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Intrusive Margin of the Baltimore Mafic Complex in Cecil County, MD: A Field and Petrographic Study

A Senior Thesis Submitted to the Department of Earth Science & The University Honors Program

By

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Abstract

The Baltimore Mafic Complex (BMC) is described as a layered intrusion(s) consisting of ultramafic to intermediate igneous bodies. Although the complex has been the subject of investigation for nearly one hundred years, uncertainty remains about its origins and tectonic history. This section of hydrothermally altered rock along the Octoraro Creek supports the hypothesis that the BMC is a mafic intrusion into sedimentary rocks, as described by Hanan and Sinha (1989). The section experienced at least two stages of deformation: the first at high temperatures associated with intrusion creating grain boundary migration and subgrain formation, and the second hydrothermally altering remaining minerals. These features indicate that the origin of the Baltimore Mafic Complex is not affiliated with a subduction or supra-subduction zone ophiolite.

Acknowledgements

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Introduction

Eastern Margin of North America

The eastern margin of North America can be traced back to the supercontinent of Rodinia. The rifting of Rodinia began during the Neoproterozoic era and led to the formation of several smaller continents, including Laurentia (North America), Baltica (northern Europe), and Gondwana (southern continents). The Appalachian Mountains later formed throughout the Paleozoic via three major orogenies: the Taconic, Acadian, and Alleghanian. The Taconic Orogeny involved the subduction of the Iapetus Oceanic crust to form the Taconic Island Arc as well as a volcanic arc on the Laurentian continent during the Ordovician.

Tectonic activity can form ultramafic to mafic plutonic rocks in multiple ways. They can form at mid-ocean ridges, convergent tectonic margins involving subduction, or at oceanic island hot spots. Rifting at back-arc basins can also generate significant mafic complexes. These types of rocks all have different geochemical signatures that distinguish them from one another. This paper will investigate whether the Baltimore Mafic Complex formed as part of late-stage rifting of the supercontinent Rodinia or whether it formed as a result of subduction-related magmatism associated with the Taconic Orogeny.

Baltimore Mafic Complex

The Baltimore Mafic Complex (BMC) is found in the Eastern Piedmont of Maryland and Pennsylvania (Figure 1). The BMC is a late Cambrian to early Ordovician aged formation of mafic to ultramafic rocks. Generally, the BMC is described as a layered intrusion or intrusions consisting of ultramafic to intermediate bodies. The rocks of the BMC are generally classified as serpentinite, pyroxenite, gabbro, gabbronorite, and pegmatite (Figure 2). Abundant primary minerals are plagioclase, pyroxene, and olivine, but retrograde and hydrothermal metamorphism is extensive forming secondary minerals including actinolite, epidote, serpentine and chlorite.

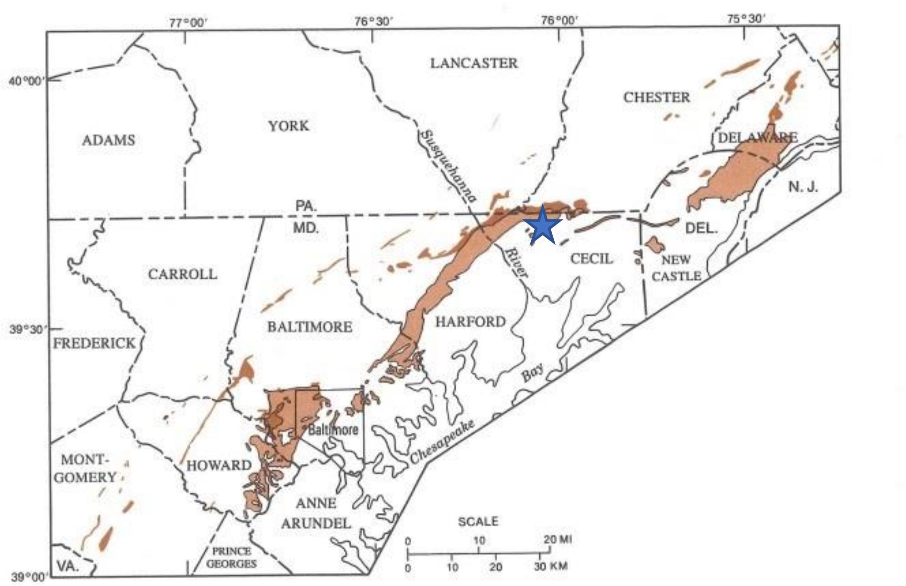


Figure 1: Map of Baltimore Mafic Complex in Pennsylvania and Maryland showing location of field area, as indicated by a star symbol, adapted from Wylie and Candela (1999).

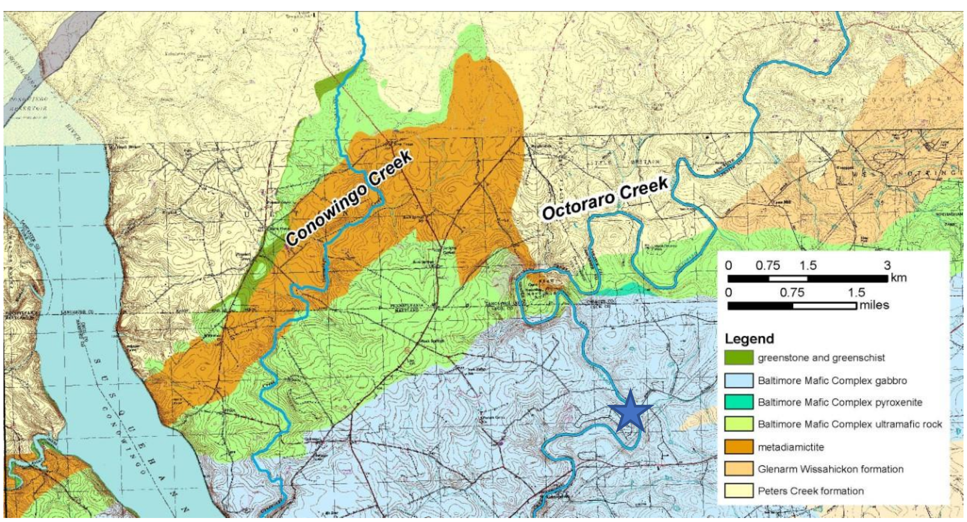


Figure 2: A map of the dominant lithological units in the State Line area, with a star indicating the field area, adapted from Shank, Marquez, and Hardy (2015).

A geochronologic study conducted on mafic rocks from the southern BMC indicates a crystallization age of 489 +/- 7 mya (Sinha et al., 1997; Guice et al., 2021). This date is consistent with Taconic magmatic arcs found throughout New England (Karabinos et al., 2017). The BMC has experienced considerable metamorphism that has been dated at 453 +/- 11 mya, that can be correlated to the Taconic Orogeny (Sinha et al., 1997; Guice et al., 2021).

Formation of the Baltimore Mafic Complex

Geochemical signatures eliminate the possibility that the Baltimore Mafic Complex formed at a mid-ocean ridge, oceanic island arc, or continental rift (Hanan and Sinha, 1989). Field relationships of the rocks are somewhat ambiguous; therefore, the remaining hypotheses remain plausible, and the origins of these rocks are still debated. Various arguments support that it belongs to part of a large mafic intrusion into continental crust (Hanan and Sinha, 1989) or a disrupted ophiolite sequence (Crowley, 1976; Morgan, 1977), or a supra-subduction zone ophiolite (Guice et al., 2021).

All of these possible interpretations describe different zones of a subduction complex. Crowley (1976) interpreted the BMC as ophiolite fragments within the accretionary prism (Figure 3). Hanan and Sinha (1989) identified the complex as a mafic intrusion into continental crust. Their hypothesis places the origin of the BMC in the back-arc basin where continental sediments were abundant (Figure 3). More recent work by Guice and others (2021) concluded that these bodies are supra-subduction zone ophiolites derived from upper mantle materials in the initial stages of island arc magmatism (Figure 3). To continue to elucidate the origin of the Baltimore Mafic Complex, a field and petrographic study was conducted along a section of the Octoraro Creek within the State Line portion of the BMC.

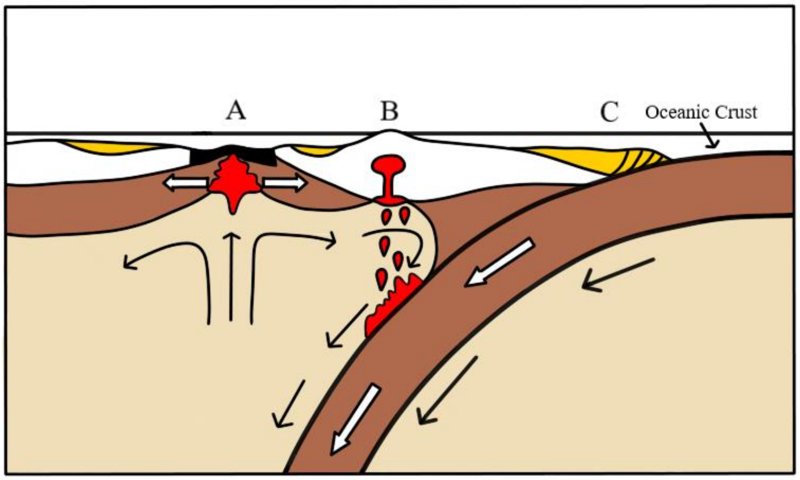


Figure 3: A diagram of a subduction zone identifying the location of each hypothesis. Zone A represents the back-arc basin proposed by Hanan and Sinha, 1989. Zone B is a primeval volcanic island arc, as suggested by Guice and others, 2020. Zone C is an accretionary prism, as interpreted by Crowley, 1976.

Local Lithology

Near the Maryland-Pennsylvania border, the BMC is characterized by two ultramafic bodies: the larger State Line serpentinite and the smaller New Texas serpentinite. Pyroxenite, gabbro, serpentinized dunite, and peridotite form the stratigraphic base (Sinha et al., 1997; Shank and Marquez, 2015). Overlying rocks are comprised of layered mafic gabbronorite and gabbro which grade into diorities and granodiorites (Southwick, 1969; Crowley, 1976; Hanan and Sinha, 1989; Sinha et al., 1997; Burgess et al., 2009). The BMC contained extensive deposits of chromite that were mined in the early to mid-nineteenth century: the largest and most recognized was the Wood Mine in Lancaster County (Wylie and Candela, 1999).

Gabbro and gabbronorite make up the bulk of the BMC and lay atop the pyroxenites and basal serpentinites (Hanan and Sinha, 1989; Shank and Marquez, 2015). Gabbro is a mafic, intrusive igneous rock that is dominantly calcium-rich plagioclase and clinopyroxene with accessory minerals such as magnetite, ilmenite, chromite, and apatite. Gabbronorite has orthopyroxene as well as clinopyroxene. All of the rocks in the BMC exhibit some degree of retograde metamorphism. The gabbros typically have a green colored appearance due to retrograde alteration to tremolite-actinolite and epidote or zoisite (Hanan and Sinha, 1989; Shank and Marquez, 2015).

The igneous rocks occur in conjuction with metamorphosed sedimentary rocks including metadiamictites and schists. Metadiamictites contain a wide range of clast sizes within a metamorphosed mud or sand matrix. Generally, the metadiamictite is a metaconglomerate or granofels composed of quartz and feldspar. The clasts in the metadiamictite have varying lithologies and sizes, with sizes ranging from a few centimeters up to 40 cm. Quartz pebbles, fine-grained biotite-rich clasts and rounded to subangular clasts of quartz sandstone are the most common clast types. Medium-grained, biotite-rich lenses are also common. Ultramafic and mafic clasts are very rare and clast distribution is also very irregular throughout the State Line area (Shank and Marquez, 2015).

Samples and Field Relationships

This study focuses on a small section of the State-Line portion of the Baltimore Mafic Complex that is exposed in Cecil County, Maryland along the Octoraro Creek (Figure 4). Outcrops and float were studied along a 900 meter section, 9 samples were collected from outcrop and analyzed using standard petrographic techniques. Another seven samples were analyzed through portable x-ray fluorescence spectrometry (pXRF), and one sample was analyzed using electron dispersive spectrometry (EDS) techniques on a scanning electron microscope. As in other areas of the Baltimore Mafic Complex, a gradation from mafic to intermediate rock is evident in the field; however, the presence of metadiamictite (Site 7) near the southern boundary suggests a possible sedimentary origin rather than an intrusive origin of quartz-rich rock (Figures 4 and 5). Metadiamictite outcrops contain lithoclasts larger than 10 centimeters (Figure 5). One outcrop, (Site 3) exhibits foliation as well as extensive alteration that may represent either the contact zone, a fault zone, or a faulted contact zone between the more mafic and felsic/metasedimentary units.

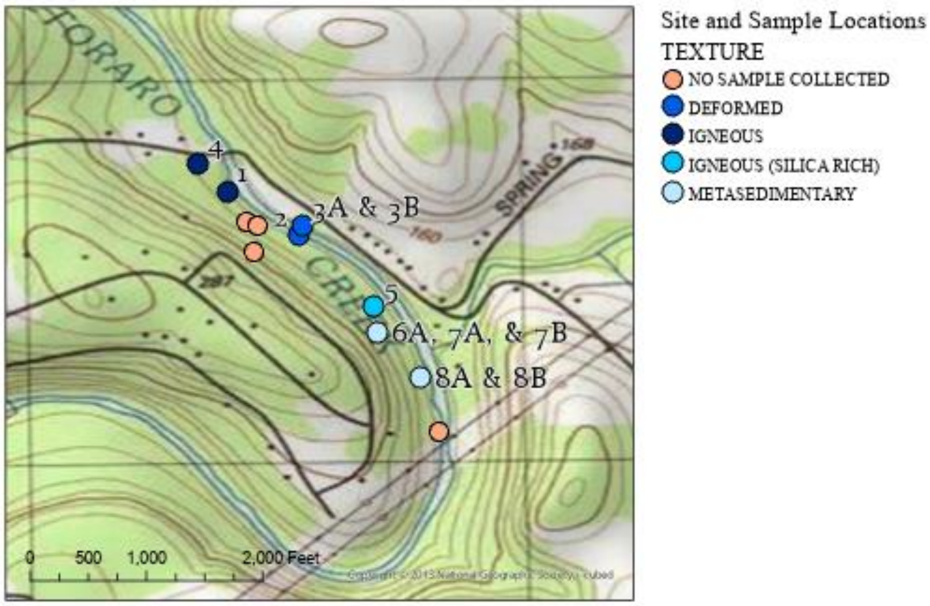


Figure 4: Field location with sites and sample numbers plotted.

Figure 5: Metadiamictite containing various clasts including biotite schist and quartzite.

Analytical Methods

Nine samples were analyzed for mineral composition, texture, and microstructural features using standard petrographic techniques. Further investigation with electron dispersive spectrometry (EDS) and x-ray fluorescence spectrometry (pXRF) methods were conducted to refine petrographic findings.

Results

Sequence 1: Mafic to Intermediate Igneous Rocks

Sequence 1 is characterized by samples 1, 2, and 4 from the northern portion of the section. These rocks exhibit classic igneous textures albeit altered and contain more mafic minerals with limited quartz. Sample 1 contains actinolite (38%), plagioclase (19%), hornblende (18%), pyroxene (15%), and serpentine (10%). Sample 2 is dominated by primary hornblende (45%) and pyroxene (35%) and lesser amounts of plagioclase (10%) and quartz (5%) with secondary minerals biotite, epidote, and chlorite (Figure 6). EDS analysis of sample 2 showed that plagioclase is sausseritized with minute epidote crystals (<25 µm) forming within plagioclase (Figure 6). Sample 4 exhibits extensive retrograde mineralization. Primary pyroxene (20%), hornblende and plagioclase have been extensively replaced with actinolite (50%), epidote (15%), and serpentine (15%). Deformation features evident in this sequence include undulose extinction and quartz subgrain development. Sample 2 contains a shear zone that cuts through the sample (Figure 11B). Although this sequence is drastically altered, relict igneous features are apparent such as poikilitic textures in both sample 2 and 4 (Figures 7 and 8).

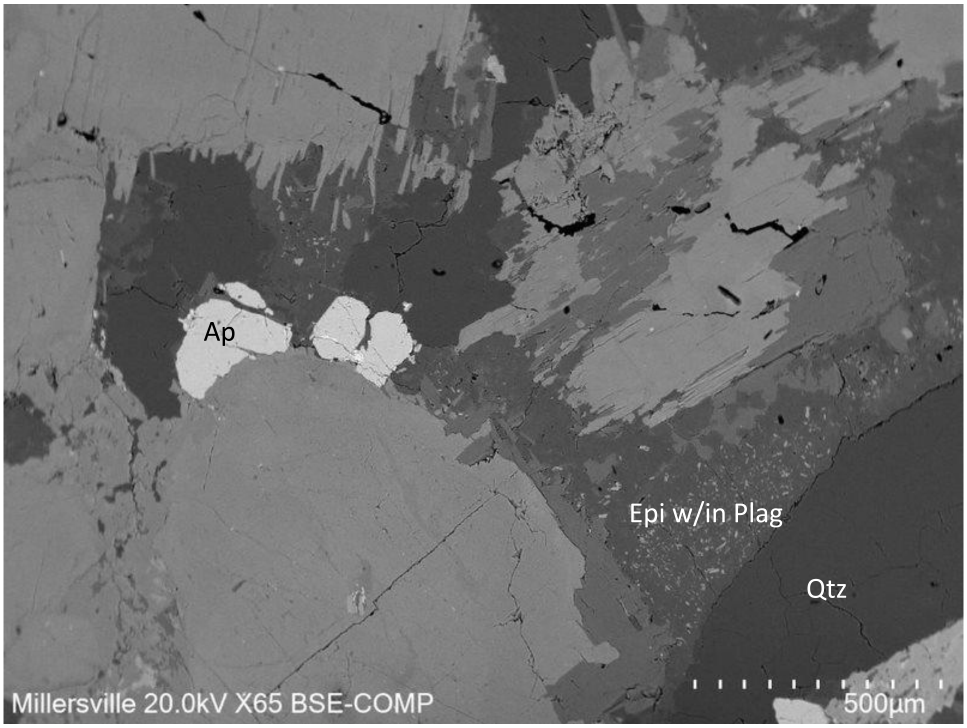


Figure 6: Compositional variation in sample 2 showcasing alteration phases. SEM.

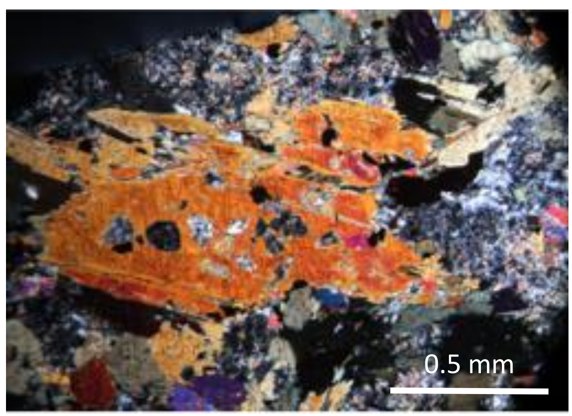


Figure 7: Relict poikilitic textures evident from sample 2. Cross polarized light.

Figure 8: Relict olivine within hornblende in sample 4. Plane-polarized and cross-polarized light.

Sample 3: The Boundary Rock

The outcrop of sample 3 occurs between sequence 1 and sequence 2 and would be described as a classic greenschist in the field with dark green minerals defining a distinctive foliation. This sample is dominated by hornblende (35%) and epidote (40%) with lesser amounts of plagioclase, quartz, biotite, and opaque minerals. Epidote occurs as both an alteration product of plagioclase through sauseritization as well as euhedral growth in vein phase (Figures 9 and 10A). Hornblende crystals have a brown core and blue-green rim and provide a biaxial negative interference figure (Figures 10A and 10B). Sample 3 contains one small shear zone (Figure 11A). The only other sample to exhibit shear zones and veining is sample 2, which is located within meters of the sample 3 outcrop (Figure 4). No field evidence indicates the presence of a large-scale deformation features.

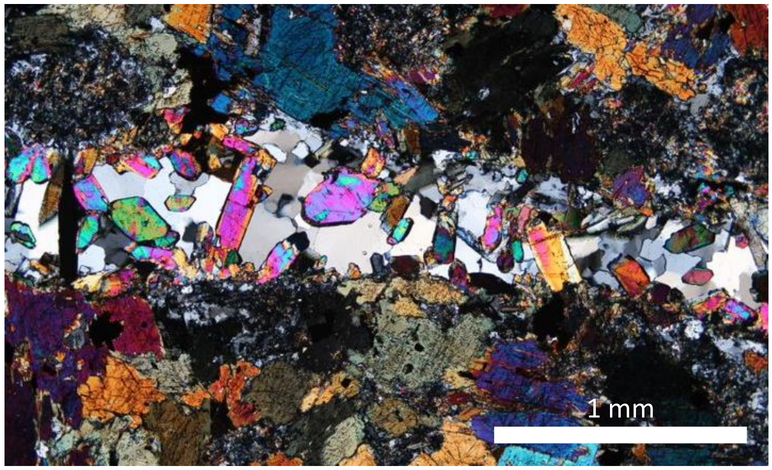


Figure 9: Vein in sample 3 with euhedral epidote and quartz. Cross-polarized light.

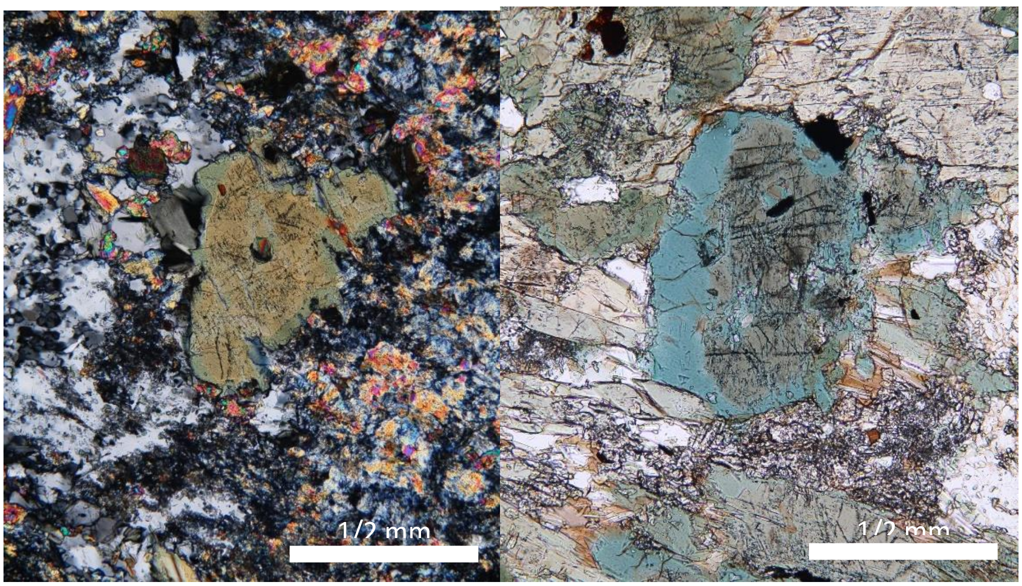


Figure 10A: Abundant epidote surrounding hornblende in sample 3. Cross-polarized light. Figure 10B: Hornblende with brown core and blue-green rim in sample 3. Plane-polarized light.

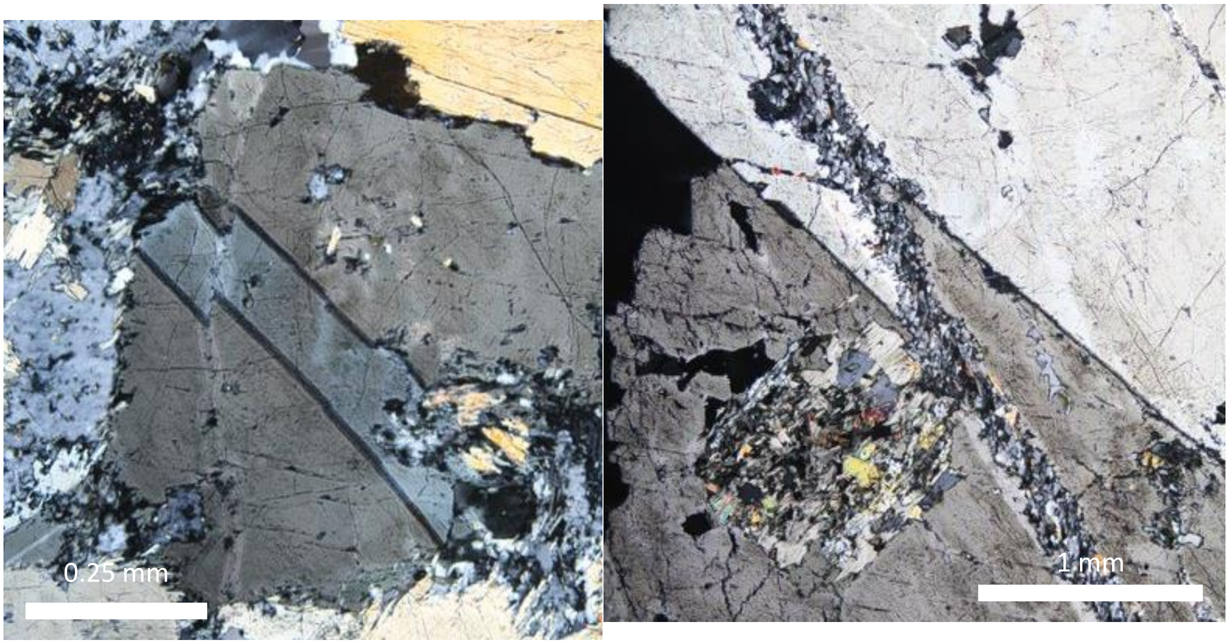


Figure 11A: Shear zone that cross cuts plagioclase in sample 3. Cross-polarized light.
Figure 11B: Shear zone in sample 2. Cross polarized light.

Sequence 2: Felsic to Medasedimentary Rocks

Sequence 2 consists of samples 5 through 8 which are characterized by a much greater abundance of quartz throughout as well as distinctive metasedimentary features in samples 6-8. Sample 5 appears to be dioritic in composition lacking any pyroxene or relict olivine. Sample 5 is dominated by hornblende (45%) and plagioclase (30%) with lesser amounts of quartz, biotite, and opaque minerals. Sample 6 is the first of the rocks that appears more sedimentary. Sample 6 is dominated by quartz (55%), biotite (25%), and plagioclase (13%), with secondary epidote.

Samples 7A and 7B, described as a metadiamictite in the field, contain clasts of what appear to be biotite schist and quartzite within a granitic-looking groundmass (Figure 5). In hand sample, there is a distinct boundary between the clasts and matrix. In thin section, this boundary is far more gradational (Figure 12). Petrographic analysis of sample 7A shows that clasts are dominated by recrytallized quartz (50%), biotite (35%), opaque minerals (5%), and alteration minerals that are too small to identify in thin section. The matrix of sample 7A has a similar composition but is more quartz-rich (65%), but also contains biotite (25%), and plagioclase (10%). Clasts in sample 7B are very similar in composition but with a greater abundance of biotite (60%). The matrix of sample 7B is quartz (60%), biotite (15%), plagioclase (15%), and epidote (10%). Trace amounts of zircon are also present in samples 6 and 7. These samples also exhibit microstructures including quartz subgrain formation.

Sample 8 is not a diamictite. In the field this rock appeared to be granitic. In thin section, the sample is dominated by quartz (58%), plagioclase (25%), and biotite (12%) with lesser amounts of hornblende and opaque minerals. More significantly, sample 8 has a meta-sedimentary texture. Quartz grains are not interlocking but are rounded clasts ranging in size from 2-3 mm. The clasts themselves have recrystallized into subgrains that are about 0.5-1 mm. Biotite is the second most common mineral within the sample and it radiates between the quartz clast grain boundaries (Figure 13)

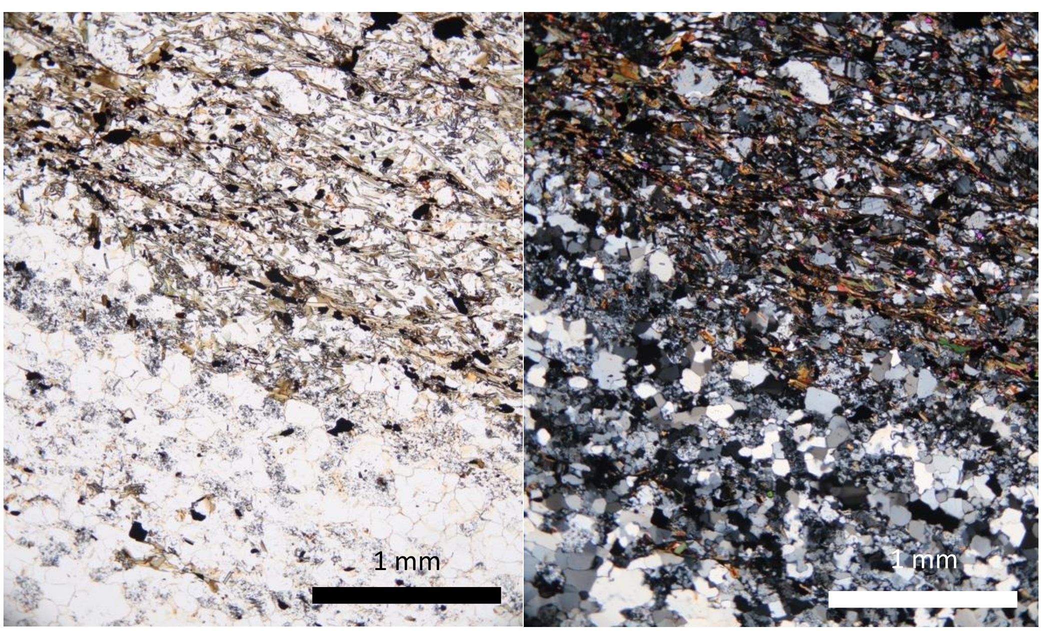


Figure 12: Gradational boundary between groundmass and clast. Plane-polarized and cross-polarized light.

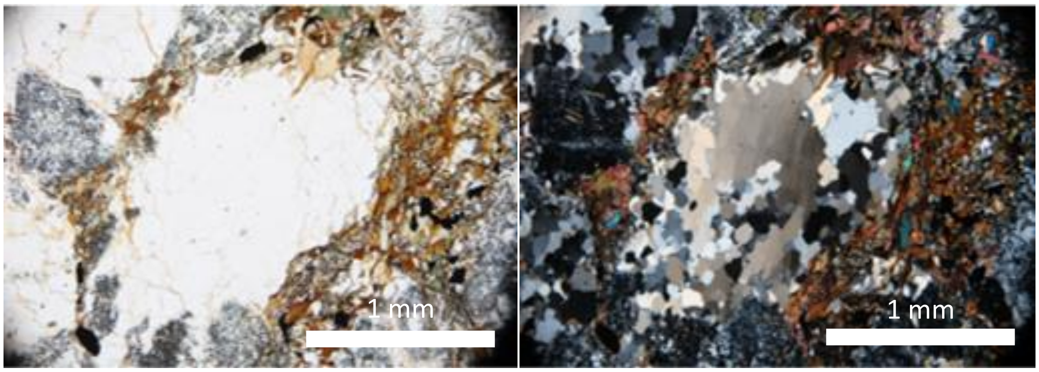


Figure 13: Quartz rich clasts and radiating biotite from sample 8. Plane and cross-polarized light.

Discussion

The nine samples studied show two distinct compositions and textures. Sequence one exhibits classic igneous minerals and textures indicative of their origin as a mafic magma. Sequence two exhibits more quartz rich samples with classic metasedimentary textures of lithic clasts and rounded grains. The presence of these two sequences adjacent to one another in the field are indicative of mafic magma intruding sedimentary rock.

Sample	Pyx %	Hbl %	Bio %	Plag %	Qtz %	Secondary Minerals %
1	15	18		19		48
2	35	45		10	5	5
3		35	5	9	6	45
4	20					80
5		45	10	25	15	5
6			25	13	55	7
7A Clast			35		50	15
7A Matrix			25	10	65	
7B Clast			60	10	30	
7B Matrix			15	15	60	10
8		3	12	25	58	2

Intrusive Origin

The composition and micro-scale features of the mafic rock that establishes sequence 1 are consistent with other outcrops seen in the State Line area of the BMC (Shank and Marquez, 2015). Sequence 1 resembles the characteristic stratigraphy of dominant gabbro to gabbronorite sequence that is medium- to coarse-grained and composed of plagioclase and pyroxene (Shank and Marquez, 2015). The gabbros are also distinguished by their pervasive alteration to actinolite and epidote, which are seen to compose 40-60% of sequence 1.

The Baltimore Mafic Complex occurs in conjunction with schists, metadiamictites and greenstones. In previous studies, these more quartz-rich rocks have been variously mapped as a diamictite (Higgins and Conant, 1990) or granodiorite (Gray, 1901; Orndorff, 1999). Although this field area is distinctly within the gabbroic portion of the Baltimore Mafic Complex, the metadiamictites and the clasts within them are evidence that this section of the BMC is an intrusion of mafic magma into a marginal sedimentary environment. The clasts of quartzite and schist larger than 10 cm found within the outcrop indicates previously existing sedimentary sequences. The groundmass of samples 7 and 8 are all quartz rich, and, more importantly, lack traditional interlocking anhedral growth of crystals indicative of an igneous origin. In sample 8, subrounded 1-2 mm quartz grains with extensive subgrain development dominate the sample. Biotite radiates between the quartz clasts, which is consistent with low-grade metamorphism of a clay-rich sandstone.

These features eliminate the possibility that the Baltimore Mafic Complex is an ophiolite. Traditionally ophiolites contain some portion of an oceanic sequence that includes sheeted dikes and/or pillow lavas, but this sequence is absent in the State Line area. If this mafic material belonged to the upper mantle or lower lithosphere, then this area would not have the characteristics of an intrusive margin into metasediments. The intermediate rocks, like diorite, that are included in this sequence are further evidence that the BMC is not an ophiolite, because intermediate to felsic rocks other than plagiogranites are exceptionally rare in oceanic crust.

Two Stages of Deformation

Microstructures and textural features throughout the section indicate that this area has undergone two phases of deformation after intrusion. In metasedimentary sequence 2, quartz displays subgrain formation (dislocation creep) and grain boundary migration (dislocation glide), which indicates a high temperature and high pressure environment (Figure 14). These microstructures become dominant deformation mechanisms in quartz between 500-1200°C (Rutter and Elliott, 1976). Typical mafic intrusions are at temperatures between 1000-1200°C (Nelson, 2015). Because this subgrain formation and grain boundary migration is concentrated in the metasedimentary sequence, it is likely that these deformation features are the result of the high temperatures correlated with the initial intrusion.

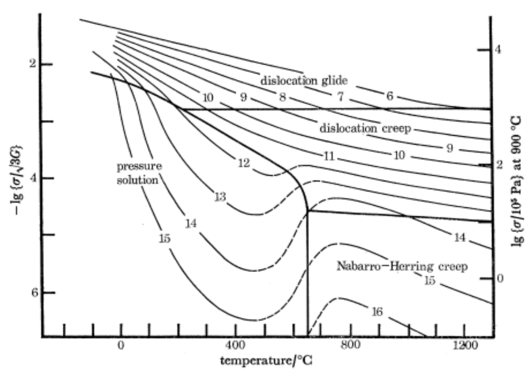


Figure 14: E 7. Deformation mechanism map for quartz with and without pressure solution adapted from Rutter and Elliott (1976).

After intrusion, the entire sequence of rock experienced late-stage hydrothermal alteration. The hydrothermal mineralization that is most extensive in sample 3, but is also present in Sequence 1, is an epidote+quartz rich phase. Epidote occurs both as replacement of plagioclase through the process of saussuritization as well as within veins. Saussuritization is associated with the hydrothermal alteration of plagioclase feldspar and typically occurs above 250°C (Absar, 1991). Epidote+Quartz veins cross-cut altered plagioclase indicating a later stage of hydrothermal mineralization. Also in sample 3, hornblende crystals have a brown core and blue-green rim and provide a biaxial negative interference figure, which indicates uralitization. Uralitization is associated with low-grade regional metamorphism and occurs between 200 and 320°C (Absar, 1991). Since uralitization and saussuritization occur within the same temperature regime, it is highly plausible that the processes occurred at the same time, mobilizing elements for the formation of epidote. Additionally, a shear zone that offsets the entire sample is displayed in sample 2.

Because of these specific temperature conditions, two stages of deformation must have occurred: the first high-temperature phase causing grain boundary migration and subgrain formation, and the second lower temperature sequence of hydrothermal alteration.

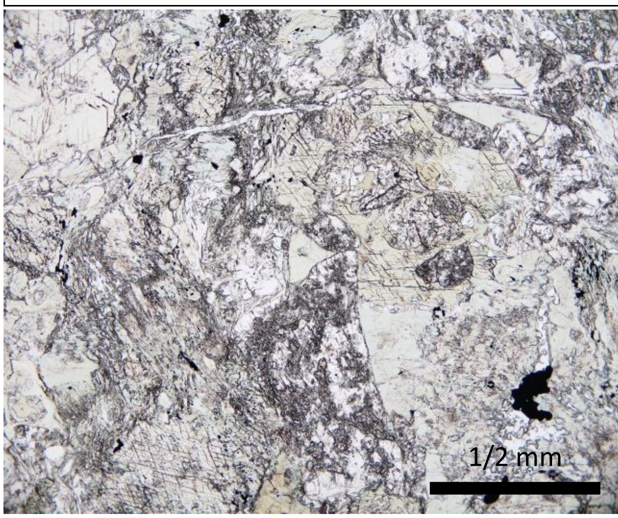
Conclusion

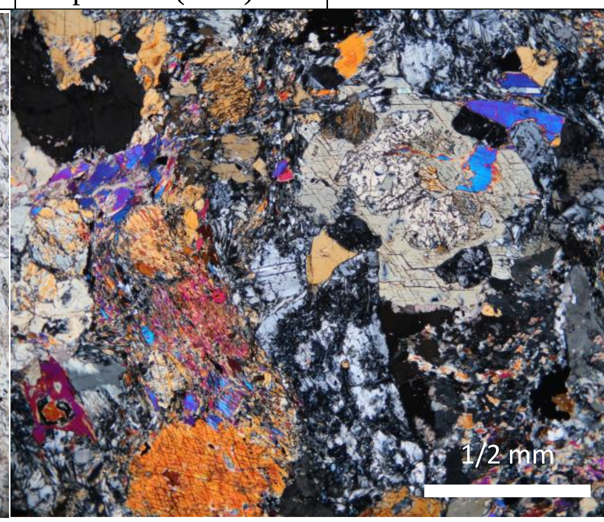
The various interpretations surrounding the Baltimore Mafic Complex's history demand different magmatic and textural characteristics. The evidence from this study supports the hypothesis that the BMC is a mafic intrusion into sedimentary rocks, as described by Hanan and Sinha (1989). These metasedimentary features eliminate the possibility that the BMC is the product of ophiolite obduction, because a typical ophiolite would not include an intrusive margin.

Appendix

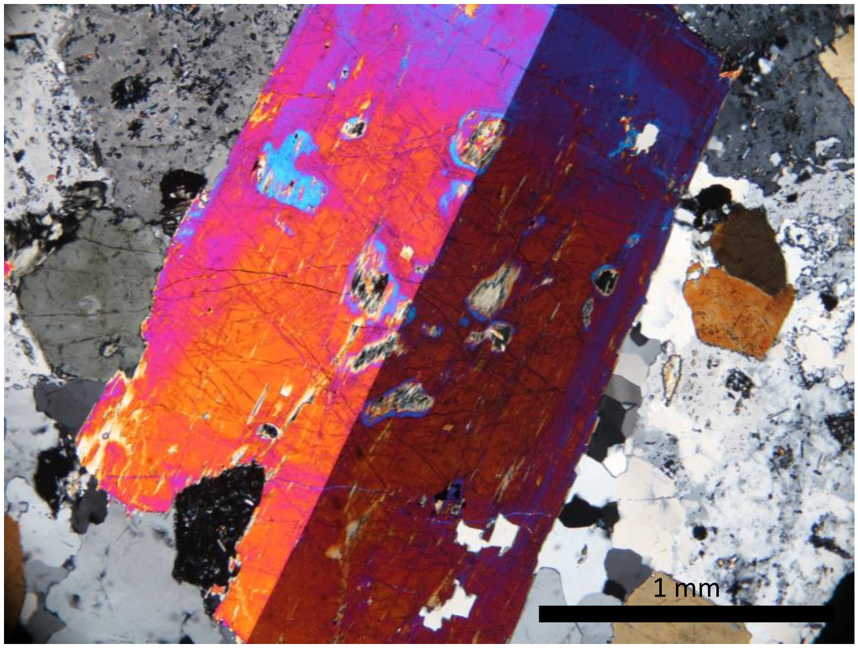
Sample Descriptions

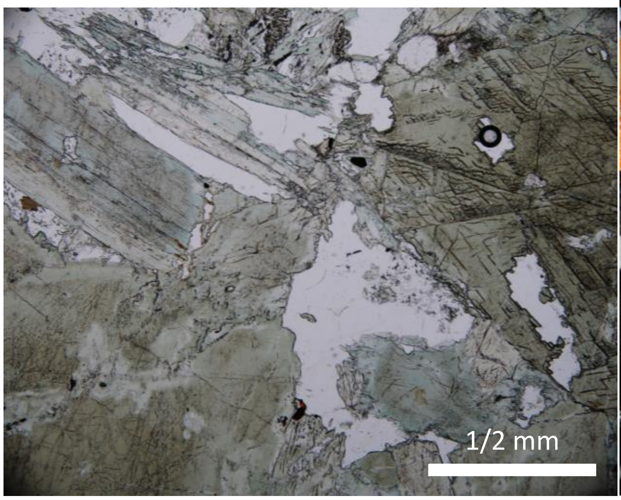
Sample 1	**Highly Altered Gabbro**	
Hand Sample/Field Description:	Large amount of plagioclase, muscovite, and lesser amount of hornblende ¼ cm grain size	
Petrographic Analysis	**Composition**	**Notes**
Primary Minerals	Pyroxene (15%)	
Secondary Phases	Actinolite (38%)	
	Plagioclase (19%)	
	Hornblende (18%)	Blue-green rims, brown core
	Serpentine (10%)	

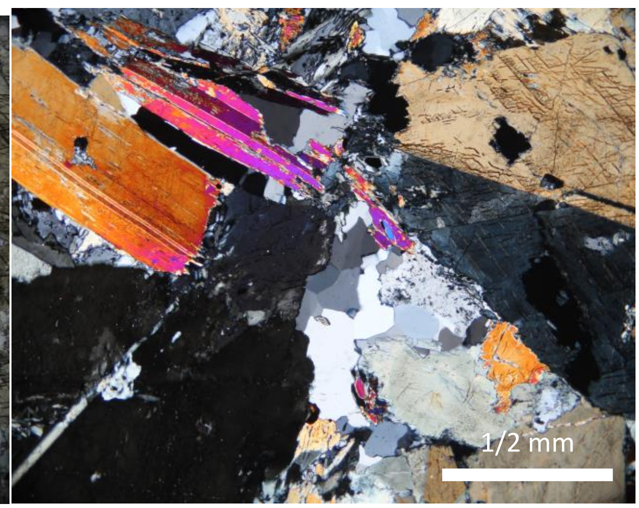




Sample 2	**Highly Altered Gabbro**	
Hand Sample/Field Description:	Large hornblende crystals (½ cm), quartz components Schist-like, obviously foliated	
Petrographic Analysis	**Composition**	**Notes**
Primary Minerals	Pyroxene (25%)	Sheared
Secondary Phases	Hornblende (60%)	
	Plagioclase (5%)	Poikilitic texture Exhibits zoning
	Quartz	Subgrains
	Acessory minerals (5%)	Chlorite and biotite

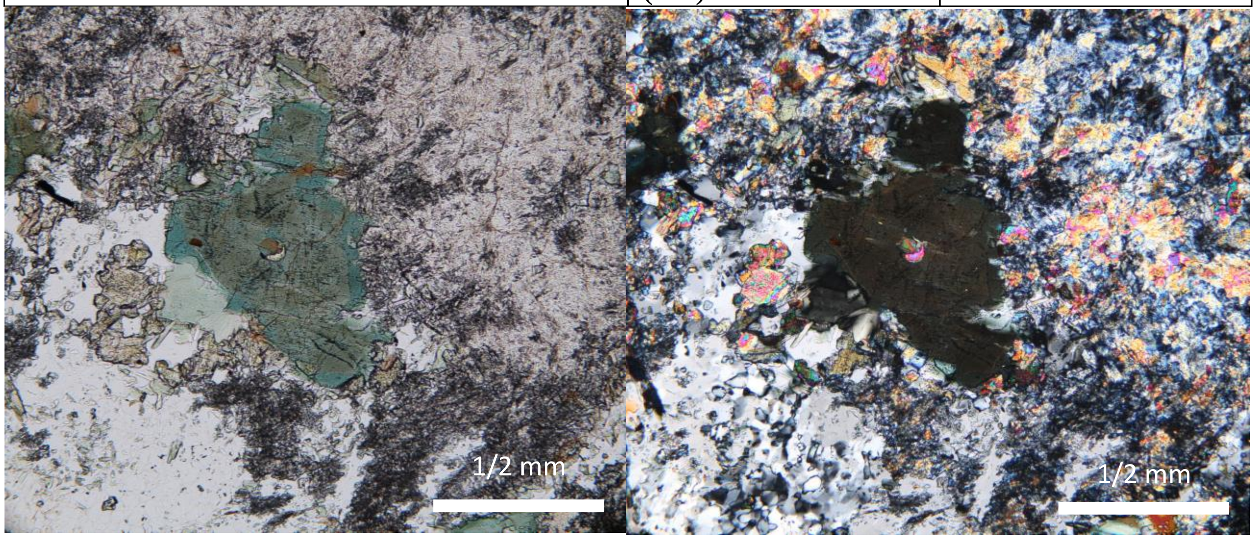


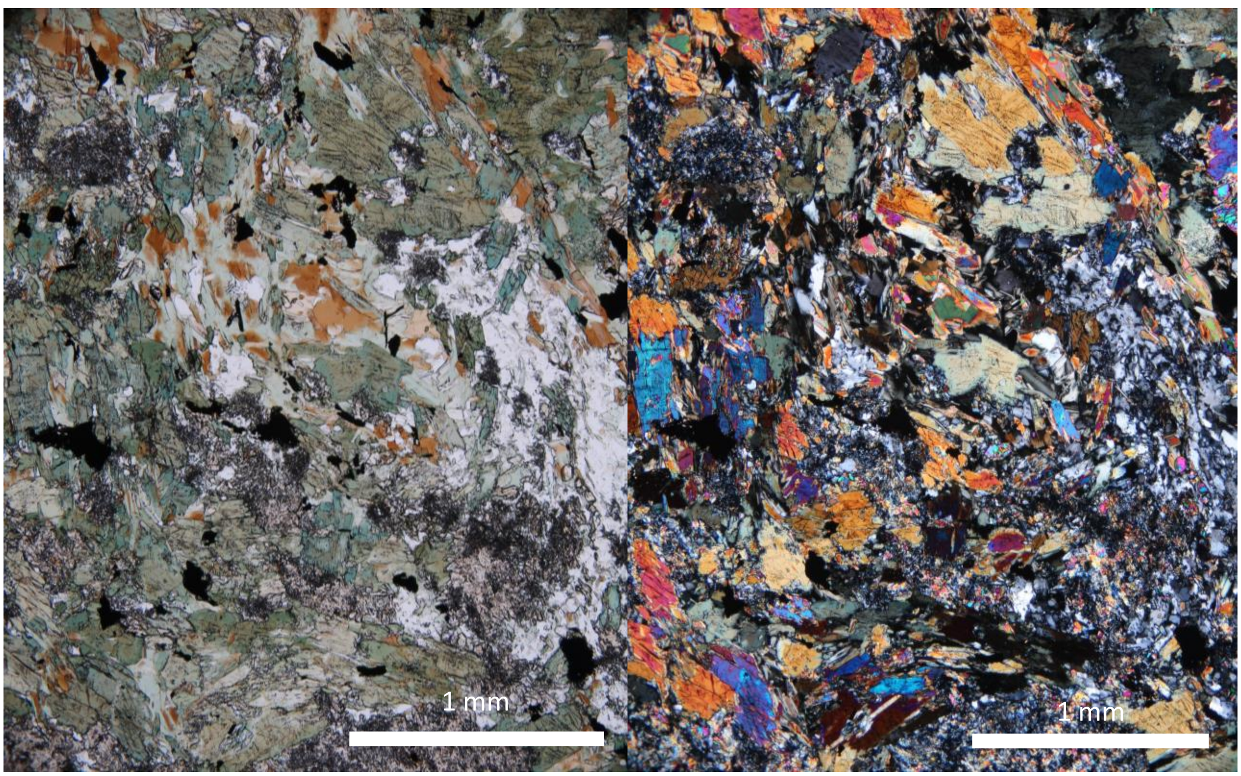




Sample 3	**Hydrothermally Altered Diorite**	
Hand Sample/Field Description:	Dioritic appearance ¼ cm grain size, hornblende crystals > 1 cm	
Petrographic Analysis	**Composition**	**Notes**
Secondary Phases	Epidote (40%)	Vein phase and secondary mineral
	Hornblende (35%)	Blue-green rims, brown core
	Recrystallized quartz and plagioclase (15%)	
	Biotite (5%)	

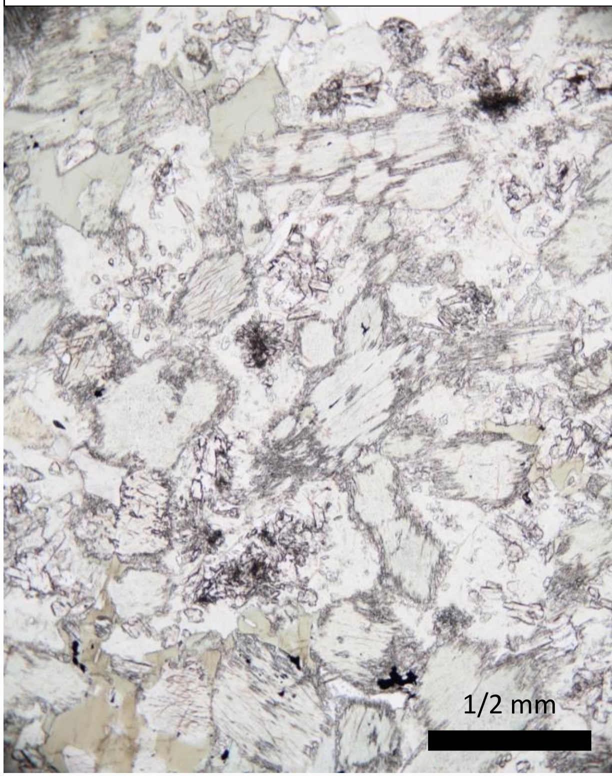
	Opaque minerals (5%)	

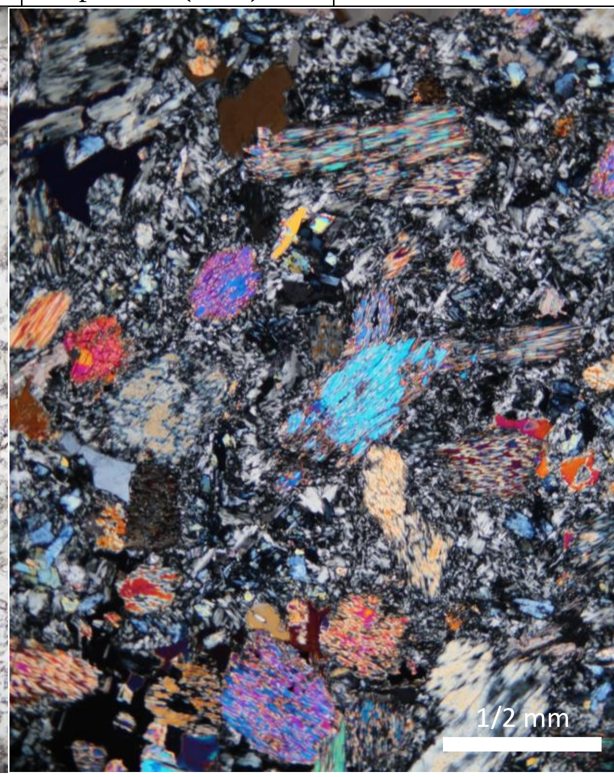




Sample 4	**Extensively Altered Gabbro**	
Hand Sample/Field Description:	Large amount of plagioclase and elongate biotite Columner jointing	
Petrographic Analysis	**Composition**	**Notes**
Secondary Phases	Actinolite (50%)	Poikilitic texture

	Relict pyroxene (20%)	Very saussuritized, crystals > 1 mm
	Epidote (15%)	
	Serpentine (15%)	

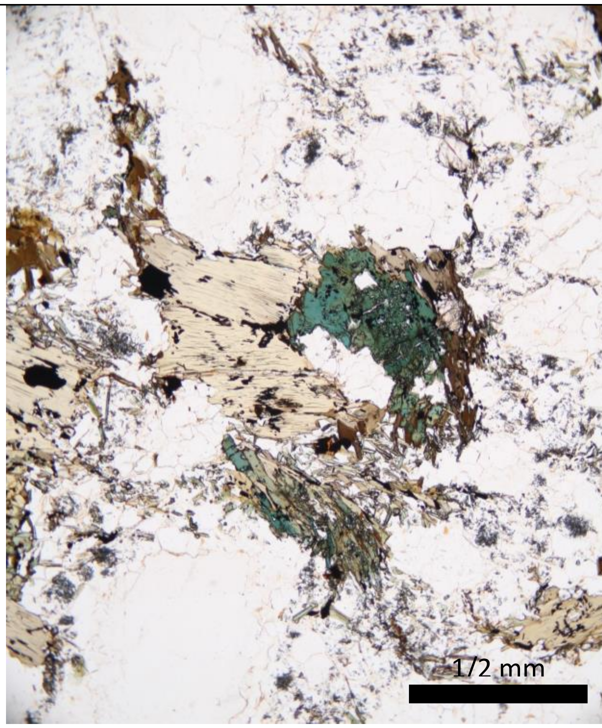


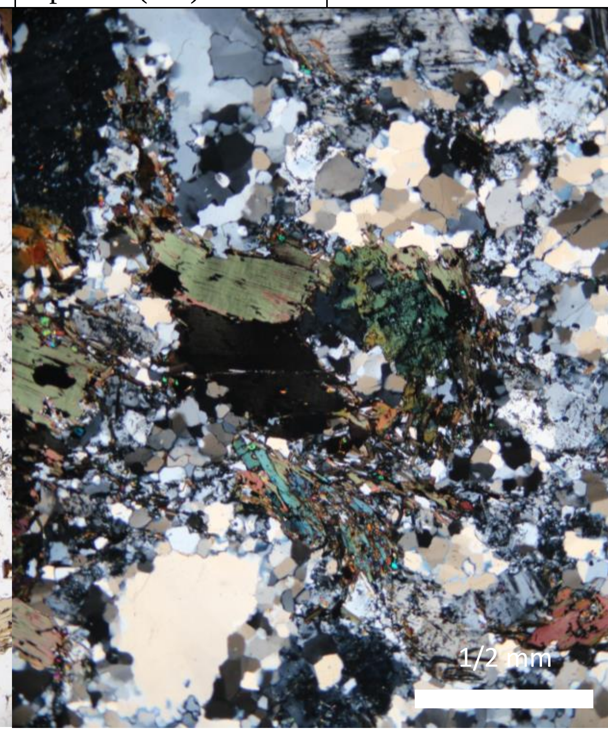


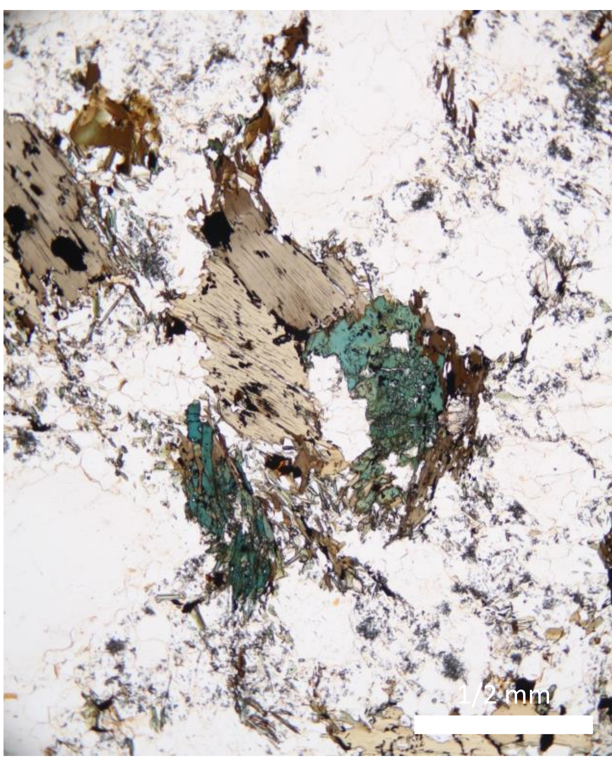
Sample 5	**Diorite**	
Hand Sample/Field Description:	More foliated and biotite rich than samples 1-4 Float (not deposited where found)	
Petrographic Analysis	**Composition**	**Notes**
Primary Minerals		
Secondary Phases	Hornblende (45%)	Blue-green color
	Plagioclase (30%)	
	Biotite (10%)	
	Quartz (10%)	Grain boundary migration
	Opaque minerals (5%)	

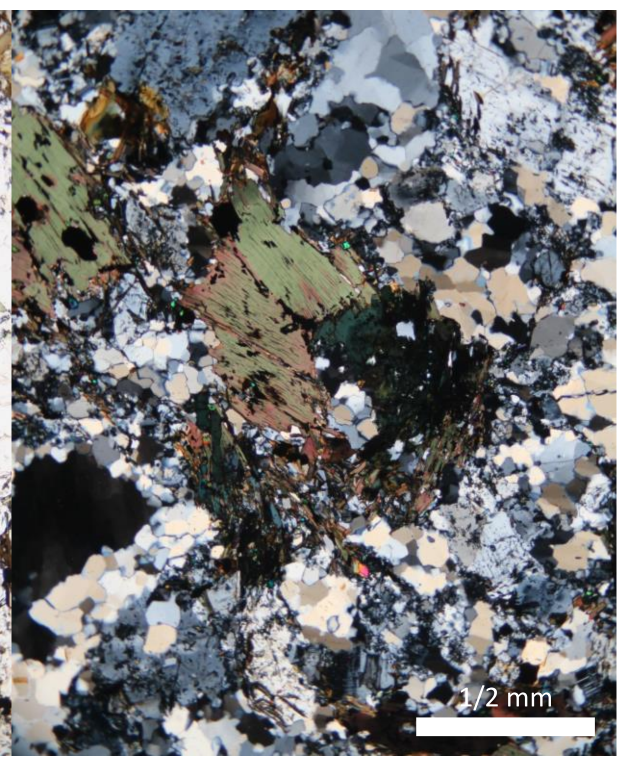
Sample 6	**Metasandstone**
Hand Sample/Field Description:	More felsic than samples 1-5 5-10 mm grain size

Petrographic Analysis	**Composition**	**Notes**
Primary Minerals	Quartz (55%)	Subgrains
Secondary Phases	Biotite (25%)	
	Plagioclase (13%)	
	Epidote (7%)	

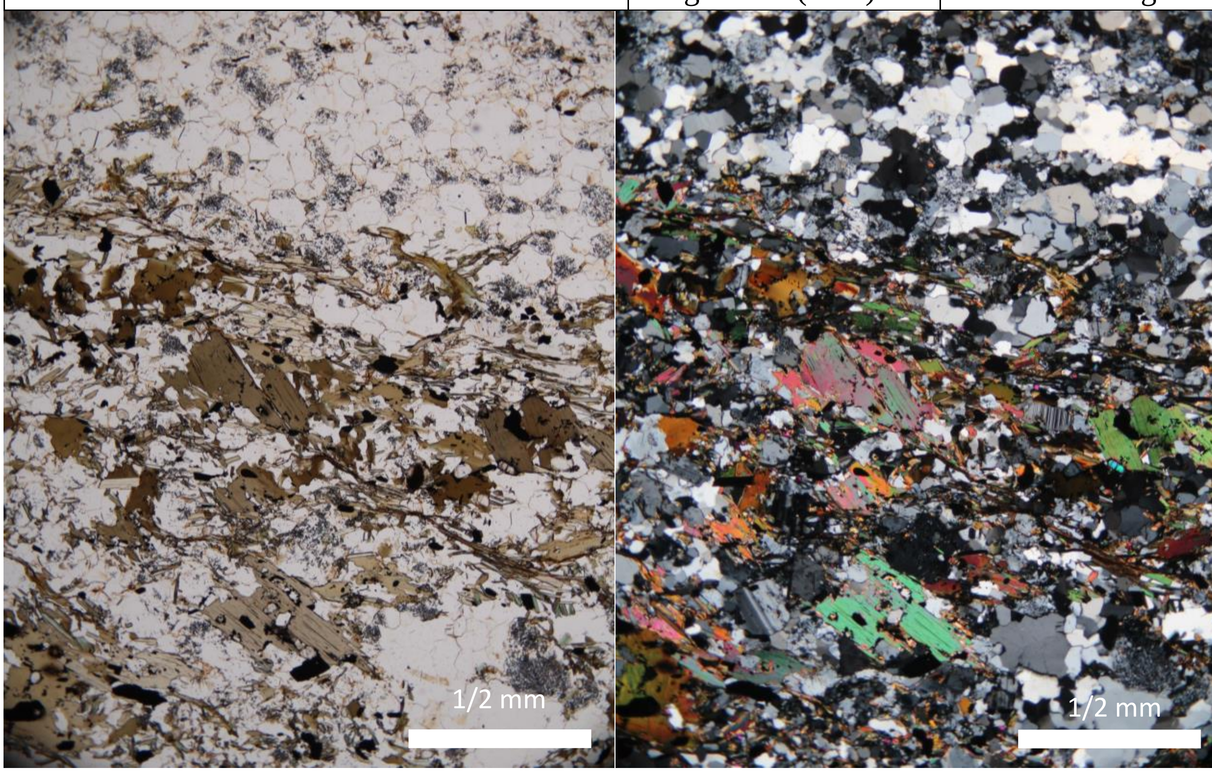






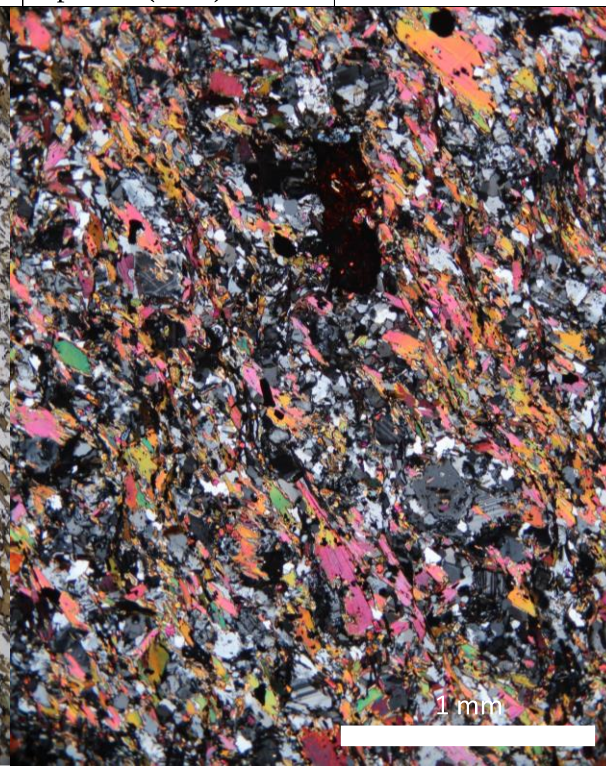


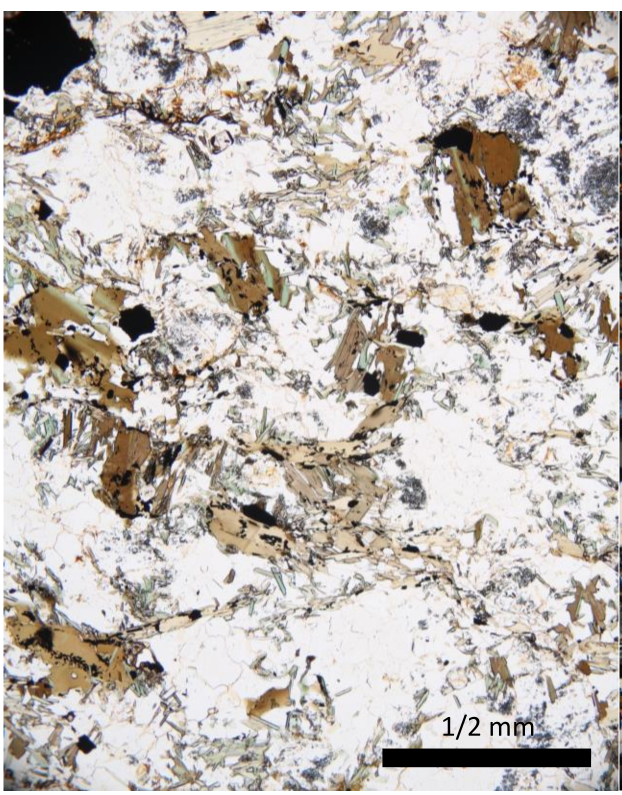
Sample 7A	**Meta-diamictite**	
Hand Sample/Field Description:	Inclusions assumed to be sandstone (>10 cm)	
Petrographic Analysis	**Clast Composition**	**Notes**
Primary Minerals	Quartz (50%)	
Secondary Phases	Opaque minerals (5%)	
	Sausserite (45%)	Alteration minerals that are too small to identify in thin section
	Matrix Composition	
	Quartz (65%)	Grain and grain boundary migration
	Biotite (25%)	
	Plagioclase (10%)	Exhibits zoning



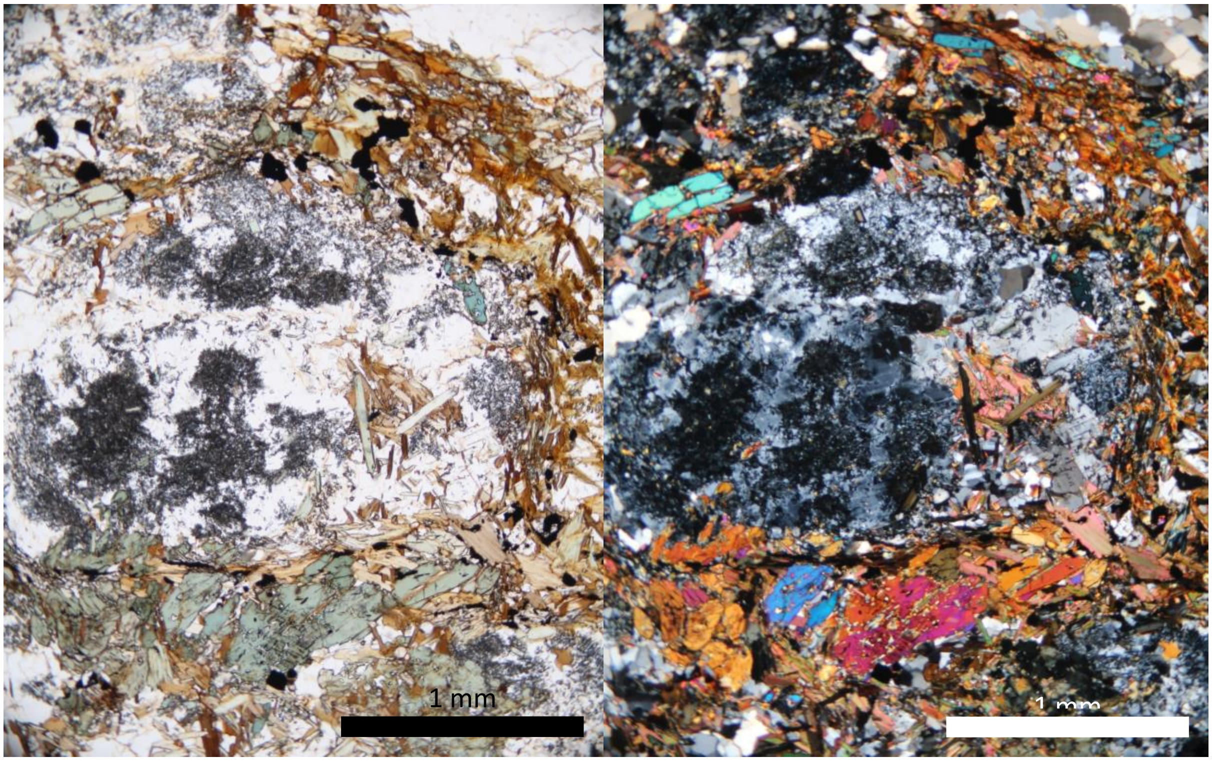
Sample 7B	**Meta-diamictite**	
Hand Sample/Field Description:	Inclusions assumed to be sandstone (>10 cm)	
Petrographic Analysis	**Clast Composition**	**Notes**
Primary Minerals	Biotite (60%)	
	Quartz (10%)	
Secondary Phases	Plagioclase (10%)	Zoning
	Matrix Composition	

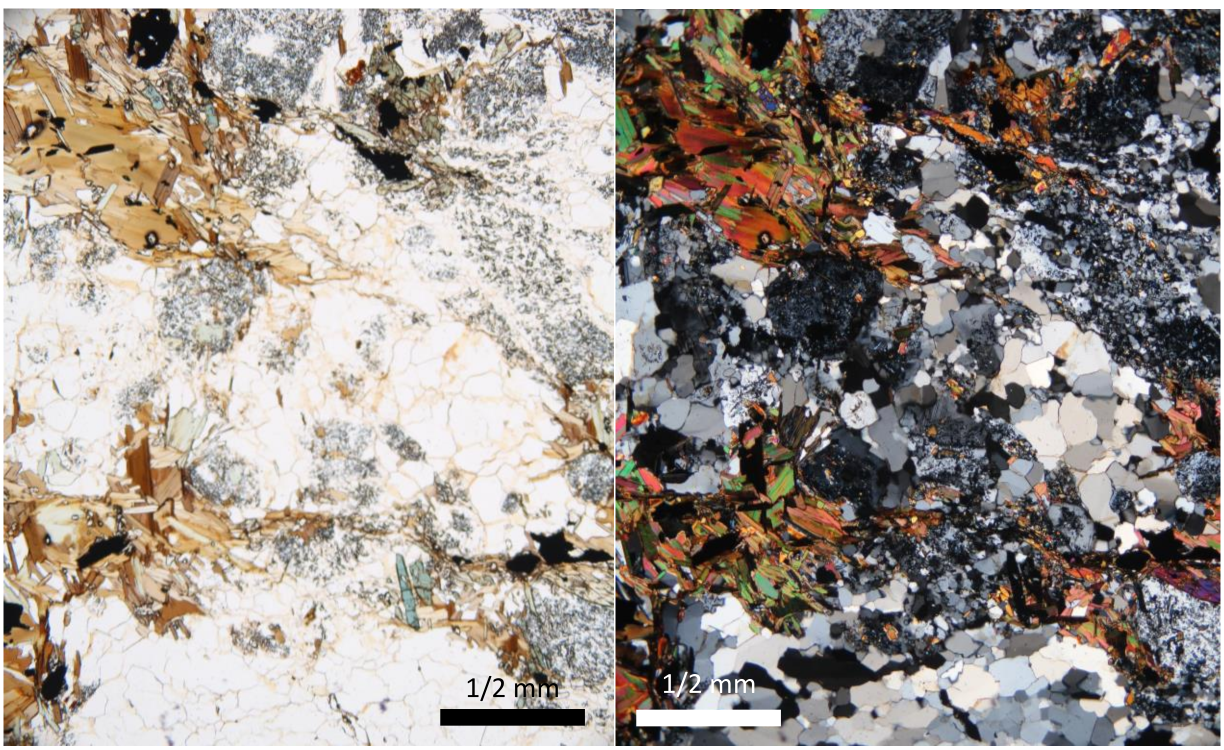
Primary Minerals	Quartz (60%)	
Secondary Phases	Biotite (15%)	
	Epidote (10%)	





Sample 8	**Metasandstone**	
Hand Sample/Field Description:	Granitic composed of plagioclase, quartz, and biotite ½ cm grain size	
Petrographic Analysis	**Composition**	**Notes**
Primary Minerals	Quartz (58%)	"Pebbles" - large groups of subgrains
Secondary Phases	Plagioclase (25%)	Largely saussuritized
	Biotite (12%)	Radiating between quartz "pebbles"
	Hornblende (3%)	Blue-green rims, brown core
	Opaque minerals (2%)	





Sources

Absar, A, 1991, Hydrothermal Epidote – An Inidcator of Temperature and Fluid Composition, Geological Survey of India, vol. 38, p. 625-628.

Burgess, J.L., Lev, S., Swan, C.M., and Szlavecz, K., 2009, Geologic and edaphic controls on a serpentine forest community: Northeastern Naturalist, v. 16, p. 366–384, https:// doi .org /10 .1656 /045 .016 .0527.

Crowley, W.P., 1976, The Geology of the Crystalline Rocks near Baltimore and Its Bearing on the Evolution of the Eastern Maryland Piedmont: Maryland Geological Survey Report of Investigations 27, 40 p.

Gray, A.L., 1901, The basic rocks of northeastern Maryland, and their relation to the granite, The American Geologist, v. 28, p. 134–176.

Guice, G.L., Ackerson, M.R., Holder, R.M., George, F.R., Browning-Hanson, J.F., Burgess, J.L., Foustoukos, D.I., Becker, N.A., Nelson, W.R., and Viete, D.R., 2021, Suprasubduction zone ophiolite fragments in the central Appalachian orogen: Evidence for mantle and Moho in the Baltimore Mafic Complex (Maryland, USA): Geosphere, v. 17, p. 1– 21, https://doi.org/10.1130/GES02289.1

Hanan, B.B., and Sinha, A.K., 1989, Petrology and tectonic affinity of the Baltimore mafic complex, Maryland, in Mittwede, S.K., and Stoddard, E.F., eds., Ultramafic Rocks of the Appalachian Piedmont: Geological Society of America Special Paper 231, p. 1–18, https://doi.org/10.1130/SPE231-p1.

Higgins, M.W., and Conant, L. B., 1990, The Geology of Cecil County, Maryland, Maryland Geological Survey, no. 37.

Hirth, G., and Tullis, J., 1992, Dislocation creep regimes in quartz aggregates, Journal of Structural Geology, https://doi.org/10.1016/0191-8141(92)90053-Y

Hopson, C.A., 1964, The crystalline rocks of Howard and Montgomery Counties, in The Geology of Howard and Montgomery Counties: Baltimore, Maryland, Maryland Geological Survey, p. 27–215.

Karabinos, P., Macdonald, F., and Crowley, J., 2017, Bridging the Gap Between the Foreland and Hinterland I: Geochronology and Plate Tectonic Geometry of Ordovician Magmatism and Terrane Accretion on the Laurentian Margin of New England, American Journal of Science, p. 515–554.

Morgan, B.A., 1977, The Baltimore Complex, Maryland, Pennsylvania, and Virginia, in Coleman, R.G., and Irwin, W.P., eds., North American Ophiolites: Oregon Department of Geology and Mineral Industries Bulletin, v. 95, p. 41–49.

Nelson, S. A., 2015, Magmas and Igneous Rocks, Tulane University, https://www2.tulane.edu/~sanelson/eens1110/igneous.htm#:~:text=Mafic%2FBasaltic%20-%201000-1200%20o%20C%20Intermediate%2FAndesitic%20-,800-1000%20o%20C%20Felsic%2FRhyolitic%20-%20650-800%20o%20C.

Orndorff, W.D., 1999, Crystalline bedrock of the lowermost Susquehanna Valley: implications for the tectonic assembly of the central Appalachian Piedmont, in The Mid-Atlantic Piedmont: Tectonic Missing Link of the Appalachians, Geological Society of America, p. 73-91.

Rutter, E. H., and Elliott, D., 1979, A Discussion on Natural Strain and Geological Structures, The Royal Society Publishing, v. 283, p. 203-219.

Shank, S., Marquez, L., and Hardy, C., 2015, Field Geology of the Baltimore Mafic Complex, Pennsylvania-Maryland State Line, in Field Trip Guide: Northeastern Section of the Geological Society of America: Lancaster, Pennsylvania, Northeastern Section of the Geological Society of America, p. 35–51.

Sinha, A.K., Hanan, B.B., and Wayne, D.M., 1997, Igneous and metamorphic U-Pb zircon ages from the Baltimore mafic complex, Maryland Piedmont, in Sinha, A.K., Whalen, J.B., and Hogan, J.P., eds., The Nature of Magmatism in the Appalachian Orogen: Geological Society of America Memoir 191, p. 275–286, https://doi.org/10.1130/0-8137-1191-6.275

Southwick, D.L., 1969, Crystalline rocks of Harford County, in Southwick, D.L., and Owens, J.P., eds., The Geology of Harford County, Maryland: Baltimore, Maryland Geological Survey, p. 1–76.

Wylie, A. G., and Candela, P. A., 1999, Metallic Mineral Deposits-Chromite. In C. H. Shultz (Ed.), The Geology of Pennsylvania, Pennsylvania Geological Survey and the Pittsburgh Geological Society, p. 589–595