

### Abstract

The Southern Oklahoma Aulacogen (SOA) records extensive bimodal magmatism associated with continental rifting during the opening of the southern Iapetus Ocean. This study presents new petrographic and geochemical data for selected Carlton Rhyolite flows, late diabase intrusions, and small gabbros from the Wichita Mountains that were previously unanalyzed or lacked complete trace element data.

Rhyolites are characterized by quartz and feldspar phenocrysts in a felsitic to spherulitic groundmass, with varying degrees of devitrification, sericitization, and alkali metasomatism. Diabases and gabbros display ophitic to subophitic textures defined by plagioclase and clinopyroxene, with olivine completely replaced by bowlingite in the gabbros.

Rhyolite samples show strong LREE enrichment, pronounced negative Eu anomalies, and elevated high-field-strength elements, consistent with A-type felsic magmatism. A rhyolite dike at the base of the thickest Carlton Rhyolite flow displays geochemical similarity to the overlying flow, identifying it as the only known feeder dike within the SOA. Diabase samples show moderate LREE enrichment, no significant Eu anomaly, and E-MORB-type patterns consistent with an enriched mantle source. Two diabase samples with elevated REE concentrations suggest at least two distinct mafic magma sources within the rift system.

### Background

The Wichita Mountains are part of the Southern Oklahoma Aulacogen (SOA), a late Ediacaran to Cambrian rift (Wall et al., 2021) formed during the breakup of Rodinia and the opening of the southern Iapetus Ocean (Fig. 1).

The SOA experienced extensive felsic and mafic magmatism and was later inverted during the Pennsylvanian Ouachita orogeny, exposing deep-seated igneous rocks.

The Carlton Rhyolite Group, Wichita Granite Group, Raggedy Mountain Gabbro and extensive subsurface basalts make up the main parts of this bimodal igneous province (Fig. 2) (Ham et al., 1964; Powell et al., 1980).

The Raggedy Mountain Gabbro Group consists of the large Glen Mountains Layered Complex, and the Roosevelt Gabbros.

The Carlton Rhyolite unconformably overlies the Glen Mountains Layered Complex. The Wichita Granite Group intrudes along the contact between the rhyolites and gabbros. Diabase dikes intrude the other units.

The Wichita Mountains granites and rhyolites exhibit the usual characteristics of A-type felsic rocks (Myers et al., 1981; Hogan and Gilbert, 1995, 1997; Hanson and Eschberger, 2014).



Figure 1. Map of the Southern Oklahoma Aulacogen, showing exposed Cambrian igneous rocks in the Wichita and Arbuckle Mountains. Modified from Hanson et al. (2013). Early Paleozoic continental margin from Keller and Stephenson (2007).

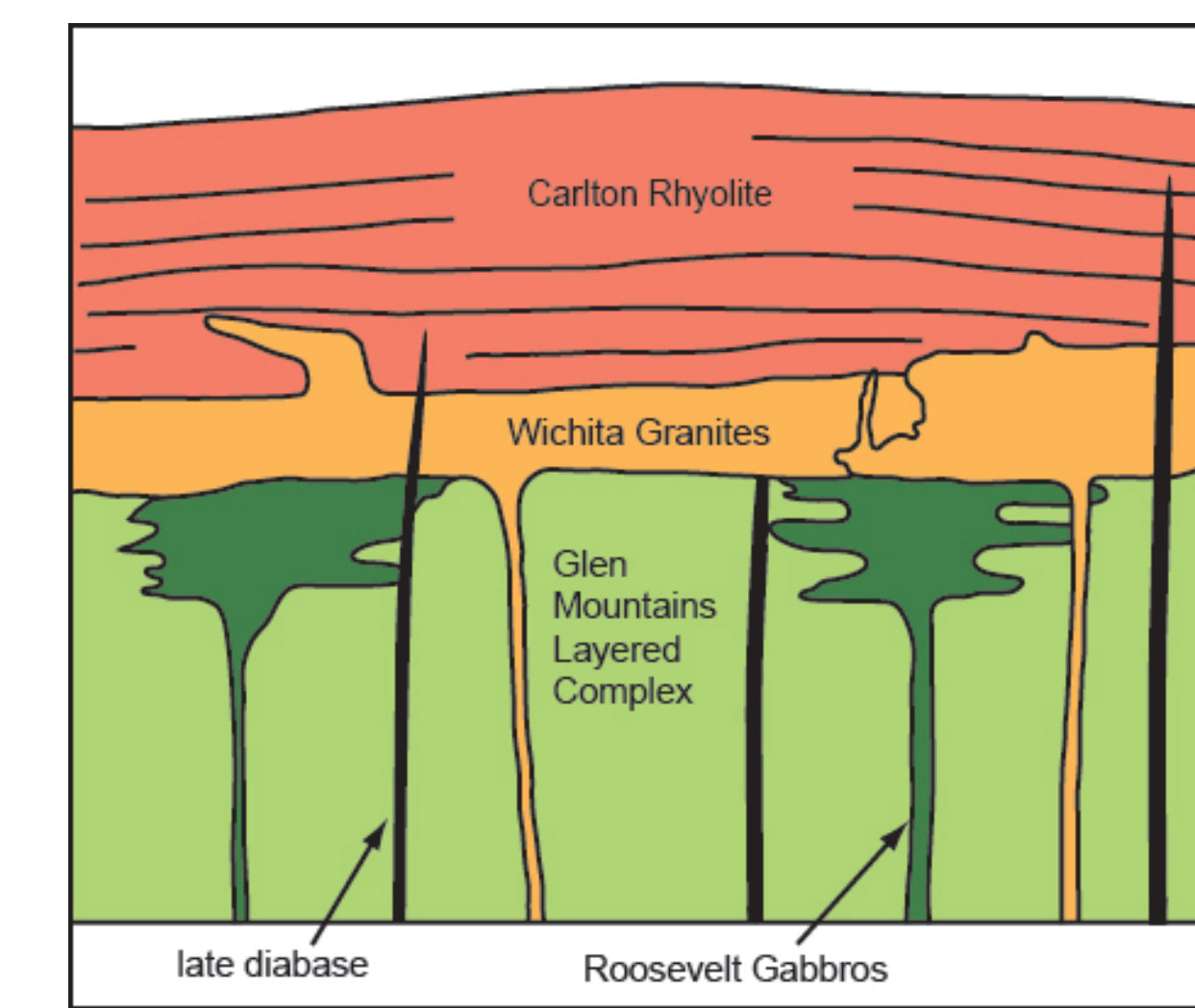


Figure 2. Schematic cross section of igneous rocks exposed in the Wichita Mountains. The Glen Mountains Layered Complex and the Roosevelt Gabbro belong to the Raggedy Mountain Gabbro Group. From Hanson et al. (2013).

### Objectives

Provide new integrated petrographic and major- and trace-element data for understudied parts of the Carlton Rhyolite Group and diabase dikes and gabbros in the western part of the SOA to refine petrogenetic interpretations.

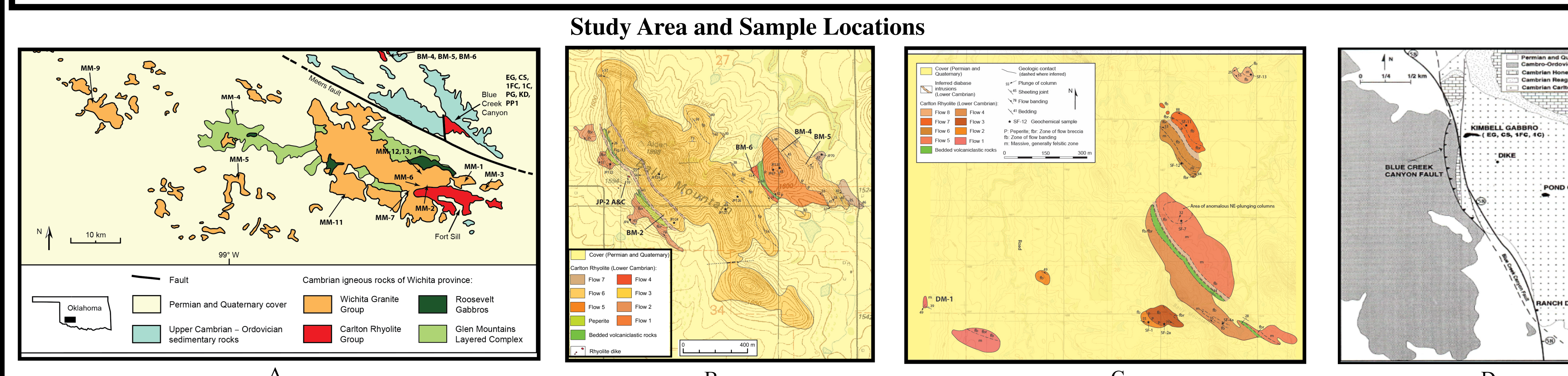


Figure 3. A. Geological map of the Wichita Mountains, showing sample locations. Modified from Powell et al. (1980) and Donovan (1995). B. Enlarged view of Bally Mountain, modified from Hanson et al. (2014). C. Enlarged view of outcrops NW of Bally Mountains, modified from Hanson et al. (2014). D. Geological map of the Blue Creek Canyon area. Modified from Donovan and others (1986). In Figures 3B, 3C, and 3D, small black stars are locations of previously analyzed samples. Sample labels in bold font are new samples that have just been analyzed.

### Petrography of Diabase Dikes and Gabbro Intrusions

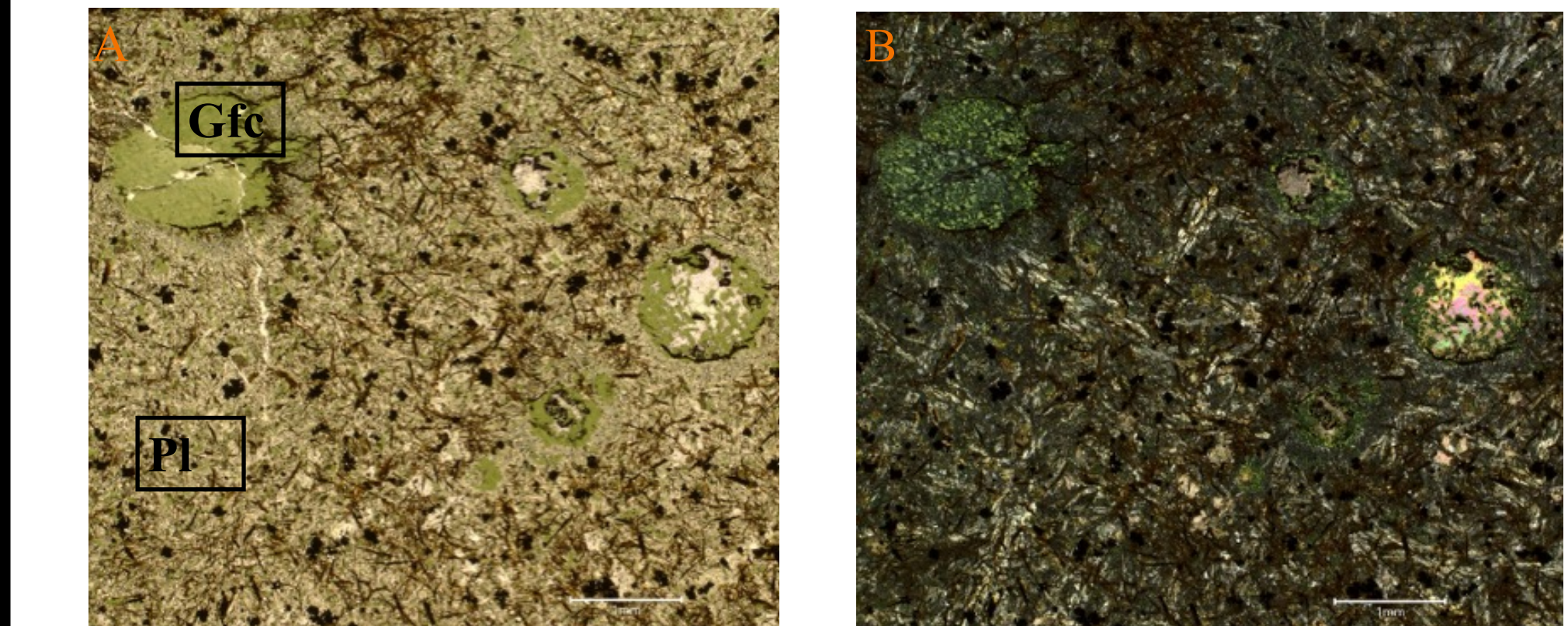


Figure 4. A. Sample KD showing plagioclase (Pl) laths in fine-grained groundmass; amygdules filled with green Fe-rich clay (Gfc), plane light. B. Same field of view, crossed polars, showing diabasic texture.

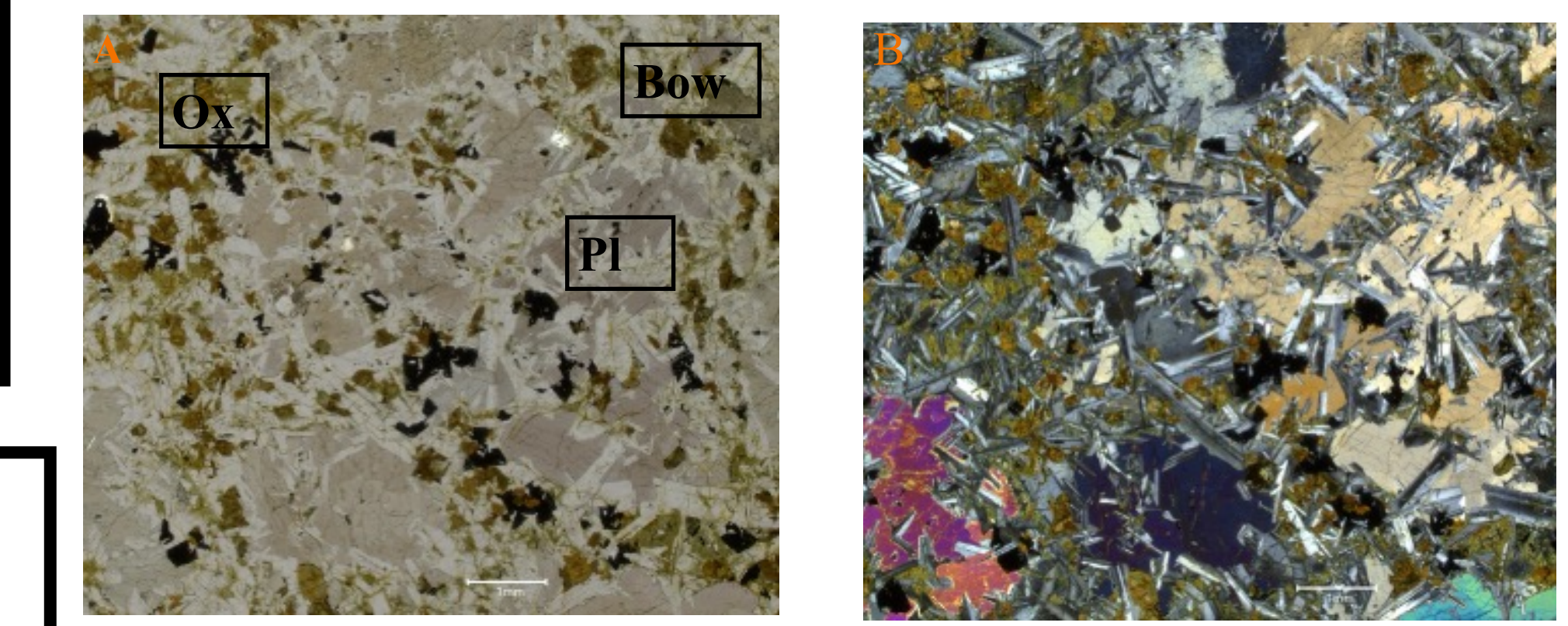


Figure 5. A. Sample PG showing augite enclosing plagioclase laths with bowingite (Bow) pseudomorphs after olivine, and Fe-Ti oxides (Ox), plane light. B. Same field of view showing higher-order interference colours in augite enclosing plagioclase laths, crossed polars.

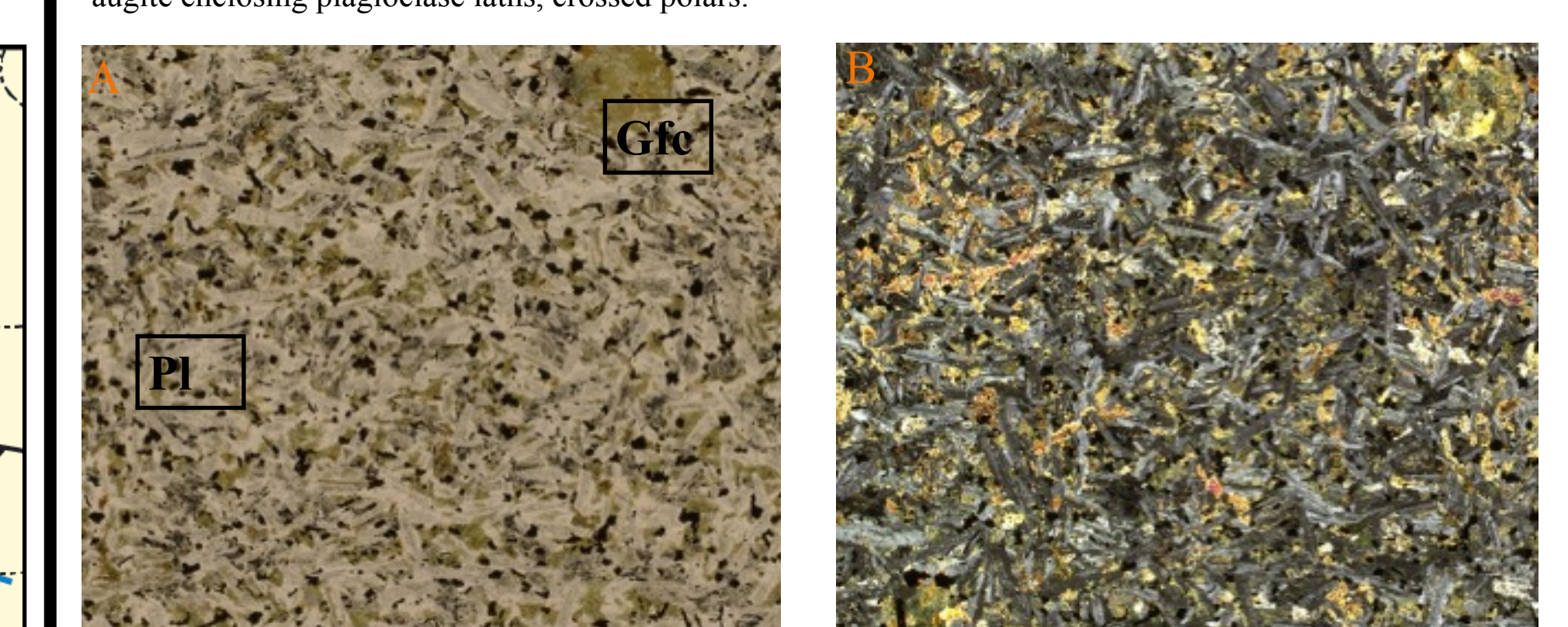


Figure 6. A. Sample MM-1, plagioclase (Pl) laths altered to sericite; green Fe-rich clay pseudomorphs (Gfc), plane light. B. Same field of view showing diabasic texture (crossed polars).

### Geochemistry of the of Diabase Dikes and Gabbro Intrusions

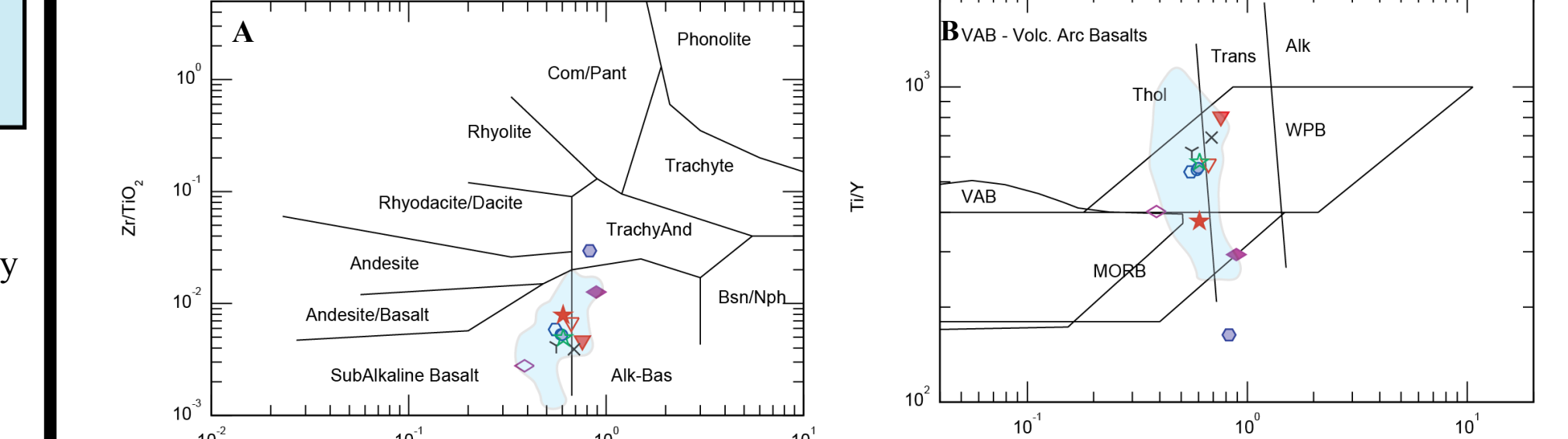


Figure 7. A. Diabase samples on the Nb/Y vs Zr/TiO<sub>2</sub> discrimination diagram of Winchester and Floyd (1977). B. Diabase samples on the Zr vs Zr/Y diagram of Pearce and Norry (1979). Blue field on this and following diagrams represents data for diabase intrusions and Roosevelt gabbros in the Wichita Mountains from Aguilar (1988), Diez de Medina (1988), and DeGroot et al. (1995).

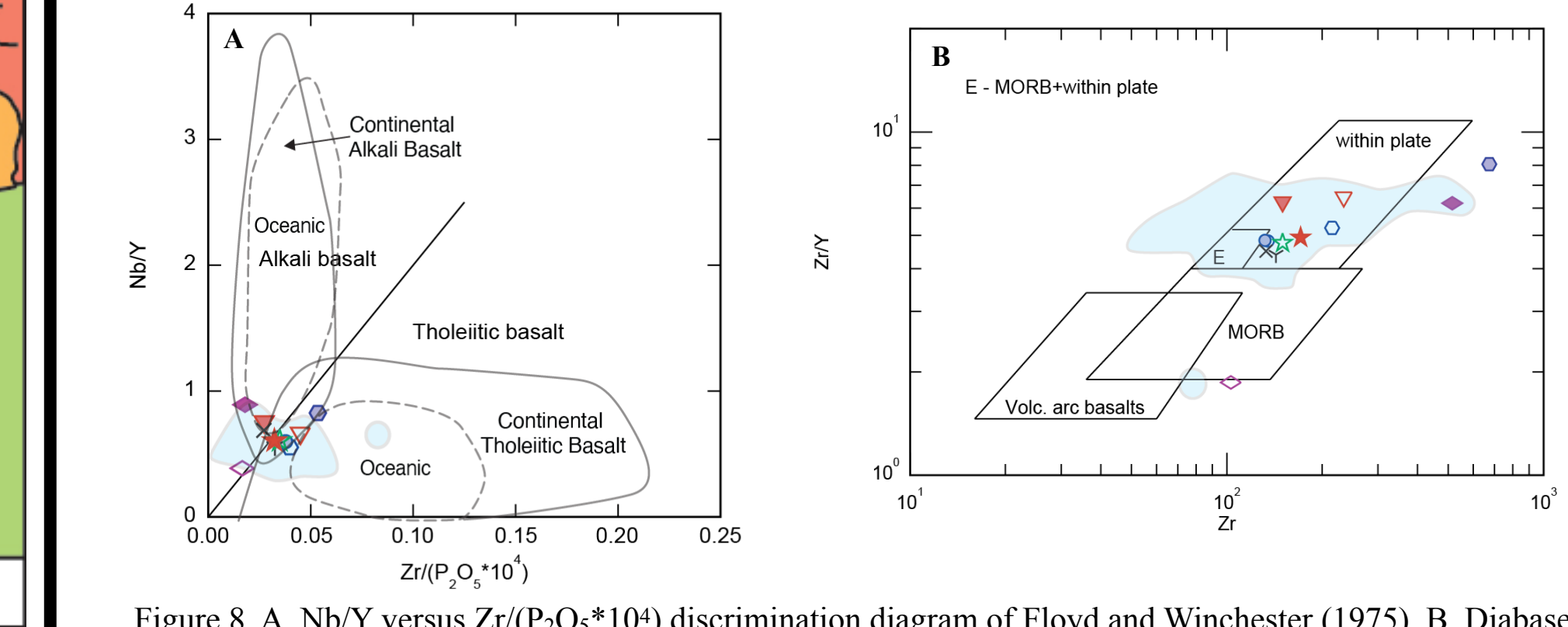


Figure 8. A. Nb/Y versus Zr/(P<sub>2</sub>O<sub>5</sub>\*10<sup>4</sup>) discrimination diagram of Floyd and Winchester (1975). B. Diabase samples on the Zr vs Zr/Y diagram of Pearce and Norry (1979).

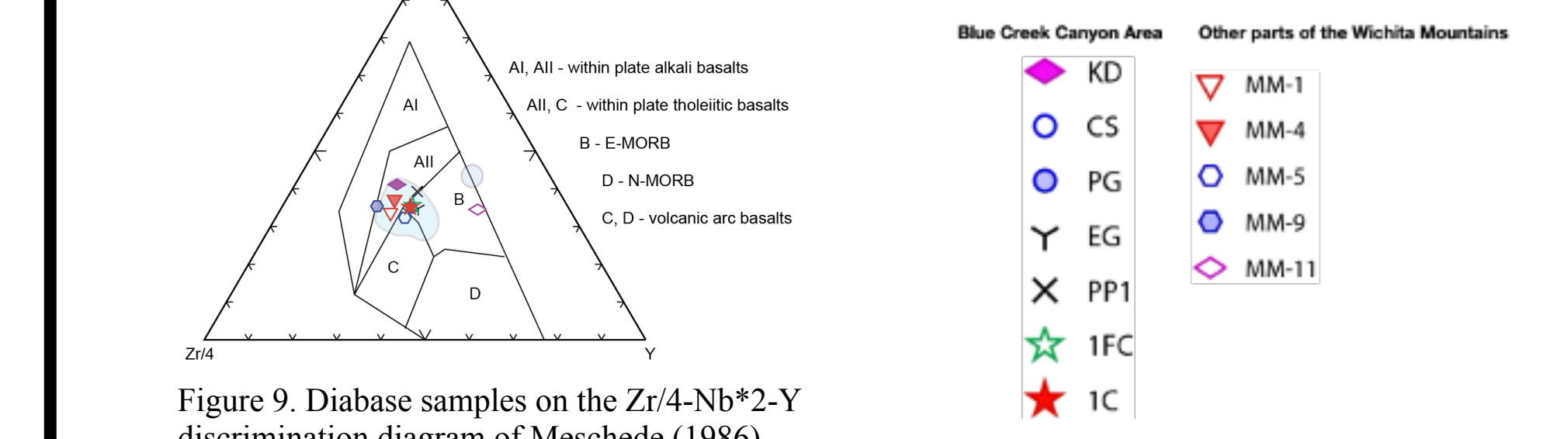


Figure 9. Diabase samples on the Zr<sub>4</sub>-Nb\*2-Y discrimination diagram of Meschede (1986).

Our new diabase samples generally fall within the fields for previously analyzed diabases in the Wichita Mountains. Our samples plot mainly in the field for subalkaline basalt, although a few plot in the alkaline basalt field in Figure 7A. Most samples fall within the tholeiitic-transitional region between the MORB and WPB fields in Figure 7B, which is broadly consistent with the results from Figure 8A. Our samples also fall within E-MORB and within plate basalt fields in Figures 8B and 9. These results are broadly consistent with emplacement in a continental rift environment.

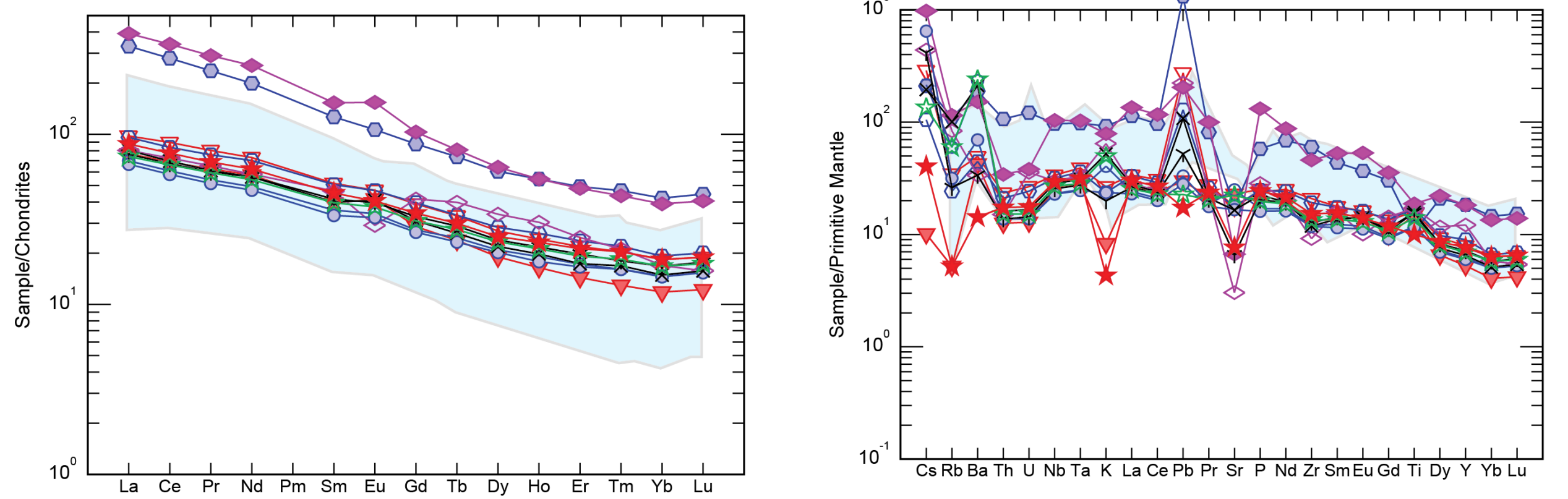


Figure 10. Chondrite-normalized REE patterns of diabase samples; normalizing values are from Sun and McDonough (1989). Figure 11. Primitive mantle-normalized trace element patterns of diabase; normalizing values are from Sun and McDonough (1989).

In Figure 10, the diabase samples show slight LREE enrichment, relatively flat HREE patterns, and no significant Eu anomaly, consistent with mantle-derived magmas similar to enriched MORB. Two samples (MM-11 and KD) show higher REE contents, indicating they have somewhat different petrogenetic histories. These two samples also plot apart from our other samples in Figure 11. Our other samples in this figure show consistent patterns for the high-field-strength elements, but the more mobile elements (e.g., Rb, K, Pb) show evidence of secondary disturbance.

### Petrography of the Carlton Rhyolite

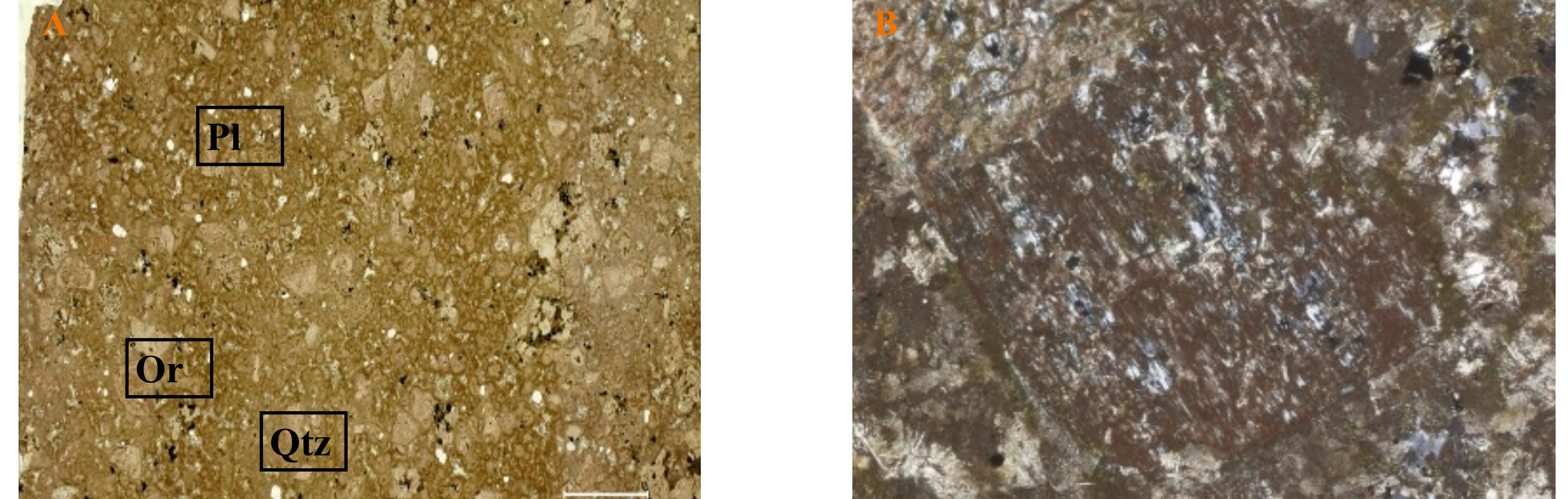


Figure 12. Sample JP-2A showing spherulitic texture, plagioclase (Pl), orthoclase and quartz phenocrysts in plane light. B. Orthoclase phenocryst showing chessboard albite in crossed polars.

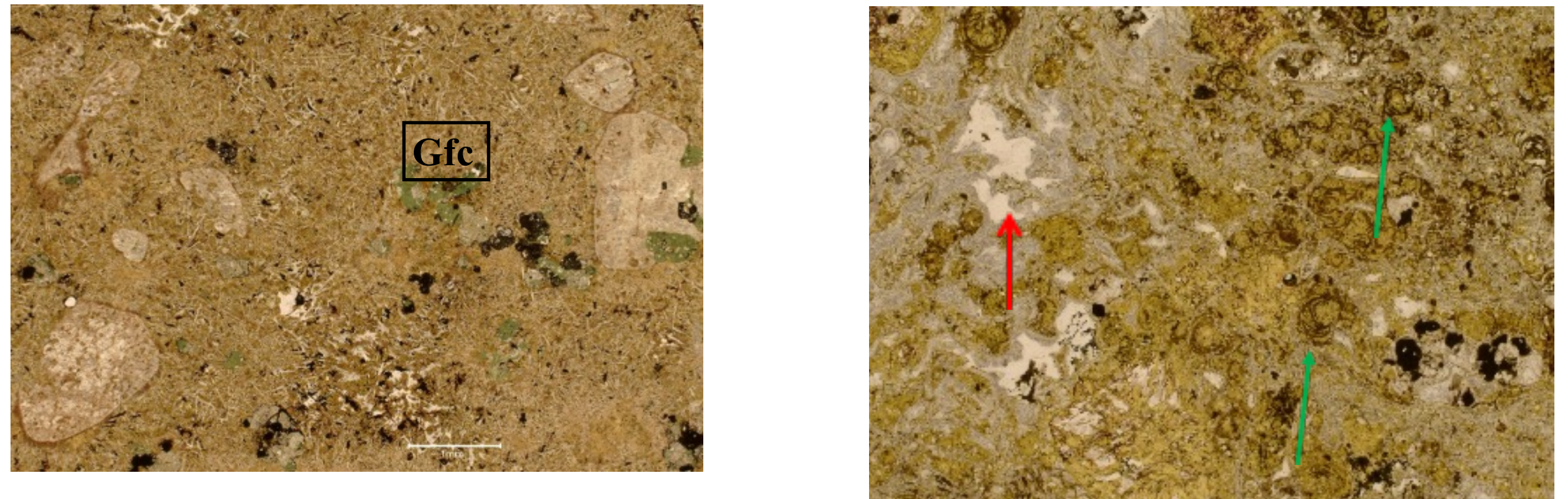


Figure 13. JP-2A, needle-like quartz paramorphs after tridymite and green Fe-rich clay pseudomorphs (Gfc), plane light.

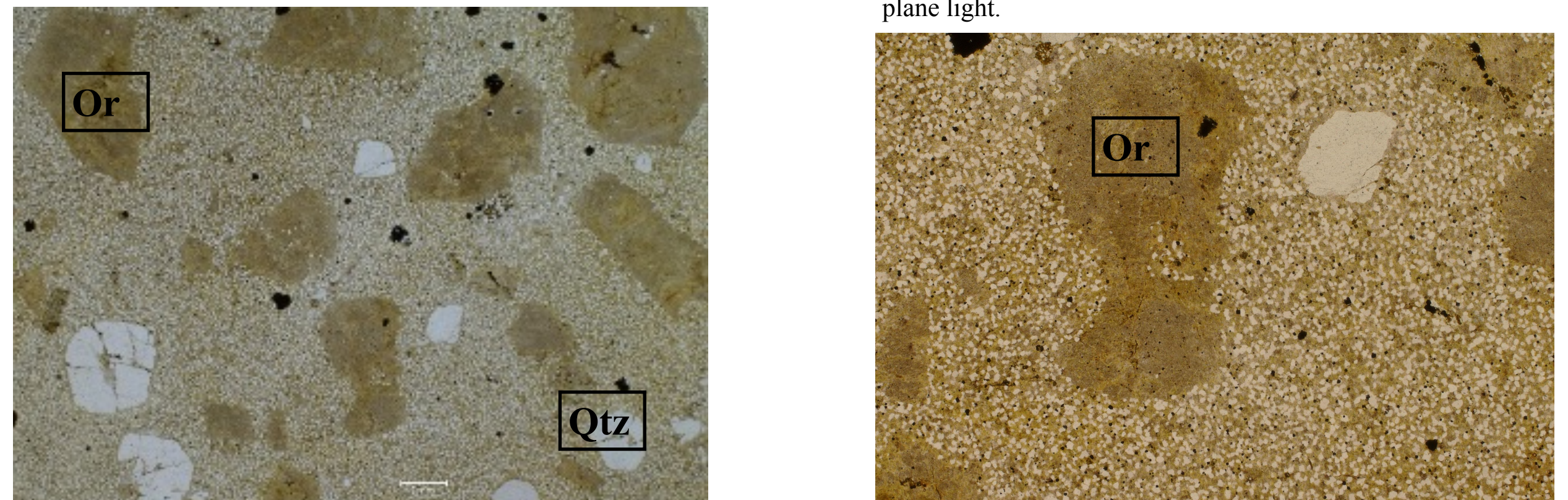


Figure 14. MM-6, rhyolite xenolith in Quana Granite: orthoclase (Or) and plagioclase (Pl) phenocrysts. Groundmass shows a granoblastic texture (plane light).



Figure 15. Sample MM-2 showing granoblastic texture with partially recrystallized orthoclase (Or) and quartz (Qtz), plane light.

### Geochemistry of the of Carlton Rhyolite

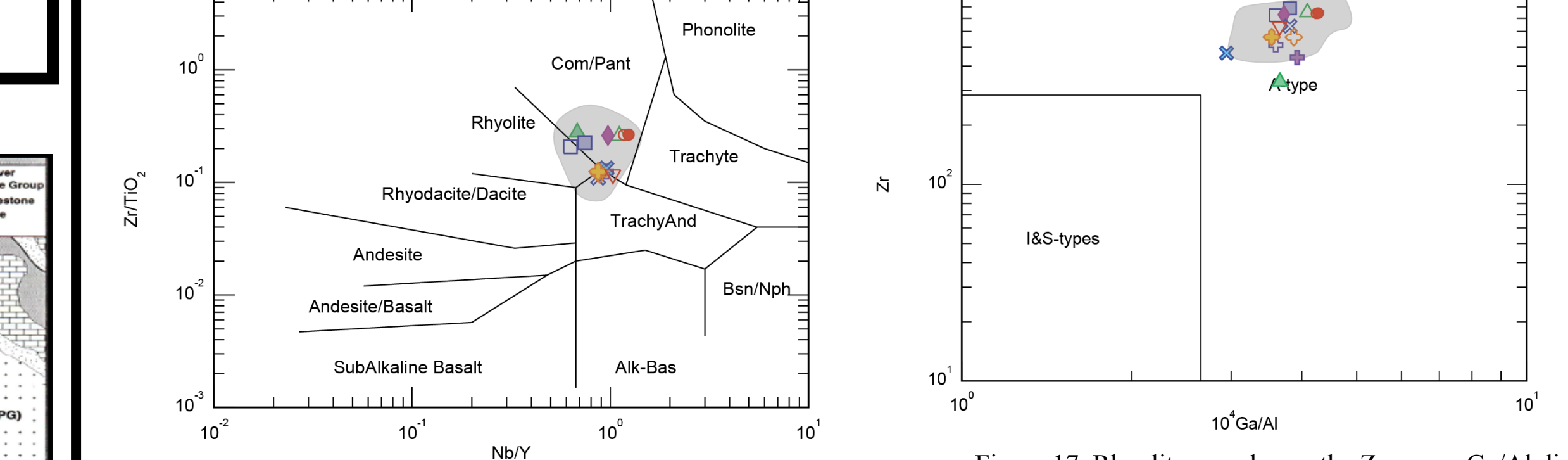


Figure 16. Nb/Y versus Zr/TiO<sub>2</sub> discrimination diagram for rhyolite samples; fields are after Winchester and Floyd (1977). Gray field on this and the following diagrams represents data for Carlton Rhyolite in the Wichita Mountains from Hanson et al. 2014 and Finegan and Hanson (2014). Figure 17. Rhyolite samples on the Zr versus Ga/Al diagram discrimination diagram of Whalen et al. (1987).

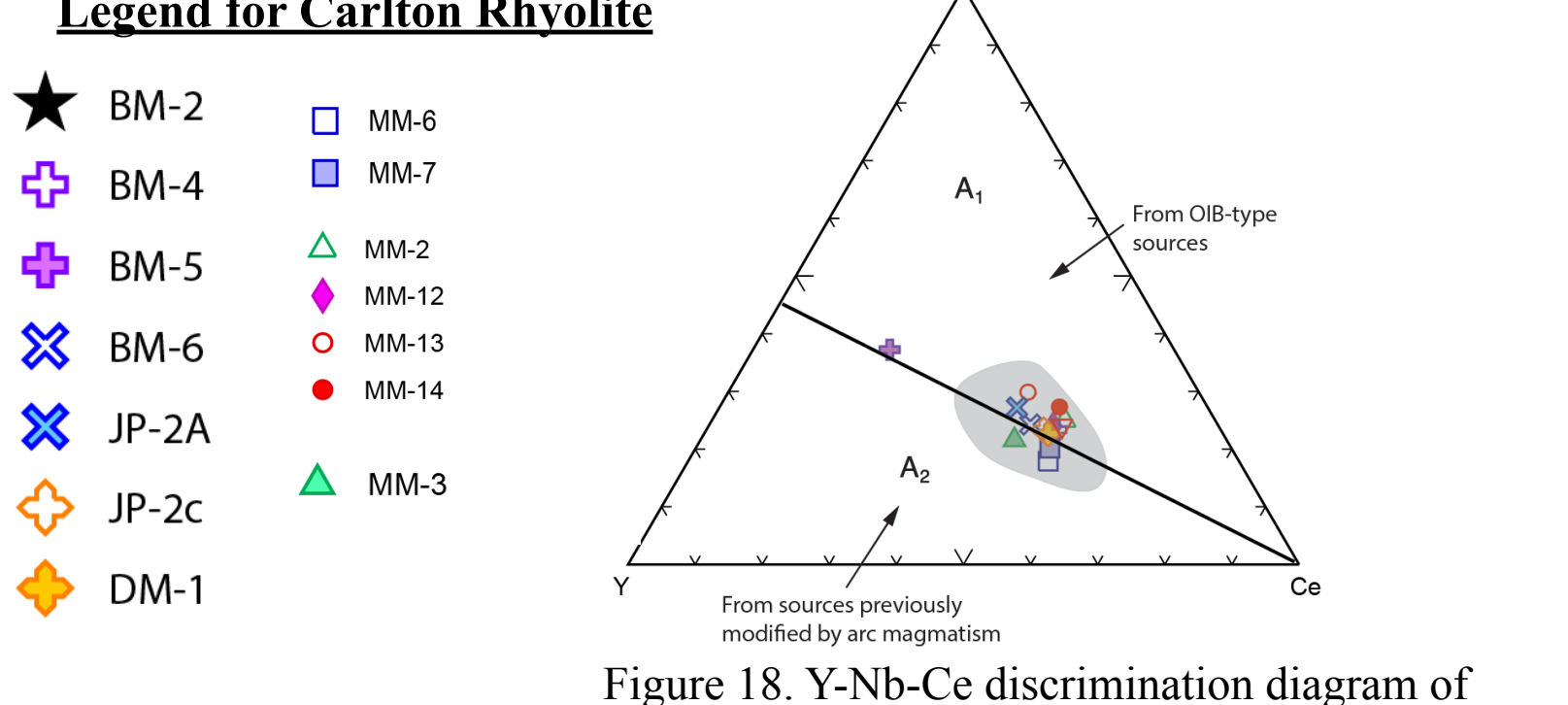


Figure 18. Y-Nb-Ce discrimination diagram of Eby (1992) for A-type felsic rocks.

All analyzed rhyolite samples from the Wichita Mountains plot within the A-type field, indicating hot, dry, ferroan magmas generated in an extensional within-plate setting.

Most samples plot within the A1 field. This indicates an anorogenic, within-plate origin. A few samples trending slightly toward A2 suggest minor interaction with continental lithosphere previously modified by subduction.

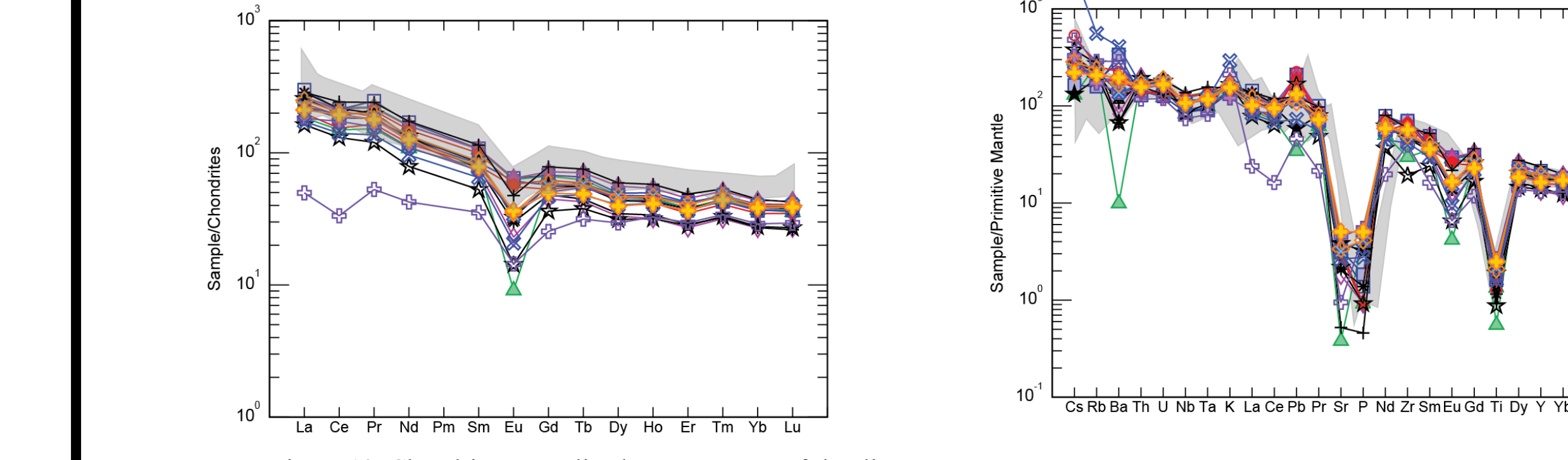


Figure 19. Chondrite-normalized REE patterns of rhyolite samples; normalizing values are from Sun and McDonough (1989). Figure 20. Primitive mantle-normalized trace element patterns of rhyolite samples; normalizing values are from Sun and McDonough (1989).

Rhyolites exhibit fairly strong LREE enrichment, depleted HREEs, and a pronounced negative Eu anomaly, reflecting plagioclase fractionation in these silica-rich magmas. These are characteristics of A-type felsic rocks. This has been observed in other Carlton Rhyolite flows (Hanson et al. 2014). Also, the negative Ce anomaly in BM-4, indicates some disturbance due to alteration.

### Trace Element Group Classification

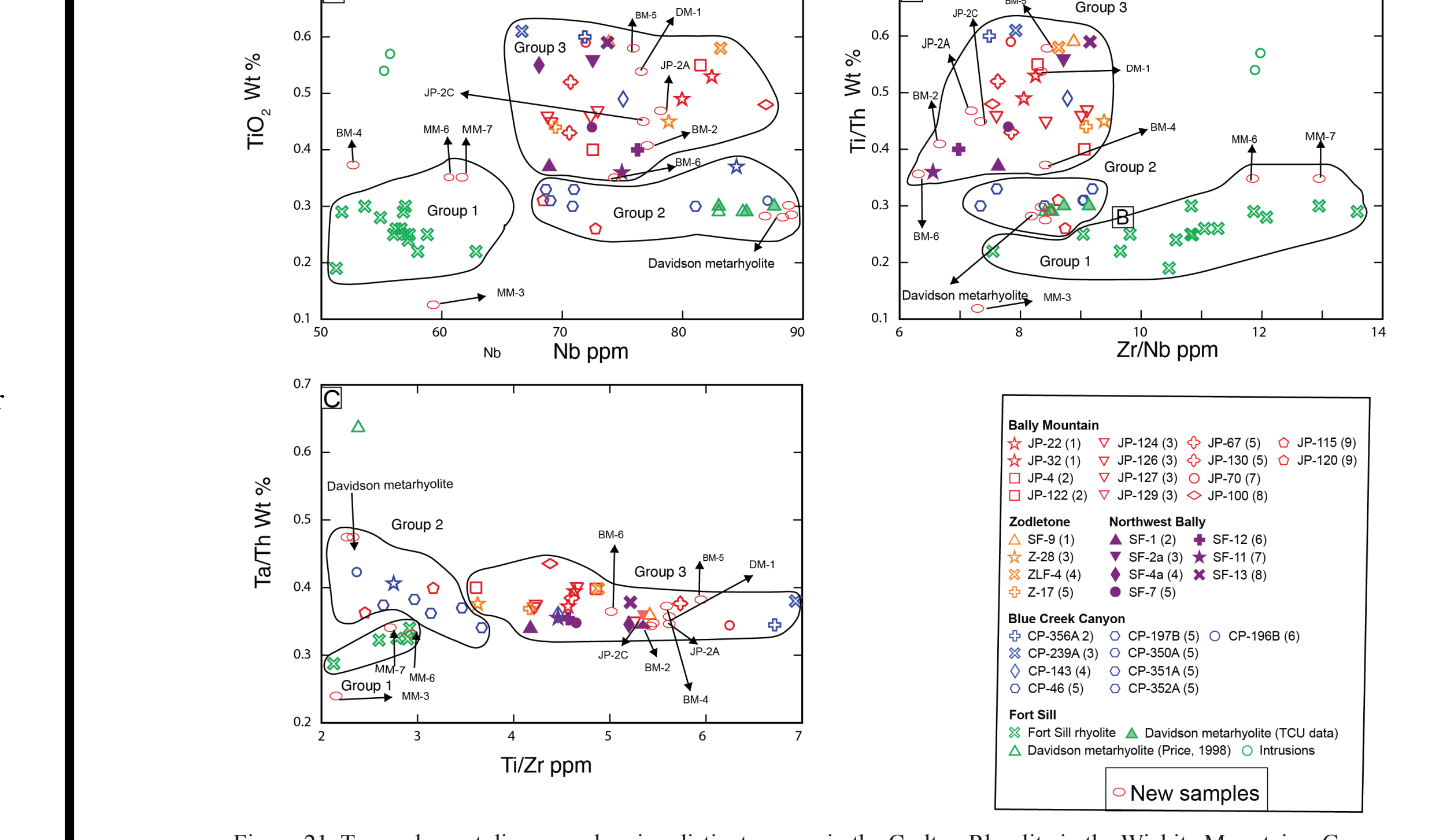


Figure 21. Trace-element diagrams showing distinct groups in the Carlton Rhyolite in the Wichita Mountains. Groups are from Hanson et al. 2014. (A) TiO<sub>2</sub> versus Nb diagram. (B) TiO<sub>2</sub> versus Zr/Nb diagram. C. Ta/Th versus Ti/Zr diagram.

Samples BM-2, BM-5, BM-6, and DM-1 all plot in Group 3, as do feeder dike samples JP-2A and JP-2C.

Samples MM-2, MM-12, MM-13, and MM-14 from the Davidson metarhyolite consistently plot in Group 2.

MM-6 and MM-7 (Fort Sill xenoliths) plot in Group 1, confirming their derivation from the Fort Sill Rhyolite prior to Quana Granite intrusion.

Sample MM-3 plots anomalously outside all group fields.

Sample BM-4 also falls outside all groups on the TiO<sub>2</sub>/Nb diagram.

### Conclusion

- For Rhyolites
  - Strong LREE enrichment, negative Eu anomalies, and high HFSE levels are consistent with an origin from high-temperature A-type magmas.
  - Sample MM-3 (filled green triangle), from a rhyolite dike intruding granite, is significantly younger than the other rhyolites.
  - At Bally Mountain, samples JP-2A and JP-2C come from a dike exposed just below the base of flow 3 (Fig. 3B), and are geochemically similar to sample BM-2 near the base of that flow. This indicates that the dike is a feeder for flow 3. This is the only confirmed feeder dike for any rhyolite flow in the SOA.
  - The rhyolites samples came from three main magma sources, and their overlapping distributions point to a complex and interconnected magmatic system.
- For Diabase
  - Most diabase dikes show characteristics of enriched MORB (Figure 17) and also plot together on Figures 13-16.
  - However, MM-9 and KD plot together and have different trace elements patterns from the rest of the diabase samples, suggesting these dikes have different petrogenetic histories. The two samples come from the extreme west and extreme east from Figure 3A. This suggests a complex plumbing system for these mafic magmas.

### References

Aguilar, J. (1988). Geochemistry of mafic rock units of the Southern Oklahoma Aulacogen, southwestern Oklahoma (Master's thesis). University of Oklahoma, Norman, OK, 167 p.

DeGroot, P. J., Donovan, R. N., Hanson, R. E., & Weaver, B. L. (1995). Cambrian diabase and gabbro in the Blue Creek Canyon area, Wichita Mountains, southwestern Oklahoma. *Oklahoma Geology Notes*, 55, 168-186.

Diez de Medina, D. M. (1988). Geochemistry of the Sandy Creek Gabbro, Wichita Mountains, Oklahoma (Master's thesis). University of Oklahoma, Norman, OK, 163 p.

Donovan, R. N., England, D. A., Rafanowski, M. B., Collins, Kathy, Taggar, Tekleh, McConnell, David, Marchini, D. M., Beuchamp, Weldon, and Sanderson, D.J. (1986). Stop 1. Geologic highlights in the Blue Creek Canyon area, in Donovan, R. N. (ed.), The Stick Hills of southwestern Oklahoma-fragments of an aulacogen? Oklahoma Geological Survey Guidebook 24, p. 84-91.

Eby, G. N. (1992). Chemical subdivision of the A-type granitoids: Petrogenetic and tectonic implications. *Geology*, v. 20, p. 641-644.

Finegan, S. A., & Hanson, R. E. (2014). Carlton Rhyolite Group in the Fort Sill area, Wichita Mountains. In N. Suneson (Ed.), *Igneous and Tectonic History of the Southern Oklahoma Aulacogen*. Oklahoma Geological Survey Guidebook 38, pp. 211-254.

Floyd, P. A., & Winchester, J. A. (1975). Magma type and tectonic setting discrimination using immobile elements. *Earth and Planetary Science Letters*, v. 27, p. 211-218.

Ham, W. E., Denison, R. E., & Merritt, C. A. (1964). Basement rocks and structural evolution of Southern Oklahoma. *Oklahoma Geological Survey Bulletin* 95, 302 pp.

Hanson, R. E., & Eschberger, A. M. (2014). An overview of the Carlton Rhyolite Group: Cambrian A-type felsic volcanism in the Southern Oklahoma Aulacogen. In N. Suneson (Ed.), *Igneous and tectonic history of the Southern Oklahoma Aulacogen*. Oklahoma Geological Survey Guidebook 38, pp. 123-141.

Hanson, R. E., Puckett, R. E., Keller, R. G., Brueske, M. E., Bales, C. L., Metzman, S. A., Finegan, S. A., & McCleery, D. A. (2013). Intraplate magmatism related to the opening of the southern Iapetus Ocean: Cambrian Wichita igneous province in the Southern Oklahoma rift Zone. *Lithos*, v.174, 57-70.

Hogan, J. P., & Gilbert, M. C. (1995). The A-type Mount Scott Granite sheet: Importance of crustal magma traps. *Journal of Geophysical Research*, 100, p.15779-15792.

Hogan, J. P., & Gilbert, M. C. (1997). Intrusive style of A-type sheet granites in a rift environment: The Southern Oklahoma aulacogen. In Ojakangas, R. W., Dickas, A. B., and Green, J. C. (Eds.), *Midle Proterozoic to Cambrian Rifting, Central North America*. Geological Society of America Special Paper, v. 312, p. 299-311.

Keller, G. R., & Stephenson, R. A. (2007). The Southern Oklahoma and Dnipropetrovsk aulacogens: A comparative analysis. In R. D. Hatcher Jr., M. P. Carlson, J. H. McBride, & J. R. Martinez-Catalan (Eds.), *4-D framework of continental crust*. Geological Society of America Memorial 200, pp. 127-143.

Meschede, M. (1986). A method of discriminating between different types of mid-ocean ridge basalts and continental tholeiites with the Nb-Zr-Y diagram. *Chemical Geology*, v. 56, p. 207-218.

Myers, J. D., Gilbert, M. C., & Loisle, M. C. (1981). Geochemistry of the Cambrian Wichita Granite Group and revisions of its lithostratigraphy. *Oklahoma Geology Notes*, v. 41, p. 172-195.

Pearce, J. A., & Norry, M. J. (1979). Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks. *Contributions to Mineralogy and Petrology*, 69(1), pp. 33-47.

Pearce, J. A. (1982). Trace element characteristics of lavas from destructive plate boundaries, in Thorpe, R. S., ed., *Andesites: Orogenic Andesites and Related Rocks*. New York: Wiley, p. 525-548.

Powell, B. N., Gilbert, M. C., & Fischer, J. F. (1980). Lithostratigraphic classification of basement rocks of the Wichita province, Oklahoma. *Geological Society of America Bulletin*, v. 91, Part 1, Summary, p. 509-514; Part II, p. 1875-1994.

Sun, S. S., & McDonough, W. F. (1989). Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. In A. D. Saunders & M. J. Norry (Eds.), *Magnatism in the ocean basins*. Geological Society of London, pp. 313-345.

Wall, C. J., Hanson, R. E., Schmitz, M., Price, J. D., Donovan, R. N., Bony, J. R., Eschberger, A. M., & Toews, C. E. (2021). Integrating zircon trace element geochemistry and high-precision U-Pb zircon geochronology to resolve the timing and petrogenesis of the late Ediacaran-Cambrian Wichita igneous province, Southern Oklahoma Aulacogen, USA. *Geology*, v. 49, p. 208-212.

Whalen, J. B., Currie, K. L., & Chappell, B. W. (1987). A-type granites: Geochemical characteristics, discrimination and petrogenesis. *Contributions to Mineralogy and Petrology*, 95(4), pp. 407-419.

Winchester, J. A., & Floyd, P. A. (1977). Geochemical discrimination of different magma series and their differentiation products using immobile trace elements. *Chemical Geology*, 20, pp. 325-343.