Archives in the Depths of High Mountain Lakes

Humans began settling remote mountain regions of the Swiss Alps over 4000 years ago. So what were the Alps like in earlier times? Downturns in climatic conditions forced humans to repeatedly abandon these areas, but as soon as conditions improved, they returned. We can decipher these fluctuations in human settlement from the sediment record that is stored in mountain lakes. These archives allow us to assess the effect of human impacts on the background of natural climatic changes.

The Alps are commonly referred to as the "water treasure chest of Europe". The preservation and sustainable use of this resource is one of the most important tasks that the Convention for the Protection of the Alps is facing (see article by M. Broggi on p. 7). The Convention presumes that Alpine regions are still largely unaffected by human activities. But is this really true? EAWAG has gone further into that question. By analyzing the sediments of high mountain lakes, it is possible to reconstruct several thousand years of history of these lakes and their watersheds. Specifically, we would like to know, if, since when, and to what extent these mountain regions have undergone changes, and whether it is possible to separate anthropogenic impacts from naturally occurring changes.

Historical Archives in the High Mountains?

As long as historic documentation or long-term monitoring data are available, we may answer such questions directly. Changes in land use patterns in the Canton of Grisons, for example, are clearly documented in the Swiss Land Use Statistics database (Tab. 1). But if we want to look at changes in earlier epochs, it becomes more difficult as we often do not have instrumental data, records or reliable historical sources. In these cases, we must relay on indirect data sources, archives of so-called environmental proxy. Lake sediments are among the most important of such archives and are used to interpret former environmental conditions. Sediments can reveal geobiochemical and physical processes that have occurred in a lake and its watershed with high temporal resolution (seasonal, annual) and over long periods of time (10^6 years) [1]. Because high mountain lakes are ecologically in a marginal situation, they react faster to changes in their environment than lakes at lower elevations. For this reason, there have recently been a series of studies in the Swiss Alps that have made use of sediment records in mountain lakes [2–4].

Sägistalsee – a High Mountain Lake in the Bernese Oberland

One high mountain lake that has been studied in detail is the Sägistalsee, which is situated at 1935 m a.s.l. in the Bernese Oberland between Grindelwald and Brienzersee (Fig. 1). As part of the interdisciplinary research project AQUAREAL funded by the Swiss National Science Foundation, a 13.5 m long sediment core was collected from Sägistalsee in 1996. This core represents an archive of the last 9000 years, i.e., for almost the entire Holocene. Layer by

	% of total area (as of 1992/1997)		**% change** (since 1979/1985)	
	GR	**CH**	**GR**	**CH**
Forest	26.7	30.8	+3.9	+1.9
«Unproductive areas»	41.7	25.5	No data	
Agriculture	29.8	36.9	–3.1	–3.1
Settlements	1.8	6.8	+12.9	+13.3

Tab 1: Land use statistics for the Canton of Grisons (GR) and Switzerland as a whole (CH); Swiss Federal Statistical Office (2002).

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Fig. 1: Sägistalsee in Canton Bern, Switzerland viewed from the west. Clearly visible are the hard ridges of the Upper Jura limestones and the soft troughs of marls and schists in the Lower Cretaceous formations [5].

Measured parameter	Indicators of past environmental conditions
Organic carbon (C_{org})	Biological productivity in the lake
Calcite/quartz ratio	Soil formation in the catchment
Mean grain size	Mineral weathering in the catchment
Manganese/iron ratio (Mn/Fe)	Oxygen conditions in deep lake water
Benthic midge larvae (Chironomidae)	Oxygen conditions in deep lake water
Pollen of trees, shrubs, grasses	Vegetation in the catchment
Charcoal remnants	Forest fires and human activities in the catchment

Tab. 2: Environmental proxy parameters determined in a sediment core from Sägistalsee functioning as indicators for environmental conditions in the past.

layer, this core has been analyzed for various parameters (Tab. 2) allowing the reconstruction of past environmental conditions and human activities in the region.

Natural Changes in the Environment

The global warming trend since the end of the last ice age led to increased nutrient input into Sägitalsee, resulting in increased biological productivity until about 6000 years ago (Fig. 2A). During this same period, soil formation increased (Fig. 2B) and mineral weathering decreased (Fig. 2C). At the deepest locations in the lake, anoxic conditions developed (Fig. 2D) allowing for the survival of only a few benthic organisms living at the sediment/water interface (Fig. 2E). During the next 2000 years, until approximately 4000 years before present, the previously sparse forest of pine and spruce grew denser and was then dominated by fir *(Abies alba).* As a consequence, the forest floor became more stable (Fig. 2B), and the oxygen supply to deep layers of the lake improved (Fig. 2D). This, in turn, led to an increase in the occurrence of midge larvae (Chironomidae) in the sediment (Fig. 2E).

Humans Begin to Change the Environment

The first signs of human settlements are evident at approximately 4000 years before the present. At this time, the Neolithic-Bronze Age civilization began to cut down the forests and use the cleared areas as pastures. This development is indicated by an increase in grass pollen (Fig. 2F), the emergence of pasture indicators (Fig. 2G), and the more frequent occurrence of charcoal remnants (Fig. 2H). In the deep-water of the lake, oxygenation decreased dramatically, and benthic organisms disappeared almost completely (Figs. 2D and 2E).

These early impacts of human activity in the Sägistalsee watershed can be followed for several centuries until about 3500 years ago, when the climate worldwide deteriorated significantly [6]. The records in the sediment archive of Sägistalsee indicate clearly that human settlements in the Alps suffered severely under these conditions. Within less than 100 years, the pastures within the watershed of Sägistalsee disappeared (Fig. 2G), forests filled in again (Fig. 2F) and mineral weathering increased (Figs. 2B and 2C). In the lake itself, the deteriorating climate led to a significant decrease in biological productivity (Fig. 2A) and, therefore, to higher oxygen concentrations in the deep-water, which in turn result once again in an increase of sediment biota (Figs. 2D and 2E).

Up and Down of Settlement and Reforestation

In the subsequent period of the Holocene, anthropogenic signals in the Sägistalsee sediments become more frequent and begin to overlay the climate signal. During the Iron Age, approximately 3000 years before the present, climatic conditions improved

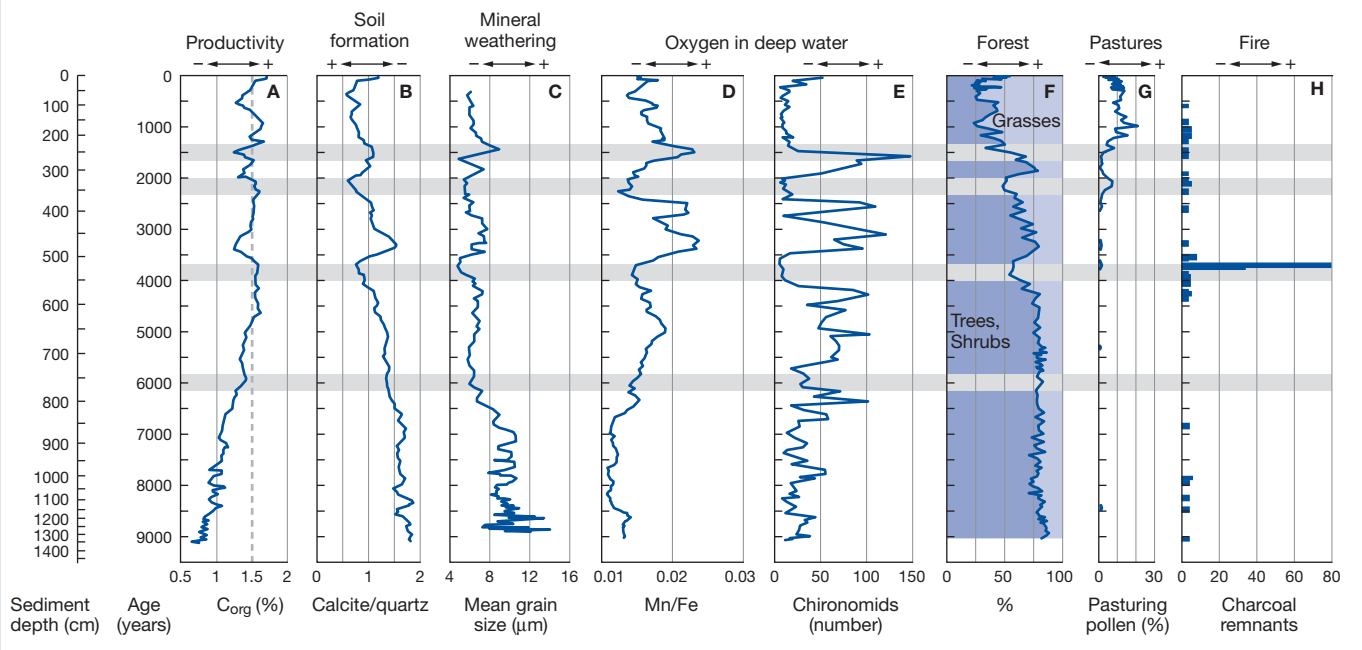

Fig. 2: Environmental parameters (see Tab. 2) as a function of time as determined in a sediment core from Sägistalsee [8–10]. Age = given in calibrated ^{14}C-years before the present. Grey bars indicate periods of drastic change.

again, allowing for continuous use of the watershed by humans until the present day. The forest was once more replaced by open areas (Fig. 2F). The alpine pastures were used intensively particularly during the time of the Roman Empire, approximately 2000 years ago (Fig. 2G). The deep-water of the lake again became anoxic and was almost depleted of organisms (Figs. 2D and 2E).

The early Middle Ages, about 1500 years ago, saw a sharp decline in anthropogenic land use, induced by changing climatic conditions. Forested areas grew (Fig. 2F) while consolidation of the soils decreased (Fig. 2B). Dramatically larger grain sizes of minerals in the lake sediment (Fig. 2C) suggest increased mineral weathering in the watershed. Oxygen was present throughout the water body, and the numbers of midge larvae increased significantly (Fig. 2E).

The renewed improvement of the climate some 1200 years ago, during the high Middle Ages, gave rise to increased agricultural use of the watershed. This level of utilization has remained high through to the present day and was not disrupted during the cold period of the little ice age, which lasted approximately from the middle of the 13th until the middle of the 19th centuries.

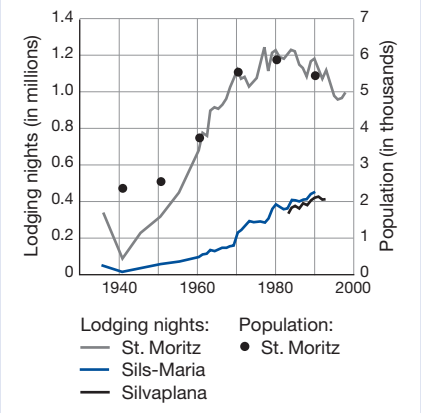

Fig. 3: Growth of the population of St. Moritz (solid circles) and lodging nights in St. Moritz (grey), Sils-Maria (dark blue) and Silvaplana (black) over the last 60 years. Source: Tourist Office St. Moritz, Sils-Maria and Silvaplana.

Sägistalsee is not an Isolated Case

Results from Sägistalsee demonstrate how quickly and how sensitively high mountain lakes respond to rapid climatic change, such as during the deterioration of the climate 3500 years ago. At the same time, they illustrate that human settlement and land use – even in remote mountain areas – began much earlier than had previously been assumed; it appears now that humans started to settle these areas as early as 4000 years ago. Human activities have left a lasting mark on the lake and its watershed. But is this also true for other mountain regions?

Studies of sediment cores from the larger lakes of the Upper Engadin revealed that these lakes, situated at 1800 m a.s.l., react rather sensitively to climatic changes like Sägistalsee. Traces of settlement and agricultural activities are evident around the same time, i.e., about 4000 years before the present. Again, we can use the sediment archive to decipher a record of alternating periods of clearing and regrowth of forests with intermittent evidence of pastures [7].

Are High Mountain Regions Really Remote?

The assumption that remote mountain regions or high mountain lakes are beyond the reach of anthropogenic impacts is clearly invalidated by our results. Although environmental changes are basically caused by natural processes (climate changes), the influence of human activities in the mountain regions of the Alps is evident as early as 4000 years ago. "Remote" is, therefore, not synonymous with "untouched". All the same, it may be said that in the past, high mountain areas have been used less intensively than the more densely settled areas in the lowlands.

Today, however, environmental change is increasingly caused by human activities; Figure 3 illustrates this trend. Within a short period, the tourism industry has transformed the region around St. Moritz from its original "remote" mountain quality to an "urban" area. Because high mountain areas react quickly and sensitively to environmental changes, increased anthropogenic pressure (e.g., vehicular traffic, ski slopes, hydroelectric power plants, filling in of new land areas) leads to far more dramatic changes of the environment than natural climate changes alone would allow. High mountain areas are, therefore, not only threatened by global warming, but also by a rapid increase in anthropogenic activities. The delicate treatment of our sensitive "resource Alps", the "water treasure chest of Europe", must be assigned the highest level of priority on European States' agenda.

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