

Vegetation changes during the Holocene in Sierra Nevada

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Postglacial history of alpine vegetation, fire, and climate from Laguna de Río Seco, Sierra Nevada, southern Spain

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The Sierra Nevada in southern Spain is a landscape with a rich biological and cultural heritage. The range was extensively glaciated during the late Pleistocene, but the postglacial paleoclimatic history of the region is less well known. In this study, we present a detailed pollen record from a high-elevation wetland lake above present-day Laguna de Río Seco at 3020 m elevation, as a paleoenvironmental study documenting over 11,500 calendar years of vegetation and climate change, addressing ecological and paleoanthropological issues in the context of the Holocene environmental evolution of the region. The early record is dominated by Pinus pollen, with Betula, deciduous Quercus, and grasses, with an uncertainty of tree presence. It is unlikely that pine trees grew around the lake, and fire was relatively uncommon. There is evidence for a significant increase in grasses and shrubs between ca. 6500 and 5500 cal yr BP, followed by a progressive aridification from 7000 cal yr BP that occurred in two steps, first shown by a decrease in Pinus, replaced by Pinus from ca. 4000 cal yr BP and then by Cyperaceae, grasses, and Ericaceae. Between ca. 3000 and 2000 cal yr BP, there is a significant increase in grasses and sedges, with a minimum in pollen diversity at ca. 2500 cal yr BP. This is in contrast to lower elevations where grasses and sedges increased earlier. The record shows that the vegetation response to the high-sea isolation may have transitioned to greater snowpack and subsequently higher lake levels at higher elevations, but not necessarily at lower elevations, where higher evaporation rates prevailed. With declining lake levels, the vegetation response to the aridification was more pronounced at higher elevations, while the highest elevation site remained high, but lake levels at lower elevation sites increased as evaporation rates decreased. Tree coverage continued to expand, especially after ca. 3700 cal yr BP, showing an increase in Betula, followed by a period of increasing grasses and shrubs, with a final stage dominated by grasses and shrubs (mainly *Quercus ilex* and *Juniperus*, Armeria, and others). The disappearance or decline of mesophytes, such as *Artemisia* from ca. 4000 cal yr BP, is interpreted as a response to drier conditions. The vegetation response to the end of the last glacial maximum has been interpreted as a response to the end of the last interglacial, and the start of the late Holocene. On the other hand, continues some increase in Laguna de Río Seco recent after ca. 4000 cal yr BP and especially in post-Holocene times, probably due to arborization. Though not as important as the vegetation response to the last glacial maximum, the human impact on the vegetation is evident in response to regional human population expansion. The local and regional impact of human activity on the vegetation is reflected in the pollen record as a significant increase in grasses and sedges, coinciding with increases in edaphic parameters such as soil depth and nutrient enrichment. The human impact is not as extensive as at high elevation as at lower elevation sites in southern Sierra Nevada, but remains continuous that even remote sites were not free of direct human influence during the Holocene.

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1. Introduction

The Sierra Nevada – the largest mountain range in southern Spain and the highest range in Europe outside of the Alps – is an immense landscape with a rich biological and cultural heritage.

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Situated in the region of Andalucía, this area has been occupied and exploited by successive waves of humans since at least Neolithic times, and perhaps even earlier (Carrón et al., 2007; Gil-Romera et al., 2010), including the Metallurgical Chalcolithic and Bronze Age (e.g., Tartessos, Iberian, etc.), Roman, Visigoths, Moors and Christians. The people that have impacted on the landscape. Within a span of ca 40 km, the mountain range rises to nearly 3500 m elevation from sea level, creating a region of



Holocene vegetation and climate change recorded in alpine bog sediments from the laguna de la Virgen, Sierra Nevada, southern Spain

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Introduction

The complex climatology of the Mediterranean basin, located at the interface between the temperate and arid climate to the north and the subtropical and the semiarid to the south, challenges and opportunities for the paleoecologist interested in the long-term environmental history of the region. More specifically, the role of the Atlantic Ocean in the climate system of the region can be best in the past, by (1) atmospheric and oceanic linkages to the North Atlantic region (Hawley et al., 2009), influenced by the North Atlantic Oscillation (NAO); (2) the influence of the North Atlantic on the Hadley Cell circulation (Roberts et al., 2010) and refraction thereof; and (3) indirect effects of the African and Asian monsoons on the climate of the Mediterranean and east (Llorente et al., 2006). The relative importance of each of these phenomena has undoubtedly varied through time (Tzedakis, 2007).

In the western Mediterranean, strong relationships have been observed between precipitation and vegetation (i.e., lake level, fire history, fluvial activity, Mediterranean surface temperature and salinity, marine sedimentation) with the main phytogeographic zones (e.g., Sub-Mediterranean, Subatlantic, Subhumid, Moors and Chaco) being particularly prominent on the landscape. Within a span of ca 40 km, the mountain range rises to nearly 3500 m elevation from sea level, creating a region of

high-relief and alpine lakes and wetlands, situated in continental vegetation records from this area. Climate and human impact are indistinctly mentioned as causes of these rapid oscillations in vegetation (see e.g., Mencuccini et al., 2011). Therefore, unanswered questions remain with respect to the timing, nature and mechanics of abrupt climate and vegetation changes in the Western Mediterranean region.

High-relief and alpine lakes and wetlands, situated in continental

vegetation during the late glacial and early Holocene (Tinner and Thébaud, 2003; Tinner and Katerleider, 2005; Jiménez-Moreno et al., 2008, 2011) and references therein; Vannière et al., 2011; Gracia et al., 2011). These records show an early humid Holocene (11,000–7000 cal yr BP), a transition period (7000–5500 cal yr BP) and a late Holocene (5500 cal yr BP–present) characterized by a progressive aridification (Jalil et al., 2011). This sequence has been reproduced recently for a high-elevation site – Laguna de la Virgen (Jiménez-Moreno et al., 2008, 2011) – which also records early Holocene (ca. 11,500–8500 cal yr BP) mesophytic maxima. However, in several lowland pollen sites from southeastern Spain, the Holocene (ca. 11,500–5500 cal yr BP) may have been the humid maxima (Carrón et al., 2010 and references therein), and perhaps the highest lake levels (e.g., Reed et al., 2009; Jiménez-Moreno et al., 2011). The timing and magnitude of the long-term climatic phases of the Holocene. Moreover, due to low temporal sample resolution, age uncertainties and/or sensitivity, there has been little work done on the timing and causes of these abrupt climate and continental-scale fluctuations in continental vegetation records from this area. Climate and human impact are indistinctly mentioned as causes of these rapid oscillations in vegetation (see e.g., Mencuccini et al., 2011). Therefore, unanswered questions remain with respect to the timing, nature and mechanics of abrupt climate and vegetation changes in the Western Mediterranean region.

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ORIGINAL PAPER

Holocene environmental change in southern Spain deduced from the isotopic record of a high-elevation wetland in Sierra Nevada

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Abstract: Small lakes and wetlands from high elevation in the Mediterranean region of southern Spain preserve a complete post-glacial Holocene record. Isotope, TOC and CN analyses, carried out on a sediment core, show various stages in the evolution of the Biogenic sediments of the laguna de la Virgen, which today constitute a small bog about 2950 m above sea level. Glacial erosion generated a cirque depression, which became a small lake during the phase of infilling from 8,200 to 5,100 cal yr BP, as suggested by sedimentary evidence, including an atomic C/N ratio generally below 20, low TOC values and the highest δ¹³C values

values of the record. These results imply significant algal production, which is also supported by the presence of algal remains. Drier conditions became established progressively in this area from 5,100–3,700 cal yr BP. Subsequently, the lake evolved into a bog as shown by geochemical evidence (C/N ratios above 20, high TOC content and low δ¹³C values). Unstable conditions prevailed from 3,600 to 700 cal yr BP, an extremely low sedimentation rate and scarcity of data from this period do not allow us to make a coherent interpretation. Fluctuating conditions were recorded during the last ~2000 yr, with a general trend of increasing precipitation. The first part of this interval (with CN values between 20 up to 2500 years ago). In general, a gradual trend toward more arid conditions occurred since ~6,900–5,100 cal yr BP, with a further increase in aridity since ~5,100 cal yr BP. This evidence is consistent with other contemporaneous peri-Mediterranean records.

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Keywords: Holocene · Wetlands · Southern Spain · Isotopic geochemistry · Organic matter

Introduction
Many recent sedimentary studies using lake sediments of the Mediterranean region have focused on Holocene climate change (deMenocal et al., 2000; Bar-Matthews et al., 2000; Magny 2004; Zanchetta et al., 2007). One recurring conclusion of this research concerns the high sensitivity of Mediterranean forests

to climate change (see reviews by Anderson et al., 2001;

Anderson and Jiménez-Moreno, 2005; Jiménez-Moreno et al., 2008, 2011).

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Anderson et al., 2011 Jiménez-Moreno & Anderson, 2012 Jiménez-Moreno et al., 2013

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Sierra Nevada

Southernmost alpine mountain range in Europe

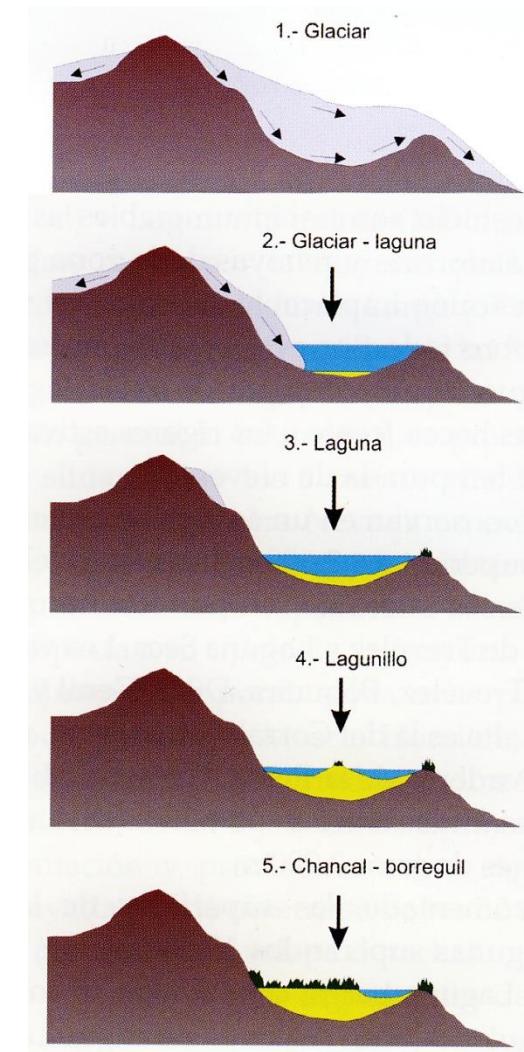
Very interesting location with respect to biogeography and Paleoclimatology



Sierra Nevada



High elevation (Mulhacén: 3478 m)
Glacial Geomorphology
Glacial Lakes



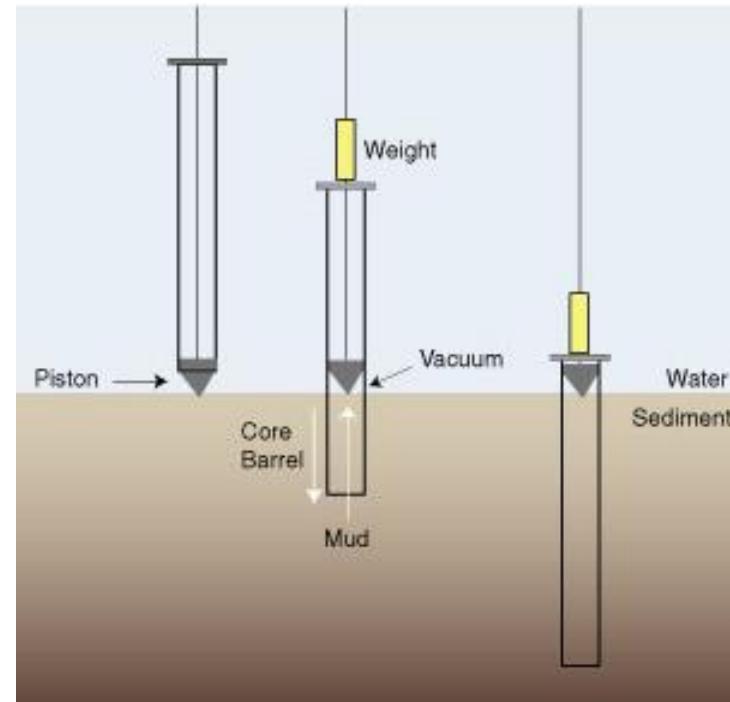
Sierra Nevada

More than 50 small lakes of glacial origin between 2800-3100 m,
many of them are permanent

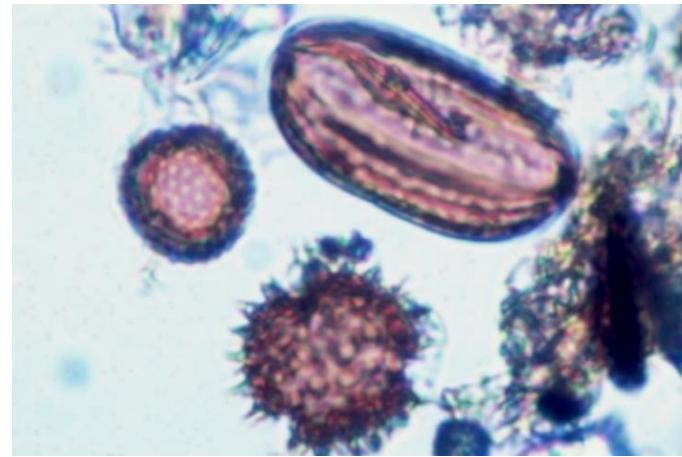


Sierra Nevada

Sediments bear fossil remains and other organic/inorganic elements that are going to give us information about processes occurring in and around the basin



Pollen grains

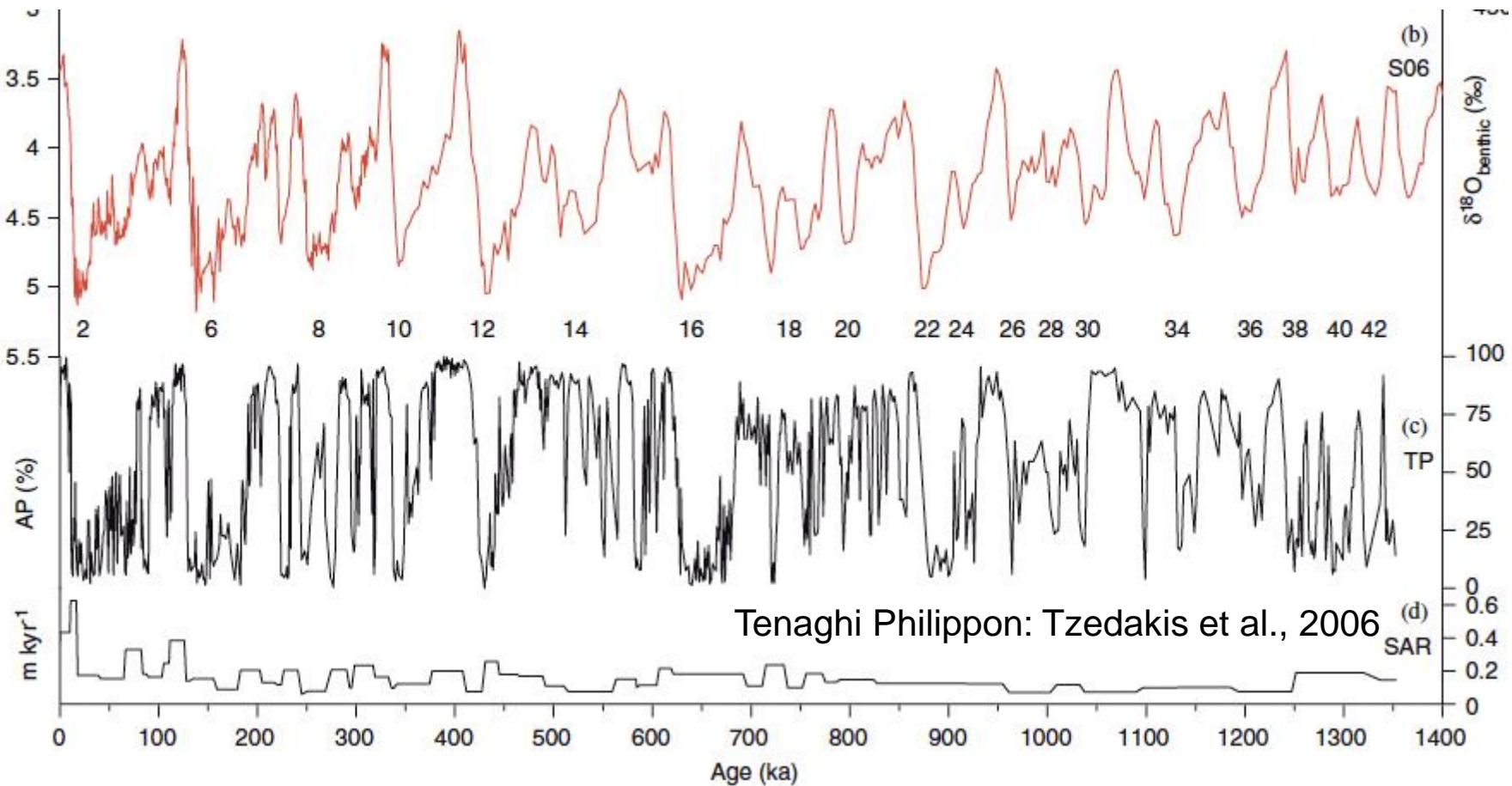


Vegetation changes



In the Mediterranean area:

-Warm and wet climates = More forest (i.e., *Quercus*)



Cold and dry conditions: steppe taxa

Vegetation belt	Elevation (m)	Most characteristic taxa
Criromediterranean	>2800	<i>Festuca clementei, Hormatophylla purpurea, Erigeron frigidus, Saxifraga nevadensis, Viola crassiuscula, and Linaria glacialis</i>
Oromediterranean	1900–2800	<i>Pinus sylvestris, P. nigra, Juniperus hemisphaerica, J. sabina, J. communis subsp. nana, Genista versicolor, Cytisus oromediterraneus, Hormatophylla spinosa, Prunus prostrata, Deschampsia iberica and Astragalus sempervirens subsp. nevadensis</i>
Supramediterranean	1400–1900	<i>Quercus pyrenaica, Q. faginea, Q. rotundifolia, Acer opalus subsp. granatense, Fraxinus angustifolia, Sorbus torminalis, Adenocarpus decorticans, Helleborus foetidus, Daphne gnidium, Clematis flammula, Cistus laurifolius, Berberis hispanicus, Festuca scariosa and Artemisia glutinosa</i>
Mesomediterranean	600–1400	<i>Quercus rotundifolia, Retama sphaerocarpa, Paeonia coriacea, Juniperus oxycedrus, Rubia peregrina, Asparagus acutifolius, D. gnidium, Ulex parviflorus, Genista umbellata, Cistus albidus and C. laurifolius</i>

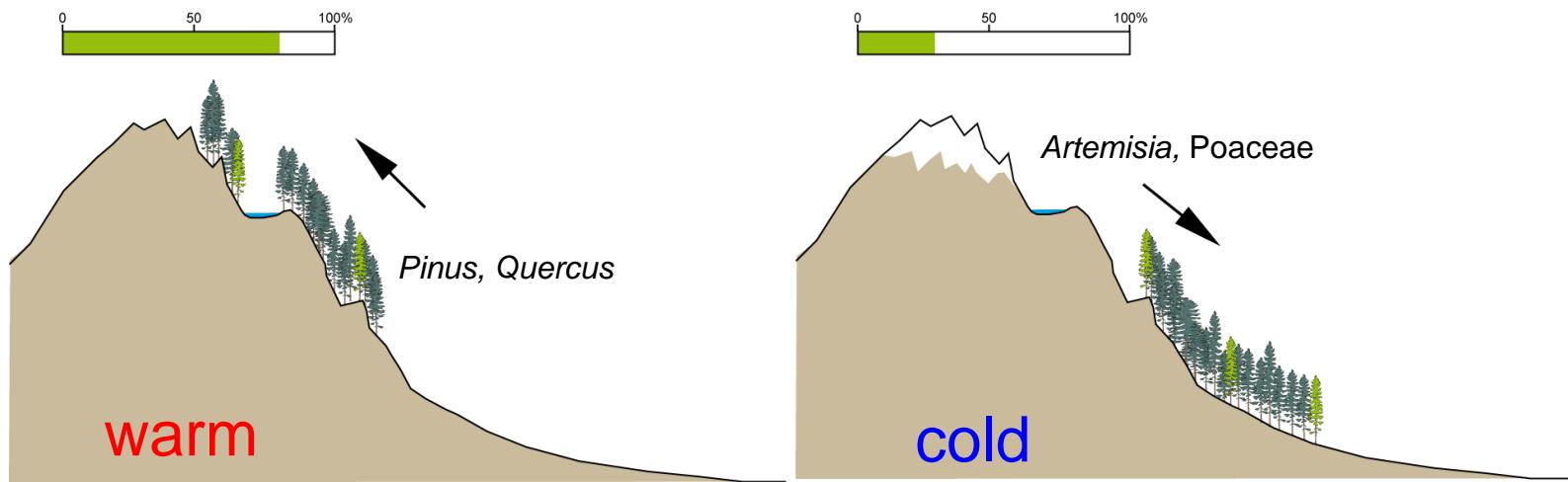
Treeline: ca. 2500 m



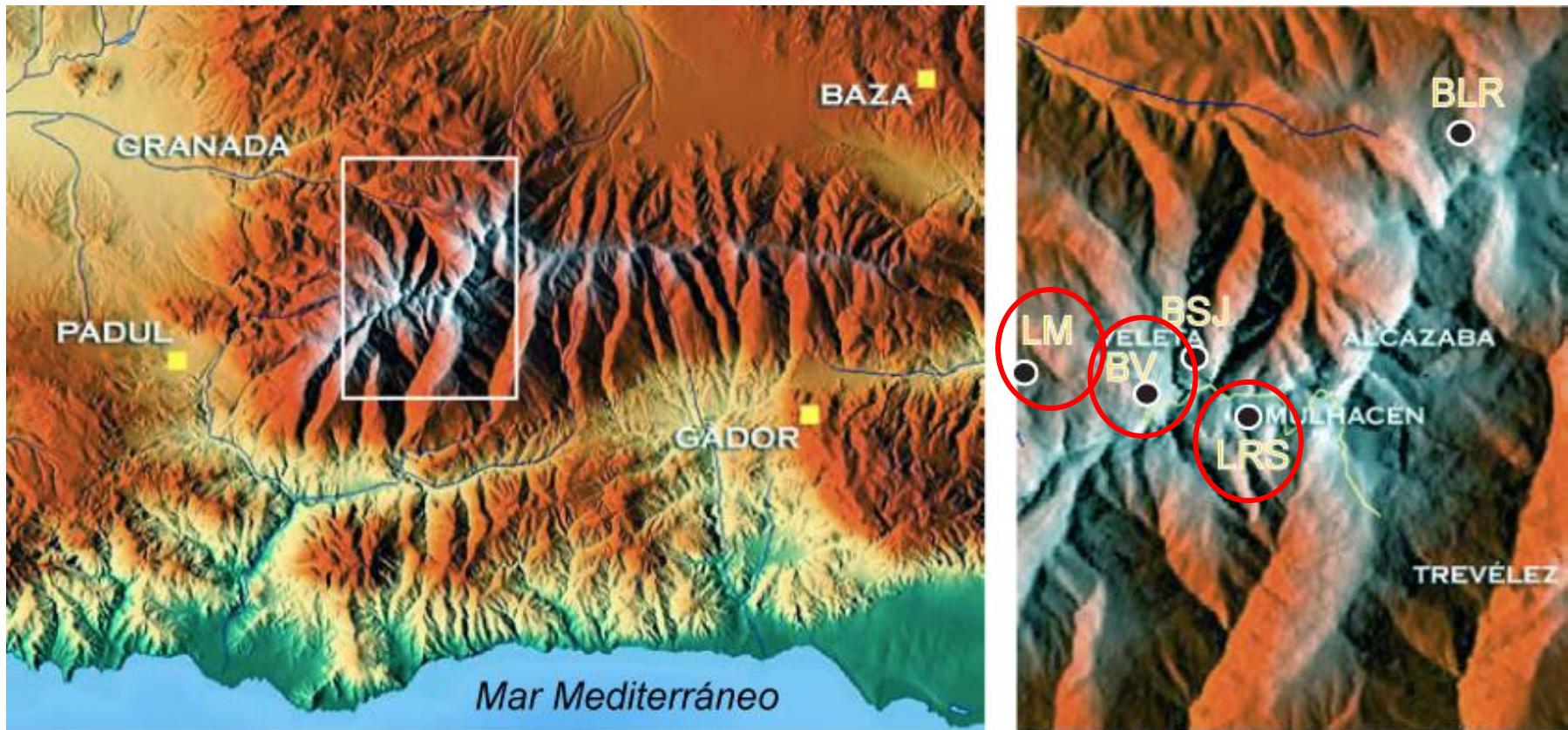
Sierra Nevada

Lakes in Sierra Nevada are close to (above) treeline.

Pollen studies in these lakes are going to record “movements” of forest species to higher elevations (warm period) or to lower elevations (cold period) and thus are very sensitive to climate (treeline elevation change).



Sites studied in Sierra Nevada



LM: Laguna y Borreguiles de la Mula; BV: Borreguiles de los Tajos de la Virgen; BSJ: Borreguiles de San Juan;
LRS: Laguna de Río Seco; BLR: Borreguiles de los Lavaderos de la Reina

Laguna de Río Seco (3020 m)

Maximum depth: 1.7 to 3 m

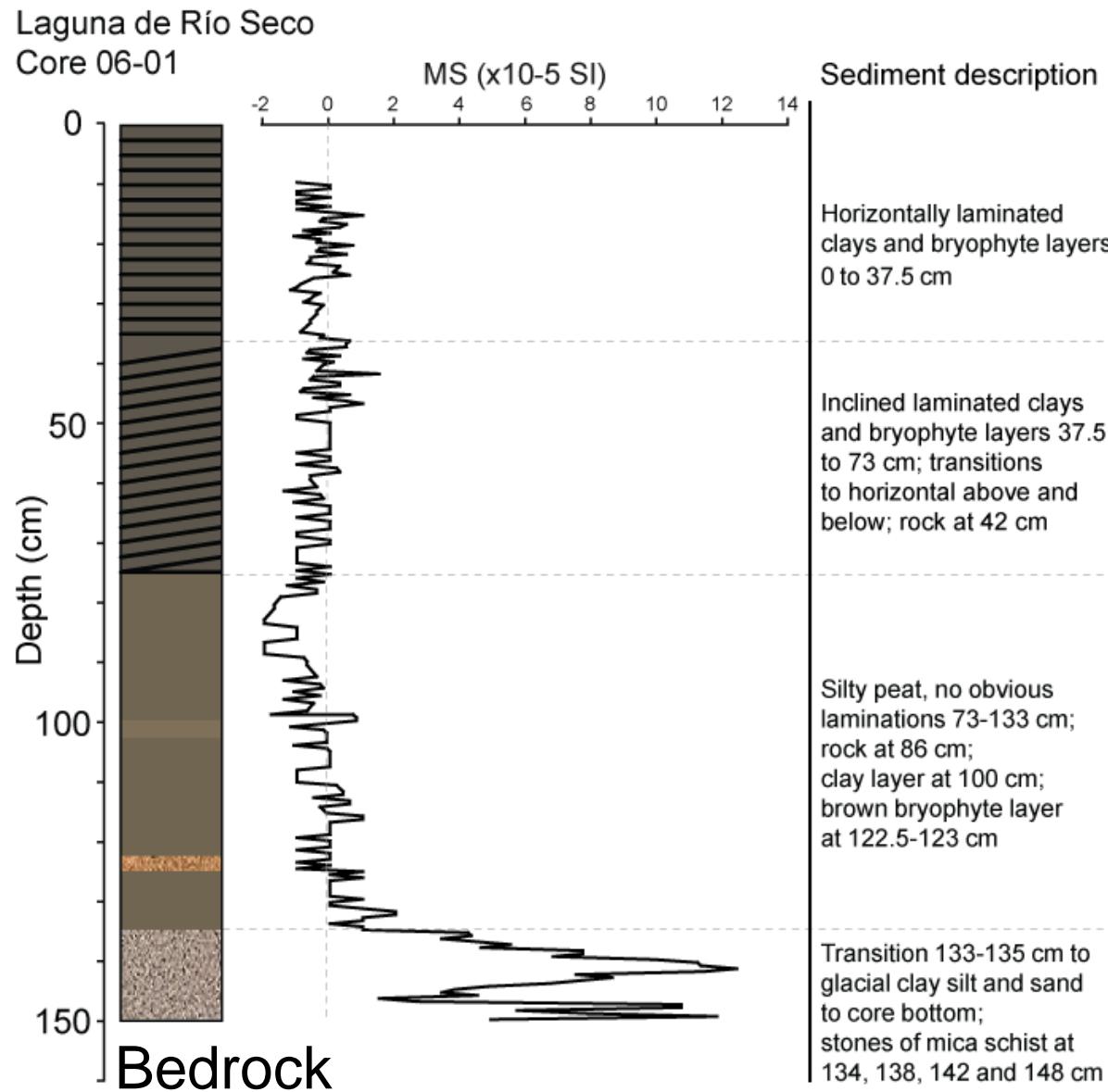


Laguna de Río Seco

Coring

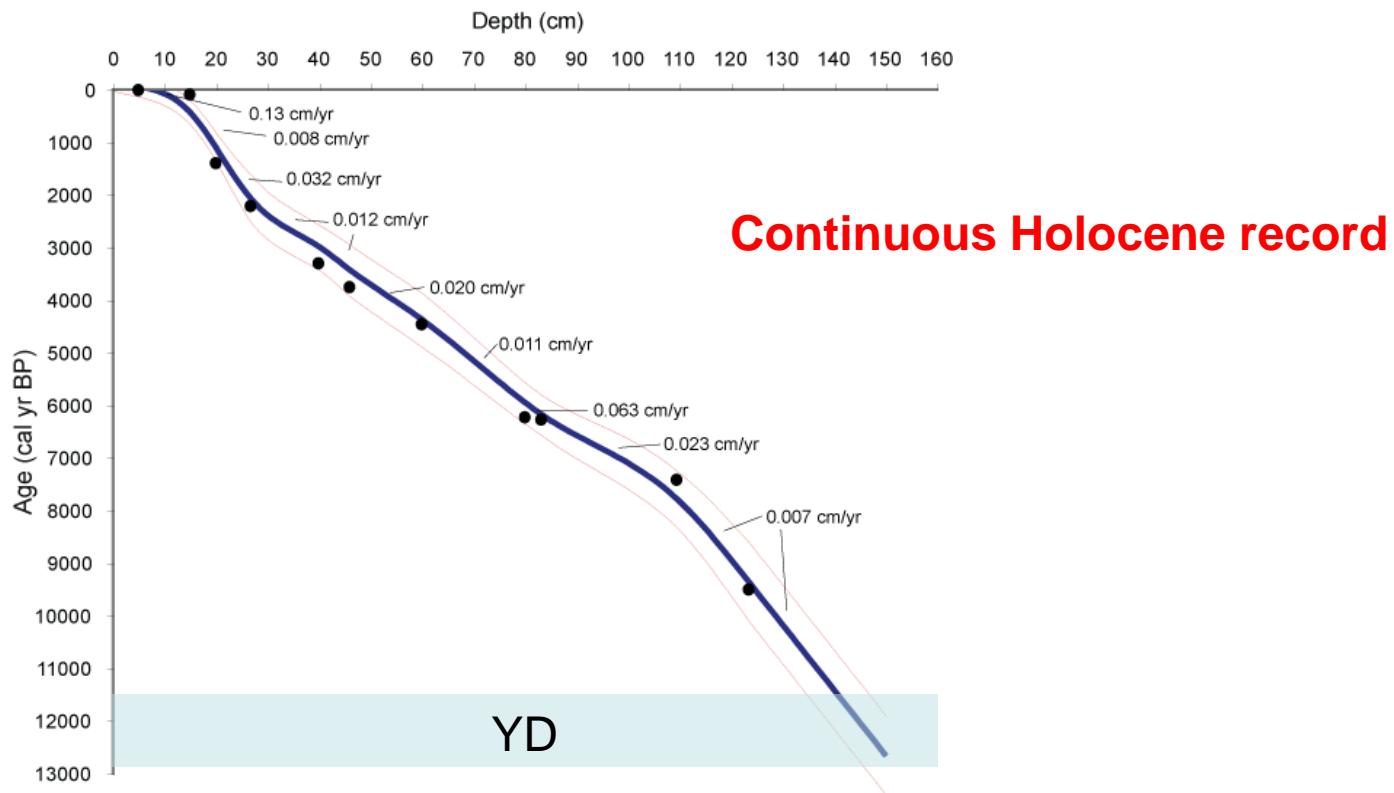


Laguna de Río Seco core



Age model Laguna de Río Seco

Laboratory Code	Core	Depth (cm)	^{14}C age (yr BP)	SD (\pm)	Calibrated Age (cal yr BP)* or yr AD
	06-02	5.0	^{137}Cs		1963 AD
	06-02	15.0	^{210}Pb		1891 AD
UCIAMS 51255	06-01	20.0	1520	15	1398
UCIAMS 63003	06-01	26.5-27.0	2255	20	2234
UCIAMS 51256	06-01	40.0	3060	15	3295
UCIAMS 63004	06-01	46.0	3525	20	3786
UCIAMS 51257	06-01	60.0	4010	15	4480
UCIAMS 51258	06-01	80.0	5450	30	6246
UCIAMS 63005	06-01	83.0-83.5	5505	20	6298
UCIAMS 63006	06-01	109.5	6550	20	7453
UCIAMS 32495	06-01	123.0-124.0	8570	60	9540



Pollen results Río Seco

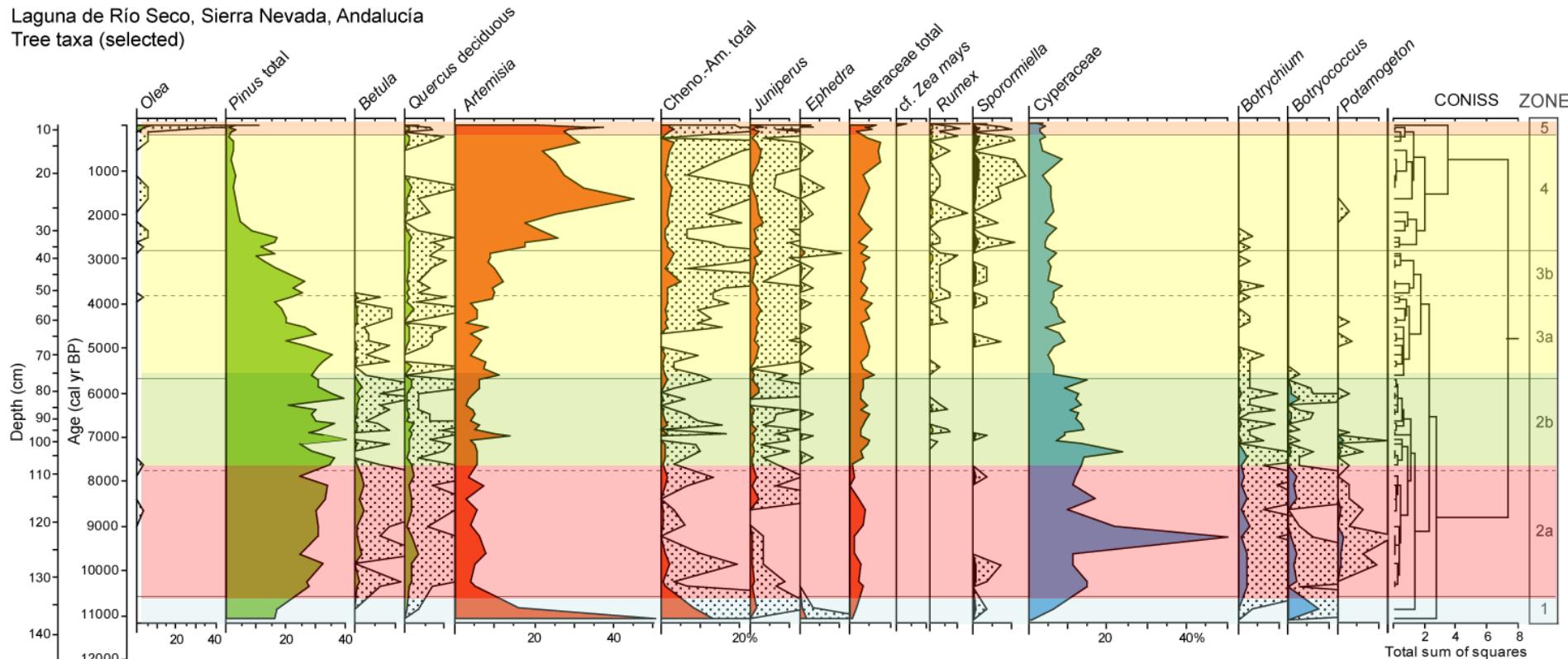
11.2-10.6 ka (zone 1)-Steppe - cold and dry;

10.6-7.8 ka (zone 2a)-Increase in *Pinus*, deciduous forest and aquatics - warm and wet;

7.8-5.8 ka (zone 2b) *Pinus* maximum but decrease in deciduous trees - warm but drier;

5.8-0.2 ka (zones 3-4)-significant decrease in *Pinus*, increase in *Artemisia* - drier;

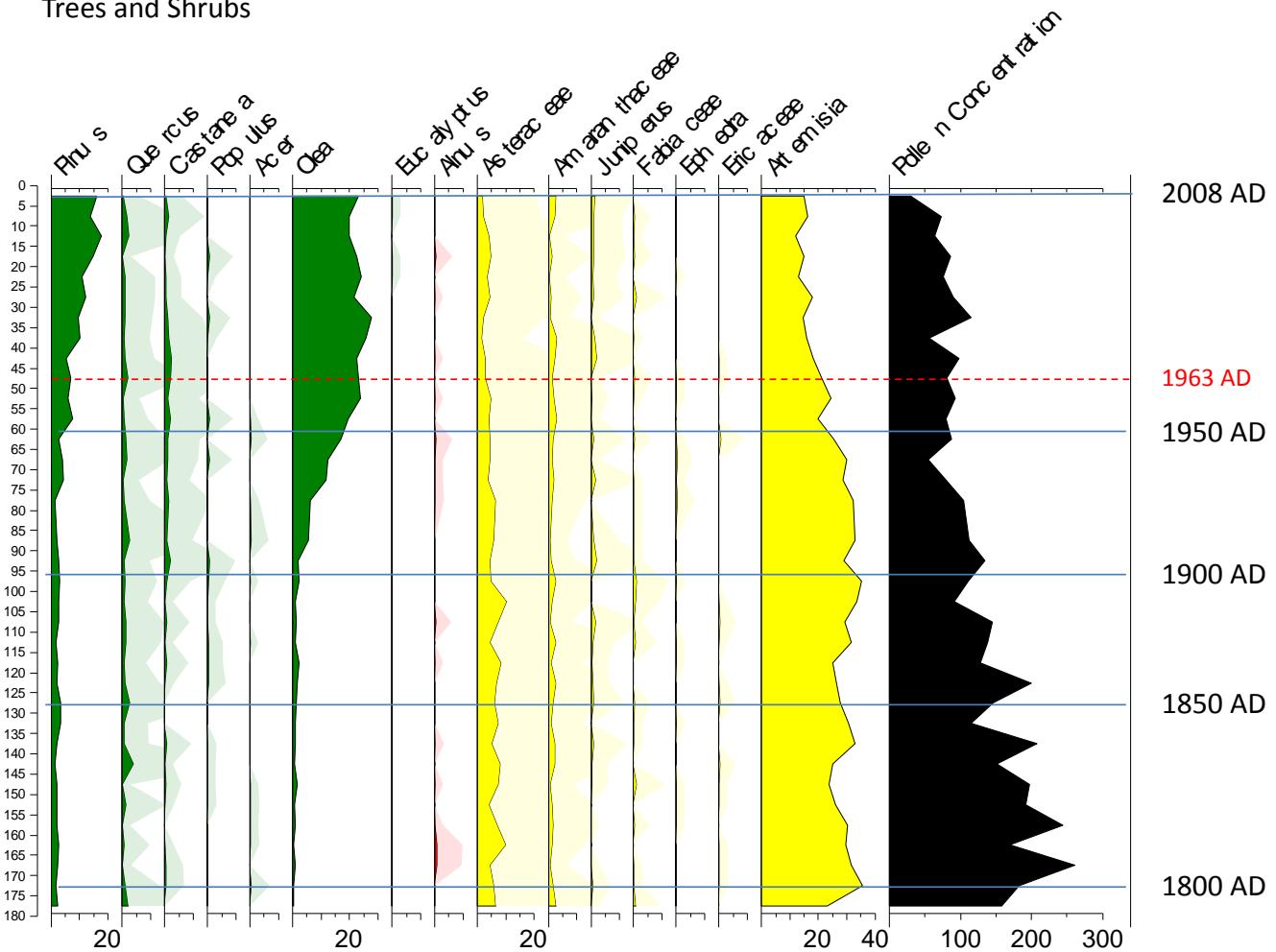
0.2-0 (zone 5)-increase in *Olea* and *Pinus* - human impact.



Anthropogenic Signals (Anderson et al., unpub.)

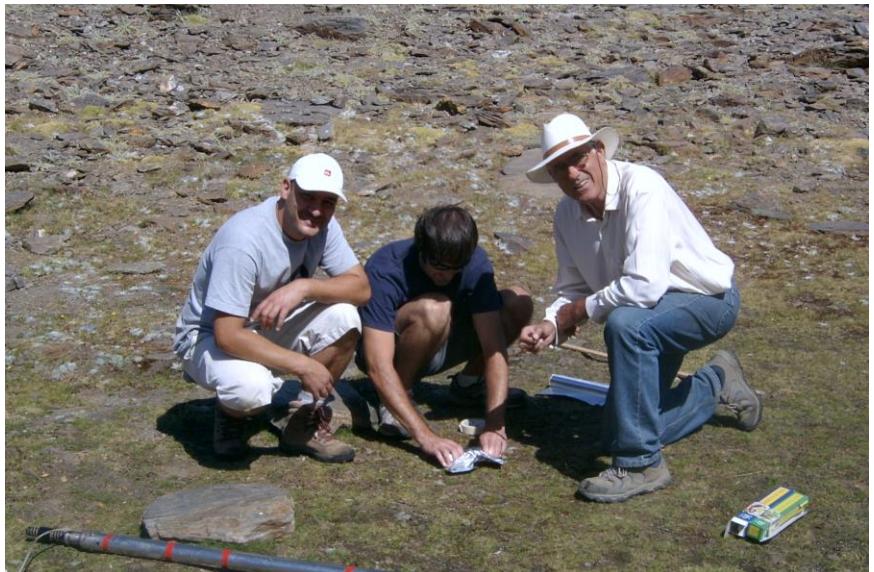
Laguna de Rio Seco, Sierra Nevada, Spain (top core 08-01)

Trees and Shrubs



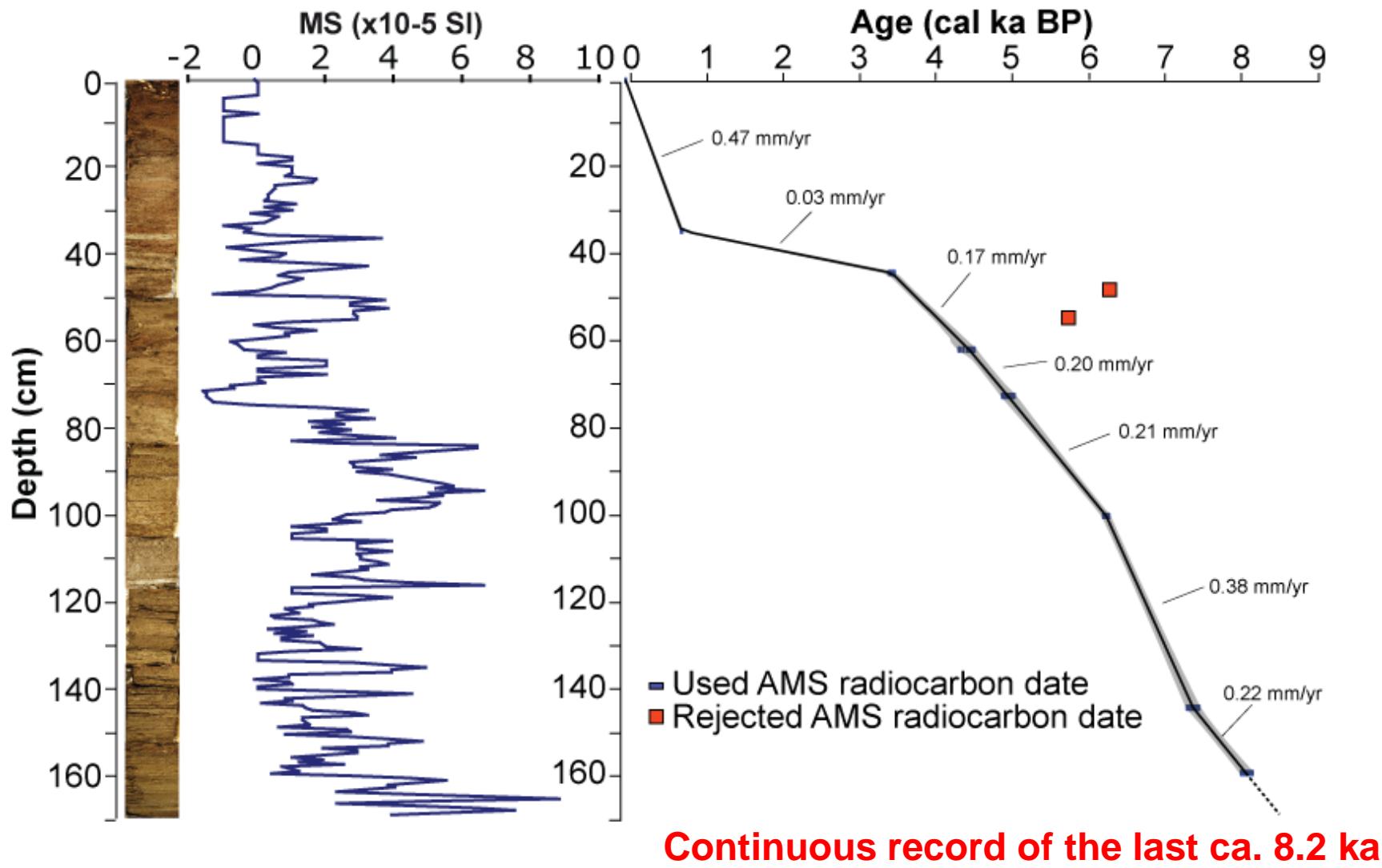
Coring Borreguiles de los Tajos de la Virgen

Elevation: 2945 m
Surface area: < 1 ha
Core length = 1.69 m

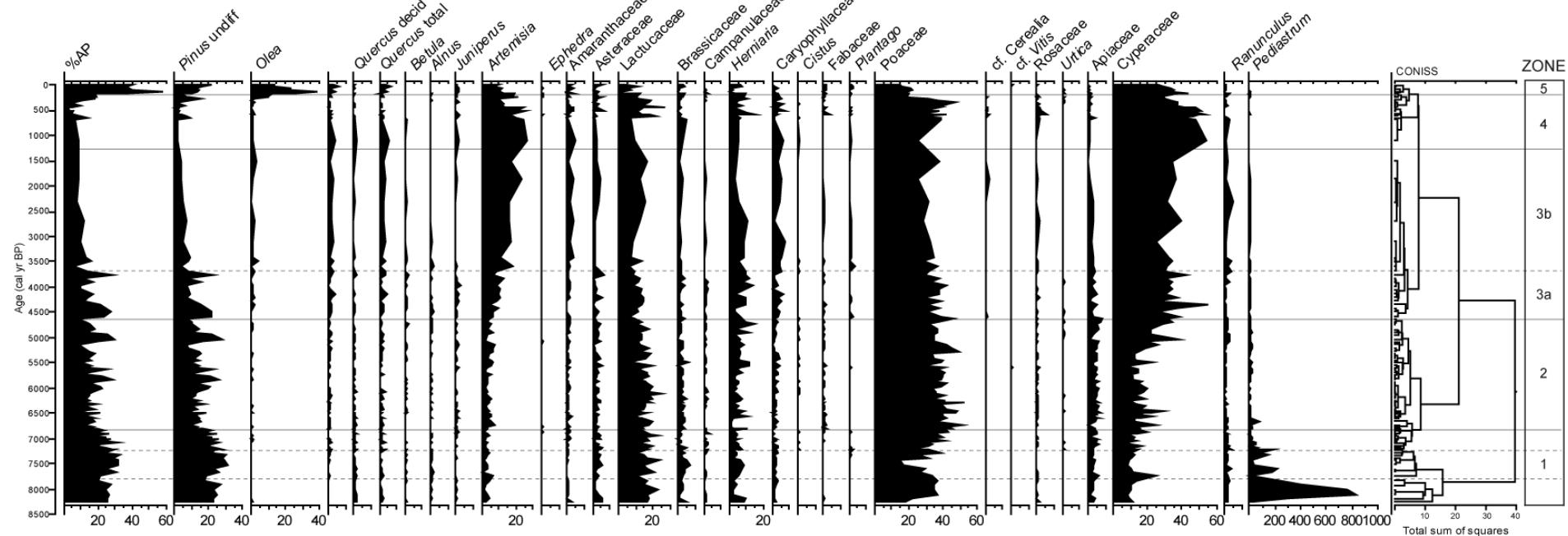


Borreguiles de los Tajos de la Virgen

Lithology - sedimentology



Pollen record Borreguiles de los Tajos de la Virgen

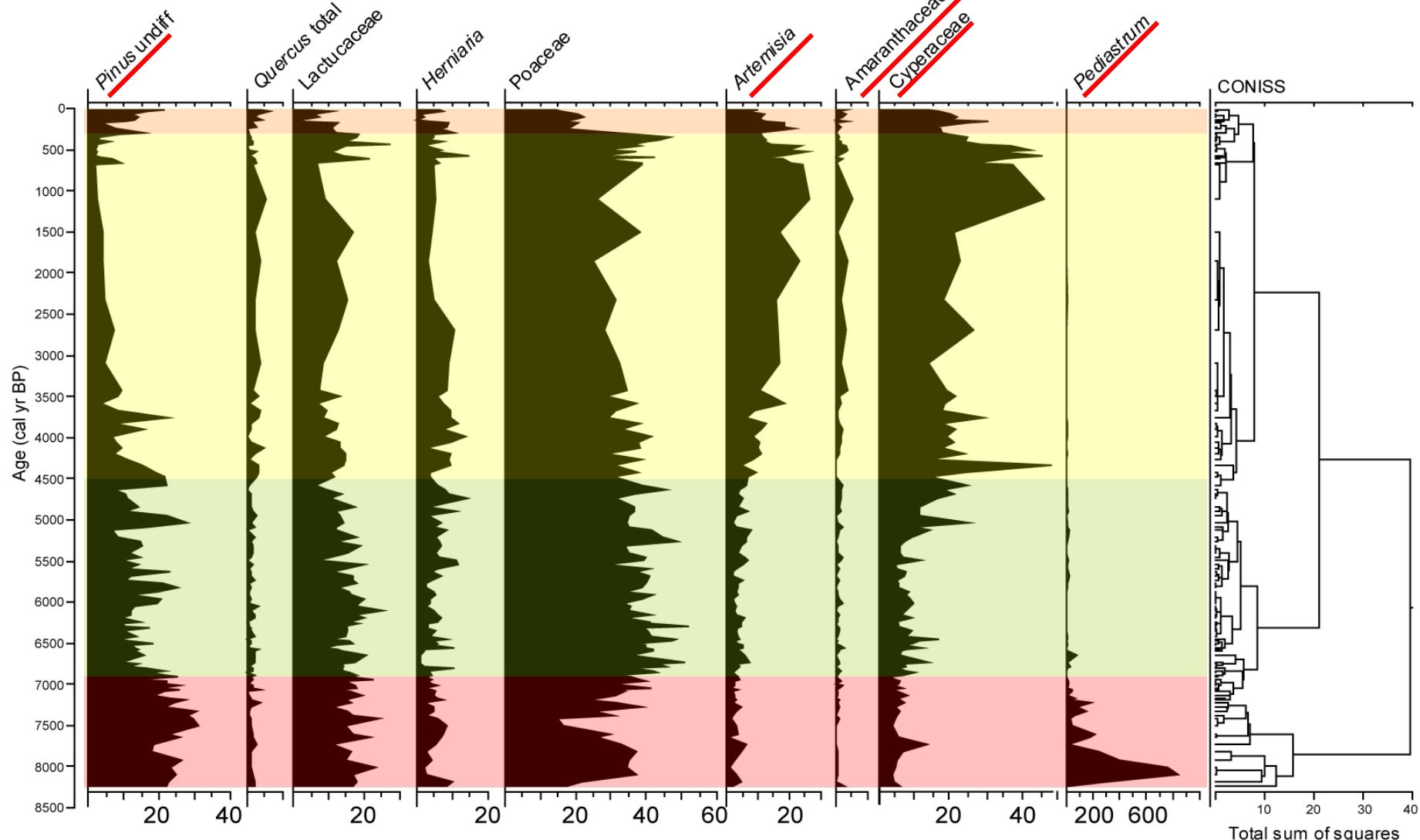


Pollen record Borreguiles de los Tajos de la Virgen

8.2-7.0 ka Very abundant *Pinus* & *Pediastrum* - warm-wet climate

7.0-4.5 ka decrease in *Pinus* & *Pediastrum*, increase Poaceae - colder-drier climate

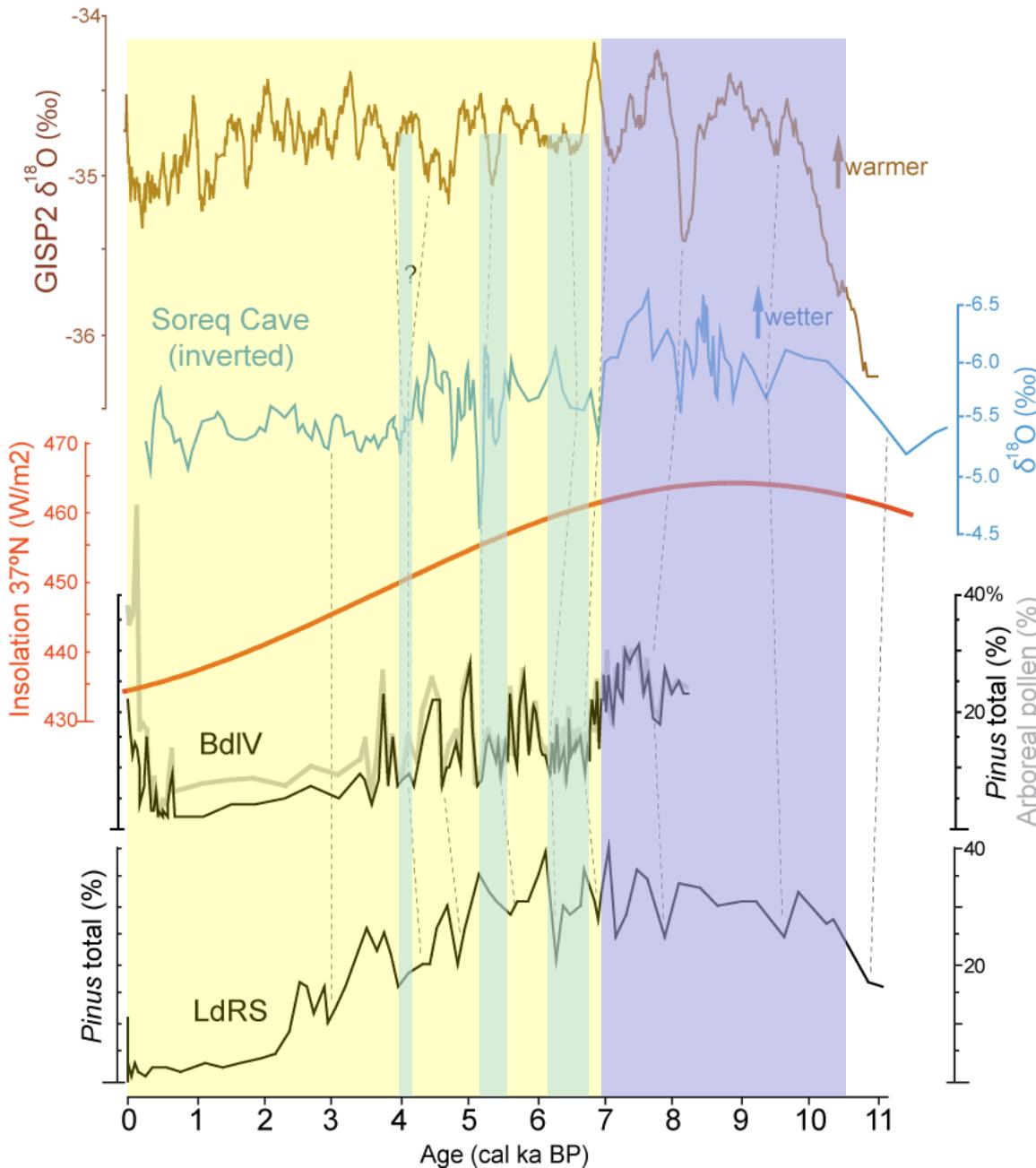
4.5 ka-250 yrs: decrease in *Pinus*, increase *Artemisia*, *Amaranthaceae* - arid climate



Last 250 yrs - increase in *Olea*, *Pinus*.

Jiménez-Moreno & Anderson, 2012

Comparison SN and other paleoclimate records Mediterranean



Vegetation in SN responded to global changes in temperature (insolation) and precipitation.

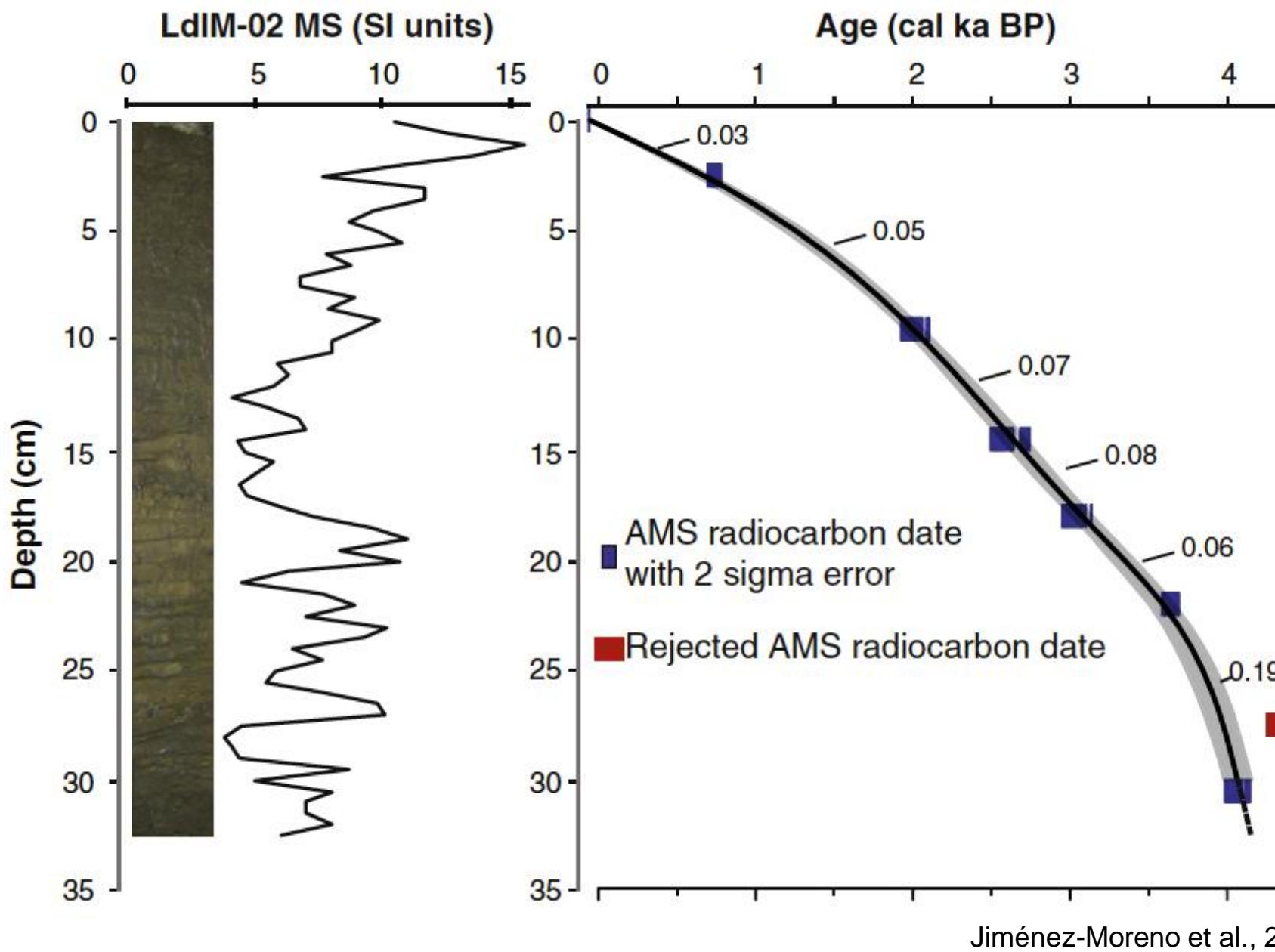
Warmest and wettest Period in SN corresponds in age with African Humid Period.

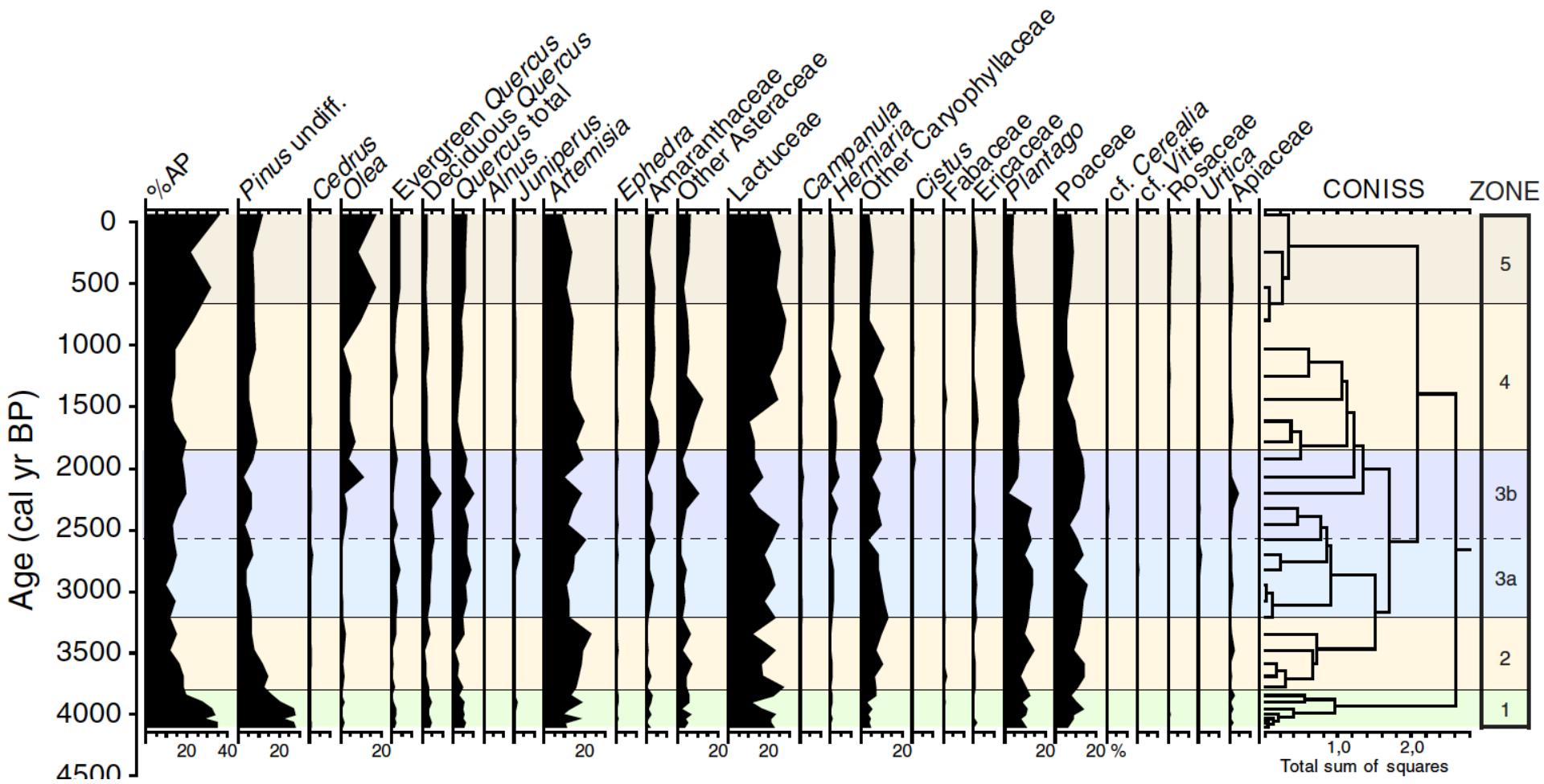
Progressive aridification is punctuated by periodically enhanced drought at ca. 6.5, 5.2 and 4 ka that coincide in timing and duration with well-known dry events in the Mediterranean and other areas.

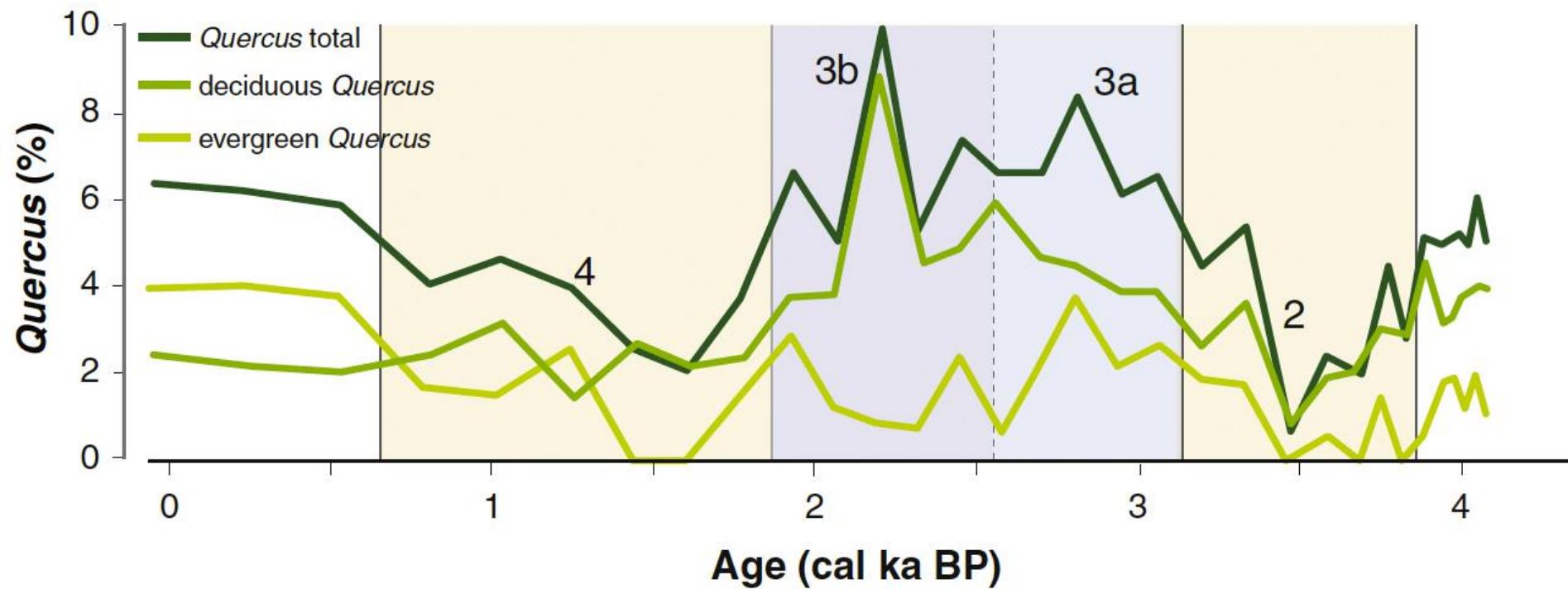
Laguna de la Mula (2497 m)



Elevation: 2497 m
Lake surface diameter: 45 m
Drainage basin: 25 ha
Maximum depth: 57 cm
Core length = 33 cm







Arid period 3.8-3.1 ka

Humid period 3.1-1.8 ka

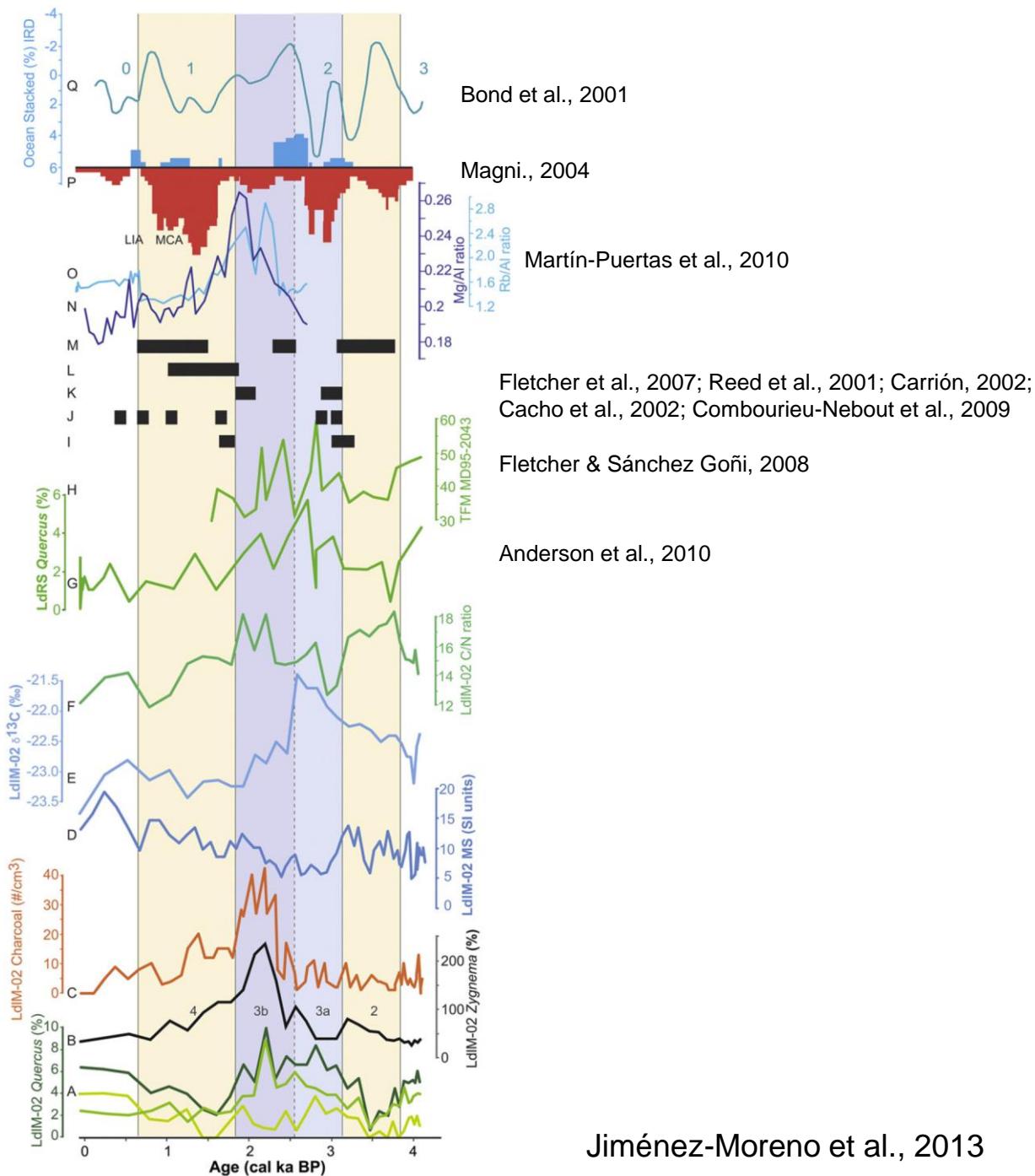
Milder conditions (e. Quercus) 3.1-2.5 ka

Humid conditions (d. Quercus; reduction seasonal contrast)

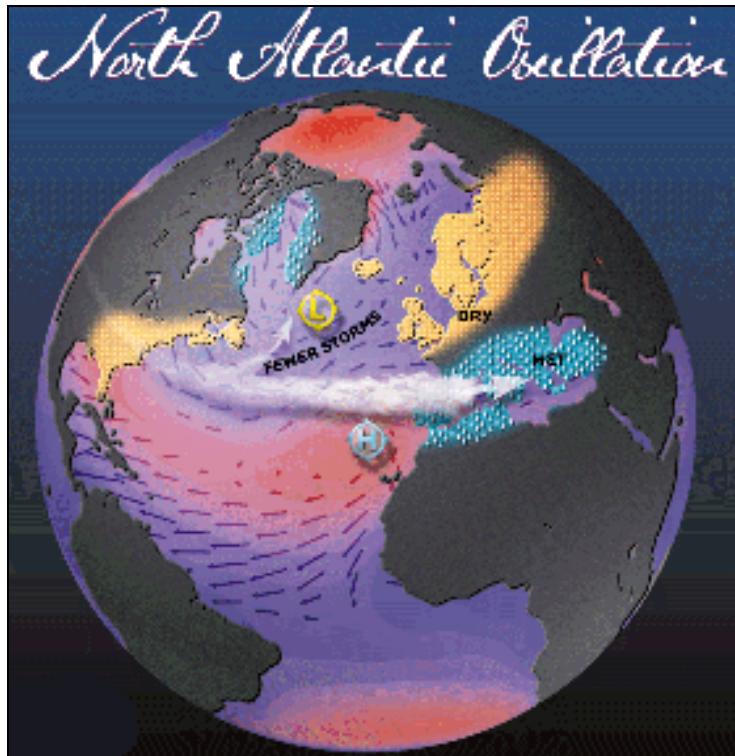
2.5-1.8 ka

Arid period 1.8-0.6 ka

Humid maxima: Roman Humid Period

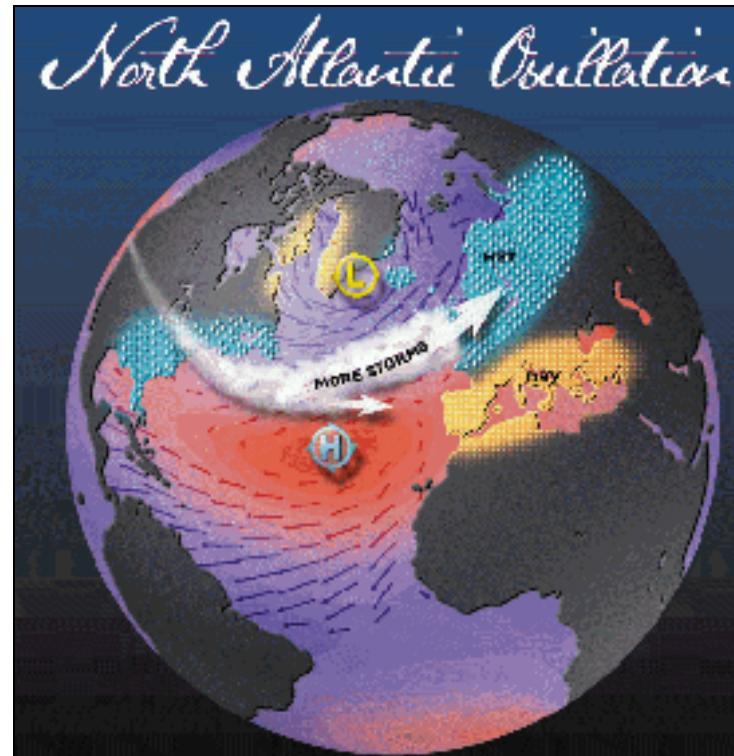


North Atlantic Oscillation



Negative Phase

Weaker High pressure at middle latitudes allows storms to penetrate south, leaving a wetter Mediterranean



Positive Phase

High pressure at middle latitudes drives North Atlantic storms further north, leaving a drier Mediterranean

CONCLUSIONS

- Alpine lake and bogs in the Sierra Nevada record vegetation changes that correspond to global climate changes.
- Vegetation responded rapidly to millennial-scale climate change and thus alpine environments in SN are shown to be very sensitive (and very fragile!).
- Human impact in the SN is very clear in the last centuries through cultivation (i.e., *Olea*) and reforestation (*Pinus*), fire and the introduction of livestock.