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Strontium isotopes and nutrient sourcing in a semi-arid woodland

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ABSTRACT

Sr isotopes are widely used as a tracer of Sr and Ca in surficial systems. Basalt flows ranging in age from 3 ka (kiloyears ago) to > 200 ka from El Malpais National Monument (EMNM), New Mexico provide an ideal setting to examine strontium, and hence calcium cycling by plants in a semi-arid woodland. To gauge plant dependence on atmospheric dust versus local weathering products for strontium and calcium, we measured $^{87}Sr/^{86}Sr$ ratios in local bedrock and soils, and compared them to leaf/wood cellulose of four different conifers, a deciduous tree, three shrubs, an annual C_4 grass, and a lichen. Sampling sites varied by parent material (limestone, sandstone, granite, and basalt) and age (Quaternary to Precambrian), providing a wide range in end-member $^{87}Sr/^{86}Sr$ ratios, whereas the target plant species varied in physiognomy, life history, and rooting depth. On non-basalt parent material, the contribution from dust changed with the supply of weatherable Sr-bearing minerals in local bedrock. Soils developed on Paleozoic limestone showed significant bedrock contributions. On basalts, the Sr budget of soils at EMNM is dominated by atmospheric dust on young, 3 ka flows, incorporates a mixture of basalt-dust in 9 ka flows, and is basalt-dominated in 120 ka flows. This is unlike the pattern observed in tropical soils developed on basalt in Hawaii, where basalt weathering dominates the Sr inventory of the youngest soils and aerosols dominate in older, deeply weathered soils. This contrast is mainly due to different water/rock (W/R) ratios: bedrock subjected to high W/R over short periods is quickly (< 10 ka) depleted in Sr (and Ca), except for the ongoing replenishment from aerosols. In arid settings where W/R are lower, soil Sr is still abundantly available first from dust, and increasingly from bedrock even after 120 ka. For plants, $^{87}Sr/^{86}Sr$ variations within and across sites at EMNP showed that evergreen trees varied most in $^{87}Sr/^{86}Sr$ ratios, shrubs were least dependent on eolian input of Sr, and both foliage density and rooting depths influence soil Sr pools.

1. Introduction

The conversion and transfer of rock-derived elements, specifically, calcium (Ca) and strontium (Sr), through soils to plants can be traced using strontium-87/strontium-86 ($^{87}Sr/^{86}Sr$) ratios. Plant Sr and Ca can come either from relatively deep in soils through the slow chemical weathering of local substrates or from shallow soil depths by the alteration of silt-sized, carbonate-rich dust. Although Sr is not itself a plant essential nutrient, it is a common chemical tracer of plant-essential nutrient Ca and exists in all common minerals where Ca is present. Therefore, $^{87}Sr/^{86}Sr$ ratios, which do not significantly fractionate with dissolution, have been used to trace Ca movement from rock or dust to soil water to plants across different climatic, vegetation, and geologic settings (e.g., Chadwick et al., 1999; Vitousek et al., 1999).

We used $^{87}Sr/^{86}Sr$ ratios to evaluate sources and rates of nutrient cycling at El Malpais National Monument (EMNM) in west-central New Mexico, USA (Fig. 1), a semi-arid setting characterized by cold winters, mild summers and bimodal precipitation patterns. This site offers an ideal setting for these kinds of studies. A range of basaltic lava flows and cinder cones (the Zuni-Bandera volcanic field), reminiscent of Hawaiian-style volcanism, erupted over the last 700,000 years in a valley flanked by outcrops of Paleozoic age carbonate rocks, Mesozoic age sandstones, and Precambrian age gneiss (Laughlin et al., 1994). The flows are easily differentiated (Fig. 2) based on very different stages of surface modification and soil development.

The flows and surrounding bedrock are dominated by pinyon-juniper and ponderosa pine woodlands and encompass a wide range of functional plant types with different foliage densities (and thus dust-trapping ability), varied rooting depths, and potentially different strategies of Sr and Ca acquisition. Growing conditions here range from the seemingly impossible – within crevasses in fresh basalt flows and in shallow pools of dust on rock surfaces – to thick, fertile soils. Because the dust and bedrock substrates at EMNM have distinguishable $^{87}Sr/^{86}Sr$ ratios, we can determine the relative contributions

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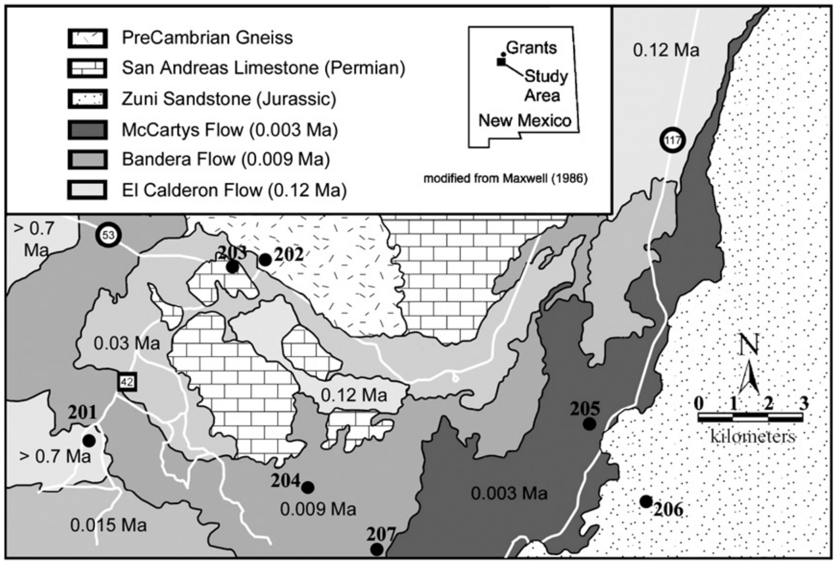

Fig. 1. Generalized geologic map in and around Malpais National Monument with sample sites numbered in bold. Ages of basalt flows indicated in millions of years (Ma). Geology drawn from Maxwell (1986).

of substrate-derived versus dust-derived Sr for different plant species, and compare plant nutrient acquisition patterns across different substrate types and ages.

We measured the $^{87}Sr/^{86}Sr$ ratios in both soils and plants across seven sites that vary by bedrock type (limestone, sandstone, granite, and basalt) and by surface age on 3 ka to 120 ka old basalts and on older non-basalt substrates (Precambrian gneiss and the Mesozoic age Zuni Sandstone and Paleozoic age San Andres Formation) (Table 1). We sampled wood or leaf cellulose from several individuals each for trees (*Pinus ponderosa, Pinus edulis, Juniperus monosperma, Juniperus scopulorum*), shrubs *(Chrysothamus nauseosus, Fallugia paradoxa, Rhus trilobata)*, grass *(Bouteloua gracilis)*, and lichen (*Xanthoparmelia lineola*) and used an isotopic mixing equation to identify Sr sources. These species exhibit a wide range of life history, growth form and rooting depths (Fig. 3 and Table 2). Typically, more than half of the listed species were represented at each site, allowing for modest replication.

Atmospheric dust contribution to Sr pools was calculated using a simple isotopic mixing equation. Dust $^{87}Sr/^{86}Sr$ ratios at EMNM are dominated by marine carbonates with minor contributions from other bedrock sources (Van der Hoven and Quade, 2002). The relative flux of plant-available Sr from atmospheric and bedrock weathering sources were used to calculate bedrock weathering rates in this semi-arid ecosystem. We compared these rates with those obtained for similar studies conducted in tropical settings at the other end of the climate spectrum (e.g., Chadwick et al., 1999; Kennedy et al., 1998; Stewart et al., 2001; Vitousek et al., 1999).

1.1. Additional background

1.1.1. The role of atmospheric dust and foliage density

Continentally derived dust is an important source of Sr in soil in southwestern United States due to its high carbonate content, high Ca and Sr concentrations, and the susceptibility of carbonate to rapid dissolution compared to silicates. Weathering of limestone and dolostone, and recycled soil caliche provide a relatively stable atmospheric dust source that can locally dominate the Sr inventory in desert soils (Capo and Chadwick, 1999; Van der Hoven and Quade, 2002). In the San Pedro/Nacimiento Mountains near Cuba, New Mexico, the overriding influence of regional atmospheric dust is reflected in conifer $^{87}Sr/^{86}Sr$ ratios, which vary much less than ratios of underlying bedrock, despite growing on three different substrates (granite, limestone, and sandstone) (English et al., 2001). In nearby southern Arizona, Ca and Sr largely derived from dust dominates regional soils and only varies on the rather course scale of ~10^4 km^2 (Naiman et al., 2000).

Several studies have quantified the eolian contribution to soils in the southwestern United States using $^{87}Sr/^{86}Sr$ ratios as a proxy for Ca movement in soils. Using mass balance and $^{87}Sr/^{86}Sr$ ratios on a 2-million-year-old soil in southern New Mexico, Capo and Chadwick (1999) estimate a minimum atmospheric contribution of ~94% to the soil carbonate Ca and 50–70% eolian contribution to the uppermost 25 cm of the soil, suggesting very slow rates of local bedrock weathering. A study of the soil carbonate within EMNM found the $^{87}Sr/^{86}Sr$ ratio of the soil carbonate (=0.7086) and the labile fraction of the A-horizon ($^{87}Sr/^{86}Sr$=0.7075) to be similar to that of the local

Fig. 2. Photographs of typical plant and soil cover on the three main age groups of basalts. From left to right, the McCarty's Flow (3 ka), the Bandera Flow (9 ka), and El Calderón Flow (120 ka).