10^{\circ}/_{oo}$. The range of $\delta^{18}O$ values are in good agreement with Taylor's [1974, in: Hoefs, 1980; p. 104] diagram typical of closed basins subject to intense evapotranspiration.

The long-term decrease in $\delta^{18}O$ values during the interval between 100,000 years B.P. and ~16,000 years B.P. suggests three alternatives: 1) changes in temperature, 2) changes in $\delta^{18}O$ of water, or 3) both. It is unlikely that a single factor is responsible for the variation of isotopic values. We assume that the decrease in $\delta^{18}O$ of lake waters is due to an increasing input of runoff and precipitation as temperature lowered and humidity increased. The decline in $\delta^{18}O$ shown in figure 4b is therefore a minimum estimate of the change in $\delta^{18}O$ of the lake because of regional climate variation during the late Pleistocene. The pollen record supports the interpretation of increasing precipitation prior to ~25,000 years B.P. [Mehringer, 1985, fig. 4; Beiswenger, 1991, fig. 6]. Isotopically lighter waters accumulated in the Lake Chewaucan Basin as the last glaciation progressed.

Carbon

The $\delta^{13}C$ values are covariant with the $\delta^{18}O$ (r=0.76) following the same interval pattern discussed above (Fig. 5). These $\delta^{13}C$ values are interpreted in terms of dissolved inorganic carbon (DIC) and alkalinity/salinity, rather than as paleoproductivity as is usually the case [Lister, 1988; Talbot and Kelts, 1990]. Values of $\delta^{13}C$ in closed basins are less influenced by primary productivity than are open basins [Stiller and Hutchinson, 1980]; rather variations in $\delta^{13}C$ in closed basins results from preferential outgassing of ^{12}C-rich CO_2 from the lake surface [Talbot and Kelts, 1990]. The characteristic covariant trend shown by $\delta^{18}O$ and $\delta^{13}C$ of pluvial Lake Chewaucan provides evidence for a long-term evolution of lake waters within a hydrologically closed basin environment.

The consistent covariant trends of both stable isotope curves is broken in two intervals (Fig. 4c). During interval 4 (~76,000 to ~74,000 years B.P.) the two curves are out of phase. A lack of covariance also occurs at the end of interval 6 (~22,000 to ~16,000 years B.P.). Rapid freshening and increased volume of Lake Chewaucan are probably responsible for these brief events.

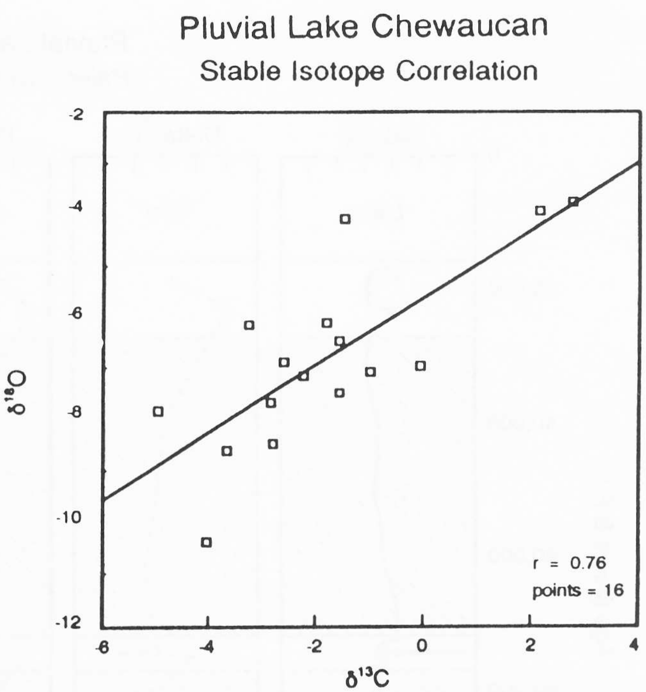

Fig. 5. Oxygen and carbon isotopes show a positive correlation coefficient which is consistent with a closed basin interpretation for pluvial Lake Chewaucan. See text for explanation.

Trace Element Data

Lake hydrochemistry plays an important role in pluvial Lake Chewaucan ostracode shell chemistry. Two variables control Mg uptake in ostracode shells, temperature and water chemistry, whereas Sr uptake is controlled only by water composition [Chivas et al., 1986a]. If the trends are covariant, as it is the case throughout most of the Lake Chewaucan record, trace element concentration in ostracode valves must be primarily driven by water chemistry. Alternating conditions are consistent with an evaporative basin subject to rapid fluctuations in salinity.

Trace metal concentrations from *L. ceriotuberosa* are plotted in figures 4d-e. Well-defined covariant trends for Mg/Ca and Sr/Ca ratios are evident throughout the section suggesting that salinity controlled the Mg and Sr content in ostracode valves. Tight clusters indicate small temperature and salinity variations more likely in a fairly deep and stable lake, whereas broad fluctuations of values imply variable conditions more probable under shallower lake conditions.

The Mg/Ca and Sr/Ca molar ratio trends generally show a zonation equivalent to that observed in assemblage and isotope data. Interval 1 from ~110,000 to ~102,000 years B.P. shows little variation in molar ratios indicating small salinity fluctuations within horizons meaning that Mg concentration rose as the lake level rose but Sr decreased probably in response to increasing precipitation.

Interval 2 (~102,000 to ~89,000 years B.P.) is characterized by higher and variable values of the Mg/Ca and Sr/Ca ratios indicating rising salinity. This is consistent with paleoecologic and isotopic data. A decrease in both ratios and tighter clustering of values occurred during interval 3 suggesting a gradual decrease of salinity (~89,000 to ~76,000 years B.P.). This event was followed by a rapid drop in trace metal concentrations suggesting freshwater conditions (interval 4: ~76,000 to ~74,000 years B.P.). As with the stable isotope data we have little information for interval 5 (~74,000 to ~22,000 years B.P.) but available points suggest a similarity with the paleoecologic profile. Although at ~50,000 years B.P. lake conditions became more variable (as shown by the broad fluctuations of values) and probably more saline (as shown by higher Sr/Ca molar values).

During interval 6 (~22,000 to ~16,000 years B.P.) both Mg and Sr ratios increased erratically suggesting that salinity increased but kept fluctuating at this time. The apparent reversal between stable isotope and trace metal trends strongly suggests that dilute water entered a salt filled basin.

PALEOCLIMATIC HISTORY OF LAKE CHEWAUCAN

Pluvial Lake Chewaucan was a closed basin sensitive to regional climatic changes for the interval between ~110,000 and ~16,000 years B.P. Immediately after a period of aridity (prior to interval 1), before ~110,000, which produced deflation in the basin (unconformity at the base of the stratigraphic column associated with marine oxygen isotope stage 5), it began to fill as indicated by the ostracode species *L. ceriotuberosa*, *C. caudata* and *C. patzcuaro*.

A well-defined correspondence of the paleoecologic profile (increasing diversity and abundance) and the geochemical (stable isotopes and trace elements) patterns suggest temperature and salinity decreases (the latter probably associated with increasing humidity and higher precipitation and stream discharge) during interval 1.

The occurrence of *L. sappaensis* and *L. ceriotuberosa*, between 102,000 and 89,000 years B.P. (interval 2) associated with increasing δO^{18} isotopic values and variable but higher Mg/Ca and Sr/Ca ratios indicates that Lake Chewaucan was shrinking in response to climate change.

From 89,000 to 76,000 years B.P. (interval 3) climatic conditions began to shift towards cooler/wetter conditions as evidenced by a lower salinity faunal assemblages, more negative $\delta^{18}O$ and $\delta^{13}C$ values, and less variable Mg/Ca and Sr/Ca ratios.

Lake temperature and salinity declined briefly to very low values between ~76,000 and ~74,000 years B.P. as evidenced by all three profiles (interval 4). During this interval both the $\delta^{18}O$ values (from $-6‰$ to $-11‰$) and the low Mg and Sr content in ostracode valves are congruent with a cold-, freshwater environment. The brief lack of covariance between $\delta^{18}O$ and $\delta^{13}C$ at this time suggests that pluvial Lake Chewaucan underwent sudden flooding as a result of rapidly increasing precipitation/evaporation ratios. It is possible that the lake overflowed into Alkali Basin at this time, although no evidence of surface connection between the Lake Chewaucan and Alkali Lake basins has been recognized, to date (D. Freidel, pers. comm., 1992).

Faunal data suggest that pluvial Lake Chewaucan remained a fairly stable basin during interval 5, from ~74,000 to ~22,000 years B.P., with smaller temperature fluctuations and slightly greater salinity variations than occurred in the prior ~50,000 years. However, a lack of geochemical information limits our confidence in interpretations of this interval. Geochemical and paleoecologic profiles suggest that rainfall and runoff were moderately high but "stable"; that is, water input versus output do not vary significantly for this time period.

By ~22,000 to ~16,000 years B.P. (interval 6) a sharp climatic change is recorded by paleoecologic and geochemical data which correlate with the cold-dry characteristics of the full glacial [Benson and Thompson, 1987; Davis, 1989; and Smith and Street-Perrot, 1983]. Drastic negative shifts in isotopic values associated with higher and wider spread trace metal values strongly suggest that pluvial Lake Chewaucan was subject to dilute water input in an evaporative basin probably during low temperature conditions. Towards the end of the record the paleoecologic and geochemical profiles are consistent. All data sets indicate that this lacustrine basin underwent fluctuating conditions, but remained at low temperatures. Another brief excursion towards fresher water conditions took place at this time although less intense than that at ~75,000 years ago (since salinity did not drop to a viable level for *Cytherissa lacustris*). The co-existence of *Candona caudata* and *Cypridopsis vidua* indicate that Lake Chewaucan received significant groundwater discharge or there is a wetland marginal to a stream, mechanisms which may be responsible for the relative dilution of the water chemistry and lake level rise to about 1330 masl [Allison, 1982].

DISCUSSION

The combined paleoecologic and geochemical (stable isotopes and trace elements) profiles provide a powerful tool for understanding Pleistocene climatic changes in western North America. For the first time paleoecologic records are combined with geochemical information generated from ostracodes to recognize the paleoclimatic signature of the Pleistocene on paleolakes. This research also allowed us to present one of the first approaches in using the same species and specimens to analyze trace elements and stable isotopes through mass spectrometry (the other is that of Chivas and co-workers in this volume). Although slightly different both approaches have proved to be highly reliable. The greates significance of this analysis is to demonstrate that it is possible to determine the paleohydrochemical history of a lake and to recognize the effects of climate on it. However, we acknowledge that more stratigraphic horizons at closer intervals would provide a more detailed record of Lake Chewaucan paleohydrochemistry.

The occurrence of environmentally sensitive species, like *L. sappaensis, L. ceriotuberosa, C. caudata, C. patzcuaro, Cypridopsis vidua* and *Cytherissa lacustris*, provide the basic criteria to determine paleohydrochemical changes in the Chewaucan Basin. Covariant trends of stable isotope data collected from *L. ceriotuberosa* strongly suggest that Lake Chewaucan remained a closed basin throughout its history with the possible exception of brief intervals at ~75,000 years B.P and between 22,000 and 16,000 years B.,P. Trace metal trends indicate that salinity played an important role in the hydrochemical evolution of Lake Chewaucan; these patterns are consistent with the paleoecologic profile and somehow to the stable isotope profiles. By combining these data it is possible to speculate about the climatic history of the Lake Chewaucan region.

Variations in local climate and Lake Chewaucan hydroclimate during the Pleistocene likely reflect regional changes in the western North America climate regime. Of primary importance in determining regional climate fluctuations, especially in temperate climates, is the position of the jet stream. Late Pleistocene western North America lake evolution suggests that the jet stream was driven mainly by the height and extent of the Laurentide ice-sheet [Benson and Thompson, 1987]. Accordingly, the ice-sheet produced a high pressure cell over the continent which in turn induced changes in the atmospheric circulation pattern forcing the jet stream southward [Kutzbach, 1987; COHMAP group, 1988]. The COHMAP group [1988] has proposed that the jet stream split into a north and a south branch which influenced climate during the full glacial (~18,000-20,000 years B.P.). If this model is correct, greater and stronger storms should be expected along western North America during episodes under the jet stream influence. The COHMAP model will be applied throughout the Lake Chewaucan record.

It is likely that during the last interglacial the jet stream had a position similar to the present. A gradual south shifting of the jet stream split south branch would introduce wetter and colder conditions to the area between ~110,000 and ~102,000 years B.P. As the jet stream moved south greater and stronger storms affected the Lake Chewaucan area. A year-round winter-like episode characterized the ~76,000 to ~74,000 years B. P. period.

If the COHMAP model is suitable, the jet stream probably retreated northward during the next ~50,000 years in response to the ice-cover reduction and then remained more or less stable until ~25,000 year. However, movement of the jet stream southward ~25,000 years B.P. is documented by woodrat midden data from further south. P.E. Wigand (pers. comm., 1992) reports that white bark pine pollen (an indicator of wetter conditions) occurs in woodrat middens near Reno, Nevada below 1400 masl prior to ~23,000 years B.P. Today it is not present at that altitude. Further south in the Pahrangat Range of southeastern Nevada, whit fir drops to elevations below 1585 masl at the same time (P.E. Wigand, pers. comm. 1992). The paleoecologic profile from Lake Chewaucan suggests that minor climatic changes occurred in this region for that time interval. Clear, Grays and Tulare lakes provide strong evidence in support of our hypothesis since for the same time period both basins indicate transitional cold-wet to cold-dry to warm-dry (short interval) conditions [Sims et al. 1988; Atwater et al., 1986; Beiswenger, 1991]. An equivalent interpretation from Lake Chewaucan is presented in this paper. However, Lake Chewaucan suggests colder temperatures as a result of both latitudinal and topographic relief differences. The microclimatic effects shown by each basin discussed in this paper do not mask the greater influence of the jet stream throughout northwestern North America.

Our stable isotope values are in good agreement with isotopic data from distant basins [Lake Searles: Phillips, 1989 in: Benson et al., 1990] supporting the idea that a strong southerly jet stream incursion affected western North America during the Wisconsin glaciation. Similarly, our trace element data indicate alternating periods of water dilution and increasing total dissolved solids probably in response to changes in climate. In consequence, ostracode paleoecology and geochemistry contribute to make a high resolution reconstruction of Lake Chewaucan paleohydrologic and paleoclimatic evolution.

Acknowledgements. This project has been possible through NSF support (EAR-8803406). We thank Dr. R. Negrini for providing us with the sediment samples used for this study and helpful suggestions to the manuscript. Dr. K. C. Lohman and colleagues from the Stable Isotope Laboratory of the University of Michigan performed oxygen and carbon isotope analyses on Lake Chewaucan ostracode valves. Drs. A. Long and O.K. Davis from the Department of Geosciences of the University of Arizona, Dr. P. E. Wigand from the Desert Research Institute of the University of Nevada-Reno, Dr. Richard M. Forester from the U.S. Geological Survey at Denver and Dr. Charles G. Oviatt from the Department of Geology, Kansas State University, made helpful contributions to the improvement of this paper.

REFERENCES

Adam, D. P., Correlations of the Clear Lake, California, core CL-73-4 pollen sequence with other long climate records, *Geol. Soc. Amer., Spec. Paper 214*, pp. 81-95, 1988.

Allison, I. S., Geology of Pluvial Lake Chewaucan, Lake County, Oregon, *Oregon State University Press*, Corvallis, Oregon, 78 pp.,1982.

Atwater, B. F., D. P. Adam, J. P. Bradbury, R. M. Forester, R. K. Mark, W. R. Lettis, G. R. Fisher, K. W. Gobalet, and S. W. Robinson, A fan dam for Tulare Lake, California, and implications for the Wisconsin glacial history of the Sierra Nevada, *Geol. Soc. Amer. Bull., 97*, pp. 97-109, 1986.

Bachhuber, F. W., Quaternary history of the Estancia Valley, central New Mexico, *New Mexico Geol. Soc. Guidebook, 33rd Field Conference*, pp.343-346, Albuquerque County, 1982.

Banfield, J. F., B. F. Jones and D. R. Veblen, An AEM-TEM study of weathering and diagenesis, Abert Lake, Oregon: I. Weathering reactions in the volcanics, *Geochim. Cosmochim. Acta, 55*, pp. 2781-2793, 1991a.

Banfield, J. F., B. F. Jones and D. R. Veblen, An AEM-TEM study of weathering and diagenesis, Abert Lake, Oregon: II. Diagenetic modification of the sedimentary assemblage, *Geochim. Cosmochim. Acta, 55*, pp. 2795-2810, 1991b.

Benson, L. V., Fluctuations in the level of pluvial Lake Lahontan during the last 40,000 years, *Quat. Res., 9*, pp. 300-318, 1978.

Benson, L. V. and R. S. Thompson, Lake-level variation in the Lahontan Basin for the past 50,000 years, *Qtny. Res., 28*, pp. 69-85, 1987.

Benson, L. V., D. R. Currey, R. I. Dorn, K. R. Lajoie, C. G. Oviatt, S. W. Robinson, G. I. Smith and S. Stine, Chronology of expansion and contraction of four Great Basin lake systems during the past 35,000 years, *Paleogeogr., Paleoclimatol., Paleoecol., 78*, pp. 241-286, 1990.

Berger, G. W., J. O. Davis and R. M. Negrini, Thermoluminescence dating of tephra from Oregon and Nevada, *INQUA-ICCT Field Conference and Workshop on Tephrochronology abstracts*, p. 3, 1990.

Beiswenger, J.M., Late Quaternary vegetational history of Grays Lake, Idaho, *Ecol. Monogr., 61* (2), pp. 165-182, 1991.

Cameron, S. P. and R. F. Lundin, Environmental interpretation of the ostracode succession in late Quaternary sediments of pluvial Lake Cochise, southeastern Arizona, *Sixth Intnal. Ostracoda Symp.*, pp. 335-352, Saalfelden, 1977.

Chivas, A. R., P. De Deckker and J. M. G. Shelley, Magnesium, strontium, and barium partitioning in nonmarine ostracode shells and their use in paleoenvironmental reconstructions: A preliminary study, in: *Applications of Ostracoda*, edited by R. F. Maddocks, pp.238-249, Dept. Geosc., University of Houston, Houston, 1983.

Chivas, A. R., P. De Deckker and J. M. G.Shelley, Magnesium and strontium in non-marine ostracod shells as indicators of paleosalinity and paleotemperature, *Hydrobiologia, 143*, pp. 135-142, 1986a.

Chivas, A. R., P. De Deckker and J. M. G. Shelley, Magnesium content of non-marine ostracod shells: a new paleosalinometer and paleothermometer, *Paleogeogr., Paleoclimatol., Paleoecol., 54*, pp. 43-61, 1986b.

COHMAP, Climatic changes of the last 18,000 years: Observations and model simulations, *Science, 241*, pp. 1043-1052, 1988.

Currey, D. R., Quaternary paleolakes in the evolution of semidesert basins, with special emphasis on Lake Bonneville and the Great Basin, U. S. A., *Paleogeogr., Paleoclimatol., Paleoecol., 76*, pp. 189-214, 1990.

Davis, J. O., Correlation of late Quaternary Tephra Layers in a long pluvial sequence near Summer Lake, Oregon, *Qtny. Res., 23*, pp. 38-53, 1985.

Davis, O. K., The regionalization of climatic change in Western North America, in: *Paleoclimatology and paleometeorology: Modern and past patterns of global atmospheric transport*, edited by M. Leinen and M. Sarnthein, pp. 617-636, Kluwer Academic Publishers, 1989.

De Deckker, P. and R. M. Forester, The use of ostracodes to reconstruct paleoenvironmental records, in: *Ostracoda in the Earth Sciences*, edited by P. De Deckker, J. P. Colin and J. P. Peypouquet, pp. 175-200, Elsevier Scientific Publishers, Amsterdam, The Netherlands, 1988.

De Deckker, P., A. R. Chivas and J. M. G. Shelley, Paleoenvironment of the Messinian Mediterranean 'Lago Mare' from strontium and magnesium in ostracode shells, *Palaois, 3*, num. 3, pp. 352-358, 1988a.

De Deckker, P., A. R. Chivas, J. M. G. Shelley and T. Torgentsen, Ostracod shell chemistry: a new paleoenvironmental indicator applied to regressive/transgressive record from the Gulf of Carpentaria, Australia, *Paleogeogr., Paleocliamtol., Paleoecol., 66*, pp. 231-241, 1988b.

Delorme, L. D., Ostracodes as Quaternary paleoecological indicators, *Can. Jour. Earth Sci., 6*, pp. 1471-1476, 1969.

Delorme, L. D., Methods in Quaternary ecology #7. Freshwater ostracodes, *Geosci. Can., 16*, num. 2, pp. 85-90, 1989.

Eyles, N. and H. P. Schwarcz, Stable isotope record of the last glacial cycle from lacustrine ostracodes, *Geol., 19*, pp. 257-260, 1991.

Forester, R. M., Relationship of two lacustrine ostracode species to solute composition and salinity: implications for paleohydrochemistry, *Geol., 11*, pp. 435-438, 1983.

Forester, R. M., Determination of the dissolved anion composition of ancient lakes from fossil ostracodes, *Geol., 14*, pp. 796-799, 1986.

Forester, R. M., Late Quaternary paleoclimate records from lacustrine ostracodes, in: *North America and adjacent oceans during the last glaciation*, edited by W. F. Ruddiman and H. E. Wright Jr., *Geol. Soc. America*, The Geology of North America, *3-K*, pp. 261-276, 1987.

Forester, R. M., Pliocene-climate history of the western United States derived from lacustrine ostracodes, *Quat. Sci. Rev., 10*, pp. 133-146, 1991a.

Forester, R. M., Ostracode assemblages from springs in the western United States: Implications for paleohydrology, *Mem. ent. Soc. Can., 155*, pp. 181-201, 1991b.

Heusser, C. J., Palynology and phytogeographical significance of a Late-Pleistocene refugium near Kalaloch, Washington, *Quat. Res., 2*, pp. 189-201, 1972.

Hoefs, J., Stable isotope geochemistry, *Springer-Verlag*, Berlin, Germany, p. 104, 1980.

Kutzbach, J. E., Model simulations of the climatic patterns during the deglaciation of North America, in: *North America and adjacent oceans during the last deglaciation*, edited by W. F. Ruddiman and H. E. Wright, pp.425-446, *Geol. Soc. America*, The Geology of North America, v. K-3, Boulder, Colorado, 1987.

Lister, G. S., Stable isotopes from lacustrine Ostracoda as tracers for continental palaeoenvironments, in: *Ostracoda in the Earth Sciences*, edited by P. De Deckker, J. P. Colin and J. P. Peypouquet, pp. 201-218, Elsevier Science Publs., Amsterdam, The Netherlands, 1988.

Markgraf, V., J. P. Bradbury, R. M. Forester, W. McCoy, G. Singh and R. S. Sternberg, Paleoenvironmental reassessment of the 1.6 million-year-old record from San Agustin Basin, New Mexico, *New Mexico Geol. Soc. Guidebook, 34th Field Conference, Socorro Region II*, pp. 291-297, 1983.

Markgraf, V., J. P. Bradbury, R. M. Forester, G. Singh, and R. S. Sternberg, San Agustin Plains, New Mexico: Age and paleoenvironmental potential reassessed, *Quat. Res., 22*, 336-343, 1984.

Mehringer, P. J. Jr., Late-Quaternary pollen records from the interior Pacific northwest and northern Great Basin of the United States, in: *Pollen records of late-Quaternary North American sediments*, edited by V. M. Bryant and R. G. Holloway, *Amer., Assoc. Strat. Palynol. Found.*, pp.165-187, 1985.

Negrini, R. M., K. L. Verosub and J. O. Davis, The middle to late Pleistocene geomagnetic field recorded in fine-grained sediments from Summer Lake, Oregon, and Double Hot Springs, Nevada, U. S. A., *Earth Planet. Sci. Letters, 87*, pp. 173-192, 1988.

Negrini, R. M. and J. O. Davis, Correlation of two paleomagnetic secular variation records from western North America and its application as a high-resolution chronological tool for late Pleistocene, non-marine sedimentary sequences, *Quat. Res.*, in press.

Oviatt, C. G., Late Pleistocene and Holocene lake fluctuations in the Sevier Lake Basin, Utah, U. S. A., *Jour. Paleolimnol., 1*, pp. 9-21, 1988.

Oviatt, C. G., D. R. Currey, and D. M. Miller, Age and paleoclimatic significance of the Stansbury Shoreline of Lake Bonneville, Northeastern Great Basin, *Quat. Res., 33*, pp. 291-305, 1990.

Robinson, S. W., D. P. Adam, and J.D. Sims, Radiocarbon content, sedimentation rates, and a time scale for core CL-73-4 from Clear Lake, California, *Geol. Soc. Amer., Special Paper 214*, pp. 151-160, 1988.

Sims, J. D.(editor), Late Quaternary climate, tectonism, and sedimentation in Clear Lake, northern California Coast Ranges, *Geol. Soc. Amer., Special Paper, 214*, 221 pp., 1988.

Stiller, M., and G. E. Hutchinson, The waters of Merom: A study of Lake Huleh, part 1- Stable isotopic composition of carbonates of a 54 m core, paleoclimatic and paleotrophic implications, *Archiv fur Hydrobiologie, 89*, pp. 275-302, 1980.

Talbot, M. R. and K. Kelts, Paleolimnological signatures from carbon and oxygen isotopic ratios in carbonates from organic carbon-rich lacustrine sediments, in: *Lacustrine basin exploration: Cases studies and modern analogs*, edited by B. J. Katz, pp. 99-112, AAPG Mem. 50, 1990.

Teeter, J. W. and T. J. Quick, Magnesium-salinity relation in the saline lake ostracode *Cyprideis americana*, *Geol., 18*, pp. 220-222, 1990.

Thompson, R. S., L. J. Toolin, R. M. Forester, and R. J. Spencer, Accelerator-mass spectrometer (AMS) radiocarbon dating of Pleistocene lake sediments in the Great Basin, *Paleogeogr., Paleoclimatol., Paleoecol., 78*, pp. 301-313, 1990.

Turpen, J. B. and R. W. Angell, Aspects of moulting and calcification in the ostracod *Heterocypris*, *Biol. Bull., 140*, pp. 331-338, 1971.

Van Denburgh, A. S., Solute balance at Abert and Summer Lakes, south-central Oregon, *U. S. Geol. Survey Prof. Paper, 502-C*, 29 pp., 1975.

Wells, S. G., R. Y. Anderson, L. D. McFadden, W. J. Brown, Y. Enzel and J. L. Miossec, Late Quaternary Paleohydrology of the eastern Mojave River drainage, southern California: Quantitative assessment of the late Quaternary hydrologic cycle in large arid watersheds, *N. Mex. Water Resources Res. Inst., New Mexico State Univ., Rep. 242*, 253 pp., 1989.

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