Pre-Grenville Ages of Basement Rocks in Central Virginia:

A Model for the Interpretation of Zircon Ages

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INTRODUCTION

In the Central Appalachian Blue Ridge anticlinorium, three northeast trending belts of mixed sedimentary, metamorphic and igneous rocks have been recognized (Bloomer and Werner, 1955). The central belt, known as the Basement Complex, consists of Middle to Late Precambrian age metasedimentary and igneous rocks. The basement rocks are overlain to the southeast and northwest by Late Precambrian metasedimentary and volcanic rocks. The geology of the younger rocks is fairly well understood, while the stratigraphic and age relations within the Basement Complex rocks have been obscurred by intrusion and polymetamorphism.

This investigation is a study of the effects of regional metamorphism and igneous intrusion on Basement Complex zircons, and the effects of possible zircon inheritance on the measured age of a relatively young granitic pluton.

SUMMARY OF GEOLOGY

Introduction:

Recent investigations of the Basement Complex of Central Virginia have been reported by a number of authors. Reconnaissance studies by Bloomer and Werner (1955), Brown (1958), Nelson (1962), Allen (1963), Werner (1966), Griffin (1971), and Bartholemew (1971 and references in it) have led to a better understanding of the Central Appalachian basement rocks.

Figure 1 shows the general stratigraphy and age relations of the basement and overlying rocks. Important investigators of each unit are mentioned where that unit is discussed. No detailed studies of the Lovingston Formation have been carried out since the reconnaissance work of Bloomer and Werner in 1955 and much more detailed structural and petrographic work is needed.

The Central Virginia portion of the Basement Complex consists of the Lovingston, Marshall and Pedlar Formations (Jonas, 1928; Bloomer and Werner, 1955). These units range from granodioritic to quartz monzonitic gneisses with included, poorly foliated granitic phases (Bloomer and Werner, 1955). These three units are so intensely deformed, variable in composition, and intimately related that no definite stratigraphic sequence has been established. Only one U-Pb zircon date was previously available to aid in any stratigraphic correlation (Tilton, et al, 1958).

Minor Late Precambrian (?) paragneisses and schists, such as those found in the Mechum River syncline (Fig. 1), seem either to have been infolded into the older Precambrian rocks (Nelson, 1962; Allen, 1963), or to be sediments whose present outcrop pattern was essentially determined by Late Precambrian graben formation (Schwab, 1974).

The general structure of the anticlinorium appears to be a series of folds, overturned to the northwest, and strongly attenuated in places (Griffin, 1971). Thrusts occur mainly along the northwestern flank of the anticlinorium and may be parallel to the fold axial planes. Foliation is nearly parallel to compositional layering, strikes northeasterly, and dips steeply to the southeast (griffin, 1971).

The Basement Complex is generally considered to have experienced at least two major thermal-metamorphic episodes (Tilton, 1960; Bryant and Reed, 1970). The first event probably occurred 1150 to 913 m.y. ago (Tilton, et al, 1958; and this paper) and is believed to have caused granulite facies metamorphism in the western flank of the basement units (Bloomer and Werner, 1955), and possibly lower grade, amphibolite facies mineral assemblages farther to the southeast in the anticlinorium.

During the final stages of deposition of the Lynchburg Formation and the basal Catoctin Group Late Precambrian sediments (Fig. 1) major volcanic activity occurred. The Catoctin Group basalts and rhyolites (restricted to the northern end of the anticlinorium) were extruded and covered large portions of the Blue Ridge. Approximately 170 miles south of this area the Mt. Rodgers volcanic pile was also being created. According to Rankin, et al (1969) most of the volcanic activity occurred a minimum of 820 ± 30 m.y. ago.

Medium to coarse-grained gabbro, amphibolite, and granitic rocks (including the Rockfish granodiorite) seem to be coeval with the volcanic activity. A "line" of granitic plutons (including the Robertson River Formation which lies approximately 30 miles northeast of the study area) intruded the Lovingston and Lynchburg Formations (Nelson, 1962; Allen, 1963; and Fig. 1, this report). The majority of these granitic plutons do not have published ages, but are similar in structure and petrography (Nelson, 1962) to the Rockfish granodiorite studied for this report. These plutons range in length from one to 35 miles (Robertson River Formation), and are generally non-foliated to faintly foliated. No evidence has been published to tie this extensive volcanic and intrusive episode with a known metamorphic event.

A second regional metamorphic episode occurred during the Paleozoic (between 430 and 269 m.y. ago) and was pervasive enough to nearly mask any earlier metamorphic fabric (Bryant and Reed, 1970). This event locally reached as high as the staurolite zone in the Lovingston Formation (parallel to that unit's strike) and decreases to greenschist facies in units to the northwest and southeast (Bloomer and Werner, 1955; and Griffin, 1971). A northeast trending lineation (cataclastic) was developed in most of the rocks of the anticlinorium sometime after the last regional metamorphism (Griffin, 1971), and probably before the last movement on the Blue Ridge thrust (Bryant and Reed, 1970; Rankin, 1970).

Basement Complex and Immediately Overlying Rocks:

Because of the complex geologic history of the basement rocks, the assignment of the individual rock units to one of the three named formations is somewhat arbitrary.

The Lovingston and Marshall Formations are highly deformed and consist predominantly of quartz monozonitic gneisses - which mantle poorly foliated granitic phases and metasediments. Metaquartzites and mica schists are found in the Marshall Formation by Bartholemew (1971). Bloomer and Werner (1955) restricted the name Lovingston Formation to those gneisses having abundant and prominent augen of potassium feldspar and blue quartz. To those gneisses lacking prominent augen they extended the name Marshall Formation. Contacts between the two formations are generally gradational in texture and structure over a width of up to 100 feet (Bloomer and Werner, 1955). However, it is not known whether the gradational contacts are the result of varying degrees of metamorphism developed during metamorphism, or of the interfingering of sedimentary units (Mertie, 1956). Bartholemew (1971), considered the Marshall and Pedlar Formations to be significantly older than the Lovingston Formation because of the presence of relict east-west foliation found only in the former two units. He interprets the wide gradational boundaries of the Marshall Formation as a possible saprolite or an unconformity in support of this concept.

The Pedlar Formation was named by Bloomer and Werner (1955) for the intimately related granite, granodiorite, syenite, quartz diorite, anorthosite and epidotized granitic rocks located along the western flank of the anticlinorium. Hypersthene granodiorite is the major rock type found in the Pedlar Formation. This formation is thought to occupy the cores of most of the antiformal structures in the Basement Complex, and in these cases consists of an inner granodioritic core mantled by gneiss (Bartholemew, 1971). The hypersthene granodiorite has numerous paragneissic xenoliths, shows relatively sharp contacts with other Pedlar rocks and may be an igneous intrusive emplaced prior to 913 m.y. ago (Lynn Glover III, pers. com.).

The Lynchburg and Mechum River Formations, and the Swift Run sediments (basal Catoctin Group) unconformably overlie the basement units, and were deposited between 913 and 810 m.y. ago. As seen in Figure 1, 820 m.t. old Catoctin greenstones are intercalated with the upper portion of the Lynchburg Formation along the eastern flank of the anticlinorium (Brown, 1958).

The basal unit of the Lynchburg Formation is the Rockfish Conglomerate (Nelson, 1962), which is as much as 1200 feet thick. Bedding in the conglomerate parallels the strike and dip of the underlying Lovingston foliation, striking approximately N 52° E and dipping variously between S 85° E and N 85° W. The Lovingston augen gneiss probably acted as a local source for the conglomerate (Nelson, 1962), and clasts of this gneiss in the conglomerate have a foliation that is discordant to the foliation of the conglomerate. Therefore, the Lovingston augen gneiss was metamorphosed and eroded prior to the deposition of the Rockfish Conglomerate member of the Lynchburg Formation.

GEOLOGY OF THE ROCKFISH GRANODIORITE AND HOST LOVINGSTON FORMATION

Introduction:

To test the effects of inherited zircons on the measured age of a relatively young granodioritic pluton (originally considered to be Late Precambrian to Early Cambrian in age) which intrudes the much older Blue Ridge Basement Complex, was chosen for study. Sample sites were selected so that country rock within as well as beyond any possible contact metamorphic aureole would be collected. Granodiorite samples were collected from the periphery and center of the outcrop area of the pluton under the supposition that the degree of any host rock assimilation (in the pluton) should vary from sample to sample, and especially from the pluton's edge to its center.

The study area lies entirely within the Lovingston Formation along the Rockfish River, one mile northwest of the town of Rockfish, Nelson County, Virginia (Fig. 2).

Discussion:

Lovingston augen gneiss, quartz monzonite and pegmatite form the host rock in the study area, but only the latter unit is in direct surface contact with the Rockfish granodiorite.

The Lovingston gneiss (WP-57, Appendix A) is a quartz monzonitic augen gneiss and is seen in thin section to be a complex polymetamorphic rock. It consists of quartz, highly saussuritized plagioclase ($An_{\sim 10-15}$, as determined from extinction angles of the twin planes), and grid twinned, perthitic microcline in approximately equal amounts. Biotite is listed as a major mineral in samples from wide schistose and more mylonitic bands located within the gneiss. Accessory minerals (in order of decreasing abundance) are: biotite, sphene (?), zircon, apatite, ilmenite, ± muscovite. Metamorphic minerals include biotite, antiperthite, chlorite, epidote, zoisite, leucoxene, ± garnet, ± calcite. In hand specimen the gneiss is a dark gray medium to coarse-grained rock with augen (porphyroblasts) of potassium feldspar (and less commonly blue quartz) as much as two inches in diameter, surrounded by prominent biotite folia. In the study area the size and abundance of augen vary from a minimum in the mylonitic, schistose bands (with nearly 65% biotite) to a maximum in the mica-poor, augen-rich pegmatite. Most samples of the gneiss show some degree of brittle deformation superimposed over an earlier metamorphic recrystallization (Griffin, 1971). This mechanical deformation usually takes the form of crushed and abraided quartz augen. According to Griffin (1971), platy minerals and augen in the gneiss have been aligned down dip (generally S 85° E) and may represent penetrative deformation in the "a" fabric direction.

The Lovingston quartz monzonite lacks the metamorphic fabric of the Lovingston augen gneiss, but has a similar mineralogy. In hand specimens of the quartz monzonite, biotite is generally clustered in equidimensional aggregates, but also occurs as randomly oriented flakes. Bloomer and Werner (1955) first noticed this characteristic in similar bodies of Lovingston quartz monzonite from outside the study area. Faint layering of feldspars and of the more mafic constituents can be seen in a few outcrops. This layering dips approximately 50° to the southeast and strikes north-northeast, and may represent a relict foliation, or compositional layering.

The Lovingston pegmatite was classified by Watson and Cline (1916) as andesine anorthosite, consisting almost entirely of andesine (with intergrowths of microcline oriented parallel to the twin lamellae), and blue quartz. They stated that the plagio clase is "about $Ab_{65}An_{35}$" (op. cit. p. 202). Typical accessory minerals observed by Watson and Cline (1916) were hypersthene (usually altered to uralitic hornblende). In the study area, the Lovingston pegmatite is a very coarse-grained rock consisting of antiperthite, perthitic microcline and blue quartz (less than 15%), with a few flakes of muscovite. The plagioclase is highly saussuritized and the perthite is surrounded by myrmekite.

The Rockfish granodiorite is a non-foliated medium to coarse-grained rock with approximately 3-4 square miles of outcrop area. The mineralogy is similar to that of the surrounding rocks, being an assemblage of saussuritized plagioclase ($An_{\sim 10-15}$), grid twinned perthitic microcline, biotite and quartz. Accessory minerals are: apatite, sphene(?), zircon, allanite, and fluorite. Metamorphic minerals include biotite (mainly along joints), chlorite (penninite), epidote, sphene, pyrite, and albite (small grains along the rims and cracks in the plagioclase and as patches in the perthite). The plagioclases are simply zoned with highly saussuritized (more calcic?) cores surrounded by thick, more sodic and less altered rims.

No foliated regions, chilled contacts, xenoliths, igneous flow structures, porphyritic masses or contact aureole have been found in or around the granodiorite. These observations suggest that the emplacement of the stock may have been relatively deep-seated. Significant amounts of erosion must have occurred to bring this pluton to the surface.

The presence of faults along extensive portions of the granodiorite's perimeter also suggest that the pluton may have experienced some movement, or may actually have been emplaced, in a semi-solid state. Tectonic emplacement of the pluton is possible, but not probable. The Lovingston pegmatite - Rockfish granodiorite contact (fig. 2) is quite sharp where it truncates the alignment of the feldspars in the pegmatite. A few veins of granodiorite intrude the Lovingston pegmatite. This contact zone also appears to be a zone of weakness. Mylonitic zones, with well developed boudin structure, parallel the contact.

The Rockfish granodiorite is structurally below a metagabbroic dike (cross-cuts regional foliation) approximately 400 feet thick and seven miles in length (figures 1 and 2). While no chilled borders, foliation or xenoliths can be found in the gabbro, weak layering of leucocratic minerals can be seen in a roadcut through the unit and may represent either relict compositional layering or metamorphic foliation. The Rockfish granodiorite - metagabbro contact can be located within three feet, but has not been observed directly.

The metagabbro is a medium to coarse-grained rock containing nearly equidimensional aggregates of metamorphic hornblende in a matrix of highly saussuritized plagioclase. Relict pyroxenes have been partially or totally altered to hornblende, zoisite, magnetite (which ofteh "ghosts" original mineral grain boundaries), and chlorite. Other metamorphic minerals are epidote, sphene (further altered to leucoxene), calcite, garnet, and rarely biotite.

Southeast of the study area this metagabbro intrudes the Lynchburg Formation, and shows a foliation along (and parallel to) its discordant contacts. The age of the metagabbro cannot be determined from the data collected during this study, but based on reconnaisance work in the area it must be younger than the lower members of the Lynchburg Formation and older than the Paleozoic regional metamorphism.

Methods and Results:

Sample locations, descriptions and zircon morphology are summarized in Appendix A. Analytical techniques, constants used in the age calculations, and sample preparation methods are given in Appendix B. Analytical results are listed in Table 1.

DISCUSSION OF AGES

Zircons from the Lovingston Formation produce a range of Pb^{207*}/Pb^{206*} and U/Pb ages (fig. 3, table 1). The coarse and fine fractions of zircons from the Lovingston gneiss (sample WP-57 collected two miles away from the Rockfish granodiorite) define a chord from 913 to 1870 m.y. The fine fraction (C_1 in fig. 3) gives a concordant age of 913 m.y., while the coarse fraction (C_2, fig. 3) has a highly discordant U/Pb age. The Pb^{207*}/Pb^{206*} age for this fraction (1422 m.y.) is the oldest age measured to date in the central and southern Appalachian basement rocks. Because of the difficulties encountered in measuring the ultralow uranium and lead concentrations (table 1) of the coarse fraction (C_2), and the numerous inclusions in each of the zircons, a large ($\pm 5\%$) Pb^{207*}/Pb^{206*} error was calculated. Because of this error, and because of a minimum 1633 m.y. age determined from a Pb^{206}/Pb^{204} versus Pb^{207}/Pb^{204} plot of C_1 and C_2 (by simple linear regression analysis), a maximum deviation of $\pm$ 200 m.y. is possible on the 1870 m.y. age. At present, 1870 m.y. is considered to be a maximum age.

Zircons from the Lovingston quartz monzonite and pegmatite yield much younger ages and are not as discordant as the zircons from the Lovingston gneiss (fig. 3; table 1). The chords generated for the quartz monzonite (points A_1 and A_2, fig. 3) and pegmatite (points B_1 and B_2 have upper and lower intercept ages of 1080 - 330 m.y., and 1080 - 180 m.y. respectively. These two samples were collected within 600 feet of the Rockfish granodiorite (fig. 2) and have 10 to 30 times as much uranium as the Lovingston gneiss sample (WP-57), suggesting that uranium gain occurred at the time of the pluton's intrusion (fig. 6). Possible contact metamorphic effects are compared to the contact effects found in the rocks surrounding the Eldora Stock (Hart, 1964), in a later section.

The best interpretation favored herein is that the Lovingston Formation augen gneiss represents a clastic sediment, metamorphosed at 913 m.y., whose maximum age (more likely the age of its source) is 1870 m.y.

The best interpretation of the Rockfish granodiorite is that it intruded the Lovingston quartz monzonite and pegmatite at 820 ± 20 m.y. ago. A small scatter of points about the 820 m.y. discordia is apparent in figure 4, and seems to be related to the difference in acid washing and aplitting procedures used for duplicate analyses. The fine fraction of sample WP-13 (B_{3*}, fig. 4) was acid washed following the procedure of Krogh (1973). An unwashed portion of the same fine fraction was split into magnetic and non-magnetic fractions (B_{1*} and B_{2*} respectively). These magnetic splits were then pulverized in a stainless steel mortar and each split washed in warm (90°C) 6.2N HCl for 15 minutes, dried, then acid washed in warm 7N HNO_3 for 20 minutes. Points B_{1*} and B_{2*} are both more clearly related to the 820 m.y. chord than the unpulverized portion B_{3*}, suggesting that radiogenic and common lead were selectively removed during acid washing. The zircons from this fine fraction are highly zoned, have inclusions of biotite and rutile(?), and as many as 10% of these zircons have cores. If both uranium and lead were leached from the pulverized samples, then the movement toward a lower Pb/Pb age may, in part, be due to more rapid leaching of radiogenic lead from the older (more metamict?) cores, and common lead leaching from inclusions. Removal of uranium bearing inclusions (if present) is not supported, because of the positions of points B_{1*} and B_{2*} relative to point B_{3*}.

The medium size fraction (C_{1*}, fig. 4 only) for sample WP-20 was split to allow different acid washing procedures prior to the measurement of isotopic compositions. Both fractions, C_{1*} (fig. 4, table 1) and C_{2*} (table 1 only), were acid washed following the procedure of Krogh (1973); then fraction C_{2*} was washed for an additional 20 minutes in warm 7N HNO_3. Comparison of the two lead isotopic compositions (see table 1) shows that radiogenic, as well as common lead, was leached from these highly zone zircons. The Pb^{206}/Pb^{204} ratio for C_{1*}(WP-20) is 340.9 while the rewashed fraction C_{2*} has a ratio of 7906.7. This significant difference in the type of lead removed during acid washing suggests that even slight differences in the length of the acid washing interval can cause scattering of data points, as shown by points B_{1*}, B_{2*} and B_{3*} (fig. 4). The possibility of leaching uranium-bearing inclusions must also be considered.

The scatter of points on figure 4 is more apparent than real and more likely represents variations in the method of processing than individual age differences. The average Pb^{207*}/Pb^{206*} age for the Rockfish granodiorite is 795 m.y. (obtained by averaging all of the Pb^{207*}/Pb^{206*} ages listed in table 1). Simple linear regression analyses of the Pb^{206}/Pb^{204} ratios listed in table 1 yields an average age of 798 m.y.

Regression analyses from data for magnetic, non-magnetic fraction pairs yields ages ranging from 795 to 835 m.t. These ages are in agreement with a best fit chord with upper and lower intercepts of 820 and 110 m.y. respectively. In an attempt to evaluate the possibility of inherited zircons in the granodiorite, a chord (with upper and lower intercepts of 1080 and 330 m.y. respectively) was drawn through five granodiorite points, the points for the Lovingston quartz monzonite (A_1 and A_2, fig. 3) and point B_2 from the pegmatite. The possible significance of this chord will be discussed later.

MODELS FOR THE INTERPRETATION OF U-Pb AGES

Introduction:

Since the zircon age pattern in figure 3 shows an "apparent" mixing trend, two models are proposed to explain the data. The purpose of these models is to show that in geologically complex areas, no unique solution to the problem of zircon discordancy is possible.

Model I: Metamorphic overgrowths on 1870 m.y. old zircons.

Model I is partially based on the results of a study by Krogh and Davis (1973) on c.a. 1850 m.y. old igneous and metasedimentary rocks from the Canadian shield. They observed that addition of uranium (at a time of metamorphism) to zircons of similar size, but different critical concentrations of uranium (and different magnetic susceptibilities) will cause rotation of data points. Therefore, a chord generated through data points with different magnetic susceptibilities and different concentrations of uranium will in general be rotated so that the concordia intercept ages of the chord will be too young.

This model is based on the chord generated by points C_1 and C_2 as shown on figures 3 and 5. It assumes that the other Lovingston zircons have been pulled off the 913 to 1870 m.y. chord and into their present positions because of the effects of locallized intrusion, several periods of metamorphism, recent weathering, and (possibly) laboratory acid washing.

It is suggested that zircons from the Lovingston quartz monzonite (A_1 and A_2) and pegmatite (B_1 and B_2) originally lay on the older discordia. Their relative discordancies at 913 m.y. are unknown, but it is possible that the 913 m.y. event was strong enough to cause major lead loss and possibly some uranium gain. The intrusion of the Rockfish granodiorite at about 820 m.y. may have caused significant uranium gain (see section on Igneous and Metamorphic Effects).

To illustrate the hypothetical movement of the real samples in response to U-Pb system opening, a hypothetical point 1 has been placed on the older discordia (fig. 5). Second generation uranium gain (and/or lead loss) at 820 m.y. would move the point along a new discordia toward 820 m.y. Sample B_2 for which the hypothetical set of points has been used has become more discordant in response to: 1) metamorphism during the Paleozoic; or 2) a combination of metamorphism, recent weathering and acid washing, and is now located at its measured position. The same arguments would apply for fractions A_1 and A_2, except that the amounts of uranium gain (and subsequent lead loss) are much lower, causing these points to lie along a slightly different chord than that generated by points B_1 and B_2. Points C_1 and C_2 were seemingly unaffected by intrusion (two miles away) of the Rockfish granodiorite (i.e. neither gained uranium nor lost lead). Because of the ultralow uranium-lead levels in these two fractions, neither point (especially C_1) is thought to have moved very far off the original mixing line.

The chords generated for the Lovingston quartz monzonite and the pegmatite have distinctly separate (not within analytical errors) lower intercepts (fig. 3). Zircons from the quartz monzonite have much lower U concentrations than those for the pegmatite, and as expected in this model, generate a chord (through A_1-A_2) with an older lower intercept age than does the chord through B_1-B_2. This observation of chords whose upper and lower intercepts are both too young is supported by similar observation of "rotated isochrons" by Krogh and Davis (1974) in rocks of similar age (i.e. 1850 m.y.), but less complex geological history. The chord drawn through points C_1 and C_2 may have been rotated in a reverse manner, to show an apparent age of crystallization at 1870 m.y. that is too old.

Model II: Pre-Grenville rocks intruded at 1080 m.y. by the Lovingston quartz monzonite and the pegmatite:

This model represents a direct interpretation of the data as it stands, but with the suggestion that the ages for the quartz monzonite and pegmatite (as determined from the chords drawn in figure 5) are minimum ages.

This model requires that two distinct igneous events: between 1422 and 1870 (shown by C_1-C_2); followed by intrusion of the quartz monzonite and pegmatite at 1080 ± 20 m.y. (minimum age). The distribution shown by all of the points on figure 5 represents the different responses of zircons (with grossly different U-Pb concentrations) from different intrusives, to the same geologic history. In this model the possible contact metamorphic effects shown in figure 6 are assumed to be the product of the sampling technique, which allowed collection of three different age intrusives. The uranium concentrations shown may reflect the actual uranium-lead concentrations of the different intrusives sampled.

For this model, it is assumed that the two different chords drawn for pairs A_1-A_2 and B_1-B_2 on figures 3 and 5 define a common upper intercept age of 1080 m.y. and lower intercept ages of 330 and 180 m.y. respectively. The upper intercepts may be considered fortuitous. Evidence for intrusion and/or metamorphism at 1080 m.y. and during lower Paleozoic times will be presented in the following section on metamorphism.

IGNEOUS AND METAMORPHIC EVENTS AFFECTING THE BLUE RIDGE ANTICLINORIUM

Introduction:

Although there are no K/Ar or Rb/Sr mineral/whole rock ages from the study area, published ages from the southern Appalachians and Maryland Piedmont show evidence of events between 1300 and 900 m.y. (Tilton, et al, 1958; 1960; Davis, et al, 1962; Wetherill, et al, 1958; 1966; 1968; Grauert, 1973; Fullagar and Odom, 1973; and Tilton, et al, 1970; Dietrich, et al, 1969), and 430 to 269 m.y., with the greatest number of ages in this last range clustered around 370 - 350 m.y. and 390 - 310 m.y. (Tilton, et al, 1959; 1960; 1962; 1970; Deuser and Herzog, 1962; Kulp and Eckelmann, 1959; Wetherill, et al, 1958; 1966; 1968; and compilations by Long, Kulp and Eckelmann, 1959; Hadley, 1964; Tilton, 1965; and Sinha, et al, unpublished).

The sequence of events proposed in Model I suggests events between 1422 and 1870 m.y., 910, and 820 m.y. An event at 1080 m.y. (shown by the apparent chord in figure 5) is considered unlikely because of the reason given in Model I. The intercept age of 1870 m.y. is considered a maximum age for the detrital zircons in the Lovingston gneiss. This event is very similar to other ages of 890-950 m.y. given by Tilton (1965). The age of the Rockfish granodiorite (820 m.y.) probably indicates the same thermal event which produced the Catoctin and Mt. Rodgers volcanics (Rankin, et al, 1969).

Because of problems in the interpretation of zircon ages given in this report, especially as related to Model I, the Eldora Stock study of Hart (1964) and Hart, et al, (1968) has been used as a model for comparing the results obtained in this study. Figure 6 is a plot of distance from the pluton (into the Lovingston Formation) versus changes in U^{238} and Pb^{206} (ppm), and apparent Pb/Pb ages.

All three indices show the same trends as those found in the Eldora study (the Pb^{206} shows an inverse relationship because the Eldora stock intruded a much older rock with high lead zircons, while the Rockfish granodiorite intruded the old, but very low lead Lovingston Formation). If this effect of enrichment of uranium in the host rock, and an increase in apparent Pb/Pb age (with increase in distance away from the pluton) is real, then it is suggested that relatively deep-seated plutons intruding a country rock (which was at an elevated temperature), may not necessarily show idealized contact metamorphic effects in the field. Under such conditions, it is possible that a very small chemical gradient would generate the effects seen in figure 6, and thus cause the movement of zircon points toward a concordia age of 820 m.y., as shown in figure 5. If the Lovingston quartz monzonite and pegmatite are intrusives in the Lovingston gneiss, as suggested in Model II, then the curves shown in figure 6 are not meaningful, but are the result of the sample collecting method used.

SUMMARY

Based on results obtained in this study, it is proposed that both of the models for the interpretation of zircon ages, herein considered, be used when analyzing U-Pb zircon data from the Appalachians.

1) Although evidence for Pre-Grenville age zircons has been reported earlier (Grauert, 1973) for rocks in the Piedmont, this

report is the first documentation of 1422-1870 m.y. old zircons in the Blue Ridge basement. Based on this evidence it is suggested that some of the basement zircons dated as yet, are products of mixing an old (inherited) component with newer metamorphic overgrowths formed at ± 900 m.y. ago.

The process of effective uranium gain, or lead loss, would move the zircons to different positions on the 913-1870 m.y. disconcordia. Subsequent lead loss or uranium gain resulting from intrusion (c.a. 820 m.y.), metamorphism or recent weathering would create a second generation discordia giving 'apparent' crystallization ages which would be too young (for example, the ages of the Lovingston quartz monzonite and pegmatite).

2) The second model suggests that the Lovingston Formation consists of c.a. 1870 m.y. old rock (metasediment?) which was intruded at 1080 m.y., and that subsequent metamorphism and intrusion have severely complicated the stratigraphic relations of rocks within this unit. This complex history makes verification of either model difficult. However, it is suggested that very careful mapping is necessary to distinguish between true intrusives and basement rocks which have undergone high grade metamorphism.

The age of the Rockfish granodiorite (820 m.y.) is very similar to the (820 m.y.) U-Pb age obtained for the Catoctin and Mt. Rodgers volcanic rocks. Since similar plutons intrude the Lynchburg Formation farther north, along strike, from the study area, an age range of 810-913 m.y. is suggested for the deposition of the Lunchburg

Formation.

Further investigations in the Blue Ridge basement will provide the data necessary for discriminating between the two models proposed in this paper.

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APPENDICES

TABLE 1: Zircon analytical data and ages.

Symbols: C = coarse (+150 microns), Med = medium (-150, +75 microns), F = fine (-75 microns), M = magnetic, NM = non-magnetic, Cr = Pulverized, AW = Sample given a third acid washing in warm 7N HNO_3 (20 minutes).

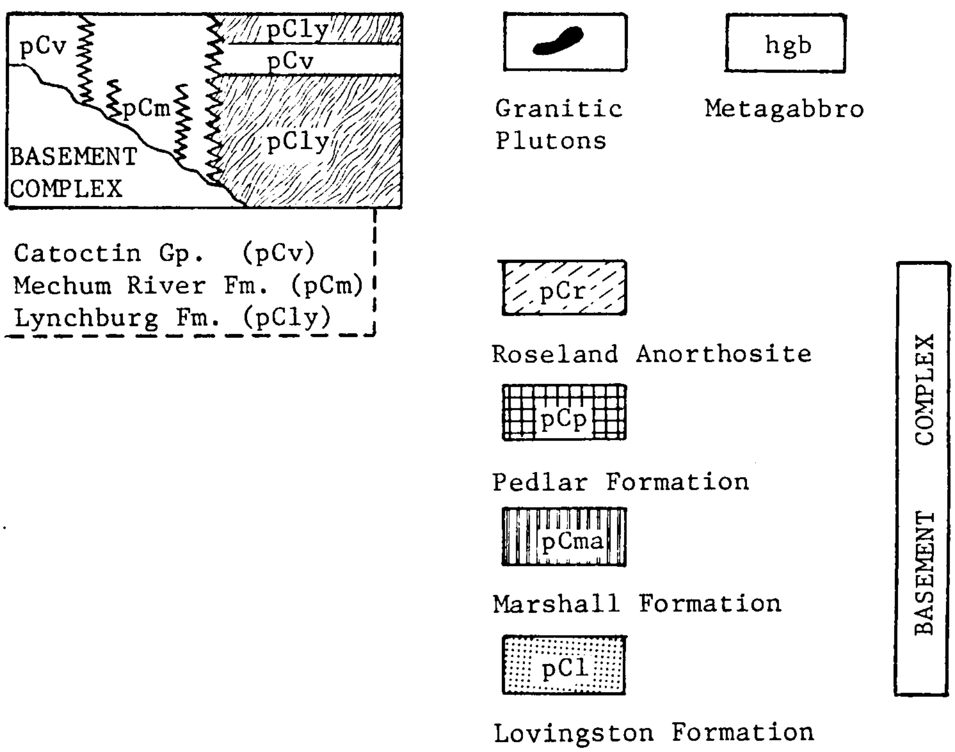
Pb^{206} values corrected for blanks only. See Appendix B for constants. NBS 983 Pb standard data is listed within.

* Letters followed by an asterisk denote Rockfish granodiorite samples only.

Sample Number	Fig. No.	Split	(ppm) U^{238}	(ppm) Pb^{206}	Isotopic Ratios $\frac{Pb^{206}}{Pb^{204}}$	Isotopic Ratios $\frac{Pb^{206}}{Pb^{207}}$	Isotopic Ratios $\frac{Pb^{206}}{Pb^{208}}$	U-Pb Ratios $\frac{Pb^{206*}}{U^{238}}$	U-Pb Ratios $\frac{Pb^{207*}}{U^{235}}$	U-Pb Ratios $\frac{Pb^{207*}}{Pb^{206*}}$	Ages (m.y.) $\frac{Pb^{206*}}{U^{238}}$	Ages (m.y.) $\frac{Pb^{207*}}{U^{235}}$	Ages (m.y.) $\frac{Pb^{207*}}{Pb^{206*}}$
Rockfish Pluton Granodiorite													
WP-13	B_{3*}	F	1159.2	101.5	2267.8	13.617	6.955	.1002	.9320	.06751	616	669	853
WP-13	B_{1*}	F,M,Cr	1934.6	136.2	994.0	12.780	6.269	.0798	.7016	.06383	495	543	736
WP-13	B_{2*}	F,NM,Cr	955.7	85.0	6198.2	14.727	8.013	.1024	.9251	.06558	629	665	793
WP-20	C_{1*}	Med	1485.8	146.2	340.9	9.364	5.039	.1080	.9675	.06504	662	687	775
WP-20	C_{2*}	Med,AW	-	-	7906.7	14.883	10.488	-	-	.06538	-	-	-
WP-20	D_{1*}	F	1364.0	110.4	3445.9	14.366	11.383	.0946	.8538	.06555	571	618	788
WP-66	A_{1*}	F,M	2424.0	196.2	1922.1	13.852	5.740	.09275	.8439	.06607	572	621	808
WP-66	A_{2*}	F,NM	1660.3	137.5	3012.6	14.233	6.239	.09483	.8639	.06614	584	632	811
Lovingston Fm. Quartz Monzonite													
WP-12A	A_1	C	253.0	35.4	2088.4	12.685	9.323	.1360	1.3568	.07243	816	866	1032
WP-12A	A_2	Med	306.8	50.7	6155.8	13.108	10.175	.1620	1.6594	.07440	968	993	1052
WP-12A	A_3	F	-	53.0	5346.6	13.186	10.574	-	-	.07337	-	-	1019
Pegmatite													
WP-83	B_2	C	615.1	82.4	636.4	10.359	7.589	.1502	1.5451	.07471	902	949	1061
WP-85	B_1	F	899.3	71.3	586.6	10.553	7.604	.0888	.8580	.07017	549	629	933
Gneiss													
WP-57	C_2	C	19.7	4.8	760.0	9.177	4.096	.2042	2.5527	.09077	1198	1287	1422
WP-57	C_1	F	21.0	4.2	255.0	7.951	3.326	.1520	1.4548	.06952	913	912	914
NBS 983					2688	14.0292	73.206						
NBS 983					2731	14.0528	73.314						
NBS 983	Absolute Values				2695	14.045	73.421	(Catanzaro, *et al*, 1968)					

FIGURE 1: The Basement Complex of Central Virginia, modified from the State Map of Virginia (Calver, and Hobbs, ed), 1962; and the Geologic Map of Albemarle County, Virginia (Nelson, 1962). Map scale is 1" ≈ 8 miles (1:500,000).

PRECAMBRIAN SEQUENCE



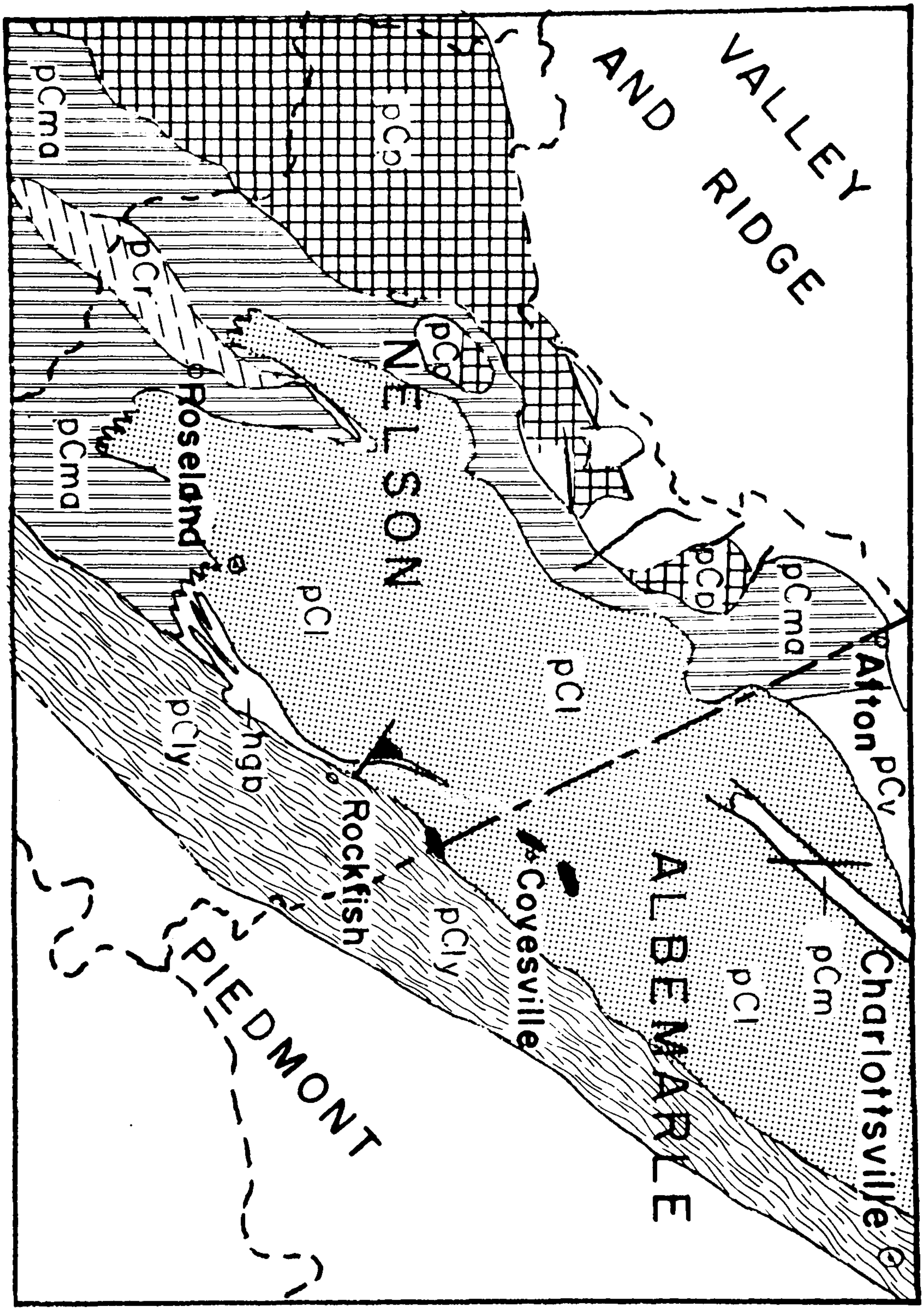

VALLEY AND RIDGE
NELSON
ALBEMARLE
PIEDMONT
Roseland
Rockfish
Covesville
Afton
Charlottesville
pCma
pCp
pCr
pCl
pCly
hgb
pCv
pCm

FIGURE 2: Geologic map of the Rockfish granodiorite and host Lovingston Formation

Sample localities are circled and marked with sample numbers. Mapped location falls in the east- central section of the Lovingston, Va. 7 1/2 minute quadrangle.

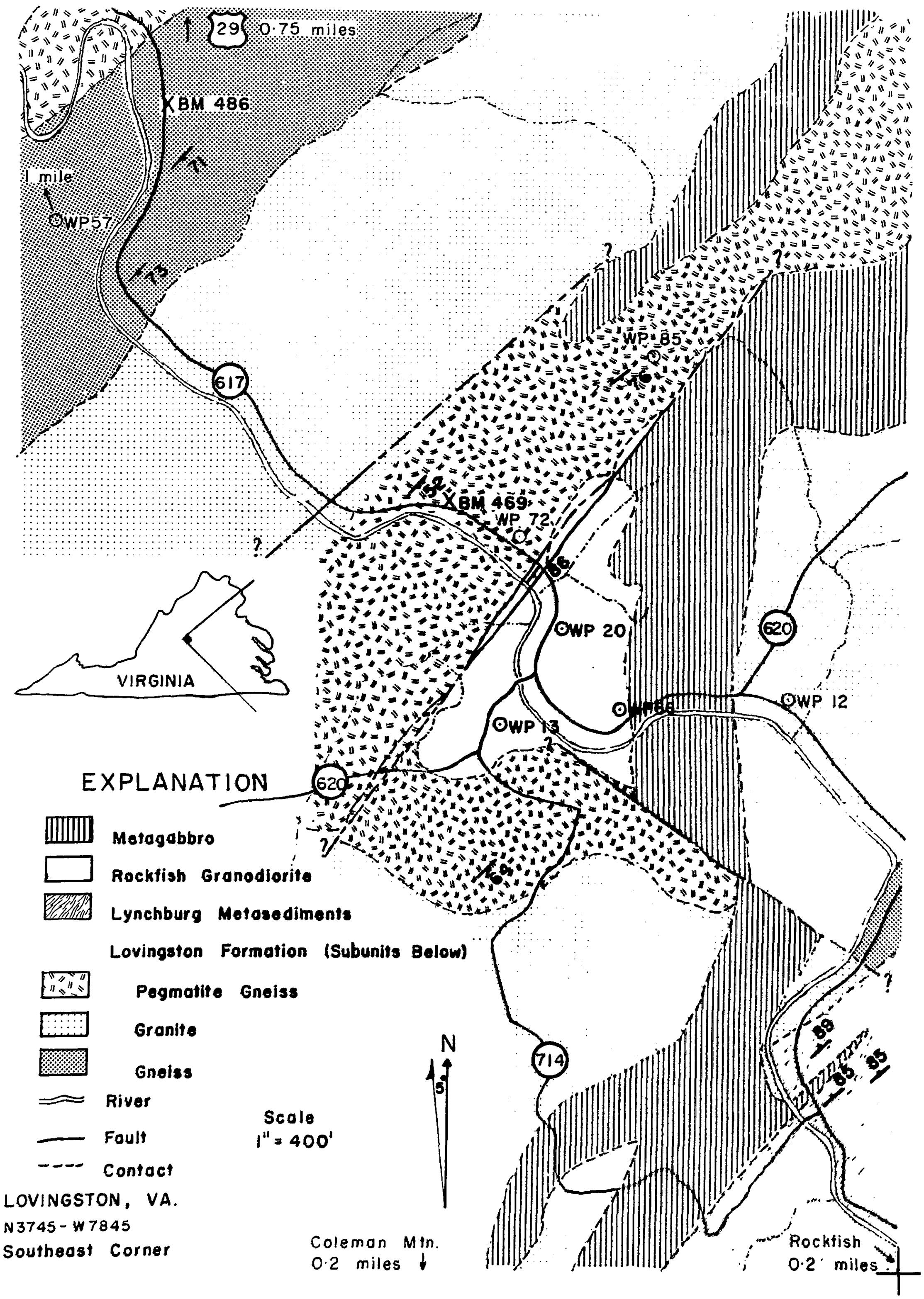

29
0·75 miles
BM 486
1 mile
WP57
617
WP 85
BM 469
WP 72
WP 20
620
WP 12
WP 13
VIRGINIA
EXPLANATION
Metagabbro
Rockfish Granodiorite
Lynchburg Metasediments
Lovingston Formation (Subunits Below)
Pegmatite Gneiss
Granite
Gneiss
River
Fault
Contact
Scale
1" = 400'
N
714
LOVINGSTON, VA.
N3745 - W7845
Southeast Corner
Coleman Mtn.
0·2 miles
Rockfish
0·2 miles

FIGURE 3: Concordia diagram showing the age relations of the Rockfish granodiorite (D) and host Lovingston Formation (A-C). See Appendix B for decay constants.

Symbols used in figure 3:

A_1 WP 12-A Coarse fraction

A_2 WP 12-A Medium fraction

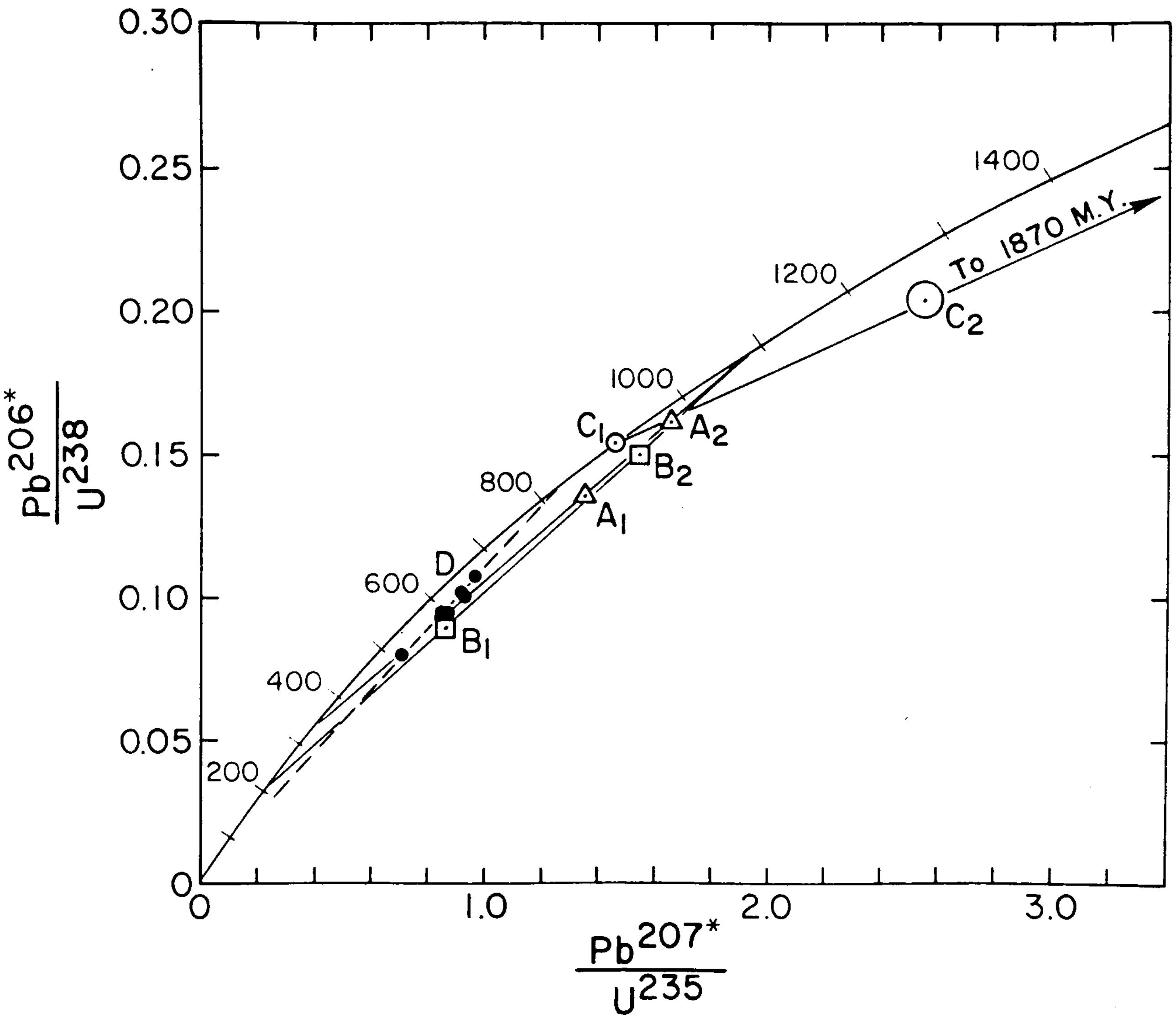
B_1 WP 85 Fine fraction

B_2 WP 85 Coarse fraction

C_1 WP 57 Fine fraction

C_2 WP 57 Coarse fraction

D Rockfish granodiorite samples



0.30
0.25
0.20
0.15
0.10
0.05
0
0
1.0
2.0
3.0
Pb206*/U238
Pb207*/U235
200
400
600
800
1000
1200
1400
To 1870 M.Y.
D
A1
A2
B1
B2
C1
C2

FIGURE 4: Enlarged Concordia diagram showing data points for seven Rockfish granodiorite sample splits. Error bars are given for each point. The U-Pb age is 820 ± 20 m.y.

Symbols used in figure 4:

A_1*	WP 66	Magnetic fine fraction
A_2*	WP 66	Non-magnetic fine fraction
B_1*	WP 13	Magnetic fine fraction (crushed)
B_2*	WP 13	Non-magnetic fine fraction (crushed)
C_1*	WP 20	Medium fraction
C_2*	WP 20	Fine fraction

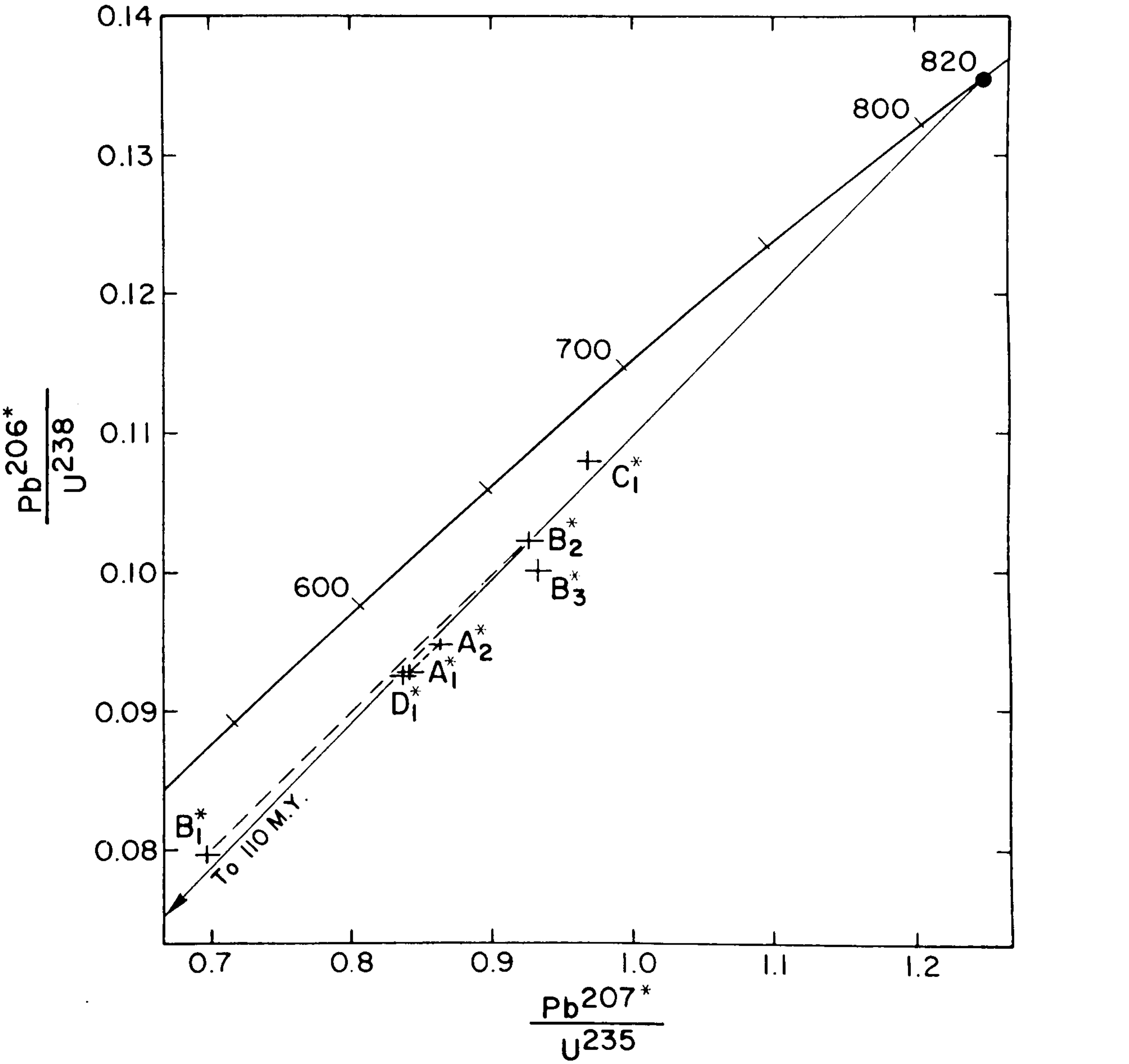
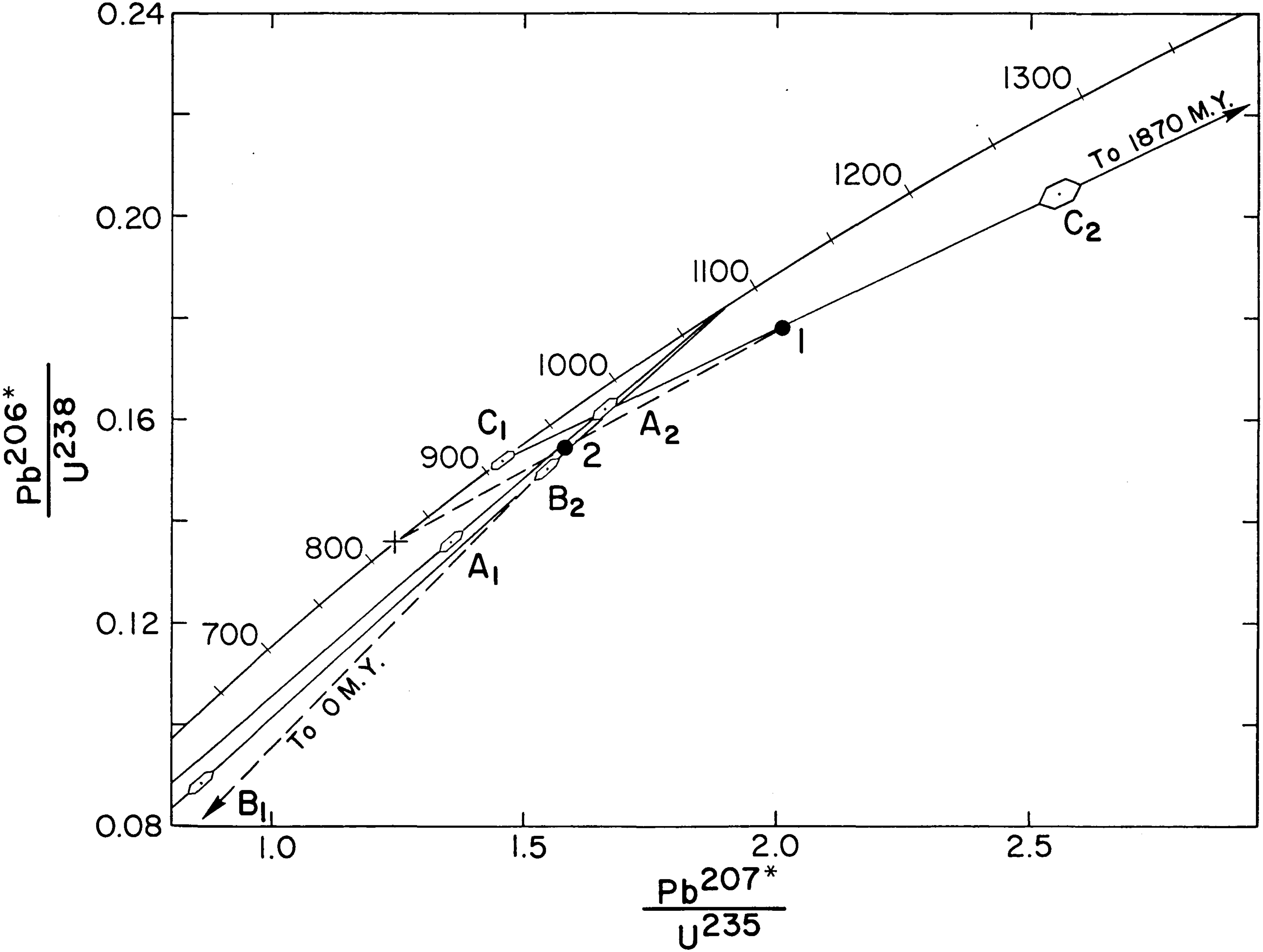

0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.7
0.8
0.9
1.0
1.1
1.2
$\frac{Pb^{206*}}{U^{238}}$
$\frac{Pb^{207*}}{U^{235}}$
820
800
700
600
C_1^*
B_2^*
B_3^*
A_2^*
A_1^*
D_1^*
B_1^*
To 110 M.Y.

FIGURE 5: Concordia diagram showing hypothetical movements of points in response to the metamorphic episodes affecting them (including recent weathering and laboratory acid washing). Lettered points are real samples and numbered points represent hypothetical positions.

Symbols used in figure 5 are:

A_1	WP 12-A		Coarse fraction
A_2	WP 12-A		Medium fraction
B_1	WP 85		Fine fraction
B_2	WP 85		Coarse fraction
C_1	WP 57		Fine fraction
C_2	WP 57		Coarse fraction
+	820 m.y.		time of intrusion



0.24
0.20
0.16
0.12
0.08
1.0
1.5
2.0
2.5
$\frac{Pb^{206*}}{U^{238}}$
$\frac{Pb^{207*}}{U^{235}}$
700
800
900
1000
1100
1200
1300
To 1870 M.Y.
To 0 M.Y.
C_1
C_2
A_1
A_2
B_1
B_2
1
2

FIGURE 6: Contact metamorphic effects around the Rockfish granodiorite.

Variations in age and U-Pb concentrations v.s. distance are compared to similar data for the Eldora Stock, Colorado (Hart, *et al*, 1968).

Symbols used in figure 6 are:

Rockfish granodiorite

△ Apparent age (m.y.)

□ Pb^{206} concentration (ppm)

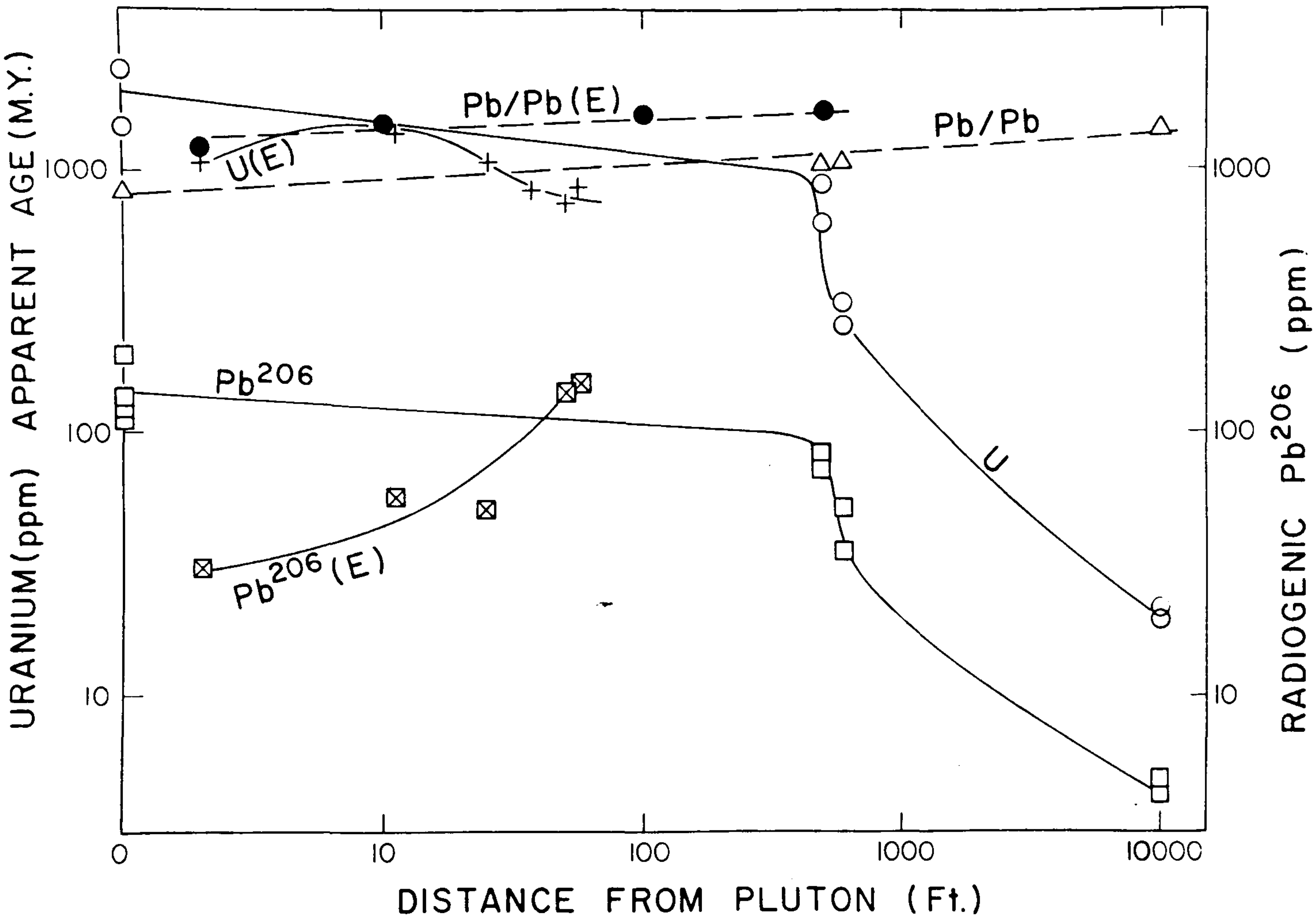
○ U^{238} concentration (ppm)

Eldora Stock (E)

● Apparent age (m.y.)

⊠ Pb concentration (ppm)

+ U concentration (ppm)


URANIUM (ppm) APPARENT AGE (M.Y.)
RADIOGENIC Pb206 (ppm)
DISTANCE FROM PLUTON (Ft.)
Pb/Pb (E)
Pb/Pb
U(E)
U
Pb206
Pb206 (E)
1000
100
10
0
10
100
1000
10000

APPENDIX A

Sample Locations, Modal Analyses, and Descriptions of Zircons:

Explanation: Each entry includes field sample number (in parenthesis), name of unit, petrographic name of rock, location (latitude and longitude), and a brief description of zircons separated from the sample.

1. (WP-12-A): Lovingston Formation, quartz monzonite. 37°48'58" N, 75°45'48" W. Zircons: Normal, euhedral to subrounded, clear, many opaque inclusions, overgrowths, outgrowths, mean length-width ratio (7:2).
2. (WP-13): Rockfish granodiorite. 37°48'52" N, 78°46'31" W. Zircon: euhedral, transparent, pinkish to brown in color, cloudy cores (up to 5% of sample), highly zoned, many inclusions (opaque minerals and biotite, and occasionally rutile), and outgrowths (up to 10% of sample). Length-width ratio averages 3:1.
3. (WP-20): Rockfish granodiorite. 37°49;90: N, 78°46'20" W. Zircons: same as WP-13, except that the length-width ratio averages 2.5:1.
4. (WP-57): Lovingston Formation, gneissic quartz monzonite (protomylonite). 37°50'50" N, 78°47'45" W. Zircons: Range from euhedral (mainly in the -200 mesh fraction) to highly rounded (+100 mesh zircons); clear and transparent, but with many inclusions (opaques, biotite, small zircons,

rutile), overgrowths and/or outgrowths common (see Fig. 7); length-width ratios of 2:1 and 5:1 predominate.

5. (WP-66): Rockfish granodiorite, biotite-granodiorite. 37°48'55" N, 78°46'12" W. Zircons: same as WP-13.

6. (WP-85): Lovingston Formation; pegmatitic-antiperthitic-quartz diorite. 37°49'47" N, 78°45'57" W. Zircons: Range in size from 2mm to 20 microns. Large zircons are translucent, brown to purple, subhedral (prisms with no terminations), often very thin (7:1 length-to-width). Small zircons are pink to yellow, transparent, euhedral to subhedral, zoned, and have cores (up to 10% of sample). Large zircons also have highly included (opaques, biotite, rutile or apatite, and small rounded zircons).

Zoning in these zircons generally refers to color banding within individual crystals, but in certain cases also refers to variations in the index of refraction across a zircon. Overgrowths were also determined from changes in the index of refraction from the core to the shell of the zircon. Inclusions were identified by optical and/or x-ray techniques.

No major statistical analysis of the physical characteristics of individual zircon populations was performed.

Distribution of zircons in the samples:

It is important to note that the majority of zircons in each of the rocks mentioned above, are associated with, and included in,the more mafic constituents. In the Lovingston gneiss, most of the +300 mesh zircons are distributed in the biotite folia, with only the smallest (-300 mesh) zircons being included in quartz and feldspar grains. Distribution of zircon in the more igneous samples (especially the Rockfish granodiorite) is more uniform, but the majority of zircons are associated with or included in flakes of biotite.

The general distributions of the zircons in each sample was determined through thin section study and observation of hand specimens under long wave ultraviolet light.

TABLE II. ESTIMATED MODAL COMPOSITIONS OF ROCKS IN THE STUDY AREA

	Rockfish Granodiorite				LOVINGSTON FORMATION Quartz Monzonite	LOVINGSTON FORMATION Peg- matite	LOVINGSTON FORMATION Gneiss	Meta- gabbro
	WP-13	WP-20	WP-33	WP-66	WP-12-A	WP-85	WP-57	WP-65
Quartz	32	26	28	31	18	12	15	1
Microcline	29	25	23	26	27*	12*	30*	2*
Plagioclase	25	26	36	30	24	20	21	41
Antiperthite	-	-	-	-	-	45	X	-
Biotite	6	6	3	8	14	1	19	X
Epidote	4	3	2	1	4	5	1	1
Chlorite	X	X	X	1	3	X	6	-
Opaque Oxides	X	X	2	1	1	X	X	2
Zircon	X	X	X	X	X	X	X	-
Sphene	X	X	-	X	X	X	X	X
Garnet	-	-	-	-	-	-	X	-
Zoisite	-	X	X	-	1	X	1	X
Apatite	X	X	X	X	-	-	-	-
Allanite	X	-	-	X	-	-	-	-
Fluorite	X	X	X	X	-	-	-	-

X = 1 percent or less

* = perthite

APPENDIX B

Analytical techniques:

Zircon samples were prepared from 5 to 100 kg. samples of rock by standard Wilfley table, heavy liquid and magnetic separations. Zircon samples were washed in warm 7N HNO_3 (pulverized zircon fractions were washed in warm 6.2N HCl for 15 minutes), handpicked, then rewashed in ultrapure 7N HNO_3 following the procedure of Krogh (1973), until sample fractions were better than 99% pure zircon.

Zircon dissolution and lead separation were done following the procedure of Krogh (1973). Ion exchange column procedure for the separation of uranium followed the nitrate method of Sinha (1973, pers. comm.).

Lead was prepared and loaded for mass spectrometric analysis using the silica gel - posphoric technique of Cameron, <u>et al</u> (1969). Uranium was loaded as a nitrate on a single rhenium filament coated with a thin film of tantalum oxide (Krogh, 1973).

Precision achieved by running duplicate samples at different times was 0.39% for Pb^{207}/Pb^{206}, 1.1% for Pb^{206} (ppm), and 1.5% for U^{238} (ppm). In-run precision ($\pm 2\sigma$) averaged ±0.45% for Pb^{207}/Pb^{206}, ±0.7% for Pb^{206} (ppm), and ±1.3% for U^{238}. NBS 983 lead standard data is presented in table 1.

Blank corrections are: $Pb_{Total} = 3.15 \times 10^{-9}$ grams; and $U_{Tot} = 0.012 \times 10^{-9}$ grams. Common Pb corrections used are:

Sample	Age	$\frac{Pb^{206}}{Pb^{204}}$	$\frac{Pb^{207}}{Pb^{204}}$	$\frac{Pb^{208}}{Pb^{204}}$
Rockfish granodiorite	750	17.217	15.413	36.419
Lovingston Fm.	(all samples)	1100	16.602	35.656

Constants used in the age calculations (Jaffey, *et al*, 1971) are:

$$U^{238} = 1.55130 \times 10^{-9} yr^{-1},$$

$$U^{235} = 9.8485 \times 10^{-9} yr^{-1}$$

$$\frac{U^{238}}{U^{235}} = 137.88$$

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Pre-Grenville ages of Basement Rocks in Central Virginia:
A Model for the Interpretation of Zircon ages

by

Robert G. Davis

(ABSTRACT)

Late to Middle Precambrian basement rocks in the Blue Ridge of Central Virginia represent a heterogeneous admixture of highly deformed gneisses, paragneisses and igneous intrusives, which have undergone multiple periods of metamorphism.

Isotopic U-Pb age determinations on the Lovingston Formation indicate that portions of these Central Appalachian basement rocks are 1633 m.y. old and may be as old as 1870 m.y. A concordant zircon from the Lovingston gneiss indicates that intense regional metamorphism occurred at least 913 m.y. ago. The Rockfish granodiorite, in Nelson County, Virginia, intruded these older basement rocks 820 ± 20 m.y. ago and appears to be coeval with the extensive Catoctin and Mt. Rodgers volcanic rocks.

Because of the complex geologic history of this area, two models are proposed to explain the U-Pb zircon data. The first model proposes that the different rock types within the Lovingston Formation were all crystallized at least 1633 m.y. ago and have each responded in a different manner to multiple periods of metamorphism and at least one period of plutonism. The second model is a direct interpretation.