# DEVELOPING A BASELINE OF NATURAL LAKE-LEVEL/HYDROLOGIC VARIABILITY AND UNDERSTANDING PAST VERSUS PRESENT LAKE PRODUCTIVITY OVER THE LATE-HOLOCENE: A PALEO-PERSPECTIVE FOR MANAGEMENT OF MODERN LAKE ELSINORE.

**A FINAL CONTRACT REPORT TO THE:**
**Lake Elsinore and San Jacinto Watersheds Authority**
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**EXECUTIVE SUMMARY.**

LESJWA contracted Drs. Matthew Kirby, Steve Lund, and Christopher Poulsen to reconstruct a baseline of natural lake-level/hydrologic variability over the late-Holocene. Dr. Anderson was contracted by LESJWA to compare and contrast historic (past 200 years) and pre-historic lake nutrient levels and lake primary productivity, with an emphasis on human impacts. Although the original contract was intended to focus on the late-Holocene (past 3,000 to 4,000 calendar years), the cores extracted from Lake Elsinore covered the past 9,800 calendar years. As a result, this report covers the entire 9,800 year record from the perspective of data analysis and interpretation. The best proxy for hydrologic variability is $\delta^{18}O$ calcite; however, these data only cover the past 3,800 calendar years before present at approximately 30-year snap-shots of time. Therefore, our detailed interpretation of hydrologic variability is constrained to the last 3,800 years only. Our most salient conclusions are bulleted below:

⇒The <u>Holocene is characterized by a long term drying</u>. This long term drying is linked to a combination of increasing winter insolation, which decreased the frequency of winter storms across the region, and decreasing summer insolation, which decreased the contribution of summer precipitation via monsoonal rains and/or the occasional tropical cyclone. Together, these long term changes in seasonal insolation produced a total decrease in regional precipitation and the observed long term drying.

⇒The <u>early to mid-Holocene (9,8000 to 5,000 cy BP) is characterized by infrequent, but large storm events</u>. These events are attributed to more frequent large winter storms and the occasional summer storm, which increased local run-off.

⇒There is a <u>distinct shift to higher amplitude climate variability after 5,000 cy BP through to present day</u> in several of the sedimentological data. We attribute this increase in the amplitude of climate variability to the onset of the modern El Nino-Southern Oscillation phenomenon, which is characterized by highly variable climate with notable alternating wet-dry phases.

⇒The last 4,000 cy BP - the only interval with $\delta^{18}O$ calcite data - is characterized by eight multi-decadal-to-multi-centennial scale wet-dry oscillations. These oscillations are shorter from 4,000 to 2,000 cy BP after which they increase in duration through to the modern. During the past 2000 cy BP, two notable wet-dry oscillations occur: the wet Medieval Warm Period between 1000 and 600 cy BP and the dry Little Ice Age between 600 and 200 cy BP. The last 200 cy have been characterized by a long term increase in climate wetness.

⇒A comparison of the Lake Elsinore $\delta^{18}O$ calcite data over the past 4,000 cy BP to Pyramid Lake $\delta^{18}O$ calcite indicates several distinct similarities. These similarities provide evidence for two important conclusions: 1) independent evidence that our Lake Elsinore age model is robust; and, 2) evidence that there is regional climate phasing across western North America at a minimum of centennial time scales.

⇒Proxy evidence for lake nutrient levels and primary productivity indicates that the past 200 years are characterized by higher nutrient levels and lake productivity than the prior 9,600 calendar years. This recent increase in lake nutrient levels and lake primary productivity is attributed to: 1) the long term climate drying, which reduces both the dilution of nutrients by sediment run-off and concentrates nutrients as lake volume decreases; and, 2) human disturbance of the lake's drainage basin, which increases local erosion of nutrients into the lake basin and increases the input of pollution. Human disturbance is certainly the most significant factor affecting the lake's trophic structure over the past 100 to 200 years.

**SOME NECESSARY VOCABULARY/TERMS.**

1. Paleoclimatology: the study of past climate;

2. Palynology: the study of pollen;

3. Proxy Data: data used as a substitution for a specific or general climate variable;

4. Lacustrine: related to lakes or lake environments;

5. Isotopes: an element with extra neutrons;

6. $\delta^{18}O_{(calcite)}$: the ratio of the stable isotope oxygen-18 to oxygen-16 as contained in calcite;

7. Terrestrial: related to land or the land environment;

8. $^{14}C$ years BP: radiocarbon-14 years before present (i.e., 1950 A.D.);

9. cy BP: calendar years before present corrected for natural variations in atmospheric $^{14}C$ over time;

10. Holocene: most recent geological epoch spanning the past 10,000 $^{14}C$ years BP – divided into early Holocene (~10,000-7,500 $^{14}C$ years BP), mid-Holocene (~7,500-5,000 $^{14}C$ years BP), and late-Holocene (~5,000 $^{14}C$ years BP to present);

11. n = : number of something measured or analyzed;

12. Oogonia: the reproductive capsule of the aquatic plant Charaphyte, indicative of shallow, carbonate-precipitating water;

13. Allochthonous: used to describe features of the landscape or elements of its geological structure that have moved to their current position by geological forces;

14. Autochthonous: used to describe a rock, mineral deposit, or geologic feature that was formed in the area where it is found;

15. Littoral: near shore lake environment;

16. Profundal: deep basin lake environment;

17. Mesic: growing in or characterized by moderate moisture;

18. Xeric: relating to or living in a dry habitat.

## 1. INTRODUCTION.

Climate variability has a significant impact on the environment and people of western North America, specifically its impact on the region's limited water resources (Dettinger et al., 1998; Wilkinson et al., 2002; Miller et a., 2003). In California, for example, the droughts of 1976-77 and 1987-92 cost the state $2.6 billion (unadjusted) (California Department of Water Resources). Southern California, home to more than 30 million people, is characterized by an arid, Mediterranean climate and faces a perennial freshwater crisis, making it particularly susceptible to multi-scale climate variability as well as extreme climate-related events such as large storms (i.e., floods) and severe droughts. To properly assess the present and future climate dynamics in Southern California, the reconstruction and interpretation of a baseline of past climate variability is essential. Unfortunately, historical records of climate variability have been maintained for less than 100 years, too short a period to provide a robust understanding of the forcing mechanisms and dynamics of multi-scale (e.g., multi-decadal-to-centennial scale) climate variability. This interval is also too short to provide a true frequency distribution analysis of extreme climate-related events, such as large storms and severe droughts. In turn, the prehistoric record (>100 yrs) of climate variability in Southern California is sparsely documented, and limited to Mission diaries, tree-ring studies, some palynology, and low-resolution lake studies (Lynch, 1931; Heusser, 1978; Meko et al., 1980; Davis, 1992; Enzel et al., 1992; Cole and Wahl, 2000; Biondi et al., 2001; D'Arrigo et al., 2001; Byrne et al., 2003; Kirby et al., 2004, 2005). The high-resolution marine records from Santa Barbara Basin (SBB) are the most complete Holocene records for the region (e.g., Heusser, 1978; Pisias, 1978; Friddell et al., 2003). However, people do not live in the ocean, and it remains unclear how the ocean's response to climate change transfers to the terrestrial realm on the timescales studied in this contract research (i.e., multi-decadal-to-centennial scale). In other words, this lack of complete, high-resolution, terrestrial, Holocene records from Southern California has limited scientists' ability to evaluate and compare existing records of Holocene climate variability in western North America (e.g., Owens Lake and Pyramid Lake) to Southern California. Consequently, there are many unresolved questions concerning the causal mechanisms driving Holocene climate in western North America and how climate is manifest in terms of development, variability, and spatial-temporal patterns. In southwestern California there is a relatively untapped resource for documenting both historical and pre-historical/geological patterns of climate variability: lakes. As a natural integrator of the climate system, lakes provide an excellent natural archive for documenting multi-scale climate variability (Stuiver, 1970; Fritz et al., 1975; Edwards and Fritz, 1988; Kelts and Talbot, 1990; McKenzie and Hollander, 1993; Drummond et al., 1995; Benson et al., 1996; Edwards et al., 1996; Anderson et al., 1997; Benson et al., 1997; Li and Ku, 1997; Benson et al., 1998a,b; Yu and Eicher, 1998; Smith and Hollander, 1999; Li et al., 2000; Teranes and McKenzie, 2001; Kirby et al., 2002a,b; Rosenmeier et al., 2002; Benson et al., 2002; Kirby et al., 2004). For this research, we focused on Lake Elsinore, a natural, pull-apart rift lake located 120 km southeast of downtown Los Angeles (Figure 1).

In addition to the limited knowledge regarding past climate variability in Southern California, there is very little research documenting pre-historical (before human development: 10,000-200 cy BP) versus modern (after human development: 200 cy BP to present) lake nutrient levels/lake productivity. Human impact on a lake's "natural" state is a significant concern facing lake management organizations. As lake nutrient levels rise in response to increased run-off and anthropogenic pollution, primary productivity increases, lake water quality decreases, and, sometimes, catastrophic lake faunal deaths occur.

As a first step towards answering climate and lake productivity-related questions for Southern California, the Lake Elsinore-San Jacinto Water Authority (LESJWA) contracted Dr. Matthew E. Kirby (CSUF), Dr. Michael Anderson (UCR), Dr. Steve Lund (USC), and Dr. Christopher Poulsen (UM) to produce a baseline of natural lake-level/hydrologic variability (Kirby, Lund, Poulsen) and lake productivity (Anderson) using sediments from Lake Elsinore over the past 3,000-5,000 years before present. To accomplish this goal, a drill rig, contracted through Gregg's Drilling, extracted three ~10 meter drill cores from the lake's deepest basin (Figure 2). A multi-proxy methodology was used to characterize both the lake's hydrologic history and to compare modern versus pre-industrialization nutrient/lake productivity levels. The proxies reported for this study include: sediment description, mass magnetic susceptibility, total carbonate, total

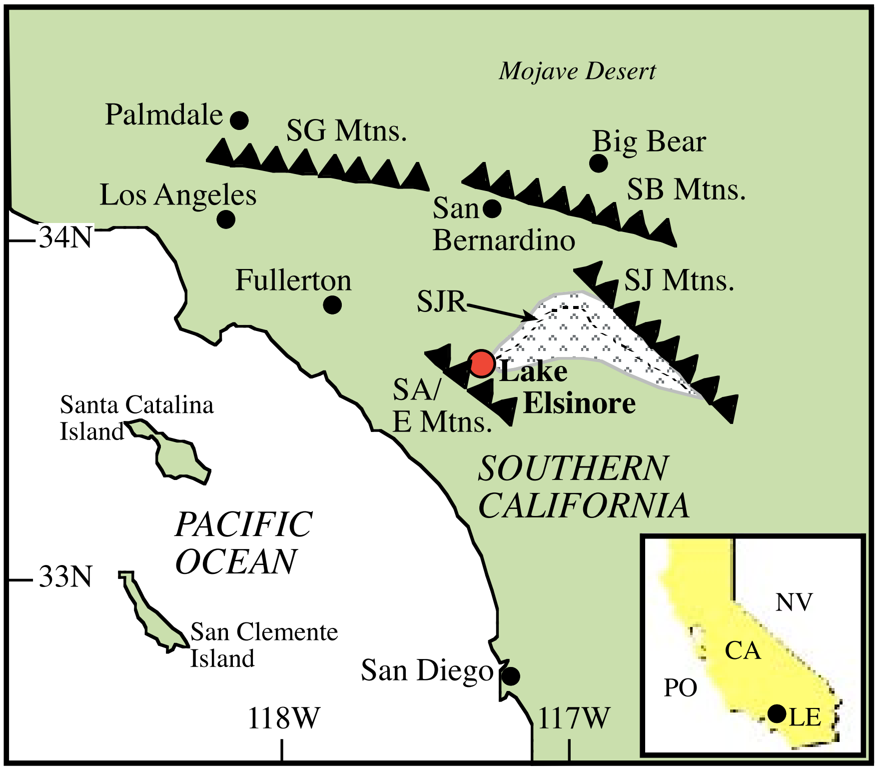



**Figure 1.** Site location map showing relevant regional information. Inset of California (CA), Nevada (NV), and the Pacific Ocean (PO) shown in lower right corner. SG = San Gabriel Mountains; SB = San Bernardino Mountains; SJ = San Jacinto Mountains; SA/E = Santa Ana/Elsinore Mountains; SJR = San Jacinto River. Area with pattern indicates the Lake Elsinore drainage basin during flow of the San Jacinto River.

organic matter, stable oxygen isotope values of lacustrine calcite ($\delta^{18}O_{(calcite)}$), organic carbon, total nitrogen, total phosphorous, inorganic phosphorous, aluminum, and iron.

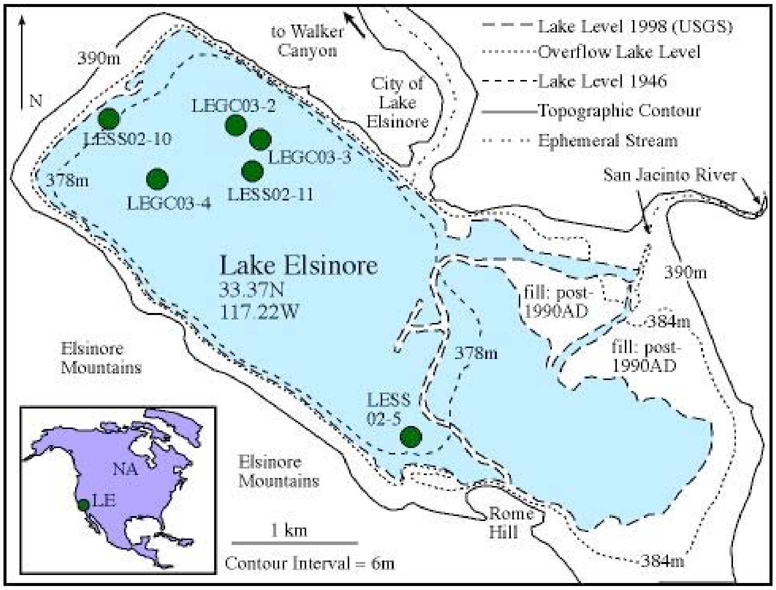



**Figure 2.** Lake Elsinore map with various relevant contours. Present day position of the lake shore is approximately 1.5 meters below the 384 m contour. Cores LEG03-2 and –3 are from the lake's deepest basin (16.5 ft. water depth when extracted). Core LEG03-4 is from the far edge of a suspected "paleo-delta" (13 ft. water depth when extracted). Depths as of November 2003. Inset at lower left of figure shows Lake Elsinore (LE) location relative to North America (NA).

## 2.0 RESEARCH JUSTIFICATION AND PURPOSE.

***The information acquired from this research will provide important insight about past lake-level/hydrologic dynamics and past versus present lake nutrient/productivity levels from which LESJWA may develop better informed policy for future lake management and sustainability.***

## 3.0 BACKGROUND.

## 3.1 Putting Lake Elsinore into a Regional Perspective.

Western North American paleoclimatological variability is most frequently characterized using either tree rings (e.g., Meko et al., 1980; Fritts, 1984; Michaelsen et al., 1987; Scuderi, 1987; Hughes and Brown, 1992; Hughes and Funkhouser, 1998; Biondi et al., 2001; D'Arrigo et al., 2001), lacustrine studies (e.g., Enzel et al., 1992; Benson et al., 1996; Li and Ku, 1997; Li et al., 2000; Benson et al., 2002, 2003), or palynology (Davis, 1992; Cole and Wahl, 2000; Mensing et al., 2004). These various studies have documented multi-decadal to centennial-scale climate variability over part of northern California and the western Great Basin (Nevada, Arizona) for most of the Holocene. But there remains a major gap in our knowledge of terrestrial Holocene climate variability for Southern California, particularly the early Holocene. Four exceptions to this gap are: 1) a Newport Bay palynological record spanning the past 7,000 years (Davis, 1992); 2) a palynological record from near San Diego spanning the past 3,800 years (Cole and Wahl, 2000); 3) Mojave region playa lake records that show wet periods at 390 $^{14}C$ years and 3,600 $^{14}C$ years BP (Enzel et al., 1992); and, 4) two low resolution, initial studies record spanning the past 3,800 and 19,250 years, respectively, from Lake Elsinore (Kirby et al., 2004, 2005). Most recently, Bird and Kirby (in review) produced a continuous, Holocene climate record from Dry Lake in the San Bernardino Mountains. This new record indicates that the early Holocene was characterized by a wetter climate than present. Bird and Kirby (in review) hypothesize that this interval of early Holocene wet climate was forced by maximum summer insolation and its affect on the strength and spatial domain of the North American Monsoon. Despite this excellent record, sedimentation rates decrease significantly in the mid-to-late Holocene precluding detailed analysis of late Holocene climate. Although these records, combined, provide important *first-order* information regarding mid-to-late Holocene terrestrial climate variability, they lack the resolution required to discern more subtle, yet important, multi-decadal-to-centennial scale climate variability and climate-related events (i.e., storms and droughts).

A current N-S transect of lake studies has been, and is being, developed for regions north of Southern California (Figure 3). The transect extends from Taylor Lake and Summer Lake in southern Oregon (Cohen et al., 2000; Negrini et al., 2000; Long and Whitlock, 2002) to Pyramid Lake in northwest Nevada (Benson et al., 2002; Mensing et al., 2004) through Walker Lake in westcentral Nevada (e.g., Bradbury et al., 1989), into Mono Lake (Newton, 1994; Li et al., 1997; Benson et al., 2003) and Owens Lake (Benson et al., 1996; Li and Ku, 1997; Li et al., 2000; Benson et al., 2002) in eastcentral California (Figure 3). The sedimentological records from these lakes are used to infer past climate variability across the western United States. The record from Pyramid Lake, for example, demonstrates that multi-decadal-length droughts have occurred throughout the last 7,600

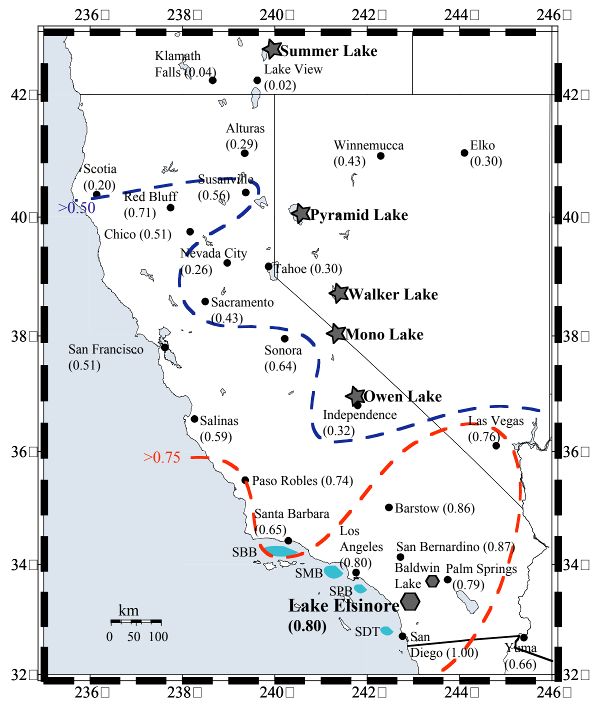



**Figure 3.** North-South Lake Study Transect illustrating the lack of lake studies in Southern California and the spatial climatological domains of western North America. Values in parentheses are R-values relative to San Diego winter ppt.; Light colored (red) dashed line is the r = 0.75 contour; dark colored (black) dashed line is the r = 0.50 contour. SBB = Santa Barbara Basin; SMB = Santa Monica Basin; SPB = San Pedro Basin; SDT = San Diego Trough.

calendar years BP, and it documents a multi-decadal periodicity in climate variability that can be traced into historic records of central California (Benson et al., 2002; Mensing et al., 2004).

Unfortunately, as shown by Figure 3, there are no lake studies from Southern California comparable to these latter studies. To illustrate the importance of developing independent paleoclimatological records from Southern California, a correlation analysis between historic winter precipitation records from 26 weather stations was produced (Figure 3). San Diego winter average precipitation is used as a center point; it strongly correlates with both Los Angeles and Lake Elsinore winter average precipitation with a Pearson's correlation coefficient of 0.80. The data analysis illustrates clearly that southwestern California lies within its own climatological spatial domain separate from that of central or northern California. In other words, the spatial patterns of winter average precipitation systematically change with increasing northerly latitudes from southwestern California. This observation is in agreement with a variety of meteorological studies that document a strong dichotomy in California climate, specifically precipitation distribution (Schonher and Nicholson, 1989; Haston and Michaelsen, 1997; Cayan et al., 1998; Dettinger et al., 1998). Consequently, to capture the full range of Holocene climate variability of western North America including its spatial and temporal phasing, ***climate proxy records from Southern California are essential***.

**3.2 Relationship Between Lake Elsinore and Climatological Variability.**

Precipitation variability in Southern California is dominated by the winter season (defined here as December-February), which accounts for >50% (up to 60%) of the annual hydrologic budget (Lynch, 1931, USGS, 1998; Redmond and Koch, 1991; Friedman et al., 1992). In Southern California, the amount of precipitation is a function of the average position of the winter season polar front as related to changes in the position of the eastern Pacific

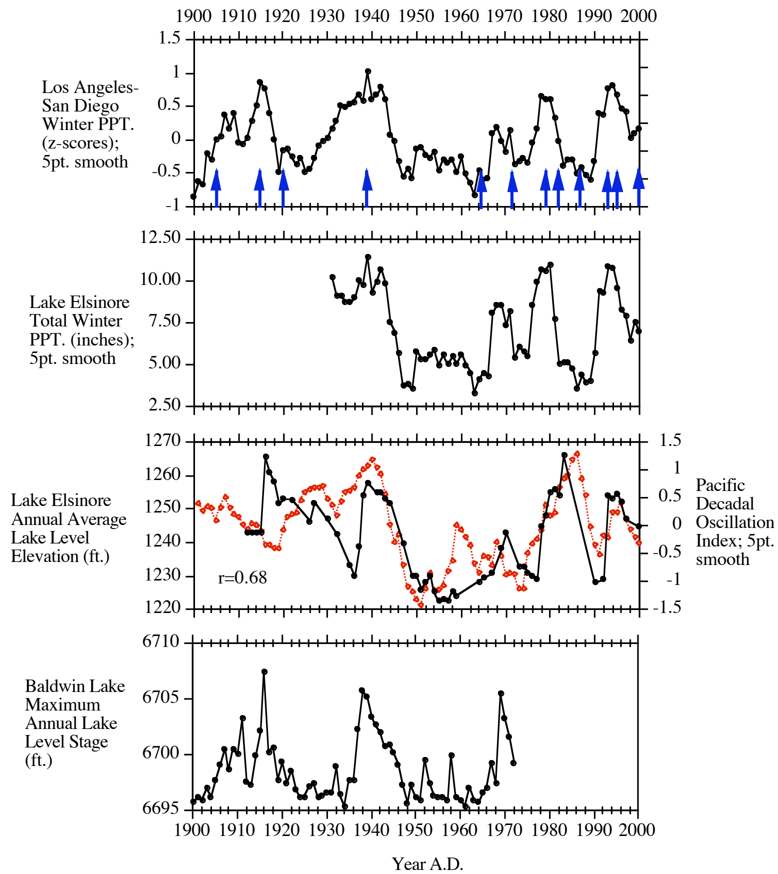



**Figure 4.** Graphs depicting winter precipitation, lake level data, strong ENSO events, and the PDO. Top = A, Bottom = D. A) Los Angeles-San Diego winter precipitation (December to February) averaged and converted to z-scores. B) Lake Elsinore total winter precipitation (December to February). Note the strong similarities between the regional precipitation data (A) and the local precipitation data (Lake Elsinore [B]). C) Lake Elsinore annual average lake level elevation (dark circles, black) versus PDO index (light diamonds, red) (Mantua and Hare, 2002). Note that several years of lake level data are missing data (e.g., 1960-63, 1984-89, etc.). D) Lake Baldwin maximum annual lake level stage. Note the strong correlation between lake level change at both lake sites and winter precipitation. Also note the strong decadal to multi-decadal relationship between Lake Elsinore lake level (an integrator of regional climate variability) and the PDO. Blue arrows in (A) highlight years of strong El Niños.

subtropical high. Historically, dry winters in Southern California are associated with a strong high-pressure ridge off the western coast of the United States, which steers storms over the northwestern United States. Wet winters are linked to a weakening of the subtropical high, causing the storm track to shift southward (Weaver, 1962; Pyke, 1972; Cayan and Roads, 1984; Lau, 1988; Schonher and Nicholson, 1989; Enzel et al., 1989, 1992; Redmond and Koch, 1991; Friedman et al., 1992 Ely, 1997). In turn, the large-scale atmospheric patterns that control the average position of the polar front are modulated by Pacific Ocean sea-surface conditions  (Namias, 1951; Weaver, 1962; Pyke, 1972; Namias and Cayan, 1981;

Douglas et al., 1982; Lau, 1988; Namias et al., 1988; Schonher and Nicholson, 1989; Latif and Barnett, 1994; Trenberth and Hurrell, 1994; Cayan et al., 1998; Dettinger et al., 1998; Biondi et al., 2001; D'Arrigo et al., 2001). There are also numerous studies that have linked interannual precipitation variability over Southern California with ENSO (El Niño = higher ppt. in southern CA and vice versa in northern CA) and inter-decadal precipitation variability to the PDO (+PDO similar to El Niño effects) (e.g., Schonher and Nicholson, 1989; Redmond and Koch, 1991; Biondi et al., 2001; Mantua and Hare, 2002) (Figure 4).

As the position of the polar front changes, the source and trajectory of storms tracking across Southern California also changes. These changes in storm tracks produce the characteristic "seasonality" of climate variability in Southern California. Kirby et al. (2004) examined the relationship between historic lake levels at Lake Elsinore and regional winter precipitation. The analysis indicates that there is a positive relationship (r=0.53) in the historic record between total winter precipitation for Los Angeles/San Diego and Lake Elsinore lake level (Figure 4). The same positive relationship is observed between total winter precipitation and lake level at Baldwin Lake, a natural lake located 70 km NE of Lake Elsinore, but at 1700 m higher elevation (Figure 1) (French and Busby, 1974). We also examined the average latitude of the winter polar vortex at the 500-hPa geopotential height field (Burnett, 1993a,b; Kalnay et al., 1996) for years of high and low lake level at Lake Elsinore since 1948 A.D. (Figure 5). Although a short data set, Figure 5 illustrates that years of high (low) lake levels are associated with an average polar vortex that is expanded (contracted) to more southern (northern) latitudes; average latitudinal difference between high and low lake level years is ~230 km (Figure 5). These results corroborate the observation that strengthening and weakening of the eastern Pacific sub-tropical high strongly modulates atmospheric circulation, storm tracks, and moisture source. Use of vortex latitude as a measure of preferential storm track migration and moisture source has been previously documented (Lawrence et al., 1982; Lawrence and White, 1991; Smith and Hollander, 1999; Kirby et al., 2001, 2002a,b). Although our lake level-vortex data represent annual-to-interannual variations, Douglas and others (1982) demonstrated that atmospheric processes on the annual-scale could be confidently extrapolated to longer time scales due to the coherency of atmospheric dynamics (i.e, the quasi-stationary planetary wave forms). Together, these results suggest that Lake Elsinore lake levels serve as a barometer of regional precipitation variability and large-scale atmospheric conditions. As a result, we assert that the <u>climatic information extracted from Lake Elsinore is transferable to the larger region of Southern California, in general</u>.

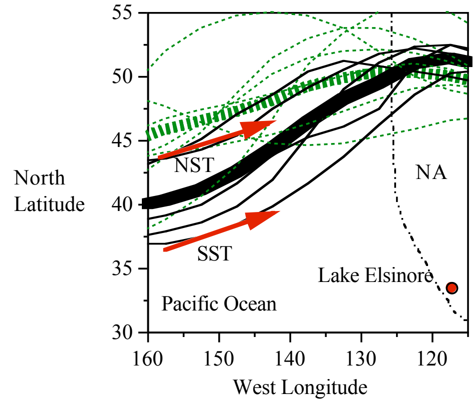



**Figure 5.** Analysis of high vs. low stand lake-levels at Lake Elsinore and associated winter vortex latitudes. Thin dark (black) lines represent high stand years; thin dashed (green) lines represent low stand years. Thick dark (black) line is average winter vortex latitude for high stand years, thick dashed (green) line is the opposite. NA = North America; NST = Northerly Storm Track; SST = Southerly Storm Track. See text for complete explanation.

Under present conditions, the impact of summer-fall precipitation on Southern California is minimal in any form (i.e., monsoonal rains, convective thunderstorms, or infrequent eastern Pacific hurricanes) (Adams and Comrie, 1997; Maloney and Hartmann, 2000). However, there is paleoclimatological evidence that the present day winter-dominated distribution of precipitation has not been constant over the Holocene (Spaulding and Graumlich, 1986; Enzel et al., 1989; Graumlich, 1993; Ely et al., 1993). In fact, there is compelling evidence that the early Holocene in Southern California was much wetter than today and characterized by a stronger monsoon and more frequent flood producing summer(?) storms (Spaulding and Graumlich, 1986; Owen et al., 2003; Kirby et al., 2005; Bird and Kirby, in review). Unfortunately, the lack of high-resolution, Holocene-length, terrestrial records from Southern California limits the breadth of this interpretation.

### 3.3 Lake Elsinore as a Study Site.

Located 120 km SE of Los Angeles, California, Lake Elsinore is the largest of only a few natural, permanent lakes in Southern California (Figures 1 and 2). Lake Elsinore is a structural depression formed within a graben along the Elsinore fault (Mann, 1956; Hull, 1990). Research on the paleoseismicity of the Elsinore fault (Vaughan et al., 1999), combined with future seismic reflection analysis of the lake sediments (with Dr. Mark Abbott), will help to constrain the possible tectonic signature in the lake sediments. Using data from Vaughan et al. (1999), it is possible to constrain major earthquake activity along the Elsinore fault over the past 4,500 calendar years BP. Geologically, Lake Elsinore is surrounded by a combination of predominantly igneous and metamorphic rocks (Engel, 1959; Hull, 1990). Lake Elsinore is constrained along its southern edge by the steep, deeply incised Elsinore Mountains that rise to more than 1000 m. The Elsinore Mountains provide a local sediment source particularly during extreme precipitation events. The San Jacinto Mountains lie 70 km to the northeast of Lake Elsinore and rise to a maximum height of 3290 m; although, the land in between the San Jacinto Mountains and Lake Elsinore is characterized by a more gentle, hilly topography. Total sediment thickness underlying Lake Elsinore is estimated to be more than 1000 m (Mann, 1956; [Anonymous] Pacific Groundwater Digest, 1979; Damiata and Lee, 1986; Hull, 1990). Two exploratory wells have been drilled at the east end of the lake to 542 m and 549 m, respectively, with sediment described as mostly fine-grained (Pacific Groundwater Digest, 1979).

Lake Elsinore has a relatively small drainage basin (<1240 km$^2$) from which the San Jacinto River flows (semi-annually) into and terminates within the lake's basin (Figure 2) (USGS, 1998). An analysis of San Jacinto River discharge near San Jacinto, CA over the interval 1920 to 2001 A.D. illustrates the river's ephemeral behavior with discharge limited to an annual average of 0.56m$^3$/sec, 70% of which occurs during the months of February, March, and April (**Figure 6**) (http://waterdata.usgs.gov; Kirby et al., 2004). The San Jacinto River originates from within the San Jacinto Mountains. These mountains achieve a maximum height of 3290 m, approximately 1000 m above the average annual snowline elevation of 2300 m in the adjacent San Bernardino Mountains (Minnich, 1986). Consequently, it is possible that low δ$^{18}$O spring run-off impacts the lake's hydrology, and thus the δ$^{18}$O$_{(calcite)}$ signal, via the San Jacinto River during above average snow accumulation winters or during long intervals of a cool, wet climate. Lake water δ$^{18}$O data, however, collected over the exceptionally wet hydrologic year of 1993 do not indicate a significant "alpine" affect (William and Rodoni, 1997).

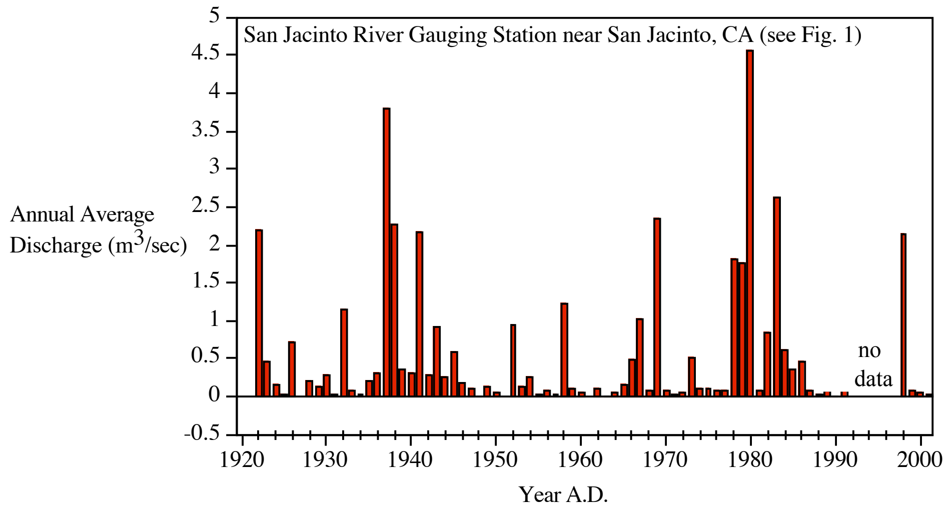



**Figure 6.** San Jacinto River gauging station near San Jacinto, CA (http://waterdata.usgs.gov). Note the large range of flow variability. Y-axis extends to –0.5 to show better the years without data (e.g., 1992-1997).

Lake Elsinore has overflowed to the northwest through Walker Canyon very rarely, only 3 times in the twentieth century and 20 times since 1769 A.D. based on Mission Diaries (Figure 2) (Lynch, 1931; USGS Lake level Data, 2002). Each overflow event was very short-lived (<several weeks) demonstrating that Lake Elsinore is essentially a closed-basin lake system (Lynch, 1931; USGS Lake level Data, 2002). Conversely, Lake Elsinore has dried completely on only 4 occasions since 1769 A.D. (Lynch, 1931, USGS Lake level Data, 2002). During periods of lake low stands, the lake is described by locals as "nothing more than a marshy patch of tules" (perennial grasses) (Mann, 1947). Interestingly, our initial sedimentological data from cores extracted from the deepest part of the profundal zone show no obvious evidence for sediment hiatuses during the documented twentieth century low stands (Kirby et al., 2004). It is likely that the proliferation of grasses during an interval of lake desiccation prevents the removal of significant sediment quantities via eolian processes. Sedimentologically, lake desiccation events may be characterized by periods of slow or no deposition, but not sediment removal; this is important to the preservation of continuous Holocene sediment record. Our multi-proxy methodology will help to identify lake desiccation intervals using both sedimentological and chemical analyses.

Limnologically, Lake Elsinore is a shallow, polymictic lake (13 m maximum depth based on historic records) (Anderson, 2001). A recent study by Anderson (2001) indicates that the hypolimnion is subject to short-lived periods of anoxia (i.e., days to weeks); although, the frequent mixing of oxygen rich epilimnion waters into the hypolimnion precludes permanent, sustained anoxia, at least during the period of observation. Annual water loss to evaporation from the lake's surface is >1.4 m; consequently, water residence time in Lake Elsinore is projected to be very short (< 5 years?), and likely much shorter during drought periods (<1 year) (Mann, 1947; USGS, 1998; Anderson, 2001). A strong grain size gradient exists from the littoral zone (i.e., coarse grained) to the profundal zone (i.e., fine grained). Mann (1947) attributes the grain size gradient to wave action winnowing and re-suspension of the finer-grained component of the littoral sediments into the profundal environment. This process of wave action winnowing and sediment re-suspension is a common and well-documented occurrence in most lake settings (Lehman, 1975; Davis and Ford, 1982; Downing and Rath, 1988, Benson et al., 2002; Gilbert, 2003; Smoot, 2003). Grain size distribution is also influenced by run-off processes, which are linked to precipitation events, specifically extreme “flood-producing” events. In addition to the clastic component, sediment trap studies also indicate that $CaCO_3$ is produced within the water column, likely linked to photosynthetic uptake of $CO_2$ by phytoplankton (Anderson, 2001). SEM analyses of lake sediment show distinct micron size $CaCO_3$ grains dispersed throughout the sediment (Anderson, 2001). Consequently, analysis of $\delta^{18}O_{(calcite)}$ should be a reliable indicator of lake water dynamics (i.e., hydrologic variability).

# 4.0 METHODS.

## 4.1 Core Collection.

Three sediment cores (LEGC03-2 [949 cm], LEGC03-3 [1074 cm], and LEGC03-4 [994 cm]) were extracted using a hollow-stemmed auger drill core aboard a floating drilling platform (Figure 2 and 7; Table 1). Cores LEGC03-2 and LEGC03-3 were taken from within 200 meters

**Table 1. Core Information.**

| Core I.D. | Water Depth (cm) | Latitude | Longitude | Core Length |
|---|---|---|---|---|
| LEGC03-2 | 16’6” (5.0 m) | N33°40.330 | W117°21.186 | 949 cm |
| LEGC03-3 | 16’ (4.9 m) | N33°40.395 | W117°21.250 | 1074 cm |
| LEGC03-4 | 13’ ( 4.0 m) | N33°40.044 | W117°21.848 | 994 cm |

horizontal distance from one another in the lake’s present day deepest basin (Figure 2). Our assumption regarding sediment gaps is that all core drives using the hollow-stemmed auger drill core were to the measured depth. Any “missing” core sections were subtracted from the top of core’s individual drive and assumed a product of over-auguring between drives. Similarly, any “re-worked” sediment at the core top was assumed a product of drilling and was not used for sediment analysis. Core LEGC03-2 is missing approximately 19%; core LEGC03-3 is missing approximately 15%; and, core LEGC03-4 is missing approximately 14%. We present the core data as a series of individual drives per core site. Lastly, all cores were split, described, and

**Figure 7.** Drilling platform with drillers from Gregg Drilling.

archived in cold storage at Cal-State Fullerton. For this contract report's discussion section, **we focus on core LEGC03-3 from which the most complete late-Holocene record and analyses are derived**. We will, however, show data for all three cores in the results section.

### 4.2 Age Control.

In the absence of salvageable macro- or micro-organic matter, bulk organic matter was used for age control. Eight dates were measured on core LEGC03-2; eighteen dates were measured on core LEGC03-3; and, four dates were measured on core LEGC03-4. All dates were measured at the University of California, Irvine Keck AMS Facility pre-treated with an acid wash to remove carbonate.

The age model for the past 200 years used in the historic interval calibration (see Discussion) is from Kirby et al. (2004).

### 4.3 Magnetic Susceptibility.

Samples were extracted from all three drill cores at 1.0 cm intervals (n = 2563). The samples were placed in pre-weighed 10 $cm^3$ plastic cubes. Mass magnetic susceptibility was measured twice on each sample with the y-axis rotated 180° once per analysis. All samples were analyzed using a Bartington MS2 Magnetic Susceptibility instrument at 0.465 kHz. All magnetic susceptibility measurements were determined on same day as cores were split and described to minimize possible magnetic mineral diagenesis with exposure to air. Following measurement of magnetic susceptibility, samples were re-weighed to obtain total sediment wet weight. The average magnetic susceptibility value for each sample was then divided by the sample weight to account for mass differences. Measurements were made to the 0.1 decimal place and reported as mass magnetic susceptibility (CHI = $\chi$) in SI units ($x10^{-7}$ $m^3kg^{-1}$).

### 4.4 LOI 550°C (Percent Total Organic Matter).

Total organic matter was determined using the loss on ignition method (Dean, 1974; Heiri et al., 2001). Samples were extracted from cores LEGC03-2 and LEGC03-3 at 1.0 cm intervals (n = 1693). Core LEGC03-4 is still being analyzed for LOI data. All samples were dried at room temperature prior to grinding with a mortar and pestle. Ground samples were placed in a drying oven at 105°C for 24 hours to remove excess moisture. Dried samples were transferred to pre-weighed crucibles, weighed to obtain dry sediment weight, and heated to 550°C in an Isotemp muffle oven for two hours. After two hours the samples were re-weighed to obtain the percentage total organic matter from total weight loss.

**4.5 LOI 950°C (Percent Total Carbonate).**

Total carbonate was determined also using the loss on ignition method (Dean, 1974; Heiri et al., 2001). Samples were extracted from cores LEGC03-2 and LEGC03-3 at 1.0 cm intervals. Following the 550°C analysis and weighing, crucibles were re-heated to 950°C for two hours in an Isotemp muffle oven. After two hours the samples were re-weighed and percentage total carbonate was calculated. As shown by Dean (1974), three to four percent total weight loss after 950°C may be a function of clay de-watering. Consequently, we interpret values less than three to four percent as essentially zero percent total carbonate.

**4.6 Microfossil Counts.**

Microfossil counts were not measured on any of the three cores due to the lack of salvageable macro-organic matter (e.g., gastropods, bivalves, oogonia). Dr. Kirby's Paleoclimate Laboratory is not equipped to analyze micro-organic matter such as diatoms, pollen, ostracods, charcoal, or other similarly small and delicate microfossils. Several samples were sent to other labs for descriptive analysis, which indicated the presence of diatoms, charcoal, pollen, and ostracods. Future work will include a complete high-resolution sampling and analysis of pollen, ostracods, charcoal, and diatoms as a collaborative project involving Dr. Kirby and several Universities.

**4.7 Stable Oxygen and Carbon Isotopes ($\delta^{18}O_{(calcite)}$).**

Samples were extracted from LEGC03-3 for $\delta^{18}O_{(calcite)}$ and $\delta^{13}C_{(calcite)}$ at 3.0 cm intervals between 0 cm and 487 cm (n = 146). Bulk sediment samples were dried at room temperature and gently ground into a powder. Bulk sediment samples were roasted *in vacuo* at 200°C to remove water and volatile organic contaminants that may confound stable isotope values of carbonate. Stable isotope values were obtained using a Finnigan Kiel-III carbonate preparation device directly coupled to the inlet of a Finnigan MAT 252 ratio mass spectrometer in the stable isotope laboratories at the University of Saskatchewan. Twenty to forty micrograms of carbonate was reacted at 70°C with 3 drops of anhydrous phosphoric acid for 90 seconds. Isotope ratios were corrected for acid fractionation and $^{17}O$ contribution and reported in per mil notation relative to the VPDB standard. Precision and calibration of data were monitored through daily analysis of NBS-18 and NBS-19 carbonate standards. $\delta^{18}O$ values of the samples are bracketed by those of the standards. Precision is better than ± 0.1‰ for both carbon and oxygen isotope values.

**4.8 Carbon, Nitrogen. Phosphorous and Other Elements.**

Sediment cores collected from Lake Elsinore by Dr. Matt Kirby at CSU-Fullerton were subsampled into Whirlpak bags to yield approximately 10-20 g wet weight, and returned to UCR for analysis. Sediment core LESS02-11 was subsampled at 3 cm intervals, while a longer 10-m core (LEGC03-3) was sampled at 10 cm intervals, except for depths of 0.7-1.4 m, where sediment was collected at 3 cm intervals. This was done to allow a 20-cm section of the LESS02-11 core that was not recovered in the original sampling (Kirby et al., 2004) to be substituted into that core. The core samples were homogenized and then subsampled into pre-weighed beakers for dry-weight determination by heating overnight at 110C. Known mass of oven-dried sediment samples (~ 1 g) were then placed in a muffle furnace and ashed at 550C, followed by quantitative transfer of the ashed material to 40 mL Oak Ridge tubes. Twenty-five mL of 1 M HCl was then added to each of tube, placed on an Eberbach shaker and reacted for 24 h for total P (TP) extraction (Aspila et al., 1976). Inorganic P (IP) was extracted from separate (unashed) samples of known weight with 1 M HCl for 24 h (Aspila et al., 1976). Dissolved P in the extracts was quantified on an Alpkem autoanalyzer.  Total C and total N was measured on dried ground samples using a Thermo Electron Corp. FlashEA 1112 NC Soil Analyzer. Calcium carbonate ($CaCO_3$) in the sediment was estimated from $Ca^{2+}$ measured on the IP extracts using a Perkin-Elmer ICP-OES; $CaCO_3$ calculated this way was in reasonable agreement with manometric measurements (Anderson, 2001). 1 M HCl-extractable Al, Fe, Mg and Mn were also measured on the IP extracts using a Perkin-Elmer Optima 3000 DV ICP-OES.

## 5.0 RESULTS.

### 5.1 Core Descriptions.

In the absence of quantitative grain size analysis, sediment descriptions are limited to subjective sand, silt, and clay classifications only (Figures 8-10). Future studies will include a full suite of grain size analyses. Color changes and other notable materials are also shown (e.g., distinctive lithologic components, etc). Core descriptions also show the depth of dating analyses (Figure 8-10).

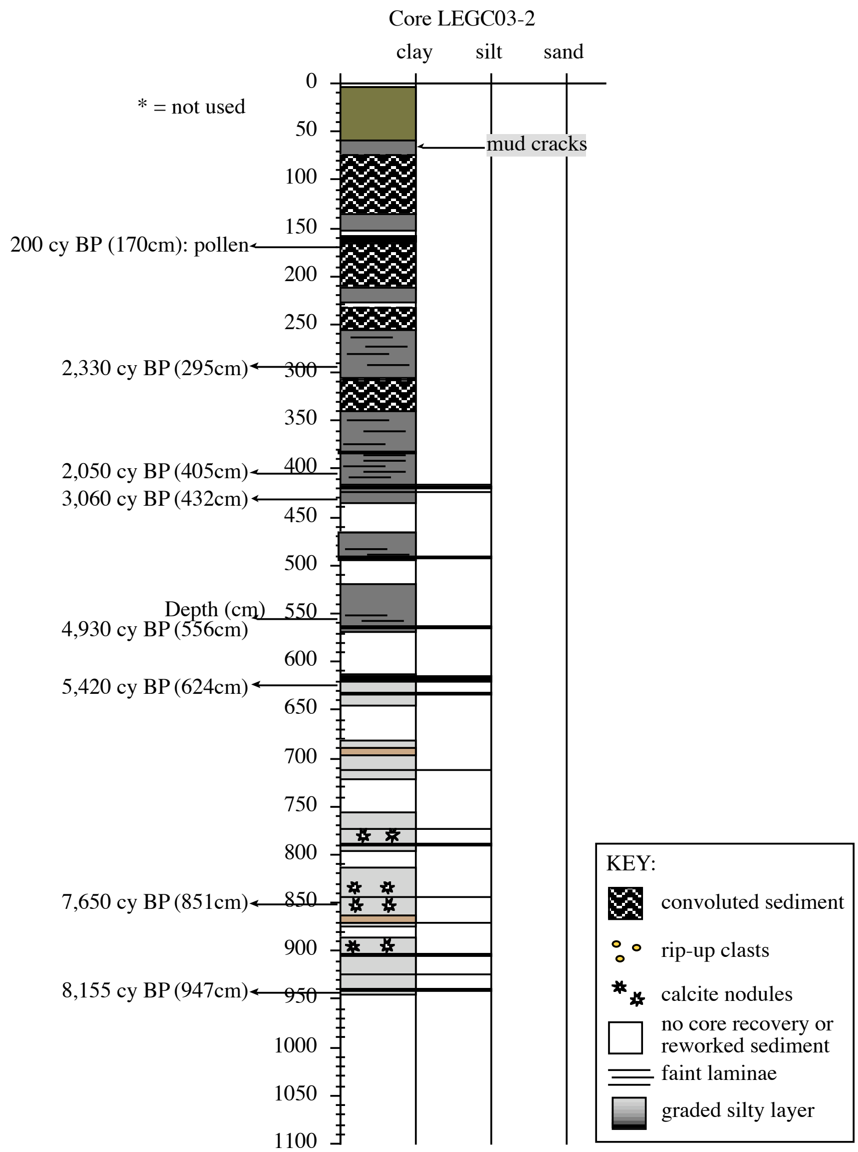



**Figure 8.** Core LEGC03-2 sediment description with AMS $^{14}C$ dates (converted to calendar years BP).

### 5.2 Age Control.

A total of 21 AMS $^{14}C$ dates were used in calculating an age model for core LEGC03-03 (Figure 11). Four dates were discarded based on their position relative to a known pollen age, correlated from core LESS02-11 (see Kirby et al., 2004), and/or their low $\delta^{13}C_{(organic}$

matter) values, which suggested a re-worked origin. Dates not used in the calculation of the age model are shown on figure 8 and 9. As shown by Kirby et al. (2004) surface sediments from the lake's deepest basin provide a modern date; as a result, we do not consider our bulk sediment organic carbon dates to be affected significantly by old carbon. Precaution was taken not to select sediment for dating from intervals interpreted as low stands to avoid obtaining false ages via reworked older carbon (Kirby et al., 2004; Smoot and Benson, 2004). Dates were cross-correlated from core LEGC03-2 to core LEGC03-3 using a combination of magnetic susceptibility, % total organic matter, and % total

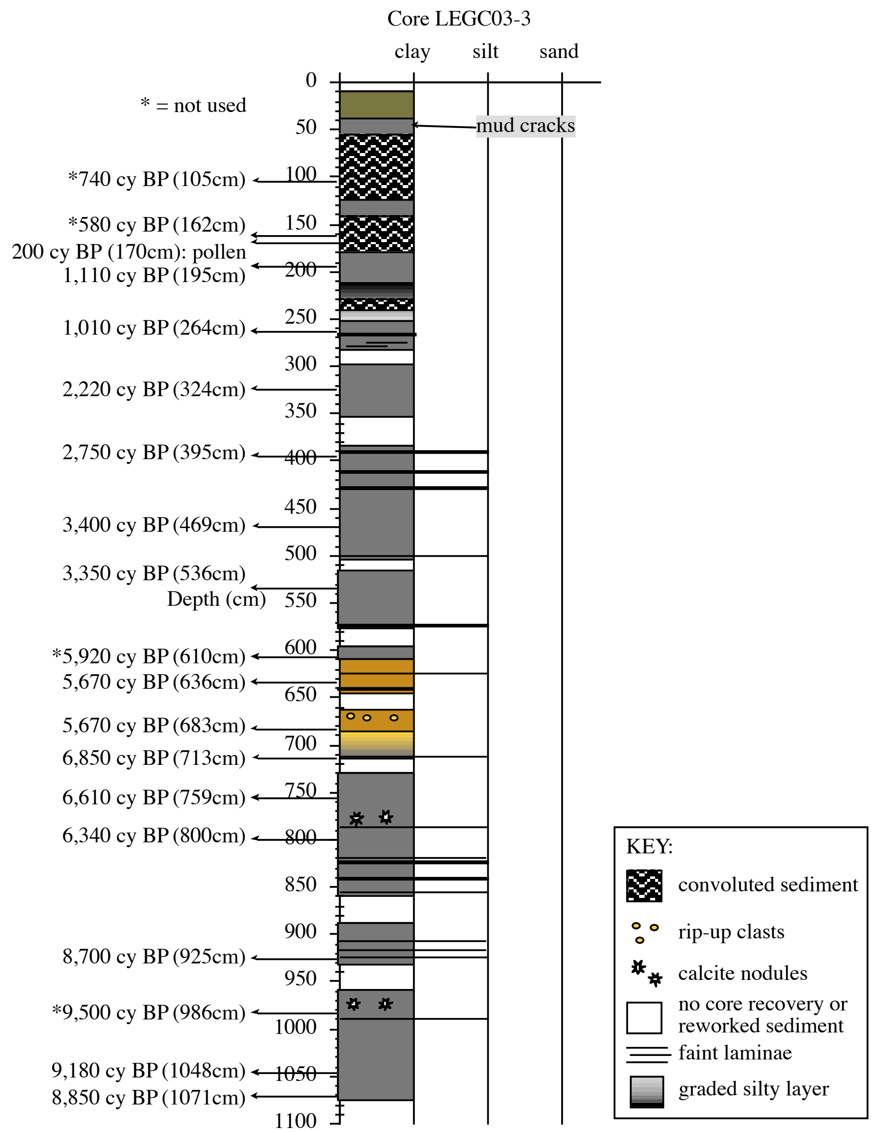



**Figure 9.** Core LEGC03-3 sediment description with AMS $^{14}C$ dates (converted to cy BP).

carbonate.

Correlation between these two cores shows remarkable coherency at the centimeter scale, In fact, over 9.5 m of similar core depth between cores LEGC03-2 (9.5 m) and LEGC03-3 (10.7 m), we determined 150 tie points, or approximately one tie point per 6 cm (Figure 12). All 30 AMS $^{14}C$ dates for all three sediment cores are shown on Table 2. One date from core LEGC03-3 was removed from consideration because of its unusually low $^{13}C$ value, which suggests contamination during processing (Table 2).

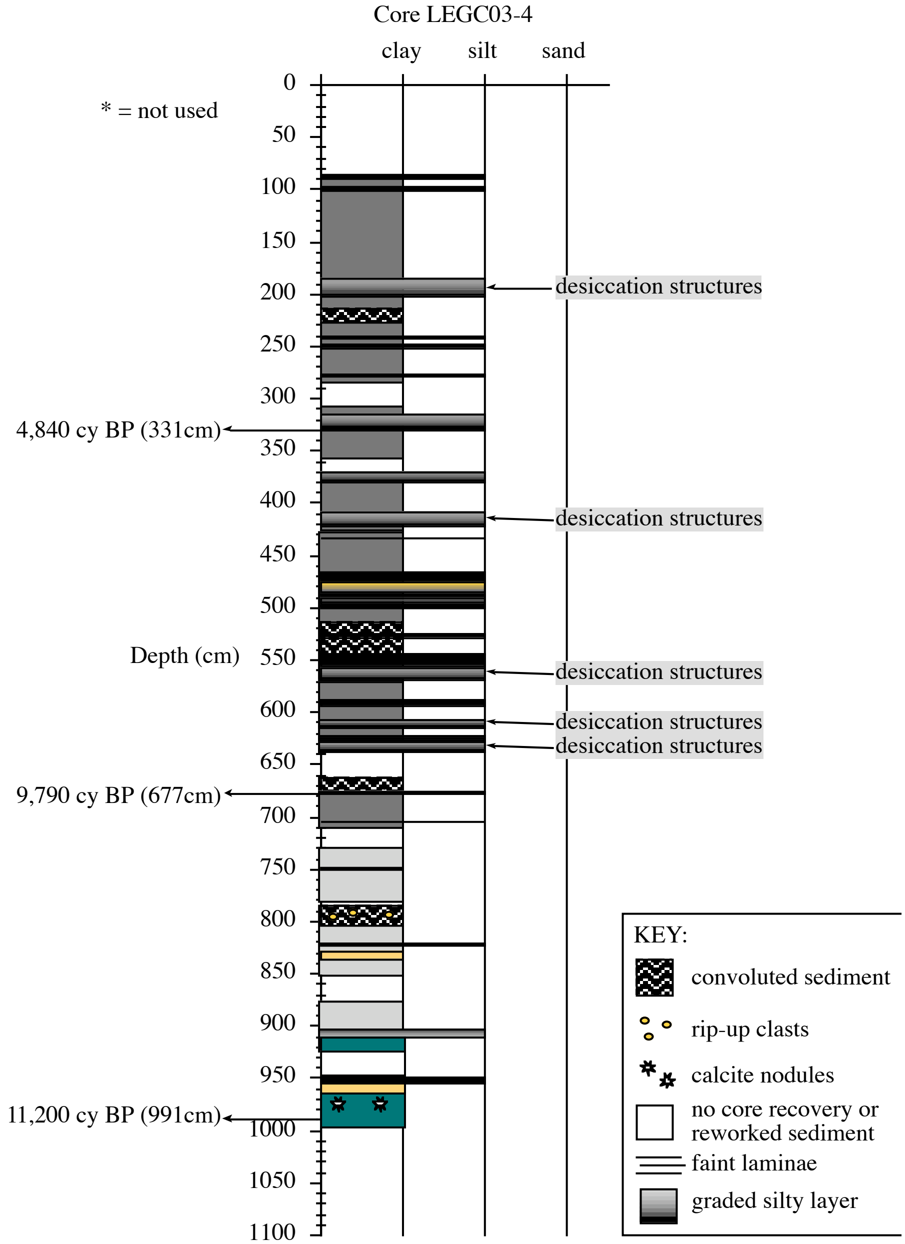



**Figure 10.** Core LEGC03-4 sediment description with AMS $^{14}C$ dates (con. to cy BP).

The purpose of an age model is to assign an absolute date to each depth of analysis. In turn, the data are compared to age directly. For this research we chose to use a single "best-fit" line to create an age model. The breadth of scatter (Figure 11) is large enough to preclude a more precise point-by-point linear fit. The best fit line for our age model is a 2nd order polynomial (r=0.98). A pollen age cross-correlated from LESS02-11 (see Kirby et al., 2004) provides the upper boundary to our age model at 200±20 cy BP. The best fit line over-estimated the pollen age. To accommodate this over-estimation, 114±10 years, depending on the sampling interval, were removed from each date in the age model. Furthermore, we recognize the temporal limitations of our age model due to the scatter of the ages and possible occurrence of sediment hiatuses or slow deposition during low lake level stands. As a result, we feel that our proxy data using this age model are, at best, resolved at multi-decadal-to-centennial scales. The centimeter scale cross-correlation (see Figure 12), however, indicates that the sediments truly record high-resolution event stratigraphy. This

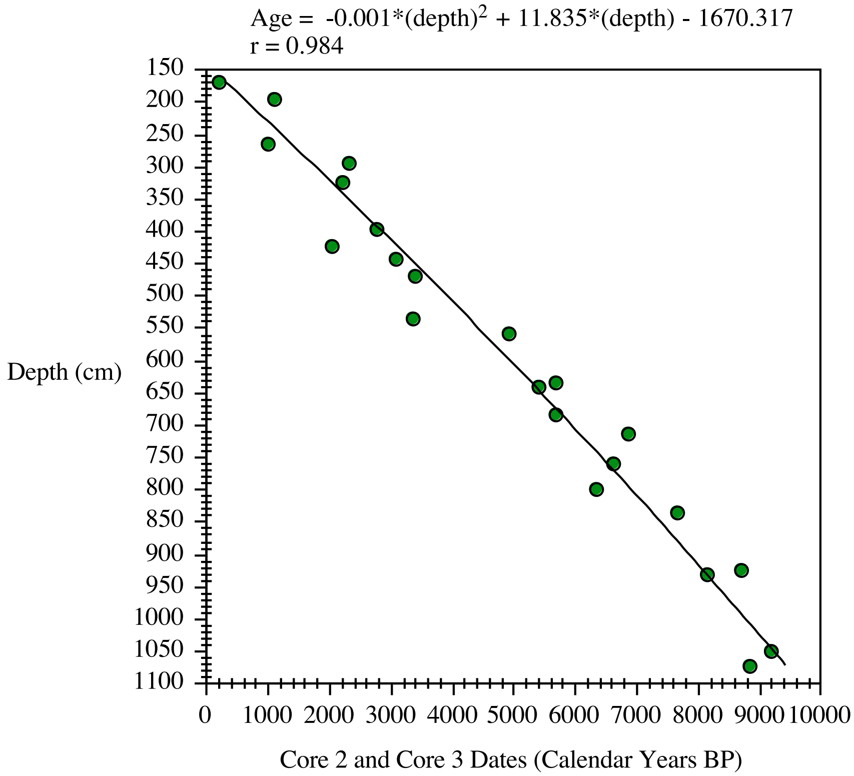



**Figure 11.** Age model plot for core LEGC03-3 using dates from both core LEGC03-3 and LEGC03-2 (see figure 12 for cross-correlation).

centimeter-scale coherency provides confidence in our interpretation of the fine-scale event stratigraphy when transferred to the age model. Lastly, as shown in the Discussion section, an independent assessment of our age model using an age model and its data from Pyramid Lake (>900km north of Lake Elsinore) shows remarkable similarities between the age model-event stratigraphies – again providing strong evidence that our age model is robust.

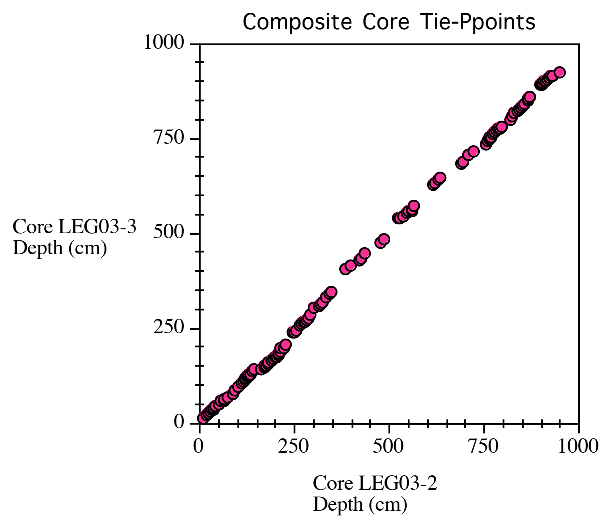



**Figure 12.** Core correlation tie-points between cores LEGC03-2 and LEGC03-3 using magnetic susceptibility, total organic matter, and total carbonate.

**<u>5.3 Magnetic Suceptibility.</u>**

**NOTE: Figures of raw data versus depth are shown for all three cores. However, only core LEGC03-3 data are shown and described in detail with the age model.**

Raw mass magnetic susceptibility values for cores LEGC03-2, -3, and –4 are shown by figures 13-15. Cores LEGC03-2 and LEGC03-3 show very similar first-order decreasing trends from the core bottom to the core top (Figures 13 and 14). Both cores 2 and 3 show occasional spikes in CHI, many of which are associated with silt-rich layers or distinct sedimentologic features (Figures 8 and 9). Core LEGC03-4 is characterized by higher average values than either cores 2 or 3 (Figure 15). Core 4 contains three sections based on its mass magnetic susceptibility values: 1) 1000-680 cm characterized by high CHI values and low amplitude variability; 2) 680-310 cm characterized by high CHI values and large amplitude variability; and, 3) 285-70 cm characterized by low, uniform CHI values (Figure 15). Similar to cores 2 and 3, the occasional spikes in CHI in core 4 are generally associated with either silt-rich layers or distinct sedimentologic features (Figure 10). Unlike cores 2 and 3, however, the CHI spikes in core 4 are

**Table 2: Radiocarbon Analyses.**

| Number | Sample ID | Depth (cm) | UCIAMS ID | d$^{13}$C (‰) | AGE (BP) | ± | Calendar Years BP | 2-Sigma Range |
|---|---|---|---|---|---|---|---|---|
| 1 | LEG03-2 | 298-299 | 8260 | -17.8 | 2,290 | 20 | 2,330 | 2,307-2,348 |
| 2 | LEG03-2 | 405-406 | 6832 | -21.0 | 2,075 | 25 | 2,060 | 1,987-2,123 |
| 3 | LEG03-2 | 405-406 | 6695 | -14.2 | 2,060 | 35 | 2,030 | 1,932-2,122 |
| 4 | LEG03-2 | 432-433 | 8261 | -16.2 | 2,915 | 25 | 3,020 | 2,957-3,081 |
| 5 | LEG03-2 | 556-557 | 8262 | -15.2 | 4,385 | 30 | 4,930 | 4,864-4,996 |
| 6 | LEG03-2 | 624-625 | 6833 | -15.8 | 4,605 | 25 | 5,420 | 5,396-5,449 |
| 7 | LEG03-2 | 850-851 | 6834 | -14.4 | 6,825 | 30 | 7,650 | 7,606-7,697 |
| 8 | LEG03-2 | 947-948 | 6835 | -17.7 | 7,350 | 30 | 8,160 | 8,106-8,196 |
| 9 | LEG03-3 | 105-106 | 8263 | -20.7 | 860 | 25 | 740 | 694-794 |
| 10 | LEG03-3 | 162-163 | 8264 | -20.4 | 650 | 20 | 580 | 559-602 |
| 11 | LEG03-3 | 195-196 | 8265 | -17.9 | 1,180 | 20 | 1,110 | 1,055-1,171 |
| 12 | LEG03-3 | 264-265 | 8266 | -17.5 | 1,115 | 25 | 1,010 | 962-1,062 |
| 13 | LEG03-3 | 324-325 | 8267 | -18.4 | 2,270 | 30 | 2,220 | 2,179-2,265 |
| 14 | LEG03-3 | 395-396 | 8268 | -20.3 | 2,610 | 20 | 2,750 | 2,734-2,774 |
| 15 | LEG03-3 | 469-470 | 8270 | -17.6 | 3,160 | 25 | 3,400 | 3,341-3,453 |
| 16 | LEG03-3 | 536-537 | 8271 | -19.2 | 3,125 | 20 | 3,350 | 3,321-3,385 |
| 17 | LEG03-3 | 610-611 | 8272 | -16.1 | 5,160 | 30 | 5,920 | 5,888-5,950 |
| 18 | LEG03-3 | 635-636 | 8274 | -18.4 | 4,955 | 30 | 5,670 | 5,609-5,735 |
| 19 | LEG03-3 | 683-684 | 8275 | -18.1 | 4,945 | 30 | 5,670 | 5,606-5,728 |
| 20 | LEG03-3 | 713-714 | 8277 | -17.6 | 6,025 | 35 | 6,850 | 6,745-6,949 |
| 21 | LEG03-3 | 759-760 | 8278 | -17.3 | 5,820 | 30 | 6,610 | 6,532-6,679 |
| 22 | LEG03-3 | 800-801 | 8279 | -18.1 | 5,540 | 40 | 6,340 | 6,279-6,407 |
| 23 | LEG03-3 | 924-925 | 8280 | -19.4 | 7,910 | 50 | 8,700 | 8,595-8,813 |
| 24 | LEG03-3 | 986-987 | 8283 | -14.9 | 8,465 | 40 | 9,500 | 9,464-9,532 |
| 25 | LEG03-3 | 1048-1049 | 8284 | -17.0 | 8,225 | 40 | 9,180 | 9,057-9,301 |
| 26 | LEG03-3 | 1071-1072 | 8286 | -18.0 | 7,965 | 40 | 8,850 | 8,695-8,999 |
| 27 | LEG03-4 | 330-332 | 6696 | -3.2 | 3,690 | 100 | contaminated | contaminated |
| 28 | LEG03-4 | 330-332 | 6836 | -18.0 | 4,245 | 25 | 4,840 | 4,813-4,858 |
| 29 | LEG03-4 | 677-678 | 6838 | -16.2 | 8,765 | 35 | 9,790 | 9,655-9,914 |
| 30 | LEG03-4 | 991-992 | 6829 | -17.0 | 9,790 | 35 | 11,200 | 11,168-11,229 |

often several centimeters to greater than 10 cm thick. We also note that there is a strong, positive logarithmic relationship between CHI and %TOM [r = 0.76; n = 911] (Figure 16).

Compared to the age model, the CHI data from core LEGC03-3 show a long-term decrease from 9,800 cy BP to the present. The highest values occur between 9,000 and 7,600 cy BP (Figure 17). Over the entire length of the record, there are 9 distinct spikes in CHI (Figure 17; Table 3). Five of these spikes occur between 7,600 and 8,900 cy BP; the other four cluster between 5,200 and 6,500 cy BP. Notably, the broadest CHI spike is centered on 8,280 cy BP, similar in time to the largest CHI spike from Dry Lake in the San Bernardino Mountains (Bird and Kirby, in review).

**5.4 LOI 550°C (Total Organic Matter).**

Total organic matter is shown for cores LEGC03-2 and LEGC03-3 by figures 13 and 14. Both cores show similar weak, first-order increasing trends from the core bottom to the core top. In addition to this first-order trend, there is also an abrupt step-function increase in the average %TOM values at 400 cm and 350 cm in cores LEGC03-2 and LEGC03-3, respectively. This abrupt increase in %TOM is also characterized by an increase in the amplitude of variability.

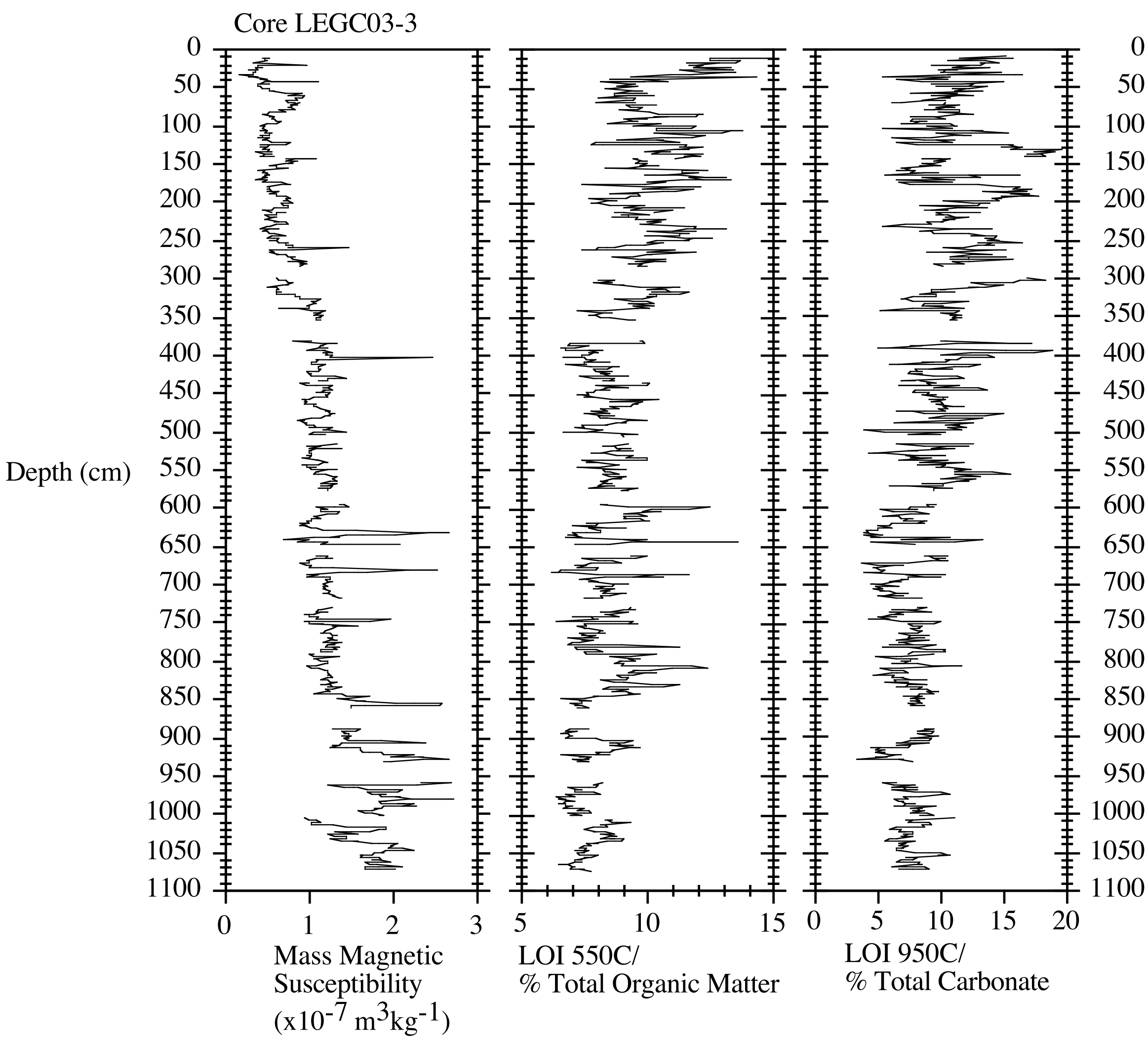



**Figure 14.** Core LEGC03-3 mass magnetic susceptibility, percent total organic matter (LOI 550°C), and percent total carbonate (LOI 950°C) data. Gaps where data are missing represent either intervals without core recovery or reworked sediment.

Core LEGC 03-3 also shows evidence for a step-function increase in %TOM at 850 cm. This change is not seen in core LEGC03-2 due to its shorter total length.

The total organic matter plotted with the age model indicate slight increasing trend from 9,800 cy BP to the present (Figure 17). Two intervals of low, small amplitude variability occur between 9, 800 and 7,600 cy BP and between 4,600 and 2,600 cy BP. The intervals between

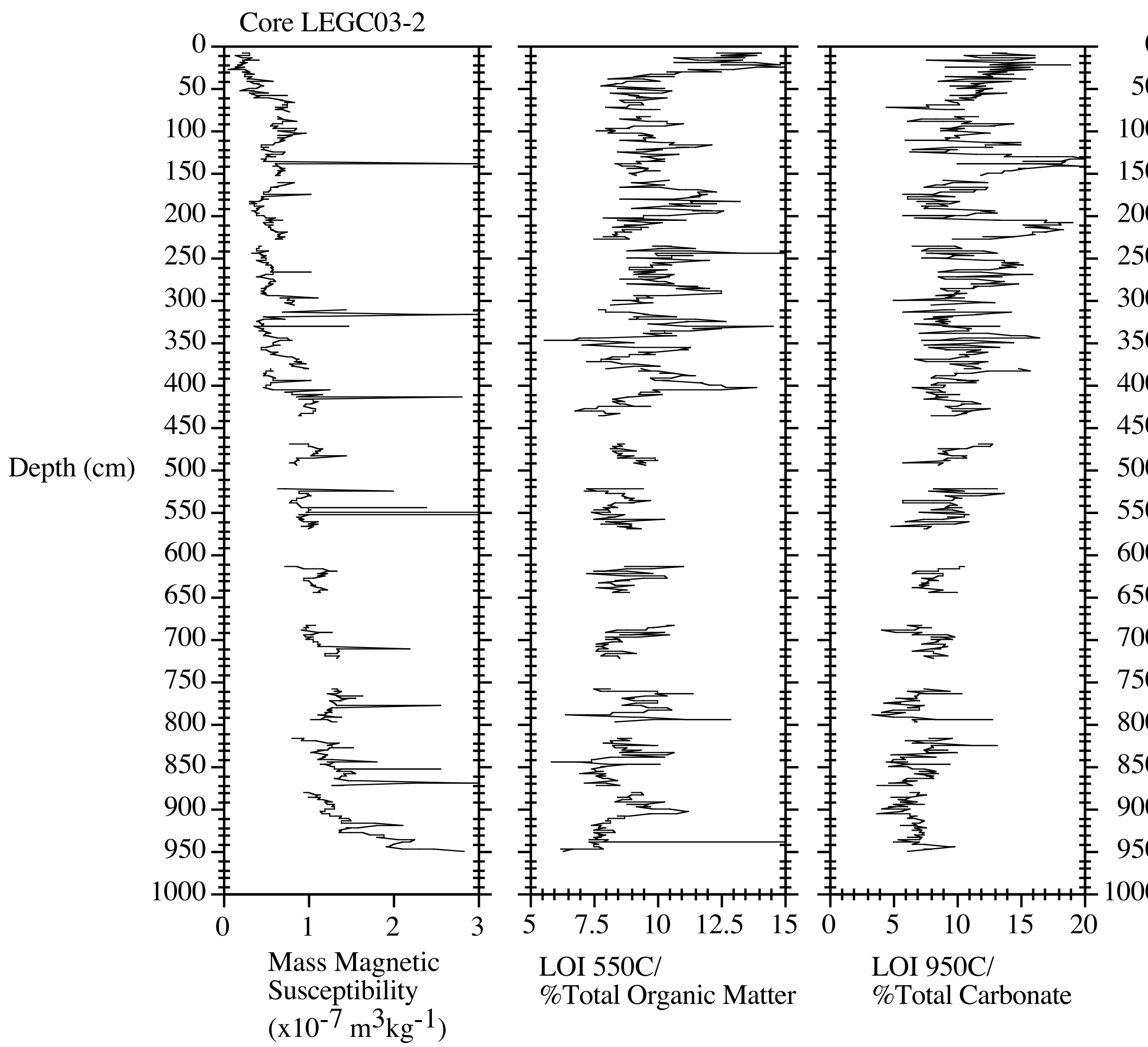



**Figure 13.** Core LEGC03-2 mass magnetic susceptibility, percent total organic matter (LOI 550°C), and percent total carbonate (LOI 950°C) data. Gaps where data are missing represent either intervals without core recovery or reworked sediment.

7,600 and 4,600 cy BP and between 2,600 cy BP and the present are characterized by high, large amplitude variability. The highest values over the past 9,800 cy BP occur over the past 200 years.

## 5.5 LOI 950°C (Total Carbonate).

Total carbonate is shown for cores LEGC03-2 and LEGC03-3 by figures 13 and 14. Both cores show similar first-order increasing trends from the core bottom to the core top. In addition to this first-order trend, there is also an abrupt step-function increased in the average values and the amplitude of variability at 530 and 570 cm in cores LEGC03-2 and LEGC03-3, respectively. We note, however, that the thick sections of missing data in core LEGC03-2 preclude the absolute depth identification of this step-function increase. There is a moderately strong, positive logarithmic relationship between CHI and %TC (r = 0.53; n = 911; figure not shown). Lastly, there is a weak, positive linear relationship between %TOM and %TC (r = 0.41; n = 911; not shown).

Total carbonate values plotted with

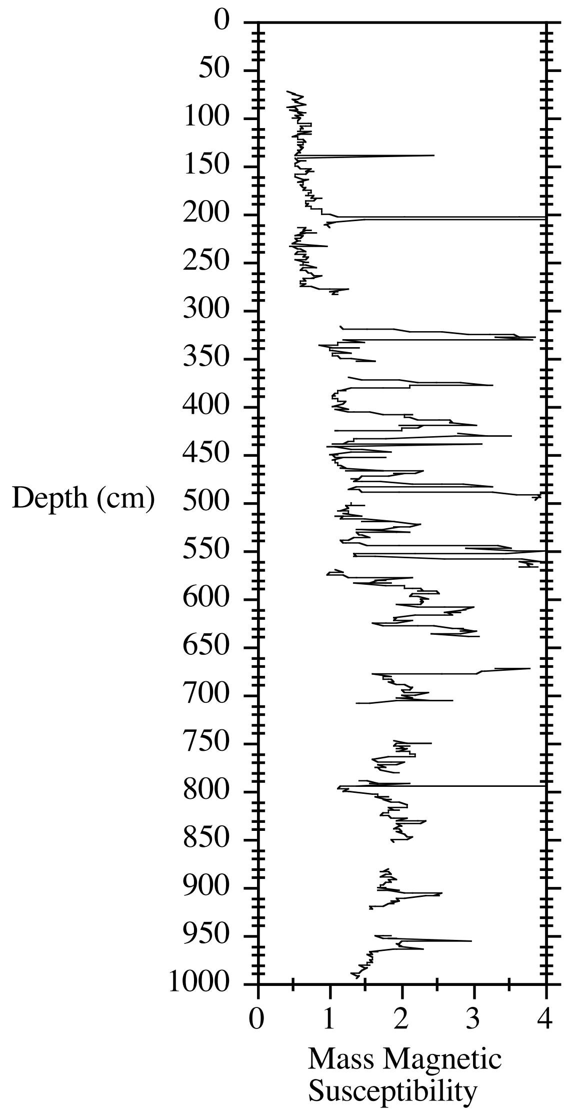



**Figure 15.** Core LEGC03-4 mass magnetic susceptibility, percent total organic matter (LOI 550°C), and percent total carbonate (LOI 950°C) data. Gaps where data are missing represent either intervals without core recovery or reworked sediment.

the age model are characterized by a long-term increasing trend from 9,800 cy BP to the present (Figure 17). There is a noticeable change from low, small amplitude variability from 9,800 to 4,500 cy BP to high, large amplitude variability from 4,500 cy BP to the present. The highest total carbonate values occur between 1,750 cy BP and the present.

**5.6 Stable Oxygen Isotopes ($\delta^{18}O_{(calcite)}$).**

$\delta^{18}O_{(calcite)}$ data are plotted with the age model for the past 4,000 cy BP only (Figure 18). Overall, the data show a range of values from less than –2‰ to greater than 3‰. Specifically, the $\delta^{18}O_{(calcite)}$ are variable from 3,800 to 3,200 cy BP. The data are generally higher than 0‰ from 3,200 to 1,000 cy BP. From 1,000 to 600 cy BP, the $\delta^{18}O_{(calcite)}$ data are very low (< -1‰). From 600 to 300 cy BP, the data are relatively high (>1‰). A general decreasing trend characterizes the interval from 300 through to the present.

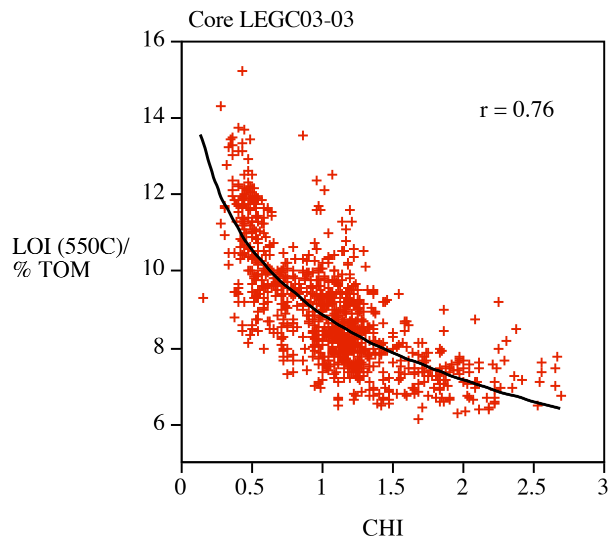



**Figure 16.** Correlation between CHI and percent total organic matter (LOI 550°C) for core LEGC03-3.

**5.7 Carbon, Nitrogen, Phosphorous, and Other Elements.**

***5.7.1 LESS02-11 (1.7 m core).***

Total and inorganic P contents of the sediments varied with depth, with TP levels ranging from 887 – 1397 mg/kg (Fig. 19a). The dating results from Kirby et al. (2004) have been included on this plot, as well as the depth where no material was recovered in the original coring (90-110 cm). Samples from within this depth interval were taken from the recent 10 m core as

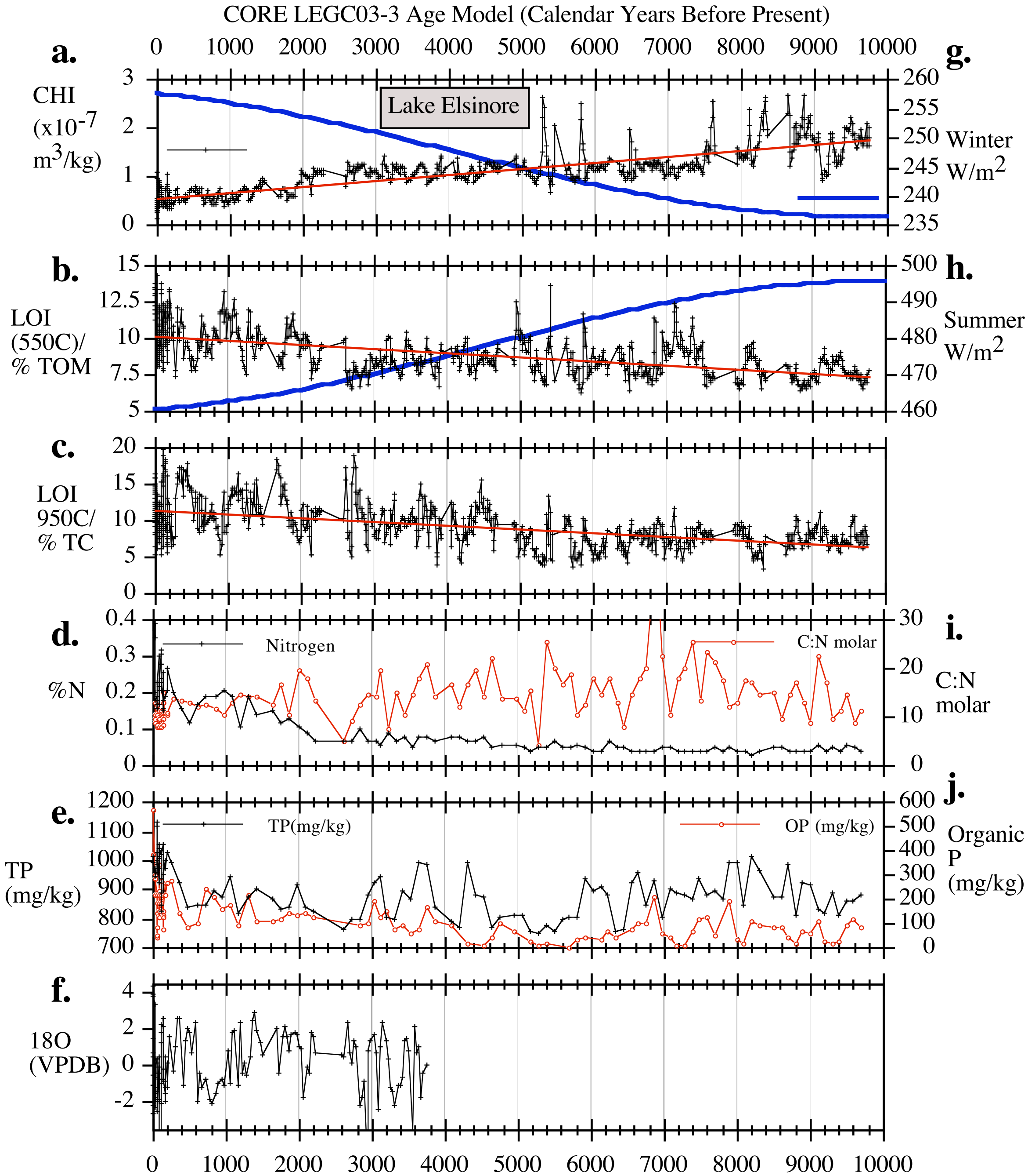



**Figure 17.** Core LEGC03-3 with all relevant data for climate interpretation plotted with the age model (see Figure 11). a) Mass magnetic susceptibility; b) Percent total organic matter (LOI 550C); c) Percent total carbonate (LOI 950C); d) Percent Nitrogen; e) Total phosphorous; f) $\delta^{18}O_{(calcite)}$ data; g) Winter (December-February) Insolation; h) Summer (June-August) Insolation; I) C:N molar ratio; and, j) Organic phosphorous.

described above and provisionally included in the profile assuming stratigraphy warrants.

Inorganic P concentrations (as defined by Aspila et al, 1976) were lower (540-1188 mg/kg) and averaged 870±136 mg/kg over the whole length of the core (Fig. 19a). For comparison, the core-averaged TP concentration was 1122±126 mg/kg. These levels are slightly higher than the TP and IP contents found in this area from grab samples collected in 2000 of 929 and 548 mg/kg, respectively (Anderson, 2001).

Total P levels increased linearly from about 950 mg/kg at the bottom of the core, near a

**Table 3. Core LEGC03-3 CHI Spike Intervals and Characteristics.**

| CHI Event Number | Depth (cm) | Event Thickness (cm) | Mean Age (cy BP) | Description |
|---|---|---|---|---|
| 1 | 631-635 | 4 | 5,300 | nothing distinguishable |
| 2 | 647 | 1 | 5455 | nothing distinguishable |
| 3 | 680-683 | 3 | 5810 | nothing distinguishable |
| 4 | 746-748 | 2 | 6495 | pinkish |
| 5 | 854-858 | 4 | 7610 | pinkish – some silt |
| 6 | 905-908 | 3 | 8120 | pinkish – some silt |
| 7 | 913-932 | 19 | 8278 | multiple faint silty layers |
| 8 | 959-962 | 13 | 8660 | nothing distinguishable |
| 9 | 978-982 | 4 | 8840 | silty |

depth of 170 cm, to almost 1400 mg/kg at a depth of 110 cm ($r^2$=0.86) (Figure 19a). Inorganic P levels also increased over this depth interval ($r^2$=0.60) that corresponds to a period <1800 A.D. to 1910 A.D. (Figure 19a). Magnetic susceptibility also increased over this period, and was associated with a period of increased precipitation, greater watershed inputs of inorganic sediment, and higher lake levels (Kirby et al., 2004).

Total and inorganic P dropped between 1910 and the construction of the Railroad Canyon Reservoir dam, and then increased again until about the 60 cm depth (or about 1960, perhaps associated with the essentially dry lakebed conditions present at that time). Since that time, TP and IP levels have varied without a clear tread (Figure 19a).

The percentage of TP as organic P in the sediments averaged 22.3±10.4% for the core (Figure 19b), with a greater proportion of the total P as organic P in the upper section of the core (0 - 90 cm) when compared with the lower portion of the core (27.3±10.8 vs. 16.1±6.3 %, respectively). This indicates that the average percent fraction of organic phosphorus increased from 16.1 to 27.3 % since development in the local watershed and construction of the Railroad Canyon Reservoir dam. A t-test with unequal variance confirmed that the fraction of organic P for the 2 depth intervals (and time intervals) were statistically significant at $p<0.01$.

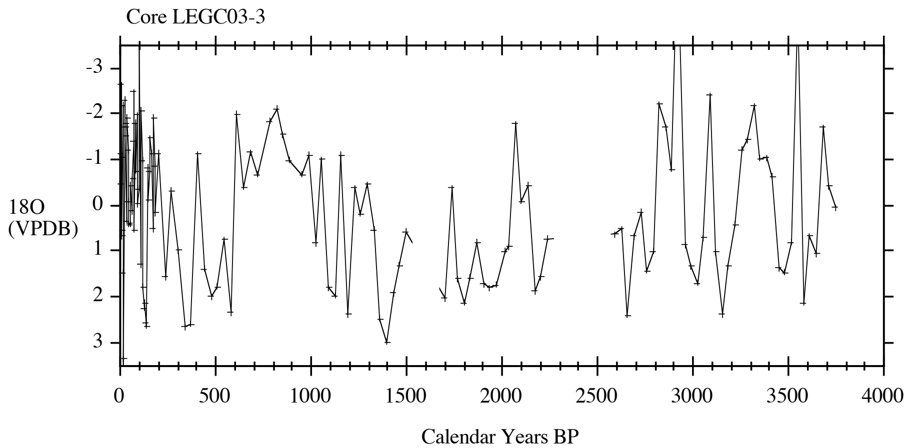
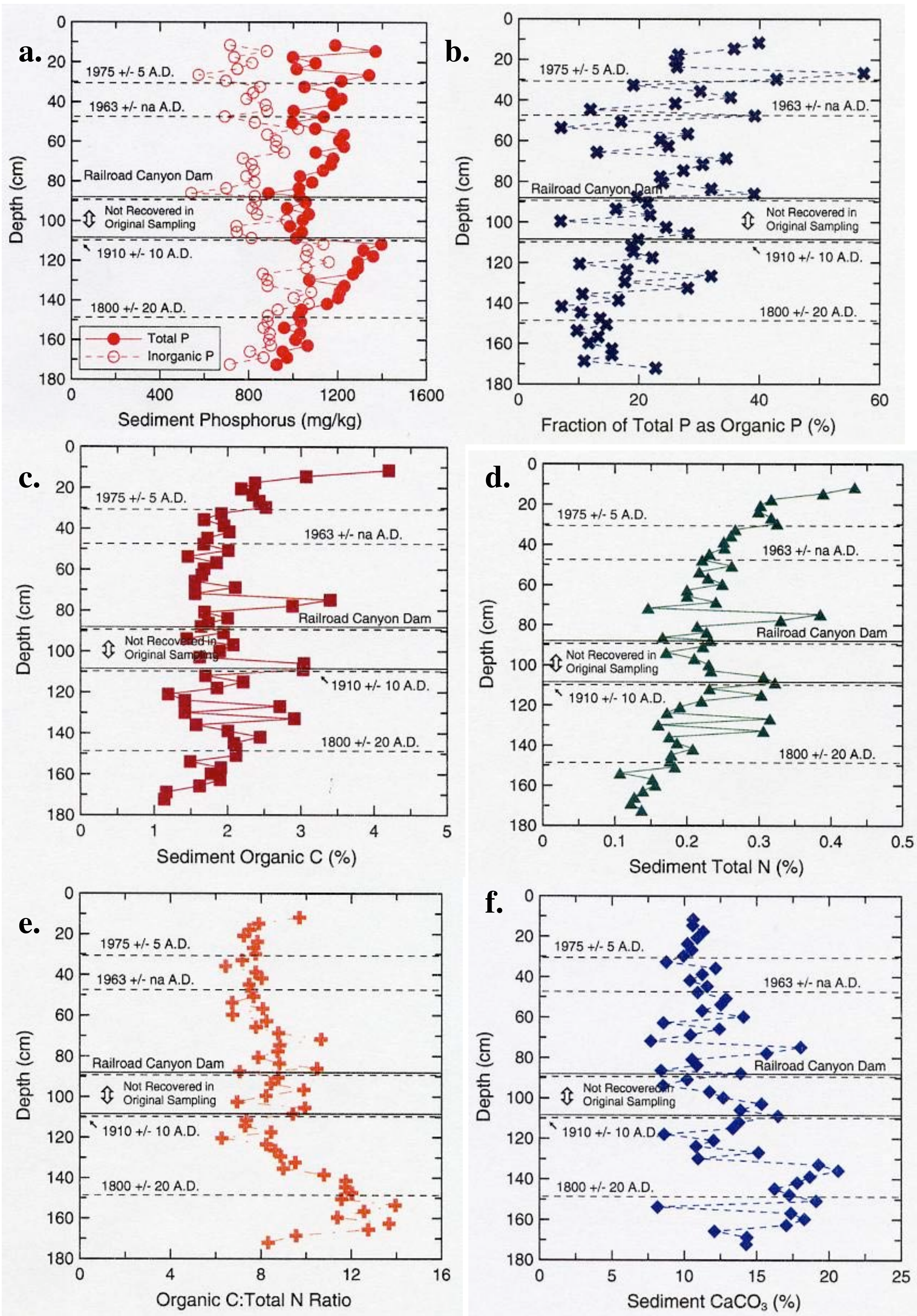



**Figure 18.** Core LEGC03-3 $\delta^{18}O_{(calcite)}$ data plotted with age model.

Organic C and total N levels in the sediments exhibited somewhat different behaviors through the sediment core (Figure 19c,d). Organic C was determined from total C measurements after correction for inorganic C that was estimated from $Ca^{2+}$ recovered in the 1 M HCl inorganic P extracts (through dissolution of $CaCO_3$, although some $Ca^{2+}$ would have also been released from exchange sites and from limited dissolution of any anorthite-type phases present in the sediments). Organic C averaged 2.1% through the core, with no statistically significant difference between the upper and lower sections of the core (Figure 19c). Total N in the sediment increased over the past ~200 yrs, from about 0.12% in sediment found at about 170 cm to >0.4% in the uppermost 10 cm ($r^2$=0.42) (Figure 19d).



The ratio of organic C to total N in the sediments has remained comparatively steady at about 8 over the past 100 yrs or so, although values were substantially higher about 2 centuries ago (Figure 19e). The $CaCO_3$ content of the sediments (Figure 19f) increased with depth, although variability was comparatively high (Figure 19f) ($r^2$=0.27).

**Figure 19.** Core LESS02-11 with missing section filled-in from core LEGC03-3 (see text for details). a) Total phosphorous and inorganic phosphorous; b) Organic phosphorous; c) Organic carbon; d) Total nitrogen; e) C:N ratio; and, f) $CaCO_3$.

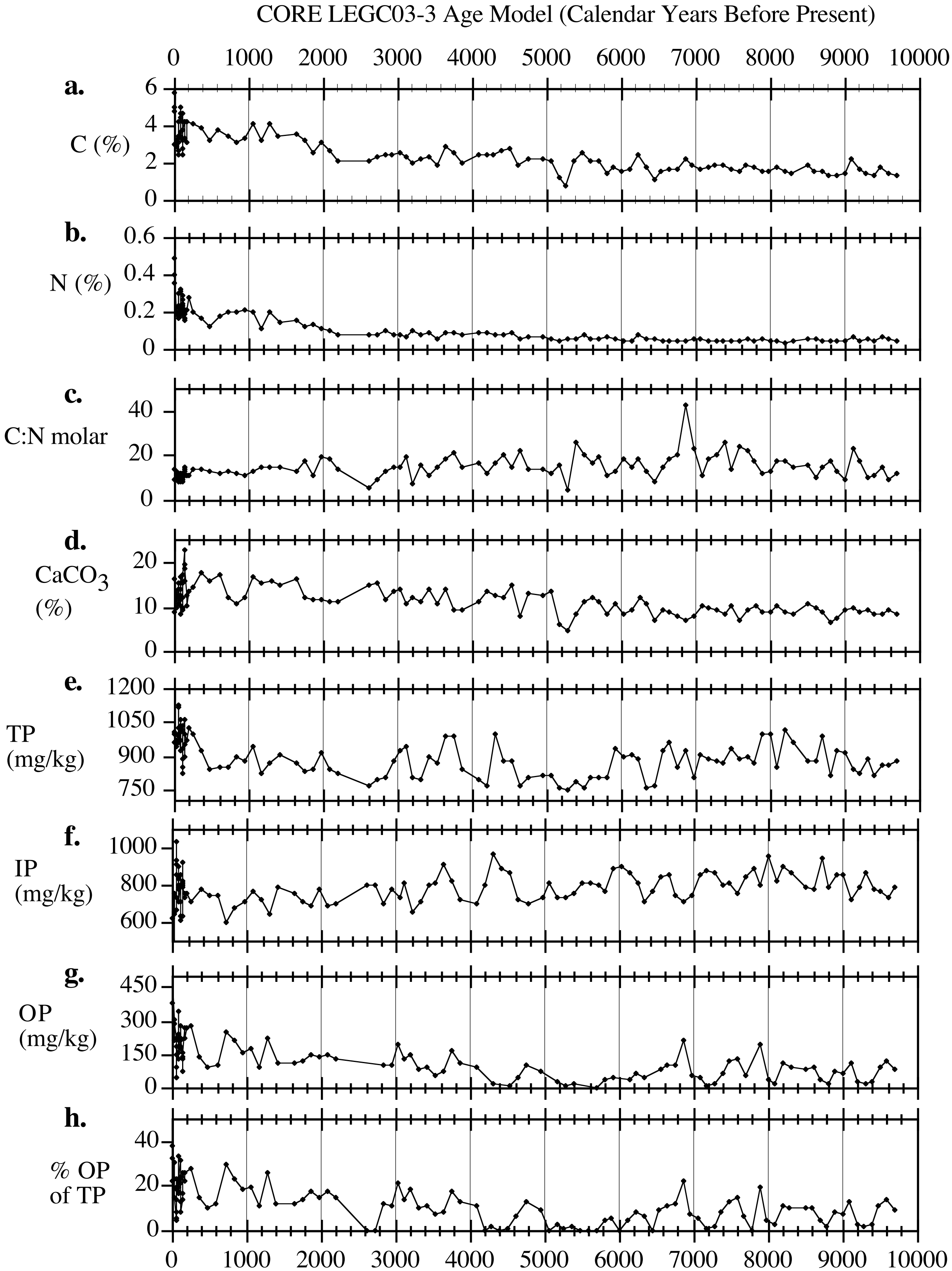
Unlike C, N, P and $CaCO_3$ (Figures 19a-f), 1 M HCl-extractable Fe and Al contents varied little with depth (data not shown). Extractable Fe averaged 1.69%, with no difference between the upper core (post-Railroad Canyon Dam) and lower core (pre-1910). Extractable Al was slightly lower (1.05±0.13%), with again no differences in the upper and lower sections of the core.

***5.7.2 LEGC03-3 (10 m core).***

AMS $^{14}C$ dating indicates that core LEGC03-3 provides a record of lake, watershed and climatic conditions over the past 9,800 cy BP (Figure 11 and 17). Sediment properties varied often quite substantially over the 10.7 m core's length.

Organic C concentrations decreased with increasing depth, especially over the upper 330 cm of the core that represents the past 2000 cy BP, where organic C levels averaged 2.02±0.59 %, compared with the average organic C content of 0.72±0.29 % in the lower 700 cm of the core (i.e., 2000 to 9,800 cy BP) (Figure 20a).

Total N concentrations followed quite closely the organic C content of the sediments (r = 0.93), and also decreased strongly with increased depth within the sediments (r = -0.83) (Figure 20b). As with organic C, total N levels declined especially strongly from the uppermost section



CORE LEGC03-3 Age Model (Calendar Years Before Present)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
a.
C (%)
b.
N (%)
c.
C:N molar
d.
$CaCO_3$ (%)
e.
TP (mg/kg)
f.
IP (mg/kg)
g.
OP (mg/kg)
h.
% OP of TP

of the core (present day), down to about 330 cm depth (approximately 2000 cy BP).

**Figure 20.** Core LEGC03-3 Lake nutrient/lake productivity data plotted with the age model. a) Organic carbon; b) Total nitrogen; c) C:N molar ratio; d) $CaCO_3$; e) Total phosphorous; f) Inorganic phosphorous; g) Organic phosphorous; and, h) Percent organic phosphorous of total phosphorous.

The organic C:total N ratio of the sediments appear to have increased slightly with depth, at least down to about 330 cm (2000 cy BP) ($r = 0.68$), although no clear trend was found at greater depths (Figure 20c). The higher degree of scatter presumably arises from the lower levels of both organic C (Figure 20a) and total N (Figure 20b) present in the sediments in the lower portion of the core. The mean organic C: total N ratio increased from 9.9±2.0 in the upper 330 cm to 13.5±4.8 in the lower section of the core. A t-test indicated these were significantly different at $p<0.01$.

Calcium carbonate contents of the sediments (as determined from $Ca^{2+}$ concentrations in overnight extractions with 1 M HCl) reached maximum levels about 130 cm below the surface, with concentrations tending to decline both above and below this depth that corresponds to about 130 cy BP (Figure 20d). The $CaCO_3$ contents were moderately correlated with organic C and total N concentrations ($r = 0.51$ and 0.52, respectively), but weakly negatively correlated with 1 M HCl-extractable Al and Fe ($r = -0.20$ and 0.09, respectively).

The total phosphorus contents of the sediments (Figure 20e) varied less dramatically than organic C or total N (Figure 20a,b). Total P averaged 901±83 mg/kg over the entire length of the core, with only modest differences between the upper 330 cm of the core (950±77 mg/kg) where higher organic C and total N levels were found, and the bottom 700 cm of the core (867±69 mg/kg). This approximately 10% increase in total P is much lower than the 300-400% increases found for organic C and total N, although a t-test indicates it is nevertheless a statistically significant increase over these depth intervals ($p<0.01$). Total P was moderately correlated with organic C and total N ($r = 0.53$ and $0.57$, respectively), but uncorrelated with 1 M HCl-extractable Fe and Al ($r = -0.04$ and $0.05$, respectively).

Inorganic P (as defined by Aspila et al., 1976) averaged 779±95 mg/kg through the entire core, or 86% of the total P in the sediments (Figure 20f). Inorganic P was weakly positively correlated with depth and age, with somewhat lower levels in the upper portion of the core compared with the lower section. Organic P, taken as the difference between total and inorganic P, shows more clearly the shift to higher organic P contents in the upper 300-350 cm of the core (i.e., over the past 2 millennia), with levels approaching or exceeding 400 mg/kg in the uppermost section of the core (Figure 20g). Organic P was highly correlated with organic C ($r = 0.74$) and total N ($r = 0.69$).

## 6.0 DISCUSSION.

**Note: the discussion will focus on core LEGC03-3. This core contains the most complete late-Holocene sediment record and the most complete spectrum of analyses, including $\delta^{18}O_{(calcite)}$ over the past 4,000 cy BP. Core LEGC03-4 will be discussed only in terms of its support of the other two core climate signals.**

### 6.1 Climate and Lake Nutrient Proxy Interpretations.

#### *6.1.1 Magnetic Susceptibility.*

Sediment magnetic susceptibility measures the concentration of magnetic material in a sediment sample (Thompson et al., 1975). In clastic-dominated sediment systems such as Lake Elsinore, the amount of magnetic material is a function largely of the flux of allochthonous sediment into the lake's basin. There are, however, other factors that can affect sediment magnetic susceptibility such as post-depositional diagenesis in the presence of high concentrations of organics (Hilton and Lishman, 1985; Hilton et al., 1986), dilution from organic matter and/or carbonates, and mineral segregation by wave action (Smoot and Benson, 2004). There is a strong positive correlation between the magnetic susceptibility and percent total organic matter data (Figure 16). We interpret this relationship to indicate the dilution of organic matter by magnetic minerals during periods of enhanced sediment flux. Conversely, periods of reduced sediment flux produce higher total organic matter due to a decreased dilution effect. We note, however, that without additional chemical analyses we cannot rule out entirely a diagenetic affect. Although, it is important to note that the effect of diagenesis would be to produce a change in the same direction as dilution. In other words, dilution and diagenesis produce similar final results in the sediment record – a decrease in magnetic susceptibility.

In terms of a climate proxy interpretation of the magnetic susceptibility data, we contend that wetter climates increase the flux of sediment into the lake basin, including magnetic minerals, similar to that proposed by Kirby et al. (2004, 2005*)*. As a result, *higher magnetic susceptibility indicates wetter climates and vice versa*. In support of this proxy interpretation, Inman and Jenkins (1999) have shown a strong positive correlation over the twentieth century between climate wetness and river sediment flux in southern California.

***6.1.2 LOI 550°C (Total Organic Matter).***

Total organic matter in lake systems reflects a combination of autochthonous and allochthonous sources. Allochthonous organic matter is derived from terrestrial organic matter washed into the lake basin. The extent to which this fraction contributes to lake sediments is controlled by several factors including drainage basin flora, regional climate, and basin topography (Meyers and Ishiwatari, 1993). In most lakes, except for extremely oligotrophic lakes, the autochthonous source dominates (Dean and Gorham, 1998). Autochthonous organic matter derives from *in situ* lake productivity of various types (Meyers and Ishiwatari, 1993). Anderson (2001) has shown that modern profundal sediments in Lake Elsinore average 4.84% organic carbon; modern littoral sediments contain 0.79% organic carbon. In both environments, carbon:nitrogen (C:N) data show that autochthonous lake organics dominate. The gradation in total organic carbon from littoral to profundal environment is produced by near shore wave action winnowing that removes preferentially the finer grained organic matter and transports it into the deeper basins.

In terms of a climate proxy interpretation of the total organic matter, we suggest that *total organic matter is a proxy for climate wetness*. The positive correlation between magnetic susceptibility and total organic matter organic matter, indicates a climate-driven, dilution interpretation. Higher total organic matter reflects dilution from an increase in the flux of magnetic minerals in response to greater run-off (i.e., wetter climate). Lower total organic matter indicates a decrease in dilution from magnetic minerals in response to less run-off (i.e., drier climate).

***6.1.3 LOI 950°C (Total Carbonate).***

In many lake systems, the carbonate sediment fraction is produced within the lake through a variety of possible processes (Thompson et al., 1997; Mullins, 1998; Hodell et al., 1998; Benson et al., 2002; Kirby et al., 2002b). Because there is no local source of detrital carbonate within Lake Elsinore's drainage basin, it is assumed that the carbonate in the lake's sediment is entirely autochthonous; although, the influence of wind-blown carbonate dust cannot be ruled out at this point (Reheis and Kihl, 1995). In addition, we cannot rule out mixing of waters with different source areas as a cause of changes in the relative saturation of lake waters with respect to calcium carbonate. Future $\delta^{18}O$ analyses on the calcite fraction may help to resolve these issues. Anderson (2001) has shown that carbonate precipitates directly within the water column in response to $CO_2$ drawdown by phytoplankton. There is also a strong seasonal contrast in carbonate precipitation that indicates a temperature role. Hydrologic models by Anderson (2001) show that carbonate precipitation will increase as lake-levels decrease in response to saturation of the water column with respect to calcium and carbonate. From this hydrologic model, <u>*we interpret total carbonate as a first-order proxy for climate-driven, relative lake-level*</u>. For example, higher total carbonate values represent lower lake levels in response to a drier climate regime. A drier climate also decreases lake size, thereby concentrating nutrients and increasing lake primary productivity.

***6.1.4 $\delta^{18}O_{(calcite)}$.***

Stable oxygen isotope geochemistry ($\delta^{18}O_{(calcite)}$) using calcite is a longtime, standard method for lacustrine studies (Stuiver, 1970; Fritz et al., 1975; Dean, 1981; Edwards and Fritz, 1988; Kelts and Talbot, 1990; McKenzie and Hollander, 1993; Drummond et al., 1995; Rosen et al.; 1995; Anderson et al., 1997; Li and Ku, 1997; Yu and Eicher, 1998; Teranes et al., 1999; Li et al., 2000; Teranes and McKenzie, 2001; Rosenmeier et al., 2002; Kirby et al., 2001, 2002a,b). Pelagic carbonate precipitates in lacustrine systems are predominantly a product of one of the following processes: bio-induced precipitation (due to photosynthetic actvitiy), biogenic precipitation (direct precipitation by organisms), bio-mediated precipitation (precipitated indirectly through biological processes), or chemical precipitation (direct precipitation from water column) (Kelts and Hsu, 1978; Dean, 1981; McKenzie, 1985; Siegenthaler and Eicher, 1986; Kelts and Talbot, 1990; McKenzie and Hollander, 1993; Thompson et al., 1997; Teranes et al., 1999). In all cases, the $\delta^{18}O_{(calcite)}$ reflects a combination of temperature of the water and the $\delta^{18}O_{(water)}$ during precipitation (Stuiver, 1970). Unraveling these effects depends largely on the lake's environment (latitude, altitude, climate) during calcite precipitation. Lakes located in warm, arid regions, such as Lake Elsinore, often reflect lake water $\delta^{18}O$ variations associated with changing P:E ratios (precipitation:evaporation) more than lake water temperature changes (Kelts and Talbot, 1990; Li and Ku, 1997; Li et al., 2000; Kirby et al., 2004). The lake's isotopic composition is directly controlled by the lake's hydrologic budget as moderated through changes in the rate of evaporation, the source and amount of precipitation, or inflow, and lake water residence time (Kelts and Talbot, 1990; Li and Ku, 1997; Li et al., 2000; Benson et al., 2002).

As shown by Anderson (2001), the calcite in Lake Elsinore is an autochthonous, bio-induced product, and precipitated in equilibrium with lake water; the latter assumption is valid and widely used in the paleoclimate community. These assumptions, however, will be tested through a future project involving the collection and analysis of water temperature, lake water $\delta^{18}O$, and $\delta^{18}O_{(calcite)}$ from the modern lake environment and assessed using the Kim and O'Neil (1997) equation for calcite equilibrium fractionation (e.g., Kirby et al., 2002b). It is expected also that the isotopic information obtained from Lake Elsinore will be similar to other lakes from warm, dry regions; in other words, there are several lake studies which provide a template for interpreting the isotopic data obtained from Lake Elsinore (e.g., Benson et al., 1996; Benson et al., 1997; Li and Ku, 1997; Benson et al., 1998; Li et al., 2000; Benson et al., 2002).

For this research, the *$\delta^{18}O_{(calcite)}$ is considered the best proxy for hydrologic variability*, specifically the P:E ratio. High $\delta^{18}O_{(calcite)}$ values are generally interpreted as indicative of low relative lake levels in response to enhanced evaporation. Low $\delta^{18}O_{(calcite)}$ values are interpreted as evidence for high relative lake levels in response to reduced evaporation and/or greater low $\delta^{18}O$ precipitation. If, for example, the controlling factor on the $\delta^{18}O$ calcite value was water temperature instead of the P:E ratio (i.e., $\delta^{18}O$ water), the change in water temperature required to explain the >4‰ range of $\delta^{18}O$ calcite is in excess of 14°C. A temperature change of 14°C is simply absurd for the Lake Elsinore system over the interval of study. As a result, and as previously stated, we attribute variations in $\delta^{18}O$ calcite as a direct measure of changing P:E ratios as recorded by variations in the $\delta^{18}O$ of the lake water and imprinted on the $\delta^{18}O$ calcite.

To test the veracity of the interpretation that the $\delta^{18}O$ calcite data record P:E ratios/hydrologic variability, we compared 20th century lake level variability from Lake Elsinore to $\delta^{18}O_{(calcite)}$ data from core LESS02-11 and LEGC03-3 (Figure 21). Age control for core LESS02-11 is provided in Kirby et al. (2004). Dates from LESS02-11 were cross-correlated to LEGC03-3 using the $\delta^{18}O_{(calcite)}$ profiles. Figure 21 demonstrates that lake level and $\delta^{18}O_{(calcite)}$ over the 20th century are related (high $\delta^{18}O_{(calcite)}$ = low lake level and vice versa). We note that the relationship is not perfect. In fact, it is not expected that a perfect relationship should exist considering the various human changes that have occurred to the lake over the past 100 years,

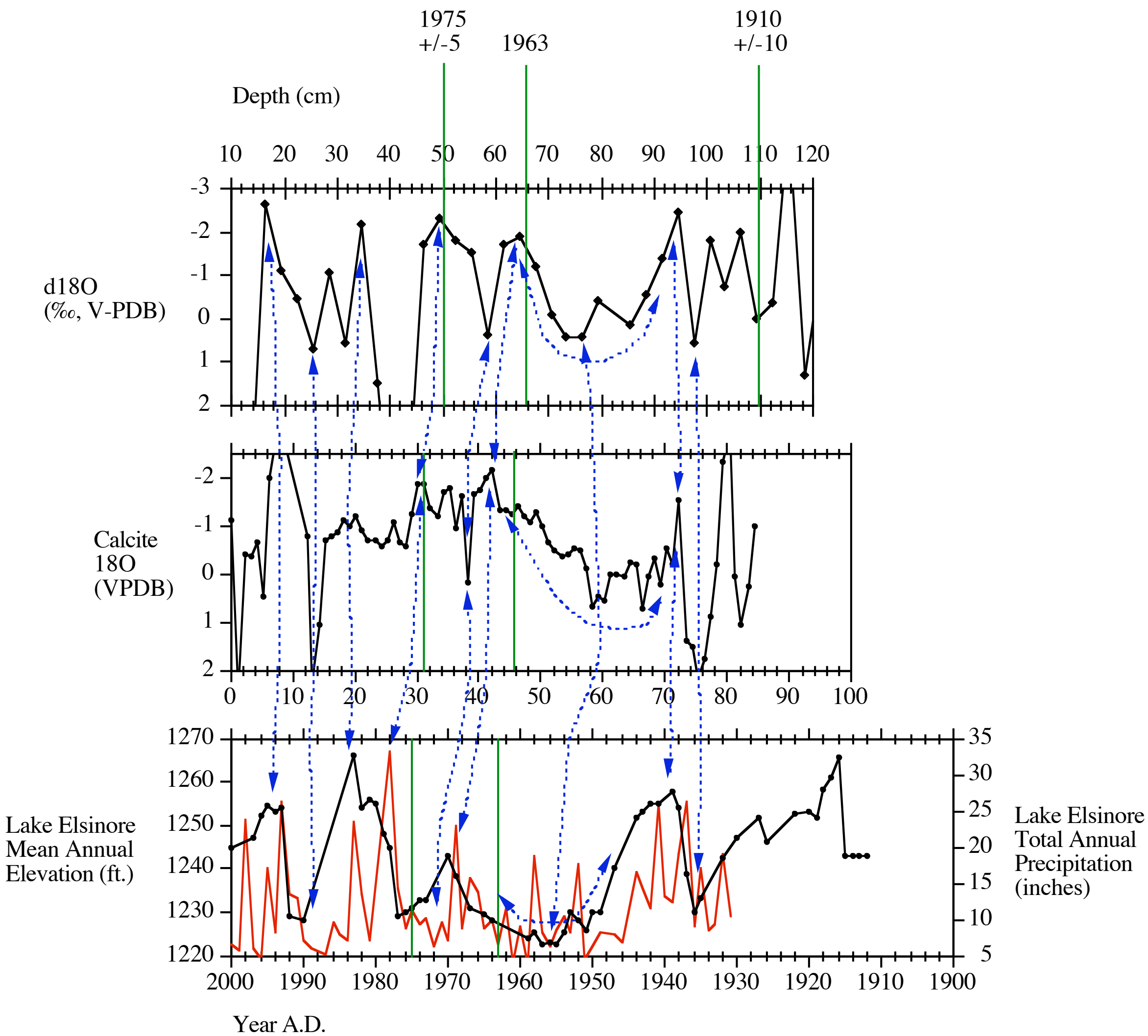



**Figure 21.** Correlation between $\delta^{18}O_{(calcite)}$ from cores LEGC03-3 (top) and LESS02-11a (middle) and Mean Annual Lake Level Elevation at Lake Elsinore. Age control is based on Kirby et al. (2004). Note the strong relationship between the $\delta^{18}O_{(calcite)}$ data and the 1950's lake level low stand.

including dam construction, well water discharge, and water extraction. Despite these anthropogenic impacts, the relationship between lake level and $\delta^{18}O_{(calcite)}$ is remarkably strong supporting our contention that *<u>$\delta^{18}O_{(calcite)}$ is a good first-order proxy for lake hydrologic variability (i.e., relative wetness vs. dryness)</u>*.

***6.1.5 C:N Ratios.***

C:N ratios provide information about the relative contribution of terrestrial versus aquatic organic matter (Meyers, 1990; Meyers and Ishiwatari, 1993; Meyers and Lallier-Verges, 1999; Huang et al., 2001; Mora et al., 2002; Meyers, 2002). Lower C/N ratios (<10) indicate a lacustrine algae source whereas higher C/N ratios (>20) indicate a land-plant source (Meyers, 2002); although, these absolute numbers may vary from lake to lake. The C:N data provides two distinct proxy signals: (1) changes in the relative contribution of terrestrial to aquatic organic matter as related to either climate driven floral diversity and subsequent run-off of detritus and/or change in lake level that either increase the aquatic contribution of organic matter (high lake levels or falling lake levels) or increase the contribution of terrestrial organic matter (dry lake with terrestrial vegetation at lake surface); or, (2) change in relative contribution of terrestrial to aquatic organic matter as related to extreme precipitation events that increase the flux of terrestrial organic detritus into the lake environment.

***6.1.6 Percent Organic Carbon, Percent Nitrogen, and Phosphorous.***

While correlations between water quality and sediment properties have frequently been demonstrated (Edmondson and Lehman, 1981; Vollenweider, 1968; Flannery et al., 1982), there remain challenges to relating organic matter, phosphorus or nitrogen levels in sediments to the trophic state of lakes (e.g., Rowan et al., 1992; Brenner and Binford, 1988). For example, from an analysis of profundal sediment data from 83 north-temperate lakes, Rowan et al. (1992) concluded that sediment organic matter content is not related to lake trophic state; rather, inorganic sediment inputs from the watershed serve to dilute organic matter production within the lake. Earlier in this report, we document a strong inverse relationship between LOI 550C (% total organic matter) and mass magnetic susceptibility over the length of the core record (Figure 16). This inverse relationship supports the argument that dilution of organic matter, nitrogen, and phosphorous by the climate-controlled flux of clastic mineral matter plays an important role in the long term variability of organic matter, nitrogen, and phosphorous. These findings have also been demonstrated in other studies (Rowan and Kalff, 1992; Gorham et al., 1974; Brenner and Binford, 1988). Climatic variability, land use changes, and other factors can alter the export of mineral material out of watersheds and into receiving water bodies over time; such variability can confound interpretation of sediment core nutrient and organic matter compositions.

Since mineral material would contribute inorganic forms of P, greater emphasis is placed on the levels of organic P, total N and organic C in the sediments. Nevertheless, since dilution by imported mineral material would affect the concentrations of all of these constituents, the relative proportion of organic P to total P in the sediments may be a reasonable index of overall trophic state (Figure 20h). The relative proportion of organic P varied in the LEGC03-3 core from very low levels at 600 cm depth to over 30% in recent times, suggesting increasing overall lake productivity over the past 4000 – 5000 yrs, although periods of higher and lower apparent productivity of finite duration seem likely (Figure 20e-h).

## **6.2 Lake Elsinore Over 10,000 Years: Hydrologic Variability and Productivity.**

### ***6.2.1 Long-Term Hydrologic Variability.***

Over the past 10,000 calendar years, hydrologic variability in southern California has been controlled by first-order forcings such as insolation (incoming solar radiation due to earth-sun orbital parameters), solar variability (a product of the sun's internal dynamics), waning glacial conditions (i.e., retreat of continental ice sheets in North America), and complex ocean-atmosphere interactions. As shown by Figure 17, both winter and summer insolation at 30°N latitude has changed dramatically. These changes affect the strength of seasonality, the mean position of the polar front jet stream (Kirby et al., 2002, 2005), and its associated storm tracks (e.g., Sawada et al., 2004). The extent and morphology of the North American ice sheet also impacts climate through its modulation of atmospheric circulation. In fact, Negrini's (2002) summary of Great Basin lake histories during the Quaternary attributes the first-order patterns of lake-level change to the mean latitude of the polar front jet stream as controlled by a combination of insolation and glacial boundary conditions. A lower latitude polar front favors the advection of moisture-rich storms across western North America. Of course, as the ice sheet decays, its influence on the position of the jet stream decreases. Moreover, as the ice sheet decays the jet stream will migrate north thus imprinting a spatial progression of lake-level change from south to north (Cole and Wahl, 2000; Enzel et al., 2003). With the disintegration of the North American ice sheets, the relative impact of the ice sheet on climate, specifically atmospheric circulation and storm tracks, will cease. For this research, the impact of ice sheets is minimal because the vast majority of the North American Ice Sheets had disintegrated by 10,000 cy BP, the start of the Lake Elsinore record presented in this study.

Insolation, however, has continued to change over the course of the Holocene. In fact, today's winter and summer insolation values are 9% higher and 7% lower than 10,000 years ago, respectively (Figure 17). Insolation is the amount of incoming solar radiation in Watts/m$^2$. As the geometry of the Earth-Sun relationship changes, the amount of insolation received at any given latitude also changes. It is well documented that greater summer insolation in southwestern North America increases the magnitude and spatial extent of the North American Monsoon (NAM) as well as the occurrence of occasional tropical cyclones (Wells and Berger, 1967;

Mitchell et al., 1988; Harrison, 1989; Spaulding, 1990; Liu et al., 2003). A high resolution early Holocene record from Dry Lake (Bird and Kirby, in review) and a low resolution littoral record from Lake Elsinore (Kirby et al., 2005) both indicate a wetter early Holocene climate. To explain this observation both papers argue that greater early Holocene summer insolation enhanced the magnitude and spatial extent of the North American Monsoon. As a result, parts of southern California, which are presently unaffected by the North American Monsoon, were influenced in the early Holocene by the monsoon. And, because the North American Monsoon produces short-lived, strong convective storms, it is often associated today with flash floods and significant erosion. In both the Dry Lake record and the low resolution Lake Elsinore record, the authors observe distinct storms sediment facies and/or sediment deposited by more vigorous hydrologic processes (Kirby et al., 2005; Bird and Kirby, in review). Similar to these records, the new Lake Elsinore, profundal, high-resolution sediment record presented in this study also shows evidence for a wetter early Holocene (Figure 17). Lithologic descriptions for all three drill cores show a preponderance of silty "storm layers" during the early-to-mid-Holocene (Figures 8-10). Magnetic susceptibility, a proxy for increased erosion of the lake's drainage basin (i.e., wetter climate), is characterized by several (n=9) anomalous spikes between 10,000 and 5,000 cy BP (Figure 17). Five of these nine spikes are recorded between 8,900 and 7,600 cy BP, during peak summer insolation (Figure 17). In addition, the average magnetic susceptibility values are highest in the early Holocene and decrease linearly through to the present. Total organic matter, % carbon, total nitrogen, and % organic phosphorous values are lowest in the early Holocene supporting our interpretation that increased erosion of magnetic minerals and other clastic sediments diluted the organic sediment fraction (Figure 17 and 20). Higher inorganic phosphorous, from eroded mineral matter, is also highest in the early Holocene supporting our interpretation that the early Holocene was wetter than present (Figure 17 and 20). Carbonate is also very low in the early Holocene, indicating a deeper lake than present (Figure 17 and 20). The C:N data further indicate a wet early Holocene (Figure 17 and 20). Higher C:N values (>15) throughout the early Holocene indicate that terrestrial land plants contributed a higher percentage of organic carbon and nitrogen than during the late-Holocene (Meyers and Ishiwatari, 1993). High C:N values in the early Holocene indicate the occurrence of various plants that require more mesic (wet) conditions than present. In fact, the C:N data are >15 throughout most of the Holocene indicating a substantially different local flora until at least 2000 cy BP when the C:N data begin to decrease and stabilize (Figure 17). In addition to an enhanced summer monsoon, it is also worth mentioning that early Holocene, lower winter insolation may have increased the frequency of large winter storms across the study region. Combined with the addition of summer monsoon precipitation, the added effect of more frequent winter storms creates optimum conditions for a wet early Holocene with a more substantial terrestrial biomass.

Following the early Holocene wet interval, the climate slowly deteriorates over 10,000 years to its present dry climate regime. All proxy data indicate a long term Holocene drying. Magnetic susceptibility decreases in response to a drier climate and its impact on reducing drainage basin erosion (Figure 17). Total organic matter, % carbon, organic phosphorous, and total nitrogen increase slowly over the Holocene indicating a decrease in dilution from magnetic minerals and other clastic sediments (Figure 17 and 20). Total carbonate values rise as well indicating an increase in the concentration of $Ca^{2+}$ and $CO_3^{2-}$ as lake levels decreased in response to less total precipitation (Figure 17 and 20). C:N ratios also decrease over the Holocene suggesting a long term drying, which changed the local vegetation from mesic (wet) to xeric (dry) (Figure 17 and 20). This long term decrease in C:N values also indicates an increase in the relative contribution of aquatic algae to the total organic sediment fraction. A decrease in lake size would concentrate nutrients and increase the proliferation of aquatic algae.

The first-order cause of the long term Holocene drying is insolation. Summer insolation steadily decreased over the past 10,000 years reducing the impact and spatial extent of the North American Monsoon and the occasional tropical cyclone. As a result, only the mountainous regions and deserts of Southern California receive occasional monsoonal rains in the present climate regime. At the same time, winter insolation increased. Although slight, this steady increase in winter insolation may have reduced the frequency of large winter storms across the study region. As a result, the combined reduction of summer and winter precipitation through insolation changes produced a long term Holocene drying as recorded in sediments from Lake Elsinore.

In addition to this first-order Holocene drying, the climate proxy data also indicate other shifts in climate over the past 10,000 years. Notably, the total organic matter/%N and total carbonate/magnetic susceptibility show a change in the amplitude of variability beginning 2,600 cy BP and 4,500/5,000 cy BP, respectively, and continuing through to the modern (Figure 17 and 20).

This purported mid-Holocene climate transition (ca. 4,500 to 5,000 cy BP) is supported by a variety of paleoclimate research studies (Sandweiss et al., 1996; Rodbell et al., 1999; Sandweiss et al., 2001; Andrus et al., 2002; Moy et al., 2002; Kirby et al., 2005). Similar to the latter studies, we suggest that this mid-Holocene climate transition represents the initiation of modern El Nino-Southern Oscillation (ENSO) conditions. It is well documented that there is a relationship between hydrologic variability in southern California and El Niño-Southern Oscillation (Schonher and Nicholson, 1989; Redmond and Koch, 1991; Piechota et al., 1997;

Cayan et al., 1999). Although the forcing mechanism driving ENSO remains debated, it is clear that changes in sea surface thermal structure, the propagation of ocean thermal anomalies, and their affect on atmospheric circulation result in hydrologic variability along the west coast of North America (Latif and Barnett, 1994; Gu and Philander, 1997; Pierce, 2002). Generally, El Niño years produce more precipitation in southern California and La Niña years produce less (Redmond and Koch, 1991; Castello and Shelton, 2004). In addition, ENSO-type interannual climate variability is superimposed on decadal patterns of climate change that may reflect "sustained" intervals of a preferred climate mode (Douglas et al., 1982; Jacobs et al., 1994; Trenberth and Hurrell, 1994; Cayan et al., 1998; Tourre et al., 2001; Mokhov et al., 2004). From these analyses, it is reasonable to suggest that the conditions that produce modern ENSO are dependent on specific forcing mechanisms that evolve through time (e.g., the presence of continental ice sheets in response to Milankovitch forcing; Loubere et al., 2003). Research indicates that ENSO exists under a variety of climate boundary conditions; although, the amplitude, duration, and frequency is subject to change (Clement et al., 2000; Tudhope et al., 2001; Moy et al., 2002).

Research from South America, where ENSO is first detected, indicates that modern ENSO conditions evolved into its present state over the Holocene (Sandweiss et al., 1996; Rodbell et al., 1999; Sandweiss et al., 2001; Andrus et al., 2002; Moy et al., 2002). Although the exact timing is still debated, it is clear that this transition occurred by the mid-Holocene (~5,000 cal years B.P.). Recently, Friddell et al. (2003) published $\delta^{18}O_{(calcite)}$ data from foraminifera in the Santa Barbara Basin. They conclude that climate variability, perhaps linked to more intense El Niño events, increased by the mid-Holocene. To the north, Barron et al. (2003) reach a similar conclusion, although slightly later in the Holocene (~3,500 cal years B.P.), using multi-proxy data from ODP Site 1019 adjacent to northern California. And, to the south, Barron et al. (2004) suggest an increase in ENSO variability beginning at 6.2 ka. In the context of these studies, we also interpret our data in terms of ENSO evolution. The increase in the amplitude of variability in the total organic matter and total carbonate suggest a more dynamic hydrologic system – a system where rapid, extreme (wet-dry cycles) hydrologic changes occur more regularly than the early Holocene (Figure 17). Magnetic susceptibility is suppressed in response to less total run-off (Figure 17). Moreover, an increase in total organic matter may have increased bacterial oxidation of magnetic minerals, thus reducing the total magnetic susceptibility values over the past 5,000 calendar years (Figure 17 and 20). This interpretation is congruent with the evolution of ENSO and its known impact on southern California hydrology. The exact forcing mechanism driving the Holocene evolution of ENSO is unclear; however, at millennial time scales, it is likely related to long-term changes in the seasonal cycle of insolation and its affect on latitudinal thermal gradients (Clement et al., 2000).

The cause of the more recent climate regime shift to additionally drier conditions at 2,000 cy BP, as shown by the %total organic matter, % carbon, and % nitrogen, is less clear at this time (Figure 17 and 20).

***6.2.2 Long-Term Productivity and Nutrient Levels: Are the Past 200 Years Unusual?***

All proxies for lake productivity and/or nutrient levels indicate that the Holocene is characterized by a long term increase in both lake productivity and nutrient levels (Figure 17, 20, and 22). Furthermore, in comparison to the entire record, the past 200 years are characterized by the highest lake productivity and nutrient levels of the past 10,000 years (Figure 22). The previously proposed long term increase in lake productivity/nutrient levels is certainly climate related. The long term Holocene drying reduced the flux of clastic sediment into the lake basin and minimized dilution of organic matter. At the same time, the size of Lake Elsinore decreased in response to less total annual precipitation. As a result, the concentration of nutrients increased promoting greater autochthonous primary productivity as recorded by higher total organic matter, higher N levels, lower C:N ratios, and higher OP values (Figure 17 and 20). Although the long term increase in lake productivity/nutrient levels is climate-driven, the abrupt increase over the past 200 years is largely anthropogenic. Figure 22 illustrates the difference between average proxy values for lake productivity/nutrient levels over the past 200 years versus the average data for the past 10,000 years (minus the past 200 years). We conclude that human modification of the lake's drainage basin has increased the sediment load, including nutrients, to the lake basin. This increase in sediment load has consequently favored a large increase in lake primary productivity (Figure 22).

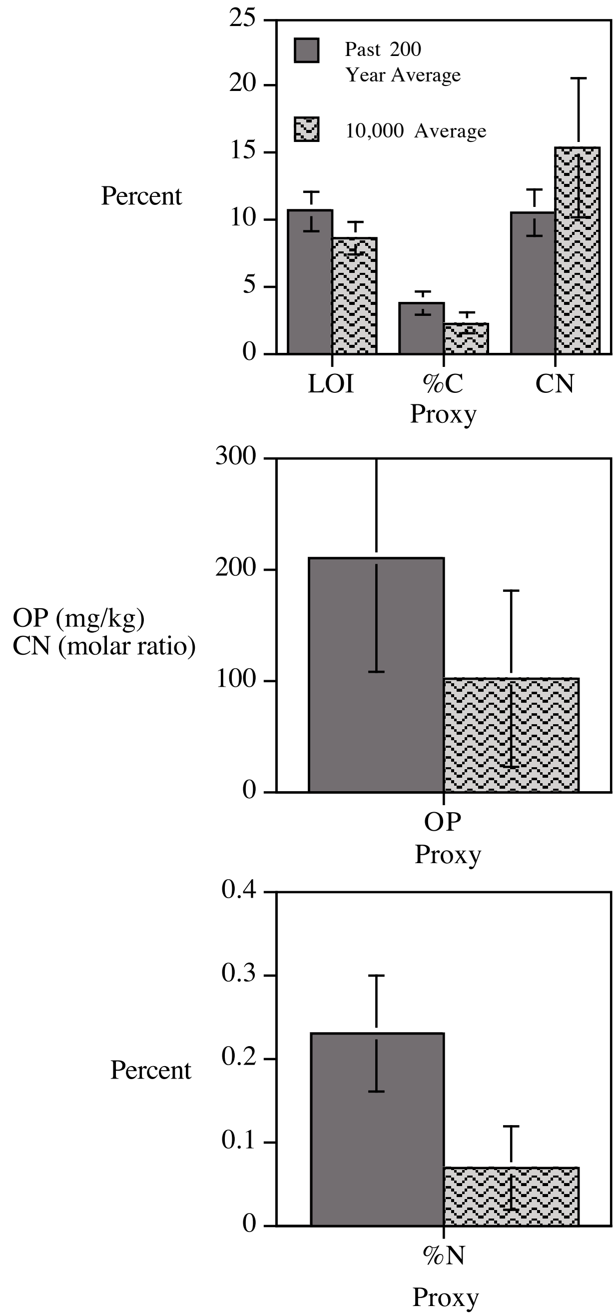



**Figure 22.** Comparison of nutrient level and lake productivity level proxies for the past 200 years versus the pre-historic record. Bars represent 1-standard deviation from mean.

The observed increase in anthropogenic sediment loading was previously documented by Bryne et al. (2003). From this study, it is unlikely that the natural state of lower productivity and lower nutrient levels can be maintained or re-established under the present state of lake use and human occupation. This conclusion is supported by similar research on lakes that have been modified or influenced by humans (Ekdahl et al., 2004). In other words, LESJWA should take measures to mitigate the nutrient/sediment load problem, but they must recognize that this problem is temporally anomalous and unlikely reversible under present lake-use conditions.

***6.2.3 Short-Term Climate Variability – The Past 4,000 Years.***

The best proxy for hydrologic variability (i.e., relative lake level - wetness vs. dryness) is the $\delta^{18}O_{(calcite)}$ data (Figure 24). As one of the more expensive analytical techniques used for this study, we were limited to 150 samples over the past 3,800 cy BP (approximately 1 analysis every 3cm). As a result, the $\delta^{18}O_{(calcite)}$ data represent "snap-shots" in time approximately every ~30 years. Nonetheless, the $\delta^{18}O_{(calcite)}$ data reveal some dramatic variability change as well as intervals of sustained high and low values (Figure 17 and 24). As an initial method for determining wet versus dry intervals, we took the 1950's lowstand $\delta^{18}O_{(calcite)}$ average value as a minimum $\delta^{18}O_{(calcite)}$ for "drought" conditions (Figure 24). Of course, it would be erroneous to infer absolute lake-level numbers from $\delta^{18}O_{(calcite)}$ data. However, we can infer relative climate wetness versus dryness using these isotope data. Using the 1950's average $\delta^{18}O_{(calcite)}$ value as a minimum "drought" value, we characterized the past 4,000 cy BP in terms of wet versus dry climate regimes. Because the resolution of our $\delta^{18}O_{(calcite)}$ data is widely spaced (every 30 years), we consider only the

**Figure 23.** Classic "green water" season at Lake Elsinore.

occurrence of multiple points of similar values as evidence for a sustained wet or dry interval. Single points are considered short-lived climate extremes until new data is available to fill in the gaps. Using the above criteria, we divide the past 4,000 cy BP into eight wet-dry climate intervals. The interval from 4,000 to 2,000 cy BP is characterized by multi-decadal-to-centennial

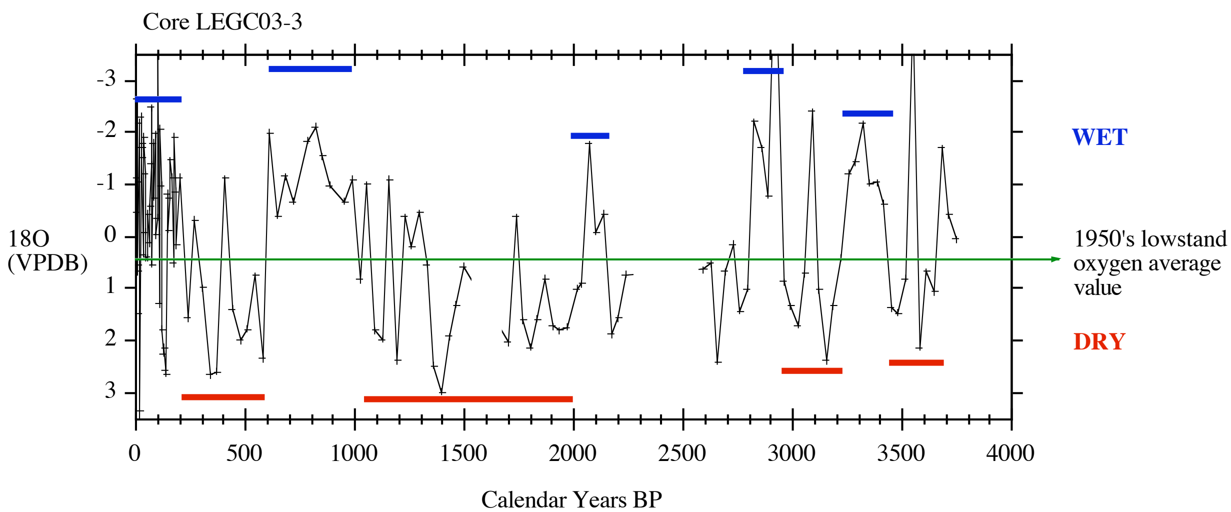



**Figure 24.** Inferred hydrologic variability (i.e., relative wetness/dryness) over the past 4,000 cy using $\delta^{18}O_{(calcite)}$ data from core LEGC03-3.

scale climate variability with several anomalous $\delta^{18}O_{(calcite)}$ excursions. Conversely, the past 2000 years are characterized by multi-centennial scale climate variability with a preference for dry climate regimes (Figure 24; 60% of the past 2000 years with values lower, or as low as, the $\delta^{18}O_{(calcite)}$ data during 1950's drought interval).

The past 1200 years are characterized by two of the more controversial climate changes of the Holocene – the Medieval Warm Period (MWP: ca. 700-1200 cy BP) and the Little Ice Age (LIA: 200-700 cy BP) (Lamb, 1982; Keigwin, 1996). The length of these climate intervals is highly debated and regionally specific (Graumlich, 1993; Keigwin, 1996; Field and Baumgartner, 2000; Haug et al., 2001). According to our Lake Elsinore sediment record, the

MWP was a 400 year interval of relative wet climate whereas the LIA was a 400 interval of relative dry climate (Figure 24). Comparison of the $\delta^{18}O_{(calcite)}$ data from core LEGC03-3 to the

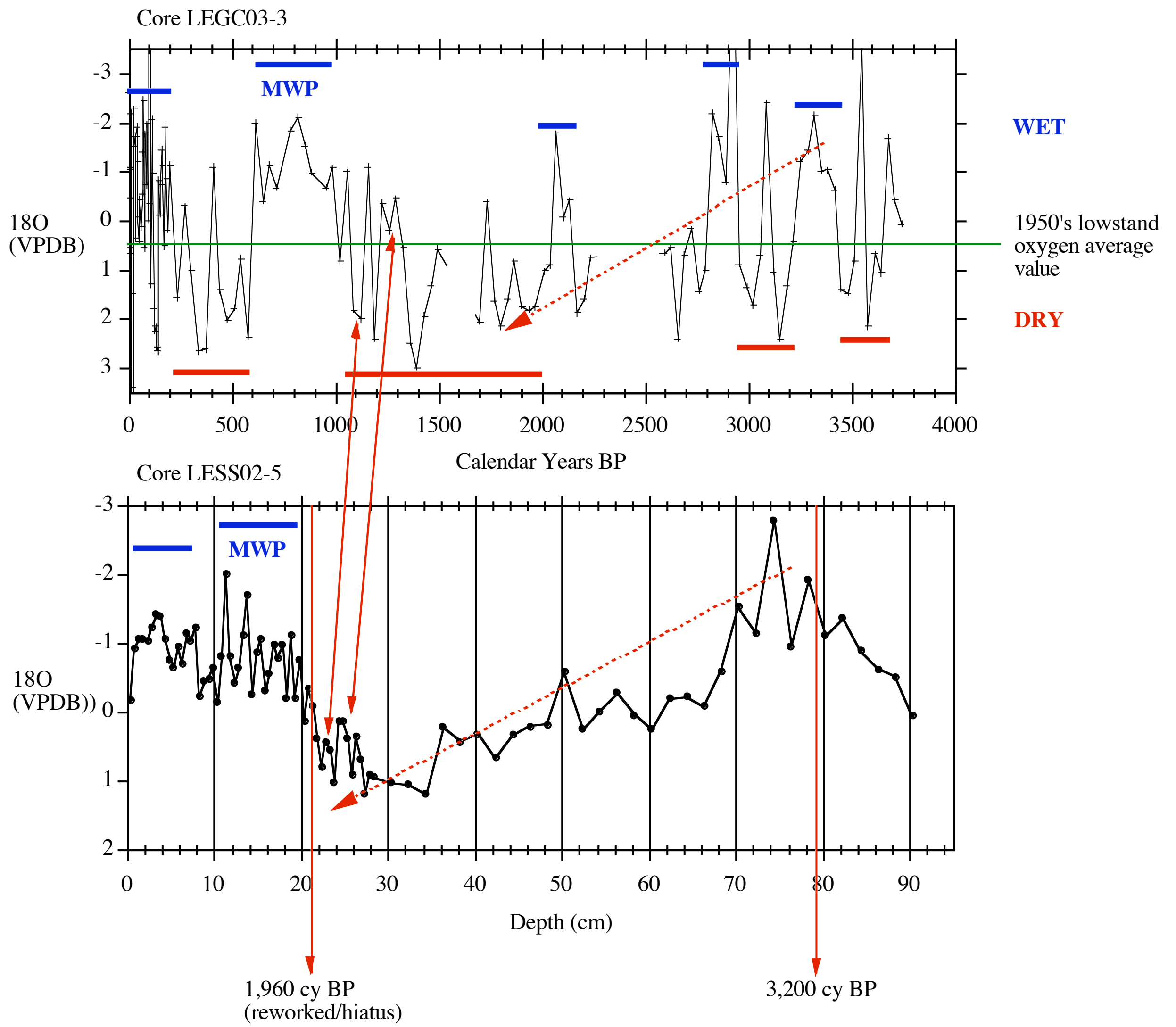



**Figure 25.** Comparison of $\delta^{18}O_{(calcite)}$ data from core LESS02-5 (from the lake's edge as of 2002) and core LEGC03-3. Similar $\delta^{18}O_{(calcite)}$ profiles indicate that the $\delta^{18}O_{(calcite)}$ data reflect basin-wide responses to hydrologic change.

$\delta^{18}O_{(calcite)}$ data from LESS02-5 (Kirby et al., 2004) shows similar MWP and LIA $\delta^{18}O_{(calcite)}$ anomalies, which indicates that the $\delta^{18}O_{(calcite)}$ data are not a local sedimentological anomaly (Figure 25). The $\delta^{18}O_{(calcite)}$ data from core LEGC03-3 also indicate that the past 200 years are an interval of relative wet climate, excepting the mid-19$^{th}$ century drought and the 1950's drought (Figure 25).

***6.2.4 Lake Elsinore in a Regional Context.***

As an independent test of our age model, we compared our data to the Pyramid Lake sediment record with its own age model (Benson et al., 2002). We reasoned that intervals of sustained climate regimes should be regionally pervasive across Western North America at multi-centennial-to-millennial scales. This assumption is not unreasonable considering that first-order climate change in western North America is driven by the same processes – insolation, ice sheet configurations, solar variability, and/or complex ocean-atmosphere interactions. In other words, climate regimes on multi-centennial-to-millennial scales should be in-phase across western North America. A comparison of the independently dated Pyramid Lake $\delta^{18}O_{(calcite)}$ record (Benson et al., 2002) over the past 4,000 cy BP to the independently dated Lake Elsinore $\delta^{18}O_{(calcite)}$ data over the past 4,000 cy BP reveals some amazing similarities (Figure 26). Most striking is the timing of the MWP (Figure 26). In fact, within the MWP are finer-scale features that match between both records. And, over the entire length of the record, there are multiple tie-points linking the two independently dated records (Figure 26). What does this mean? It means that the Lake Elsinore age model is very robust from which we can extract meaningful climate information over the past 4,000 cy BP. However, higher resolution $\delta^{18}O_{(calcite)}$ analyses are required from the Lake Elsinore record to discern more subtle variability and its timing. We note, however, there are also noticeable differences, such as the scale of amplitude, which may imply physical difference in the magnitude of regional climate variability (Figure 26).

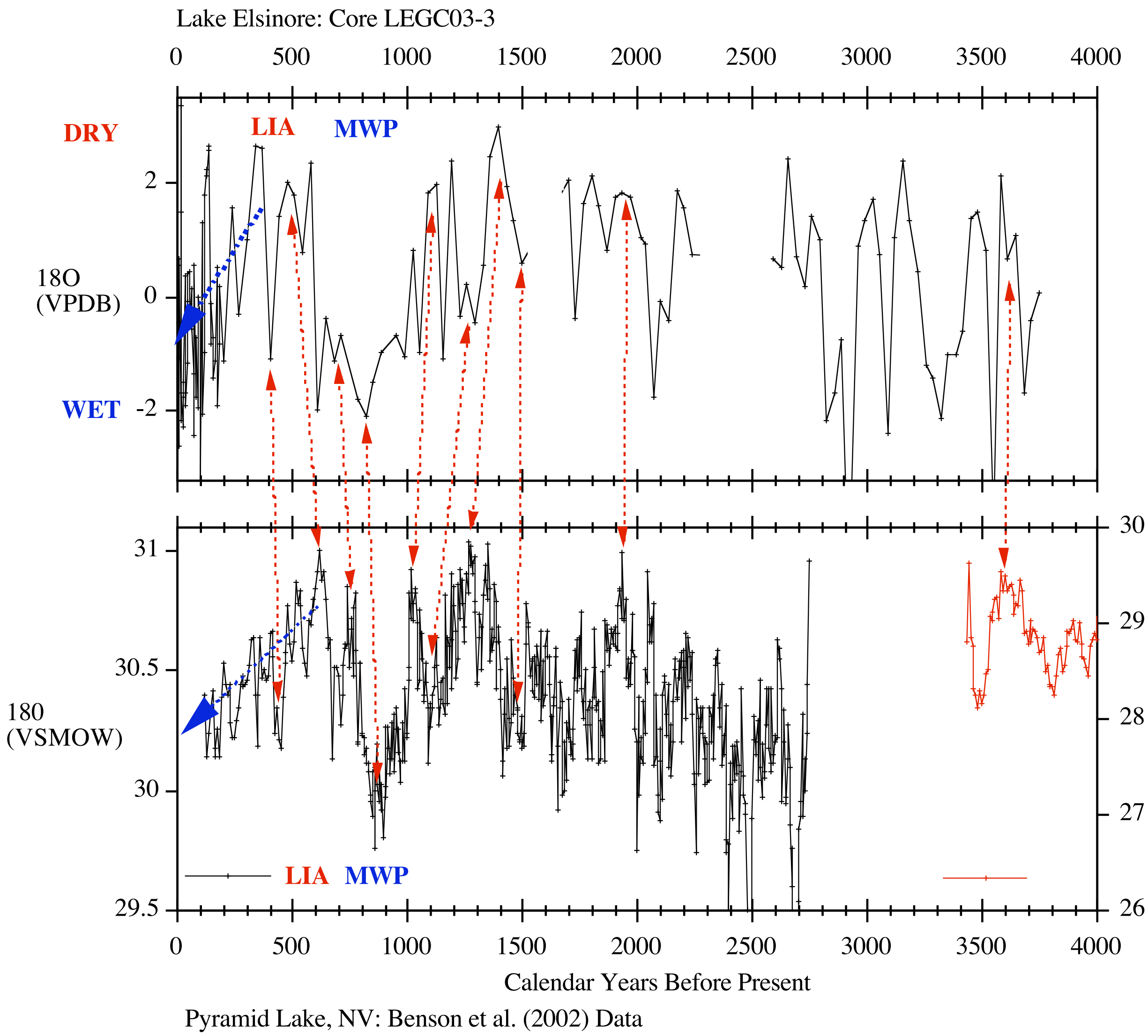



**Figure 26.** Comparison of $\delta^{18}O_{(calcite)}$ data from Lake Elsinore (core LEGC03-3) and a core from Pyramid Lake (Benson et al. (2002)). Note the strong first-order, multi-decadal-to-centennial scale variability including the MWP, the LIA, and the most recent long term shift to a wetter climate.

## 7.0 SUMMARY.

a) The Holocene is characterized by a long term drying. This long term drying is linked to a combination of increasing winter insolation which decreased the frequency of winter storms across the region and decreasing summer insolation which decreased the contribution of summer precipitation via monsoonal rains and/or the occasional tropical cyclone. Together, these long term changes in seasonal insolation produced a total decrease in regional precipitation and the observed long term drying.

b) The early to mid-Holocene (9,8000 to 5,000 cy BP) is characterized by sedimentological evidence for large storm events. These events are attributed to more frequent large winter storms and the occasional summer storm, which increased local run-off.

c) There is a distinct shift to higher amplitude variability after 5,000 cy BP in several of the sedimentological data. We attribute this increase in the amplitude of variability to the onset of the modern El Nino-Southern Oscillation phenomenon, which is characterized by highly variable climate with notable alternating wet-dry phases.

d) The last 4,000 cy BP - the only interval with $\delta^{18}O$ calcite data - is characterized by eight multi-decadal-to-multi-centennial scale wet-dry oscillations. These oscillations are shorter from 4,000 to 2,000 cy BP after which they increase in duration through to the modern. During the past 2000 cy BP, two notable wet-dry oscillations occur: the wet MWP between 1000 and 600 cy BP and the dry LIA between 600 and 200 cy BP. The last 200 cy have been characterized by a long term increase in climate wetness.

e) A comparison of the Lake Elsinore $\delta^{18}O$ calcite data over the past 4,000 cy BP to Pyramid Lake $\delta^{18}O$ calcite indicate several distinct similarities. These similarities provide evidence for two important conclusions: 1) independent evidence that our Lake Elsinore age model is robust; and, 2) evidence that there is regional climate phasing across western North America at centennial scales.

f) Proxy evidence for lake nutrient levels and primary productivity indicates that the past 200 years are characterized by higher nutrient levels and lake productivity than the prior 9,600 calendar years. This recent increase in lake nutrient levels and lake primary productivity is attributed to: 1) the long term climate drying, which reduces both the dilution of nutrients by sediment run-off and concentrates nutrients as lake volume decreases; and, 2) human disturbance of the lake's drainage basin, which increases local erosion of nutrients into the lake basin and increases the input of pollution. Human disturbance is certainly the most significant factor affecting the lake's trophic structure over the past 100 to 200 years.

## 8.0 CONCLUSIONS REGARDING LAKE MANAGEMENT.

1. Climate proxy data ($\delta^{18}O$ calcite) indicate that the past 4,000 calendar years have been characterized by multi-scale wet-dry oscillations. Until additional analyses are produced to fill in the temporal gaps over the length of the record, it is not possible to determine the statistical frequency of these oscillations or their evolution through time. In other words, we cannot conclude with a high level of confidence that the past 2000 calendar years, for example, are characterized by a distinct climate shift, which produces longer duration wet-dry cycles without additional $\delta^{18}O$ calcite data. Nonetheless, this research indicates clearly that intervals of prolonged climate dryness (multi-decadal to multi-centennial) can and have occurred in the recent past – likely longer and more severe than the 1950's drought. From this conclusion, it is important that LESJWA institutes policy that can maintain lake level or eliminate desiccation over a multi-decadal scale drought. Conversely, LESJWA must also prepare for prolonged intervals of wet climate, which may produce local flooding. Notably, the past 200 years are characterized by a shift to a wetter climate. Yet, it is during this time that the lake underwent desiccation indicating that wet climate regimes can have intervals of extreme drying.

2. Humans have almost certainly impacted Lake Elsinore's natural trophic structure. Reversing the affects of humans on the lake is probably not a reasonable goal. LESJWA should, however, continue to institute and explore options that will mitigate further damage to the lake. Realistic results for TDML's based on research by Dr. Anderson, and with consideration from this report, should be set that can reduce future human-impact damage.

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