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Northern Appalachian Geochronology as a Model for Interpreting ages in Older Orogens

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ABSTRACT

Isochron plots of whole-rock Rb-Sr measurements on crystalline rocks randomly collected over ancient orogens generally show a scatter of points entirely within a bounding isochron envelope. There has been controversy over the interpretation of these. A plot of isochron data from the Northern Appalachians, where correlation between the Paleozoic succession and radiometric ages has been established, is remarkably similar, so that this region may be taken as a model for interpreting the plots observed in the more ancient cases. The interpretation states that:

1. The observed age band actually consists of a complex of discrete intrusive or metasomatic events that covers the time range within the bounding isochrons.
2. The initial Sr^{87}/Sr^{86} ratios given by separate isochrons on granitoid rocks are similar enough so that age values calculated on individual samples using the observed "common" initial Sr^{87}/Sr^{86} ratio are more likely to be true than not.
3. Acid extrusive volcanic rocks frequently give age values less than the time of extrusion, and have higher initial Sr^{87}/Sr^{86} ratios, so that they should be avoided in the sampling program.
4. A regional thermal rejuvenation of K-Ar age values in the Northern Appalachians has not affected the whole-rock Rb-Sr dating, so that a similar happening will not invalidate the above general interpretations in the case of an ancient orogenic region.

Whole-rock Rb-Sr analyses on granitoid rocks

About 200 samples of granitoid rocks from the northern Appalachian province have been analysed by various investigators for whole-rock Rb-Sr isotopic relationships. The results are plotted in Figure 1. Coordinate scales have been chosen that will include most of the analyses; a few having too high a ratio of Rb/Sr to fall on the diagram have been reduced in scale and plotted with a tick mark. This is not a random sampling but represents a dispersed collection of samples from individual rock units that are themselves scattered throughout the province.

It can be seen that the points fall within a bounding envelope representing isochrons at 227 m.y. and 608 m.y., or roughly a 400 m.y. spread in time. From these data alone it is impossible to say anything definite about the initial ratio of Sr^{87}/Sr^{86} because the apparent constriction to a limited range of Sr^{87}/Sr^{86} ratio at the lower left corner of the plot may be due entirely to a different origin for the more basic, or less alkalic, rocks in the sampling. This question has been bothersome in the interpretation of whole-rock Rb-Sr ages in ancient orogens where it is not always possible to carry out the detailed work that has been done in the Northern Appalachians. We have therefore been interested in the question of whether the limited Sr^{87}/Sr^{86} ratio at the low-rubidium end of such a scatter plot can be used to provide a reasonable estimate of individual whole-rock ages.

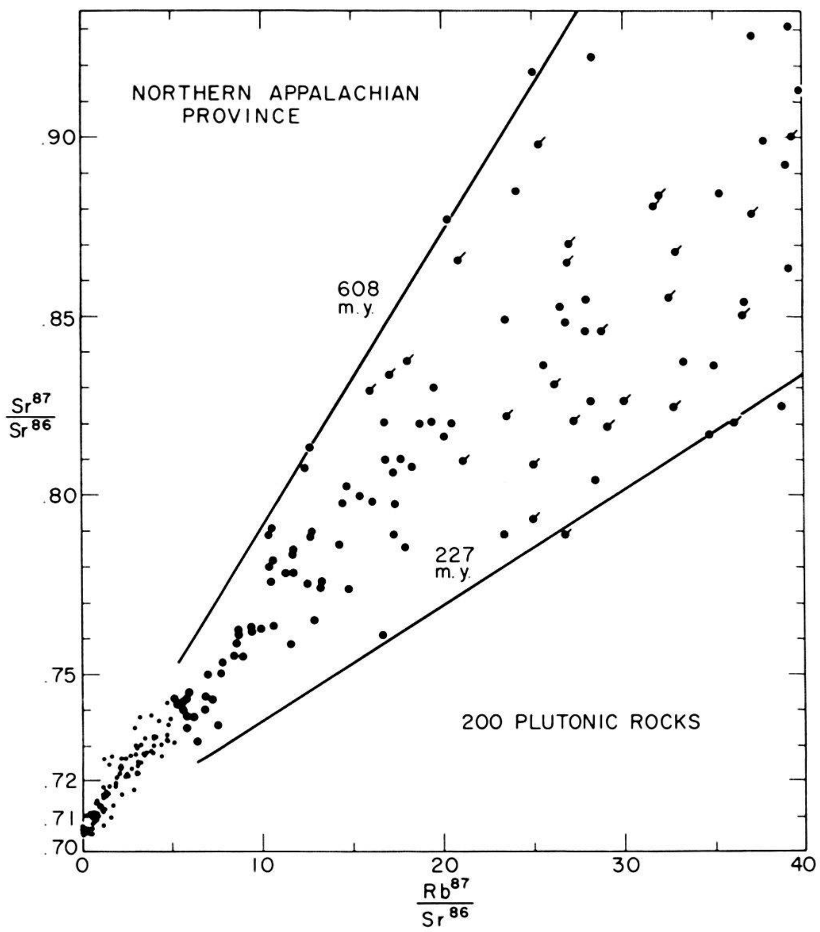

Fig. 1. Isochron plot of 200 whole-rock Rb-Sr analyses of plutonic rocks from the Northern Appalachian province.

We have also been interested in the question of whether the scatter shown by this kind of diagram is the result of later migrations of Rb or Sr, or whether there are discrete episodes of plutonism and metamorphism and these scattered points in fact represent individual isochrons that mark the true age of each of these individual episodes. For example, having determined such a scatter plot by collecting a number of samples over a wide region in an ancient orogen, can we now say that the bounding isochrons truly represent the beginning and end of the plutonic and metamorphic activity in that orogenic province?

An example of the kind of scatter found in Rb-Sr whole-rock analyses on randomly collected rocks from an ancient orogenic region is shown in Figure 2. Prior to continental drift it appears that the Imataca Complex of the northern Guayana Shield in Venezuela was part of an extremely ancient province represented by the basement rocks in Western Liberia and Sierra Leone. Details of the geochronology of this region are to be presented elsewhere by one of us (P.M.H.) in collaboration with G. W. Leo and R. W. White for the case of Liberia, and J. Kalliokoski for Venezuela. We present this example as a comparison with the Northern Appalachian case in order to interpret the meaning of the scattered points and their bounding isochrons.

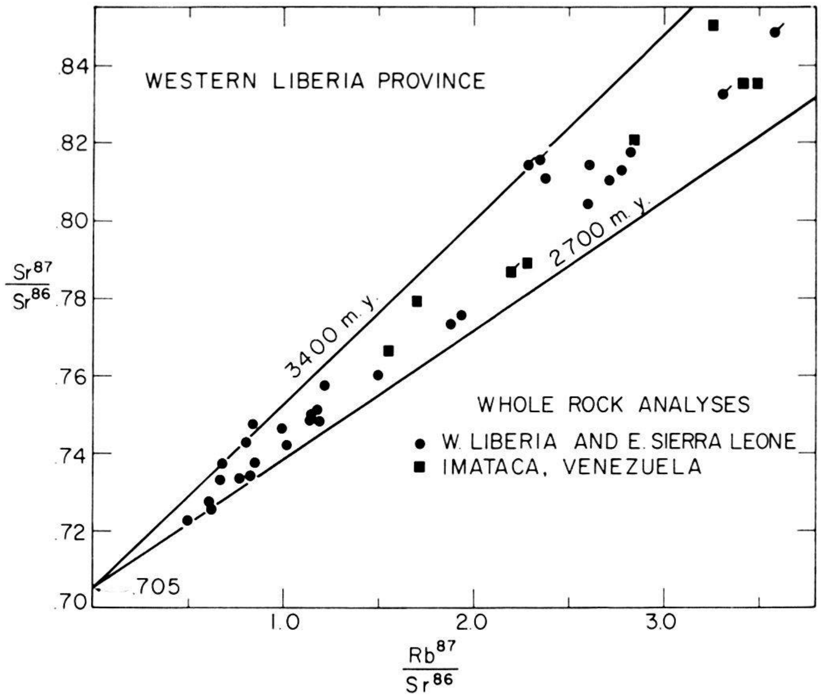

Fig. 2. Isochron plot of 38 whole-rock Rb-Sr analyses from Western Liberia, East Sierra Leone, and Imataca, Venezuela.

The question is whether or not the Liberian orogeny actually started at 3400 m.y., and closed its activity at about 2700 m.y. Without the test of individual isochrons we can at least be encouraged to suggest from this comparison that this might be the case. Also, as demonstrated below, we can have more confidence in utilizing the observed common initial ratio of Sr^{87}/Sr^{86} in Figure 2 for an age estimate on individual samples of the ancient rocks. This statement does not necessarily apply to volcanics, as we shall note in the following examples of case studies in the Northern Appalachians.

Detailed geochronological work in the Northern Appalachians has disclosed a series of magmatic and metamorphic episodes as indicated by linear isochron arrays that are compatible with geological interpretations from stratigraphy. Figures 3, 4 and 5 show examples of isochron plots of analyses on samples from individual rock units. Figures 3 and 4 show the bounding isochrons indicated in Figure 1, represented by the Holyrood granite in Newfoundland and the granite of Mt. Agamenticus in Maine. Figure 3 represents a study by McCartney, Poole, Wanless Williams, and Loveridge (1966) of the Geological Survey of Canada. The Holyrood granite is clearly a late Precambrian pluton as it unconformably underlies Lower Cambrian fossiliferous shales. We have used the Rb^{87} decay constant of 1.39×10^{-11} yr^{-1} to obtain the value of 608 m.y.

Figure 4 is a replot of analyses made at M.I.T. by J. Hoefs (1967) on the granite of Mt. Agamenticus. The lower age of 223 is given by an isochron that excludes the three samples with lowest Rb/Sr ratio, which may be non-sanguinous with the alkaline Agamenticus intrusive. The upper limit of age is given by utilizing these samples and points in the lower part of the plot only. In this case the age of 250 m.y.

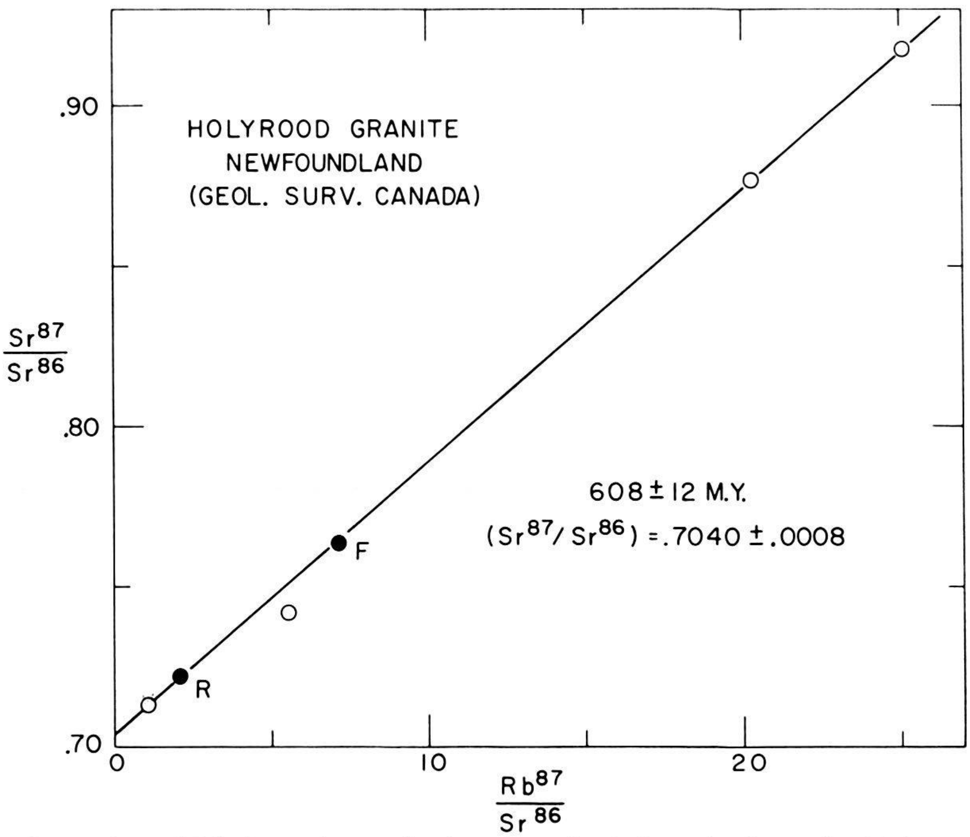

Fig. 3. Isochron plot of Rb-Sr analyses of minerals and whole-rocks from the Holyrood granite, Newfoundland.

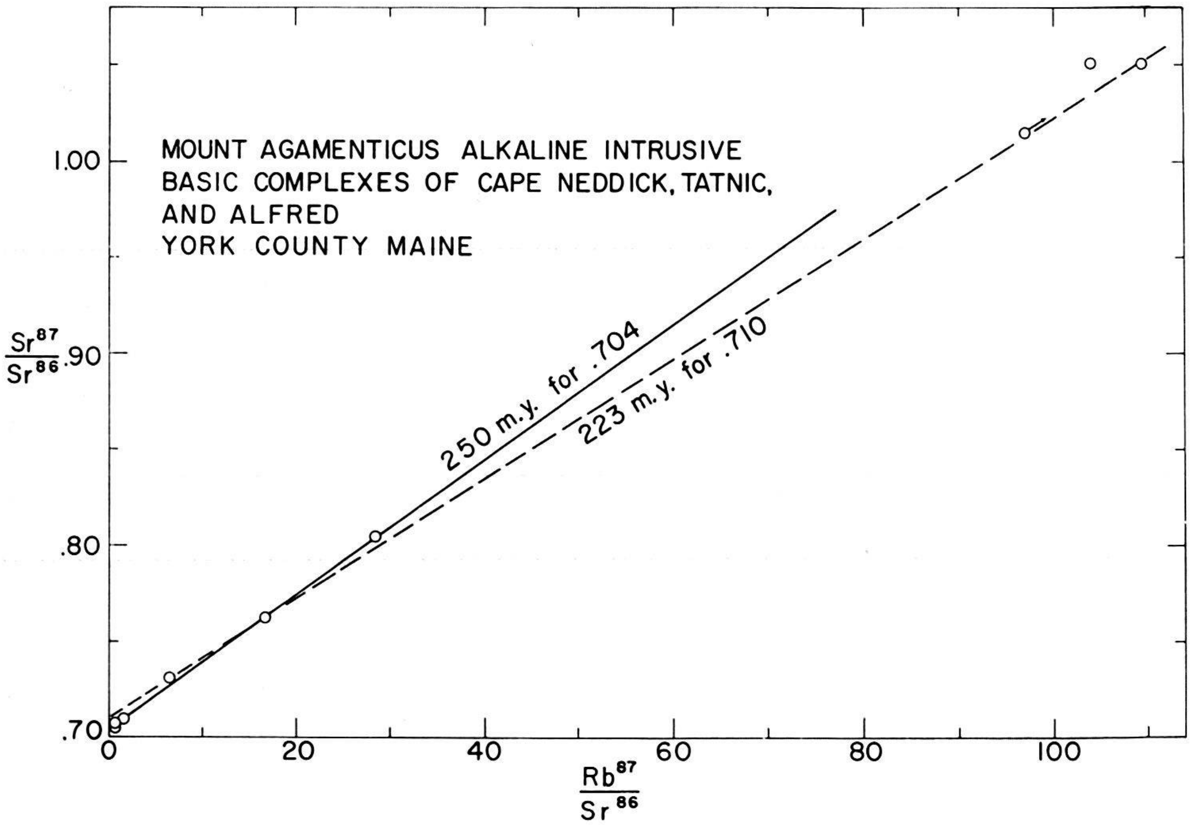

Fig. 4. Isochron plot of whole-rock Rb-Sr analyses from the Mount Agamenticus alkaline intrusive, and from basic complexes of Cape Neddick, Tatnic, and Alfred (York County, Maine).

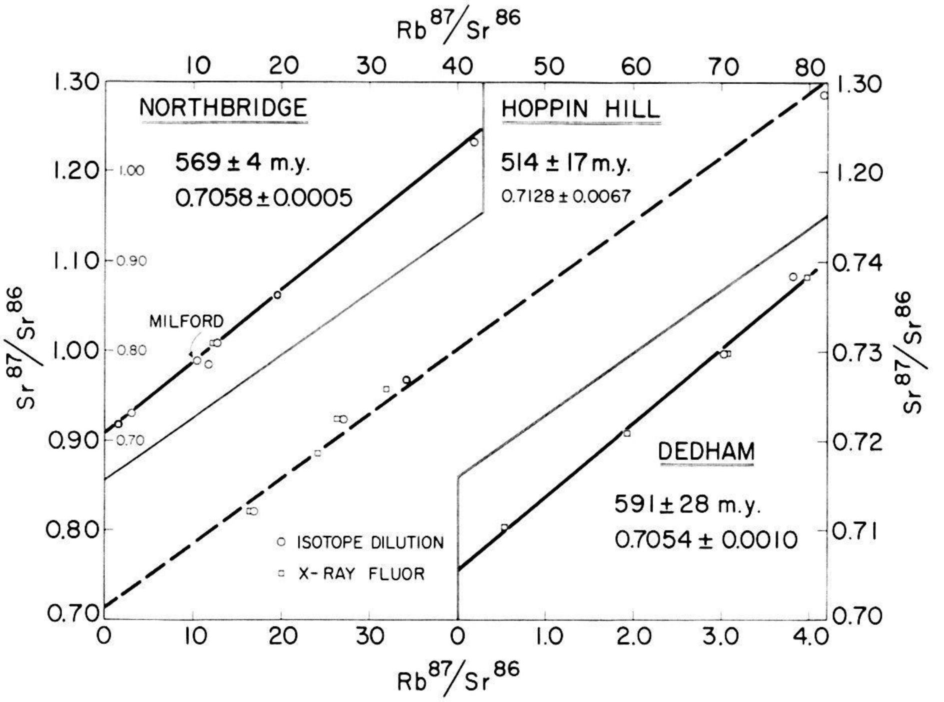

Fig. 5. Isochron plot of whole-rock Rb-Sr analyses of the Northbridge gneiss, Hoppin Hill granite, and Dedham granodiorite.

would coincide with the time of a Permo-Triassic pervasive thermal overprinting of a large region in the Northern Appalachians as described by ZARTMAN, HURLEY, KRUEGER and GILETTI (in preparation). A K-Ar analysis by GILETTI (personal communication) supports the younger age value.

A third example is given by an isochron on granitic and gneissic rocks in southeastern Massachusetts, from data presented by FAIRBAIRN, MOORBATH, RAMO, PINSON, and HURLEY (1967). In this study the Hoppin Hill granite, which is thought to be a correlative of the Dedham granodiorite, and with points falling on the isochron, appears to underlie a Lower Cambrian *Obolella* assemblage. The isochron age is therefore compatible with this geological observation, if the Holyrood granite is also taken to be late Precambrian. FAIRBAIRN et al. (1965) have referred to this event as the Neponset, in a publication which slightly antedates the proposal by LILLY (1966) that this event be called the Avalonian after the locality of the Holyrood granite on the Avalon Peninsula in Newfoundland.

These examples, and others unpublished, indicate that the apparent scatter of points in Figure 1 is actually made up of a series of discrete isochrons representing individual episodes of orogenic activity. The common value for the initial ratio of Sr^{87}/Sr^{86} in Figure 1 coincides quite well in general with the values found by the individual isochron plots. This applies to the granitoid rock samples, but not to extrusive volcanics.

Analyses on volcanic rocks

There have been continuing problems with the dating of extrusive volcanic rocks by the whole-rock Rb-Sr method. In Figure 6 the analytical results by various investigators on 170 volcanic rocks from the Northern Appalachian province are plotted in a single diagram. This plot differs considerably from that in Figure 1. There appears to be a curvature to the general trend, with the less alkalic samples following a steeper trend than the remainder. Bounding isochrons are more difficult to draw, and there appears to be a greater range in initial ratio of Sr^{87}/Sr^{86}. These observations are brought out by more detailed studies.

As an example, in Figure 7 the Coldbrook group of volcanics in New Brunswick, which is overlain by fossiliferous Lower Cambrian beds, shows a plot of points that has a marked curvature, and which could be interpreted as ranging in age from 405 to 777 m.y. depending on which part of the plot is used. This is a plot of sixty analyses, representing work by R. F. CORMIER (1969), and FAIRBAIRN et al. (1966). The strange dropping-off of the age trend for rocks containing higher values of Rb/Sr, seems to be accompanied by an increase in extrapolated initial ratio of Sr^{87}/Sr^{86}. This effect was first noted and clearly defined by CORMIER, and has been a source of query and concern to many others who have attempted to date acid volcanics. In Figure 7 only the lower part of the "anisochron" could fit the field relations. It is also the only part that has a low initial ratio of Sr^{87}/Sr^{86}.

MOORBATH and BELL (1965) have observed in the basic igneous rocks at Skye that the low initial strontium ratios do not hold for the acid igneous members, and suggest partial melting of crustal material as a cause. PANKHURST (1969) found high Sr^{87}/Sr^{86} ratios in gabbros in Scotland and believed that these rocks could not have assimilated enough crustal material to produce this effect. Instead he proposed isotopic equilibration with the host environment involving no great addition of material. We shall have to leave this observation as an unsettled problem in the dating of Phanerozoic orogenic belts, and simply state that the use of acid volcanics should involve a large program of sampling and analysis in order to assure that meaningful results may be obtained.

An example of the case in which acid volcanics appear to work well in whole-rock Rb-Sr dating is given in Figure 8. This is a study by BOTTINO and FULLAGAR (1966) on the Eastport formation in Maine. Here the age of 412 m.y. is quite compatible with the Silurian-Devonian boundary close to which these rocks lie. In this case the analytical points are not scattered. Therefore all we can say at the present time is that a scattering of points, or non-linear trend, is a danger signal in working with these kinds of rocks.

Conclusion

In conclusion we have found supporting evidence by a study of granitoid rocks in the Northern Appalachians that the bounding isochrons enclosing scattered Rb-Sr age data in ancient orogens may be truly representative of the beginning and end of the orogenic activity. The evidence points to a rather narrow range for initial ratios of Sr^{87}/Sr^{86}, which can be used to estimate the age value of any particular sample. It is also suggested that this scatter is not due to migrations of rubidium or strontium but is more likely to be due to an actual distribution of discrete events within the time range of the orogenic activity. These conclusions do not apply invariably to analyses on acid volcanic rocks, which tend to show too low an age for some unexplained reason. A late stage overprinting or cooling history that has reset K-Ar age values to

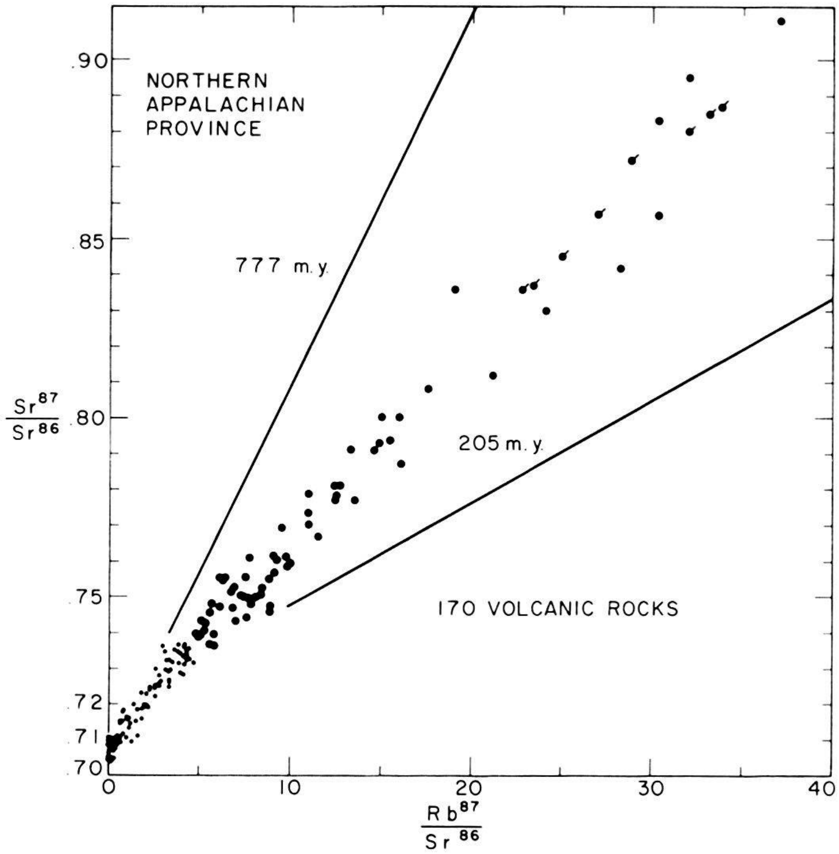

Fig. 6. Isochron plot of 170 whole-rock Rb-Sr analyses of volcanic rocks from the Northern Appalachian province.

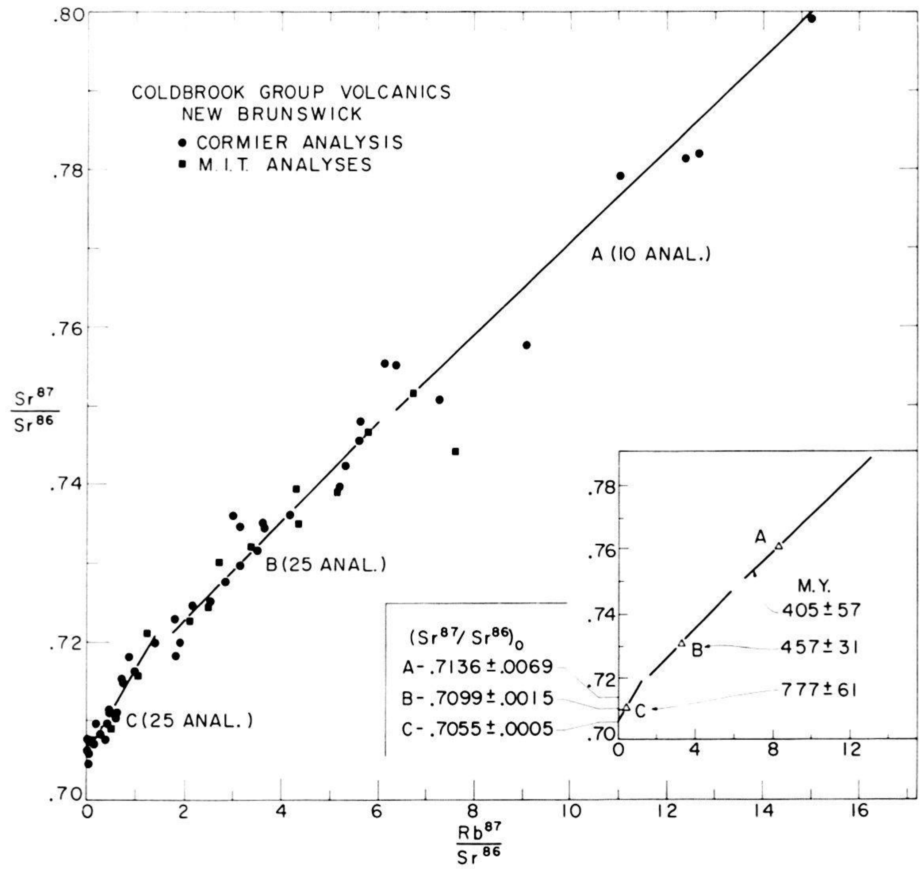

Fig. 7. Isochron plot of 60 whole-rock Rb-Sr analyses of volcanic rocks of the Coldbrook group, New Brunswick.

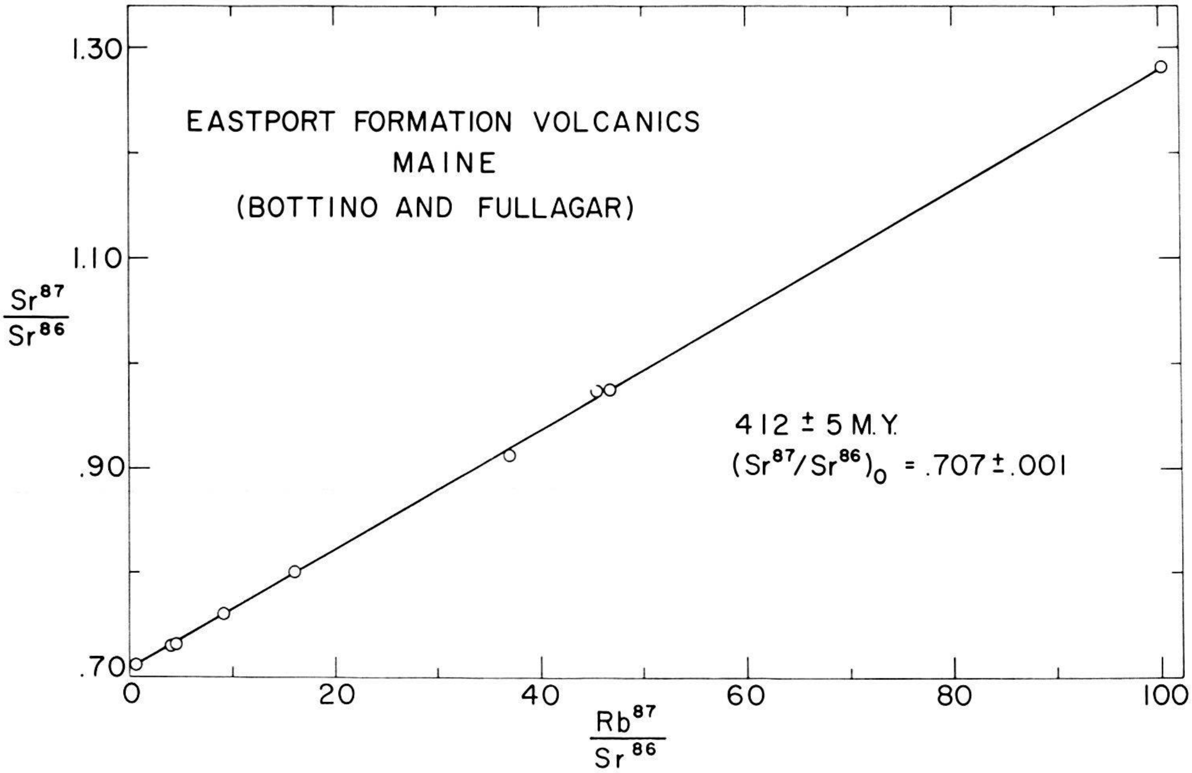

Fig. 8. Isochron plot of Rb-Sr whole-rock analyses of volcanics from the Eastport Formation, Maine.

250 m.y. in a large region in the Northern Appalachian province, has not affected the whole-rock Rb-Sr isochron age determinations. It is thus suggested that thermal rejuvenation may also not be too serious in the case of the older orogenic regions.

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Geochronology of the Cretaceous-Tertiary Boundary of the Western Plains of North America

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SUMMARY

A complete marine and continental late Cretaceous sequence in Alberta and Montana contains datable bentonite beds (sanidine and biotite bearing volcanic ash) and has presented unique opportunities to obtain a sequence of dates through latest Cretaceous into Paleocene time and to define radiometrically the Cretaceous-Tertiary boundary.

The Bearpaw Formation is a marine shale, formed in a transgression that started 72–73 m.y. ago, containing the diagnostic fossil *Acanthoscaphites nodosus* (Campanian). The Bearpaw sea was pushed progressively to the southeast by a deltaic continental wedge of sandstone, shale and coal (Edmonton Formation) with a well known duckbill dinosaur fauna. In the northwest, at Edmonton, continental beds were first present about 69.5 m.y. ago; the time of first deltaic sedimentation at Drumheller is dated at 68.3 m.y.; and at Hell Creek in Montana the latest Bearpaw sea is dated at 67.8 m.y., indicating that marine conditions persisted longer in the southeast as the sea retreated slowly towards the Gulf of Mexico.

The most distinctive of the Cretaceous volcanic horizons is the Kneehills Tuff member of the upper Edmonton; it was synchronous with the beginning of Lance time, and was marked by a pronounced restriction in the dinosaurian fauna. The Kneehills Tuff has been dated at three widely separated points to arrive at a date of 65.2 $\pm$ 0.7 m.y. (11 determinations on biotite and sanidine).

Dinosaurs became extinct by the end of Lance time, marked in Alberta by the upper Ardley coal seam 62.6 m.y. (5 sanidine and biotite dates) and in Montana by the Z coal 63.6 m.y. (2 biotite and 2 sanidine dates). Overlying Paleocene bentonites are dated at 62 to 60 m.y., indicating continuous sedimentation across the boundary. The dinosaurian extinction is accompanied by a progressive change in palynology and by marked changes in the mammalian fauna. All of the more than forty dates that bear on the boundary problem fall into the correct stratigraphic sequence, and suggest rather uniform rates of sedimentation, higher in the Edmonton continental sandstones (116 m/m.y.) than in the marine Bearpaw shales (46 m/m.y.). These allow us to arrive at a 63–64 m.y. figure for the end of the Mesozoic era with some confidence.