Geol. 656 Isotope Geochemistry

Lecture 31 **Spring 2003**

HIGH TEMPERATURE APPLICATIONS III: SUBDUCTION STUDIES

SEDIMENT SUBDUCTION VS. ASSIMILATION

Magmas erupted and emplaced in subduction zones have unique geochemistry that is apparent in both their trace element and radiogenic isotopic compositions. Most often, this unique geochemistry is taken as evidence that the sources of these magmas contain subducted sediments. However, in many instances, this interpretation is non-unique. The geochemical signature of subducted sediment is, in many respects, simply the signature of continental crust. In general, it is just as plausible that magmas have acquired this signature through assimilation of continental crust as by partial melting of a mantle containing subducted sediment. Magaritz et al. (1978) pointed out that by combining radiogenic isotope and oxygen isotope analyses, it is possible to distinguish between these two possibilities.

Magaritz et al. reasoned as follows. First, many continental materials have oxygen isotope ratios that are quite different from mantle values (e.g., Figure 30.4). Then they noted that all rocks have similar oxygen concentrations. Because of this, addition of 10% sediment with $\delta^{18}O$ of +20 to the mantle (+6) followed by melting of that mantle produces a magma with the same $\delta^{18}O$ (+8.4), as adding 10% sediment directly to the magma (i.e., in this case the magma also ends up with $\delta^{18}O$ = +8.4). However, addition of 10% sediment to the mantle, followed by melting of that mantle produces a magma with a very different Sr isotope ratio than does adding 10% sediment directly to the magma. The reason for this difference is that the Sr concentration of the magma is much higher (something like an order of magnitude higher) than that of the mantle. Thus addition of sediment to magma affects the Sr isotope ratio less than addition of sediment to the mantle. Indeed, most subduction-related magmas are richer in Sr (~ 400 ppm) than most continental materials and sediments; but sediments invariably have more Sr than does the mantle (10-40 ppm).

This point is illustrated in a more quantitative fashion in Figure 31.1. We discussed mixing trajectories in an earlier lecture and noted that when two materials are mixed in varying proportions, a curve results on a plot of one ratio against another. The degree and sense of curvature depended on the ratio of the ratio of the two denominators in the two end-members. Since the concentration of oxygen is the same in most rocks, the ratio of ^{16}O in the two end-members can be taken as 1. So, for example, in plot of $^{87}Sr/^{86}Sr$ vs. oxygen isotope ratio, the degree of curvature depends only on the ratio of Sr in the two end-members. In Figure 31.1, when the ratio of Sr in end-member M (magma or mantle) to Sr in end-member C (crust or sediment) is greater than 1, a concave downward mixing curve results. If that ratio is less than 1 (i.e., concentration of Sr in C is greater than in M), a concave upward curve results. Assimilation of crust by magma essentially corresponds to the concave downward case ($Sr_M > Sr_C$) and mixing of subducted sediment and mantle corresponds to the concave upward case ($Sr_M < Sr_C$). Thus these two processes are readily distinguished on such a plot.

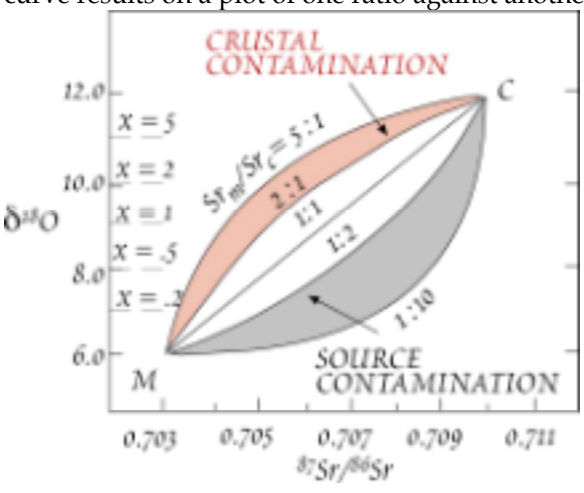


Figure 31.1. Mixing curves on a plot of $\delta^{18}O$ vs. $^{87}Sr/^{86}Sr$. The labels on the lines refer to different ratios of Sr concentration in the two end-members. From James (1981).

Figure 31.2 shows the data of Magaritz et al.

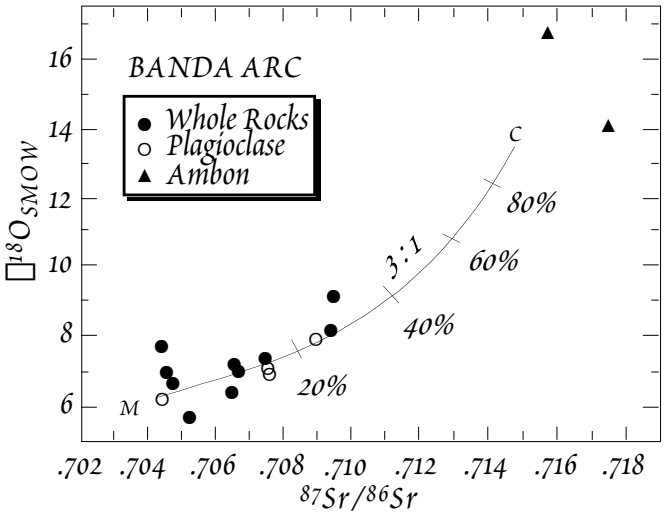


Figure 31.2. Oxygen and Sr isotopic composition of Banda arc magmas. Mixing curve constructed assuming a concentration ratio of $Sr_C/Sr_M = 3$. End member M has $^{87}Sr/^{86}Sr = 0.7035$ and $\delta^{18}O = +6$; end member C has $^{87}Sr/^{86}Sr = .715$ and $\delta^{18}O = +14$. Ticks indicate the percentage of end member C in the mixture.

(1978) for the Banda arc. These data fall roughly along a mixing curve for $Sr_C/Sr_M = 3$. The samples are mainly basaltic andesites and andesites and have reasonably high Sr concentrations (150-500 ppm). Magaritz et al. (1978) argued that the apparent 3:1 concentration ratio between the C and M members was more consistent with mixing of pelitic sediments (which have 100-150 ppm Sr) with mantle than assimilation of crust by magma. The two triangles represent the isotopic composition of corderite-bearing lavas from the island of Ambon. The petrology and composition of these lavas suggest they are produced directly by melting of pelitic sediments in the deep crust. Thus their isotopic compositions were taken as potentially representative of the assimilant.

Considerable care must be exercised in the interpretation of oxygen isotope ratios in igneous rocks, particularly when the rocks come from a tropical region such as the Banda Arc. In such regions, rocks quickly begin to react with water and primary phases in the groundmass are replaced with various secondary minerals. The isotopic composition of such minerals will be much higher ($\delta^{18}O \approx +20$ to $+30$) than the original ones. Thus the O isotopic composition of weathered igneous rocks will be higher than that of the original magma. Thus in their study, Magaritz et al. (1978) also analyzed plagioclase phenocrysts. Phenocrysts generally weather less rapidly than does the groundmass and alteration effects can be easily identified visually, which is not always the case with the groundmass. Thus phenocrysts often provide a better measure of the oxygen isotopic composition of the original magma than does the whole rock. This is true even though there might have been a small equilibrium fractionation between the magma and the phenocryst.

The amount of subducted sediment implied by the mixing curve in Figure 31.2 is much greater than has been inferred to be involved in other arcs (about 1-3%). The Banda arc is directly adjacent to the Australian continent, so extensive involvement of sediment and crustal material is perhaps to be expected. On the other hand, the amount of sediment, or crustal material in the mixture is sensitive to assumptions about the oxygen isotope composition of that material. If the $\delta^{18}O$ of the crustal material is assumed to be +22 rather than +14, the calculated percentage of sediment involved would decrease by 50%.

The mean $\delta^{18}O$ of Marianas lavas is, in contrast to Banda, about +6.2 (Ito and Stern, 1986; Woodhead et al., 1987). This implies the amount of sediment involved in the source is less than 1%, which is consistent with the amount inferred from radiogenic isotope studies.

In contrast to this interpretation, James and Murcia (1984) have used radiogenic and stable isotope systematics to argue for extensive assimilation of crust by magmas in the northern Andes. As shown in Figure 31.3, andesites from Nevado del Ruiz and Galeras volcanos in Columbia define a steep array on plots of $\delta^{18}O$ vs. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$. Comparing this with Figure 31.1, we see that such steep arrays imply mixing between magma and crust rather than mantle and sediment. As we observed in the last lecture, assimilation will inevitably be accompanied by fractionation crystallization. James and Murcia (1984) modeled this assimilation using the equations similar to 30.4- 30.6 and the assumed concentrations listed in Table 31.1. The model fits the data reasonably well and implies assimilation of up to about 12% country rock. An R of 0.33 provided the best fit, though James and Murcia (1984)

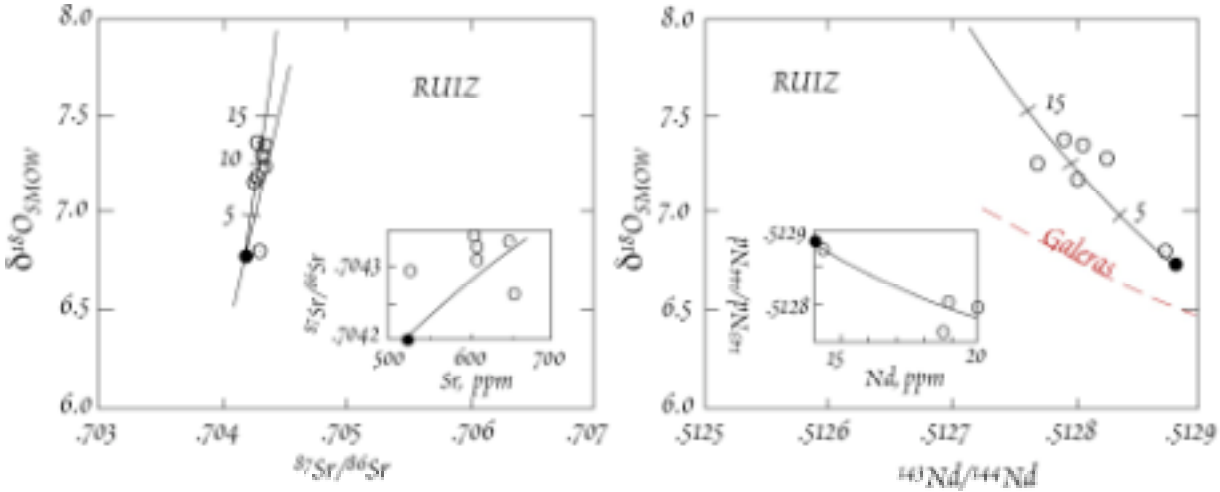


Figure 31.3. Sr, Nd, and O isotopes in lavas from Nevado del Ruiz Volcano in Columbia and an AFC model calculation. Dashed line shows AFC trajectory for another Colombian volcano, Galeras. After James and Murcia (1984).

Table 31.1: Parameter for Ruiz Assimilation Model

		Original Magma	Assimilant
$\delta^{18}O$		6.5‰	11‰
Δ	0.5‰		
$^{87}Sr/^{86}Sr$		0.7041	0.710
r_{Sr}	0.2		
Sr, ppm		650	100
$^{143}Nd/^{144}Nd$		0.51288	0.5122
Nd, ppm		20	20
r_{Nd}	0.2		
R	0.33		

noted this parameter was not well constrained. A high value of R suggests the assimilation is occurring at moderate depth (< 10 km), because it suggests only moderate input of heat in melting the country rock.

On a broader basis, Harmon et al. (1984) have used O isotope ratios to show that extent of crustal assimilation in Andean magmas varies regionally and correlates with crustal thickness. The Andes are divided into 3 distinct volcanic provinces. In the north, the subduction zone is steeply dipping, and the volcanos are located approximately 140 km over the Benioff zone. The crust in the *Northern Volcanic Zone* (NVZ), located in Columbia and Ecuador, is approximately 40 km thick and is mainly Cretaceous and Cenozoic in age. Volcanics are primarily basaltic andesites and andesites. In the *Central Volcanic Zone* (CVZ), which extends from southern Peru to northern Chile and Argentina, the crust is 50 to 70 km thick and Precambrian to Paleozoic in age. The Benioff Zone lies approximately 140 km beneath these volcanos. The volcanics range from andesite through rhyolite, and include extensive ignimbrites. The *Southern Volcanic Zone* (SVZ) is located in south-central Chile and overlies a shallower, more gently dipping Benioff Zone. These volcanos lie roughly 90 km above the Benioff Zone and atop 30-35 km of Mesozoic and Cenozoic crust. Here the volcanics are mainly basaltic, with minor andesite and dacite.

Figure 31.4 shows that $\delta^{18}O$ is most mantle-like in the SVZ, with a mean $\delta^{18}O$ of about +6.0, just slightly higher than the mean for MORB. $^{87}Sr/^{86}Sr$ ratios average about 0.704, just slightly higher than the mean for intra-oceanic arcs. The NVZ has higher $\delta^{18}O$, with a mean about +6.9, and somewhat higher $^{87}Sr/^{86}Sr$. $\delta^{18}O$ in the CVZ is highest, ranging from +7 to +14. This corresponds to the region of the thickest and oldest crust in the Andes. Volcanics in the southern part of the CVZ, from 21-26° S, have apparently experienced the greatest assimilation. Minimum $\delta^{18}O$ values of around +7 in this region suggest that all magmas have assimilated at least some crust. Figure 31.5 shows an example of data from one volcano in the CVZ, Cerro Galan in northwest Argentina. Sr and O isotope data define broad, slightly convex-upward array that is reminiscent of the AFC curves in Figure 31.5 for a value of $r \approx 2$.

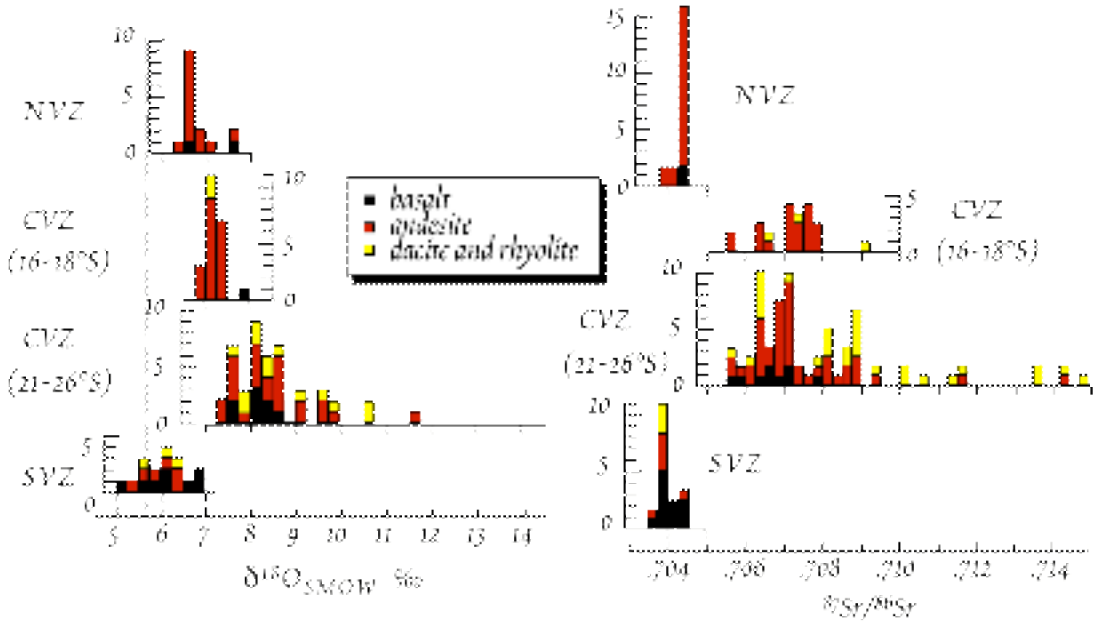


Figure 31.4. Oxygen and Sr isotope ratios in Andean volcanics. Dashed line shows the mean $\delta^{18}O$ of MORB. After Harmon et al. (1984).

STABLE ISOTOPES AS INDICATORS OF CRUST-TO-MANTLE RECYCLING

As we noted in an earlier lecture, the potential importance of the crust–to–mantle flux resulting from subduction was first pointed out by Armstrong in 1968. More specifically, Hofmann and White (1982) proposed that mantle plumes consist in part of subducted oceanic crust. As we shall see, the oceanic crust undergoes substantial modification of its oxygen isotopic composition as a result of the hydrothermal activity and metamorphism that occurs virtually simultaneously with formation of the oceanic crust and as a result of low-temperature reactions with seawater. The hydrothermal activity tends to lower the $\delta^{18}O$ of the middle and lower oceanic crust, while the low-temperature weathering raises the $\delta^{18}O$ of the upper oceanic crust.

Interestingly, there is little or no net change in oxygen isotope composition of the oceanic crust as a result of these processes. Thus subduction of the crystalline portion of the oceanic crust should have not net effect on the oxygen isotopic composition of the mantle as a whole, but it might increase isotopic heterogeneity.

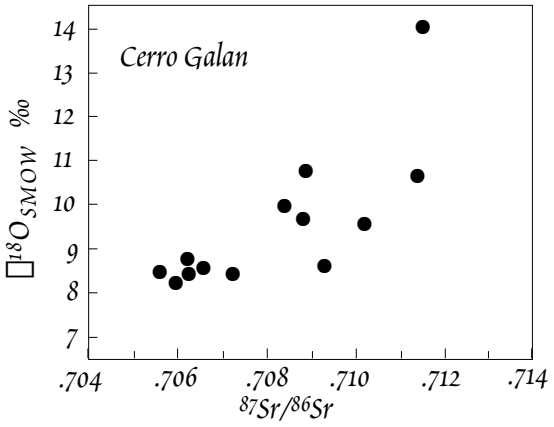


Figure 31.5. $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ in Cerro Galan, and ignimbrite center in Northwest Argentina. After Harmon et al. (1984).

The lower average $\delta^{18}O$ of OIB (Figure 29.7) is nevertheless interesting in the context of the Hofmann and White hypothesis. Accepting the axiom of Taylor and Sheppard (1986) that material with $\delta^{18}O$ substantially different from the mantle value (as a working definition of the mantle value, we will adopt the mean value of MORB of +5.7), the lower average $\delta^{18}O$ and the greater heterogeneity of $\delta^{18}O$ in OIB strongly supports the interpretation that the plumes that produce these magmas contain material that was once at the surface of the Earth. One might speculate that the lower mean value for OIB arises because upper oceanic crust is somehow less likely to survive subduction into the deeper mantle, perhaps because it partially melts in subduction zones (or has in the past when the

Earth was hotter).

The subduction process may also influence the composition of the subcontinental lithosphere. As may be seen in Figure 31.6, eclogite* xenoliths from the Roberts Victor Mine (South Africa) kimberlite have remarkably variable oxygen isotope compositions (MacGregor and Manton (1986). The range in $\delta^{18}O$ is similar to that of "mature" oceanic crust (i.e., subsequent to hydrothermal low temperature metamorphism), and contrasts with the homogeneity of peridotite xenoliths (Figure 31.6), many of which also come from kimberlites. Since eclogites are the high pressure equivalent of basalts, this suggests the ecolgites come from subducted oceanic crust. Further evidence to this effect is the correlation observed between O isotope ratios, Sr isotope ratios, and K and Rb concentrations, as these will also be affected by metamorphism of the oceanic crust. Geobarometry suggests these eclogites last equilibrated at depths of 165-190 km. Radiogenic isotope evidence suggests they are 2.47 Ga old.

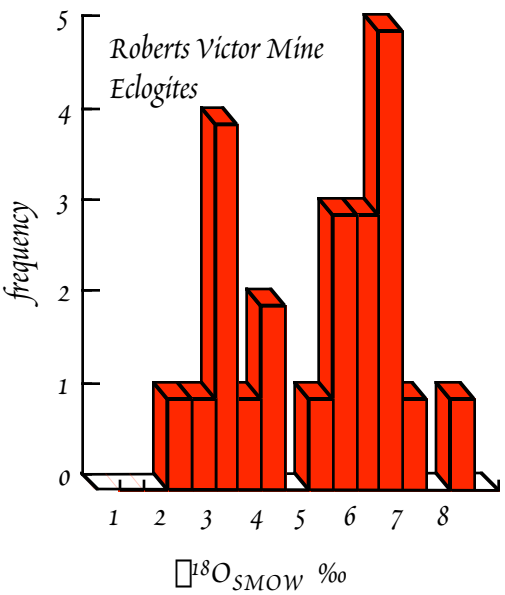


Figure 31.6. Oxygen isotope ratios in eclogite xenoliths from the Roberts Victor Mine kimberlite.

REFERENCES AND SUGGESTIONS FOR FURTHER READING

Harmon, R. S., B. A. Barreiro, S. Moorbath, J. Hoefs, P. W. Francis, et al., Regional O-, S-, and Pb-isotope relationships in late Cenozoic calc-alkaline lavas of the Andean Cordillera, *J. Geol. Soc. Lond.*, 141, 803-822, 1984.

Hofmann, A. W. and W. M. White, Mantle Plumes from ancient oceanic crust, *Earth Planet. Sci. Lett.*, 57, 421-436, 1982.

Ito, E. and R. J. Stern, Oxygen and strontium isotopic investigations of subduction zone volcanism: the case of the Volcano Arc and the Marianas Island arc, *Earth Planet. Sci. Lett.*, 76, 312-320, 1986.

James, D. E. and A. Murcia, Crustal contamination in northern Andean volcanics, *J. Geol. Soc. Lond*, 141, 823-830, 1984.

James, D. E., The combined use of oxygen and radiogenic isotopes as indicators of crustal contamination., *Ann. Rev. Earth Planet. Sci. Lett.*, 9, 311-344, 1981.

MacGregor, I. D. and W. I. Manton, Robert Victor Eclogites: ancient oceanic crust, *J. Geophys. Res.*, 91, 14063-14079079, 1986.

Magaritz, M., D. J. Whitford and D. E. James, Oxygen isotopes and the origin of high $^{87}Sr/^{86}Sr$ andesites, *Earth Planet. Sci. Lett.*, 40, 220-230, 1978.

Woodhead, J. D., R. S. Harmon and D. G. Fraser, O, S, Sr, and Pb isotope variations in volcanic rocks from the Northern Mariana Islands: implications for crustal recycling in intra-oceanic arcs, *Earth Planet. Sci. Lett.*, 83, 39-52, 1987.

* Eclogite is a rock consisting primarily of Na-rich pyroxene and garnet that forms only at high pressures. Compositionally these eclogites are similar to basalts, as are most.