GEOCHEMISTRY AND ORIGINS OF ANORTHOSITES FROM THE DULUTH COMPLEX, MINNESOTA

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Geology 422

Petrology

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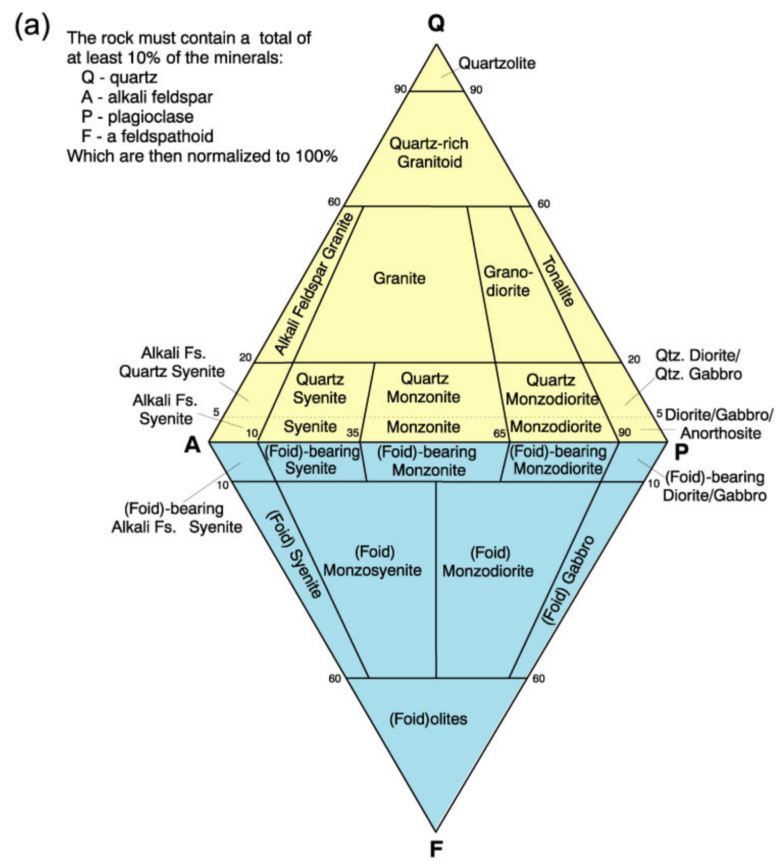
What is Anorthosite?

- By definition:
  - Phaneritic
  - More than 90% plagioclase feldspar



Winter, 2010

What is Anorthosite?

- Composed of:
  - Albite
    - $NaAlSi_3O_8$
  - Anorthite
    - $CaAl_2Si_2O_8$

Albite (webmineral.com)

Anorthite (webmineral.com)

What is Anorthosite?

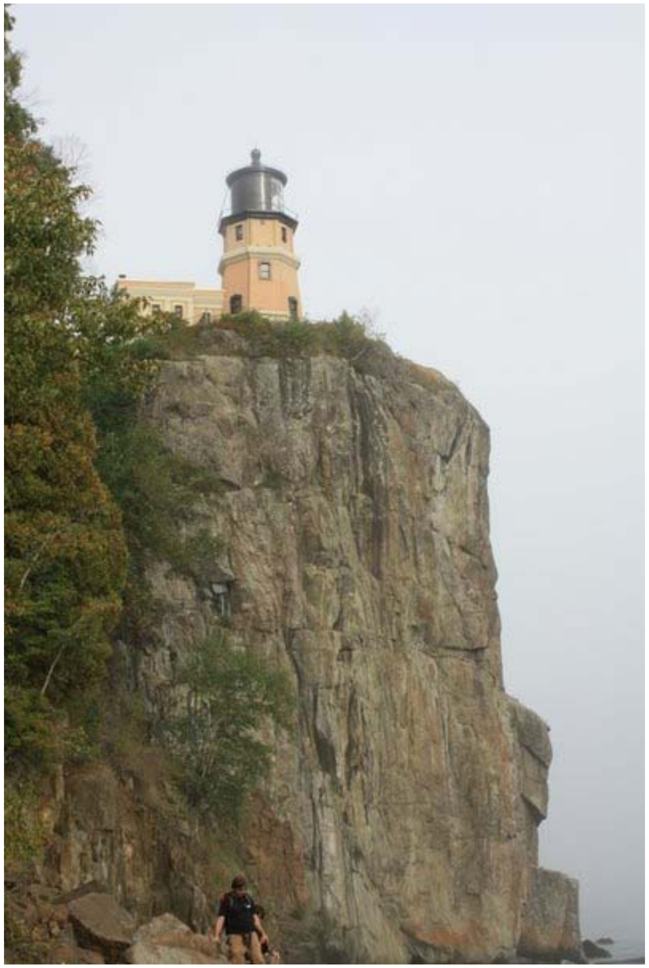
- Six major anorthosite occurrences (Ashwal, 1993)
  1. Archean anorthosite plutons
  2. Proterozoic “massif-type” anorthosite plutons
  3. 1-cm to 100-m thick layers in layered mafic intrusions
  4. Thin cumulate layers in ophiolites/oceanic crust
  5. Small inclusions in other rock types (xenoliths and cognate inclusions)
  6. Lunar highland anorthosites

Area of Study

- Duluth Complex
  - Layered mafic intrusive complex
  - Keweenawan rift system
    - 1.13 billion years old (Sims and Morey, 1972)
    - Failed midcontinent rift system
  - Mostly gabbro and granite
    - Contain anorthosite inclusions

Area of Study

- Anorthosite inclusions can vary greatly in Duluth Complex (Morrison et al., 1983)
  - Size: less than 1 cm to several hundred meters
  - Shape: angular to rounded
  - Color: grey, white, brown, green, pink, purple



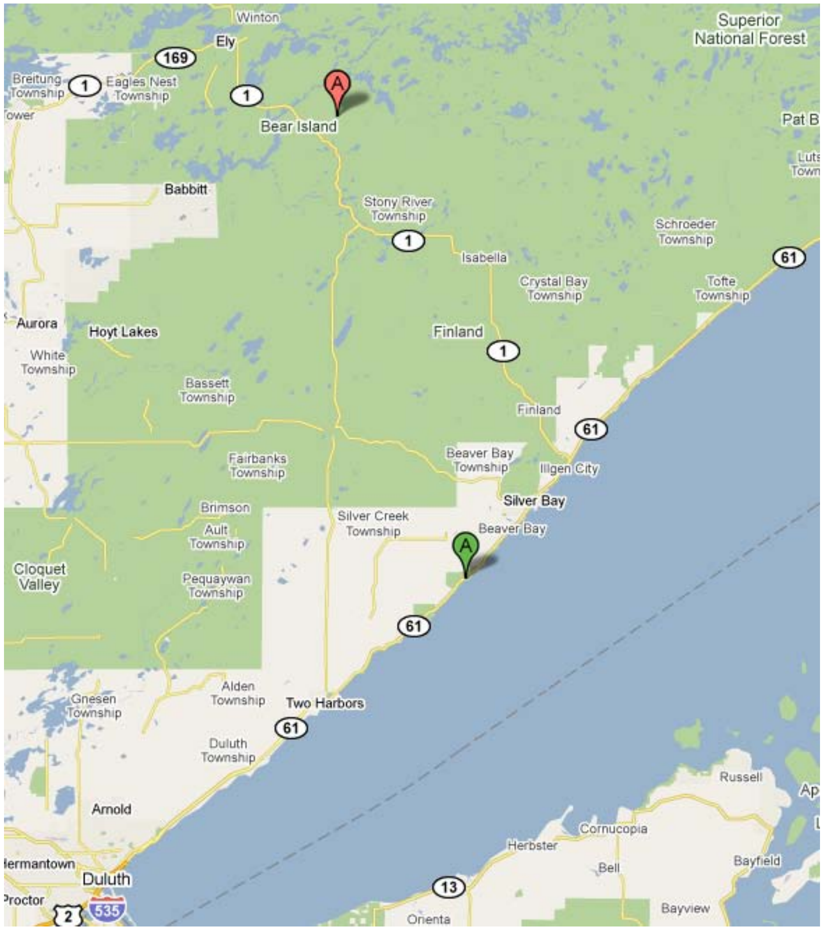
Ginsbach, 2009

Area of Study

- Anorthosite inclusions can be one of four groups (Morrison et al., 1983)
  - Inclusions that have been recrystallized
  - Igneous inclusions
  - Intermediate (halfway between metamorphic and igneous)
  - Cataclastic and brecciated inclusions containing deformation not found in the host rock

Area of Study

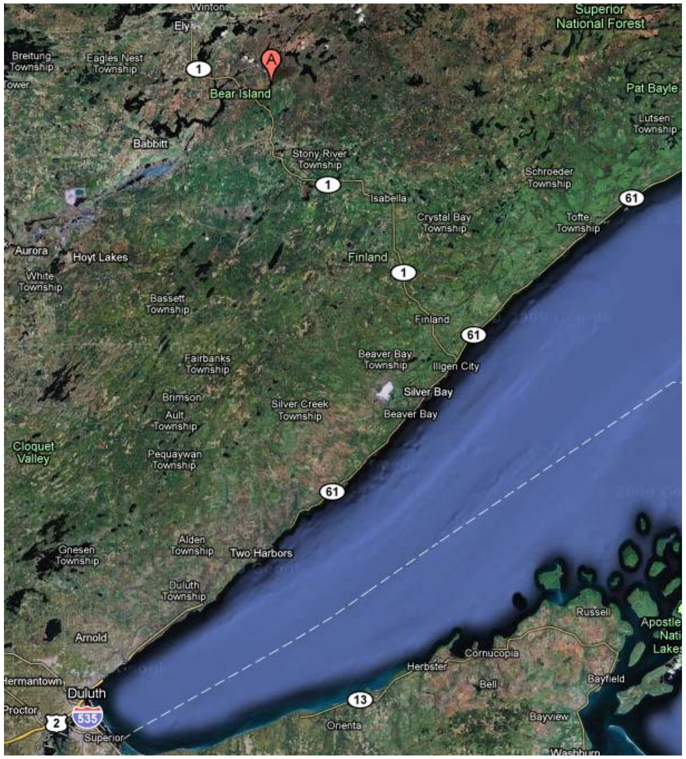
- Two locations in Duluth Complex
  - Near Bogberry Lake (Red A)
  - Near Split Rock Lighthouse (Green A)

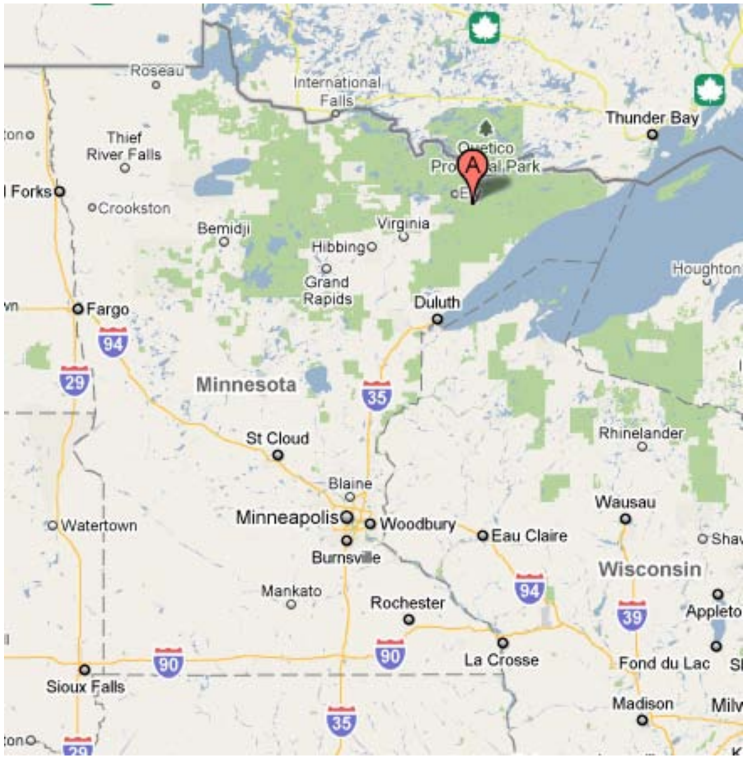


http://maps.google.com

Area of Study

Near Bogberry Lake (NBL)





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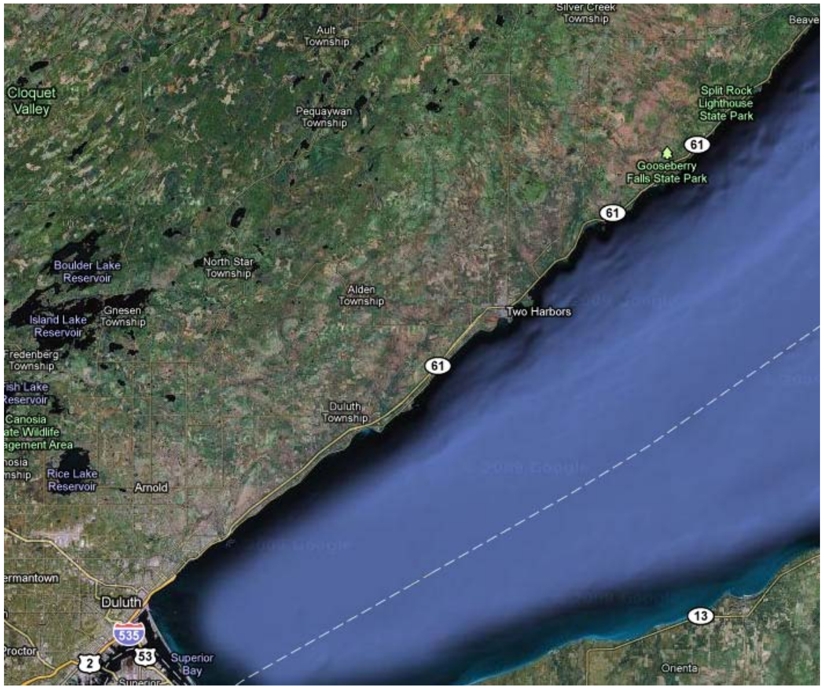
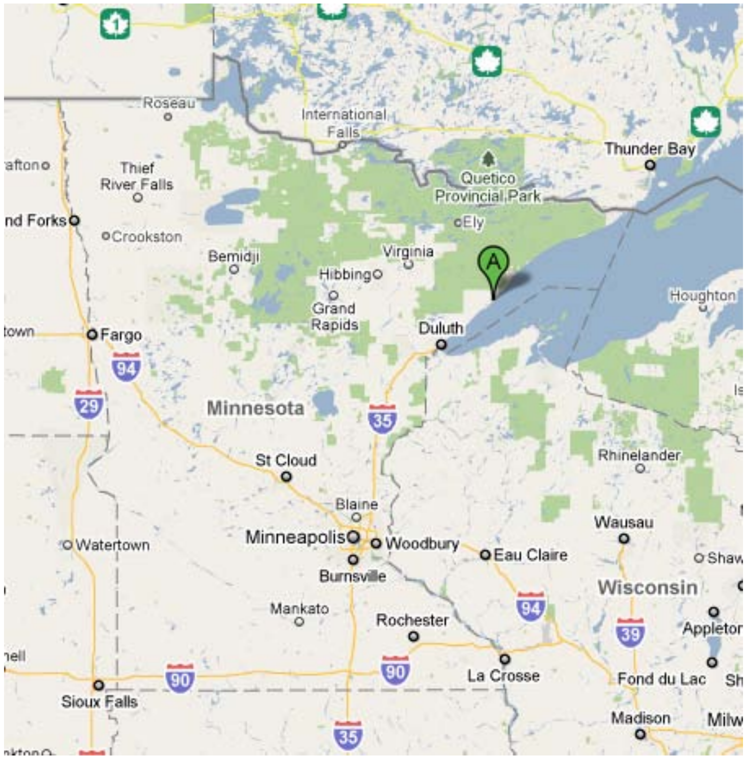
Area of Study

Near Split Rock Lighthouse (NSR)

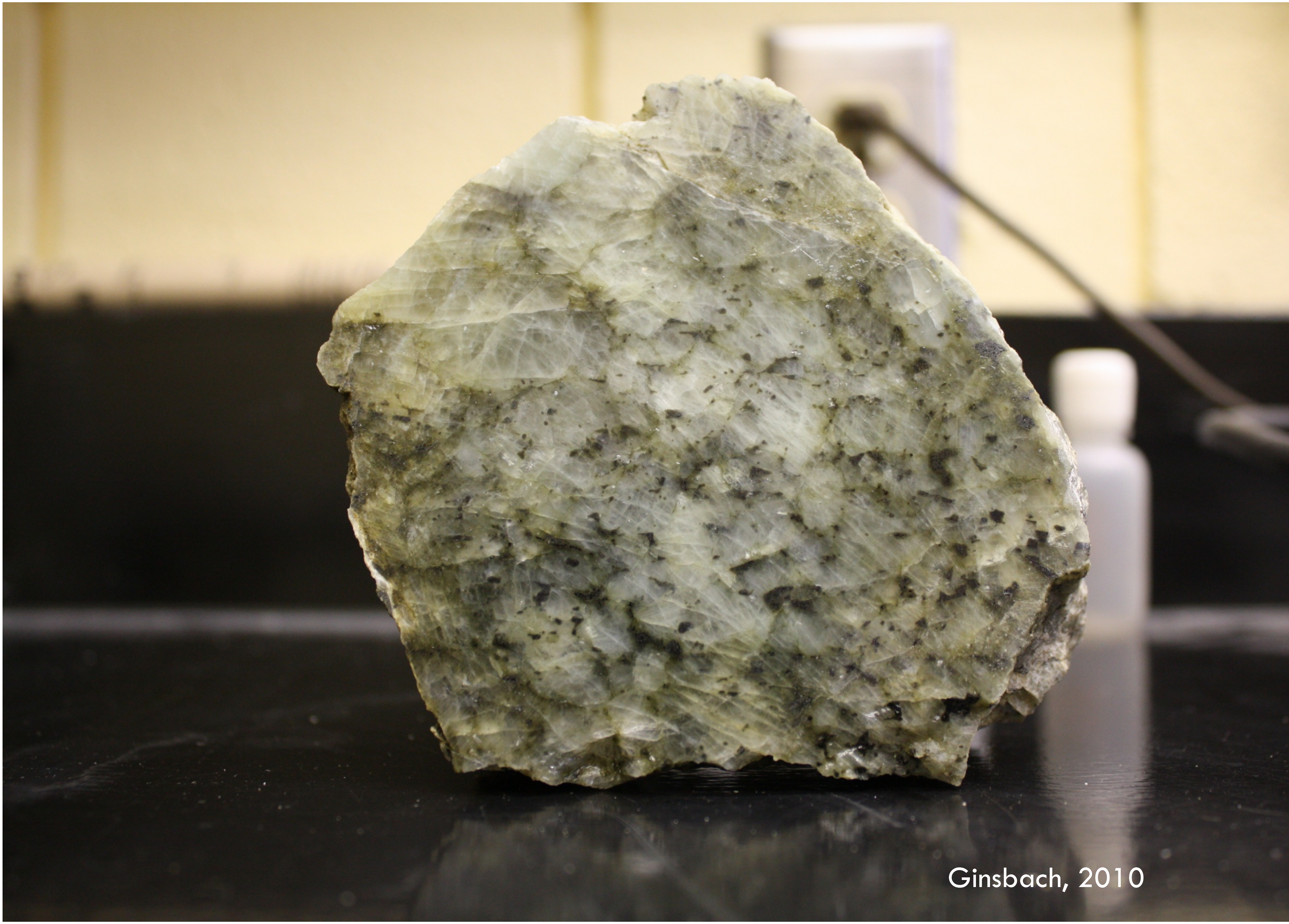




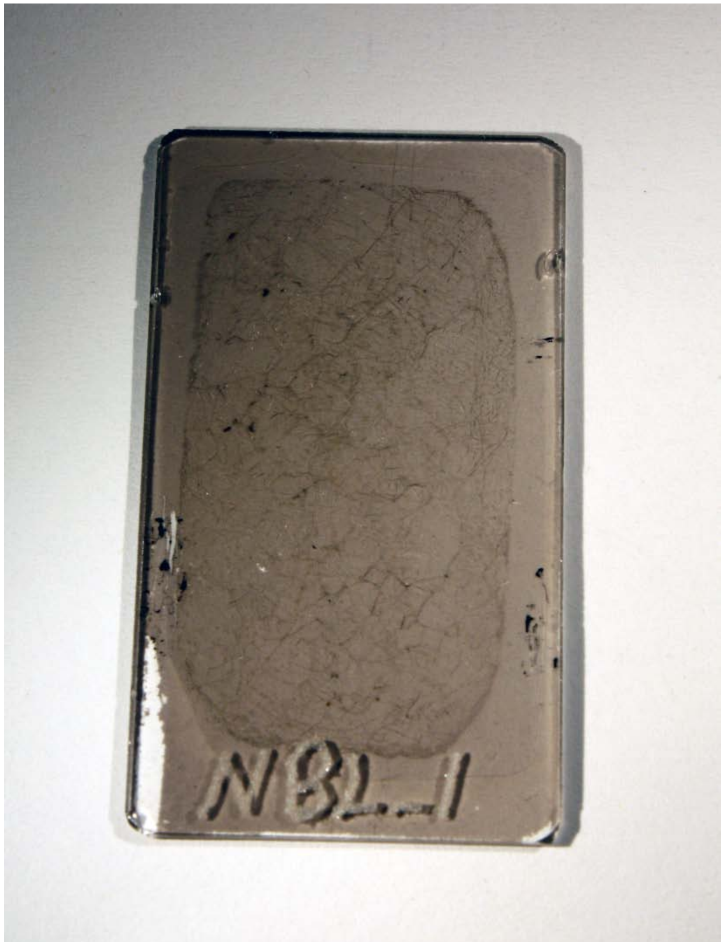
http://maps.google.com

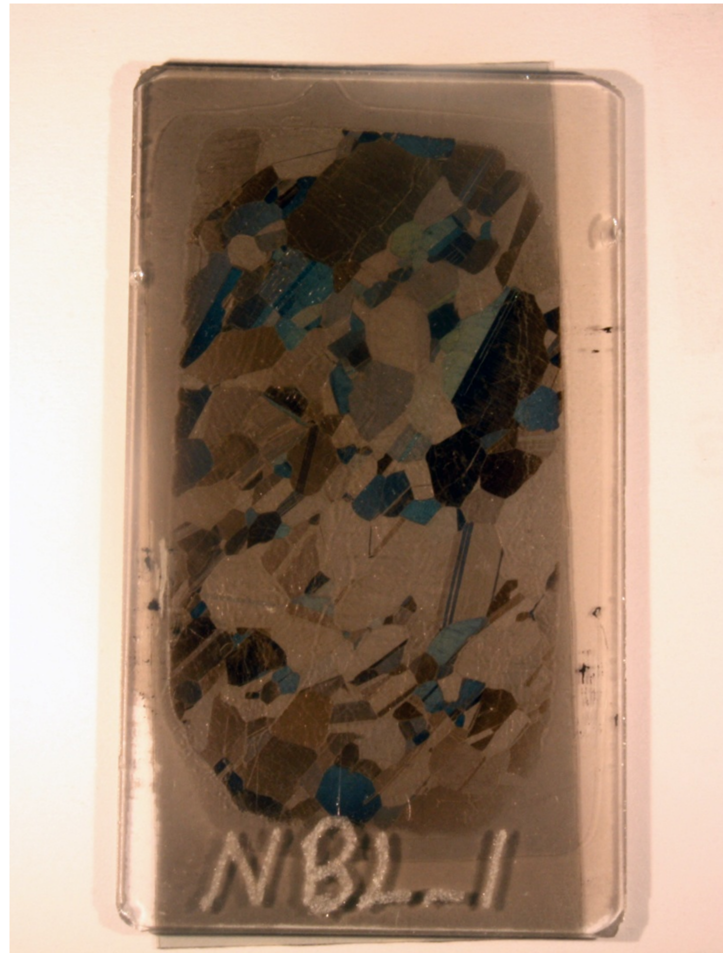
Samples - NBL

Ginsbach, 2010


Ginsbach, 2010

Samples - NBL





Ginsbach, 2010

Samples - NSR

Ginsbach, 2010


Ginsbach, 2010

Samples - NSR

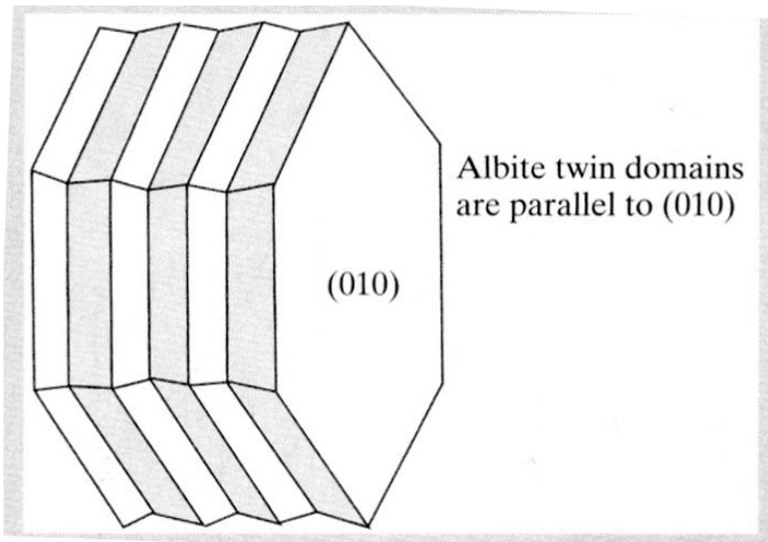
Ginsbach, 2010

Purpose

- The purpose of this project was to use various methods to get the ratios of albite and anorthite for the samples of anorthosite.
- Methods used include the Michel-Lévy (ML) method, X-ray diffraction (XRD), and scanning electron microscopy (SEM).
- Once albite and anorthite ratios have been determined an approximate temperature of crystallization can be determined.

Michel-Lévy Method

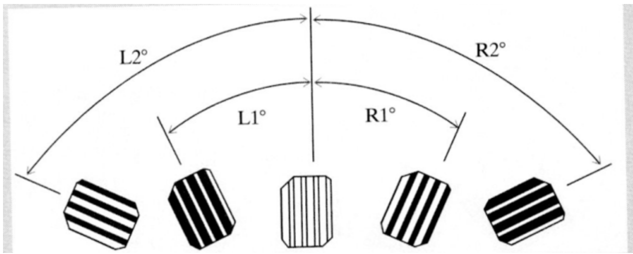
- Based upon angle of extinction
- (010) planes of albite twins varies systematically with composition (Perkins and Henke, 2004)
- Twins must have (010) plane perpendicular to stage



Perkins and Henke, 2004

Michel-Lévy Method

- To find suitable grain:
  - Use XP light and find a grain that has all twin lamellae the same interference color
    - Record angle
- To get measurements
  - Rotate stage right so that one set of twins go extinct
    - Record angle
  - Rotate stage left so other set goes extinct
    - Record angle



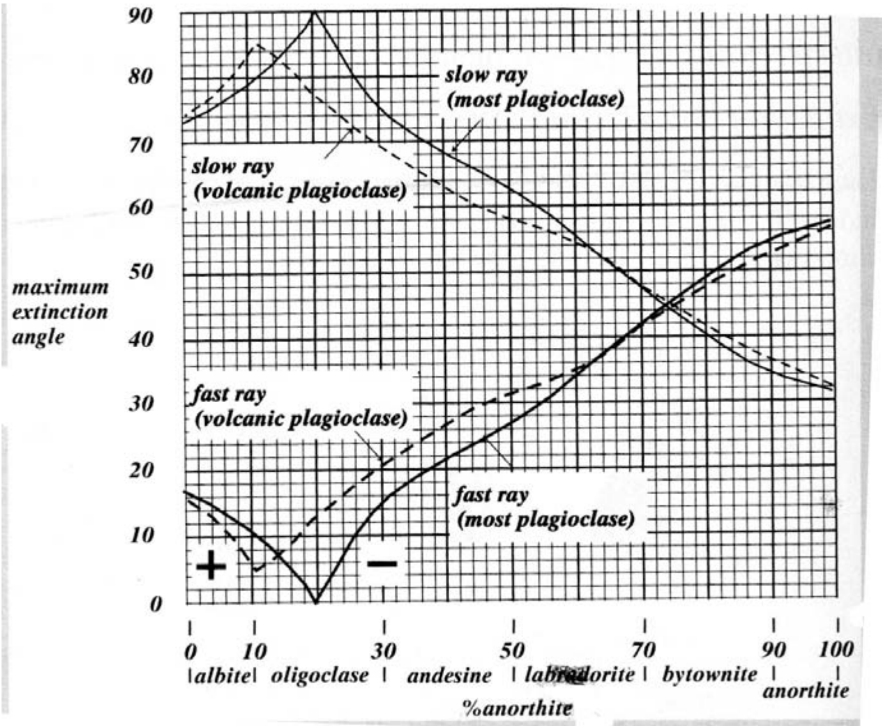
Perkins and Henke, 2004

Michel-Lévy Method

- Check to make sure angles are no more than 4° different
- Average left and right
- Can continue rotation in either direction to get a second extinction angle
  - Hard to determine

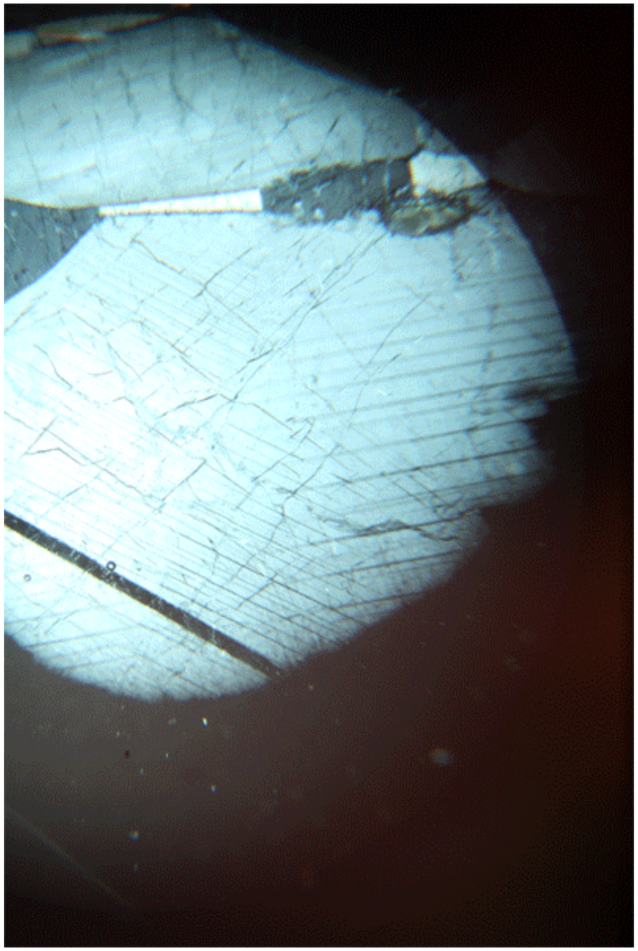
Michel-Lévy Method

- Repeat for a number of grains (at least six)
- Take average of readings
- Compare to chart



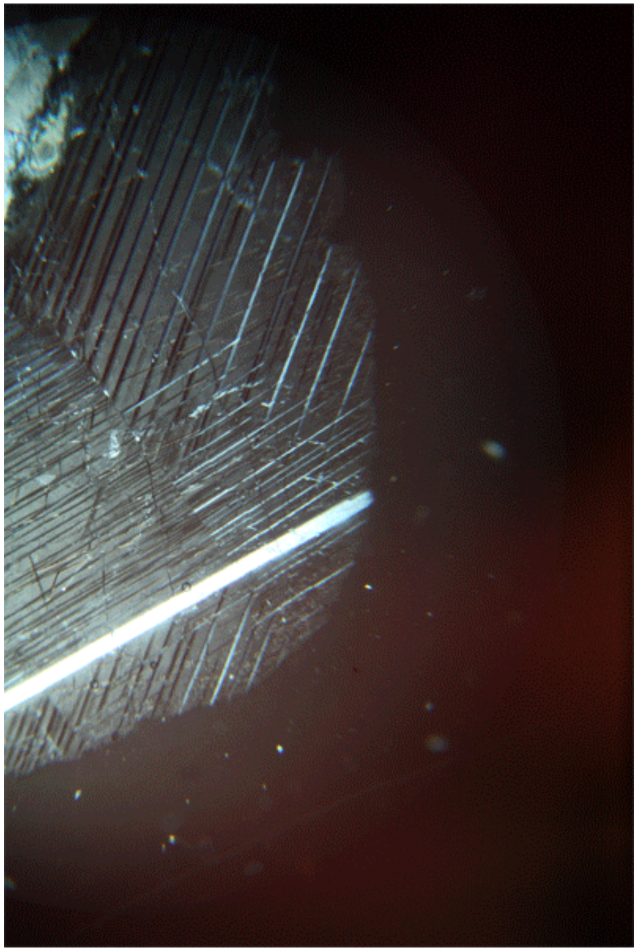
Perkins and Henke, 2004

Michel-Lévy Method



Ginsbach, 2010

Michel-Lévy Method



Ginsbach, 2010

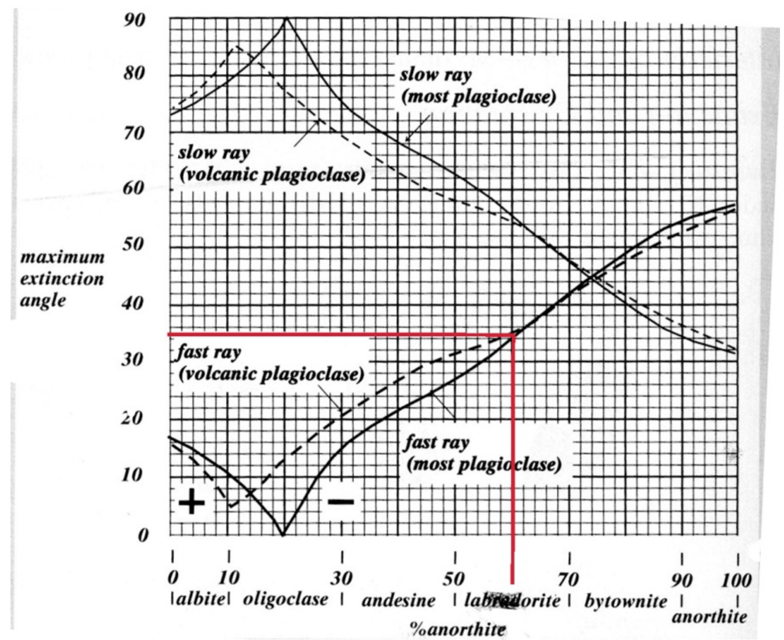
Michel-Lévy Method - NBL

Ldeg	L	Base	R	Rdeg	Dif	Valid?	Avg
37	205	168	132	36	1	Yes	36.5
40	292	252	221	31	9	No	
38	300	262	232	30	8	No	
27	244	217	168	49	-22	No	
33	334	301	264	37	-4	Yes	35
30	235	205	171	34	-4	Yes	32
35	280	245	212	33	2	Yes	34
25	225	200	155	45	-20	No	
30	215	185	145	40	-10	No	
40	320	280	237	43	-3	Yes	41.5
35	315	280	247	33	2	Yes	34
39	196	157	120	37	2	Yes	38
31	326	295	249	46	-15	No	
38	223	185	145	40	-2	Yes	39
32	247	215	183	32	0	Yes	32
33	255	222	187	35	-2	Yes	34
30	238	208	181	27	3	Yes	28.5
32	267	235	200	35	-3	Yes	33.5
31	275	244	213	31	0	Yes	31
38	209	171	141	30	8	No	

Ginsbach, 2010

Michel-Lévy Method - NBL

	41.5
	39
	38
	36.5
	35
	34
	34
	34
	33.5
	32
	32
	31
	28.5
Average	**34.53846**



Result: An_{60}

Perkins and Henke, 2004

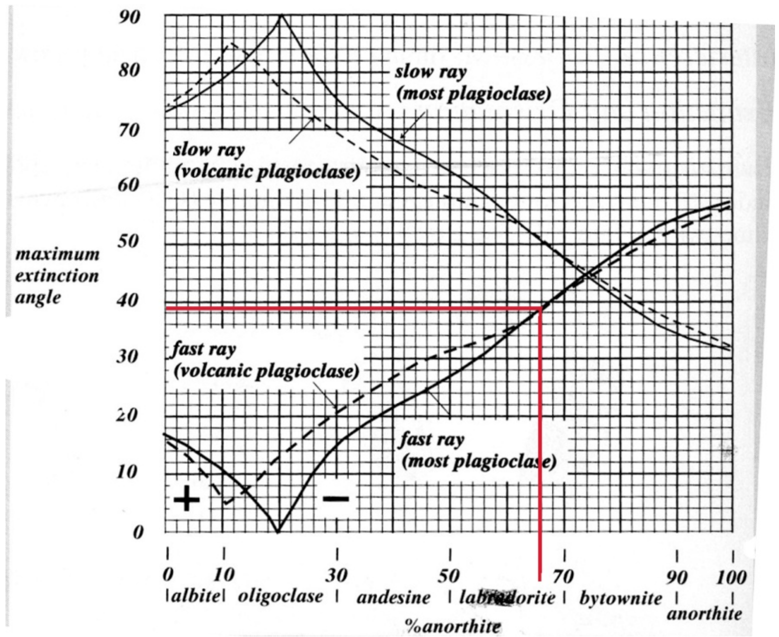
Michel-Lévy Method - NSR

Ldeg	L	Base	R	Rdeg	Dif	Valid?	Avg
37	40	3	324	39	-2	Yes	38
37	37	360	327	36	1	Yes	36.5
38	45	7	326	41	-3	Yes	39.5
40	41	8	327	41	-1	Yes	40.5
38	39	1	322	39	-1	Yes	38.5

Ginsbach, 2010

Michel-Lévy Method - NBL

	38
	36.5
	39.5
	40.5
	38.5
Average	**38.6**



Result: An_{66}

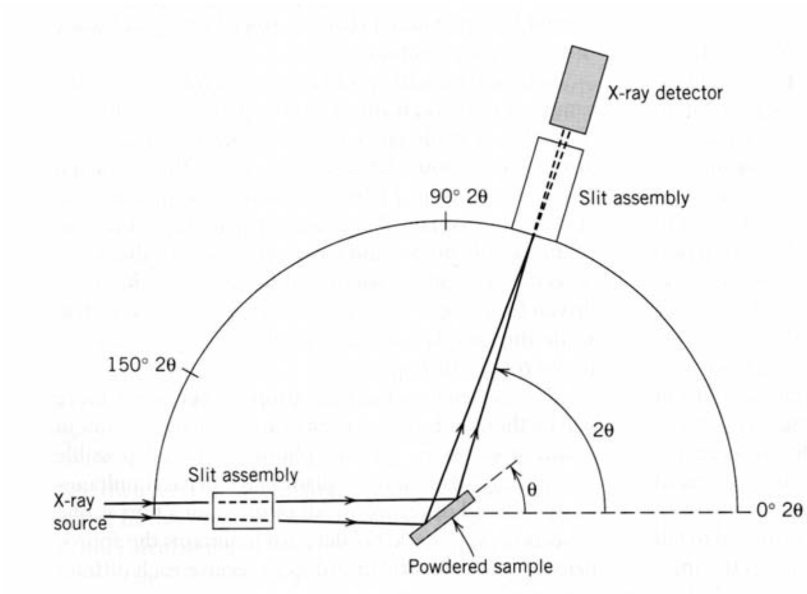
Perkins and Henke, 2004

Michel-Lévy Method

- NBL
  - An_{60}
- NSR
  - An_{66}

X-Ray Diffraction

- Method used for mineral identification and structural information (Klein and Dutrow, 2008)
- Monochromatic X-rays strike powered mineral
  - X-rays are diffracted
  - Angle of diffraction (expressed as 2Θ) can be determined
  - Peak height is directly proportional to intensity of diffracted effect



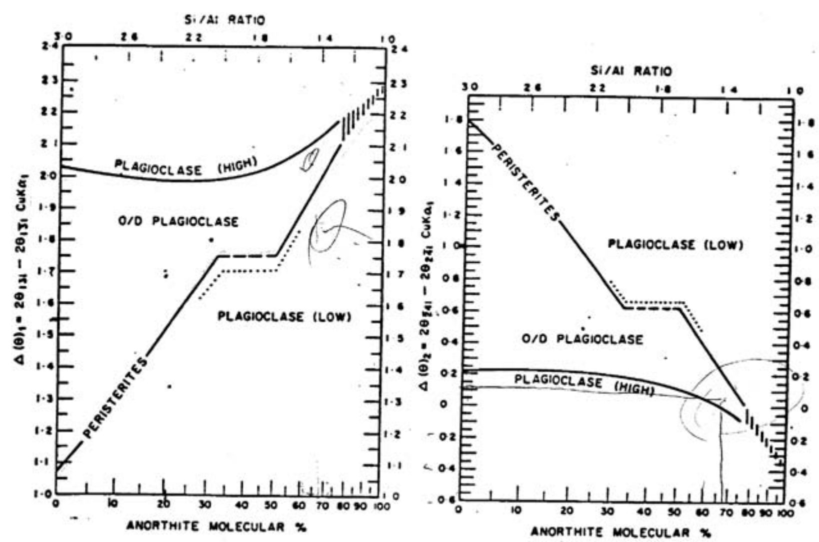
Klein and Dutrow, 2008

X-Ray Diffraction

- To prepare sample-
  - Break sample into small pieces
  - Grind sample into fine powder
    - No tactile grains
  - Place fine powder on glass slide
  - Wet with ethanol
  - Allow to dry
  - Bring to XRD machine - let tech run sample
    - Dr. Angel Ugrinov
  - Receive data output
  - Use software to remove background, find peaks, and determine mineral matches

X-Ray Diffraction

- Composition of plagioclase can be determined based on specific Miller Indices (Bambauer et al., 1967)
- Method 1
  - $\Delta\Theta 1 = 2\Theta 131 - 2\Theta 1\text{-}31$
- Method 2
  - $\Delta\Theta 2 = 2\Theta\text{-}241 - 2\Theta 24\text{-}1$
- After determining differences in indices, plot on graphs

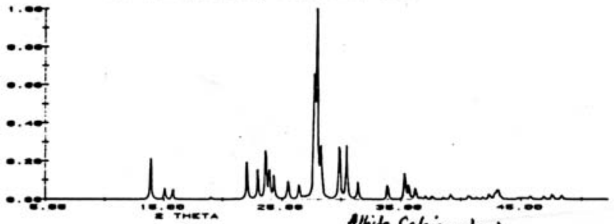


Bambauer et al., 1967

X-Ray Diffraction

Plagioclase Composition by XRD

This feldspar is used commercially as the abrasive component in some cleansers and as raw material for some ceramics. It occurs as very coarse grains in igneous rocks. Find the pattern(s) in the Mineral File which most closely matches these data.



2θ	d	I	Albite, Calcian, low 9-457	
25.52	3.488	10	3.49_{50}	$11\bar{2}$
26.45	3.367	7	3.36_{50}	$\bar{1}12$
27.79	3.208	60	3.20_{80}	$20\bar{2}$
28.00	3.184	100	3.18_{100}	040
28.34	3.147	25	3.15_{50}	$\bar{2}\bar{2}0$
29.85	2.990	30	2.98_{60}	$1\bar{3}1$
30.45	2.933	30	2.93_{70}	$0\bar{4}1$
31.40	2.846	10	2.84_{60}	131
33.90	2.643	8	2.65_{50}	$\bar{1}31$
35.34	2.538	15	2.55_{60}	$2\bar{4}\bar{1}$
36.34	2.470	4	2.47_{50}	$\bar{2}41$

Data are best obtained from a least squares refinement of unit cell data

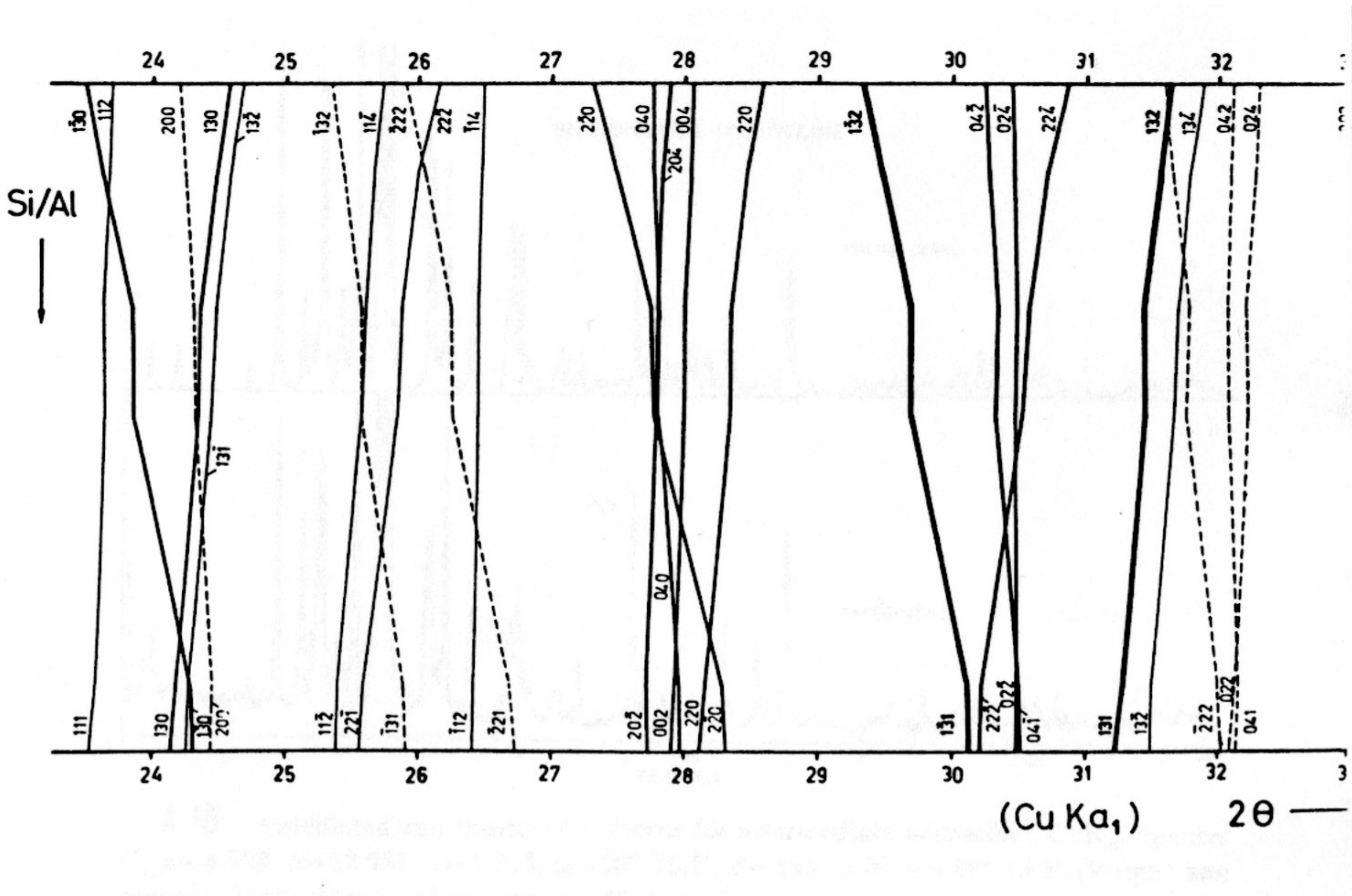
The composition of a plagioclase may be estimated from either $\Delta\theta_1 = 2\theta_{131} - 2\theta_{1\bar{3}1}$ or $\Delta(\theta)_2 = 2\theta_{\bar{2}41} - 2\theta_{24\bar{1}}$ if the structural state is known. The determination depends on the resolution of the necessary reflections. This resolution varies as the composition varies. For problem 4.2.3 identify the reflections needed.

$2\theta_{131}$ = 31.40 } 1.55
$2\theta_{1\bar{3}1}$ = 29.85

$2\theta_{\bar{2}41}$ = 36.34 } 1.00
$2\theta_{2\bar{4}\bar{1}}$ = 35.34

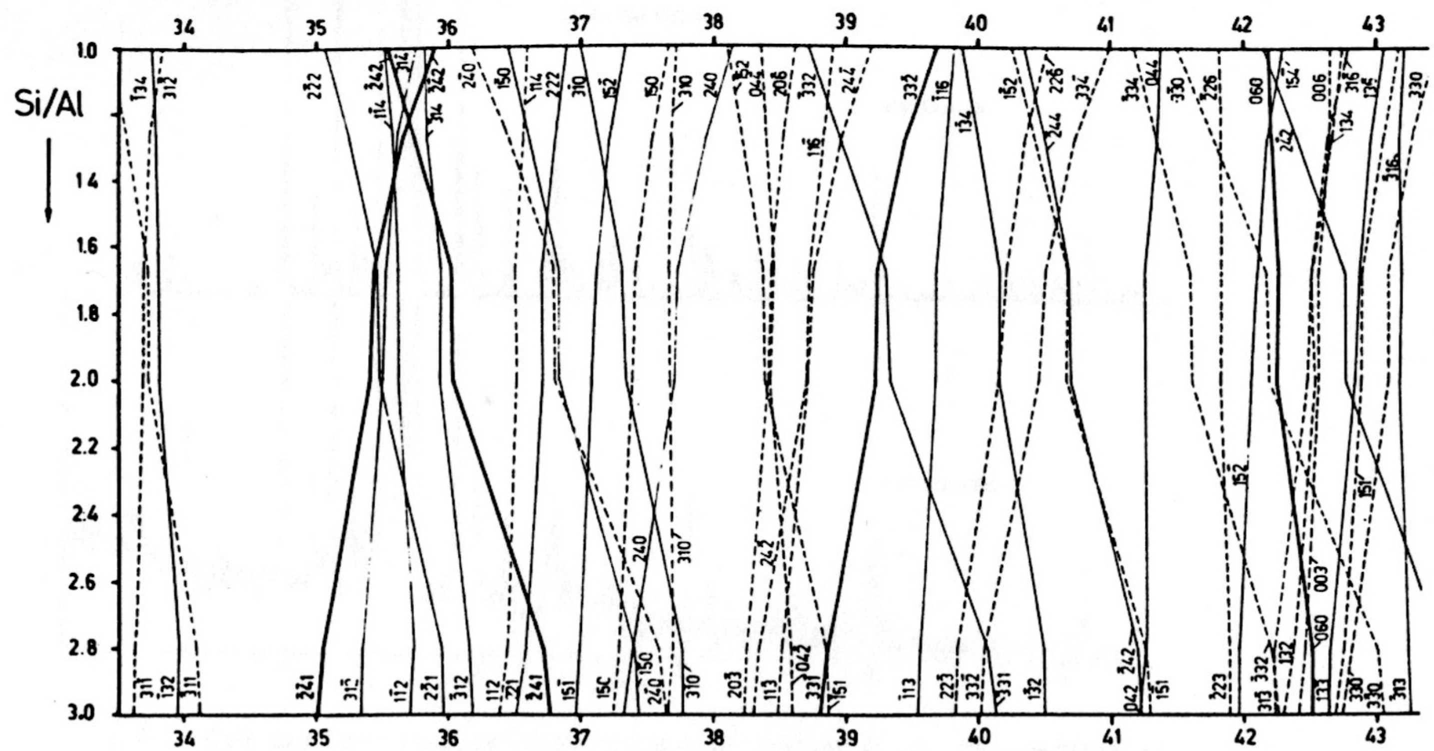
BSE, 2010

X-Ray Diffraction



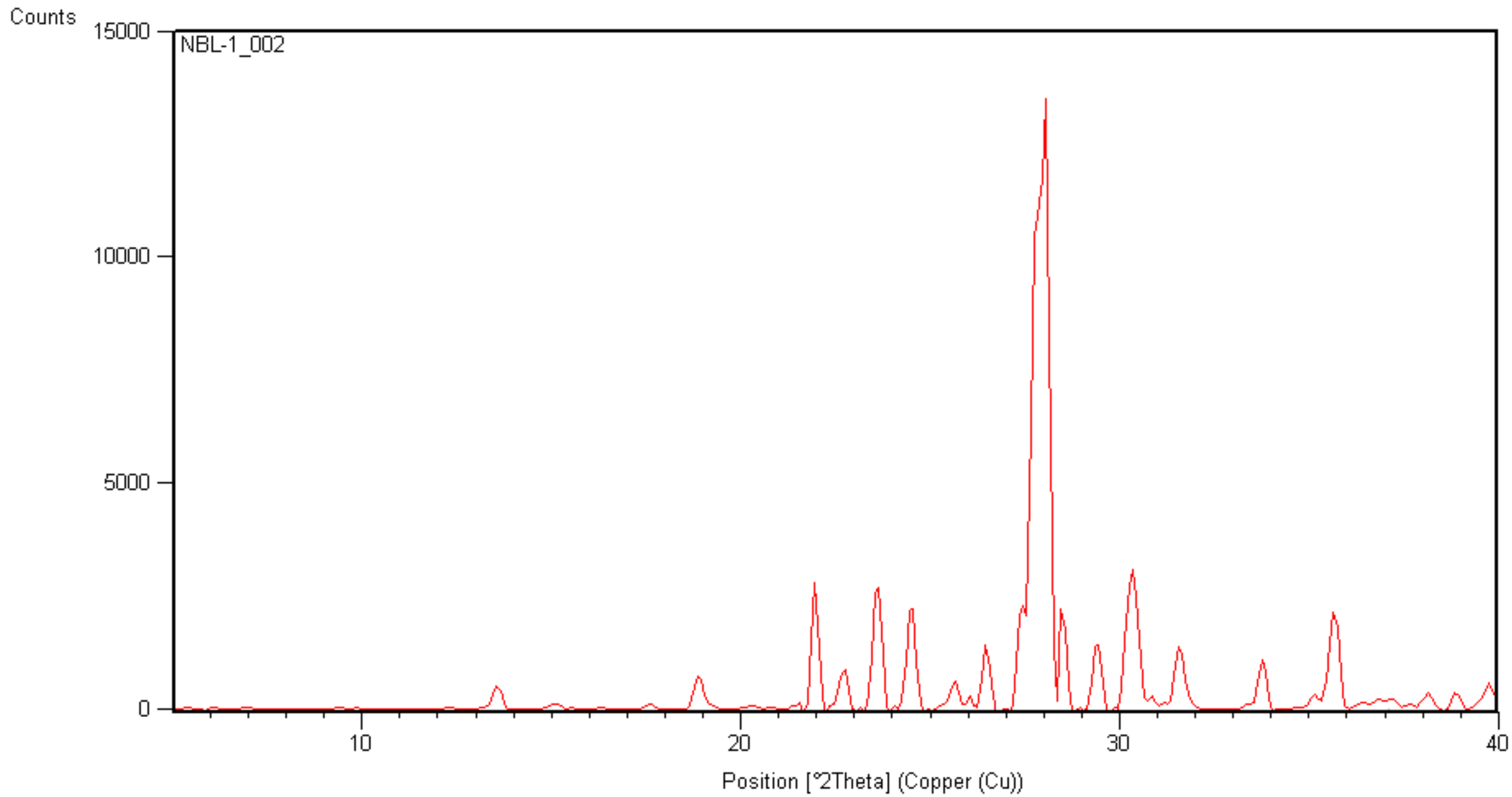
Ribbe, 1983

X-Ray Diffraction

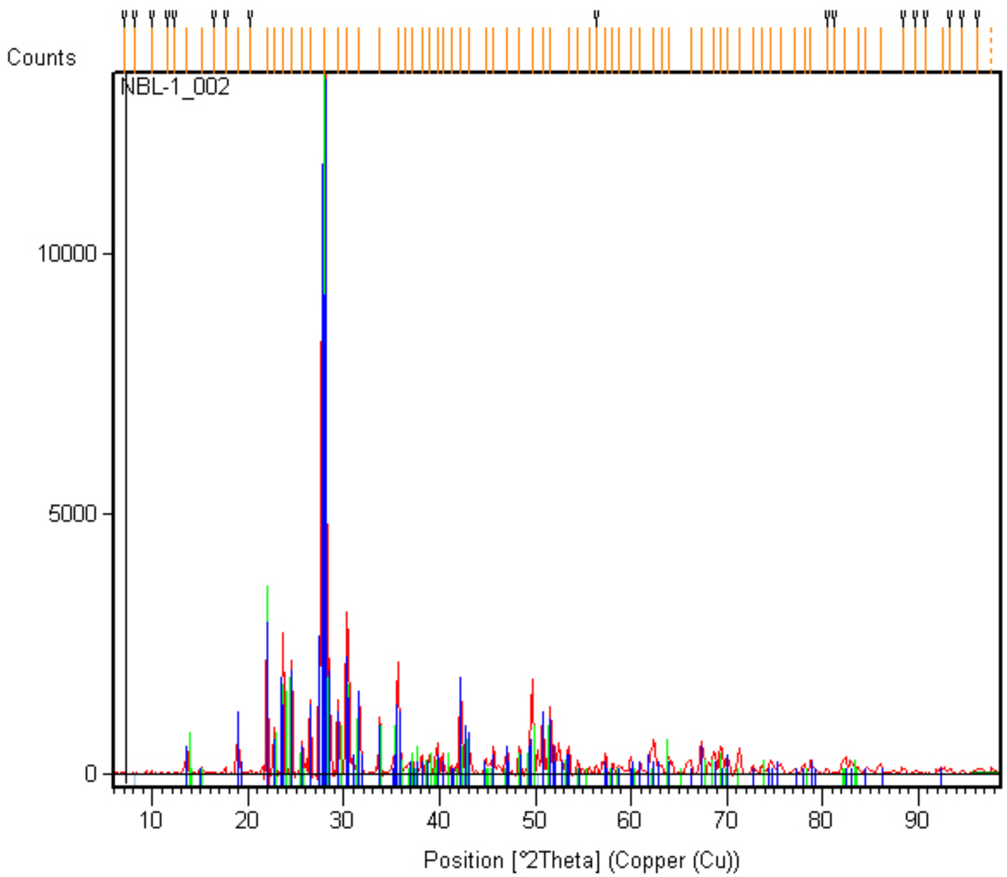


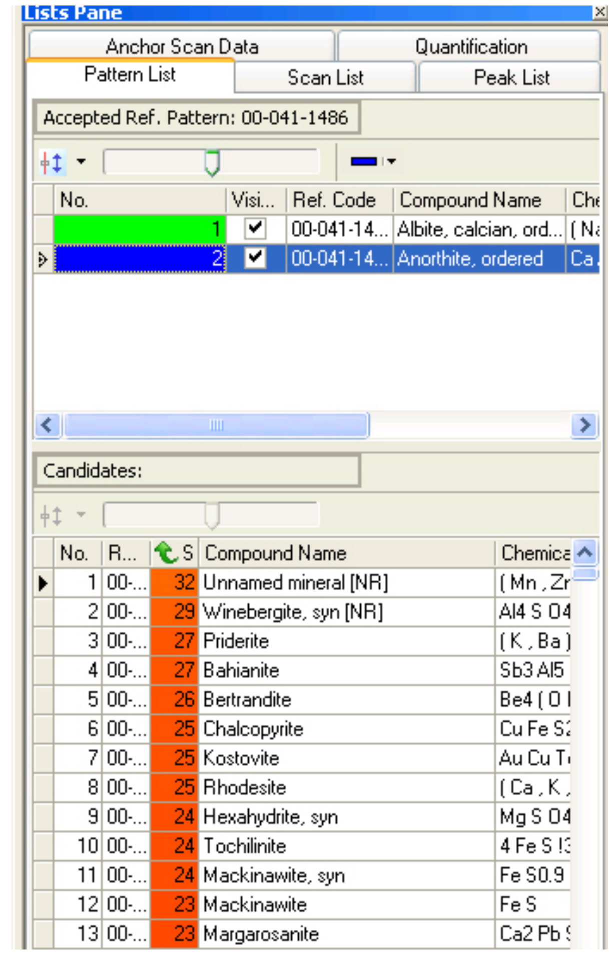
Ribbe, 1983

X-Ray Diffraction – NBL

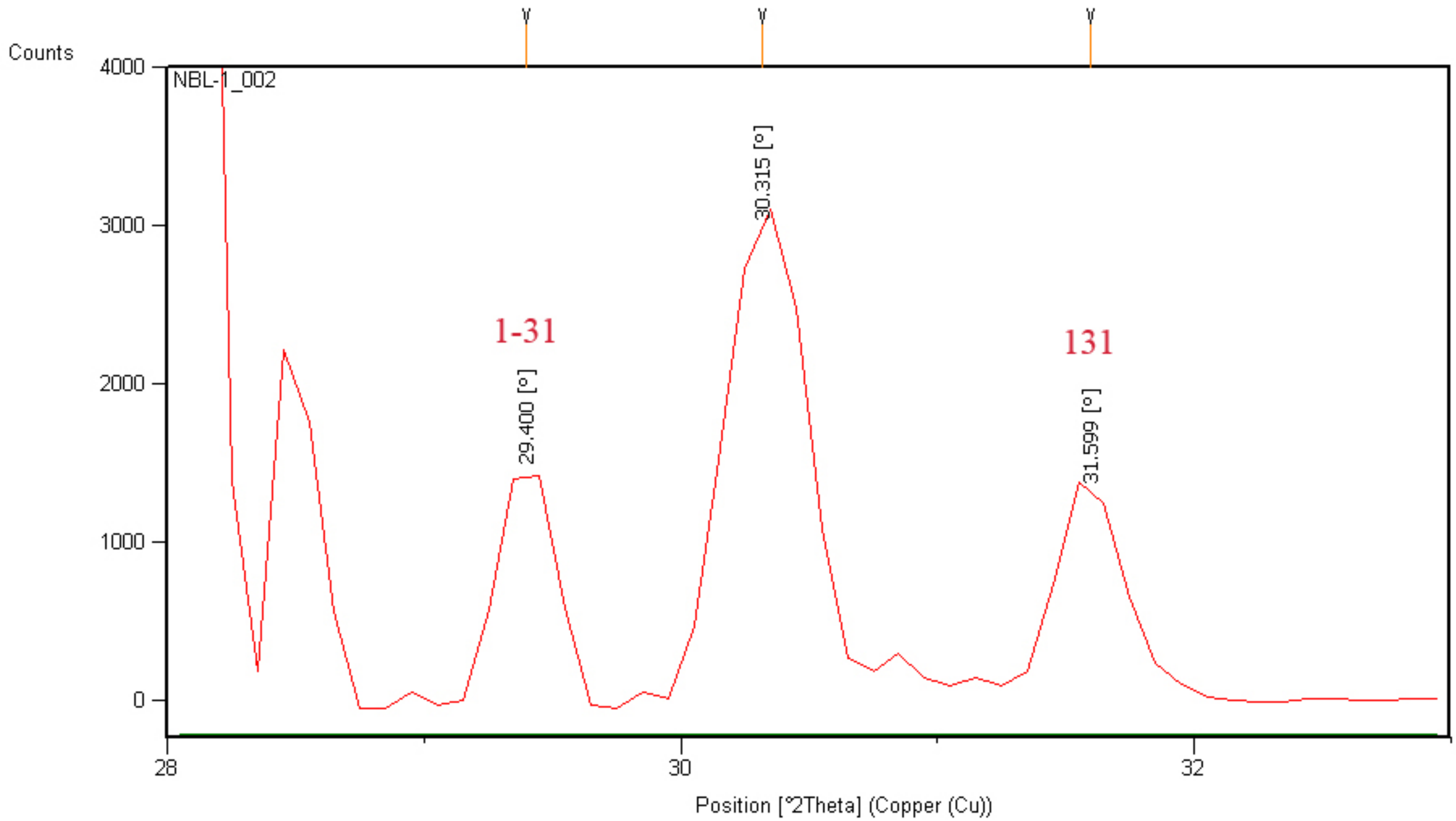


X-Ray Diffraction – NBL

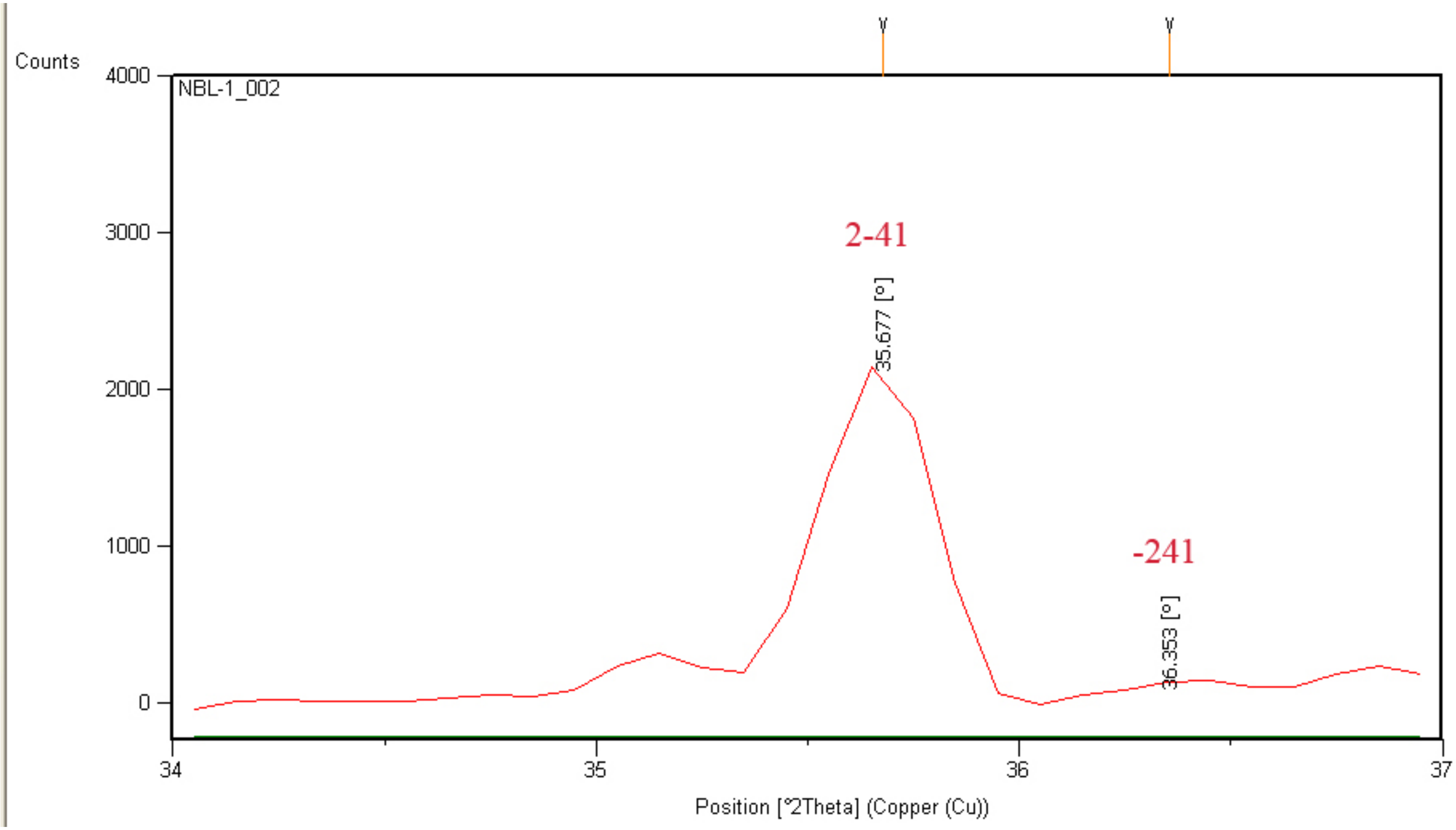




X-Ray Diffraction – NBL

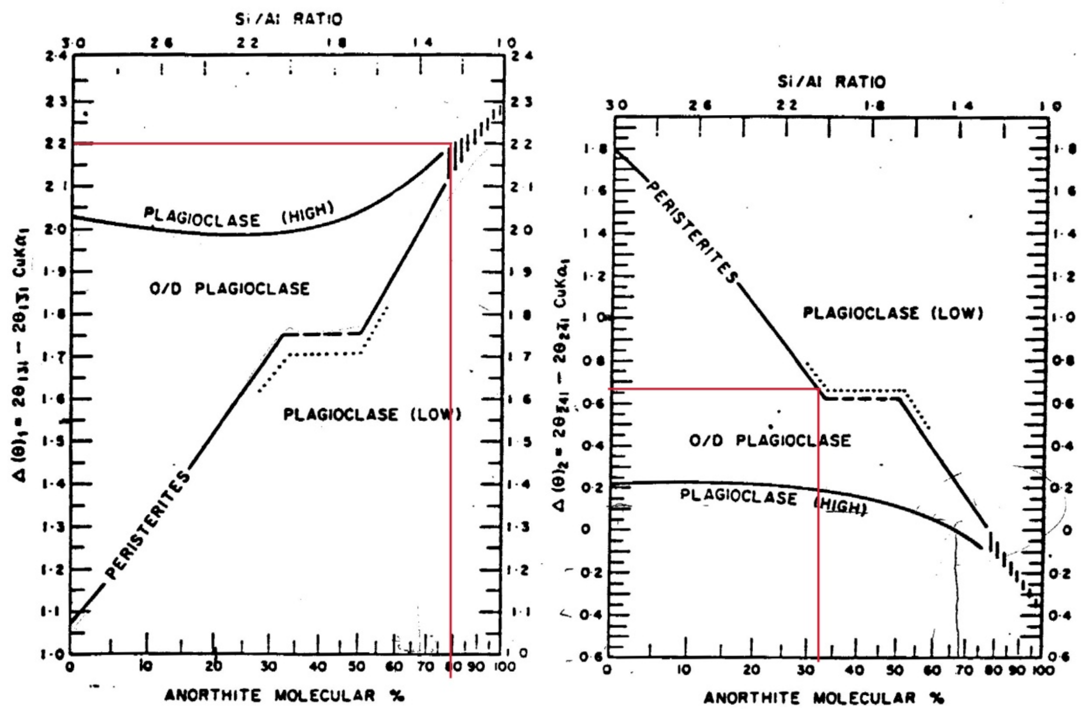


X-Ray Diffraction – NBL



X-Ray Diffraction – NBL

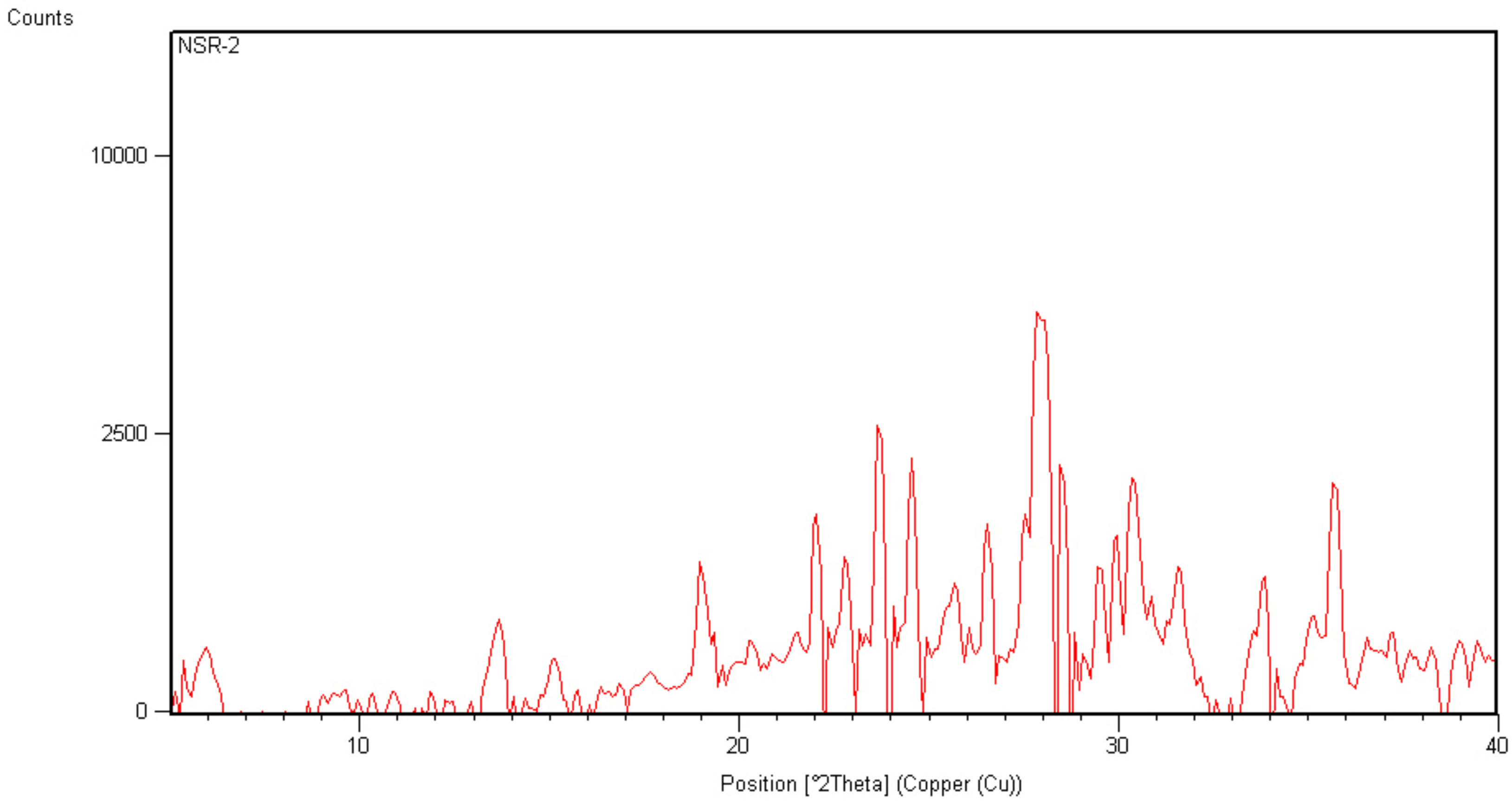
	NBL
1 3 -1	31.599
1 -3 1	29.4
Δ Θ 1	2.199
-2 4 1	36.353
2 -4 1	35.677
Δ Θ 2	0.676



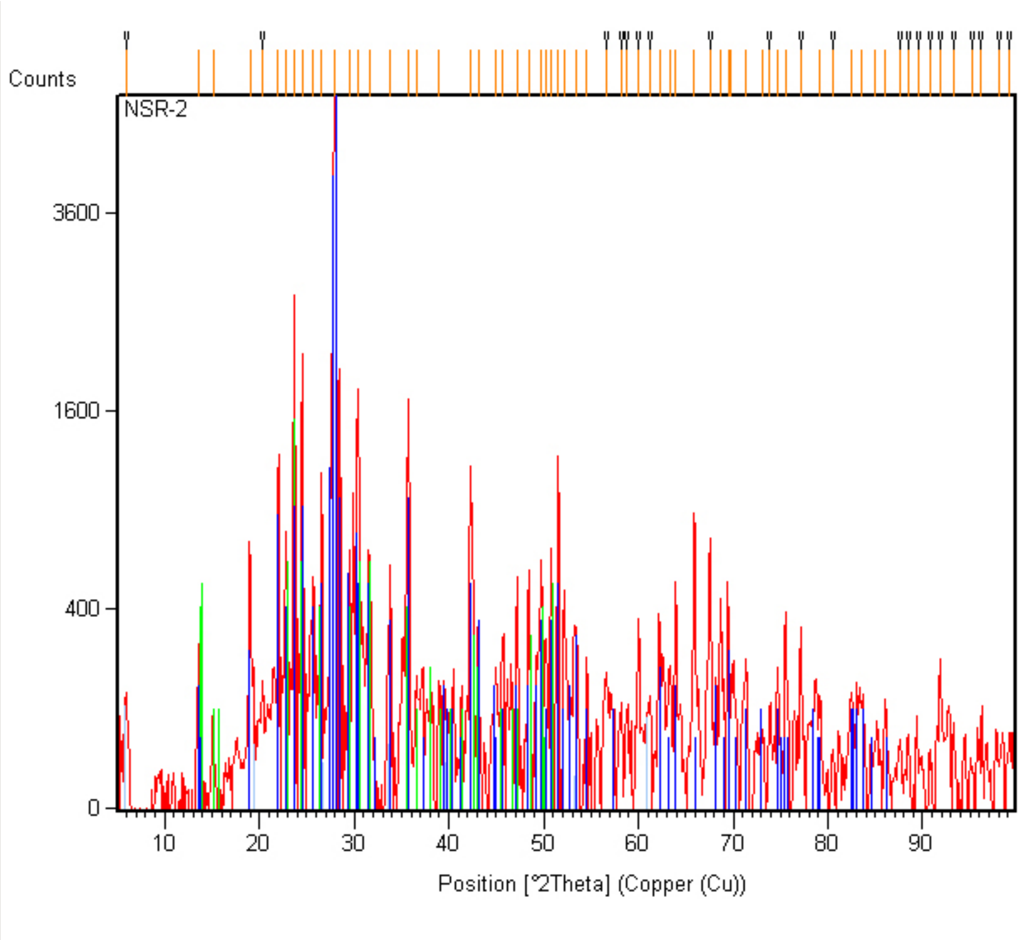
Δ Θ 1 – An_{80}
Δ Θ 2 – An_{33}

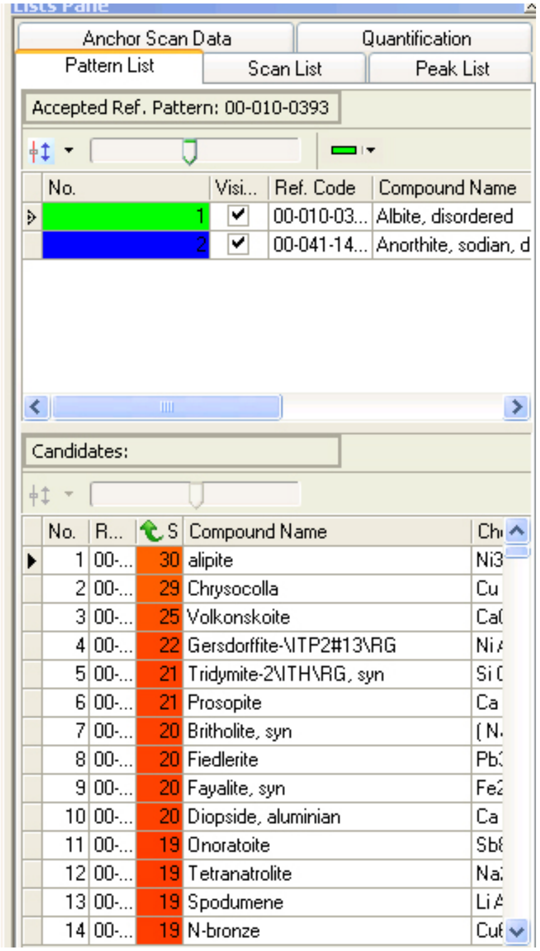
Bambauer et al., 1967

X-Ray Diffraction – NSR

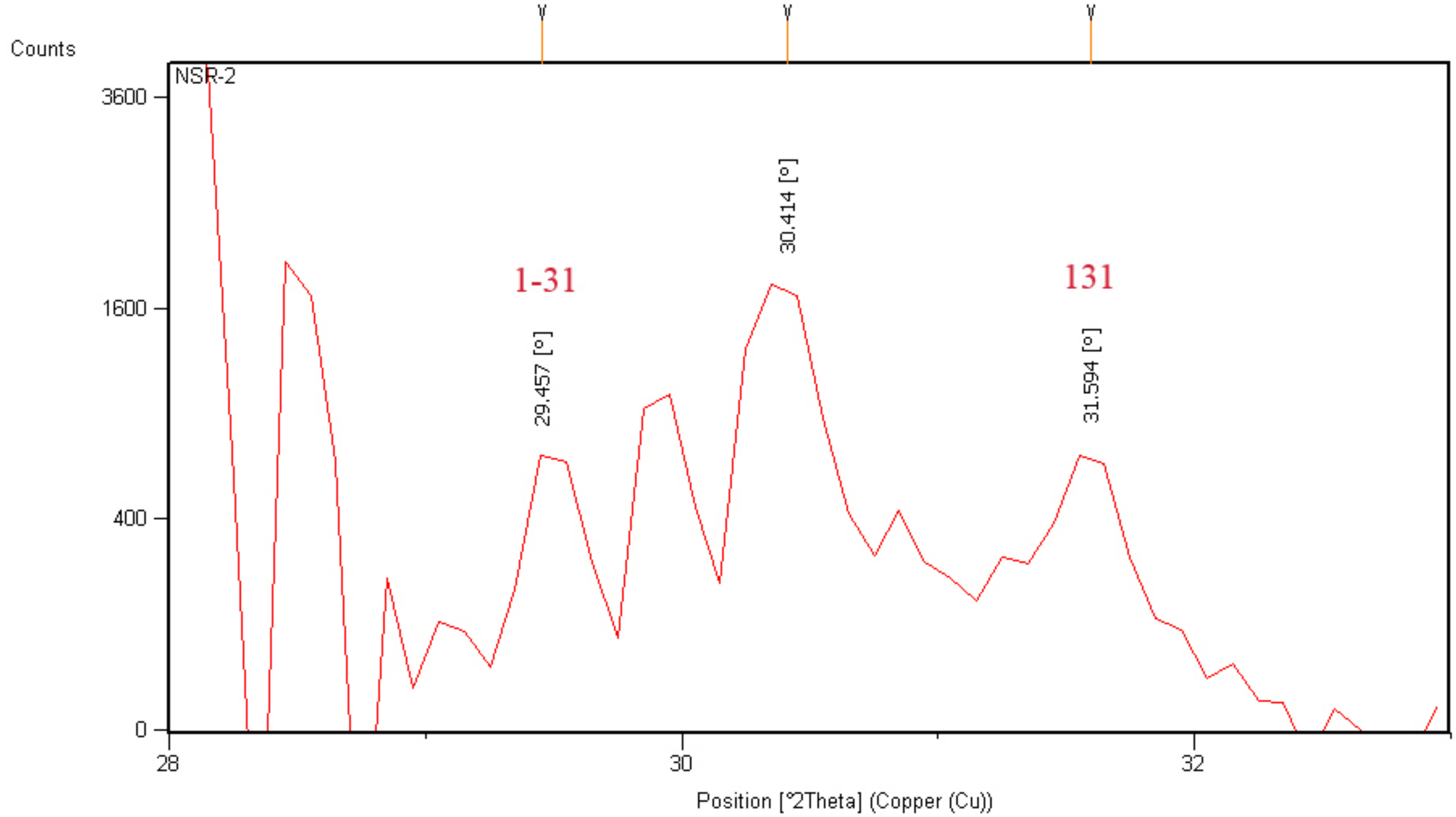


X-Ray Diffraction – NSR

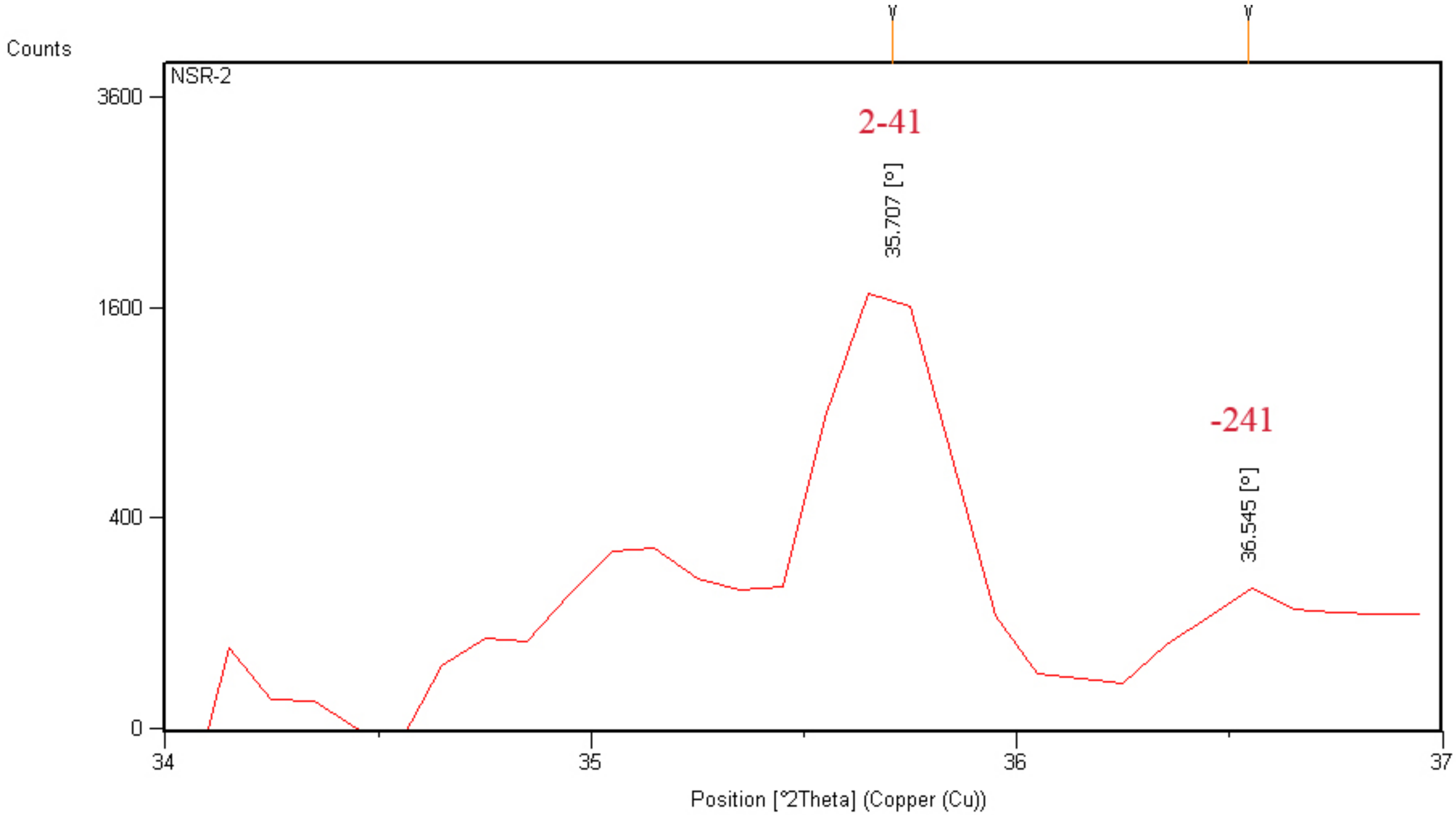




X-Ray Diffraction – NSR



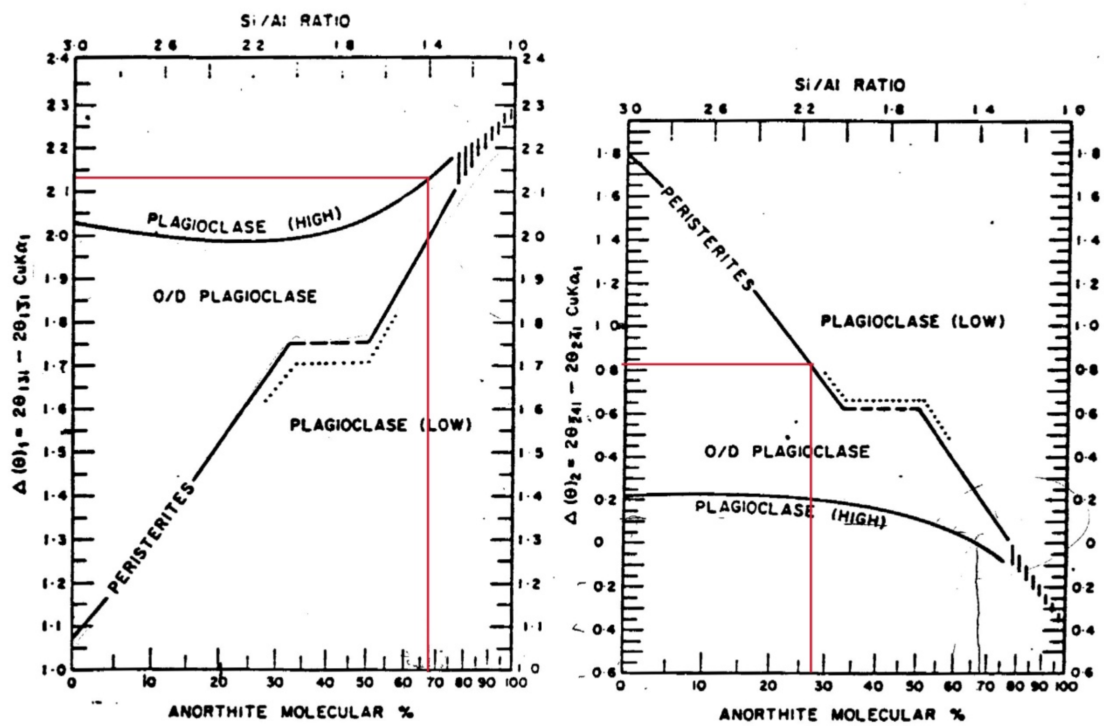
X-Ray Diffraction – NSR



X-Ray Diffraction – NSR

	NSR
1 3 -1	31.594
1 -3 1	29.457
Δ Θ 1	2.137
-2 4 1	36.545
2 -4 1	35.707
Δ Θ 2	0.838

Δ Θ 1 – An_{68}
Δ Θ 2 – An_{27}



Bambauer et al., 1967

X-Ray Diffraction

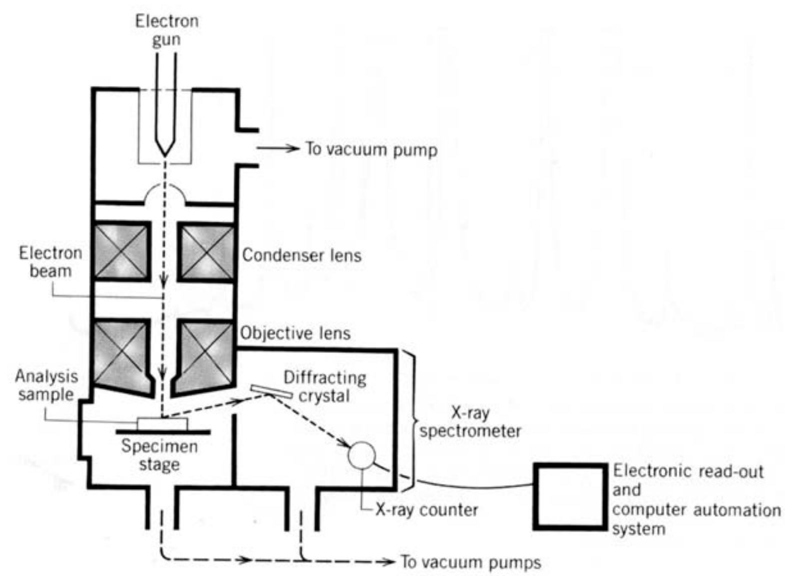
- NBL
  - Δ Θ 1 – An_{80}
  - Δ Θ 2 – An_{33}
- NSR
  - Δ Θ 1 – An_{68}
  - Δ Θ 2 – An_{27}

Scanning Electron Microscopy

- Analytical technique primarily used to find morphology and surface features (Klein and Dutrow, 2008)
- Electron beam scans across surface
- Electron beam creates radiation signals
  - Secondary electrons
  - Backscattered electrons
  - X-rays

Scanning Electron Microscopy

- Concerned mostly with x-ray detection system (EDS)
  - Allows for spectral analysis of x-rays
  - Quantitative



Klein and Dutrow, 2008

Scanning Electron Microscopy

- Preparation involves pre-prepared thin section
- Thin section must be coated (UGA, 2010)
  - Increased conductivity
  - Reduction of thermal damage
  - Increased secondary and backscattered electron emission
  - Increased mechanical stability
- Thin section run through SEM
- Images and EDS information gathered
- Software can remove any unwanted elements
  - Coating

Scanning Electron Microscopy

-

Atom % NBL

	O-K	Na-K	Mg-K	Al-K	Si-K	Cl-K	K-K	Ca-K
NBL1	49.73	9.79	1.69	1.5	32.75	0.29	0.65	3.6

Atom % NSR

	O-K	Na-K	Mg-K	Al-K	Si-K	K-K	Ca-K
NSR2	49.83	10.25	2.02	0.54	33.12	0.59	3.65

Scanning Electron Microscopy

NBL	Na-K	Ca-K	Sum	100%
	9.79	3.60	13.39	7.47
Percentage	73.11	26.89		

NSR	Na-K	Ca-K	Sum	100%
	10.25	3.65	13.90	7.19
Percentage	73.74	26.26		

Scanning Electron Microscopy

- NBL
  - An_{27}
- NSR
  - An_{26}

Results and Discussion

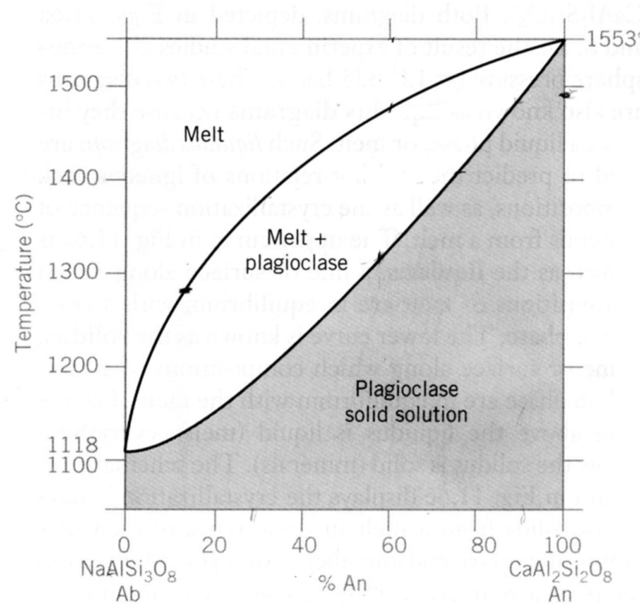
- Literature studies
  - Anorthosite in Duluth Complex (Morrison et al., 1983)
    - An_{69}–An_{39}
- Michel-Lévy
  - NBL - An_{60}
  - NSR – An_{66}
- XRD
  - NBL
    - $\Delta\ \Theta\ 1$ – An_{80}
    - $\Delta\ \Theta\ 2$ – An_{33}
  - NSR
    - $\Delta\ \Theta\ 1$ – An_{68}
    - $\Delta\ \Theta\ 2$ – An_{27}
- SEM
  - NBL - An_{27}
  - NSR - An_{26}

Results and Discussion

- Take best data
  - M-L and XRD $\Delta\Theta 1$
    - NBL – An_{70}
    - NSR – An_{67}
  - Very close to literature values
    - An slightly high
- Issues?
    - $\Delta\Theta 2$
      - Peaks very small and hard to pinpoint
    - SEM
      - Contamination (skin oil)
      - Unable to focus

Results and Discussion

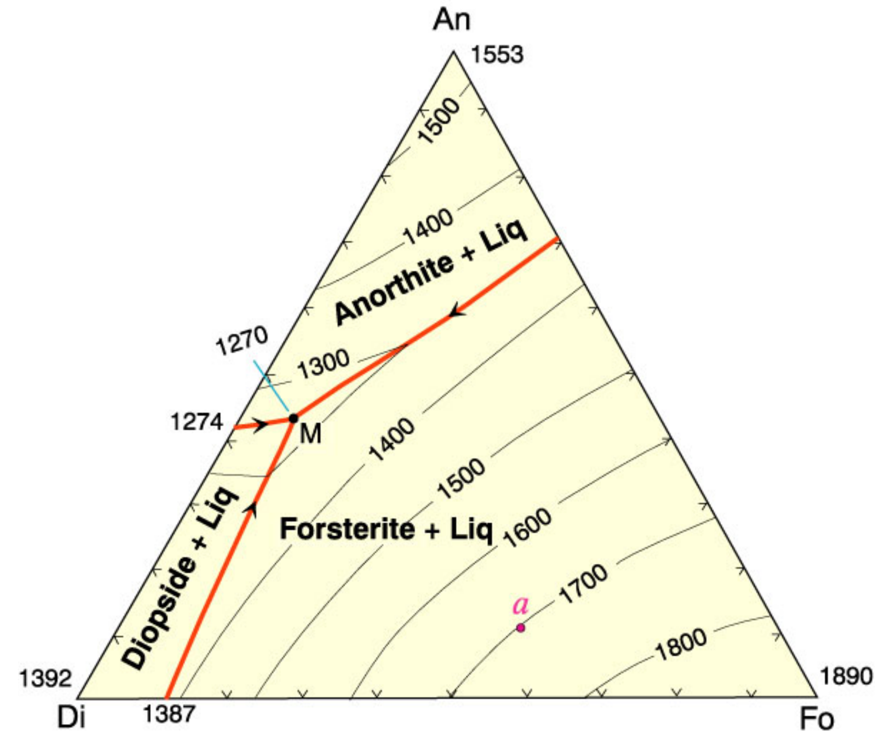
- Phase Diagrams
  - Can see results of difference under idealized, simplified conditions
  - Albite and anorthite form a solid solution
  - Two-component phase diagram (Klein and Dutrow, 2008)
  - Knowing %An can give us temperature first crystal comes out of melt
    - Conceptual exercise
    - Not full system for formation of these anorthosites



Klein and Dutrow, 2008

Results and Discussion

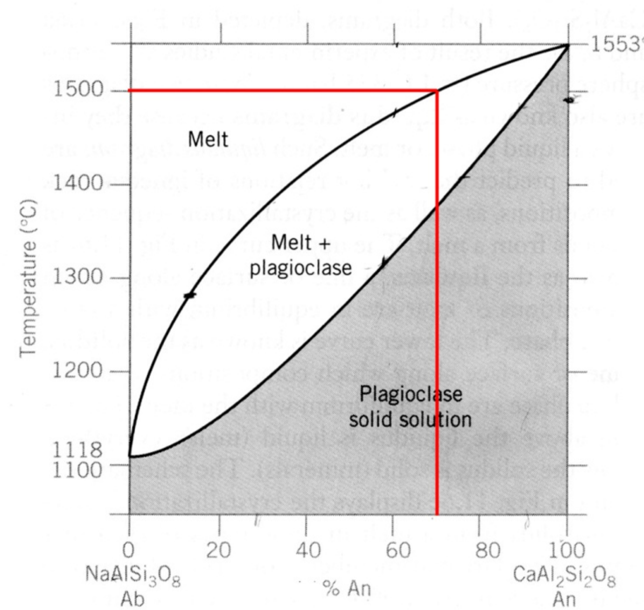
- Phase Diagrams
  - Real phase diagram is at least ternary
  - Complex
  - Easier to conceptualize using simpler binary diagrams
    - Binary diagram used does not represent full system or actual conditions of formation



Winter, 2010

Results and Discussion

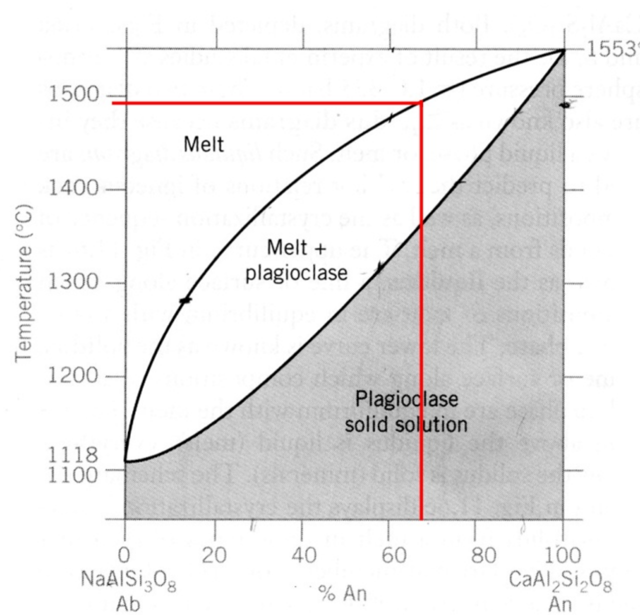
- NBL
  - An_{70}
  - First crystals at temperature of 1500°C



Klein and Dutrow, 2008

Results and Discussion

- NSR
  - An_{67}
  - First crystals at temperature of 1490°C



Klein and Dutrow, 2008

Results and Discussion

- Under ideal, 2 phase conditions, the anorthosite near Bogberry Lake would have first formed crystals in slightly warmer conditions than anorthosite from near Split Rock Lighthouse

Conclusion

- Experimental results were very close to literature results with a few exceptions
- Data generated can be used to understand ideal conditions these rocks underwent
  - Both samples underwent conditions of high heat

References Cited

- Ashwal, L., 1993, Anorthosites: Berlin, Springer-Verlag
- Bambauer, H., Corlett, M., Eberhard, E., and Viswanathan, K., 1967, Diagrams for the determination of plagioclases using X-ray powder patterns of low structural state plagiclases: Scweiz. Min. Petro. Mitt., v. 45, p. 327-330
- Google Maps, http://www.maps.google.com, accessed May 3, 2010
- Klein, C., and Dutrow, B., 2008, The Manual of Mineral Science: New Jersey, John Wiley & Sons
- Kroll, H., and Ribbe, P., 1980, Determinative diagrams for Al,Si order in plagioclases: American Mineralogist, v.65, p. 449-457
- Morrison, D., Ashwal, L., Phinney, W., Shih, C., and Wooden, J., 1983, Pre-Keweenawan anorthosite inclusions in the Keweenawan Beaver Bay and Duluth Complexes, northeastern Minnesota: Geological Society of American Bulletin, v. 94, p. 206-221
- Perkins, D., and Henke, K., 2004, Minerals in Thin Section: New Jersey, Pearson Education
- Ribbe, P., Guides to Indexing Feldspar Powder Patterns: Reviews in Mineralogy, v. 2, p. 325-341
- Sims, P., and Morey, G., 1972, Geology of Minnesota - A centennial volume: Minnesota, Minnesota Geological Survey
- University of Georgia, 2010, Goals of Specimen Preparation, http://www.uga.edu/caur/ppt/semprep.ppt
- Webmineral, http://www.webmineral.com, accessed May 3, 2010
- Winter, J., 2010, Principles of Igneous and Metamorphic Petrology: New Jersey, Prentice Hall

Questions?