Abstract

Various radioactive isotopic dating methods for geochronology and tracer studies are used to provide insight into the formation of various geological sites. Several isotopic dating methods used in conjunction allows for the most accurate reading of the field relationships of samples to determine possible emplacement, crystallization activity, and the nature of the formation of igneous rocks. The given granitic pluton dataset can be analyzed from a series of Rubidium-Strontium dating (Rb-Sr), Uranium-Lead Dating (U-Pb), and Samarium-Neodymium dating (Sm-Nd) methods for a comparative analysis of the three plutons to minimize variation from the calculated age. The benefits of using U-Pb dating method is to estimate magma cooling age to indicate possible emplacement type. Granitic plutons especially benefit from Rb-Sr dating analysis to detect fractional crystallization potential, as Strontium concentrates in plagioclase causing a potential increase in residual magma with a general increase in overall differentiation, which can be seen in the Rb/Sr ratios. Likewise, U-Pb dating with applications in determining the cooling conditions to determine bulk or incremental emplacement, respectively. Modern geochemical studies of mantle derived rock have included Sm-Nd isotopic dating analysis to determine magmatic origination combined with standard Rb-Sr analysis to determine origin and composition. After a varied application of the isotopic dating methods across the three plutons, the suspected age disparity revealed that the samples from the plutons were emplaced incrementally, experienced fractional crystallization, and were derived from the same source.

Introduction

The identified compositional material of the quartz diorite, granodiorite, and granite contain increasingly higher silicate content respectively. Due to the nature of the compositional samples, the expected Rb-Sr isotopic ratios should progressively increase from Plutons A to C if the igneous rocks were emplaced incrementally rather than in bulk. The plutonic age should increase as differentiation increases. Another indicator of incremental emplacement of the plutons is that within the Rb/Sr analysis there should be some fractional crystallization, in which the initial ratio of $^{87}Sr/^{86}Sr$ should eventually cross the predefined threshold for assimilation or a crustal source of 0.706, this will most likely present in the latter plutons of a younger age. The source of $^{87}Sr/^{86}Sr$ ratio in this way assists in the distinction between a series of plutons which derive from crustal formation/assimilation or were derived from a mantle source. The Rb-Sr dating analysis is limited; however, in its capacity to give an accurate estimate if the sample was affected by external hyperthermic pressures or more common metasomatism, beyond the general tendency to give a younger age due to interference from crustal accretion. The Sm-Nd isotopic dating method is used together with the Rb-Sr dating, as it is less susceptible to metasomatism and shifting in which the parent magma could be identified. A negative epsilon value of the Nd based on the modern chondritic uniform reservoir equation in the Sm-Nd dating would also support incremental emplacement. Lastly, the effective use of the zircon analysis via U-Pb dating would be ideal to support the occurrence of fractional crystallization given a descending age value across the plutons, as it is more resistant to external hyperthermal interference.

Approach

Across the three isotopic dating method s initial Rb-Sr dating analysis was performed on seventeen samples of various types. Each sample was measured for Rb and Sr content in parts per million (ppm), from which $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios could be derived respectively. The initial biotite sample across the three plutons exhibited an extremely large Rb content with the some of the lowest Sr content shown altering the $^{87}Rb/^{86}Sr$ ratio on the order of hundreds in magnitude. This analysis shown in Figure 1 allows for the formation of an isochron plot to better identify the source of the pluton (mantle or crustal) from the calculated line of best fit as well as isotopic ratio which can be determined by the y-intercept. The age estimates can also be made by using the slope of the best fit trendline as well as the Rb-Sr decay constant of 1.42×10^{-11}.

	sample	**Rb (ppm)**	**Sr (ppm)**	**87Rb/86Sr**	**87Sr/86Sr**
Pluton A	biotite	508	10.3	145.5	0.88108
(quartz diorite)	plag	1.6	1062	0.004	0.70572
	K-spar	212.5	925	0.66	0.70664
	hornblende	3.5	45.3	0.22	0.70607
	apatite	0.7	373	0.006	0.70585
	whole rock	60.2	621	0.28	0.70612
Pluton B	biotite	846	18.9	131.8	0.86108
(granodiorite)	plag	37	508	0.21	0.70593
	K-spar	360	636	1.64	0.70764
	titanite	3.6	34.8	0.3	0.70622
	whole rock	135	460	0.89	0.70667
Pluton C	biotite	1018	20.7	142	0.86919
(granite)	plag	9.7	581.5	0.05	0.70652
	apatite	23	525	0.13	0.70651
	K-spar	236.6	1040	0.66	0.70724
	hornblende	10.7	37	0.84	0.70745
	titanite	1.9	48	0.12	0.70662
	whole rock	125	633	0.57	0.70717

Figure 1: Rb-Sr Analysis of various samples of Pluton A, B, and C respectively. The following biotite, plag, K-spar, hornblende apatite, titanite and whole rock samples were analyzed for Rb-Sr content in ppm with isotopic decay ratios calculated.

Comparative Sm-Nd isotopic analysis was also performed on five whole rock samples on Pluton B as a complement to the Rb-Sr data, as this method is less susceptible to metasomatism and common hyperthermal events which alter the values of Rb-Sr data. The lower mobility of the Sm-Nd creates a higher threshold for the requisite Sm/Nd ratio to determine whether the pluton derived from a crustal source. The various whole samples, therefore, similarly to the Rb-Sr analysis, was used to measure the Sm and Nd content in ppm, as well as the derived 87Rb/86Sr and 87Sr/86Sr ratios as shown in Figure 2. Similar isochron plot analysis can be used to determine the initial isotopic ratio as well as an age estimate based on the trendline of best fit using the decay constant of Sm-Nd of 6.54×10^{-12}. The smaller isotopic 143Nd/144Nd ratios are the basis of calculating the εND which gives further indication of a enriched mantle source or crustal source for the pluton.

	sample	Sm (ppm)	Nd (ppm)	147Sm/144Nd	143Nd/144Nd
Pluton B	whole rock	0.841	5.642	0.0901	0.512342
(granodiorite)	whole rock	0.427	2.975	0.0867	0.51228
	whole rock	3.35	20.62	0.0981	0.512326
	whole rock	3.21	22.89	0.0848	0.512349
	whole rock	5.27	30.86	0.1032	0.512344

Figure 2: Pluton B whole rock samples were collected and analyzed for Sm-Nd content in ppm with isotopic decay ratios calculated.

Lastly, U-Pb isotopic dating analysis was conduct on 4 zircon samples derived from Pluton A as well as 5 zircon samples from Pluton B for specific isotopic ratios of 206Pb/238U and 207Pb/235U shown in Figure 3. The variable isotopic Pb and U values will allow for two ages to be calculated based on the varied decay constants of 238 U (1.55 x$10^{-10)}$ and 235 U (9.8571x10^{-10}). From which varied age calculations based on the multiple U-Pb age equations. Subsequent Concordia Diagrams could also be used to determine any potential U or Pb lose for greater accuracy depending upon the derived calculation from the other two isotopic dating methods.

	sample	206Pb/238U	207Pb/235U
Pluton A	zircon 1	0.01456	0.0961
(quartz diorite)	zircon 2	0.01455	0.09605
	zircon 3	0.01455	0.09598
	zircon 4	0.0145	0.09586
Pluton B	zircon 1	0.01379	0.09082
(granodiorite)	zircon 2	0.01484	0.09822
	zircon 3	0.01394	0.09179
	zircon 4	0.01421	0.09381
	zircon 5	0.01389	0.09144

Figure 3: Pluton A and Pluton B zircon samples were collected and analyzed for U-Pb isotopic decay ratios calculations.

Results

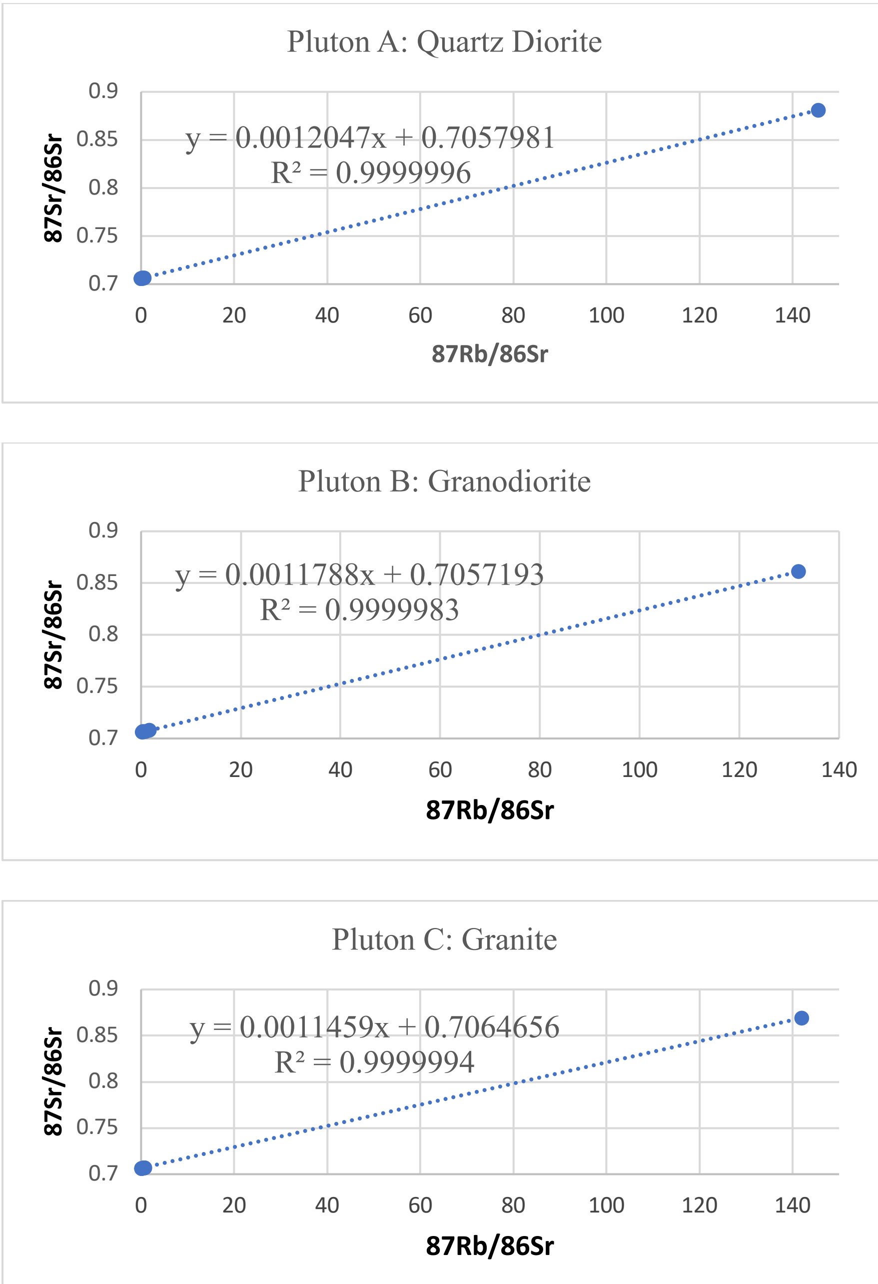


Figure 4: Isochron Plots for the Rb-Sr data for Pluton A, B, and C were plotted with a trendline of best fit. The equation of the best fit line is shown above along with the R squared vale to determine the accuracy of the line.

The isochron plot showing 87Rb/86Sr ratios across from 87Sr/86Sr ratios were used to determine the initial 87Sr/86Sr values which gives an indication of the source of the pluton based on the y-intercept. Pluton A holds an initial 87Sr/86Sr value of 0.705798 indicating a mantle source. While the R squared value seems to indicate very high accuracy of 0.9999996, the given slope from the line of best fit is 0.0012047 which can be used to calculate the age using the following equation Pluton A: t = ln (1+ 0.0012047)/1.42 x 10^{-11} = 84786967 years. Pluton B holds an initial 87Sr/86Sr value of 0.7057193 which, again, indicates a mantle source that perhaps experience some assimilation to alter the value slightly. While the R squared value indicates high accuracy of 0.9999983, the given slope from the line of best fit is 0.0011788 which can be used to calculate the age using the following equation Pluton B: t = ln (1+ 0.0011788)/1.42 x 10^{-11} = 82965194 years. Pluton C holds an initial 87Sr/86Sr value of 0.7064656 indicating a crustal source or possibly even more assimilation. While the R squared value consistent with the other plutons hold a high accuracy of 0.9999994, the given slope from the line of best fit is 0.0011459 which can be used to calculate the age using the following equation Pluton C: t = ln (1+ 0.0011788)/1.42 x 10^{-11} = 80650983 years (All age calculations rounded to nearest whole number).

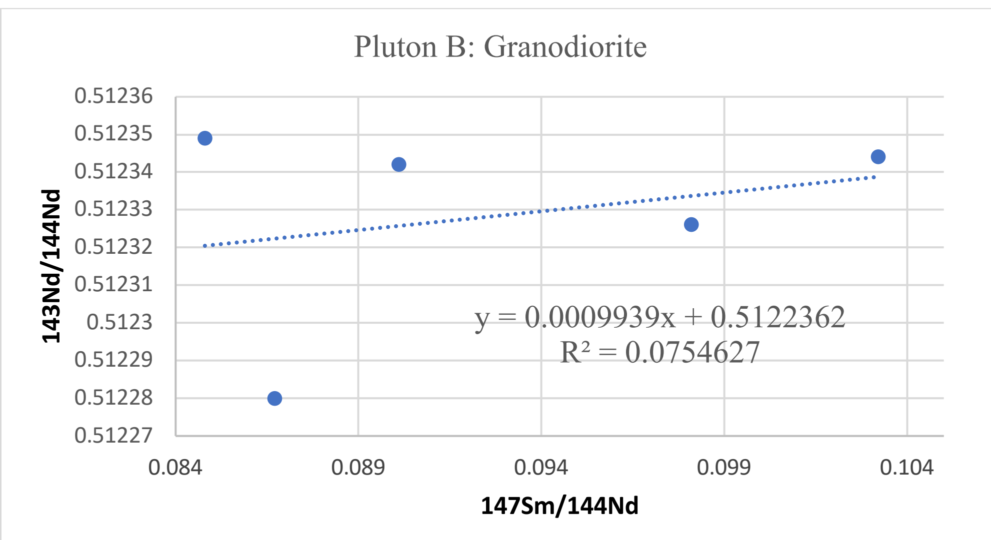


Figure 5: An isochron plot for the Sm-Nd data for Pluton B is shown with a trendline of best fit. The equation of the best fit line is shown above along with the R squared vale to determine the accuracy of the line.

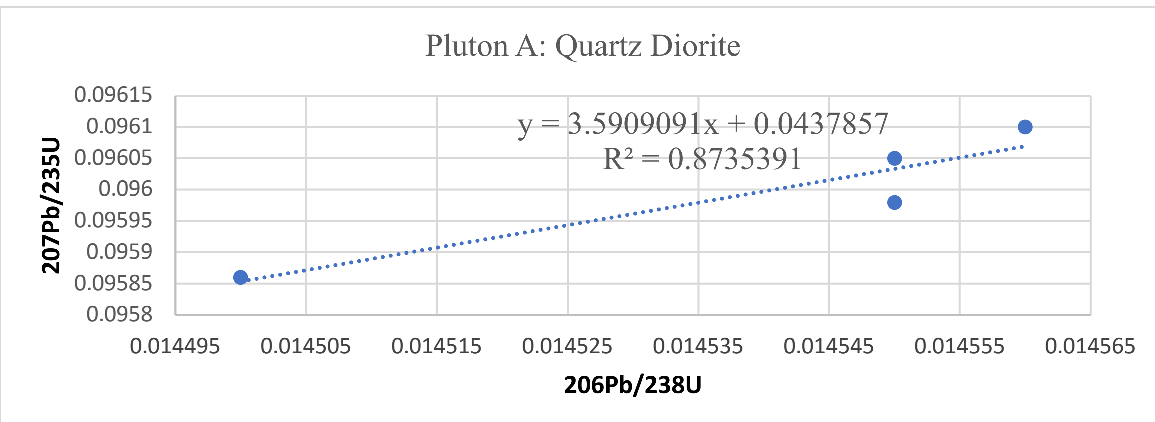
The samples of the whole rock analysis of the granodiorite are plotted on the above isochron in Figure 5 against isotopic ratios of 147Sm/144Nd and 143Nd/144Nd. The initial 143Nd/144Nd is shown as 0.5122362. The R squared value of 0.0754627 indicates a very low accuracy trendline of best fit. The given slope was identified as 0.0009939 which was then used to calculate an age estimate from the same equation used in the Rb-Sr dating. The decay constant being 6.54×10^{-12} input into the equation = $\ln(1+ 0.0009939)/ 6.54 \times 10^{-12}$ = 151897004 years. The subsequent need to calculate the epsilon Nd was calculated by deriving the chondritic uniform reservoir using the following series of equations.

$(^{143}Nd/^{144}Nd)_{CHUR,\ today} = 0.512638$ and $(^{147}Sm/^{144}Nd)_{CHUR,\ today} = 0.1967$; therefore:

$(^{143}Nd/^{144}Nd)_{CHUR,\ t} = (0.512638)_{CHUR\ today} - (0.1967)_{CHUR\ today} * (e^{\wedge(6.54 \times 10^{\wedge}-12 * 1.52 \times 10^{\wedge}8)} - 1)$

$(^{143}Nd/^{144}Nd)_{CHUR,\ t} = 0.5124413$

$\varepsilon_{ND} = (^{143}Nd/^{144}Nd_{sample} - {^{143}Nd}/^{144}Nd_{CHUR} / {^{143}Nd}/^{144}Nd_{CHUR})$ $\varepsilon_{ND} = (0.512236 - 0.512443)/0.512443)$ $= -0.0004041$



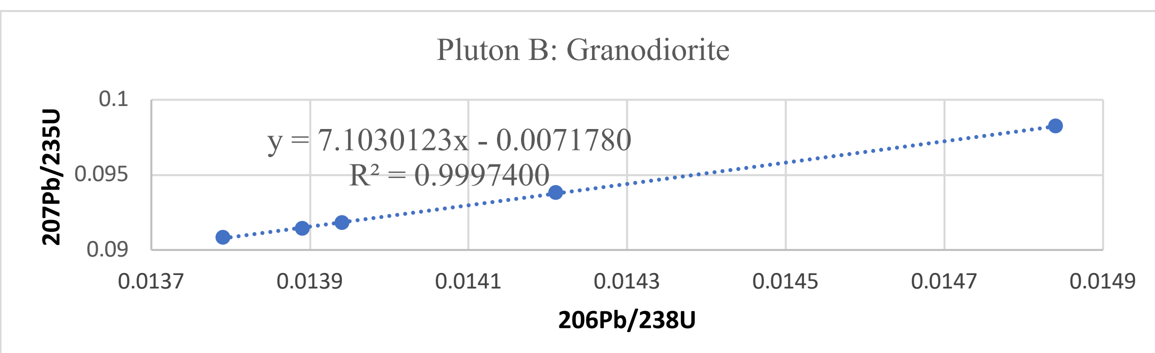
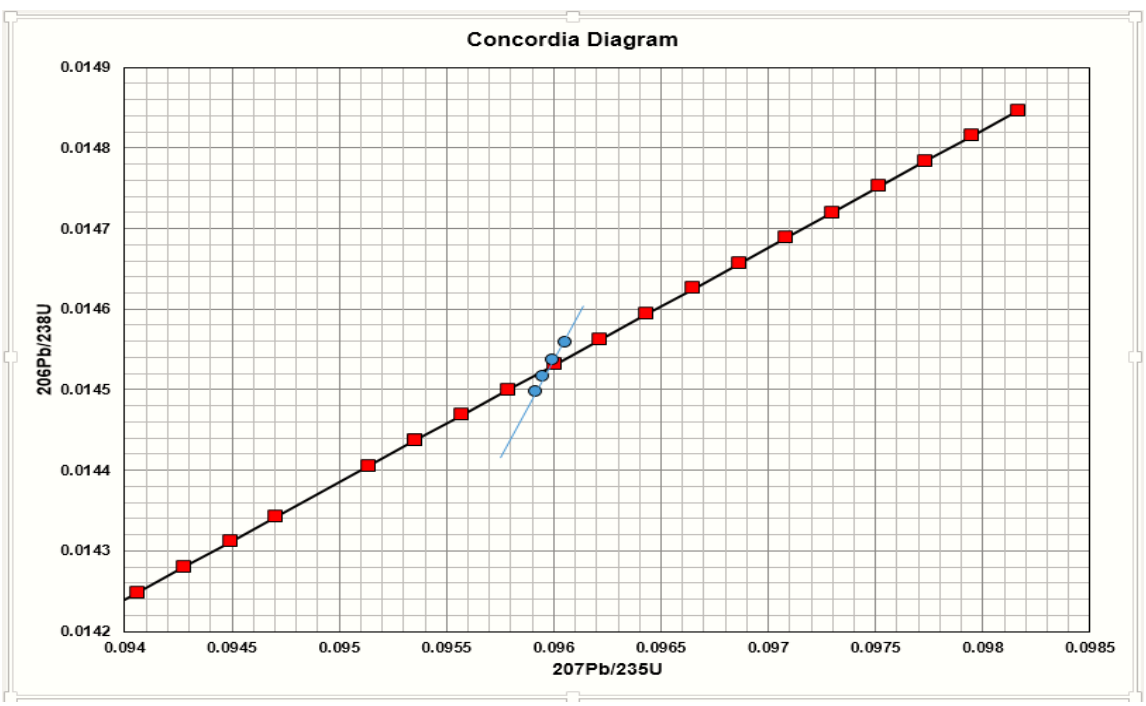


Figure 6:U-Pb isochron data for Pluton A and B plotted with trendline, equation of trendline and R squared value.

The isochron plot of Pluton A showing 206Pb/238U ratios across from 207Pb/235U ratios were used to calculate various age estimates based on the two decay constants. While the R squared value seems to indicate a relatively high accuracy of 0.8735391, the given slope from the line of best fit is 3.5909091 which can be used to calculate two age estimates using the following equations Pluton A: $t = \ln(1+ 3.5909)/ 9.8571\text{x}10^{-10}$ = 1,546,100,000 years and $t = \ln(1+ 3.5909)/1.55125\text{x}10^{-10}$ = 9,824,000,000 years. The isochron plot of Pluton B showing 206Pb/238U ratios across from 207Pb/235U ratios were used to calculate various age estimates based on the two decay constants. While the R squared value seems to indicate a high accuracy of 0.9997400, the given slope from the line of best fit is 7.1030123 again used to calculate two age estimates using the following equations Pluton B: $t = \ln(1+ 7.1030123)/ 9.8571\text{x}10^{-10}$ = 2,110,000,000 years and $t = \ln(1+ 7.1030123)/1.55125\text{x}10^{-10}$ = 13,487,000,000 years.

The age estimate averages being far above the other two isotopic dating methods prompted the Concordia diagram to derive an age calculation which factored in U and Pb loss. Concordia Diagrams for both Pluton A and Pluton B were plotted in Figure 7 to give a better age estimate.



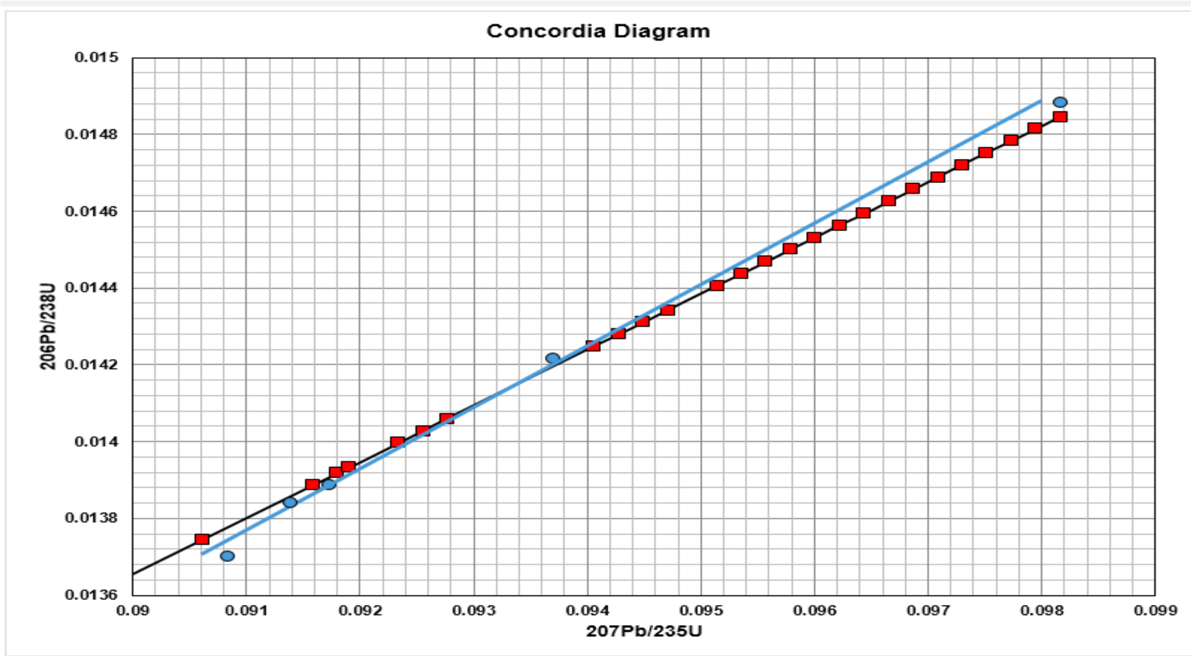


Figure 7: Concordia Diagrams for Pluton A and Pluton B were plotted to calculate U and Pb loss with the discordant curve plotted along the Concordia curve.

The estimated age as a result of the Concordia curve in which the trendline of the U-Pb Isochron for Pluton A was superimposed on the diagram gave an age of about 92,900,000 years. While the estimated age from the Concordia curve of Pluton B gave an estimated age value of 91,600,000 years. The decreasing age values across the plutons is consistent with the Rb-Sr data.

Discussion & Conclusion

Overview of Isotopic Data Analysis	Pluton A	Pluton B	Pluton C
Age from Rb-Sr (Ma)	84.79	82.97	80.65
Initial 87Sr/86Sr ratio	0.705798	0.7057193	0.7064656
Age from Sm-Nd (Ma)		151.9	
Initial 143Nd/143Nd ratio		0.5122362	
Epislon of Nd		-0.0004041	
Age from U-Pb (Ma)	92.9	91.6	

The isotopic data analysis of the Rb-Sr data reveals a decreasing age calculation from Pluton A to Pluton C, respectively. The indication of Pluton A and Pluton B deriving from a mantle source is born out of the initial isotopic Sr ratio value while Pluton C seems to present with a value characteristic of a crustal derived source; however, it seems more likely that this is a result of assimilation. The R squared values are all consistently high among all the plutons in the isochron plot indicating an accurate trendline of best fit. The only ratio which seemed to have a widely varied value was the measurement of the biotite. The values of the ages of the Rb-Sr around 80~85Ma seems to show a consistent measurement along all the isochron plots. The Rb-Sr data alone presents strong support for an incremental emplacement as well as evidence of fractional crystallization.

The Sm-Nd data initially presented with a poor R squared value which would indicate that the trendline of best fit would not give an accurate initial Nd isotopic ratio and thereby affecting the epsilon of Nd value needed to determine the source of the pluton. The estimated age of 151.9 Ma of Pluton B is consistent with the nature of Sm-Nd dating in that often Rb-Sr data contains a bias toward a younger age due to common metasomatism as well as hyperthermal and metamorphic alteration presenting with a younger age. The likelihood of the Sm-Nd age being more accurate than the Rb-Sr data given the poor R squared value is low.

The U-Pb data analysis plotting of the isochron initially presented with age calculation which were on the order of ten to hundreds of magnitudes higher than the other age estimates. This confirmed U-Pb loss as shown by the Concordia plot, however the Concordia curve estimated an age which resembled the other two isotopic dating methods.

Despite the lack of an age estimate from Pluton A via the Sm-Nd dating analysis, and Pluton C with neither Sm-Nd nor U-Pb dating analysis. The expected negative ε_{ND} value coupled with an increasing $^{87}Sr/^{86}Sr$ ratio which rises above the 0.706 value is an indication of fractional crystallization. The hypothesis that all three plutons were emplaced incrementally with increasing degrees of fractional crystallization is supported by all the isotopic dating methods. Lacking context of the specifics of the isotopic dating analysis the Sm-Nd dating is generally the most accurate all things being equal, however due to the poor R squared value and the Sm-Nd application to solely Pluton B the most accurate dating method would seem to be the Rb-Sr data. The U-Pb lead loss also factored into the need for a Concordia curve. However the consistently high R squared values in the Rb-Sr data would confirm the accuracy of its application.