NAME________________________

89.304 - IGNEOUS & METAMORPHIC PETROLOGY
RADIOGENIC ISOTOPES IN IGNEOUS PETROLOGY

Radiogenic isotopes are those produced by the decay of radioactive elements. It should be noted that the radiogenic isotopes are stable, it is their radioactive parent isotopes that are unstable. Table 1 lists the radioactive isotopes commonly used in igneous petrology.

Table 1. Radiogenic isotopes used in igneous petrology

Radioactive parent	Natural abundance (atom%)	Half-life (years)	Decay type	Decay constant (λ) (x 10^{-11} y^{-1})	Radiogenic progeny
^{40}K	0.0118	1.25 x 10^{9}	K-capture	5.81	^{40}Ar
^{87}Rb	27.85	4.88 x 10^{10}	Beta	1.42	^{87}Sr
^{147}Sm	14.97	1.06 x 10^{11}	Alpha	0.654	^{143}Nd
^{232}Th	100	1.40 x 10^{10}	Chain	4.95	^{208}Pb
^{235}U	0.72	7.04 x 10^{8}	Chain	98.485	^{207}Pb
^{238}U	99.28	4.47 x 10^{9}	Chain	15.5125	^{206}Pb

All these isotopic systems can be used to determine the age of a rock and all but K-Ar can be used as isotopic tracers. We shall illustrate these applications using the Sr-isotope system.

The isochron method for dating co-magmatic suites of igneous rocks, which may be applied to all the above decay schemes, depends on the fact that in a given sample the rate of accumulation of the radiogenic isotope, relative to a non-radiogenic isotope of the same element, is related to the concentration ratio of parent and progeny elements. Thus the *isochron equation* for the Rb-Sr scheme is

$$\left(\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}\right)_{\mathrm{meas}} = \left(\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}\right)_{\mathrm{init}} + \left(\frac{^{87}\mathrm{Rb}}{^{86}\mathrm{Sr}}\right)_{\mathrm{meas}} \left(e^{\lambda t} - 1\right)$$

where t is the time since the rock crystallized from an isotopically homogeneous magma and λ is the decay constant. The subscript *init* refers to the initial (magmatic) Sr-isotope composition. All the other ratios are as measured today.

If we have a series of rocks crystallized from the same isotopically homogeneous magma but with a range of initial Rb/Sr ratios, a plot of measured ^{87}Rb/^{86}Sr versus measured ^{87}Sr/^{86}Sr should yield a straight line (the isochron). This straight line has the form y = mx + b where $y = (^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_{\mathrm{meas}}$, $m = (e^{\lambda t} - 1)$, $x = (^{87}\mathrm{Rb}/^{86}\mathrm{Sr})_{\mathrm{meas}}$, and $b = (^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_{\mathrm{init}}$. The slope of the line gives the age of the rock unit and the y-intercept yields the ^{87}Sr/^{86}Sr ratio at the time of emplacement of the magma (the initial ratio).

The initial ratio is of interest since it can fingerprint the source region of a magma and may reveal information concerning magma contamination. In a simplified way this approach is based on the idea that during differentiation of the earth Rb is preferentially concentrated, with respect to Sr, in the crust. The time integrated Rb/Sr ratio of the crust, therefore, will be greater than that of the mantle and at any instant in time crustal $^{87}Sr/^{86}Sr$ ratios will be higher than mantle ratios. The present mantle is believed to have $^{87}Sr/^{86}Sr$ ratios between 0.7034 and 0.7040. Crustal material would have higher ratios unless it was recently formed from the mantle. The lower and upper crust may also be isotopically distinctive because during high grade metamorphism Rb is more mobile than Sr. One might picture a generalized situation in which the mantle has the lowest $^{87}Sr/^{86}Sr$ ratios, the lower curst somewhat higher ratios, and the upper crust relatively high ratios.

Not all rocks suites collected from a single magmatic body yield isochrons. This may be due to original isotopic heterogeneity of the magma, variable contamination by crustal material, or post-emplacement loss or gain of Rb and Sr (or other elements depending on the isotopic system). In the case of contamination, if the process involves simple mixing between the initial magma and an isotopically uniform contaminant, a relationship exists between the Sr concentration and the $^{87}Sr/^{86}Sr$ ratio. If you've already had Environmental Geochemistry, we looked as these mixing relationships in the isotope chapter.

The White Mountain Batholith

The White Mountain batholith of New Hampshire was formed by a number of intrusive events. Hence, the batholith is composite in nature. Mount Lafayette consists of a series of differentiated bodies apparently emplaced relatively early in the history of the batholith. The Mount Osceola and Conway granites are the major units of the batholith and are somewhat heterogeneous in nature. A rhyolitic volcanic sequence, the Most Volcanics, is preserved at several locations in down-dropped blocks. The following data have been obtained for these units. Normally it is the Rb/Sr ratio that is measured and this ratio must be converted to $^{87}Rb/^{86}Sr$ (already done in this case). The data for the Mount Lafayette, Osceola, and Moat sequences are given in Table 2.

Table 2. Isotopic data for various units in the White Mountain Batholith

Mount Lafayette			Mount Osceola			Moat Volcanics		
Sample	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Sample	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Sample	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
ML1	10.11	0.73119	MO1	17.3	0.74994	MV1	108.2	0.98451
ML4	4.45	0.71640	MO2	14.4	0.74498	MV2	94.2	0.95286
ML5	2.17	0.70982	MO3	190.2	1.20900	MV3	112.4	1.00410
ML7	2.19	0.70996	MO6	249.1	1.36300	MV5	55.5	0.85397
ML8	12.18	0.73798	MO7	119.1	1.02105	MV10	197.6	1.21010
ML9	18.95	0.75525	MO8	112.2	1.00590	MV12	160.1	1.11860
			MO9	52.5	0.84483	MV13	433.3	1.80380
			MO10	22.9	0.76726	MV14	338.9	1.56150

1. Using a spreadsheet program, draw isochrons for each suite. Plot $^{87}Rb/^{86}Sr$ on the x-axis and $^{87}Sr/^{86}Sr$ on the y-axis. Fit a trend line to the data. NOTE: In practice an isochron is fit to the data using a least squares regression technique that considers variability in both the x and y values (Derek York became famous for developing this particular equation for a straight line). A simple linear regression equation only considers variation in the y value. Hence, one would not use this equation to determine an isochron. However, for the purpose of this exercise simple linear regression provides an adequate model.

   a. Determine the slope of the isochrons and from these the age of the rock suites. [$m = e^{\lambda t} - 1$, therefore, $t = \ln(m+1)/\lambda$].

   b. Field evidence suggests that the relative order of emplacement is Mount Lafayette (oldest), then Mount Osceola, and then the Moat Volcanics (youngest). Do your ages agree with this sequence?

   c. What are the initial ratios for the three units?

   d. Based on these initial ratios, what can you conclude about the sources of these magmas and their interaction with the crust?

2. The Rb-Sr data for the Conway granite do not yield an isochron. U-Pb zircon ages give an emplacement age of 181 Ma for this unit.

   a. The Conway granite data are listed in Table 3. Correct the Conway $^{87}Sr/^{86}Sr$ ratios for the radioactive decay that has occurred since the granite was emplaced. That is, determine the $^{87}Sr/^{86}Sr$ ratio for these rocks 181 million years ago.

Table 3. Data for Conway granite

Sample	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Sr (ppm)	1/Sr	$(^{87}Sr/^{86}Sr)_I$
CG1	17.4	0.75136	52.4		
CG2	47.5	0.83390	21.5		
CG3	78.4	0.92864	18.5		
CG4	126.6	1.06230	11.7		
CG5	15.1	0.74689	41.6		
CG6	18.0	0.75339	46.3		
CG7	9.1	0.72901	103.0		
CG8	43.1	0.82374	19.1		
CG9	11.3	0.73458	90.0		
CG10	41.0	0.81438	31.2		

   b. Plot 1/Sr on the x-axis and $(^{87}Sr/^{86}Sr)_i$ on the y-axis.

   c. Is there any pattern to this plot? Explain. You may want to refer to the section in *Principles of Environmental Geochemistry* that discusses isotopic mixing. Samples CG3 and CG4 are from contact zones between the Conway granite and the surrounding sediments. The other samples are from within the Conway granite.