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Environmental changes in Sierra Nevada during the last 6 ky BP inferred from solifluction lobes and lake sediments

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Holocene climate variability drove important landscape changes in Sierra Nevada, heightened due to the emplacement of Sierra Nevada at 37ºN in southwestern Europe and, therefore, the different crossing influences in this region: geographical Europe/Africa), maritime (Atlantic/Mediterranean), climatic (subtropical high-pressure belt/ mid-latitude westerlies). Despite the existence of several kinds of sedimentary records in Sierra Nevada, only two of them can provide further information about Holocene landscape changes in this massif: solifluction lobes and mountain lakes. The numerous sedimentological changes inferred from terrestrial and aquatic records suggest the proximity of geomorphological processes in the massif of their climate boundaries and the small climate range necessary to carry environmental changes in the summits of the Sierra Nevada.

Sierra Nevada holds the highest lakes in Europe, all of them related to a glacial origin. Four lakes were cored in Sierra Nevada, three of them southern exposed (Aguas Verdes, Rio Seco and Rio Seco lagoon) and only one with northern orientation (San Juan lagoon).

Sedimentological properties of these cores assert evidences of different phases of coarse-grained inputs into the lakes, with low organic matter proportion and high mineral contents. These pulses correspond to geomorphic periods with enhanced slope instability, interfingered in phases with lower sediment transfer onto the lakes. These relative stable periods show a fine-grained texture with less mineral fraction and increases in the organic composition of the sediments. The similar evolution of the C/N ratio and Corg contents reflects the low productivity of these oligotrophic lakes and the terrestrial origin of the organic matter present in their sediments; both proxies also confirm a general pattern characterized in Sierra Nevada by an arid trend since the HWP, when the headwaters of the highest catchments stored a denser vegetation cover.

We report an approximate chronology of environmental changes inferred from lake sediments with several geomorphic periods determined for the last 6 ky BP. Our relative chronostratigraphy of active slope phases derived from the analyzed cores matches reasonably well with the Holocene solifluction chronology previously obtained for the massif (Oliva et al., in press).

Periods with high mineral input into the lakes and low vegetation cover in the headwaters of the highest cirques coincide with phases of solifluction activity. By contrast, during those periods with less mineral material deposited into the lakes, edaphic processes were dominant in favourable topographical emplacements at high altitudes, a dense vegetation cover expanded surrounding the lakes and a patchy and sparse grass vegetation recover could also spread over the gentle slopes covered by debris.

Solifluction and slope dynamics are favoured by low temperatures in summer and substantial snow precipitations in winter, with a decisive role of late-lying snow patches; depending on the range and persistence of this wet cooling trend, glacial conditions and permafrost extension can also return in the highest northern cirques (e.g. LIA). We consider that a weak slope activity could also take place associated with shifts in moisture regimes. Soil development is enhanced with high precipitations (both in summer and winter) and warm summer temperatures. After a solifluction period, the thermal raise combined with a relative increase in moisture availability induces an incipient soil formation (regosols) and if this climate trend continues well-structured soils can develop (histosols).

During cold and wet periods, a longer persistence of snow patches in northern valleys turned on feed-back mechanisms that played a decisive role in Holocene landscape changes (providing more water supply, prolonging the frozen ground, shortening the vegetation growing season, etc), crucial to trigger slope instability in the massif, entailing slopes with scarcer vegetation cover and activating solifluction. Depending on temperature and moisture conditions, this pattern could also favour the existence of small glaciers in the highest northern cirques; the enhanced periglacial activity made also more efficient gelifraction which provided further material to be mobilized to valley floors by solifluction when snow cover melted.

On the other hand, warmer periods tend to slow mass wasting and induce soil formation: during arid phases poor developed soils prevailed (regosols) and in those periods with wetter conditions highly organic soils formed (histosols).

Solifluction records also indicate that the LIA has been the wettest and coldest period during the Mid-Late Holocene, with the most rigorous climate conditions from 1590 to 1650 (Rodrigo et al., 1999). This climate variability has shifted vertically the periglacial belt in the massif. During cold and wet periods, our study area was located in the nival ecotone where the scarce vegetation cover enhances erosion and mineral mobilization. By contrast, during warm periods, the nival ecotone moved upwards and our study area was affected by typical processes of the subnival ecotone: soil development was favoured in gentle topographical places with high water availability and the previous sparse vegetation cover became denser, reducing mass wasting effectiveness.

Lake sediments point out a clear arid trend initiated around 6 ky BP in Sierra Nevada parallel to the same pattern observed in northern Africa and southeastern Spain since the HWP (Gasse, 2000; Burjachs et al., 2007). Until the Late Holocene, conditions were more suitable to more vegetated headwaters in the southern cirques, which in turns make more difficult solifluction movements. In effect, according to our studied archives, solifluction activity in Rio Seco started during the last 1500-2000 years BP: we have no signs of previous solifluction during the Holocene. The existence of a paleosoil dated 12.973 $\pm$ 112 years BP suggests that solifluction processes prevailed during the Lateglacial cold pulses but stopped during the Early to Mid Holocene, with no sedimentological evidences of mass wasting activity in Rio Seco before the last two millennia.

The increasing climate variability of the last millennia in southern Iberian Peninsula is reflected in the southern slope of Sierra Nevada in three cycles of alternated solifluction and soil formation phases. The southern exposition of Rio Seco cirque, with extremely low vegetated hillsides, is crucial to explain a relative major geomorphic stability in contrast to northern slopes, as in San Juan valley, where dynamism was enhanced due to more water availability: increased slope instability is reported both in solifluction lobes and glacial lakes. Up to nine different solifluction-edaphic phases have been reported in San Juan valley during the last 8 ky BP.