Reconstructing the paleotopography of mountain belts from the isotopic composition of authigenic minerals

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ABSTRACT

The paleorelief of mountain belts can be estimated from the δ18O value of authigenic minerals. Development of relief during mountain building often creates lee-side rain shadows in which precipitation is depleted in 18O and D. The magnitude of this rain-shadow effect is strongly correlated to relief. A compilation of δ18O data from surface waters throughout the globe shows a linear relationship between net elevation change and Δδ18O (R² = 0.79). Through the use of this relationship, we investigated the timing and magnitude of elevation change in the Southern Alps of New Zealand and the Sierra Nevada of California. The δ18O values of kaolinites from New Zealand show an ~6‰ decrease in the early Pliocene that corresponds to an ~2 km elevation change in the Southern Alps. The δ18O of smectites from the Sierra Nevada show little change since 16 Ma, suggesting that these mountains have been a long-standing topographic feature.

Keywords: topography, climate change, stable isotopes, uplift, mountain belts.

INTRODUCTION

The relationship between the topographic and tectonic development of mountain belts is a poorly understood yet important problem in earth sciences. Numerical models show that climate, topography, and tectonics of mountain belts are intimately linked and that the rise of mountains can influence both local and global climate (Rudiman and Kutzbach, 1989). Thus, estimating paleorelief will place constraints on both paleoclimatic and tectonic models of mountain-building events. At present, there are few methods available that allow quantitative estimates of paleorelief. Information from cooling age, petrologic, and sedimentological studies provide constraints on the exhumation of mountains but yield little information on its elevational history. Therefore, recent studies for determining paleoaltitudes have concentrated on other methods, such as basin vesicularity (Sahagian and Maus, 1994), cosmogenic nuclides (Brook et al., 1995), and paleobotany (Forest et al., 1999). Although these paleorelief methods are useful, they all have inherent limitations. Thus, it is important to develop other methods that can provide independent estimates of paleorelief.

We develop a model whereby the isotopic composition of authigenic minerals in terrestrial sedimentary and volcanic rocks can be used as an indicator of paleorelief. It has been shown that the δ18O and δD of authigenic minerals provide information on past surface temperatures and sources of surface waters (Lawrence and Taylor, 1971), and isotopic values of authigenic minerals can be used to constrain the topography of mountainous regions (Kolody and Luz, 1991; Rye et al., 1993; Lawrence and Rashkes-Meaux, 1993; Chamberlain et al., 1999). The distillation of 18O and D in precipitation as air masses move from the oceans to continents causes the isotopic values of precipitation to decrease. This lowering of δ18O and δD values is enhanced as air masses pass over mountains, resulting in the well-documented “altitude effect” (Ambach et al., 1968). As a result the δ18O and δD values of precipitation on the rain-shadow side of mountain belts are often much lower than those of the lee-side of mountain belts. The magnitude of this isotopic depletion is related to the height of the mountains. Because there is a quantitative relationship between elevation change and isotopic depletion of precipitation (isotopic lapse rates) and because the isotopic composition of authigenic minerals records that of surface waters, it is possible to estimate past topography. The isotopic composition of authigenic minerals from terrestrial sedimentary sequences from the rain-shadow side of mountain belts should record the surficial uplift (relief) of mountain ranges.

We show that (1) the topographic development of mountains can be quantitatively estimated by using the relationship between δ18O of surface waters and elevation, and (2) the δ18O values of clay minerals from sedimentary and volcanic rocks from the Southern Alps of New Zealand and the Sierra Nevada of California provide quantitative information on the development of these mountains as topographic features.

ISOTOPIC COMPOSITION OF SURFACE WATERS AND ELEVATION

The isotopic values of precipitation are a function of temperature, source, evaporation during precipitation, degree of cooling since condensation, and kinetic effects (Dansgaard, 1964). De-
Despite these complications, studies have shown that there is a relationship between the isotopic composition of surface waters and elevation (Table 1). In a Rayleigh model, continued precipitation from an air mass as it cools during orographic ascent results in progressive depletion of $^{18}\text{O}$ and $^D$ of the remaining water vapor.

To explore further the relationship between altitude and $^{18}\text{O}$ of surface waters, we plotted the change in the isotopic composition ($\Delta^{18}\text{O}$) of surface waters with elevation change (net elevation) for isotopic data sets collected throughout the world (Fig. 1; Table 1). The slope of the best-fit line ($R^2 = 0.79$) through these data gives a global isotopic lapse rate of 0.21‰/100 m. Figure 1 can be used to estimate elevation change of developing mountain ranges. For example, if authigenic minerals in a terrestrial sequence on the lee side of a mountain range show a 5‰ decrease in $^{18}\text{O}$ with time, and all other factors that influence the isotopic values remain constant, then the net elevation increase would be 2350 ± 300 m. Larger isotopic changes have a greater uncertainty because of the few data sets available for large elevation changes.

Determining the elevation change from the $^{18}\text{O}$ value of minerals is complicated by numerous other factors, such as surface temperature changes, changes of source of precipitation, seasonality of mineral formation, changes in the isotopic composition of ocean water through time, and distance from evaporative moisture source. As such, these factors must be considered in any isotopic study of authigenic minerals. However, the change in the $^{18}\text{O}$ value of surface waters as a result of the altitude effect is relatively large compared to many of these factors and, thus, the change in the $^{18}\text{O}$ value of surface waters is a first-order effect that will strongly influence the isotopic composition of authigenic minerals. For example, the rain shadows on the east side of the Sierra Nevada and the Southern Alps result in a $\Delta^{18}\text{O}$ of ~7‰ and 5‰, respectively (Ingraham and Taylor, 1991; Chamberlain et al., 1999). These isotopic anomalies are a direct result of elevation and are larger than isotopic effects due to temperature changes and changes in the $^{18}\text{O}$ of ocean water. In the Southern Alps, for example, regional cooling events (~6 °C) and isotopic changes of ocean waters since the Miocene will cause a decrease of ~2‰ of kaolinite rather than the observed ~6‰ decrease in $^{18}\text{O}$ values of kaolinite (Chamberlain et al., 1999).

Studying the history of these isotopic anomalies provides constraints on elevation changes during mountain building. This approach is best used by examining the $^{18}\text{O}$ of authigenic minerals on the rain-shadow side of the mountain range rather than using a chronosequence of minerals collected along an altitudinal transect or an uplifted plateau. Interpretation of the $^{18}\text{O}$ of authigenic minerals collected along an altitudinal transect or uplifted plateau is complicated by the fact that temperature changes with elevation changes. In addition, by measuring the isotopic composition of authigenic minerals in rocks both from the lee and rain-shadow sides of a mountain belt it should be possible to separate the effect of changes of topography from other factors that also influence the isotopic composition of minerals.

TOPOGRAPHIC DEVELOPMENT OF THE SOUTHERN ALPS AND SIERRA NEVADA

Southern Alps, New Zealand

In a previous study (Chamberlain et al., 1999) we constrained the topographic evolution of the Southern Alps by examining the $^{18}\text{O}$ of kaolinite from weathered horizons in sedimentary rocks on the rain-shadow side of the mountains. We selected this area for study because the Southern Alps is a modern mountain belt (~12 Ma), and is situated on the western edge of New Zealand, where the weather pattern is dominated by westerly air streams. The effects of changes in atmospheric circulation patterns and source of precipitation on $^{18}\text{O}$ values are therefore minimized. We discuss the results of our study of the Southern Alps because it provides a baseline for further studies of other mountain belts in which weather patterns could be considerably more complicated. We present the published data of the Southern Alps study and use these data to quantify its elevation changes (Fig. 1).

The Southern Alps are along the Alpine fault between the Australian and Pacific plates. Oblique compression along the Alpine fault gave rise to the Southern Alps sometime since 12 Ma. Despite the large number of studies on the uplift and exhumation history, it is still uncertain when the Southern Alps formed as a topographic feature; estimates range from 12 to 2.5 Ma (Cutten, 1979; Kamp and Tippet, 1993).

Our study shows (1) a 5‰–6‰ decrease in $^{18}\text{O}$ of kaolinite in lower Pliocene rocks; the values drop from 18.2‰ in pre-Pliocene rocks to 12.3‰ in post-Pliocene rocks (Fig. 2A), and (2) post-Pliocene kaolinites are in isotopic equilibrium with modern surface waters. We interpret the decrease in $^{18}\text{O}$ of kaolinite to be the result of the development of the rain shadow behind the Southern Alps. Other possible causes for this isotopic shift cannot account for the observed change in $^{18}\text{O}$ values (Chamberlain et al., 1999).

By using Figure 1, it is possible to estimate the elevation change that corresponds with this isotopic shift. It is assumed that the $^{18}\text{O}$ value of kaolinite reflects that of surface waters; a 5‰–6‰ change in surface waters corresponds to a net elevation change of 2350 ± 300 to 2800 ± 400 m (Fig. 1). This elevation change is approximately the same as the mean elevation of the Southern Alps (~2400 m).

Because of the uncertainty in the age of kaolinite formation (Fig. 2A), it is impossible to discern the precise age and rate of topographic development of the Southern Alps. However, the isotopic shift occurs in the lower Pliocene section, which suggests that before the early Pliocene the Southern Alps did not exist as a mountain chain. Our interpretation is consistent with paleoclimate studies (Mildenhall and Pocknall, 1989) that show that through the Miocene the South Island had a temperate moist climate, after which arid cool conditions prevailed; such a climatic change is consistent with the development of a rain shadow on the east side of the rising Southern Alps. The development of the Southern Alps as a mountain chain in the early Pliocene corresponds to a change in plate-motion vectors along the Alpine fault from dominantly strike-slip motion to oblique convergence ca. 5 Ma (Sutherland, 1995).

Sierra Nevada, California

The Sierra Nevada is an ~640-km-long, north–west-trending mountain belt located in eastern California. The average elevation is ~2800 m and peaks are as high as 4419 m. On the east side of the Sierra there is a rain shadow created by storms that track from either the west or southwest. The precipitation is complex in this region. Winter storms track mainly from the west, and
their source is from the Pacific Ocean, whereas summer storms are a mixture of Pacific-source precipitation and precipitation originating from either the Gulf of Mexico or Gulf of California. The area immediately east of the Sierra Nevada, where we collected isotopic data on clay minerals, is dominated by winter precipitation with winter:summer ratios ranging from 1.1 to 3.7 (Friedman et al., 1992). Studies have documented a 50%–60% difference in the δD of precipitation and surface waters across the Sierra Nevada (Ingraham and Taylor, 1991); the more negative values are on the east side. This creates one of the largest isotopic anomalies on Earth and is the direct result of the present-day topography of the Sierra Nevada.

There has been debate concerning the timing of the topographic development of the Sierra Nevada, and understanding the long-term stability of this isotopic anomaly will provide information about its elevational history. The long-standing view was that the development of topography was largely a post–10 Ma event (e.g., Huber, 1981). It has been suggested that the Sierra Nevada existed as a prominent topographic feature as early as 20 Ma and may have actually decreased in elevation since 10 Ma (Small and Anderson, 1995; Wernicke et al., 1996; Wolfe et al., 1997).

To test this hypothesis, we determined the δ18O values of smectite in ash layers along the east side of the Sierra Nevada. These ash layers are interbedded within lower Miocene to Pleistocene terrestrial sedimentary units exposed in basins of the western Basin and Range province. Because there is no complete stratigraphic section spanning the range in ages proposed for the Sierra, we sampled numerous sections and created a composite section that ranges in age from ca. 2 to 16 Ma (Fig. 2B).

We concentrated our studies on ash layers for three reasons. First, by using ash layers, it is possible to place a maximum age on the time of smectite formation. Second, we found smectite as a weathering product even in our youngest samples, suggesting that smectite forms soon after deposition. This observation is consistent with studies showing that smectite forms relatively rapidly during the weathering of terrestrial sedimentary rocks (Blum and Erel, 1997). Third, it has been shown that smectite preserves its isotopic composition after formation (Stamp et al., 1997).

Our results show that (1) there is little change of δ18O values of smectite from 2 to 16 Ma and (2) smectites are in equilibrium with modern isotopic composition with modern water. There are several possible interpretations of these isotopic data. First, all smectites formed recently and records only modern surface-water values. Second, smectite δ18O values have been reset by recent interaction with surface waters. Third, there has been no significant change in the δ18O values of surface waters on the east side of the Sierra Nevada since 16 Ma. We prefer the latter explanation because it has been shown that smectites retain their δ18O values after formation and, because of the rapid rate of smectite formation during weathering, it is unlikely that smectite formed in the ashes only recently.

We suggest that the isotopic anomaly in modern surface waters observed on the east side of the Sierra Nevada has been present at least since 16 Ma. The persistence of this anomaly suggests that the Sierra Nevada has been approximately at the same elevation at least since 16 Ma, which is consistent with results from recent studies mentioned here. Our data, however, are inconsistent with a similar study by Winograd et al. (1985), who presented an ~2 m.y. δD isotope record of fluid inclusions from a calcite vein from the east side of Death Valley. They found a 40% decrease in δD values and the recent samples were isotopically similar to modern ground water. They assigned this isotopic shift to the rise of the Sierra Nevada during the past 2 m.y. As it appears that our smectite samples are also in isotopic equilibrium with modern ground waters, and we observe little change in the δ18O of smectite from 16 to 2 Ma, it is unclear why our interpretation differs from that of Winograd et al. (1985). Smectites examined in our study were directly in the rain shadow of the Sierra Nevada and should, therefore, more closely record any elevation changes.

The decrease of δD values of fluid inclusions in the past 2 m.y. in Death Valley may record other influences such as decreased evaporation coincident with the onset of Pleistocene glaciation. We have not measured the δ18O values of smectites from ashes younger than 2 Ma, so a direct comparison of the two data sets is not possible.

CONCLUSIONS

The relationship between the δ18O of surface waters and net elevation shown in Figure 1 can be used to infer paleorelief. Because of topographic effects, surface waters are strongly depleted in 18O and D on the rain-shadow sides of mountain ranges. Therefore, by determining the isotopic composition of paleo–surface waters in chronosequences on the rain-shadow side of mountain belts, it is possible to reconstruct their topographic development. By using this approach, we suggest that the Southern Alps of New Zealand formed ca. 5 Ma, during a time when the Alpine fault changed from strike slip to oblique convergence, and that the Sierra Nevada of California has been a long-standing topographic feature since 16 Ma.

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