CHAPTER 3

PALAEOCLIMATIC STUDIES

In the last few decades, a series of climate related disasters have focused attention on the importance of understanding and modelling of process of climate change, with a view to optimise land use and planning strategies. Since instrumental climatic records are available for only last 100-150 years, scientists are turning to proxy recorders of climate to calibrate their models. Studies on ocean cores have provided information about global climatic changes for the Quaternary period. However, these records have the twin constraints of coarse time resolution and inability to provide a regional/local picture - the latter is especially important because features like mountains, deserts etc. are known to locally influence the climate of an area. To an extent both these limitations can be overcome by using continental palaeoclimatic records from climatically sensitive regions. It is now being realised that the use of continental records in combination with oceanic data could provide a better understanding of the climatic system.

Instrumental records have indicated the sensitivity of Afro-Asian arid/semi-arid regions to small perturbations in the climatic system (Yan and Petit-Maire, 1994). For example, a wet episode was recorded from the 1920's until the 1960's in Sahel, India and northern China (Parthasarathy et al, 1986; Zhang, 1989) associated with a rapid warming over the northern hemisphere during the 1920's (Jones et al, 1986; Gossens and Berger, 1987). In contrast, shortly following a significant cooling over the northern hemisphere (Yan, Z. et al, 1990), a sharp dry phase was recorded since the 1960's in the northern Sahel (Demaree and Nicholis, 1990), the Arabian peninsula (Winstanley, 1976), India, the Tibetan plateau and northern China. This has led to a renewed interest in studying the palaeoclimate in these regions.

To date, paleoclimatic studies from the Indian subcontinent have been fragmentary, being confined to certain areas like Ladakh (Bhattacharya, 1989) and Kashmir in the north (Agrawal and Gupta, 1988; Agrawal et al, 1989; Krishnamurthy et al, 1986), Rajasthan lakes in the west (Singh et al, 1972; Bryson and Swain, 1981; Wasson et al, 1984; Singh et al, 1990; Chawla et al, 1992) and Nilgiris in the south (Sukumar et al, 1993; Caratini et al, 1994). The semi-arid regions of Gujarat, show evidence of past climatic variability in the form of stabilised dunes indicating a westwards spatial shift (Fig 3.1), of the order of 300km, of the 250mm isohyet (Goudie et al, 1973). However, paleoclimatic changes, with firm chronological control, in this arid/semi-arid zone, have not yet been adequately studied or documented. It is in this context that the present study becomes important.

3.1 Background information

This section is divided into three subsections. The first part deals with methods available for dating of young sediments. The second part discusses the sources of palaeoclimatic information. The third part summarises the palaeoclimatic studies from north-west India as the Nal region is closest to it and forms part of Palaeo-Thar (Goudie et al, 1973).

3.1.1 Dating of young sediments

Accurate dating control is essential to put the palaeoclimatic information in a suitable chronological framework. Without reliable estimates on ages of past events, it is not possible to investigate if they occurred synchronously or some events lagged behind others. Studies to understand the evolution of the Nal region (Chapter 2) have indicated that the lacustrine record (Horizon-1) extends back at least upto a few thousand years whereas the entire 54m core should extend back upto last major interglacial. The available dating methods, for the time scales involved, are discussed in the following.

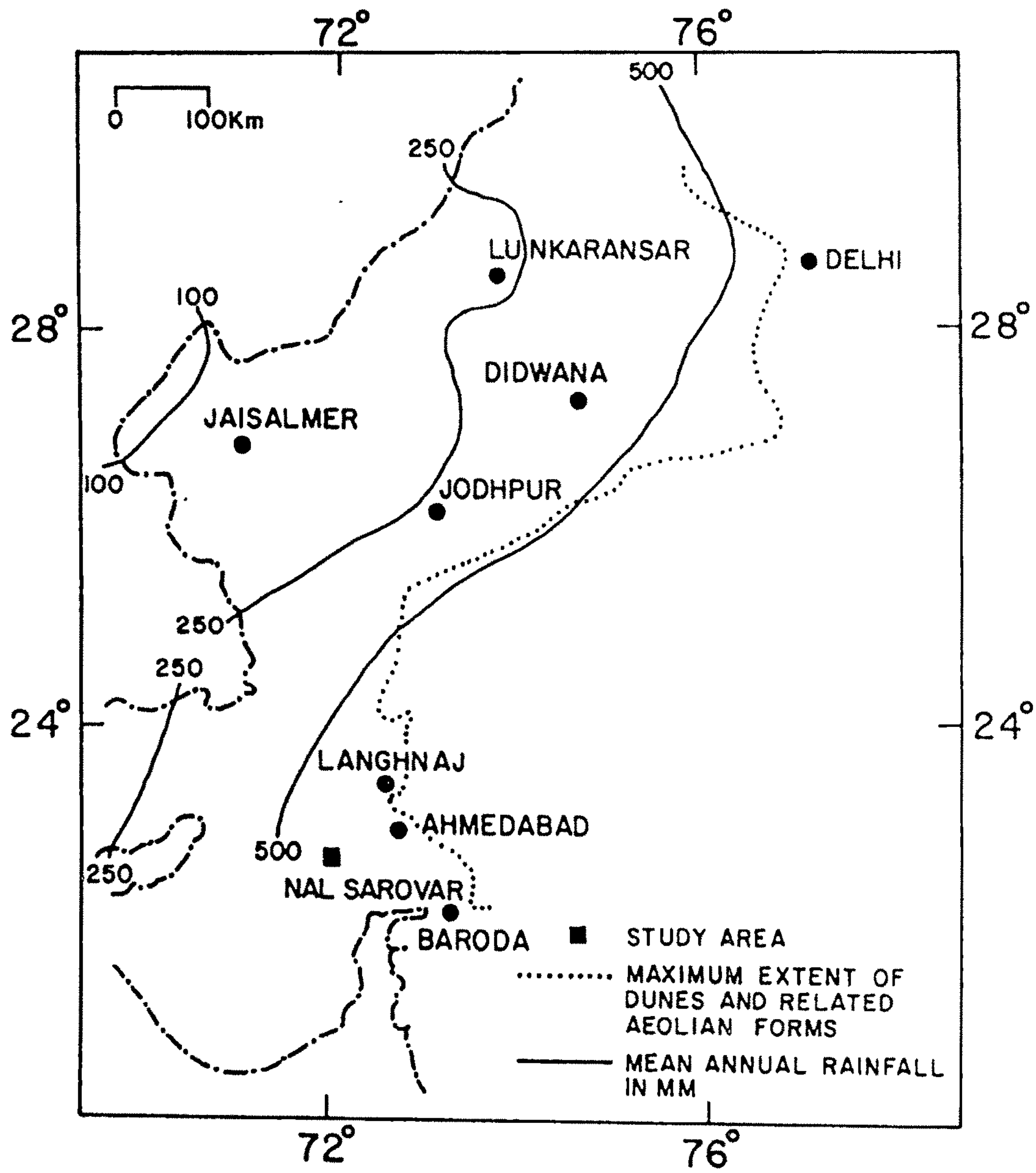

Fig. 3.1 The extent of fossil aeolian features and isohyet contours in north western India (modified version largely redrawn from Chawla et al, 1992). Sites mentioned in text are indicated.

^{210}Pb method: This method can be used to date sediments upto ~100 years. ^{222}Rn escapes from the soil into the atmosphere and through a series of short lived daughter products decays into ^{210}Pb (half life ~22 yrs). This isotope is subsequently removed through precipitation and gets incorporated into the sediments. The decay of ^{210}Pb is monitored to estimate the age of sediments.

^{137}Cs method: Another method used for dating of young sediments is based on identifying the layer that was deposited in the 1960's when the bomb produced ^{137}Cs (half life ~30 yrs) activity was the highest. ^{137}Cs too is incorporated in the sediments through scavenging from atmosphere by precipitation.

Radiocarbon method: In this method, activity of ^{14}C in the carbon containing matter is used to date sediments younger than ~40ka. Radiocarbon (^{14}C) is produced in the atmosphere by the capture of a cosmic ray produced neutron (n) by nitrogen (^{14}N) resulting in the emission of a proton and creation of ^{14}C which is then oxidised to $^{14}CO_2$. It is then distributed throughout the atmosphere and all carbon containing reservoirs through carbon cycle. Plants assimilate ^{14}C during photosynthesis. Animals feed on living plants or take up carbon in a variety of ways. As long as a sample is part of active carbon cycle, its ^{14}C activity is maintained at a constant level due to equilibrium between intake on one hand and radioactive decay on the other. Thus, all living creatures maintain their ^{14}C level during their lifetime. After the death of the organism or otherwise removal of the specimen from the active carbon reservoir, the ^{14}C input ceases. Time of death/removal can be established by determining residual ^{14}C content of the specimen and its initial activity in the active carbon reservoir, since without fresh intake, ^{14}C decays with a half life of 5730 ± 40 years.

Luminescence method: This method gives the time of last sun exposure of the sediments, prior to deposition. The basic principles of this method and results are discussed in detail in the next Chapter.

For the present study, considering the time scales involved, radiocarbon and luminescence method of dating were used. The experimental procedures employed are described in Appendix C and Appendix E respectively.

3.1.2 Sources of palaeoclimatic information

The palaeoclimatic information can be derived from a variety of data sources e.g. ocean and lake sediments, ice cores, tree rings etc. A list of data sources with the climatically sensitive variable, range of application, is summarised in Table 3.1.

However, on continents, in most geographical locations, many of these proxy recorders do not often provide long records and it becomes necessary to investigate other systems which may be expected to preserve fairly continuous, long record of palaeoclimate. A particularly promising source is the record preserved in lake sediments from climatically sensitive regions. Lakes have the advantage of providing generally undisturbed, continuous, high resolution palaeoclimatic records. Additionally, they have a far wider geographical distribution; this is especially useful for studying the latitudinal dependence of climate. Hydrological and biological changes within the lake, as well as in its catchment area, are recorded in the sediments, in a variety of ways including the isotopic composition of the organic components preserved in the lake sediments.

3.1.3 Palaeoclimatic studies in north-west India

From palaeoclimatic perspective, Rajasthan in north-west India, is one of the most extensively studied regions. A variety of proxy climate indicators e.g. pollens, mineralogy, geomorphology, have been used to infer the palaeoclimate. Some of the studies are summarised in the following.

Pollen and geochemical studies in the best studied Didwana lake show oscillating fresh and saline conditions from 9.3 to 7.5ka. Lake levels peaked in the interval 7.5-6.2ka; moderately fresh conditions persisted between 6.2-4.2ka (Wasson et al, 1984; Singh et al, 1990). Between 10.5-3.5ka, the estimated summer precipitation was nearly 2-3 times the present day value (Bryson and Swain, 1981; Swain et al 1983). By about 5ka the Indus valley culture was well established. Paleoclimatic

Table 3.1. Major palaeoclimatic data sources and their characteristics. (Compiled from Bradley, 1985; Matsumoto, 1991)

Data Source	Variable measured	Continuity of Evidence	Range (years)	Minimum Sampling Interval (years)	Climate Related Inferences
Ocean sediments	Isotopic composition of planktonic and benthic fossils, floral and faunal assemblages, morphological characteristics of fossils, mineralogical composition and abundance.	Continuous	10^6	Depends on sedimentation rate	T, S, B, I, W
Ice cores	Oxygen isotope composition, trace chemistry.	Continuous	10^5 +	variabie but optimally 1-10 yrs for last 10^4 yrs	T, C, S_a
Mountain glaciers	Terminal positions, equilibrium line altitudes.	Episodic	$5X10^4$	-	T, P
Bog or Lake sediments	Stable isotopes, pollen, sedimentology & mineralogy	Continuous	$5X10^4$	50 yrs	T, P, B
Dunes	Sand accumulation and stabilisation phases	Episodic	$5X10^4$	-	P
Tree rings	Ring width anomaly, density, isotopic composition	Continuous	$8X10^3$	1	T, P, S_a
Historical records	Phenology, weather logs etc.	Continuous	10^3 +	1	T, P, B, L
Corals	Stable Isotopes	Continuous	10^5	seasonal	T, C, L
Closed basin lakes	Lake level	Episodic	$5X10^4$	-	P

S = Salinity T = Temperature I = Ice volume W = Wind direction and strength B= Biota

C= Atmospheric composition S_a = Solar activity P= Effective precipitation L= Sea level.

reconstruction based on pollen data suggest not only more summer rainfall than present but maximum winter precipitation during the Indus valley culture, 5.5-3.5 ka BP (Bryson and Swain, 1981; Swain et al, 1983). From 4.2ka to present, in Didwana, only an ephemeral lake has persisted (Wasson et al, 1984; Singh et al 1990). Palynological data indicates increased salinity in lakes at ~3.7ka (Singh et al, 1972). However, according to Bryson and Swain (1981), the termination of the wet phase is around 3.5ka in Lunkaransar and 2.5ka in Didwana. At 3ka an extensive arid phase begins with rapid dune building (Singhvi et al 1989; Chawla et al, 1992). Archaeological evidence suggests diminishing aridity around 2ka and re-establishment of a seasonal lake at this time. The estimated summer precipitation in the subsequent period is only half of its pre-arid phase value. In this period highest rainfall amounts have been computed for the period 1.1-0.7ka BP (Bryson and Swain, 1981). Reconstruction of lake level (Wasson et al, 1984) and precipitation (Bryson and Swain, 1981) from Rajasthan are shown in Fig. 3.5.

3.2 Present study

In the present study stable isotopic composition of lacustrine organic matter from Nal Sarovar, together with C/N ratios, have been used for palaeoclimatic reconstruction. In the following section a brief account of the basic principles involved and results of present investigations are presented.

3.2.1 Basic principles

The application of stable isotopes in palaeoclimatic studies is based on the fact that there are finite differences between isotopic masses of elements (e.g. H, C, N, O) that lead to partitioning of isotopes in any physico-chemical process (Urey, 1947). In isotope geochemistry the concern is with measuring small changes in isotope ratios relative to a standard. The accepted unit of isotopic ratio measurement is 'δ', expressed as parts per mil (‰). Thus,

$$\delta = \frac{R\,(\text{sample}) - R(\text{standard})}{R\,(\text{standard})} \times 1000$$

where R denotes the isotopic ratio $^{18}O/^{16}O$, $^{13}C/^{12}C$ or D/H as the case may be. In the present study carbon isotopes were used and $\delta^{13}C$ values expressed with reference to PDB standard.

Isotopic fractionation is also observed in plant organic matter. Atmospheric carbon dioxide contains approx. 1.1% of ^{13}C. In the absence of industrial activity, the $\delta^{13}C$ value of atmospheric CO_2 would be -7‰ (Craig, 1957; Keeling, 1961). This forms the reservoir from which the carbon is fixed in organic matter via photosynthesis. During photosynthesis, plants discriminate against ^{13}C because of small differences in chemical and physical properties imparted by difference in mass. This difference can be used to assign plants to the following groups.

The first category comprises **C_3 plants** (Craig, 1953; Park and Epstein, 1960), which fix CO_2 by the action of the enzyme ribulose biphosphate carboxylase (Park and Epstein, 1960). In these plants, the initial chemical product formed during photosynthesis is a three carbon molecule - phosphoglyceric acid, hence the name. The process is called as the **Calvin cycle**.

The **C_4 plants**, in which CO_2 is initially taken up through carboxylation of phosphoenolpyruvate, were discovered in the 1960's (Kortschak et al, 1965; Hatch and Slack, 1970). The initial chemical product formed is a four carbon molecule, malic acid. This process is called as the **Hatch-Slack pathway**. Following this discovery, Bender (1968); Smith and Epstein (1971), discovered that C_4 plants are isotopically distinct from C_3 plants.

Application of stable isotopes as climatic indicators is based on the differing carbon isotopic values and ecological preferences of the C_3 and C_4 type of plants. C_4 plants favour conditions of aridity and low soil moisture whereas C_3 plants dominate areas of higher precipitation and higher soil moisture (Tieszen et al, 1979; O'Leary, 1988).

A third group of plants has also been reported which show $\delta^{13}C$ values overlapping between those of C_3 and C_4 plants (O'Leary, 1981). These comprise desert plants and other succulents which absorb CO_2 by the pathway known as Crassulacean acid metabolism (Kluge and Ting, 1978; Osmond, 1978) and are known as the **CAM plants.**

A survey of over 1000 published $\delta^{13}C$ analysis of whole plants, wood, leaves and seeds (Deines, 1980) showed the following average $\delta^{13}C$ values of the three categories of plants

C_3	..	-27 ‰
C_4	..	-14 ‰
CAM	..	-14 ‰ to -27 ‰

Of the aquatic plants, which are also present in a lake, the floating pond weeds utilise atmospheric CO_2, as the diffusion of CO_2 dissolved in water is several orders of magnitude slower than diffusion of CO_2 in air (O'Leary, 1988); these plants have $\delta^{13}C$ ratios similar to terrestrial plants (Oana and Deevey, 1960). For the submerged aquatics the picture is entirely different as the organic carbon is enriched in ^{13}C in proportion with the hardness of water (Oana and Deevey, 1960; Smith and Epstein, 1971). With increasing hardness an enrichment in ^{13}C has been observed in *Chara, Potomogeton, Nitella* etc. This effect has been attributed to increased utilisation by submerged plants of the bicarbonate component in hard water lakes, instead of dissolved CO_2. Any change in hardness of water associated with a long term climatic factors could result in a change in $\delta^{13}C$ component of upto 10‰ (Stuiver, 1975).

The organic matter in a lake is contributed both by terrestrial and aquatic plants. Hence, for a meaningful interpretation of $\delta^{13}C$ variations, it becomes necessary to be able to establish the dominance of either at any particular period of time. To distinguish between organic matter of terrestrial and aquatic origin, carbon to nitrogen ratios have been used (Sweeny et al, 1980; Wetzel, 1983). Autochthonous organic matter (from within the lake) comprising aquatic plants and algae have a C/N ratio of less than 10 (Meybeck, 1982). This is because organic nitrogen occurs preferentially in proteins and nucleic acids (Blackburn, 1983) which are relatively more abundant in lower plants like aquatic phytoplankton and in bacteria. Higher terrestrial plants have lignin and cellulose which are nitrogen poor; hence allochthonous organic matter (from catchment area) has C/N values which are higher than 20 and may even go as high as 200 (Hedges et al, 1986). Higher values of C/N are indicative of a dominant terrestrial contribution whereas lower values are indicative of a dominant aquatic contribution to the organic matter. Some of the lakes where these techniques have been applied, for palaeoclimatic reconstruction, are lake Biwa, Japan (Nakai and Koyama, 1987); Karewa lake sediments in India (Krishnamurthy et al, 1986); lake Bosumtwi, W. Africa (Talbot and Johannessen, 1992).

3.2.2 Results and discussion

<u>Horizon-3 and Horizon-2</u>

Chronology: Between 3-54m depth, the amount of organic matter was very small (<0.01%). Hence, ^{14}C dating could be done only on carbonate nodules found occasionally. These gave a date of >38ka at 16m depth and below. The results are shown in table 3.2 below.

Table 3.2 Radiocarbon dates for Horizon-2 & 3, Nal Sarovar core.

Lab. No.	Radiocarbon Lab. No.	Depth (cm)	^{14}C Age (ka) (carbonate)
N-164	PRL-1735	1645-1662	>38
N-167	PRL-1731	1825-1835	>38
N-424	PRL-1720	5465-5485	>38

In the absence of significant organic matter and adequate chronological control, no palaeoclimatic studies were carried out on these two horizons. For Horizon-2, the presence of red beds with calcareous cement is indicative of their formation in an arid environment. The presence of gypsum (at 4m, 5m and 7m depth) is also indicative of aridity. A broad picture of depositional environment emerging from geomorphological and sedimentological studies has already been discussed in Chapter 2 (Section 2.2).

Horizon-1

Chronology: The radiocarbon dates were obtained on bulk organic matter from samples which had been treated by dilute HCl to remove carbonate material (refer to Appendix C for experimental details). Eight samples were dated (see Table 3.3, Fig 3.2) and the estimated age, for any particular depth, was calculated by interpolation using a second order fit to the depth vs. radiocarbon age data, as under,

$$\text{Age (ka)} = -0.00003*(\text{Depth})^2 + 0.0308*(\text{Depth}) - 0.037 \quad \text{... (equation 3.1)}$$

where "Depth" is in cm.

Table 3.3 Radiocarbon dates for Horizon-1, Nal Sarovar core.

Lab. No.	Radiocarbon Lab. No.	Depth (cm)	$^{14}C^*$ Age (years) (organic)
N-1+N-2	PRL (1753+1754)	0-10	Bomb
N-3+N-4	PRL (1755+1756)	10-20	490±110
N-20+N-21	PRL (1773+1774)	58.5-62.5	1780±100
N-52	PRL-1818	124-126	3110±110
N-69+N-70+N-71	PRL-1830	158-164	4400±120
N-76	PRL-1817	207-220	5100±120
N-82	PRL-1876	270-280	5380±130
N-86	PRL-1826	300-309	6750±130

* ^{14}C half life is 5730±40 years.

Stable Isotope studies: A special glass, vacuum line for gas extraction and C/N analysis was constructed. The same is described in Appendix D alongwith other experimental procedures involved in $\delta^{13}C$ and C/N analyses of the sample. Preliminary measurements indicated that only the top 3m of the core had any significant proportion (~1%) of organic matter, thus limiting the study to Horizon-1.

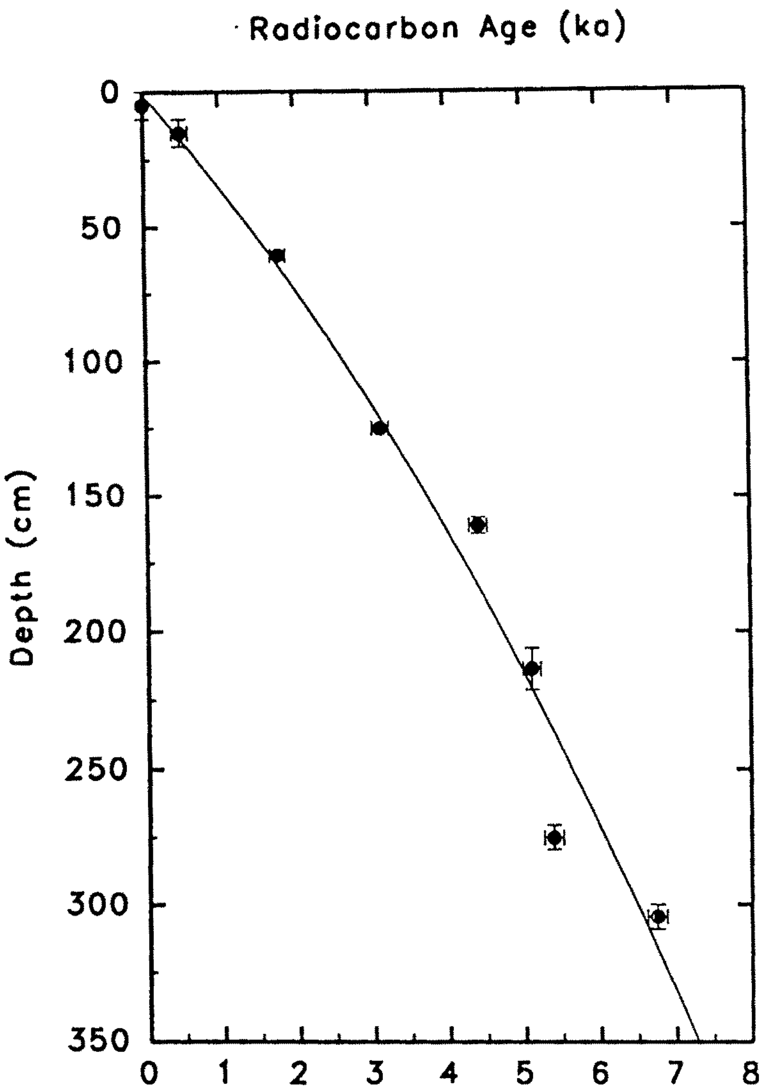

Fig. 3.2 Plot of radiocarbon dates vs. depth, Nal Sarovar core.

Modern samples To investigate the range of $\delta^{13}C$ and C/N in terrestrial and aquatic plants, as also to constrain the limits of $\delta^{13}C$ variation in submerged plants, a few present day plants from Nal Sarovar were also analysed (Table 3.4). Of the present day plants analysed, the terrestrial plant *Cyanadon* showed a C/N value of 24.3 and a $\delta^{13}C$ value of -13.2‰ indicating it to be of C_4 type plant. The aquatic types showed, as expected, a C/N value <10. The decayed vegetation matter, 'scum' floating on the surface of the water was also analysed and showed a C/N value of 15.2 indicating contribution from both aquatics as well as from terrestrial plants. The surface sediment however shows a C/N value of 5.9. This indicated that, at least today, the dominant contribution to sediment organic matter in the lake is from aquatic plants.

Najas is a free floating plant that takes up CO_2 chiefly from atmosphere. The diffusion of CO_2 into the plants from water is several orders of magnitude slower than in air (O'Leary, 1988). Hence the isotopic signal, $\delta^{13}C$ = -22 ‰, from *Najas* is dominated by atmospheric CO_2. In view of the enrichment of 10‰ for submerged aquatics due to climatic factors (Stuiver, 1975), the maximum enriched value of $\delta^{13}C$ that could be expected at Nal Sarovar in totally submerged plants are around -12 ‰.

Table 3.4 Results of C, N and $\delta^{13}C$ analyses on present day samples from Nal Sarovar.

Sample	Habitat	$\delta^{13}C$ (‰)	C/N
Nitella Sp.	Bottom aquatic	-23.5	8.1
Najas Sp.	Floating aquatic	-22.1	9.9
Cyanadon Sp.	Terrestrial	-13.2	24.3
Cyprus Sp.	Aquatic/terres.	-27.5	nm
Scum	-	-16.8	15.2
Top sediment	-	-21.3	5.9

1. nm = not measured
2. Identification of plant species and habitat by botany dept. Gujarat Univ. Ahmedabad.

Core Samples The results of %c, %N, $\delta^{13}C$, C/N analyses on organic matter and % sand in sediments from the Nal Sarovar core samples are shown in Table 3.5. These are also plotted in Fig 3.3 in the form of %C, %N, $\delta^{13}C$, C/N and % sand vs. radiocarbon age. Regression equation 3.1 was used for interpolation of ^{14}C ages.

The organic matter from Nal Sarovar samples showed a range of $\delta^{13}C$ from -15‰ to -23‰. C/N values varied from 6 to 50. Both these factors indicated that there had been variation in the relative contribution from aquatic and terrestrial plants as also in the nature of terrestrial plant population.

Table 3.5 Results of C, N, $\delta^{13}C$ and % sand analyses on samples from Nal Sarovar core.

Lab. No.	Depth (cm)	C (Wt %)	N (Wt %)	C/N	$\delta^{13}C$ (‰)	Sand (%)
N-1	5	1.43	0.09	15.88	-19.9	4.1
N-4	15	0.91	0.12	7.58	-18.8	3.84
N-5	27	1.03	0.06	17.16	-19.1	1.38
N-8	33	1.00	0.05	20	-18.9	1.42
N-11	39.5	0.95	0.09	10.55	-19.2	4.17
N-13	43.5	0.87	0.08	10.87	-18.2	1.91
N-17	49.5	0.89	0.11	8.09	-18.6	1.55
N-18	53.5	0.90	0.05	18	-18.3	2.17
N-20	57.5	0.90	0.05	18	-18.8	2.02
N-21	59.5	0.77	0.06	12.83	-19.8	1.18
N-23	63.5	0.93	0.06	15.5	-18.2	1.91
N-26	69.5	0.85	0.12	7.08	-18.1	2.33
N-28	73.5	0.89	0.06	14.8	-20.4	2.51
N-31	79.5	0.79	0.06	13.16	-18.8	2.24
N-33	85	1.02	0.09	11.33	-18.9	2.08
N-37	94	1.71	0.12	14.25	-20.0	3.38

... continued

Table 3.5 Continued

Lab. No.	Depth (cm)	C (Wt %)	N (Wt %)	C/N	$\delta^{13}C$ (‰)	Sand (%)
N-40	100	0.94	0.09	10.44	-21.4	1.87
N-47	115	0.98	0.15	6.53	-21.9	5.72
N-49	119	0.98	0.05	19.6	-22.8	7.26
N-52	125	1.18	0.06	19.66	-19.8	3.89
N-55	130	1.22	0.09	13.55	-22.9	6.17
N-60	141	0.96	0.05	19.2	-21.7	3.31
N-65	151	1.09	0.06	18.16	-21.6	2.55
N-70	161	0.94	0.06	15.66	-20.9	2.77
N-72	165	1.03	0.07	14.71	-19.3	9.74
N-73	171	1.09	0.08	13.62	-20.4	6.62
N-74	184.5	0.91	0.05	18.2	-19.9	2.91
N-75	201	0.82	0.02	41	-20.6	6.38
N-76	213.5	0.72	0.02	36	-20.6	4.93
N-77	225	1.01	0.02	50.5	-20.5	6.65
N-78	235	1.21	0.06	20.16	-21.9	5.61
N-79	245	1.06	0.05	21.2	-21.7	6.16
N-80	255.5	0.98	0.02	49	-22.8	7.98
N-82	275	0.82	0.09	9.11	-20.7	10.09
N-84	291.5	1.47	0.14	10.5	-17.7	14.94
N-85	296	0.75	0.04	18.75	-16.3	32.22
N-86	304.5	3.31	0.09	17.42	-16.8	39.78
N-87	310.5	0.64	0.03	21.33	-14.9	57.28

Note

1. $\delta^{13}C$ values are relative to the PDB standard.

2. The experimental procedure and the results of standards are given in Appendix D.

3. Reproducibility on repeated measurements of UCLA standard were 0.2‰

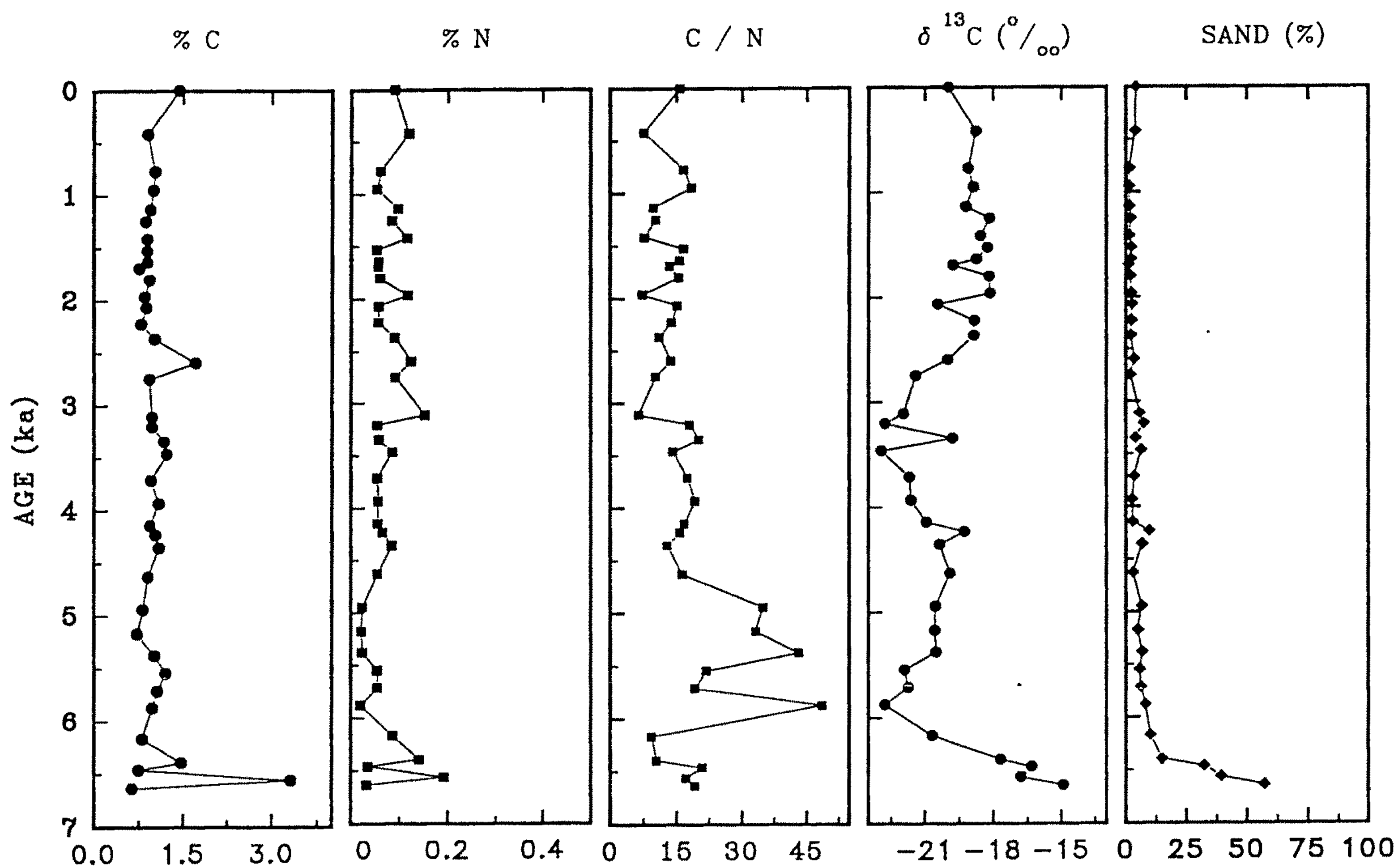

Fig. 3.3 Age variation of %C, %N, C/N, $\delta^{13}C$, and % sand in sediment samples from Nal Sarovar core.

It is possible that the observed variation in C/N vs. age (Fig. 3.3) may be due to loss of nitrogen with age as, nitrogen bearing compounds are more prone to loss during decomposition (Lee and Olson, 1984). The following interpretation assumes that there has not been any loss of nitrogen. This is also supported by plots of nitrogen and carbon versus age which do not show any systematic loss of nitrogen with age. Also, there is a strong correlation between C and N (r^2=0.64, at 95% confidence interval) suggesting that both C and N are organically bound. Though C/N and $\delta^{13}C$ do not show any correlation as a whole, it is possible to identify certain periods where a systematic trend in variation of C/N and $\delta^{13}C$ can be observed (Fig. 3.4). The climatic implications of these systematic variations are discussed below. In the following discussion, the terms 'wetter' or 'drier' are with respect to 'present'. Due to inherent errors in radiocarbon dating and of interpolation, the climatic boundaries may have an error of upto ±250 years.

Period 5 (~6.6-6ka): At the beginning of this period C/N ratios are close to ~20 indicating significant terrestrial contribution to the lake. The $\delta^{13}C$ values are enriched (~-15‰) indicating a dominance of C_4 type of vegetation and/or aquatics growing in waters rich in dissolved carbonate. This period also shows a relatively higher proportion of sand (Fig 3.3) which is interpreted to indicate that the surrounding sediments had not yet been stabilised by vegetation and were easily eroded and deposited into the lake.

The climate during early part of this period must have been dry. This is followed by a phase during which there is a decrease in C/N, accompanied by rapid depletion in $\delta^{13}C$, indicating a shift to a wetter climate towards the end of this period.

Period 4 (6-4.8ka): High C/N values, at times close to 40, are indicative of an increased dominance of the terrestrial plants to the lake sediments. This is accompanied by 3‰ enrichment in $\delta^{13}C$, indicating a small shift towards C_4 type of vegetation. As noted earlier (Chapter 2; Section 2.2.3.1), fresh water shells of *Bittium* and few land snail shells were found in this zone (Fig. 3.4,

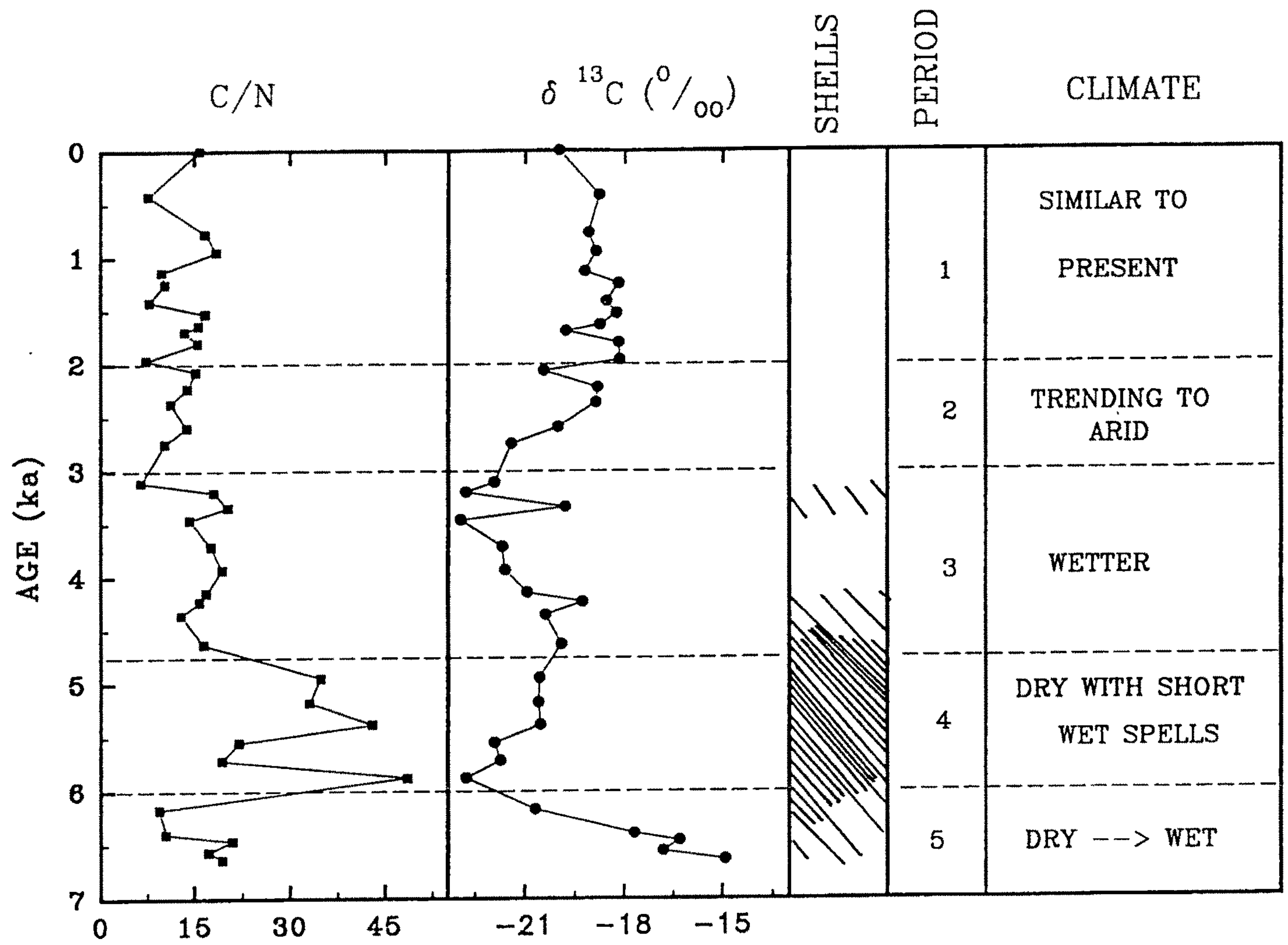

Fig. 3.4 Palaeoclimatic interpretation of C/N and $\delta^{13}C$ variations in sediment samples from Nal Sarovar core.

PLATE 3). Based on their presence in large abundance and small size, the lake environment was described as shallow fresh water with periodic drying up of the water body (Jain, pers. comm. 1996).

The almost complete absence of aquatic plants is also indicative of a dry or a shallow lake bed with evenly distributed short wet spells which, though capable of sustaining and bringing in the terrestrial organic matter, were insufficient to sustain aquatic vegetation in the lake. It is likely that the even distribution was achieved by an increase in winter rainfall and decrease in summer rainfall relative to present. Such a shift would explain high C/N and hence absence of aquatic vegetation, yet an abundance of shallow fresh water shells, as also a slight shift towards C_4 type of vegetation. The overall climate in this period can be described as dominantly dry with short wet spells.

Period 3 (4.8-3ka): In this period, average C/N ratio declined to ~15 indicating a mixed contribution from both aquatic and terrestrial biota. The $\delta^{13}C$ values of organic component began to deplete again from the start of this period and reached their lowest around ~3ka.

Increase in aquatic contribution accompanied by depletion in $\delta^{13}C$ of lake organic matter, indicates a higher lake level. Overall, during this period the climate was wet.

Period 2 (3-2ka): Presence of mixed terrestrial and aquatic vegetation was indicated by C/N value of ~15. This, together with, gradual enrichment of $\delta^{13}C$ values, indicates lower effective precipitation so that the aquatic vegetation was utilising dissolved bicarbonate from the lake.

The overall climate in this period was still wetter than present but the trend towards aridity had begun at 3ka. Present day conditions were reached at about 2ka.

Period 1 (2ka-Present): The $\delta^{13}C$ values did not show any significant variation. C/N ratios showed a generally mixed vegetation but at certain periods the organic matter was increasingly dominated by the aquatic contribution as at 1.9, 1-1.3 and 0.4 ka BP. This, perhaps, represented short spells when the water level was high. The overall climate in this period was similar to present.

The above presented basic isotopic data and climatic interpretation from Nal Sarovar indicated a drier than present period from ~6.6 to ~4.8ka. This was interrupted by a short wet episode at ~6.2 ka. In the period 4.8-3ka the climatic conditions are inferred to have been wetter than present and the lake generally had fresh water conditions. It is interesting to note that around this period, the Indus valley civilisation had flourished in NW India and Pakistan. Nal lake data shows a short (probably a couple of hundred years) arid interval at ~3.2 ka. One may be tempted to ascribe the observed decline of Indus valley civilisation to this arid phase but there is only one data point suggesting this short dry period. Even though this data point has been rechecked, its archaeological significance needs confirmation from other sources. From 3ka onwards, the aridity seems to increase until the present day climate was established at 2ka.

This climatic interpretation is significantly different from the palaeoclimatic interpretations based on palynological and geochemical data obtained from Lunkaransar (Bryson and Swain, 1981; Swain et al, 1983) and Didwana (Bryson et al, 1981; Wasson et al, 1984; Singh et al, 1990) lakes in Rajasthan (Fig. 3.5). The palaeoclimatic record for the period 6.5-4.8ka from both the lakes in Rajasthan showed higher annual rainfall (nearly 2-3 times the present value - Bryson and Swain, 1981; Swain et al, 1983). This is in contradiction to present data for the same period which indicated a shallow lake level, with periodic drying, and an almost complete absence of aquatics, except for a short wet episode ~6.2 ka. It is possible that the inferred uniform distribution of wet spells in Period 4 (6-4.8ka) was achieved through increase in winter precipitation accompanied by a larger decrease in summer rainfall as the overall climate has been inferred to have been dry. Nal lake data, indicating a wetter than present climate in the succeeding period (4.8-3ka), is comparable with the Rajasthan precipitation

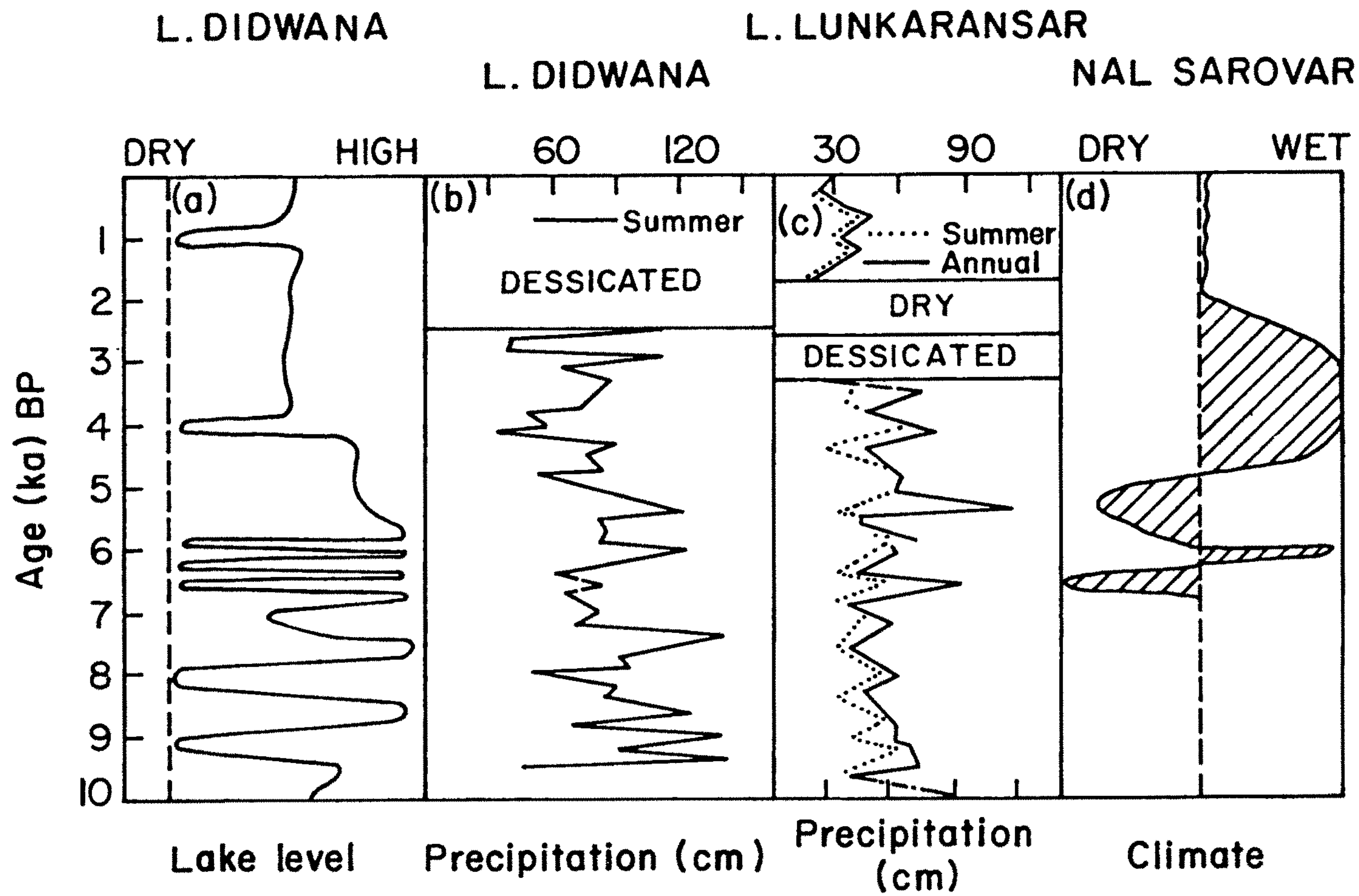

Fig. 3.5 A comparison of palaeoclimatic data from Didwana and Lunkaransar lakes in Rajasthan with Nal Sarovar (a) Wasson et al. 1984; (b)&(c), Bryson and Swain, (1981)

data which too indicated a higher than present rainfall. While it has not been possible to quantify the Nal lake data in terms of rainfall changes, the observed shifts in C/N ratio and $\delta^{13}C$ are not large enough to have been caused by very significant increase in rainfall (2-3 times the present value) in the catchment areas of Nal Sarovar, as has been interpreted by Bryson and Swain (1981), for the Rajasthan lakes for the same period.

As indicated in Fig 3.5, the termination of the wet phase is around 3.5ka in Lunkaransar and 2.5ka in Didwana (Bryson and Swain, 1981). However, according to Wasson et al (1984), this wet phase at Didwana ended earlier at 4ka when present day dry conditions were established. Singhvi et al (1989), and Chawla et al (1992), based on TL dating of dune sands, indicated an arid phase with rapid dune building activity at 3ka followed by diminishing aridity at 2ka and establishment of present day conditions. The Nal data also indicates the beginning of aridity around 3ka BP and onset of present day conditions around 2ka BP. There appears to be a general agreement in all data sets regarding establishment of present day conditions ~2 ka BP.

It is possible that the palaeoclimatic variations recorded at Nal Sarovar largely reflect a local picture. At present this can only be checked by the use of other indirect parameters which influence the climate in this region. Nal Sarovar lies in the region where SW monsoon is the most important factor in influencing the climatic record. Sensitivity experiments with GCM's have already shown that albedo changes induced by changing snow cover over Eurasia exert considerable control over the development of continental heat low over Asia, which in turn, affects the strength and duration of the south-west monsoon over the Arabian sea (Barnett et al, 1989). In the past, there is evidence of expanded glacier cover between 5.7-4ka BP in China (Li, 1990) and colder climates between ~5.5-5ka from N. China (Yan and Petit-Maire, 1994). There are also evidences, in Europe, of Holocene glacier expansion at 6.5ka, repeated expansions around 5ka

BP (Bradley, 1985 and references therein) and between 3-2.2ka (Denton and Karlen, 1973). These cold periods with expanded glaciers in Eurasia appear to correlate well with the drier periods recorded at Nal lake. This suggests that the monsoon influenced palaeoclimatic record at Nal Sarovar may reflect a regional history of past climatic variations.