Crustal tilting and differential exhumation of Gangdese Batholith revealed by bedrock pressures

Supplementary Materials

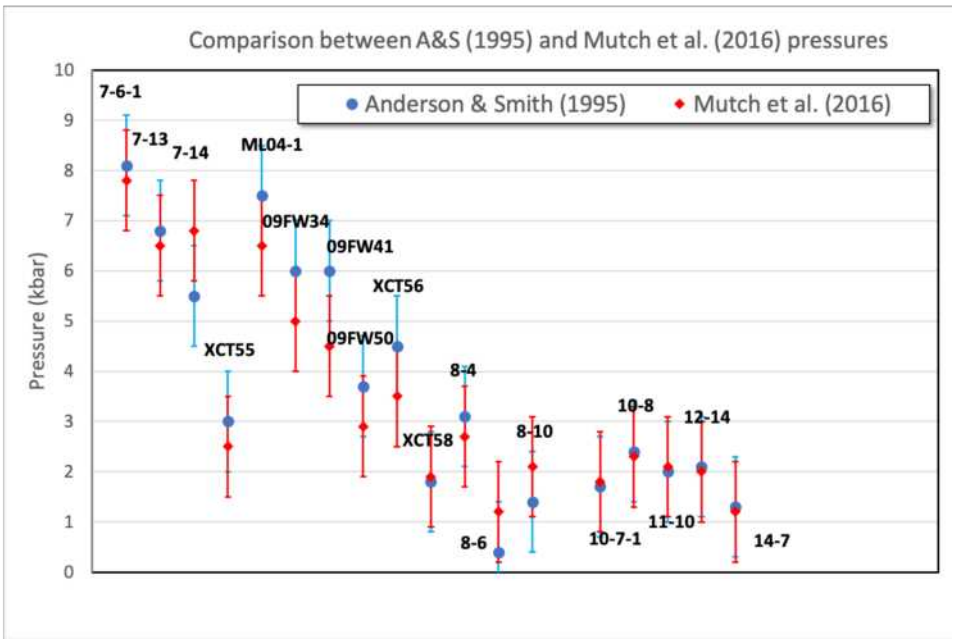
Wenrong Cao[1], Jiaming Yang[1], Andrew V. Zuza[2], Wei-Qiang Ji[3], Xu-Xuan Ma[4], Xu Chu[5], Quentin P. Burgess[1]

1. Department of Geological Sciences and Engineering, University of Nevada, Reno
2. Nevada Bureau of Mines and Geology, University of Nevada, Reno
3. Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing
4. Chinese Academy of Geological Sciences, Beijing
5. Department of Earth Sciences, University of Toronto, Toronto

The supplementary materials contain the following items:

1. Figure S1. Comparison between pressure calculated based on Anderson and Smith (1995) and Mutch et al. (2016) – presented in this Word file
2. Technical details of LA-ICP-MS analysis – presented in this Word file
3. Technical details of EPMA analysis – presented in this Word file
4. Descriptions on petrography of EPMA samples - presented in this Word file
5. Compiled bedrock pressure database of Gangdese Batholith
   - presented in a separate Excel file: pressuredataALL_RR_Final.xlsx
6. Compiled cooling ages in the study area
   - presented in a separate Excel file: Compiled cooling ages_RR_Final.xlsx
7. LA-ICPMS analysis datatable with plots
   - presented in a separate Excel file: ICPMS datatable_RR_Final.xlsx
8. EPMA analysis datatable
   - presented in a separate Excel file: EPMA datatable_RR_Final.xlsx
9. Al-in-hornblende pressure calculator spreadsheet
   - presented in a separate Excel file: AlinHBL pressure calculator_RR_Final.xlsx
10. MATLAB code used to generated Figure 7
    - presented in a separate MATLAB file: exhumation_analytical_RR_Final.m

1. *Figure S1. Comparison between pressures calculated based on Anderson and Smith (1995) and Mutch et al. (2016)*



This figure presents the pressure results with uncertainties from Anderson and Smith (1995)'s and Mutch et al. (2016)'s calibrations. The numerical results are presented in the Table 1 in the manuscript. Here, sample numbers are labeled on top of the results. Within the uncertainties ($\pm$1 kbar), two pressures overlap with each other validating the results.

2. Technical details of LA-ICP-MS analysis

Zircon separates from samples are incorporated into a 1" epoxy mount together with fragments or loose grains of Sri Lanka, FC-1, and R33 zircon crystals that are used as primary standards. The mounts are sanded down to a depth of ~20 microns, polished, imaged, and cleaned prior to isotopic analysis. U-Pb geochronology of zircons is conducted by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) at the Arizona LaserChron Center (Gehrels et al., 2006, 2008; Gehrels and Pecha, 2014). The analyses involve ablation of zircon with a Photon Machines Analyte G2 excimer laser equipped with HelEx ablation cell using a spot diameter of 20 microns. The ablated material is carried in helium into the plasma source of an Element2 HR ICPMS, which sequences rapidly through U, Th, and Pb isotopes. Signal intensities are measured with an SEM that operates in pulse counting mode for signals less than 50K cps, in both pulse-counting and analog mode for signals between 50K and 5M cps, and in analog mode above 5M cps. The calibration between pulse-counting and analog signals is determined line-by-line for signals between 50K and 5M cps, and is applied to >5M cps signals. Four intensities are determined and averaged for each isotope, with dwell times of 0.0052 sec for 202, 0.0075 sec for

204, 0.0202 sec for 206, 0.0284 sec for 207, 0.0026 sec for 208, 0.0026 sec for 232, and 0.0104 sec for 238. With the laser set an energy density of ~5 J/cm^2, a repetition rate of 8 hz, and an ablation time of 10 seconds, ablation pits are ~12 microns in depth. Sensitivity with these settings is approximately ~5,000 cps/ppm. Each analysis consists of 5 sec on peaks with the laser off (for backgrounds), 10 sec with the laser firing (for peak intensities), and a 20 second delay to purge the previous sample and save files. More information can be found at Arizona LaserChron Center's website: https://sites.google.com/a/laserchron.org/laserchron.

We applied the following filters before we calculate the crystallization ages: (1) Individual analyses with U/Th>10 are excluded since they are likely affected by metamorphic processes (e.g., Yakymchuk et al., 2018); (2) Since all dated samples are younger than 400 Ma, analysis whose concordance (ratio of $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages) is smaller than 85% or its reverse concordance (ratio of $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages minus 1) is larger than 10% is excluded.

3. Technical details of EPMA analysis

Samples are prepared as polished, epoxy mounted thin sections with a ~20 nm carbon coating. Electron probe microanalysis (EPMA) was carried out with a JEOL JXA8530F Hyperprobe at the Department of Earth, Environmental and Planetary Sciences at Rice University, using 5 crystal wavelength-dispersive spectrometers. The field-emission gun was set at a 15 kV accelerating voltage, with a beam current of 20 nA. For hornblende analyses, the electron beam size was focused to a 300 nm spot while plagioclase analyses utilized a larger, 20 μm spot size to minimize potential alkali migration during analysis. 10 major element compositions (Na, Si, K, Ca, Fe, Ti, Al, Mg, Cr, Mn) of plagioclase and hornblende were collected. Counting times were 10 s on peak and 5 s on lower and upper bounds. Natural and synthetic mineral standards were used for measuring the characteristic X-rays and ZAF matrix correction procedure was applied for quantification.

References

Anderson, J.L. and Smith, D.R., 1995. The effects of temperature and fO_2 on the Al-in-hornblende barometer. American Mineralogist, 80, p.549-559.

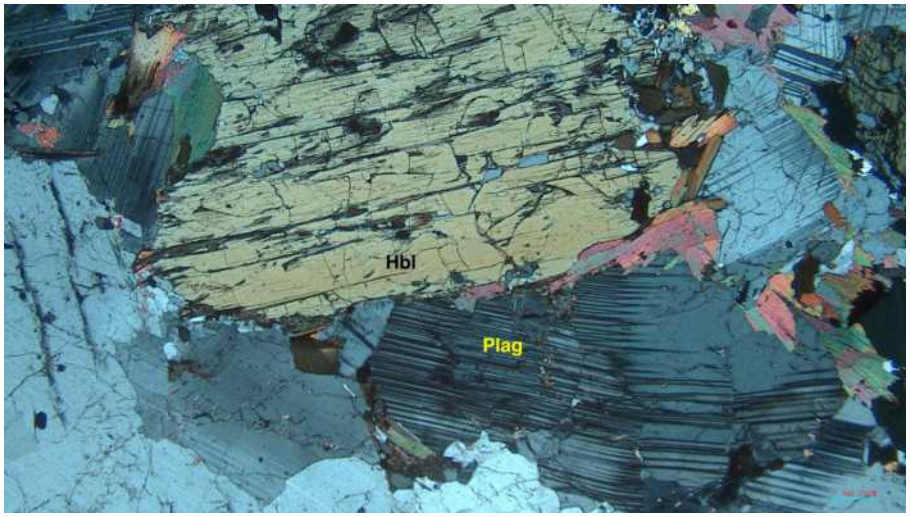
Gehrels, G.E., Valencia, V., Ruiz, J., 2008. Enhanced precision, accuracy, efficiency, and spatial resolution of U-Pb ages by laser ablation-multicollector-inductively coupled plasma-mass spectrometry: Geochemistry, Geophysics,Geosystems, v. 9, Q03017, doi:10.1029/2007GC001805.

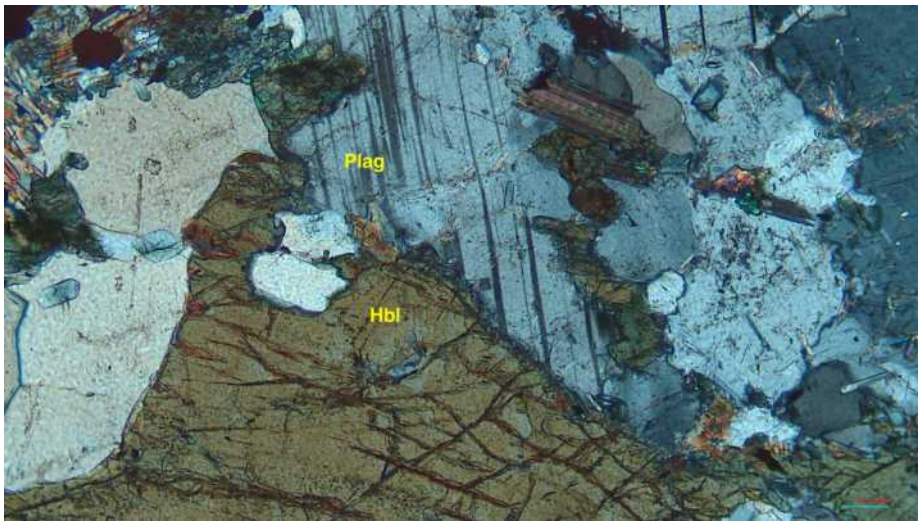
Gehrels, G. and Pecha, M., 2014. Detrital zircon U-Pb geochronology and Hf isotope geochemistry of Paleozoic and Triassic passive margin strata of western North America: Geosphere, 10, p. 49-65.

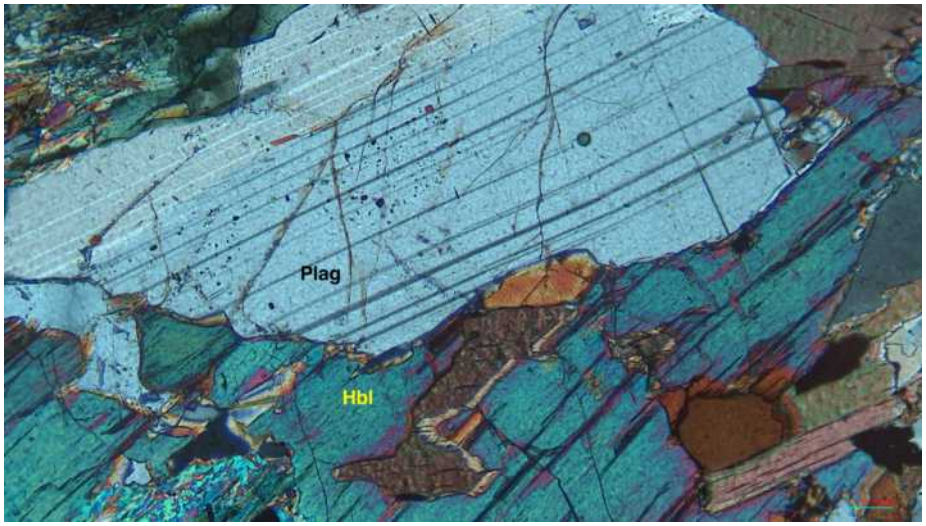
Mutch, E.J.F., Blundy, J.D., Tattitch, B.C., Cooper, F.J. and Brooker, R.A., 2016. An experimental study of amphibole stability in low-pressure granitic magmas and a revised Al-in-hornblende geobarometer. Contributions to Mineralogy and Petrology, 171, p.85.

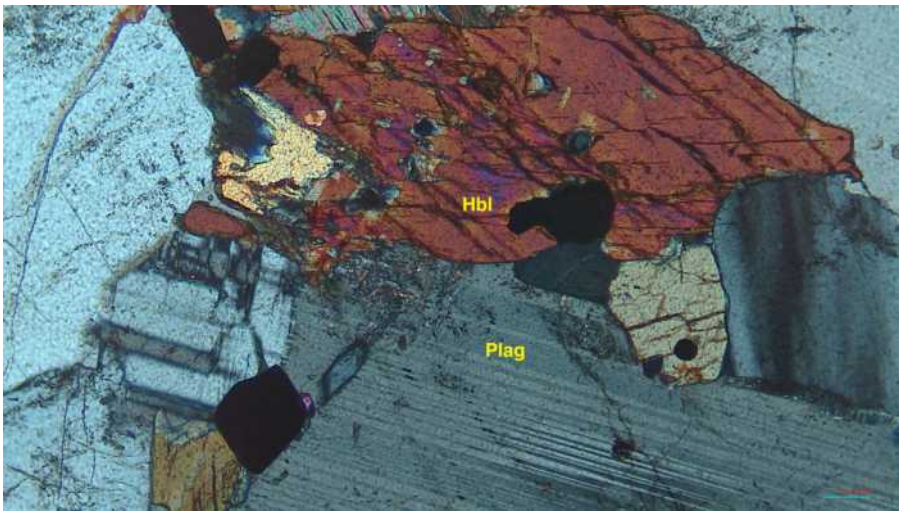
Yakymchuk, C., Kirkland, C.L., Clark, C., 2018. Th/U ratios in metamorphic zircon. Journal of Metamorphic Geology 1–41. doi:10.1111/jmg.12307.

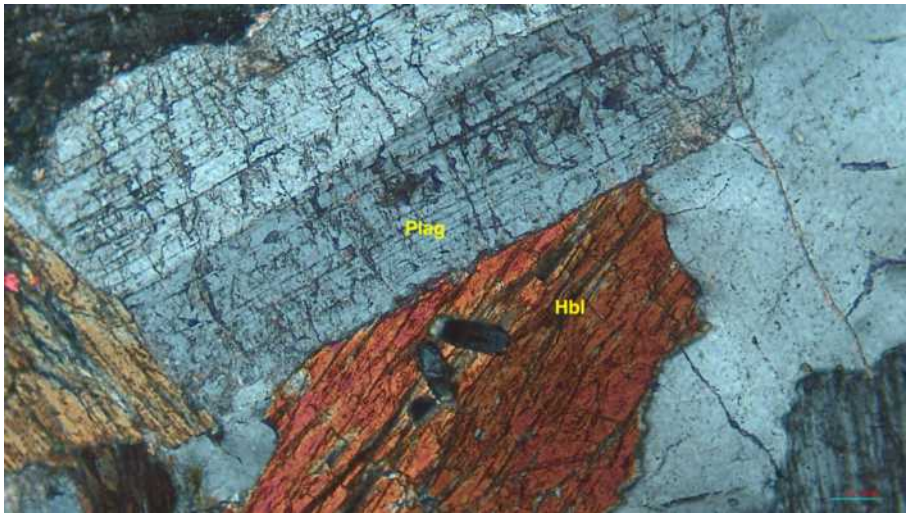
4. *Petrographic descriptions of EPMA samples*

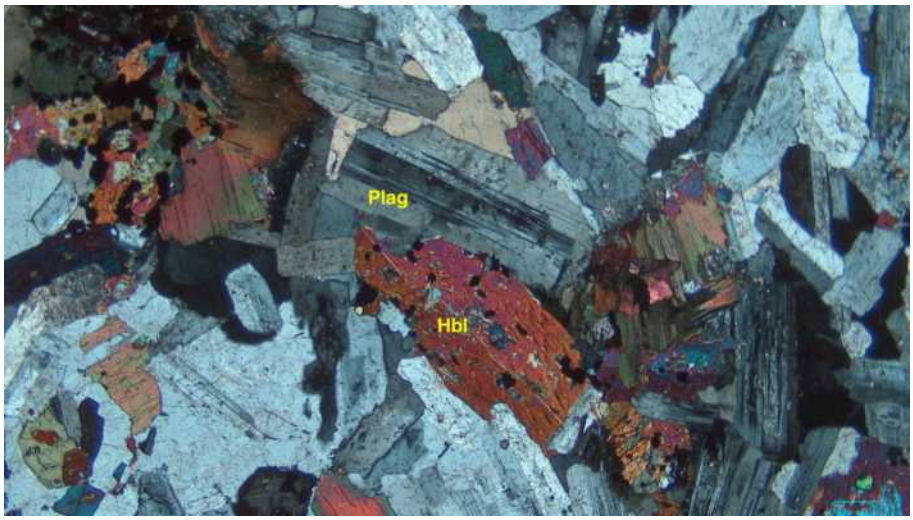
Sample	7-6-1
Mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite ☑ Ilmenite
Description	Fresh sample. Hornblende: 15%, 2-5mm, subhedral-euhedral, showing two sets of cleavage, and twinning. Biotite: 5%, 1-2mm, subhedral-euhedral, basal cleavage. Plagioclase: 65%, 3-7mm, euhedral, albite twinning, undulatory extinction. Quartz: 7%, 0.5-1mm, interstitial. K-spar: 7%, 0.5-1mm, interstitial. Other phases (epidote, Fe-oxide): 1%. Ilmenite: pinkish lamellae in magnetite showing pleochroism under CPL (reflective light). Magnetite: euhedral/subhedral crystal, isotropic, nonpleochroic, not hematite, since no red internal reflection.
Note	Contains magmatic epidote (subhedral, 0.5-1mm)
Optical photo	

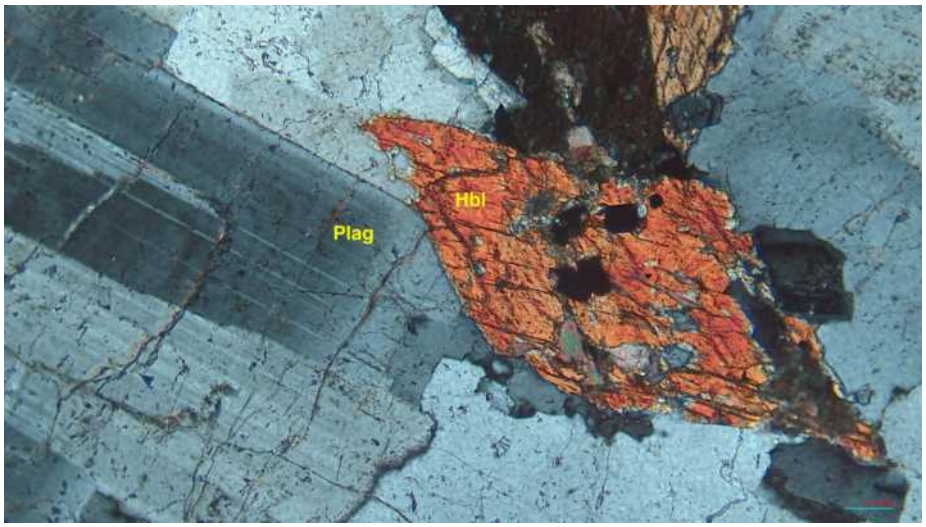
Sample	7-13
Mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite ☑ Ilmenite
Description	Relatively fresh with some "cloudy" feldspar (retrograded sericite). Hornblende: 20%, 2-4mm, anhedral-subhedral, clear hornblende cleavage, some hornblende grains show retrogradation. Biotite: 10%, 0.5-1mm, subhedral-euhedral, basal cleavage. Plagioclase, 55%, 2-4mm, subhedral-euhedral, albite twinning, fractures. Quartz: 8%, 0.5-1mm, interstitial. K-spar: 7%, 0.5-1mm, interstitial. Other phases (epidote, Fe-oxide) <1%. Ilmenite: lamellae in magnetite or subhedral crystal showing pleochroism under CPL. Magnetite: euhedral/subhedral crystal, isotropic, nonpleochroic.
Note	Contains magmatic epidote (subhedral, 0.5-1mm, retrograded).
Optical photo	

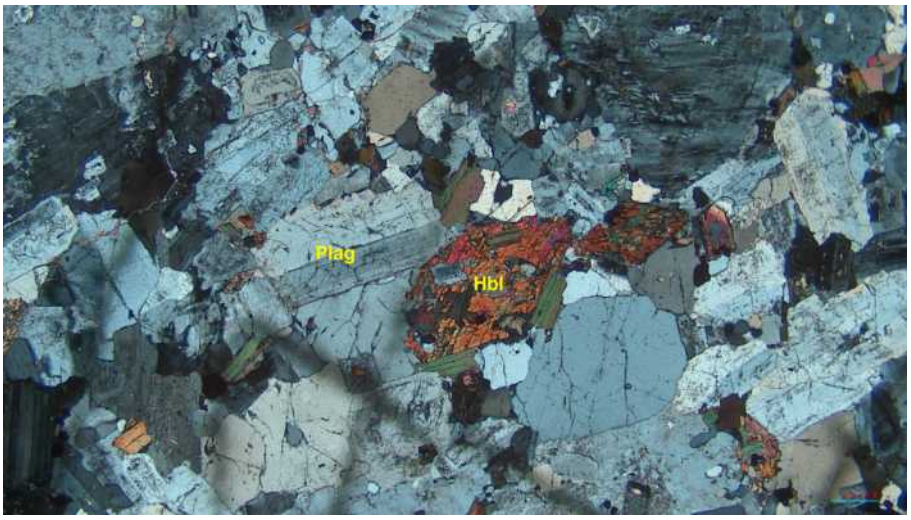
Sample	7-14
Mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite ☑ Ilmenite
Description	Fresh sample. Hornblende: 15%, 1-5mm, anhedral-euhedral, showing two sets of cleavage, and twinning. Biotite: 10%, 1-2mm, subhedral-euhedral, basal cleavage. Plagioclase: 60%, 1-2mm, euhedral, albite and Carlsbad twinning. Quartz: 8%, 0.5-1mm, interstitial, undulatory extinction. K-spar: 7%, 0.5-1mm, interstitial. Other phases (Fe-oxide): 1%. Ilmenite: subhedral crystal with bands showing pleochroism under CPL Magnetite: euhedral/subhedral crystal, isotropic, nonpleochroic.
Note	Local retrograded ring of clinopyroxene (1mm, <1%) to hornblende.
Optical photo	

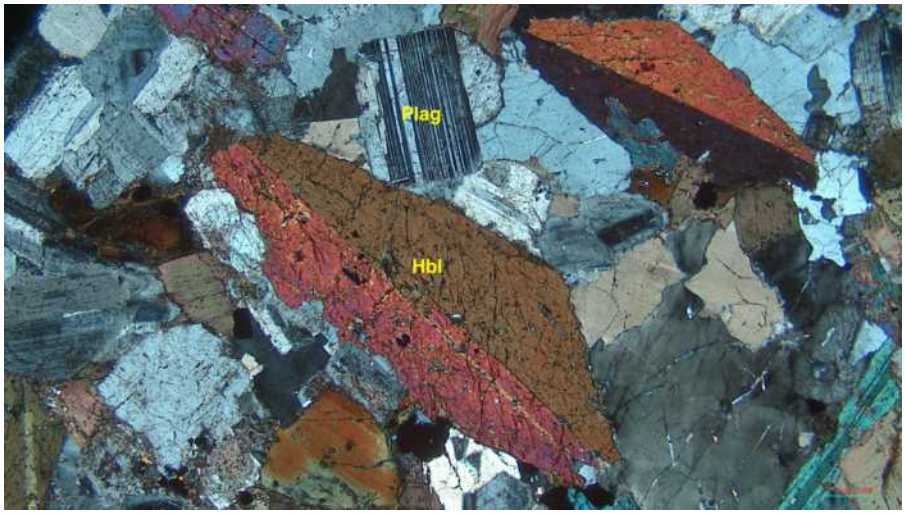
Sample	10-8
Mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite, ☑ Titanite
Description	Fresh sample. Hornblende: 15%, 2-3mm, anhedral-subhedral, clear hornblende cleavage. Biotite: 10%, 0.5-1mm, subhedral-euhedral, basal cleavage. Plagioclase, 50%, 2-5 mm, euhedral, albite and Carlsbad twinning, fractures. Microcline:15% tartan twinning, 2-3 mm, euhedral, Quartz: 10%, 0.5-1mm, interstitial. Other phases <1%. Titanite: euhedral crystal, ~1mm. Magnetite: euhedral/subhedral crystal, isotropic, nonpleochroic.
Note	
Optical photos	

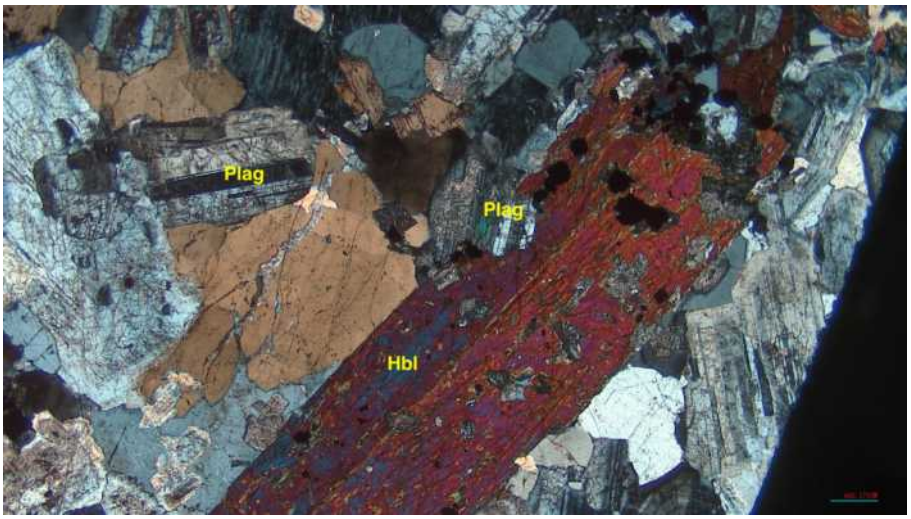
Sample	8-4
Mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite, ☑ Titanite
Description	Relative fresh sample. Hornblende: 10%, 2-5mm, anhedral-euhedral, showing two sets of cleavage, twinning, some retrograded to biotite. Biotite: 5%, 1-2mm, subhedral-euhedral, basal cleavage, some retrograded to chlorite. Plagioclase: 60%, 1-2mm, euhedral, albite twinning, many of them have "cloudy surface" indicative of sericite retrogradation Microcline: 15%, relatively fresh with tartan twinning. Quartz: 10%, 0.5-1mm, interstitial, undulatory extinction. Other phases < 1%. Titanite: subhedral crystal, 2mm. Magnetite: euhedral crystal, isotropic, nonpleochroic.
Note	
Optical photo	

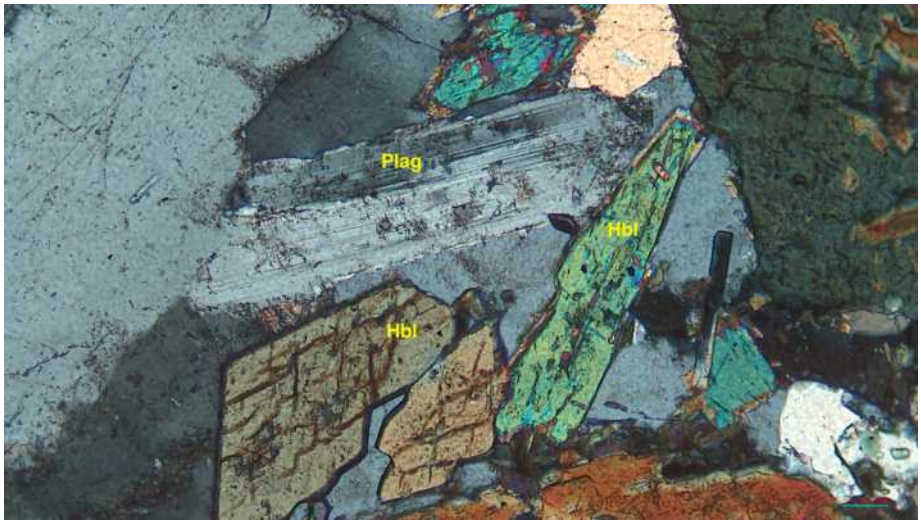
Sample	12-14
Mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite, ☑ Titanite
Description	Fresh sample. Hornblende: 20%, 3 mm, euhedral, showing two sets of cleavage, and twinning. Biotite: 15%, 3 mm, euhedral, basal cleavage. Plagioclase: 45%, 2-4mm, euhedral, albite, zoning. Microcline: 15%, tartan twinning, euhedral, 2-3mm. Quartz: 10%, 0.5-1mm, interstitial. Other phases< 1%. Titanite: euhedral, showing one set of cleavage, 1mm. Magnetite: euhedral/subhedral crystal, isotropic, nonpleochroic.
Note	
Optical photo	

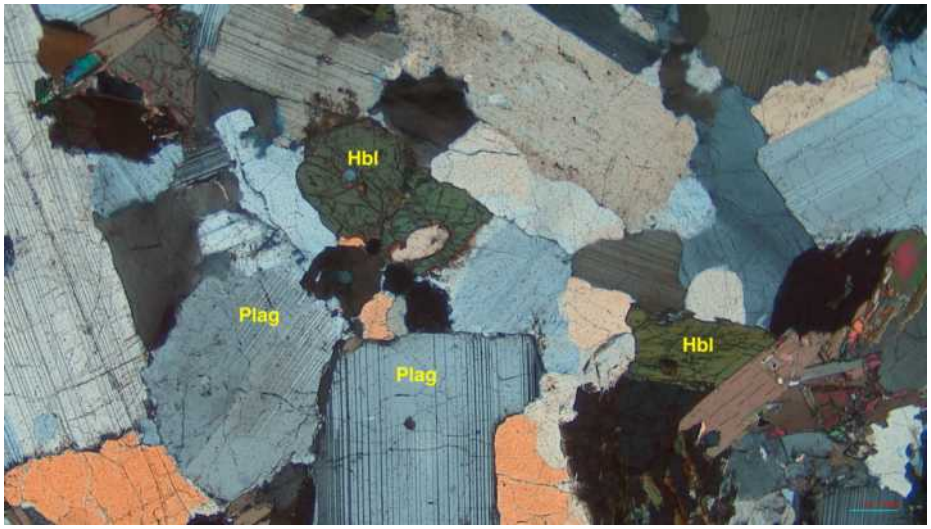
Sample	8-6
Mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite, ☑ Titanite
Description	Fresh sample. Hornblende: 15%, 1-5mm, euhedral, showing two sets of cleavage, and twinning. Biotite: 5%, 1-2mm, euhedral, basal cleavage. Plagioclase: 50%, 2-5mm, euhedral, albite twinning. Quartz: 10%, 1-3mm, subhedral, undulatory extinction. K-spar (Perthite): 10%, 0.5-1mm, interstitial. Other phases <1%. Titanite: euhedral, 1mm. Magnetite: euhedral/subhedral crystal, isotropic, nonpleochroic.
Note	
Optical photo	

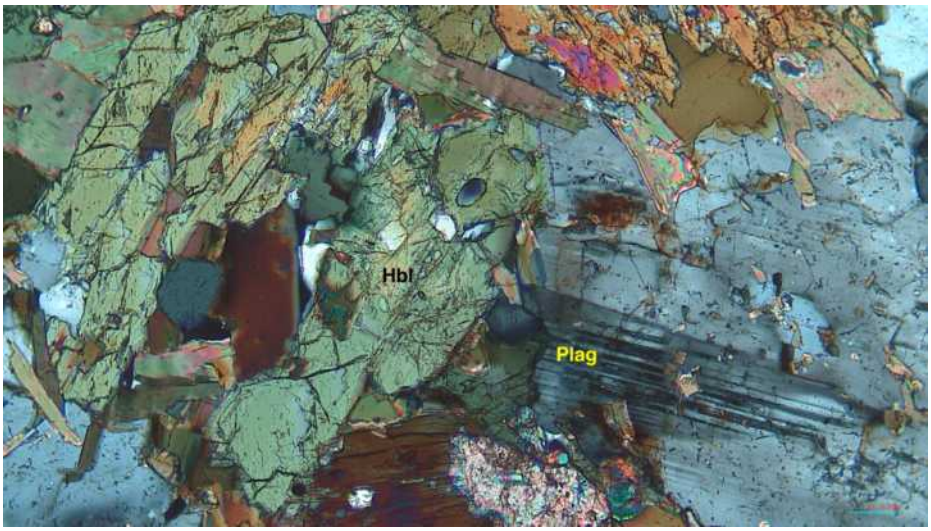
Sample	14-7
Mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite ☑ Titanite
Description	Relatively fresh sample. Hornblende: 10%, 1-3mm, anhedral-euhedral, showing two sets of cleavage. Biotite: 5%, 0.5-1mm, subhedral, basal cleavage. Plagioclase: 55%, 2-3mm, euhedral, albite twinning. Sericite alteration. K-spar (Perthite): 15%, 2-5mm. Quartz: 15%, 1-3mm, euhedral. Other phases <1%. Titanite: euhedral, 0.5-2mm. Magnetite: euhedral/subhedral crystal, isotropic, nonpleochroic.
Note	
Optical photo	

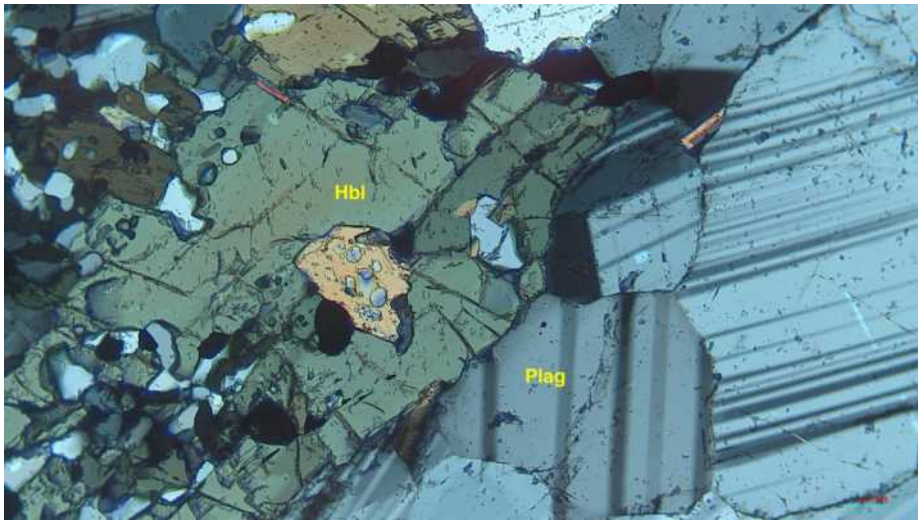
Sample	11-10
Check for mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite, ☑ Ilmenite
Description	Fresh sample. Hornblende: 15%, 1-5mm, euhedral, showing two sets of cleavage, and twinning. Biotite: 10%, 1-2mm, euhedral, basal cleavage. Plagioclase: 45%, 1-2mm, euhedral, albite and Carlsbad twinning. Quartz: 15%, 2-3mm, euhedral, undulatory extinction. Microcline:15%, tartan twinning, euhedral. Other phases < 1%. Ilmenite: subhedral crystal with internal blocks of pleochroism. Magnetite: euhedral/subhedral crystal, isotropic, nonpleochroic.
Note	
Optical photo	

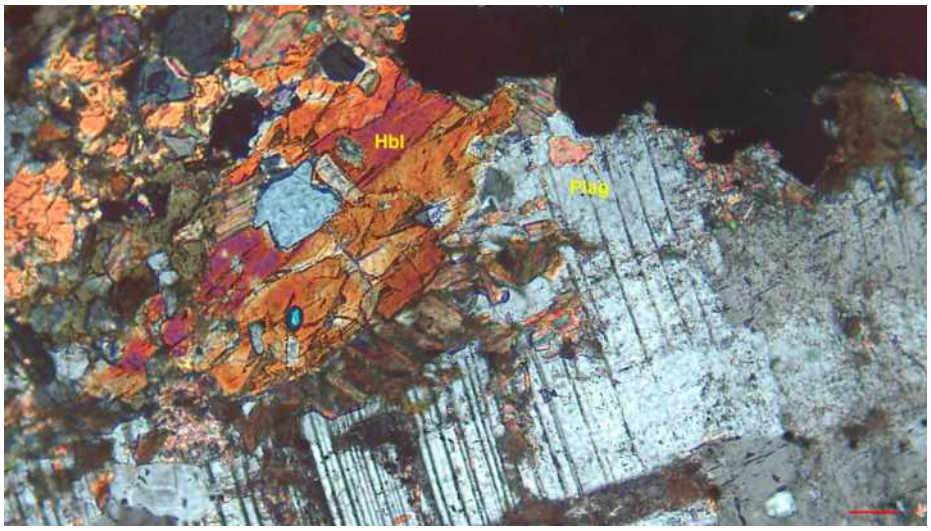
Sample	8-10
Mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite, ☑ Ilmenite
Description	Fresh sample. Hornblende: 15%, 1-3mm, euhedral, showing two sets of cleavage, and twinning. Biotite: 5%, 1-2mm, euhedral, basal cleavage. Plagioclase: 50%, 2-5mm, euhedral, albite twinning, zoning, sericite alteration. Quartz: 15%, 1-3mm, subhedral, undulatory extinction. K-spar (Perthite): 15%, 2-4mm, interstitial. Other phases <1%. Ilmenite: euhedral crystal with internal blocks showing pleochroism under CPL. Magnetite: euhedral/subhedral crystal, isotropic, nonpleochroic.
Note	
Optical photo	

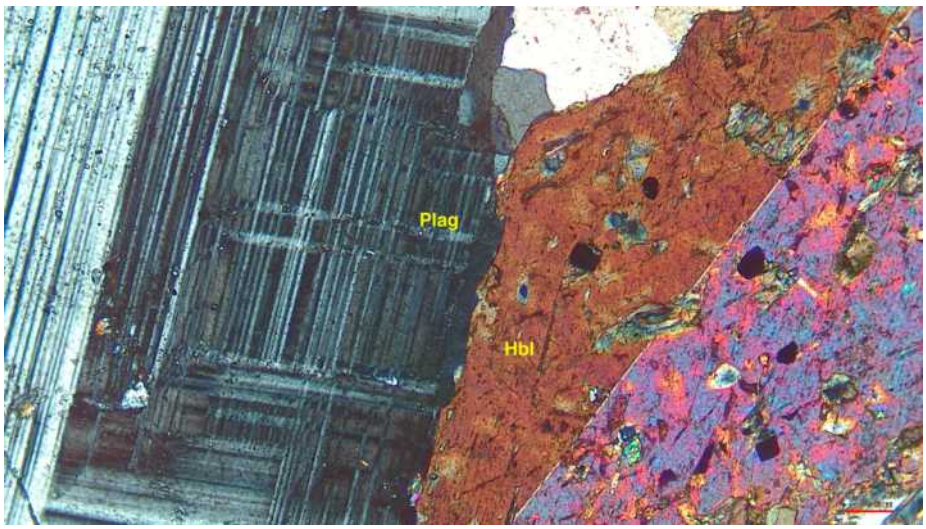
Sample	10-7-1
Mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite, ☑ Titanite
Description	Fresh sample. Hornblende: 20%, 1-3mm, euhedral, showing two sets of cleavage, and twinning. Biotite: 5%, 0.5 mm, interstitial, subhedral, basal cleavage. Plagioclase: 60%, 1-2mm, euhedral, albite twinning, zoning. Quartz: 8%, 0.5-1mm, interstitial. Microcline 7%: tartan twinning, euhedral, 2 mm. Other phases < 1%. Titanite: euhedral, 0.5-1 mm. Magnetite: euhedral/subhedral crystal, isotropic, nonpleochroic.
Note	
Optical photo	

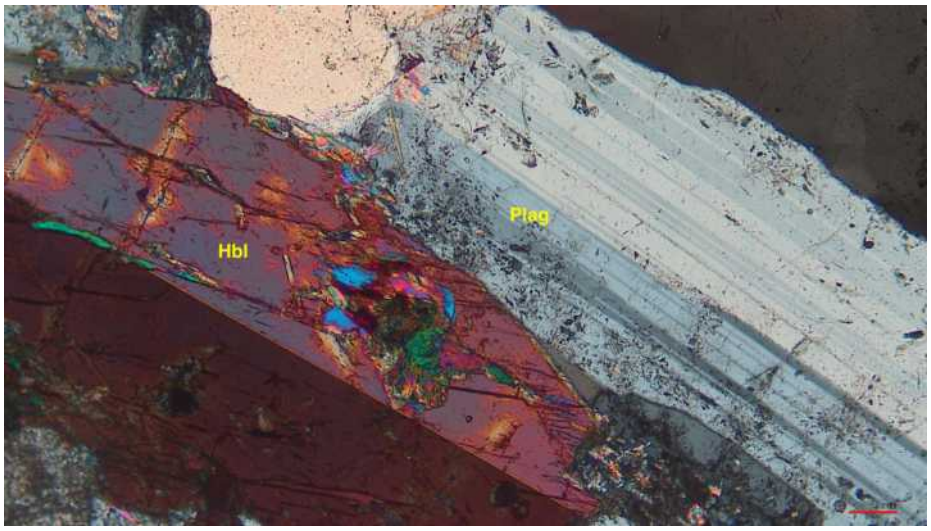
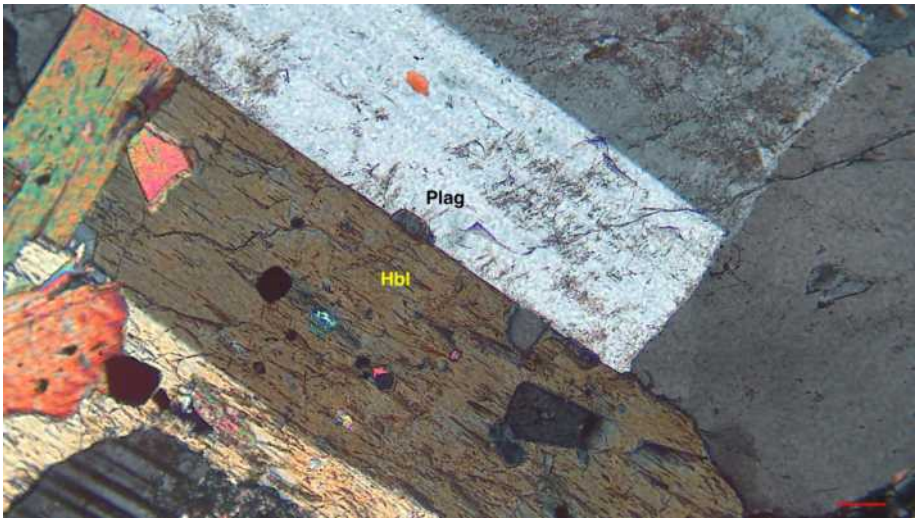
Sample	09FW34
Mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite, ☑ Titanite
Description	Fresh sample. Hornblende: 15%, 2-3mm, euhedral, showing two sets of cleavage, and twinning. Biotite: 15%, 1-2mm, subhedral-euhedral, basal cleavage. Plagioclase: 55%, 2-5mm, euhedral, albite twinning. Quartz: 10%, 2-3mm, subhedral. K-spar: 5%, 1mm, subhedral. Other phases < 1%. Titanite: euhedral, 1-2 mm. Magnetite: small euhedral/subhedral crystal, isotropic, nonpleochroic.
Note	Contain magmatic epidote, 1-2 mm.
Optical photo	

Sample	09FW41
Mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite, ☑ Titanite
Description	Fresh sample. Hornblende: 5%, 0.5-2mm, anhedral-subhedral, showing two sets of cleavage. Biotite: 5%, 0.5-2mm, subhedral-subhedral, basal cleavage. Plagioclase: 50%, 2-4mm, euhedral, albite twinning, zoning. Quartz: 20%, 0.5-3mm, interstitial and subhedral. K-spar (Perthite): 20%, tartan twinning, Carlsbad twinning. 0.5-1mm, interstitial. Other phases <1%. Titanite: subhedral, 0.5mm. Magnetite: euhedral/subhedral crystal, isotropic, nonpleochroic.
Note	
Optical photo	

Sample	ML04-1
Mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite, ☑ Ilmenite
Description	Fresh sample. Hornblende: 40%, 0.5-5mm, subhedral-euhedral, showing two sets of cleavage. Biotite: 5%, 0.5-1mm, euhedral, basal cleavage. Plagioclase: 40%, 1-2mm, euhedral, albite twinning. Quartz: 7%, 0.5-1mm, interstitial. K-spar: 8%, 0.5-1mm, interstitial. Other phases < 1%. Ilmenite: euhedral crystal with internal blocks showing pleochroism under CPL. Magnetite: euhedral/subhedral crystal, isotropic, nonpleochroic.
Note	Contain magmatic epidote, 0.5mm.
Optical photo	

Sample	XCT55
Mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite, ☑ Titanite
Description	Fresh sample. Hornblende: 10%, 1-2mm, anhedral-subhedral, some retrograded to biotite. Biotite: 5%, 2-3mm, subhedral-euhedral, basal cleavage. Plagioclase: 45%, 1-2mm, euhedral, albite twinning, sericite retrogradation. K-spar: 20%, 2-3mm, subhedral. Quartz: 20%, 2-3mm, subhedral, undulatory extinction. Other phases <1%. Titanite: euhedral, 0.5-1mm. Magnetite: euhedral/subhedral crystal, isotropic, nonpleochroic.
Note	
Optical photo	

Sample	XCT56
Mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite, ☑ Ilmenite
Description	Fresh sample. Hornblende: 20%, 1-3mm, euhedral, showing two sets of cleavage, and twinning. Biotite: 15%, 1-3mm, subhedral-euhedral, basal cleavage. Plagioclase: 35%, 1-2mm, euhedral, albite twinning, zoning. Quartz: 15%, 1mm, interstitial. K-spar: 15%, 1-2mm, interstitial. Other phases < 1%. Ilmenite: euhedral crystal with internal blocks showing pleochroism under CPL. Magnetite: euhedral/subhedral crystal, isotropic, nonpleochroic.
Note	
Optical photo	

Sample	09FW50
Mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite ☑ Titanite
Description	Fresh sample. Hornblende: 10%, 2-3mm, euhedral, showing two sets of cleavage, and twinning. Biotite: 10%, 2-3mm, subhedral-euhedral, basal cleavage. Plagioclase: 45%, 2-3mm, euhedral, albite twinning. Quartz: 20%, 2-4mm, euhedral, undulatory extinction. K-spar: 15%, Perthite and Microcline, 2-3mm, subhedral. Other phases < 1%. Titanite: subhedral, 0.5 mm. Magnetite: euhedral/subhedral crystal, isotropic, nonpleochroic.
Note	Contain magmatic epidote, 0.5-1 mm.
Optical photo	

Sample	XCT58
Mineral assemblage for Al-in-Hbl barometry	☑ Quartz, ☑ Plagioclase, ☑ K-feldspar, ☑ Hornblende, ☑ Biotite, ☑ Magnetite, ☑ Titanite
Description	Fresh sample. Hornblende: 15%, 2-3mm, subhedral-euhedral, showing two sets of cleavage, and twinning. Biotite: 15%, 1-2mm, subhedral-euhedral, basal cleavage. Plagioclase: 25%, 2-3mm, euhedral, albite twinning. K-spar: 25%, Perthite and Microcline, 3 mm, Carlsbad twinning. Quartz: 20%, 2-3mm, undulatory extinction. Other phases <1%. Titanite: euhedral, 0.5-2 mm. Magnetite: euhedral/subhedral crystal, isotropic, nonpleochroic.
Note	
Optical photo