Locating the Westminster-Potomac Terrane Boundary in the Maryland Piedmont Province

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Geology 394

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Abstract

The eastern part of the Piedmont Province consists of exotic terranes that rifted from Gondwana during the close of the Iapetus and Rheic Oceans. The Piedmont extends lengthwise from Newfoundland to Georgia and from the Bull Run Mountain fault to the west, until the Potomac Formation to the east, in the northeastern United States. Studies of foliations and cleavages in rocks of the Piedmont Province have been conducted to locate and understand the kinematics of the faults between the terranes within the province. Previous workers used isotopic data from micas in Piedmont rocks to locate the Parrs Ridge fault, which is the newly defined contact between the Westminster and Potomac terranes. Previously, this contact was accepted to be the Pleasant Grove fault, located between the Mather Gorge and Marburg Formations. I have studied four formations within the Piedmont by using petrographic analysis and U/Pb dating in detrital zircons to increase the certainty of the location of the Parrs Ridge Fault, and its function as a terrane boundary within the Piedmont.

Introduction

For over a century, geologists have been working toward understanding the formation of the Appalachian mountain range and of the Piedmont Province. According to Dalla Salda et al. (1992), the Appalachians may have extended through southern South America, but end abruptly at the Gulf of Mexico coastal plain in Georgia. Dalla Salda observed that the Andes and Appalachian mountain ranges are nearly parallel to one another (see figure 1), and contends that the Andes and the Appalachians formed during the Taconic and Famatinian orogenies which occurred along the east and west Laurentian margins, respectively. The eastern Laurentian margin underwent multiple collisions by terranes which rifted from Gondwana. These collisions are responsible for the formation of the Piedmont Province and the multiple generations of foliation found within the province.

Within the Piedmont are the Westminster and Potomac terranes, located in central Maryland. Historically, the contact between the Westminster and Potomac terranes was accepted to be the Pleasant Grove fault, which separates the Mather Gorge Formation from the Marburg Formation and the southernmost wedge of the Prettyboy Schist (see figure 1). Wintsch et al. (2010) proposed that a fault within the Westminster terrane, named the Parrs Ridge fault, separates the Westminster from the Potomac terrane. Wintsch used $^{40}Ar/^{39}Ar$ ages in white micas in rock cleavages to locate this boundary. By observing changes in the microstructures and U/Pb ages in detrital zircons of the formations in the northern region of the Maryland Piedmont, the contact between the Westminster and Potomac terranes can be located with more confidence. Studying the microstructures in all major minerals will give us a broad understanding of the deformation during continental collision between Laurentia and the peri-Gondwanan terranes. $^{238}U/^{206}Pb$ analysis in zircons differs from the study of $^{40}Ar/^{39}Ar$ closure temperatures in micas in that the age of zircons will give us a firm constraint on the depositional age of rocks, while argon closure temperatures will give us an understanding of the metamorphism in rocks. Both methods are useful in understanding the tectonic history of the Piedmont. Understanding these collisions helps to locate the thrust faults that they caused, including the boundary between the Westminster and Potomac terranes within the Piedmont Province.

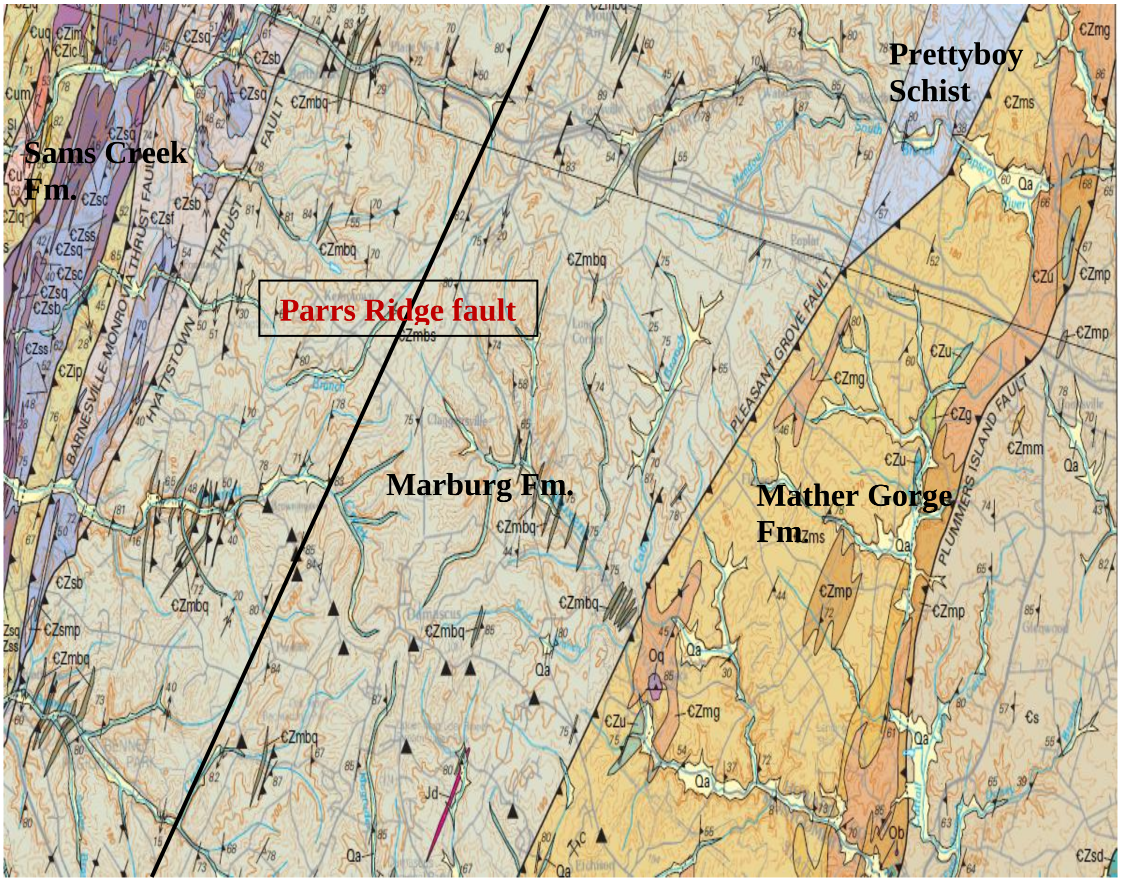


Fig. 1: Map of the northern region of Maryland. The Pleasant Grove fault represents the previously accepted contact between the Potomac and Westminster terranes. Figure from Southworth et al., 2007.

<u>Previous U/Pb Studies on the Piedmont</u>

Aleinikoff et al. used similar methods to those used in this study to determine the maximum depositional age of Piedmont rocks in 2002. Zircons were analyzed by using the sensitive high resolution ion microprobe (SHRIMP) and thermal ionization mass spectrometry (TIMS). Aleinikoff used the U/Pb age of the zircons within plutonic and igneous bodies to determine that they are parts of an extensive Early to Middle Ordovician magmatic arc (2002). The Dale City Quartz Monzonite, Kensington Tonalite, and the Occoquan Granite are among over ten formations studied.

Before Aleinikoff's study, U/Pb ages of zircons within these igneous bodies were determined by previous workers. The Kensington Tonalite was dated 546 Ma by Sinha, Hund, and Hogan in 1989; the Occoquan Granite was dated 558 Ma by Seiders et al. in 1975; and the Dale City Quartz Monzonite was dated 560 Ma, also by Seiders et al. in 1975; and (Aleinikoff, 2002). According to Aleinikoff, none of these ages are correct, thus he used the SHRIMP and TIMS geochronology to determine more accurate ages for these bodies.

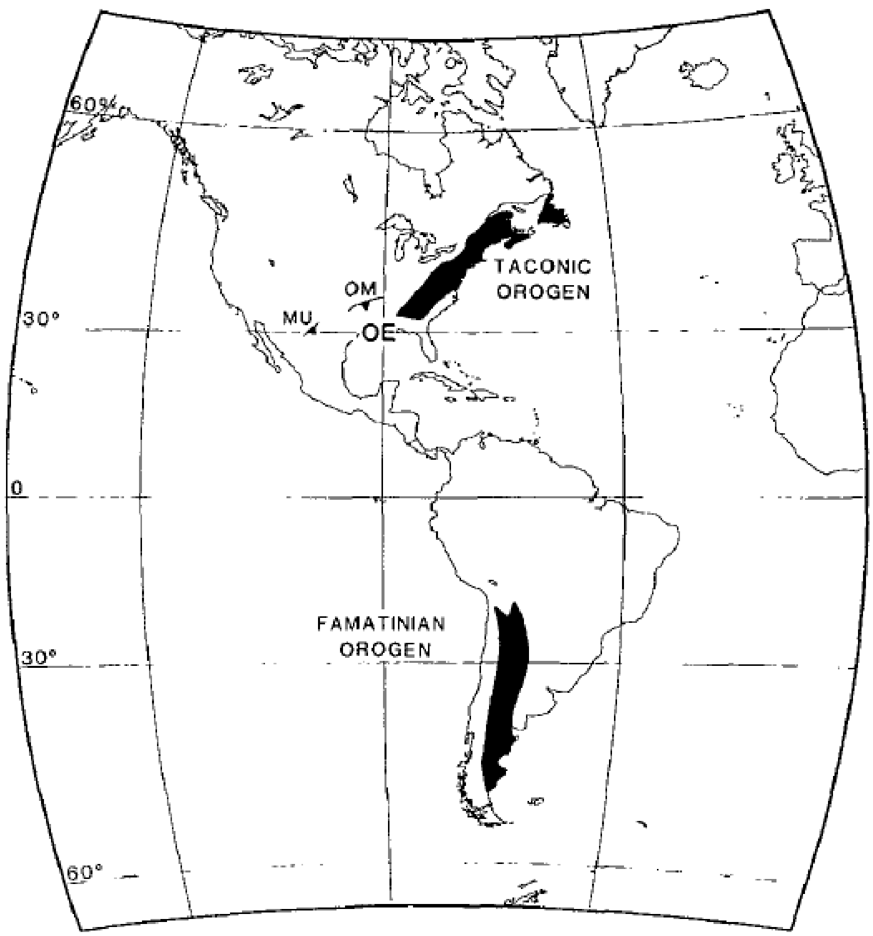


Fig. 2: Taconic orogen (Appalachian mountains) and Famatinian orogen (Andes mountains). From Dalla Salda et al. (1992).

Aleinikoff separated zircons from the rocks by pulverization, magnetic, and dense mineral separation with methylene iodide (2002). Zircons from the Dale City Quartz Monzonite were analyzed by using TIMS geochronology and have a maximum age of 459±4 Ma. The Kensington Tonalite was analyzed by both TIMS and SHRIMP analyses. TIMS data resulted in a maximum age of 468±8 Ma. SHRIMP analysis yielded a wide range of ages; the weighted average of 19 analyses resulted in an age of 463±8 Ma. The Occoquan Granite was analyzed by SHRIMP geochronology, and was dated 472±4 Ma, which is inferred to be the time of emplacement of the Occoquan Granite batholith (Aleinikoff, 2002). Detailed results of Aleinikoff's study can be found in Appendix 1. The intrusive rocks of the Maryland-D.C.-Virginia Piedmont were deposited between 485 to 450 Ma (Aleinikoff, 2002). These zircon ages represent the minimum ages for metamorphic bodies that were intruded by the granitoids analyzed in Aleinikoff's study; these units were determined to be Ordovician in age rather than Cambrian, as previously accepted (Aleinikoff, 2002). Silurian and Devonian ages of intrusions indicate Paleozoic tectonic events not previously recognized in rocks within the Central Appalachians (Aleinikoff, 2002).

Gus Kingman conducted U/Pb analysis on detrital zircons of formations within the Potomac terrane for his senior thesis in 2009. The formations sampled for this study are the Laurel Formation, and within the Mather Gorge Formation, the Bear Island and Blockhouse Point domains (Kingman, 2009). Detrital zircons were analyzed using the LA-MC-ICP-MS at the University of Arizona to determine the ages of crystallization of the rock bodies previously listed. Knowing the age of crystallization of the zircons help to place a maximum constraint on the rocks of the Piedmont; this will help us to determine whether the relationships of these formations have been placed properly in the Appalachian tectonic history (Kingman, 2009). The maximum depositional age of zircons within the Laurel Formation is 520 Ma, interpreted from probability distribution and concordia graphs. The Blockhouse Point domain was interpreted to have a maximum depositional age of 960 Ma. Lastly, the Bear Island domain was interpreted to have a maximum depositional age of 540 Ma. See Appendix 2 for graphs of analysis results.

Steven Fisher studied the north and south Sykesville formation as well as the Setters Formation, all located in the Potomac terrane. By using U/Pb analysis, clast aspect ratios, and thin section microtextural analysis, the age and source of the Sykesville formation was determined (Fisher, 2010). Fisher also used the LA-MC-ICP-MS at the University of Arizona to determine the age of crystallization of detrital zircons and thus a maximum depositional age of the Sykesville and Setters Formations. The weighted averages of the zircons analyzed were taken to interpret the maximum depositional ages of the formations sampled. A maximum depositional age of 1000 Ma was determined for the Setters Formation. The maximum depositional age of the north Sykesville Formation was interpreted to be 600 Ma. Lastly, the maximum depositional age of the south Sykesville Formation was interpreted to be 1000 Ma. See Appendix 3 for graphs of the analysis results.

Geologic Setting

Open and close of the Iapetus and Rheic Oceans

The Piedmont Province extends from Newfoundland to Georgia in the southeastern United States, and was formed by the open and close of the Iapetus and Rheic oceans, as shown in figure 3 (Hibbard, 2002). The Iapetus Ocean was formed by the separation of landmasses that had collided during the Grenville orogeny ca. 1.1-0.9 Ga, during the formation of Rodinia (Cawood et al., 2001; Murphy et al., 2010). Data from rocks from the Laurentian margin suggest that there was a multistage rift history in which separation from Baltica occurred between 620 and 570 Ma, and separation from West Gondwana occurred at 570 Ma (Cawood et al., 2001; Cawood and Pisarevsky, 2006; Murphy et al., 2010). The Dashwood terrane, located in the northern Appalachian mountain range, and the Precordillera in the southern Appalachians formed microcontinents in the Iapetus Ocean; according to Thomas and Astini (1999), separation between the Precordillera and Laurentia occurred along asymmetric, low angle rifts with the Precordillera on the lower plate (Murphy et al., 2010).

The Iapetus Ocean began to subduct along the Laurentian and Gondwanan margins in the Late Cambrian period, forming passive margins represented today by ophiolitic structures displaying supra-subduction zone characteristics (Stephens, 1970; Williams and Stephens, 1974; Williams, 1979; Jenner and Swinden, 1993; MacLachlan and Dunning, 1998; Bédard et al., 1998; Bédard and Stevenson, 1999; Murphy et al., 2010). Subduction along the east Laurentian margin brought about the Taconic orogeny, and along the west Gondwanan margin, subduction caused the Penobscot orogeny (see figure 4). The Iapetus was closed by the Carolinia, Ganderia, and Avalonia terranes colliding with Baltica in the early Silurian and into Laurentia in the Late Ordovician-Early Silurian (Chandler et al., 1987; Pickering et al., 1988; McKerrow and Scotese, 1990; Cawood et al., 1994; Keppie et al., 1996; Murphy et al., 1996; MacNiocaill et al., 1997; van Staal et al., 1998, 2009; Hibbard, 2000; Hibbard et al., 2002; Murphy and Nance, 1991, 2002; Stampfli and Borel, 2002; Keppie et al., 2003; van Staal, 2007; Murphy et al., 2010).

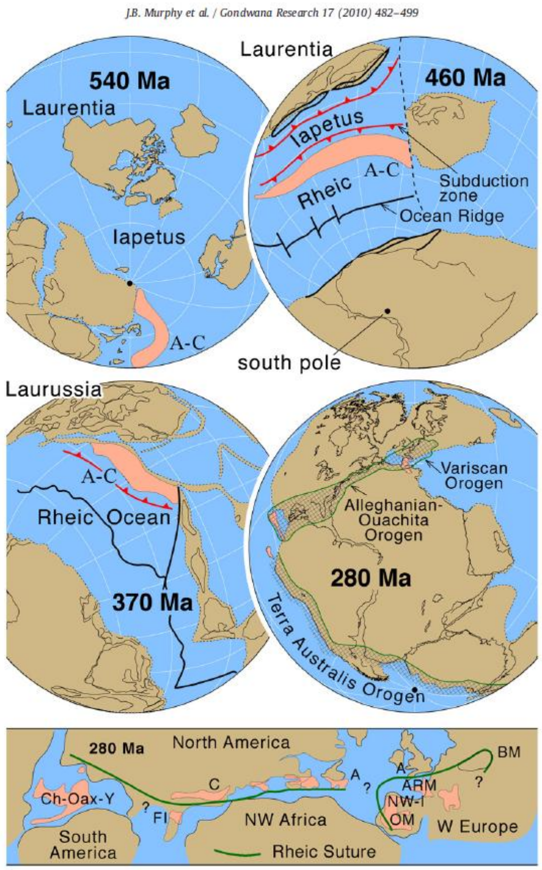


Fig. 3: Schematic of opening and closing of the Iapetus and Rheic Oceans. From Murphy et al., 2010

The Rheic Ocean was formed when peri-Gondwanan terranes Avalonia, Carolinia, and Ganderia, separated from the northern Gondwanan margin (Murphy et al., 2006; Nance and Linneman, 2008; Nance et al., 2010; Murphy et al., 2010). The peri-Gondwanan terranes acted as the boundary between the Iapetus and Rheic Oceans after their separation from Gondwana (Murphy et al., 2010). The opening of the Rheic Ocean also formed passive margins along Gondwana and can be observed from igneous bodies such as the Acatlán complex in Mexico and the Bohemian Massif in Eastern Europe, which could exhibit evidence of rifting and the development of the Rheic Ocean (Murphy et al., 2009, 2010).

Northwest trending subduction in the Rheic Ocean began underneath the Laurentian margin at 440 Ma and continued until 370 Ma, when continental collisions occurred (Martínez Catalán et al., 1997; Murphy et al., 1999, 2010). Subduction in the Rheic Ocean is accepted to be a response to the elimination of subduction zones in the Iapetus Ocean following the accretion of the peri-Gondwanan terranes to Laurentia (van Staal et al., 1998; Murphy et al., 2010). The closure of the Rheic ocean is assigned to either the Acadian (Murphy and Keppie, 2005; Murphy et al., 2010) or Neoacadian orogeny (van Staal, 2007; Murphy et al., 2010). Many aspects of the closure of the Rheic Ocean are still unclear; for example, there is uncertainty whether Siluro-Devonian tectonic activity is due to post-collisional separation and suturing of oceanic slabs within the Iapetus Ocean, or due to Andean-type subduction along the northern region of the Rheic Ocean (Murphy et al., 2010). Also, geologists do not fully understand the systematic northward migration of the onset of deformation across the entire Appalachian orogen from the Late Silurian in the southeast to the Early Devonian to the northwest (Keppie, 1993; Robinson et al., 1998; Murphy et al., 2010).

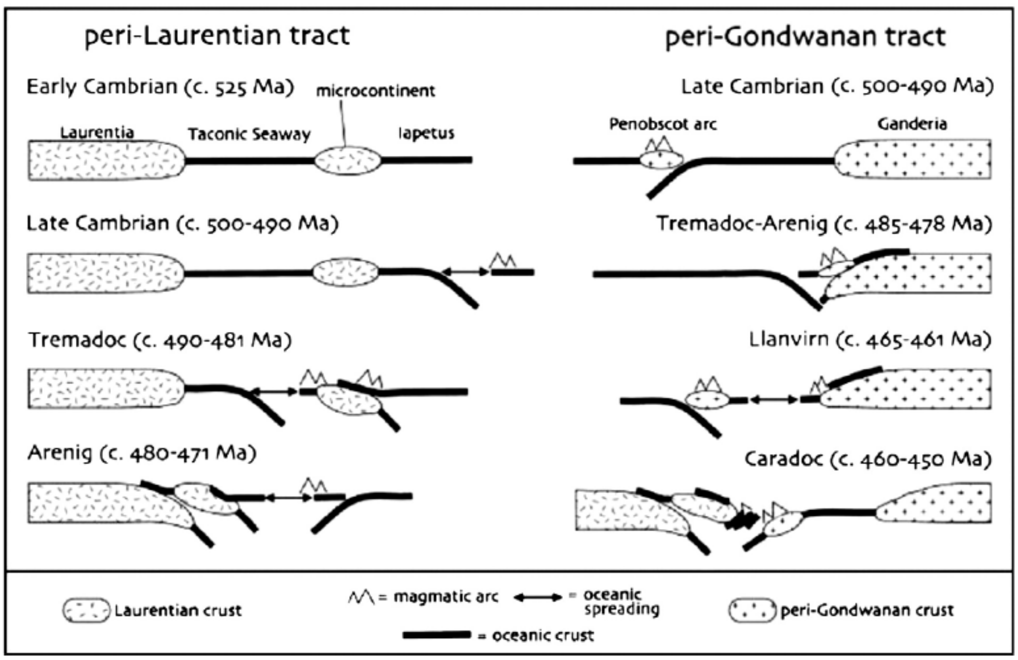


Fig. 4: Tectonic models of the Taconic and Penobscot orogenies (Hibbard et al., 2007; Murphy et al., 2010)

Significance of the Rheic Ocean

The Rheic Ocean opened in the Early Ordovician, as a result of the Avalonia, Ganderia, and Carolinia terranes rifting from Gondwana. Murphy et al. (2006) suggested that the rifting occurred along the line of a former Neoproterozoic suture (Nance et al., 2010). The Rheic Ocean reached a width of about 4000 km before beginning to close in the Early Devonian. Its closure was facilitated by northward subduction underneath the southern margin of Baltica in the

Variscan belt and by southward subduction underneath the northwestern margin of Gondwana in the Appalachian-Ouachita belt where Laurentia was the lower plate (Hatcher, 1989; Viele and Thomas, 1989; Nance et al., 2010). With the closure of the Rheic Ocean, ophiolites were emplaced onto the southern margin of eastern Avalonia in southern Great Britain, and in northwest and southern Iberia (Quesada et al., 1994; Nutman et al., 2001; Martínez et al., 2007; Ribeiro et al., 2010; Nance et al., 2010). The closure of the Rheic Ocean may have been accelerated by ridge subduction along its northern margin (Woodcock et al., 2007; Gutiérrez-Alonso et al., 2008; Nance et al., 2010). The Rheic Ocean may be one of the most significant ancient oceans because its closure caused Gondwana and Laurentia to collide and form the supercontinent Pangaea; it also formed the Variscan-Alleghanian-Ouachita belt, which is the largest collisional orogen of the Paleozoic (Nance et al., 2010).

Hypothesis

Before Wintsch's study in 2010, the terrane boundary between the Westminster and Potomac terranes was accepted to be the Pleasant Grove fault (see figure 1). Wintsch found that the white micas in the rocks of these two terranes differed in age by 60 Ma by using the closure temperatures of argon diffusion. Ages of the cleavages in rocks within the Westminster and Potomac terranes were determined using $^{40}Ar/^{39}Ar$ analysis of micas. In the western part of the Westminster terrane, cleavages are Early Silurian in age; and in the eastern part of the Westminster terrane and western Potomac terrane, cleavages are Late Devonian in age (Wintsch, 2010). From these cleavage domains, Wintsch proposed that the Parrs Ridge fault is the terrane boundary between the Potomac and Westminster terranes. I hypothesize that detrital zircon U/Pb age signatures and microstructural analyses will indicate that the Parrs Ridge fault is the boundary between the Westminster and Potomac terranes.

Tests of hypothesis

I tested the hypothesis by studying thin sections of the four formations sampled and observing any microstructural or compositional differences within them. Also, I analyzed detrital zircons for U/Pb ages by using laser ablation multicollector inductively coupled plasma mass spectrometry to observe differences in age signatures between the formations. Significant dissimilarity in age signatures of zircons in samples collected in the field could suggest a terrane boundary between these formations.

Methods

Samples were collected for detrital zircon analysis and thin section study. Samples collected for thin sections were oriented in the field; that is, strike and dip were measured and then recorded on the top surface of the rock taken from the outcrop. Rocks from the Prettyboy Schist were crushed to a grain size of ≤400 µm by using a steel mortar, pestle, and sieve. The magnetic grains were then separated out of the sample by using the Frantz magnetic barrier separator (see figure 5). The strength of the magnet increases with amperage, so this step was repeated four times at increasing levels of amperage to remove as many magnetic grains as possible.

Once the nonmagnetic grains are isolated, they are subjected to dense liquid separation, by using methylene iodide (MEI). MEI has a density of approximately 3.30 g/cm^3, so zircon, which has a density of approximately 4.65 g/cm^3, will sink to the bottom of the 100 mL beaker used to perform this separation. All grains with densities less than that of zircon will float on the surface of the MEI, and the zircon will be almost completely isolated. Ideally, by the end of this step, the zircon grains will be completely isolated. However, we often find that lighter minerals such as quartz or feldspar are attached to zircon grains, thus will sink to the bottom of the beaker as well. Therefore, the dense liquid separation must be repeated, sometimes more than once. The zircon grains are poured onto a piece of tape, and then mounted in an epoxy resin mixture, which is left to cure for approximately 24 hours. The mount is polished until two thirds of the smallest grains have been polished away. This is to ensure that the U/Pb ages that are recorded are of the cores, which will record the age of crystallization of the mineral. The age of crystallization of the zircons will help us in two ways. First, it will help us to determine the age signatures of the zircons in each formation. Second, the age of crystallization constrains the maximum depositional age of the zircons. If there is a significant difference in age signature or maximum depositional age between the zircons within any of these formations, it is one indication of the existence of a contact.

Fig. 5: Frantz magnetic barrier separator located in the Chemistry Building.

Uranium-lead isotopic analysis

Isotopic analysis was conducted on detrital zircons by using the Laser Ablation Multicollector Inductively Coupled Plasma Mass Spectrometer (LA-MC-ICP-MS) at the University of Arizona in Tucson. For this study, the $^{238}U/^{206}Pb$ decay series is used to determine the ages of the zircons. Briefly, ^{238}U decays to ^{234}Th via α-decay, which eventually decays to ^{206}Pb via α- and β-decay (see figure 7). An uncertainty of 2.0σ for $^{208}Pb/^{204}Pb$ is used for common lead occurring in the sample. Accurately measuring $^{208}Pb/^{204}Pb$ is important in order to differentiate between common lead and isotopic lead, and to obtain more accurate U-Th-Pb ages (Gehrels et al., 2006).

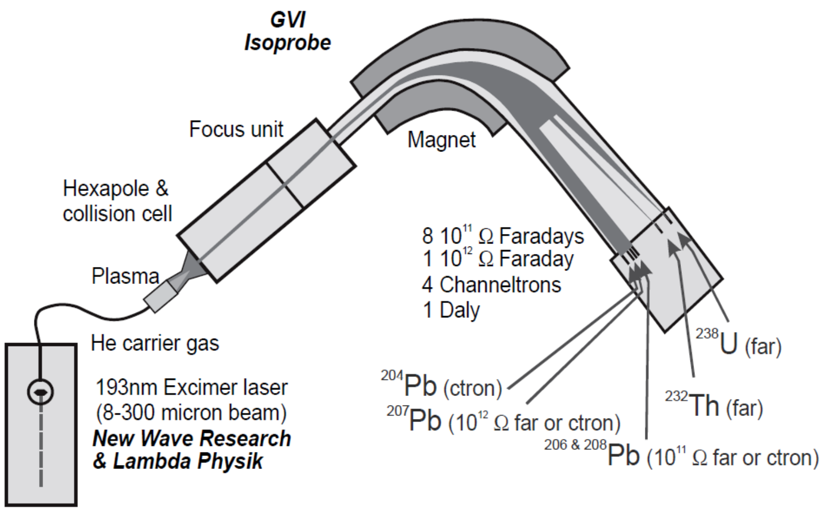


Fig. 6: LA-MC-ICP-MS at Arizona LaserChron Center in Tucson, AZ. Figure from Gehrels et al., 2006.

Detrital zircons are prepared in epoxy mounts with a diameter of 1" after they are separated from the rock. Two hundred zircon grains are shot with the laser, and the vaporized material travels via helium gas into the plasma in the MC-ICP-MS, and uranium, lead, and thorium ratios are measured simultaneously in different chambers (Gehrels et al., 2006).

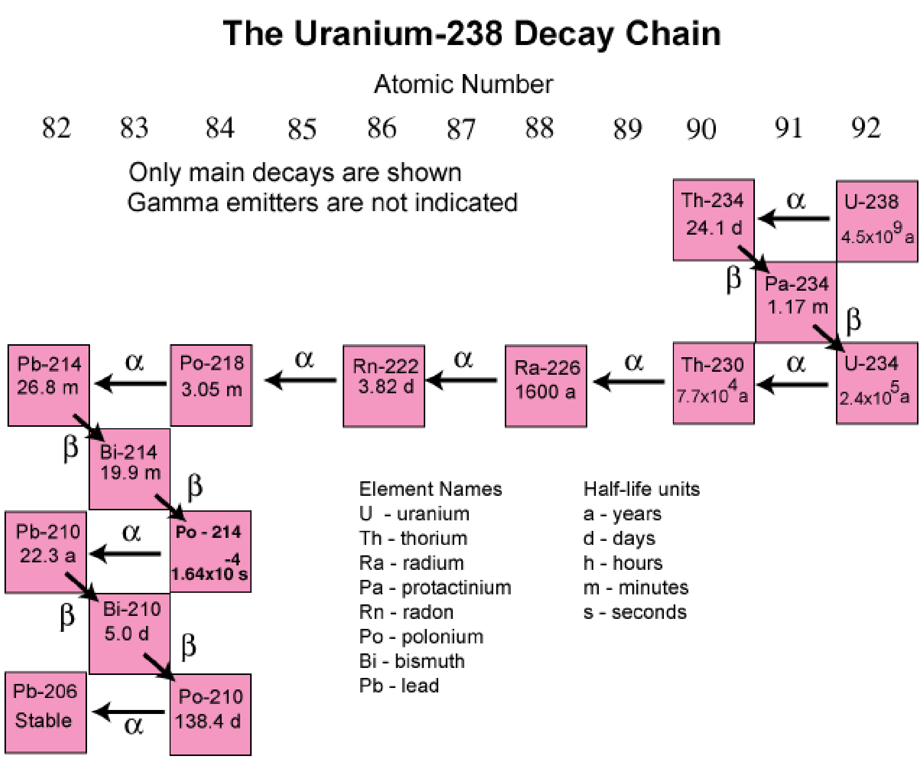


Fig. 7: ^{238}U decay series from usgs.gov.

Fractionation of Pb/U and Pb/Th occurs in the pit formed by the laser, which lowers the accuracy of the readings. To correct for fractionation, fragments from a Sri Lanka zircon, aged 564±4 Ma at 2σ, are analyzed once every 5 unknowns (Gehrels et al., 2006).

Formations sampled

Samples were taken from three formations within the Westminster terrane and one formation within the Potomac terrane, both located in the Piedmont province in northern Maryland. The Piedmont is a portion of what was once the continent Laurentia. The thrust faults that separate the Potomac terrane from the Westminster terrane were formed by the collision of the Carolina terrane with Laurentia from the southwest over a west dipping subduction zone (Wintsch et al., 2010).The Potomac terrane was thrust onto the Westminster terrane along the Pleasant Grove fault; Westminster terrane was also thrust westward along the Martic fault. This collision produced two cleavage domains in muscovites within the rocks of the Westminster terrane; Early Silurian cleavage formed ~430 Myo to the east, and Late Devonian cleavage formed ~370 Myo to the west (Wintsch et al., 2010).

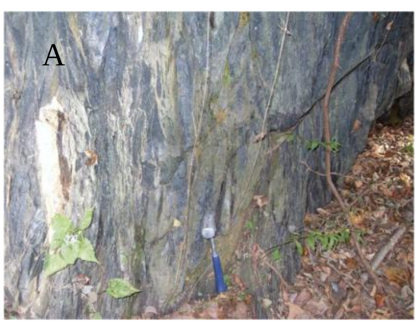
The Mather Gorge Formation is located in the western part of the Potomac terrane (see figure 1). It consists of metagraywackes and quartz-mica schists. A Barrovian sequence of chlorite to sillimanite grade rocks has been observed from Culpeper basin phyllites to the Bear Island domain migmatites (Kunk et al., 2004). Centimeter scale folding was observed in the field, and the foliations dip to the west. The Mather Gorge Formation is divided into three domains; from east to west they are: Blockhouse Point, Bear Island, and Stubble Falls (Kunk et al., 2004). Samples were taken from the Blockhouse Point domain.

Within the Westminster terrane, the formations studied from east to west are the Prettyboy Schist, Marburg Formation, and Sams Creek Formation. These units are stacked and folded into overlapping thrust sheets that cut and divide these formations (Wintsch et al., 2010). Foliations within all formations dip east to southeast. Rocks in the Westminster terrane have experienced multiple metamorphic events under greenschist-grade conditions (Kunk et al., 2004; Southworth et al., 2007). The Westminster terrane is the result of the rifting event that opened the Iapetus Ocean; it represents deepwater, post-rift deposits with no direct stratigraphic ties with Laurentia (Kunk et al., 2004).

The Prettyboy Schist comprises quartz-muscovite-chlorite-albite schist and muscovite-quartz-albite schist containing white, euhedral albite porphyroblasts and oxidized cubes of pyrite (Southworth et al., 2007). Rocks in the Prettyboy formation are of a higher metamorphic grade than those of the Marburg formation, therefore the contact between the two formations is an isograd (Fisher, 1978; Southworth, 2007). The orientation of the main tectonic foliation of the first station, located on Lisbon Center Drive in Woodbine, Maryland, is 215°, 72° SE. However, this station was not sampled because there were too many quartz veins and the formation was not well exposed. The second station, on Woodbine Morgan Road, was coarser grained, had better exposure and a much smaller occurrence of quartz veins, so samples for detrital zircon dating were taken. The orientation of tectonic foliation at this location is 22°, 77° SE.

Fig. 8: Prettyboy Schist on Woodbine Morgan Road.

The Marburg Formation was sampled east and west of the Parrs Ridge Fault, the boundary between the east and west Piedmont proposed by Wintsch et al. (2010). The formation consists of phyllitic metasiltstone and small bodies of metagraywacke, metabasalt, and quartzite (Southworth et al., 2007). Quartz veins <1 cm were observed throughout the Marburg Formation. The orientation of foliation of the east Marburg Formation is 21°, 84° SE. The portion of the west Marburg Formation located on Frederick Road in Clarksburg, Maryland is micaceous and fine grained with some sandier patches. The foliation also dips to the southeast, but is slightly shallower, with an orientation of 35°, 68° SE. The portion of the west Marburg Formation on Barnes Road in Damascus, Maryland is coarser grained and folded. The orientation of foliation is 27°, 81° SE.



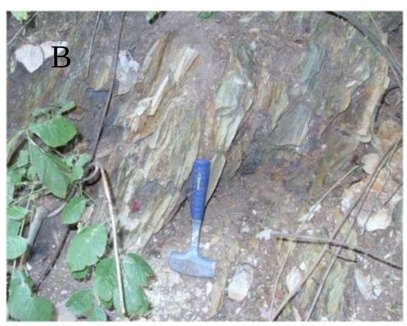


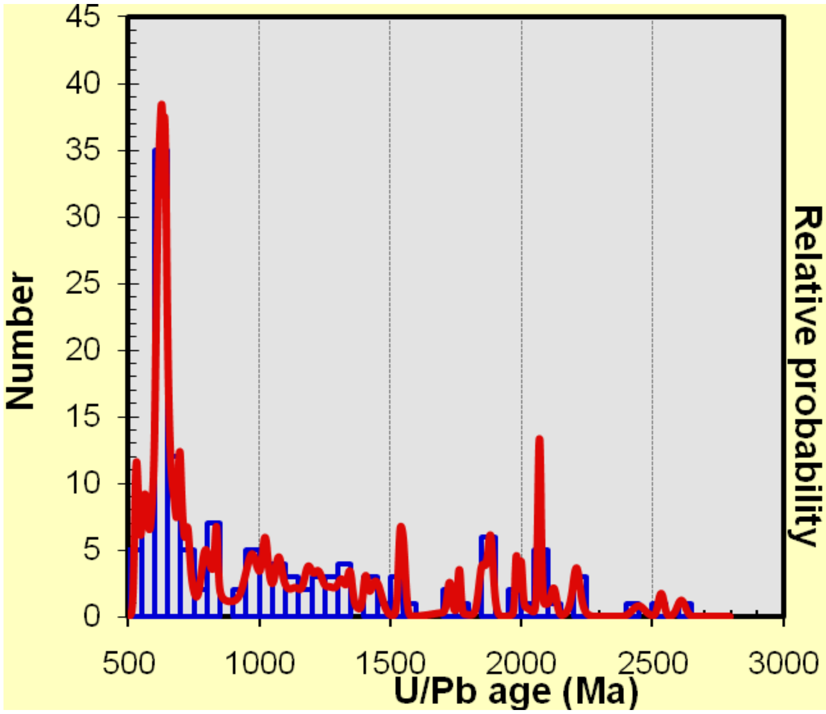
Fig. 9: A) east Marburg Fm.; B) west Marburg Fm.; C) folding in west Marburg Fm. on Barnes Road.

The Sams Creek Formation comprises coarse grained quartz interbedded with phyllite and an elongate orange-brown mineral to be identified in thin section (Southworth et al., 2007). The rocks that make up Sams Creek Formation are felsic schist, metasiltstone, quartzite, and eight other rock types as observed by Southworth et al. (2007). 1-5 cm thick quartz veins crosscut foliation and the outcrop is poorly exposed on Arlington Mill Road in Libertytown, Maryland. The orientation of foliation is 353°, 43° E.

Fig. 10: Sams Creek Fm. on Arlington Mill Road.

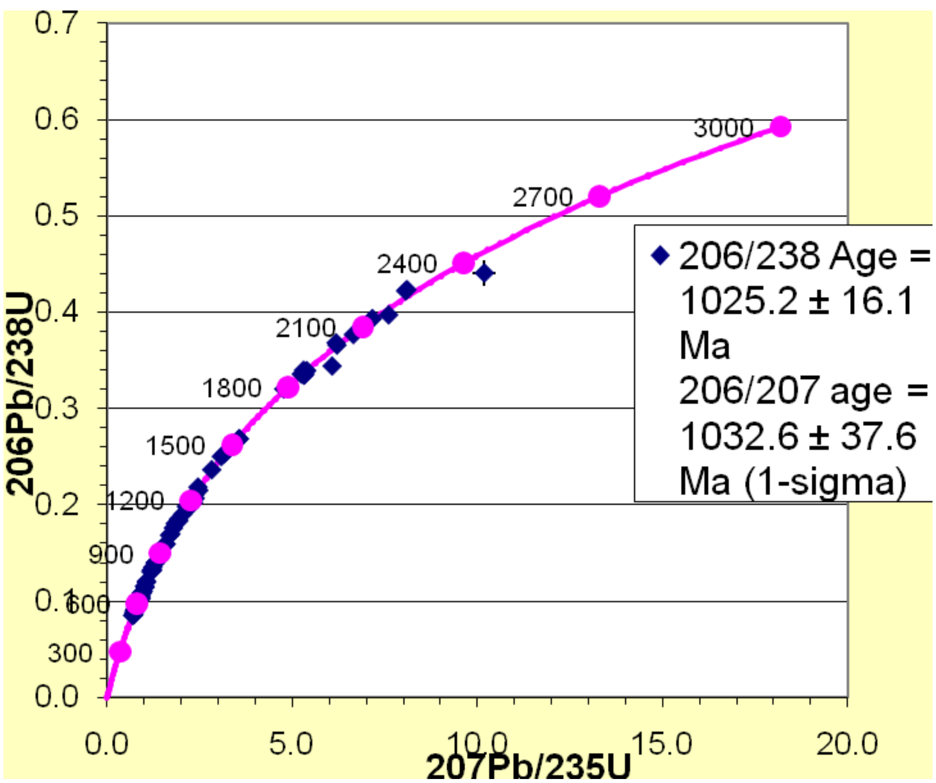
Results

After reviewing the zircon age populations of the formations sampled for this study as well as for previous work, there appears to be a similar age signature for “Western-type” formations and “Eastern-type” formations. Eastern-type formations, including the Mather Gorge, Prettyboy Schist, and Marburg Formations (figures 11a, b, c, and d), exhibit high U/Pb age peaks between 900 and 1600 Ma, with smaller peaks at 500-600 Ma, and at ~2000-3000 Ma. Western-type formations, including the Sams Creek Formation (figures 11e), as well as the Urbana and Ijamsville Formations from previous studies, exhibit U/Pb age peaks between 800 and 1300 Ma, with no zircons with older or younger ages.

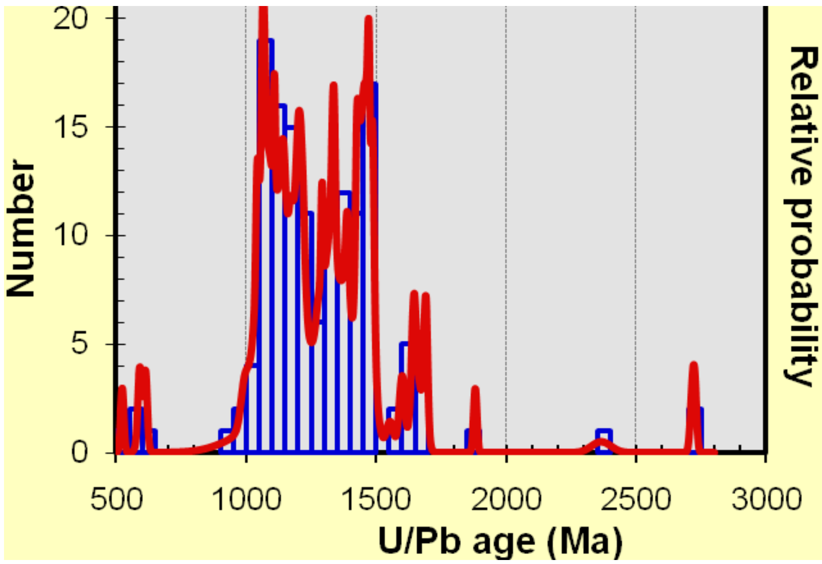


Number
Relative probability
U/Pb age (Ma)

a.

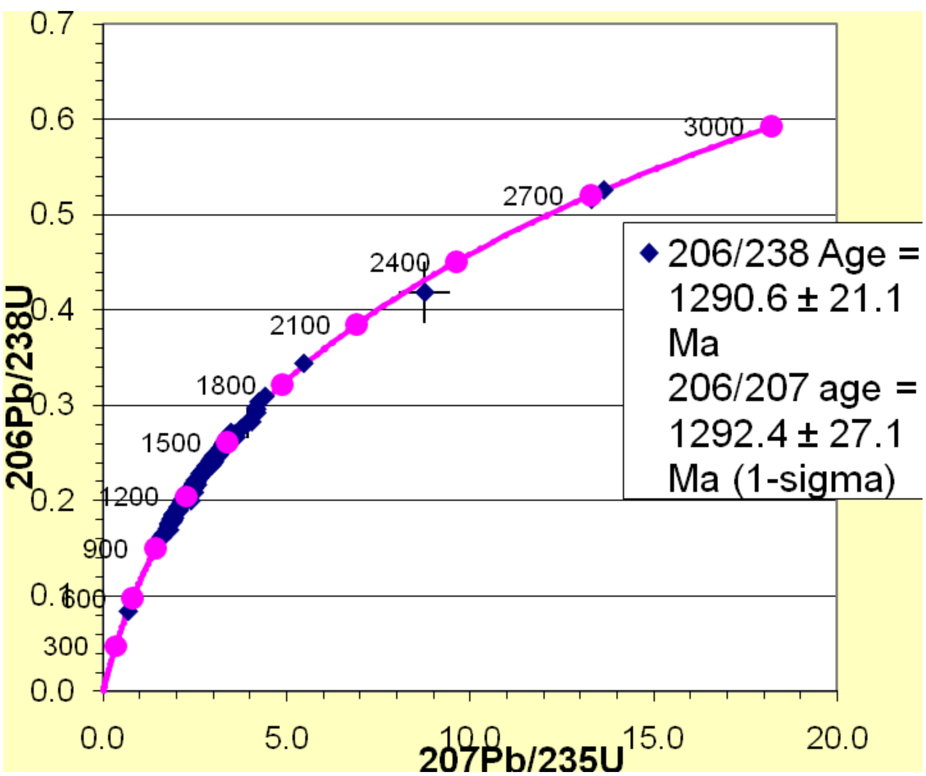


206Pb/238U
207Pb/235U
206/238 Age = 1025.2 ± 16.1 Ma
206/207 age = 1032.6 ± 37.6 Ma (1-sigma)

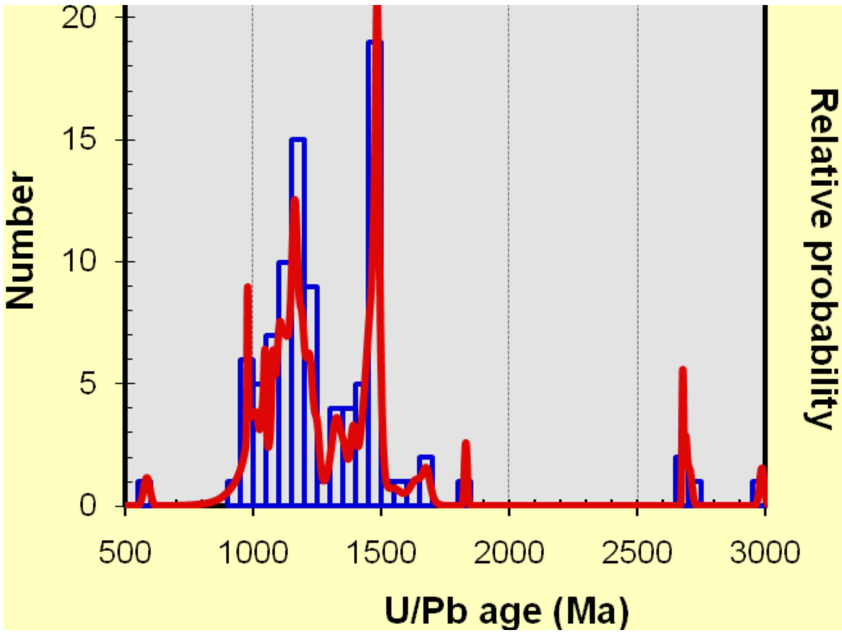


Number
Relative probability
U/Pb age (Ma)

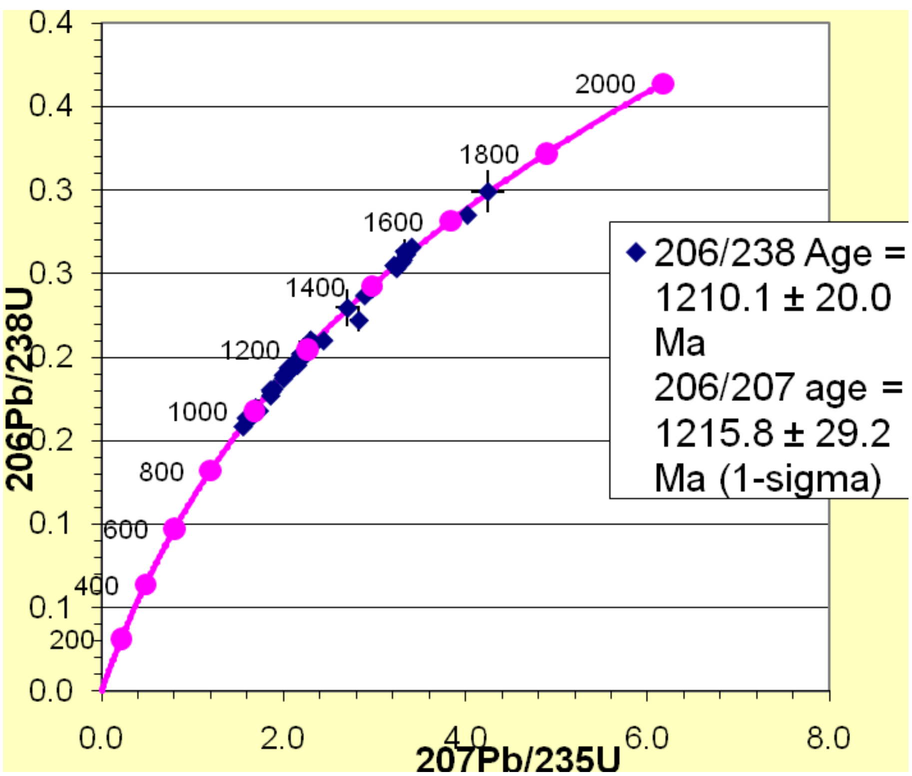
b.

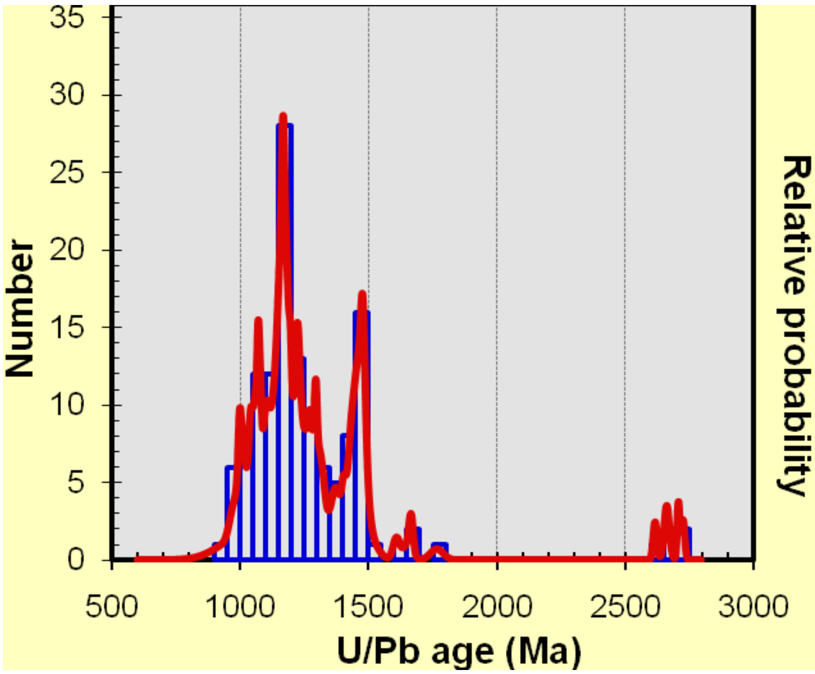


206Pb/238U
207Pb/235U
206/238 Age = 1290.6 ± 21.1 Ma
206/207 age = 1292.4 ± 27.1 Ma (1-sigma)

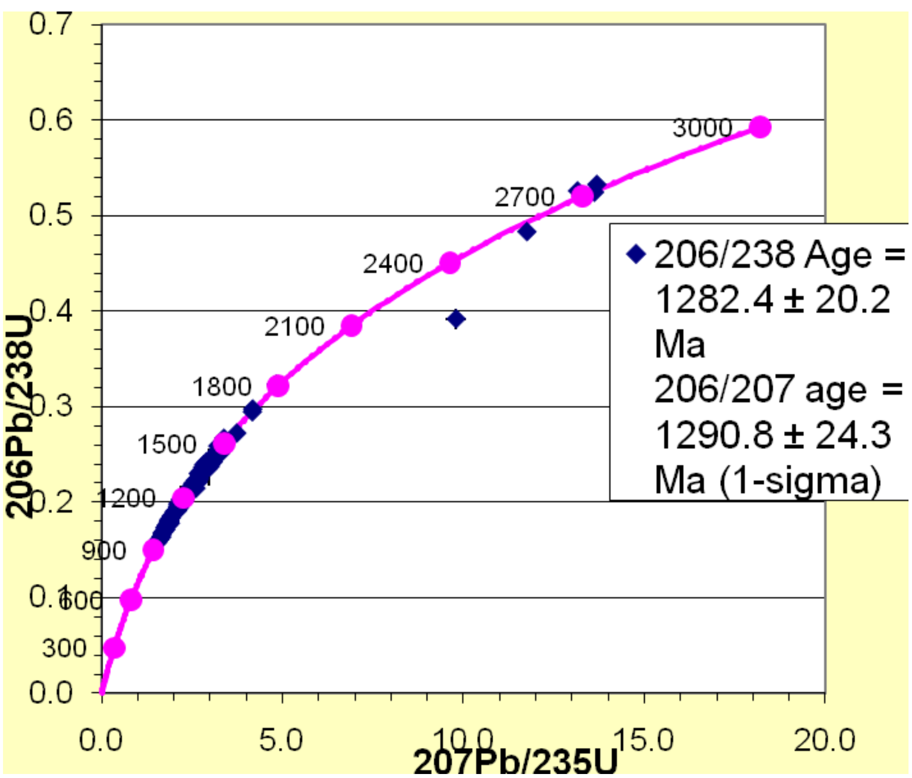

Number
Relative probability
U/Pb age (Ma)
0
5
10
15
20
500
1000
1500
2000
2500
3000

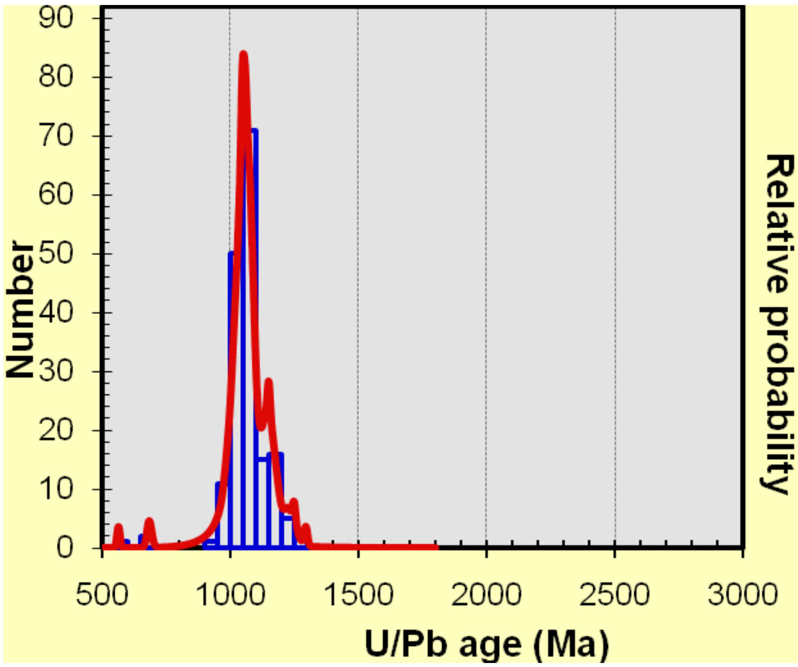
c.


206Pb/238U
207Pb/235U
◆ 206/238 Age = 1210.1 ± 20.0 Ma
206/207 age = 1215.8 ± 29.2 Ma (1-sigma)
200
400
600
800
1000
1200
1400
1600
1800
2000
0.0
2.0
4.0
6.0
8.0


Number
Relative probability
U/Pb age (Ma)
35
30
25
20
15
10
5
0
500
1000
1500
2000
2500
3000

d.


206Pb/238U
207Pb/235U
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
5.0
10.0
15.0
20.0
300
600
900
1200
1500
1800
2100
2400
2700
3000
206/238 Age = 1282.4 ± 20.2 Ma
206/207 age = 1290.8 ± 24.3 Ma (1-sigma)



e.

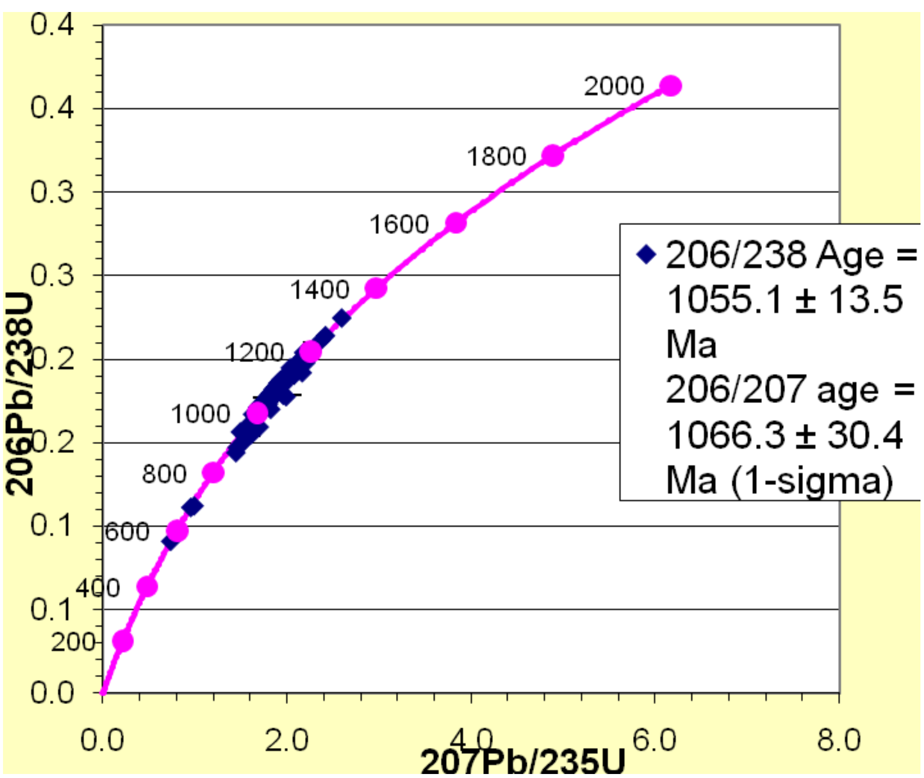
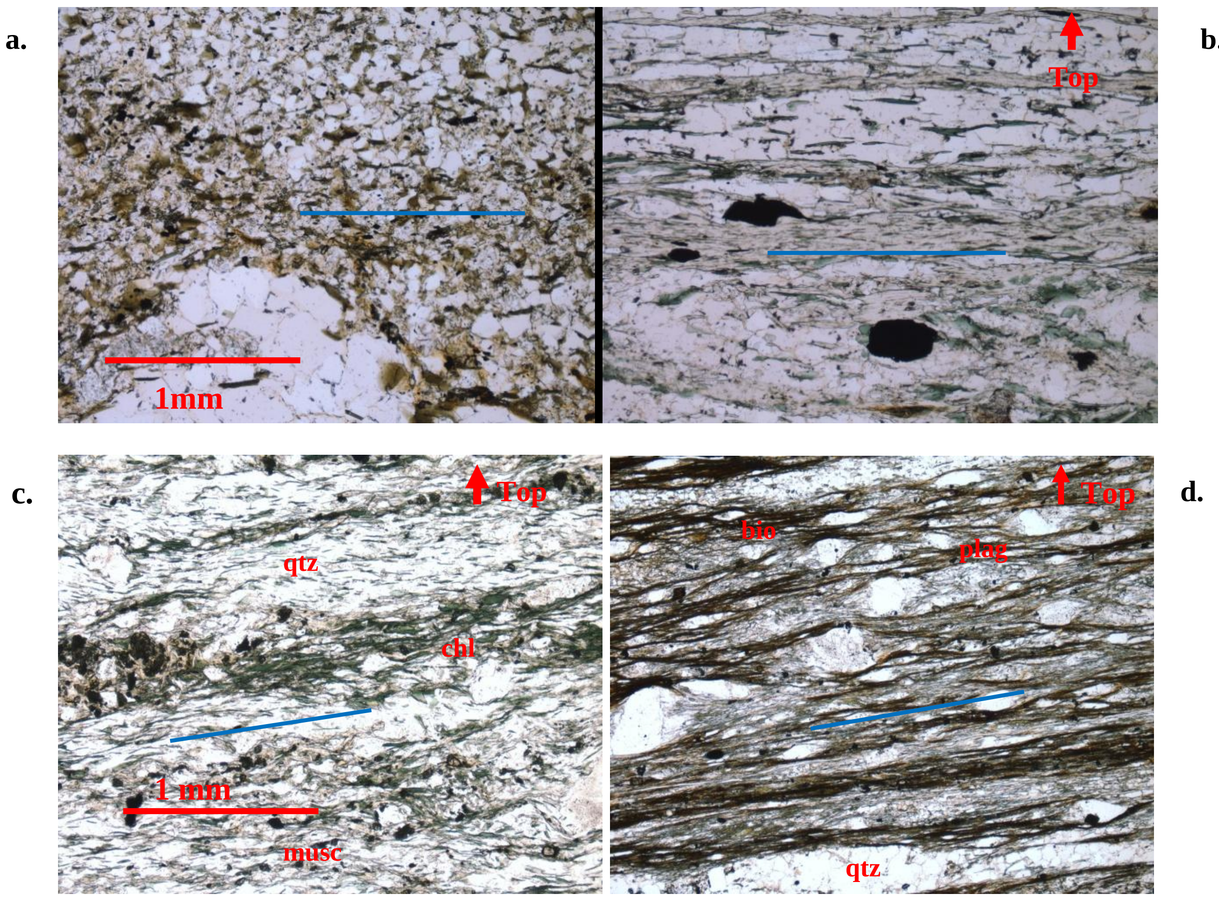
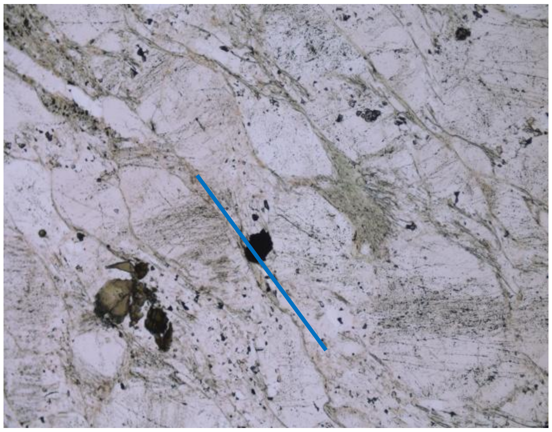


Figure 11: Relative probability and Concordia plots of the formations sampled in this study. In order from east to west: a) Mather Gorge Fm., b) Prettyboy Schist, c) East Marburg Fm., d) West Marburg Fm., e) Sams Creek Fm.

Thin sections of the formations were studied to determine mineralogical or structural differences which may indicate a terrane boundary within the Marburg Formation. All samples exhibit approximately east-west foliation, except for Sams Creek Formation (fig. 12e), whose foliation is oriented northwest-southeast. Eastern-type formations are similar in mineralogy; all comprise quartz, muscovite, biotite, plagioclase, and an opaque phase, which is most likely pyrite. The Prettyboy Schist and Marburg Formation also contain chlorite. Sams Creek Formation, a western-type formation, consists mostly of quartz and plagioclase, but contains ~10% muscovite and <5% of the opaque phase.





e.

Figure 12: Photomicrographs of formations sampled: a) Mather Gorge Fm., b) Prettyboy Schist, c) E. Marburg Fm., d) W. Marburg Fm., e) Sams Creek Fm. All taken at 5x (2.7mm field of view), in plain polarized light. Blue lines indicate approximate orientation of foliation.

Discussion

Observation of thin sections of the formations indicates that there is no mineralogical or structural boundary within the Marburg Formation. Eastern-type samples exhibit similar mineralogy, in that they contain a considerable amount of pyrite and micas. The western-type sample has a relatively small amount of micas and almost no pyrite. When analyzing the U/Pb data, it was observed that western-type samples had a different detrital zircon age signature that the eastern-type samples. While eastern-type rocks had a wider range of zircon ages, western-type rocks only contain zircons of one age, with very few outliers. These observations may indicate that the Westminster-Potomac terrane boundary is located along the Hyattstown Thrust Fault, which separates the Sams Creek Formation from the Marburg Formation. This finding disproves the hypothesis that the Westminster-Potomac terrane boundary is the Parrs Ridge fault, located within the Marburg Formation. Although not impossible, it seems unlikely that a terrane boundary would exist within a single formation.

The previously stated observations lead to the following implications about the Westminster and Potomac terranes. There is no evidence suggesting that the Westminster terrane is not located on the supercontinent Laurentia in the Neoproterozoic. In what I have classified as “western-type” formations, including the Sams Creek Formation, as well as the Urbana and Ijamsville Formations from previous studies, there is only one age population between the U/Pb ages of ~900-1300 Ma in these rocks. This suggests that the formations within the Westminster terrane had one source, similar to that of the Blue Ridge Anticlinorium, which contains gneissic rocks with zircons that exhibit U/Pb ages ranging from approximately 570 Ma-2000 Ma (Tollo, 1996; Fullagar, 2002).

There are three possible implications on the position of the Potomac terrane. The first and most conservative explanation is that the Potomac terrane has not been displaced, and was also located on Laurentia. The problem with this explanation is that the Potomac and Westminster terranes do not share sources, seen in the transition from one zircon population to many between the two terranes, and differences in mineralogy. If this were true, there must have been some tectonic barrier, such as a basin or mountain range, to separate the rocks of these formations and cause such a difference in the behavior of the zircon populations. The tectonic barrier could be a remnant of the failed rift on Laurentia at approximately 735 Ma (Hatcher, 2007).

The second implication is that the Potomac terrane was located where Newfoundland in eastern Canada is located today. U/Pb ages expected of rocks from this area are Grenvillian, ranging from approximately 1000-1300 Ma; there are also rocks associated with rifting sequences which opened the Iapetus Ocean which date ~550-760 Ma (Cawood, 2001). Formations within the Potomac terrane do exhibit these ages, but do not contain Archean aged zircons, which would be expected, since Grenvillian rocks have an Archean and Paleoproterozoic provenance (Gower and Krogh, 2002).

The last explanation is that the Potomac terrane was located on the Western portion of Gondwana, and was transferred to the Laurentian margin, colliding with the Westminster terrane. However, the age of the rocks in northwestern Gondwana are not well known, and most agree that the Potomac terrane was thrust onto the Laurentian margin along with the Westminster terrane (Hatcher, 2007; Tollo, 2004).

Conclusion

The collision of Carolinia into the southeast region of Laurentia, as well as the collision of Baltica, Avalonia, and Ganderia to the north caused thrust faulting that eventually formed the Piedmont Province, a result of the Taconic and Penobscot orogenies. The Westminster-Potomac terrane boundary represents contacts between Laurentia (to the west) and the peri-Gondwanan terranes that collided with the continent (to the east). If the Westminster-Potomac terrane boundary is located within the Marburg Formation, the width of the Potomac terrane would be extended westward, contrary to studies done before the early 2000s.

Acknowledgements

I would like to thank Dr. Aaron Martin and Dr. Phil Piccoli for advising my research; Rebecca Ohly and Irene Kadel-Harder for helping me with the analyses in Tucson during their Spring Break; Dr. Phil Candela for helping me to improve my scientific writing skills; and Dr. George Gehrels, Nicky Giesler, and Dr. Clayton Loehn at the University of Arizona for their assistance with the mass spectrometer.

Appendix 1: U/Pb analyses from Aleinikoff et al., 2002

TABLE 2

TIMS U-Pb isotopic data for zircon from granitic and tonalitic rocks, Piedmont of Maryland-D.C.-Virginia

Size fraction[1]	Weight (mg)	Concentrations (ppm) U	Concentrations (ppm) Pb	measured $^{206}Pb/^{204}Pb$	Pb composition[2] $^{206}Pb/^{204}Pb$	Pb composition[2] $^{206}Pb/^{207}Pb$	Pb composition[2] $^{206}Pb/^{208}Pb$	Ratios (percent error)[3] $^{206}Pb/^{238}U$	Ratios (percent error)[3] $^{207}Pb/^{235}U$	Ratios (percent error)[3] $^{207}Pb/^{206}Pb$	Ages (Ma)[4] $^{206}Pb/^{238}U$	Ages (Ma)[4] $^{207}Pb/^{235}U$	Ages (Ma)[4] $^{207}Pb/^{206}Pb$
1. SA-F-2-11 Guilford Granite [39°12'40"N, 76°51'14"W] **[no TIMS data; SHRIMP data only]**													
2. Oc-1-96 monzodiorite, Dale City Quartz Monzonite [38°37'47"N, 77°18'26"W]													
(+150)1	.107	226.3	21.08	9190	48018	17.707	2.4675	.0739(.19)	.5726(.21)	.0562(.10)	460	460	459
(+150)3	.036	360.2	33.30	2933.2	5674.7	17.027	2.4748	.0731(.25)	.5662(.27)	.0562(.10)	455	456	459
(+150)4	.049	343.5	32.81	1135.6	11323.2	14.901	2.3073	.0728(.22)	.5634(.31)	.0561(.21)	453	454	456
(+150)5	.041	444.0	45.08	404.9	423.69	11.042	2.2147	.0731(.53)	.5656(.56)	.0562(.18)	455	455	459
(+100)1	.120	381.8	36.30	675.42	708.69	13.038	2.5036	.0728(.30)	.5633(.32)	.0561(.11)	453	454	457
(+100)4	.090	268.6	25.87	1042.5	1207.5	14.690	2.2251	.0725(.22)	.5600(.26)	.0560(.15)	451	451	452
3. K-E-1-9 tonalite, Norbeck Intrusive Suite [39°03'58"N, 77°06'54"W]													
(-100+150)1	.036	125.8	10.43	552.3	1396.7	14.981	4.7605	.0744(.59)	.5780(.68)	.0563(.33)	463	463	465
(-100+150)2	.030	165.3	13.62	1072.5	2403.4	16.010	4.6470	.0743(.45)	.5780(.50)	.0564(.20)	462	463	468
(-100+150)4	.028	109.8	10.69	206.32	290.59	9.3836	3.1367	.0743(.91)	.5777(1.1)	.0564(.52)	462	463	469
(-100+150)5	.030	192.2	20.55	1859.0	4692.9	14.611	7.6248	.1032(.26)	.9304(.30)	.0654(.14)	633	668	786
(-100+150)	.054	217.0	21.12	497.27	789.86	12.773	4.2909	.0842(.46)	.6957(.52)	.0599(.23)	521	536	601
(-100+150)Eq	.082	128.4	10.97	1054.6	27515	16.968	5.4895	.0799(.51)	.6436(.57)	.0584(.25)	496	505	545
(-100+150)Eq	.043	147.4	16.557	865.0	1759.3	11.210	5.4345	.1014(.36)	1.135(.43)	.0812(.23)	623	770	1226
4. WW9000 Kensington Tonalite [38°56'26"N, 77°03'21"W]													
(-100+150)EC1	.020	989.9	70.89	1323.2	1547.2	15.169	11.252	.0712(.27)	.5551(.29)	.0565(.09)	445	448	472
(-100+150)EC2	.020	1190	86.25	1249.7	1409.3	14.965	10.778	.0717(.30)	.5583(.31)	.0565(.08)	446	450	471
(-100+150)EC3	.016	1577	112.1	1131.5	1255.0	14.667	10.264	.0698(.20)	.5448(.35)	.0566(.28)	435	442	475
(-100+150)EC4	.025	1042	78.66	994.1	1080.5	14.346	9.6094	.0734(.20)	.5693(.27)	.0562(.18)	457	458	461
(-100+150)EC5	.032	1032	74.66	1397.9	1539.215160		11.496	.0721(.21)	.5614(.23)	.0565(.09)	449	452	472
5. P82-69 granite, Goldvein pluton [38°30'50"N, 77°37'29"W]													
(-150+250)1	.026	244.3	24.36	1019.1	2194.4	13.831	5.2596	.09102(.52)	.8250(.56)	.0657(.18)	562	611	798
(-150+250)2	.030	230.3	22.76	1022.0	2041.5	14.025	5.1743	.0900(.50)	.7978(.62)	.0643(.35)	556	596	751
(-150+250)3	.014	290.0	23.52	1008.0	2019.5	15.800	5.3489	.0747(.49)	.5775(.62)	.0561(.35)	464	462	455
(-150+250)4	.005	306.5	26.17	394.00	6514.8	16.751	5.1431	.0789(.70)	.6250(1.1)	.0575(.75)	489	493	509

6. P82-71 tonalite, Lake Jackson pluton [38°39'29"N, 77°27'28"W]													
(-150)1	.023	462.7	45.02	305.66	339.14	9.8567	4.2890	.0800(1.0)	.6466(1.9)	.0586(1.5)	496	506	552
(-150)3	.009	901.9	70.67	2443.0	6519.5	17.007	6.5085	.0749(.28)	.5842(.32)	.0566(.14)	466	467	475
(-150)4	.011	374.2	33.64	1258.8	2762.2	14.338	7.0091	.0856(.43)	.7616(.47)	.0645(.18)	530	575	759
(-150)5	.011	471.1	36.55	842.21	2526.0	16.049	6.4755	.0736(.82)	.5734(.86)	.0565(.25)	458	460	474
7. AN1000 tonalite, Falls Church Intrusive Suite [38°51'37"N, 77°09'56"W]													
(-150+200)EC1	.033	228.4	21.14	1702.7	8781.6	16.106	5.6358	.0866(.61)	.7215(.68)	.0604(.29)	535	552	619
(-150+200)EC2	.028	232.7	33.28	93.100	96.463	4.8087	1.7820	.0756(.53)	.5960(.76)	.0570(.51)	471	475	491
(-150+200)EC3	.050	248.6	20.97	4165.0	12240	17.024	5.8655	.0796(.28)	.6319(.30)	.0576(.10)	494	497	513
(-150+200)EC4	.037	234.8	18.89	2046.7	60684	17.642	5.6023	.0757(.49)	.5889(.54)	.0564(.22)	470	470	470
8. Oc-3-98 Occoquan Granite (main batholith) [38°41'41"N, 77°16'04"W] **[no TIMS data; SHRIMP data only]**													
9. IH1000 Occoquan Granite of Bull Run Marina pluton [38°44'22"N, 77°22'05"W]													
(+150)1	.062	318.0	30.77	1450.2	1934.0	13.507	6.4503	.0906(.32)	.8321(.34)	.0666(.09)	559	615	825
(+150)2	.022	269.6	21.88	1584.0	3387.4	16.378	6.4339	.0771(.36)	.6036(.38)	.0568(.12)	479	480	482
(+150)3	.027	299.3	25.46	1331.8	3483.7	15.824	7.2292	.0818(.46)	.6661(.48)	.0590(.13)	507	518	568
(+150)4	.039	287.4	26.30	2503.7	11520	15.829	7.4893	.0888(.32)	.7578(.34)	.0619(.10)	548	572	671
9. P82-74 Occoquan Granite of Bull Run Marina pluton [38°42'53"N, 77°23'28"W]													
(-150+200)1	.011	371.2	32.56	335.9	844.29	13.371	4.958	.0781(.92)	.6195(1.1)	.0576(.58)	484	489	513
(-150+200)2	.056	354.0	30.51	5666.0	12563	15.867	6.3671	.0820(.19)	.6993(.20)	.0619(.06)	508	538	670
(-150+200)3	.035	411.3	32.82	3889.0	8676.1	16.449	6.9440	.0768(.20)	.6261(.23)	.0591(.11)	477	494	572
10. WW5000 monzogranite, Dalecarlia Intrusive Suite [38°57'03"N, 77°06'03"W]													
(-150+200)EC1	.020	443.0	35.29	3341.0	12038	16.113	14.040	.0816(.33)	.6849(.36)	.0609(.12)	506	530	634
(-150+200)EC2	.012	486.2	34.84	1015.0	1597.2	15.202	11.269	.0713(.63)	.5572(.84)	.0567(.55)	444	450	478
(-150+200)EC3	.014	375.7	32.57	2408.0	11397	15.820	19.273	.0903(.35)	.7710(.38)	.0619(.13)	557	580	672
11. WW6000 tonalite, Georgetown Intrusive Suite [38°54'20"N, 77°04'47"W]													
(-100+150)EC	.030	284.7	25.05	395.59	433.18	11.111	4.6081	.0748(.32)	.5815(.38)	.0564(.18)	465	465	466
(-100+150)EC2	.012	136.2	10.965	495.0	1183.4	14.556	6.1733	.0749(.63)	.5820(1.2)	.0564(.95)	465	466	468
(-100+150)EC3	.013	157.1	12.632	513.4	993.78	14.199	6.3979	.0748(.54)	.5748(.66)	.0558(.37)	464	461	443
(-100+150)EC4	.015	163.12	13.526	533.6	918.58	13.848	5.2264	.0747(.82)	.5804(.89)	.0563(.31)	464	465	466

[Constants: $^{235}\lambda = 9.8485$ E-10/yr; $^{238}\lambda = 1.55125$ E-10/yr; $^{238}U/^{235}U = 137.88$ (Steiger and Jäger, 1977)]

1 All zircons hand-picked and abraded (Aleinikoff and others, 1990, modified from Krogh, 1982). Abbreviations: Eq (equant), El (elongate), C (clear).

2 Blank (8-25 pg, ±50%) and fractionation (0.14 ± .03%) corrected. Assumed blank composition is 204:206:207:208: = 1:18.8:15.65:38.65.

3 2σ uncertainties.

4 Common lead corrections from Stacey and Kramers (1975) model.

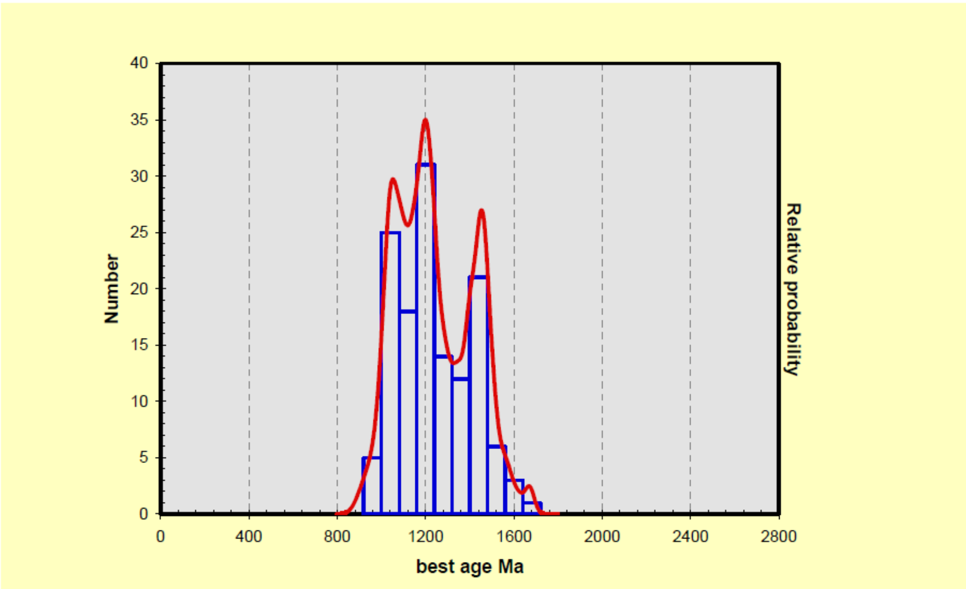
Summary of conventional and SHRIMP U-Pb ages of granitic and tonalitic rocks, Piedmont of Maryland-D.C.-Virginia

sample number	name	zircon morphology[1]	previous age (Ma)[2]	ID-TIMS age (Ma)	SHRIMP age (Ma)[3]
1. SA-F-2-11	Guilford Granite	el, eu, cl, fi	370a	nd	362 ± 3
2. Oc-1-96	monzodiorite, Dale City Quartz Monzonite	p, eu, cl, fi	~560e	459 ± 4	nd
3. K-E-1-9	tonalite, Norbeck Intrusive Suite	el, eu, cl, fi	570 ± 50f; 554c	460 ± 3	449 ± 7
4. WW9000	Kensington Tonalite	p, eu, cr, mi	550b; 528c; 546d	468 ± 8 (or 461 ± 4)	463 ± 8
5. P82-69	granite, Goldvein pluton	p, eu, cl, fi	487-524h	455 ± 8	456 ± 9
6. P82-71	tonalite, Lake Jackson pluton	el, eu-su, cr, fi	472-487h	476 ± 3	461 ± 7
7. AN1000	tonalite, Falls Church Intrusive Suite	el, eu, cl, mi		470 ± 5	469 ± 6
8. Oc-3-98	Occoquan Granite (main batholith)	el, eu, cl mi, cr	558e; 494 ± 14g	nd	472 ± 4
9. IH1000, P82-74	Occoquan Granite of Bull Run Marina pluton	el, eu, cl, fi, cr		482 ± 3	483 ± 9
10. WW5000	monzogranite, Dalecarlia Intrusive Suite	p, eu, cl, fi, eq, cr		478 ± 12 discordant	478 ± 6
11. WW6000	tonalite, Georgetown Intrusive Suite	el, eu, cl, fi		466 ± 3	472 ± 4

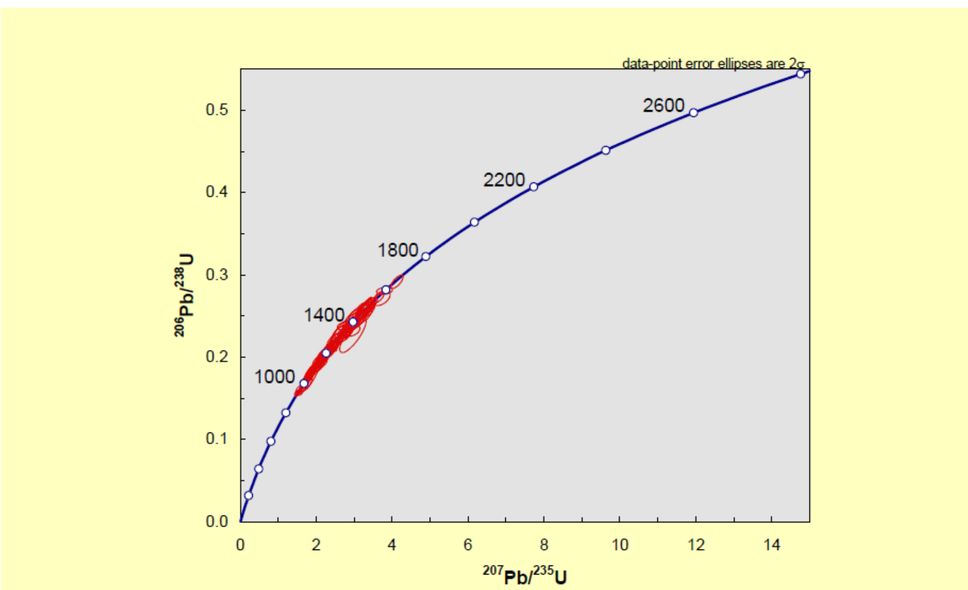
1 Abbreviations: el (elongate), eu (euhedral), cl (clear), fi (few inclusions), p (prismatic), cr (cracks), mi (many inclusions), eq (equant), su (subhedral). Prismatic (length-to-width ratio 2-4); elongate (length-to-width ratio >6); nd (not determined).
2 References: a Tilton and others (1959), b Davis and others (1958), c Wetherill and others (1966), d Sinha and others (1989), e Seiders and others (1975), f Davis and others (1960), g Mose and Nagel, (1982), h T. Stern, unpublished data-Pb/Pb ages.
3 weighted average of $^{206}Pb/^{238}U$ ages.

Appendix 2: Relative probability and concordia plots from Kingman, 2009

Blockhouse Point domain of the Mather Gorge formation

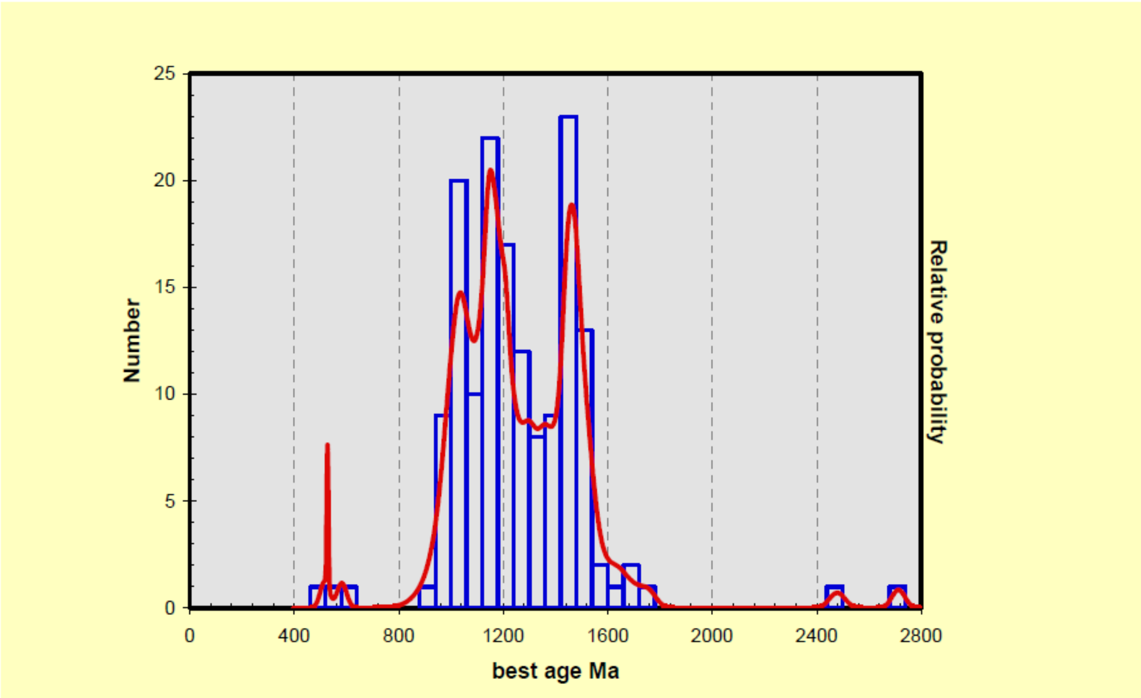


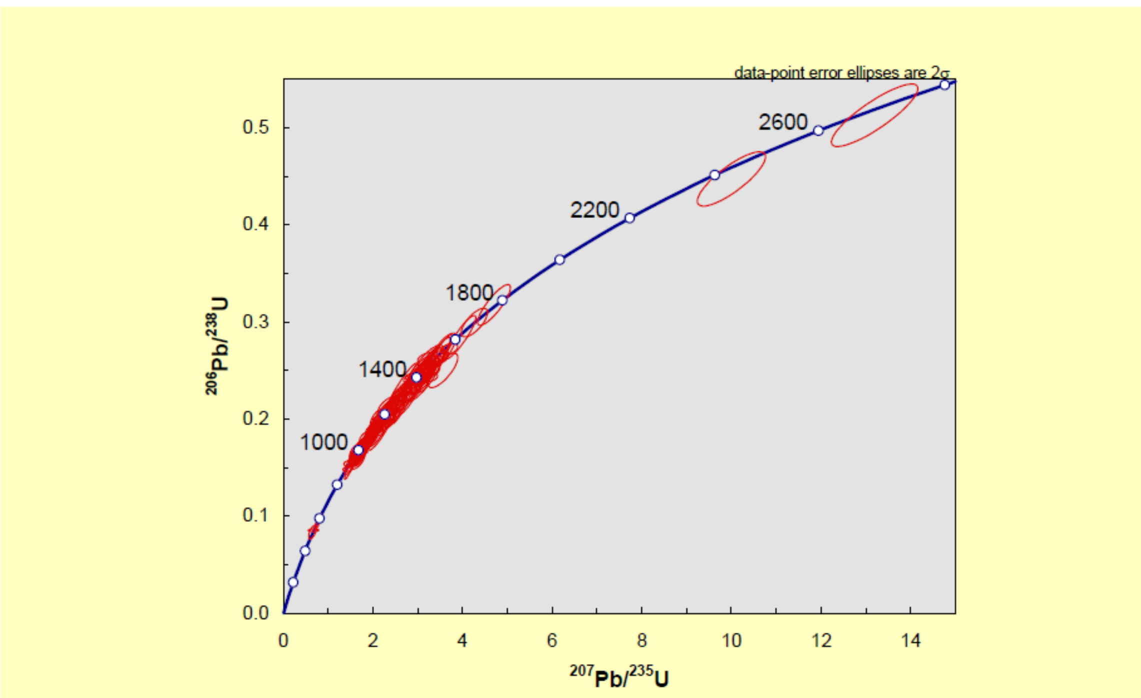
Relative probability plot of zircons analyzed. Bars represent the number of zircons determined to be of certain ages



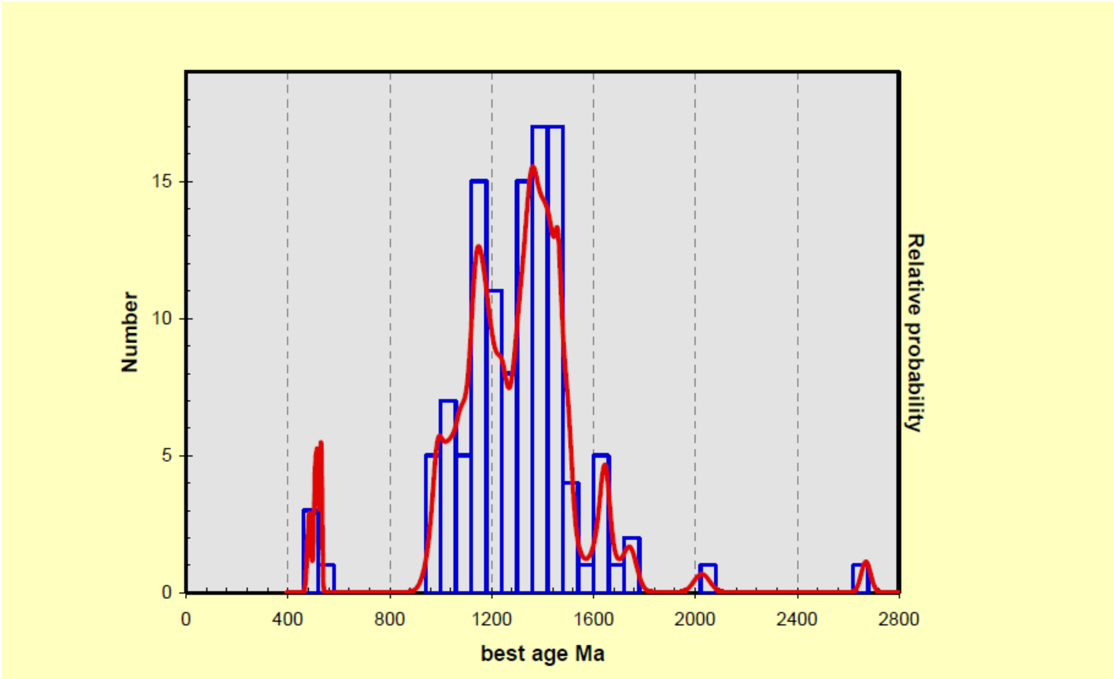
Unknown zircon concordia plot of Pb/U fractions. Used to visualize discordance of analyses.

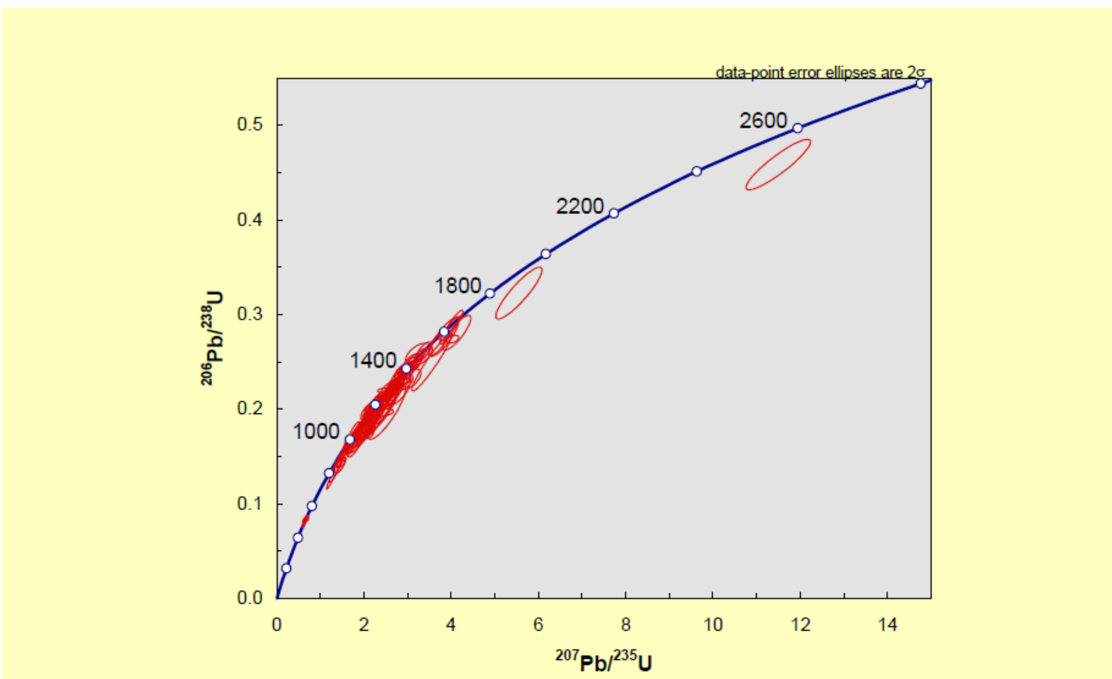
Bear Island domain of the Mather Gorge formation



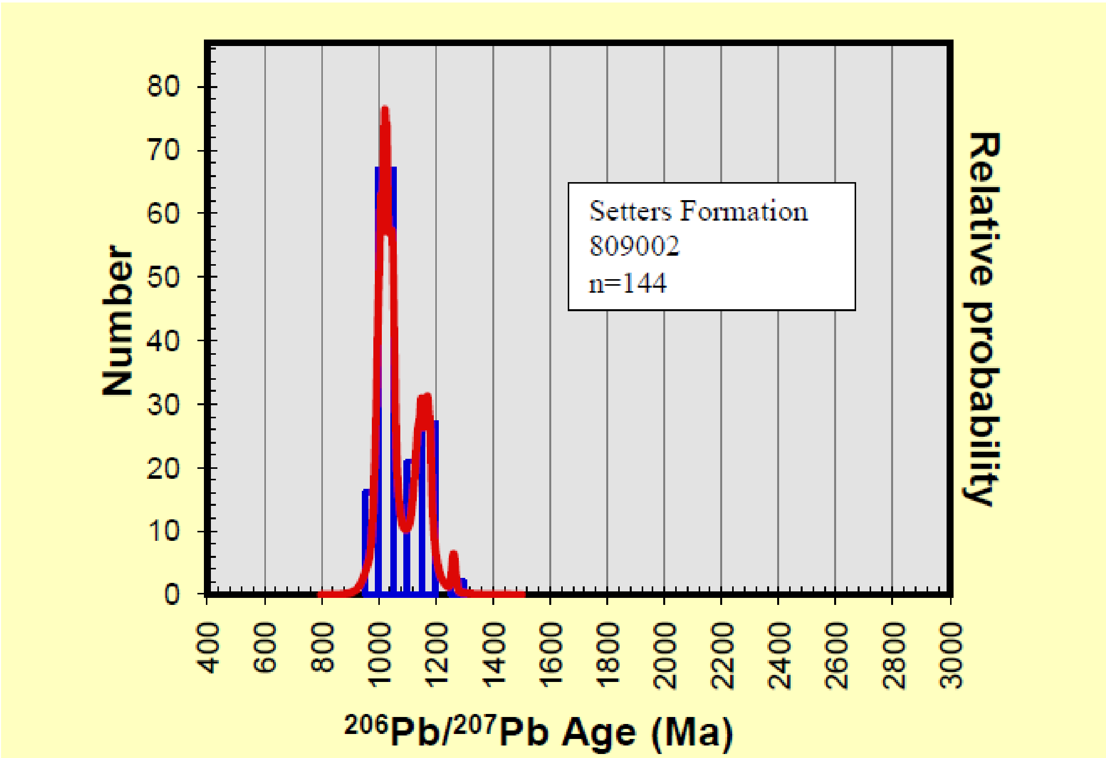


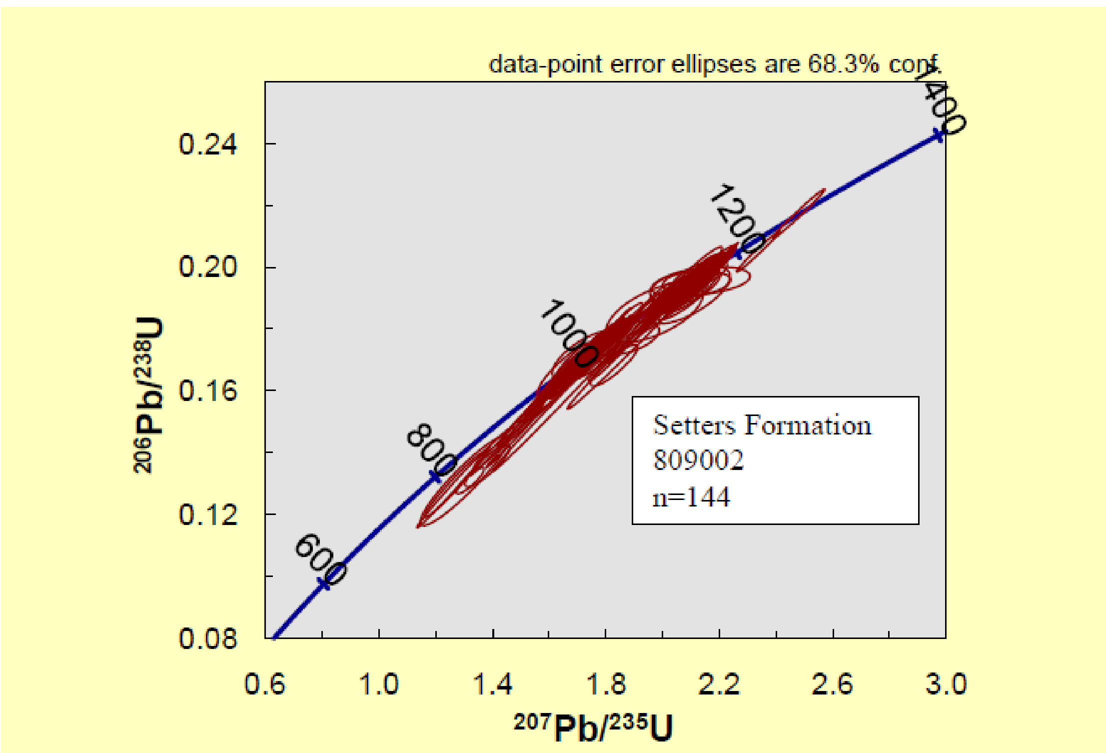
Laurel formation

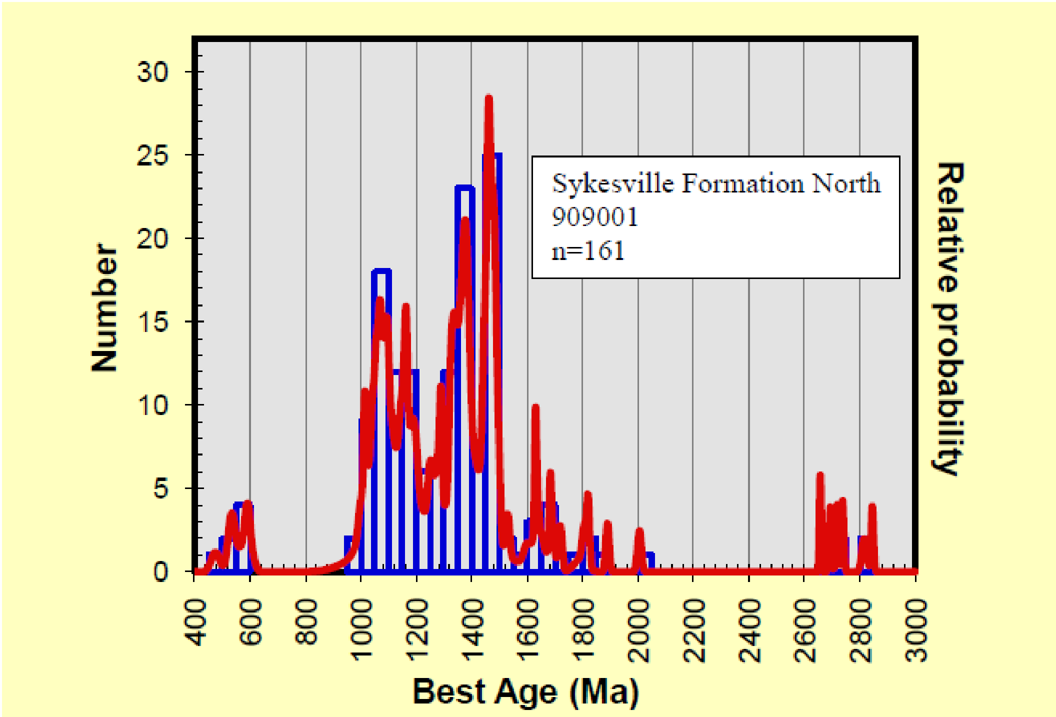


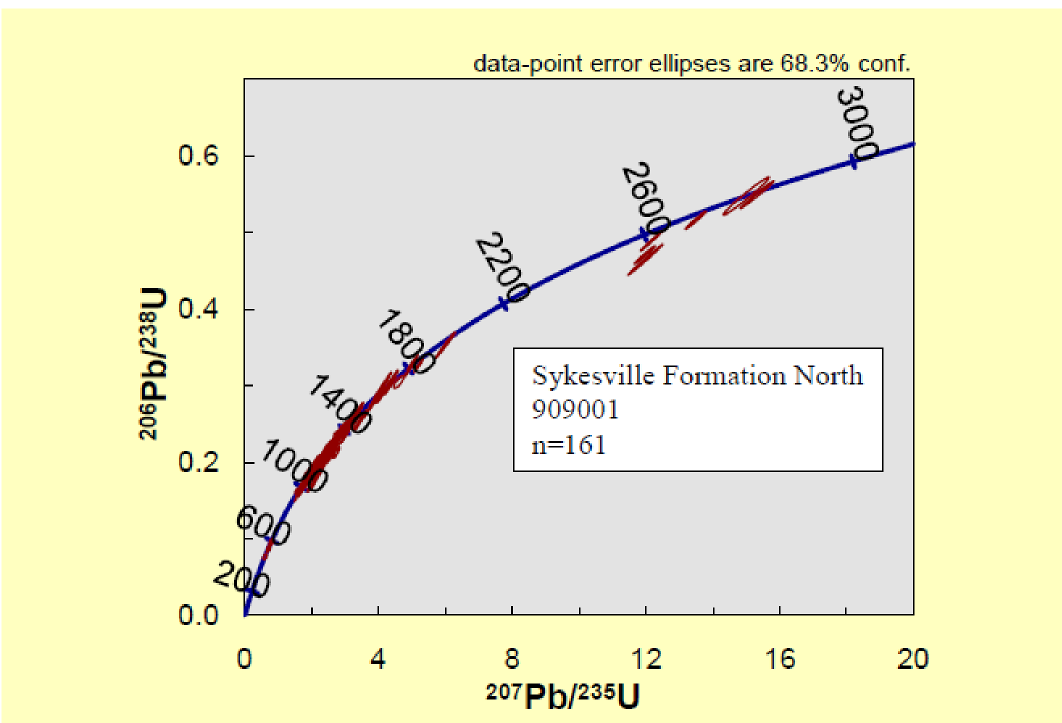


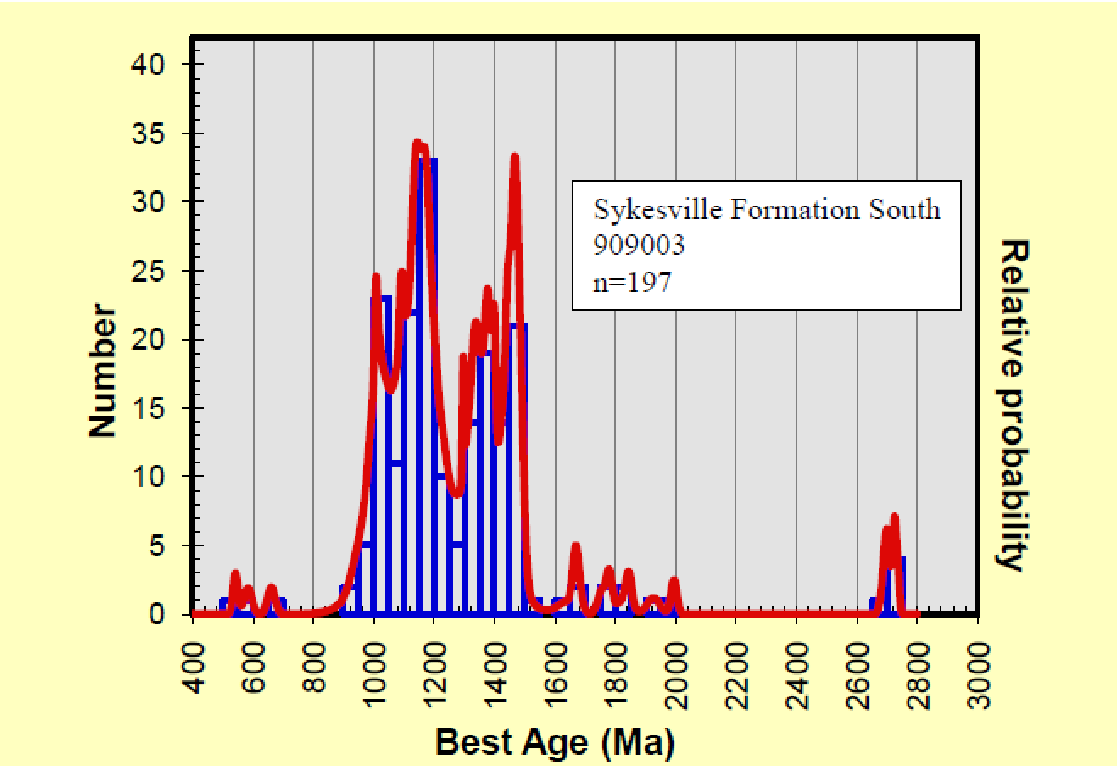
Appendix 3: Relative Probability and concordia plots from Fisher, 2010






Number
Relative probability
Best Age (Ma)
Sykesville Formation North
909001
n=161
0
5
10
15
20
25
30
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000


data-point error ellipses are 68.3% conf.
Sykesville Formation North
909001
n=161
206Pb/238U
207Pb/235U
0.0
0.2
0.4
0.6
0
4
8
12
16
20
200
600
1000
1400
1800
2200
2600
3000


Sykesville Formation South
909003
n=197
Number
Relative probability
Best Age (Ma)
0
5
10
15
20
25
30
35
40
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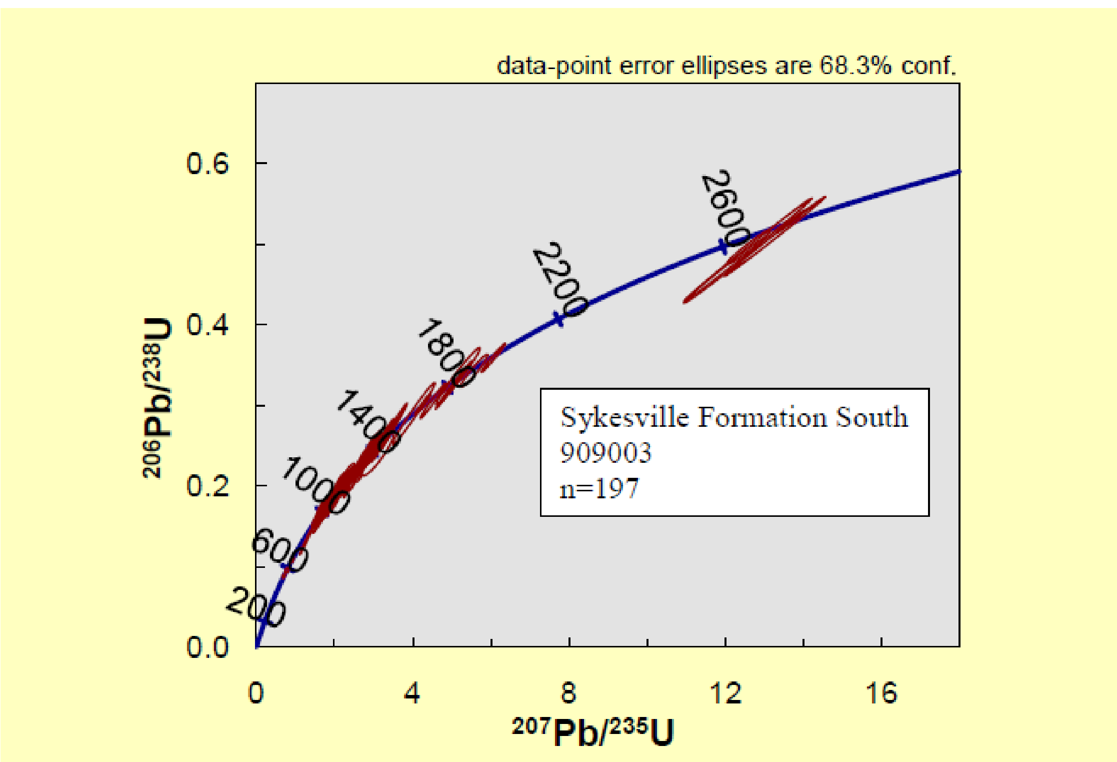
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000


data-point error ellipses are 68.3% conf.
Sykesville Formation South
909003
n=197
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$
0.0
0.2
0.4
0.6
0
4
8
12
16
200
600
1000
1400
1800
2200
2600

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