Cambrian Wichita igneous province in the Southern Oklahoma rift zone

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Abstract: Southern Oklahoma and adjacent parts of Texas contain an extensive igneous province emplaced during Early Cambrian rifting within the Southern Oklahoma rift zone. The rift zone was initiated in association with opening of the southern Iapetus Ocean during Rodinia supercontinent breakup and later became the site of a series of linked uplifts and basins as a result of late Paleozoic inversion. Igneous rocks within the rift are referred to as the Wichita province and are present mostly in the subsurface, with critical exposures located in the Wichita and Arbuckle Mountains in southwestern and southern Oklahoma. Wells drilled into basement in the region provide a wealth of information on the distribution and relations of the major igneous units in the upper crust, and geophysical data provide important constraints on deeper levels of the rift zone.

The upper parts of the igneous rift fill comprise the Carlton Rhyolite Group, which has a subsurface areal extent of ~40,000 km2, and the related Wichita sheet granites, which intrude the base of the rhyolite succession. These rocks have A-type characteristics and were emplaced after intrusion, tilting and uplift of a major tholeiitic layered mafic complex; smaller bodies of gabbro also intruded the layered complex after it was tilted. U−Pb zircon and 40Ar/39Ar geochronology indicates the felsic rocks and at least some of the mafic units were emplaced in a relatively narrow time frame at ~539−530 Ma. Basalts and intermediate lavas are present only in the subsurface. Our new work shows these lavas to have tholeiitic to mildly alkaline compositions and to be more extensive than previously realized, forming thick sequences that both underlie and are intercalated with the rhyolites. A suite of late diabase dikes also cuts the rhyolites and granites, indicating that mafic magma was supplied to the rift throughout its magmatic history. Geophysical data show that an enormous mass of mafic rock occupies deeper parts of the rift, extending to depths of at least ~10 km beneath the surface. The total volume of igneous rock emplaced within the rift is estimated to be in excess of 250,000 km3.

Detailed studies of Carlton Rhyolite exposures in the Wichita Mountains, complemented by studies of drill cuttings from basement wells, indicate that the rhyolites comprise a series of lava flows up to 400 m thick stacked on top of each other or separated by intervals of rhyolitic volcaniclastic deposits. The generally limited exposures of these rhyolite lavas in the Wichita Mountains are interpreted to be remnants of laterally extensive flow units similar to those documented from other A-type felsic provinces. Trace element contents define three distinct geochemical groups of rhyolite, suggesting derivation from three different sources or magma reservoirs. Flows belonging to the different

geochemical groups are intercalated in the Wichita Mountains exposures, which may indicate that laterally extensive flows from separate magma chambers came to rest on top of one another during accumulation of the rhyolitic volcanic pile.

Cover letter

This paper is being submitted for the special issue on LIPs and Supercontinents. The topic of the paper is the Cambrian Wichita LIP in the Southern Oklahoma rift zone, which has received little attention in the LIP literature. We provide a review of the main igneous units and their geological relations, and present new data on the volcanic fill and geophysical signature of the rift.

Highlights

- Geophysics shows large mafic complex extending to depths of $\geq$ 10 km beneath rift.
- Total magma volume emplaced in Early Cambrian estimated to be > 250,000 km^3.
- A-type rhyolites and sheet granites form upper part of igneous assemblage in rift.
- Large volumes of mafic and intermediate lavas occur with rhyolites in subsurface.
- Limited rhyolite outcrops inferred to be remnants of laterally extensive flows.

Cambrian Wichita igneous province in the Southern Oklahoma rift zone

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ABSTRACT

Southern Oklahoma and adjacent parts of Texas contain an extensive igneous province emplaced during Early Cambrian rifting within the Southern Oklahoma rift zone. The rift zone was initiated in association with opening of the southern Iapetus Ocean during Rodinia supercontinent breakup and later became the site of a series of linked uplifts and basins as a result of late Paleozoic inversion. Igneous rocks within the rift are referred to as the Wichita province and are present mostly in the subsurface, with critical exposures located in the Wichita and Arbuckle Mountains in southwestern and southern Oklahoma. Wells drilled into basement in the region provide a wealth of information on the distribution and relations of the major igneous units in the upper crust, and geophysical data provide important constraints on deeper levels of the rift zone.

The upper parts of the igneous rift fill comprise the Carlton Rhyolite Group, which has a subsurface areal extent of ~40,000 km^2, and the related Wichita sheet granites, which intrude the base of the rhyolite succession. These rocks have A-type characteristics and were emplaced after intrusion, tilting and uplift of a major tholeiitic layered mafic complex; smaller bodies of gabbro also intruded the layered complex after it was tilted. U–Pb zircon and ^{40}Ar/^{39}Ar geochronology indicates the felsic rocks and at least some of the mafic units were emplaced in a relatively narrow time frame at ~539–530 Ma. Basalts and intermediate lavas are present only in the subsurface. Our new work shows these lavas to have tholeiitic to mildly alkaline compositions and to be more extensive than previously realized, forming thick sequences that both underlie and are intercalated with the rhyolites. A suite of late diabase dikes also cuts the rhyolites and granites, indicating that mafic magma was supplied to the rift throughout its magmatic history. Geophysical data show that an enormous mass of mafic rock occupies deeper parts of the rift, extending to depths of at least ~10 km beneath the surface. The total volume of igneous rock emplaced within the rift is estimated to be in excess of 250,000 km^3.

Detailed studies of Carlton Rhyolite exposures in the Wichita Mountains, complemented by studies of drill cuttings from basement wells, indicate that the rhyolites comprise a series of lava flows up to 400 m thick stacked on top of each other or separated by intervals of rhyolitic volcaniclastic deposits. The generally limited exposures of these rhyolite lavas in the Wichita Mountains are interpreted to be remnants of laterally extensive flow units similar to those documented from other A-type felsic provinces. Trace element contents define three distinct geochemical groups of rhyolite, suggesting derivation from three different sources or magma reservoirs. Flows belonging to the different geochemical groups are intercalated in the Wichita Mountains exposures, which may indicate that laterally extensive flows from separate magma chambers came to rest on top of one another during accumulation of the rhyolitic volcanic pile.

1. Introduction

Opening of the Iapetus Ocean during breakup of the Rodinia supercontinent was preceded and accompanied by Neoproterozoic to Cambrian intraplate magmatism at numerous sites along the eastern margin of the Laurentian craton (Aleinikoff et al., 1995; Cawood et al., 2001; Tollo et al., 2004). There is less evidence for similar magmatism along the southeast margin of Laurentia. One notable exception occurs in southern Oklahoma and adjacent parts of Texas, the location of the Southern Oklahoma rift zone (Fig. 1). The rift zone contains an extensive, largely bimodal igneous assemblage that is typically considered to be Early Cambrian in age but may also extend back into the late Neoproterozoic. These rocks are grouped together as the Wichita province (Ham et al., 1964), and they represent one of the single largest magmatic episodes associated with the opening of Iapetus anywhere along the eastern or southern Laurentian margins. In spite of this, the Wichita province has received only limited attention in the LIP literature. Here we summarize important aspects of the rift-related igneous rocks and present some results of our work in progress on the geophysical signature and volcanic fill of the Southern Oklahoma rift zone.

2. Geological setting

The early work of Shatski (1946) recognized the large structures in southern Oklahoma as an inverted rift zone penetrating into the craton interior at a high angle to the Paleozoic continental margin (Fig. 1). Hoffman et al. (1974) considered the rift zone to represent an aulacogen or failed arm of a rift-rift-rift triple junction, with the other two arms evolving into sites of seafloor spreading as Iapetus began to open. More recently, Thomas (1991, 2011) has argued against the aulacogen model and has instead interpreted the magmatism in the rift zone to have occurred in a leaky transform fault zone associated with a pronounced offset in the Paleozoic continental margin.

An older basin containing Proterozoic strata ~12 km thick occurs in the subsurface to the south of the Southern Oklahoma rift zone (Pratt et al., 1992), raising the possibility that the latter feature developed along a pre-existing line of structural weakness in the craton. Felsic igneous rocks of the ~1.4 Ga southern midcontinent granite-rhyolite province form the main subsurface basement units to each side of the Southern Oklahoma rift zone (Van Schmus et al., 1996; Rohs and Van Schmus, 2007) and are locally exposed along the northern rift margin in the Arbuckle Mountains (Ham et al., 1964).

Inversion of the Southern Oklahoma rift zone occurred in the Pennsylvanian and Early Permian, related either to collisional Ouachita orogenesis along the southeast continental margin, or to far-field stresses transmitted inboard from the Cordilleran margin to the west (Perry, 1989; Ye et al., 1996). Major Cambrian rift faults were reactivated at this time to form reverse faults or thrusts in a compressional to transpressional regime (McConnell, 1989; Perry, 1989), resulting in exposure at the surface of parts of the Cambrian bimodal igneous assemblage within the rift. Deep basins developed in association with fault-bounded uplifts along the trend of the earlier rift and became the sites of major petroleum accumulations. The most notable example is the Anadarko basin, one of the deepest continental basins in the world.

Cambrian igneous rocks within the rift form relatively limited exposures in the Wichita Mountains in southwest Oklahoma and in the Arbuckle Mountains farther east (Fig. 1). Elsewhere it is necessary to rely on subsurface data to constrain the distribution and relations of the igneous units in the rift. A surprising number of wells have been drilled into the igneous rocks, because they form the hanging walls of reverse faults that place them over petroleum-bearing Paleozoic strata. The information from these basement wells allows a much better understanding of the subsurface igneous assemblage within the rift than would otherwise be possible, although our knowledge along these lines is still far from complete. Ham et al. (1964) produced the first synthesis of the distribution of igneous rocks in the subsurface of southern Oklahoma, based on studies of basement wells then available, and much of this pioneering work has stood the test of time.

Following cessation of Cambrian extensional tectonics and magmatism, thermal subsidence of the rift zone occurred during marine transgression across the region. The oldest strata to be deposited unconformably on the Cambrian igneous rocks during the transgression are Upper Cambrian (Ham et al., 1964), providing a younger limit on the timing of magmatism.

3. Cambrian igneous rocks in the Southern Oklahoma rift zone

The best exposures of the Cambrian igneous assemblage in the Southern Oklahoma rift zone occur in the Wichita Mountains (Fig. 2), and much of our understanding of the early phases of rift evolution is based on studies of those outcrops. Schematic relations of the main igneous units in the Wichita Mountains are illustrated in Figure 3. More limited exposures in the Arbuckle Mountains consist dominantly of rhyolite.

3.1. Raggedy Mountain Gabbro Group

Abundant gabbroic rocks in the Wichita province have been assigned to the Raggedy Mountain Gabbro Group by Ham et al. (1964). The oldest examples of these rocks that crop out in the Wichita Mountains belong to the Glen Mountains Layered Complex. A composite vertical sequence ~1.l km thick of parts of the complex is exposed at the surface (Powell et al., 1980; Powell, 1986), but subsurface data show the complex to be more extensive (Ham et al., 1964). The exposed rocks consist of anorthosite, anorthositic gabbro, troctolite and olivine gabbro showing typical rhythmic and cryptic layering (Powell, 1986; Cooper, 1991). These rocks represent the middle parts of a standard tholeiitic layered complex and require the presence of ultramafic rocks at deeper levels (Powell and Phelps, 1977). Prior to emplacement of younger igneous rocks in the province, the layered rocks were tilted gently to the north, and Powell and Phelps (1977) have estimated that 2–4 km of overlying, more differentiated parts of the complex were removed by erosion, as well as an unknown thickness of roof rock. The uplift has been attributed to block rotation during normal faulting within the developing rift zone (McConnell and Gilbert, 1990). Following this tilting and erosion, a series of smaller intrusions of biotite-bearing tholeiitic gabbro (Roosevelt Gabbros) were intruded into the layered complex and are petrogenetically unrelated to it (Powell et al., 1980; Price et al., 1998a). Subsurface data indicate that similar biotite-bearing gabbros are widespread in the subsurface in western Oklahoma and adjacent parts of the Texas panhandle. Also present in the subsurface in that region are fairly extensive amounts of hornblende diorite and quartz diorite (Ham et al., 1964). The dioritic rocks have not been studied in detail, and their petrogenetic relations to other parts of the Wichita province are unclear.

3.2. Navajoe Mountain Basalt-Spilite Group

Ham et al. (1964) introduced the term Navajoe Mountain Basalt-Spilite Group for a sequence of variably altered basaltic to intermediate volcanic rocks penetrated by eleven basement wells in the western part of the Wichita province; the thickest penetration was 320 m, and the base of the volcanic rocks was not reached. The exact relations of this volcanic sequence to the Glen Mountains Layered Complex are unknown. Most of the rocks are lavas, but palagonite tuffs occur in the lower ~50 m of drilled section in one well, suggesting that some of the volcanism involved explosive phreatomagmatic eruptions in subaqueous settings or in terrestrial environments where uprising magma came in contact with groundwater-rich zones beneath the surface. Chemical studies by Shapiro (1981) and Aquilar (1988) indicate tholeiitic compositions for the lavas, but those authors only analyzed selected major and trace elements because of small sample size. Limited whole-rock chemical analyses and optical determinations of plagioclase compositions indicate that intermediate rocks are present as well as basalts within parts of the succession (Ham et al., 1964; Aquilar, 1988).

3.3. Carlton Rhyolite and Wichita Granite Groups

The uppermost major igneous unit within the Southern Oklahoma rift zone is the Carlton Rhyolite Group, which can be traced for at least 40,000 km^2 in the subsurface (Fig. 1; Ham et al., 1964). The rhyolites overlie the Navajoe Mountain Basalt-Spilite Group in the subsurface in the western part of the province, and regional relations indicate they originally covered the erosional surface developed on top of the Glen Mountains Layered Complex (Ham et al., 1964). The greatest known thickness of rhyolite occurs at Bally Mountain in the Wichitas (Fig. 2), where a number of different rhyolite flows form a sequence ~2 km thick (Hanson et al., 2009); this is a minimum thickness because the base of the sequence is truncated by a Pennsylvanian fault. The maximum subsurface rhyolite thickness penetrated by drilling is 1.4 km in the Arbuckle Mountains region. Stratigraphic relations in that area demonstrate that the rhyolites were ponded against a major rift fault (Washita Valley fault) along the northern margin of the rift zone (Ham et al., 1964); this fault was reactivated as a compressional to transpressional structure during Pennsylvanian inversion of the rift zone. Elsewhere, geophysical evidence suggests that the rhyolites poured across the rift-bounding faults and extended farther north, as discussed in section 4.3. There is no evidence for the presence of calderas within the Southern Oklahoma rift zone, and it is likely that the rhyolites issued from fissure-type vents (Hogan and Gilbert, 1998).

Major components of the Wichita Granite Group are a series of sheet granites injected along the contact between the layered complex and the overlying rhyolites (Figs. 3 and 4). The most extensive of these sheet granites is the Mount Scott Granite (Fig. 4), which forms a sill that can be traced a minimum of 55 km laterally but is only 0.5 km thick (Hogan and Gilbert, 1995; Price, 1998). Granite sills also occur between the rhyolites and the underlying basalts in the subsurface (Ham et al., 1964). Both the rhyolites and granites have typical features of A-type felsic rocks (Myers et al., 1981; Hogan and Gilbert, 1995, 1997). They plot uniformly in fields for within-plate, A-type granites on standard discrimination diagrams using elements resistant to secondary alteration (Fig. 5). High F contents in magmatic amphiboles in the granites and experimentally determined phase relations indicate the felsic magmas had high F contents (Hogan and Gilbert, 1995; Price et al., 1999), and Zr geothermometry on the granites and rhyolites yields temperatures up to ~950° C (Hogan and Gilbert, 1997), in keeping with the A-type affinities of these rocks. The relatively low viscosity of these A-type felsic magmas presumably explains their ability to form extensive granite sills that are surprisingly thin relative to their lateral extents.

3.4. Diabase dikes

The youngest igneous rocks in the Southern Oklahoma rift zone consist of a large number of diabase dikes and sills or transgressive sheets that cut all the other igneous units and are exposed both in the Wichita and Arbuckle Mountains. These so-called “late diabases” have tholeiitic to transitional affinities (Cameron et al., 1986; Gilbert and Hughes, 1986; DeGroat et al., 1995). They show variable trends but generally strike northwest, parallel to the trend of the rift (Ham et al., 1964; Denison, 1995).

Similar tholeiitic diabase dikes, typically with northwest trends, intrude the 1.4 Ga basement rocks exposed in the Arbuckle Mountains on the north side of the rift zone, and they increase in abundance as the margin of the rift is approached (Denison, 1995; Lidiak et al., 2005). The dikes tend to be poorly exposed at the surface, but quarries in Proterozoic basement near the rift margin reveal the dikes to occupy up to ~30% of the rock volume (Fig. 6). Denison (1995) has suggested that this episode of dike injection preceded emplacement of the felsic rocks inside the rift zone.

3.5. Temporal relations and magma sources

Considerable progress has been made in developing good isotopic age constraints for the magmatic evolution of the Southern Oklahoma rift zone, although some units remain poorly dated, and some data are available only in abstract form. There are currently no robust age constraints on the Navajoe Mountain Basalt-Spilite Group. Lambert et al. (1988) obtained an internal Sm–Nd whole-rock–mineral isochron date of 528 ± 29 Ma for the Glen Mountains Layered Complex, the oldest igneous unit exposed at the surface within the rift zone. The Wichita granites and a rhyolite xenolith within the granites have yielded U–Pb zircon ages of 533 ± 1 to 530 ± 1 Ma (Wright et al., 1996). Hanson et al. (2009) reported preliminary zircon ages of ~532 Ma for two flows from the base and top of the rhyolite sequence at Bally Mountain, and rhyolites exposed in the Arbuckle Mountains have yielded zircon ages of 539 ± 5 and 536 ± 5 Ma (Thomas et al., 2000).

One of the Roosevelt Gabbros intrusive into the Glen Mountains Layered Complex has yielded ^{40}Ar/^{39}Ar hornblende and biotite dates of 533 ± 2 and 533 ± 4, respectively (Hames et al., 1998). Bowring and Hoppe (1982) obtained a U–Pb zircon age of 552 ± 7 Ma for the same body of

Roosevelt Gabbro dated by Hames et al. (1998). This result appears to conflict with field evidence that emplacement of the Roosevelt Gabbros was penecontemporaneous with granite intrusion, raising the possibility that the U–Pb isotopic data may be influenced by an inherited component (Hogan and Gilbert, 1998). The diabase dikes in the rift zone have not yielded reliable geochronological results, but they clearly predate deposition of Upper Cambrian sediments across the igneous rocks within the rift zone, and field evidence indicates that their emplacement overlapped in time with the felsic magmatism (Price et al., 1996; Hogan and Gilbert, 1998).

Prior to the availability of isotopic constraints on source regions for the magmas, it was commonly thought that the voluminous felsic rocks in the Wichita province were generated from partial melting of older crust at depth (e.g., Gilbert and Denison, 1993). However, the felsic rocks have yielded low initial $^{87}Sr/^{86}Sr$ ratios and positive ε_{Nd} values that overlap with values for the late diabases (Hogan et al., 1995), suggesting that the felsic magmas were derived either by differentiation of basaltic parental magmas or by partial melting of a mafic underplate. Trace-element patterns for both the granites and rhyolites point to derivation from ocean-island-basalt-type precursors (Hogan et al., 1995; McCleery and Hanson, 2010).

4. Work in progress on the volcanic fill of the Southern Oklahoma rift zone

4.1. New subsurface data for mafic and intermediate volcanic rocks in the rift zone

Basement wells drilled since the work of Ham et al. (1964) provide the opportunity to better constrain the distribution of igneous units within the Southern Oklahoma rift zone. To this end, we have initiated a study of 41 wells drilled into the volcanic fill of the rift zone in the area within and to the northwest of the Arbuckle Mountains (Puckett, 2011; Puckett et al., 2011; Brueseke, Bulen and Mertzman, unpubl. data). The wells span an along-strike distance of 42 km south of and parallel to the Washita Valley fault that forms the northern margin of the rift zone in this region. Ham et al. (1964) previously documented the extensive amount of Carlton Rhyolite present in the subsurface in the area. A surprising result of the new work has been the recognition of extensive amounts of mafic to intermediate lava flows which both underlie and are intercalated with the rhyolites, as shown in Figure 7. In that figure, the very thin mafic units within intervals of rhyolite and granite are diabase dikes or sills, whereas the thicker mafic intervals are dominantly lava, with some intrusive diabase also present.

Thicknesses of volcanic rocks penetrated in the wells range from 475 m to 4.3 km. These wells present a cumulative total in excess of 37 km of non-correlated igneous section available for examination and reveal a much more complete profile of the volcanic section in the Arbuckles than is available on outcrop, where only rhyolites and diabase dikes are exposed. Representative lithological logs from some of the wells are shown in Figure 7. These logs were compiled by examination of drill- cutting samples taken at intervals of 10 feet (~3 m) and correlated with gamma-ray logs, which readily distinguish between the mafic and felsic rock types. Flow boundaries of thick extrusive units, buried weathering surfaces, and important thrust faults have also been identified. The deepest well in Figure 7 represents the thickest penetration of igneous rocks in Oklahoma (Puckett, 2011). None of the wells in the study area penetrated completely through the volcanic section; in most wells the base of the section is truncated by the Washita Valley fault. One well (labeled Sec. 19-T1N-R2W in Fig. 7) contains a thick clastic section of arkosic sandstone interpreted as a fan delta sequence derived from Proterozoic basement rocks exposed outside the rift zone. The clastic interval also contains thin rhyolitic volcaniclastic units and was covered by later volcanic eruptions after it accumulated.

Phenocrysts in the basalts are dominantly plagioclase, with less common olivine (?) replaced by Fe-rich clay minerals. Many cuttings exhibit intergranular groundmass textures (Fig. 8a), consisting of randomly arranged plagioclase microlites and interstitial mafic grains, including clinopyroxene and magnetite. A smaller number of cuttings have a groundmass consisting of dark tachylitic glass (Fig. 8b). These textural variations suggest the wells penetrated a series of lava flows, with intergranular textures representing slowly cooled flow interiors and tachylite being derived from more rapidly chilled flow margins. Some intervals also contain vesicular, ash- and lapilli-sized particles of altered sideromelane glass (Fig. 8c), indicating that explosive hydrovolcanic eruptions played a role in the evolution of parts of the volcanic sequence.

Our recent work yields major and trace element whole-rock geochemical results from three of the wells. Sampling protocols and analytical techniques are discussed in Appendix A. This work is in progress and a detailed discussion of these data is beyond the scope of this contribution. However, first order observations shed light on nomenclature, geochemical diversity, tectonic implications, and potential mantle sources of these lava flows. Figure 9 illustrates the general nomenclature of these samples and indicates that they range from basalt to andesite and are dominantly subalkaline to mildy alkaline [e.g., they straddle the subalkaline-alkaline boundary on the Zr/TiO_2 vs. Nb/Y diagram of Winchester and Floyd (1977) and the total alkalis vs. silica diagram of Le Bas et al. (1986)]. That the samples yield the same nomenclature in the classifications of Winchester and Floyd (1977) and Le Bas et al. (1986), coupled with acceptable analytical totals (Brueseke, unpubl. data), points to the robustness of the major and trace element results. CIPW norm calculations (assuming 70% of Fe is ferrous) for two of the samples yield olivine tholeiite to quartz tholeiite compositions.

Representative Harker diagrams are shown in Figure 10, and Figure 11 is the tectonic discrimination diagram of Meschede (1986). All drill-cutting samples plot within a region that straddles the boundary between intraplate tholeiites and E-MORB. Figure 12 illustrates that the samples have Zr/Nb values of ~7-11 (average = 8.7), similar to EMI OIB (Weaver, 1991). Other incompatible trace element ratios show similar relationships (e.g., OIB-like Ba/Nb, Nb/Y, etc.). The bulk chemical trends (Fig. 10) suggest that the more evolved samples are related to the least evolved samples via fractional crystallization (± assimilation of crust). In summary, the wells penetrate a volumetrically significant package of mafic to intermediate rocks that have OIB-like, tholeiitic to slightly alkaline chemistries, similar to flood basalt packages exposed in other LIPs.

4.2. Ongoing work on the Carlton Rhyolite Group

Work on the Carlton Rhyolite in the Wichita Mountains has been carried out in the Zodletone Mountain, Bally Mountain, Blue Creek Canyon, and Fort Sill areas (Fig. 2; Bigger and Hanson, 1992; Hanson et al., 2009, 2011). The rhyolite outcrops are generally fairly limited, but they give us an intriguing window into the extensive, mostly buried Cambrian rhyolitic volcanic field forming the upper part of the igneous fill within the Southern Oklahoma rift zone. We have mapped ~30 individual flows in the Wichitas, none of which can be correlated between the four main outcrop areas shown in Figure 2 because of structural complications. Individual flow units are up to 400 m thick and form tabular bodies stacked on top of each other or separated by generally thin rhyolitic volcaniclastic deposits. On outcrop most of these flows can only be traced a few kilometers before going under cover or being faulted out. The most extensive rhyolite flow we have mapped in the Wichita Mountains occurs in the Fort Sill area. This flow is > 190 m thick and can be traced ~18 km before going under cover or being truncated by intrusive granite (Finegan and Hanson, 2006); the original extent of the flow may have been considerably greater.

Rhyolite flows in the Wichita Mountains generally exhibit a standard vertical zonation (Fig. 13; Philips, 2002; Hanson et al., 2011). Originally glassy zones, now devitrified and altered, define the upper and lower margins to the flows and show relict perlitic texture, together with well-developed flow banding extending down to the thin-section scale (Figs. 14a and 14b). Peperite is developed at the base of many of the flows, where lava flowed over, quenched against, and mixed with unlithified, wet tuffaceous sediment (Fig. 14c). The inner parts of the glassy margins in many cases contain distinctive zones rich in lithophysae (Fig. 14d). Flow interiors consist of thick, monotonous, holocrystalline zones that lack flow banding and in thin section are seen to contain quartz paramorphs after tridymite crystals (Fig. 15). The tridymite needles increase in size towards flow centers, indicating that these flows were emplaced as single thick cooling units. Very similar textures shown by tridymite needles in the groundmass of other A-type felsic units have been described by Twist and French (1983) and Trendall (1995).

Drill cuttings of the rhyolites penetrated by the wells in the Arbuckle region (Fig. 7) exhibit a comparable range of groundmass textures to that seen in Carlton Rhyolite exposed in the Wichita Mountains. In some intervals, the cuttings show relict perlitic texture (Fig. 16a), and we interpret these samples to be derived from chilled, originally glassy margins to the lava flows. In many intervals, the cuttings contain randomly oriented tridymite crystals (inverted to quartz), which vary significantly in size between different cuttings (Figs. 16b and 16c). By analogy with rhyolite outcrops in the Wichita Mountains, we interpret these cuttings to record cooling gradients within thick flows after the lava had come to rest. Pyroclastic textures, including unwelded pumice fragments and tricuspate shards, generally occur in a small proportion of the cuttings, which we interpret to be derived from relatively thin pyroclastic interbeds between flows.

So far, we have found no convincing evidence for the presence of welded ignimbrites within the rhyolite succession penetrated by the Arbuckle wells. In most of the wells examined to date, the rhyolites appear to consist dominantly of lava flows ranging from tens of meters to possibly as much as several hundred meters thick. These data suggest that flow units comparable to those documented in the Wichita Mountains are probably a standard feature of the Cambrian rhyolitic volcanic field within the Southern Oklahoma rift zone.

Geochemical studies on the Carlton Rhyolite are also in progress (McCleery and Hanson, 2010), and some of the preliminary results of this work are presented here (see Appendix A for analytical techniques). Representative data from individual flows within the different rhyolite outcrops in the Wichita Mountains are shown on Harker diagrams in Figure 17. Scatter in the data is partly due to secondary alteration, but overall the rhyolites show a relatively restricted compositional range that overlaps with available data for the coeval Wichita granites. Note that the laterally extensive Fort Sill rhyolite flow shows significant within-flow compositional differences, which is also true to a lesser extent of a few other flows shown in Figure 17, suggesting that these flows tapped heterogeneous magma batches during eruption. Comparison of Figures 10 and 17 indicates that a Daly gap amounting to ~10 wt. % SiO_2 separates the most evolved intermediate lavas in the subsurface from the Carlton Rhyolite exposed in the Wichita Mountains.

Evidence that crystal-liquid fractionation accounts for some of the compositional variations in the rhyolites is shown in Figures 18a-c, where the trends can be explained by fractionation of clinopyroxene, plagioclase and alkali feldspar, consistent with observed phenocryst assemblages. However, note that the main Fort Sill rhyolite defines a separate trend from the other rhyolites, raising the possibility that some of the rhyolite flows were derived from separate magma reservoirs. This concept is tested further in Fig. 19, which shows several plots of elements that are resistant to secondary alteration. These diagrams show that, except for a few anomalous points, samples from the main Fort Sill rhyolite define a distinct group (Group 1) that is separate from the other rhyolite flows. The other rhyolites also consistently fall into two distinct groups (Groups 2 and 3). We infer that these groups record derivation of the rhyolite magmas from three distinct sources or magma reservoirs. An interesting point is that another rhyolite flow in the Fort Sill area, which occurs beneath the main Fort Sill flow, falls in Group 2 on the diagrams, along with three units in the Blue Creek Canyon area and one flow at Bally Mountain. The rest of the Bally Mountain flows plot with three of the Blue Creek Canyon flows and the Zodletone Mountain flows to define Group 3. These data suggest that flows exposed within the same area in some cases tapped different magma reservoirs.

4.3. Geophysical results

The Arbuckle and Wichita uplifts have long been recognized as being associated with very large linear gravity anomalies (Lyons, 1964). The relief of these anomalies across the uplifts exceeds 100 mGal in many locations. The residual gravity anomaly map shown in Figure 20 demonstrates the intensity and continuity of the gravity anomalies, which extend ~530 km from northeast Texas, across southern Oklahoma, and into the Texas Panhandle. The integrated geophysical model shown in Figure 21 shows that the source of the anomaly beneath the Southern Oklahoma rift is a high density-high velocity body (mafic igneous complex) that is ~40 km wide and extends at least to a depth of 10 km. This model is the result of gravity modeling of public domain data and seismic modeling of a data set collected jointly by the University of Texas at El Paso and the University of Texas at Dallas along the central portion of the white line shown in Figure 20. The seismic velocities were derived from a series of modeling efforts (Hamilton, 1989; Zhu and McMechan, 1989; Hsueh, 1991; Suleiman, 1993; Rondot, 2009) and sonic logs and some extrapolation from density values used in the modeling. The geometry of the model was derived from these modeling efforts, the imaging study of Chang et al. (1989) and COCORP reflection profiling (Brewer et al., 1981, 1983). Also, the seismic modeling efforts have revealed considerable reflectivity in the mafic complex, which is indicative of multiple episodes of magmatism and possibly igneous layering within one or more large intrusive bodies similar to the Glen Mountains Layered Complex exposed at the surface. The velocity and density values are consistent with the primary composition of the complex being gabbroic (e.g., Christensen and Mooney, 1996).

The integrated modeling shows that the cross-sectional area of the upper crustal mafic complex is ~400 km^2. A length of 530 km thus yields an estimated volume of 212,000 km^3 for the complex. This does not count the bodies under the Anadarko basin that are interpreted to be Carlton Rhyolite and/or sedimentary rift fill. The velocity and density of these features are not as well resolved as those in the Wichita uplift, and they are too deep to have been drilled. The structure of the lower crust has not been resolved by the seismic data presently available, but the fact that the gravity anomaly can be modeled without the presence of significant density contrasts indicates that any Cambrian magmatic products present below ~10 km have a density similar to that of the adjacent material.

5. Discussion

The original volume of magma emplaced during formation of the Wichita province cannot be determined with certainty. Lower Cambrian igneous rocks in the uppermost preserved parts of the province are separated by a significant erosional unconformity from overlying Upper Cambrian sedimentary strata. The unconformity is highly irregular where it is exposed in the Wichita Mountains, with paleohills of Carlton Rhyolite rising for as much as ~300 m above the general surface of the unconformity (Donovan and Bucheit, 2000). A substantial amount of Cambrian rhyolite was likely stripped away during formation of this erosional surface. The abundant diabase dikes cutting exposed Proterozoic basement rocks north of the rift in the Arbuckle Mountains most probably were feeders to extensive basaltic lavas. If so, the basalts were entirely removed by erosion prior to deposition of Upper Cambrian strata across the region, adding another element of uncertainty regarding the amount of volcanic rock originally present within the Wichita province.

Nonetheless, it is possible to arrive at an approximate estimate of igneous rock volumes within the province from available data. As noted above, the Carlton Rhyolite Group has a subsurface extent of at least ~40,000 km^2. Assuming an average thickness of one kilometer, which is a conservative estimate, the total volume of magma erupted to form the rhyolitic volcanic field is a minimum of 40,000 km^3. The volume of felsic magma emplaced as granite intrusions in the same time frame is more difficult to estimate but is also significant. The geophysical evidence indicates the presence of massive amounts of mafic rock at deeper levels along the entire axis of the rift zone, with an estimated volume in excess of 200,000 km^3. This results in an original magmatic volume probably in excess of 250,000 km^3 for the entire province, with the caveat that an unknown amount of igneous rock was removed by erosion prior to deposition of Upper Cambrian sedimentary strata across the region, and during late Paleozoic inversion of the rift. The province thus qualifies as an LIP, although certainly not one of the larger ones known (cf., Bryan and Ernst, 2008).

Emplacement of the felsic rocks within the province is bracketed by U–Pb zircon ages of 539 ± 5 Ma to 530 ± 1 Ma (Wright et al., 1996; Thomas et al., 2000), and other geochronological data and stratigraphic relations indicate that a significant proportion of the mafic rock within the province was probably emplaced in the same time frame. The Glen Mountains Layered Complex clearly predates the felsic magmatism and underwent tilting and erosion prior to extrusion of the Carlton Rhyolite and intrusion of the Wichita granites. These relations indicate that emplacement of magmas at high crustal levels was punctuated by block uplift in at least parts of the Southern Oklahoma rift zone, followed by renewed magmatism. A more precise age for the layered complex is needed, but the present data are consistent with emplacement of all the igneous units in a relatively narrow time frame within a dynamically evolving rift setting. Better age constraints are also needed for other parts of the province before reasonable estimates on magma production rates will be possible.

The most likely explanation for the anomalous production of magma along this part of the Laurentian margin is that it records the impact of a mantle plume during the rifting that led to Cambrian opening of the Iapetus Ocean to the southeast. Whether such an uprising mantle plume can be accommodated within the leaky transform model of Thomas (1991, 2011) for the development of the Wichita province requires further investigation. Any model for the Southern Oklahoma rift zone and the associated Wichita province must take into account the fact that the rift lines up to the northwest with a discontinuous belt of early Paleozoic alkaline complexes and diabase dike swarms exposed in parts of Colorado and New Mexico (Larson et al., 1985; McMillan and McLemore, 2004). Some of these rocks have yielded Rb−Sr and K−Ar isotopic dates as young as ~500 Ma (Larson et al., 1985), but these data should be treated with caution. Significantly, one of the alkaline complexes in Colorado has yielded a U−Pb zircon age of 523.98 ± 0.12 Ma (Schoene and Bowring, 2006), implying a possible link with Cambrian magmatism in the Wichita province. Moreover, gravity anomalies comparable to that beneath the Southern Oklahoma rift can be traced discontinuously along the same trend all the way into Utah (Keller and Stephenson, 2007), implying that larger volumes of mafic igneous rock were emplaced at deeper levels beneath these scattered igneous exposures. Further work is required to determine whether these early Paleozoic igneous rocks to the northwest of the Southern Oklahoma rift zone might represent an age-progressive hotspot track related to initial impact of a mantle plume along the southeastern Laurentian margin during Rodinia breakup. It should be noted, however, that scattered occurrences of Cambrian–Ordovician alkaline and carbonatitic rocks also occur in central and southern New Mexico (McMillan and McLemore, 2004), and relations between parts of this diffuse alkaline province and the Southern Oklahoma rift are unclear.

Ham et al. (1964) interpreted the Navajoe Mountain Basalt-Spilite Group in the subsurface in the northwest part of the Southern Oklahoma rift to be separated from the overlying Carlton Rhyolite Group by an unconformity. Our more recent work on a series of wells penetrating the volcanic fill of the rift farther to the southeast in the Arbuckle region indicates that substantial amounts of mafic to intermediate lava with tholeiitic to slightly alkaline compositions both underlie and are intercalated with the rhyolites. Mafic to intermediate volcanic rocks are probably an important constituent of the rift fill throughout its extent. Possibly a significant proportion of the mafic rocks detected geophysically at deeper levels in the rift also consist of basalt, with some more evolved lavas, rather than plutonic rocks. Textural features in drill cuttings from the Arbuckle wells indicate the presence of a series of basaltic to intermediate lavas stacked on top of each other. An interesting point is that basaltic phreatomagmatic deposits make up parts of the subsurface volcanic sequence both in the Arbuckle region and in the Navajoe Mountain Basalt-Spilite Group farther northwest. This suggests that the Wichita province may provide another example of an LIP in which explosive interactions between basaltic magma and external water at times played an important role during the volcanic evolution of the province (e.g., Hanson and Elliot, 1996; White et al., 2009).

Textural zonations within individual Carlton Rhyolite flows studied in detail in the Wichita Mountains are consistent with the interpretation that the generally limited rhyolite outcrops present there are remnants of more extensive flows similar to those documented from many other, better exposed A-type volcanic provinces (Henry and Wolff, 1992). Injection of some of the Wichita granites as thin, laterally persistent sills (Fig. 4) certainly suggests that the extrusive counterparts of these A-type granites could have flowed for considerable distances on the surface. Laterally extensive flow units in other A-type felsic provinces are interpreted in some cases to be true lavas, sometimes referred to as flood rhyolites (Henry and Wolff, 1992), whereas others are believed to represent explosively generated pyroclastic flows that became nearly completely homogenized during or after emplacement to form lava-like rheoignimbrites (Branney and Kokelaar, 1992). In the Carlton Rhyolite, pyroclastic-like textures are absent in most of the flows. We conclude that, if any of the Carlton Rhyolite flows represent rheoignimbrites, they must have traveled for some distance in a lava-like state before coming to rest.

The Wichita province is broadly bimodal in character, although significant amounts of intermediate igneous rock occur in places in the subsurface. Data from wells in the Arbuckle region indicate that there was no significant break in time between extrusion of mafic to intermediate lavas and rhyolitic volcanism in the Wichita province. The occurrence of late diabase dikes cutting rhyolites and granites throughout the province provides additional evidence that mafic magmas were being produced during the entire igneous history of the rift. Influx of heat and mafic magma from the mantle was undoubtedly the driving force for production of the voluminous A-type felsic magmas within the province. In other bimodal igneous provinces, the felsic magmas in some cases are inferred to have formed either from fractionation of basaltic parental magmas (e.g., Turner and Rushmer, 2010), or by partial melting of a mafic underplate (e.g., Miller and Harris, 2007). Hogan et al. (1995) suggest that the latter model is more plausible for the Wichita felsic rocks, which lack pronounced negative Eu anomalies, arguing against significant fractionation of plagioclase of the type that might be expected during prolonged differentiation from a basaltic precursor. Fractionation trends shown by the Carlton Rhyolite (Fig. 18) may record differentiation within felsic magma batches after their initial production by partial melting.

Trace element geochemistry indicates that rhyolite flows in the Wichita Mountains can be divided into distinct groups, suggesting derivation from separate magma reservoirs. Flows belonging to more than one group are intercalated with each other in the main rhyolite outcrop areas. This may imply a complex subsurface magma plumbing system, or may mean that laterally extensive flows derived from different source vents and magma chambers came to rest on top of each other. These data obviously pertain only to a limited area in the Wichita Mountains, and we are now extending these geochemical studies to other parts of the rift zone to see if similar compositional groups can be recognized in the rhyolites elsewhere in the rift. Future work should also include detailed isotopic studies of the different rhyolite compositional groups tied to similar studies of the voluminous basaltic to intermediate lavas within the Wichita province, in order to develop better constraints on magma source regions and petrogenetic relations between the main igneous units.

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Appendix A. Analytical methods

Drill cuttings of subsurface basaltic to intermediate volcanic rocks were collected from the sample library at the Oklahoma Petroleum Information Center, managed by the Oklahoma Geological Survey. Approximately 20 g of cuttings were collected in 50-foot intervals from three wells northwest along strike from the Arbuckle Mountains (Pan-Am Williams D-2, Pan-Am Jarman 1-19, and Pan-Am Newberry 1). Sample locations are shown in Figure 7. Samples were limited to depths where mafic cuttings appeared to be dominant in hand sample or under a binocular microscope and were collected at least 300 m below the upper contact of the basaltic sequence to minimize contamination. In total, 61 samples were collected from the wells (21 samples from the Williams, 17 samples from the Jarman, and 23 samples from the Newberry).

Samples were prepared at Kansas State University for geochemical analyses, with an emphasis on minimizing the effect of post-emplacement alteration and potential contamination during well site sampling. The bulk sample was handpicked using a research grade binocular microscope in order to remove any zeolite/carbonate minerals, foreign rock (e.g. rhyolite, granitoid, etc.), and/or altered rock chips. After picking, samples with at least 10 g of "purified" rock chips were pulverized to a clay size fraction in a Spex Industries aluminum oxide shatterbox. In total, 48 samples were pulverized and then sent to Franklin and Marshall College, for x-ray fluorescence (XRF) spectroscopy following the methods outlined in Mertzman (2000) and/or http://www.fandm.edu/earth-and-environment/x-ray-laboratory. In all, major and trace element compositions and LOI values were obtained on 21 samples from the Williams, 12 samples from the Jarman, and 15 samples from the Newberry wells.

Geochemical samples from outcrops of Carlton Rhyolite in the Wichita Mountains were analyzed at the GeoAnalytical Laboratory at Washington State University by XRF and ICP-MS, following standard techniques used in that laboratory (see http://www.sees.wsu.edu/Geolab/index.html).

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Figure captions

Fig. 1. Neoproterozoic and Cambrian rift zones in southeastern North America related to opening of the Iapetus Ocean. Modified from McConnell and Gilbert (1990); subsurface rhyolite extent

modified from Ham et al. (1964); early Paleozoic continental margin from Keller and Stephenson (2007).

Fig. 2. Geological map of the Wichita Mountains, modified from Powell et al. (1980). Main outcrop areas of Carlton Rhyolite are indicated.

Fig. 3. Schematic cross section of igneous rocks exposed in the Wichita Mountains, modified from Hogan and Gilbert (1998).

Fig. 4. View of part of Mount Scott Granite sill, looking west from top of Mount Scott (Fig. 2). Sill dips gently to the south; vegetated slopes beneath granite are underlain by gabbroic rocks.

Fig. 5. Data for Carlton Rhyolite in Wichita Mountains plotted on Zr vs. 10^4Ga/Al diagram of Whalen et al. (1987) and Nb vs. Y diagram of Pearce et al. (1984). Data for Wichita granites from Price (1998) and Hogan et al. (2000).

Fig. 6. Northwest-trending diabase dikes cutting Mesoproterozoic granite exposed in quarry in Arbuckle Mountains ~10 km north of northern margin of Southern Oklahoma rift zone. Note truck for scale in lower left (arrowed). See Price et al. (1998b) for a more complete description of these dikes and their country rocks.

Fig. 7. Lithologic logs of representative wells drilled into the volcanic succession in the Southern Oklahoma rift zone, based on study of drill cutting samples taken at 10-foot intervals and correlated with gamma-ray logs; depth in wells is given in feet. Locations of wells is shown in Fig. 1. In the deepest well, which represents the greatest penetration of igneous rocks in Oklahoma, the volcanic succession is truncated by the Washita Valley fault. Locations of photomicrographs and geochemical samples are indicated.

Fig. 8. Photomicrographs of basaltic drill cuttings, all in plane light. (A) Intergranular texture defined by randomly arranged plagioclase microlites and altered, interstitial mafic minerals. (B) Flow-aligned plagioclase crystals in a dark groundmass of altered tachylitic glass. (C) Basaltic pyroclastic rock. Two relatively coarse-grained basaltic pyroclasts consisting of altered sideromelane (Si) and containing vesicles (V) filled with zeolites and chlorite are outlined. The coarser pyroclasts are set in a matrix of finer grained sideromelane ash particles.

Fig. 9. Discrimination diagrams of Winchester and Floyd (1977) and Le Bas et al. (1986) illustrating geochemical classification of Southern Oklahoma rift zone drill cuttings. R/D, rhyodacite/dacite; TA, trachyandesite; A, andesite; A/B, andesite/basalt; SAB, subalkaline basalt; AB, alkaline basalt; TB, trachybasalt; BTA, basaltic trachyandesite; B, basalt; BA, basaltic andesite.

Fig. 10. Harker diagrams illustrating major and trace element variations of drill cuttings.

Fig. 11. Zr-Nb-Y tectonomagmatic discrimination diagram after Meschede (1986); IP, intraplate.

Fig. 12. Zr/Nb vs. wt.% SiO_2 diagram illustrating fairly restricted Zr/Nb values for drill cuttings.

Fig. 13. Generalized cooling unit in the Carlton Rhyolite, based on outcrops in the Wichita Mountains.

Fig. 14. Volcanic features in the Carlton Rhyolite. (A) Laterally persistent flow banding near base of lava flow, Bally Mountain area; daypack (arrowed) at base of outcrop for scale. (B) Photomicrograph of flow lamination in thin section, wrapping altered feldspar phenocryst in lower right. Plane light. (C) Peperite at base of lava flow, Bally Mountain area. Peperite consists of irregular fragments of porphyritic rhyolite (P) separated by dark brown tuffaceous sediment (T). (D) View of lithophysal zone within rhyolite flow, Bally Mountain area; lithophysal cavities are lined by quartz.

Fig. 15. Photomicrograph in plane light of randomly arranged tridymite crystals (clear, now inverted to quartz) within holocrystalline felsitic groundmass in center of rhyolite flow, Zodletone Mountain.

Fig. 16. Photomicrographs of rhyolitic drill cuttings, all in plane light. (A) Relict perlitic texture (P) in altered and devitrified, originally glassy rhyolite. Dark-green areas consist of Fe-rich clay that has replaced glass. (B) Fine-grained tridymite needles (now inverted to quartz) in rhyolite groundmass. (C) Rhyolite groundmass showing randomly arranged, relatively coarse tridymite needles, with interstitial alkali feldspar.

Fig. 17. Representative Harker variation diagrams for Carlton Rhyolite flows in the Wichita Mountains. Sample symbols correspond to individual rhyolite flows grouped according to different outcrop areas, as shown in legend. Granite data shown for comparison are from Price (1998) and Hogan et al. (2000).

Fig. 18. Trace element diagrams for Carlton Rhyolite in Wichita Mountains. Fractionation trends in Sc/Nb vs. Y/Nb diagram for clinopyroxene in quartz trachyte (Cpx_L) and high-silica rhyolite (Cpx_H) magmas from Eby (1990); feldspar fractionation trends in Rb/Sr vs. Rb/Ba diagram from Tollo et al. (2004).

Fig. 19. Trace-element diagrams showing distinct groups in Carlton Rhyolite in the Wichita Mountains.

Fig. 20. Residual gravity anomaly map produced from complete Bouguer gravity values derived from the U. S. National database (http://gis.utep.edu/rgsc) that were gridded. The gridded data were upward continued to 40 km to approximate the regional gravity field and then subtracted from the grid of complete Bouguer anomaly values to produce the residual values shown here. The dashed white line shows the location of the model depicted in Fig. 21.

Fig. 21. Integrated geophysical model derived from the University of Texas at Dallas/University of Texas at El Paso seismic experiment. Numbers in italics indicate P-wave velocities in km/s. Numbers in parenthesis indicate densities in gm/cm^3. MVF – Mountain View fault zone, which separates Wichita uplift from Anadarko basin. Modified from Keller and Stephenson (2007).

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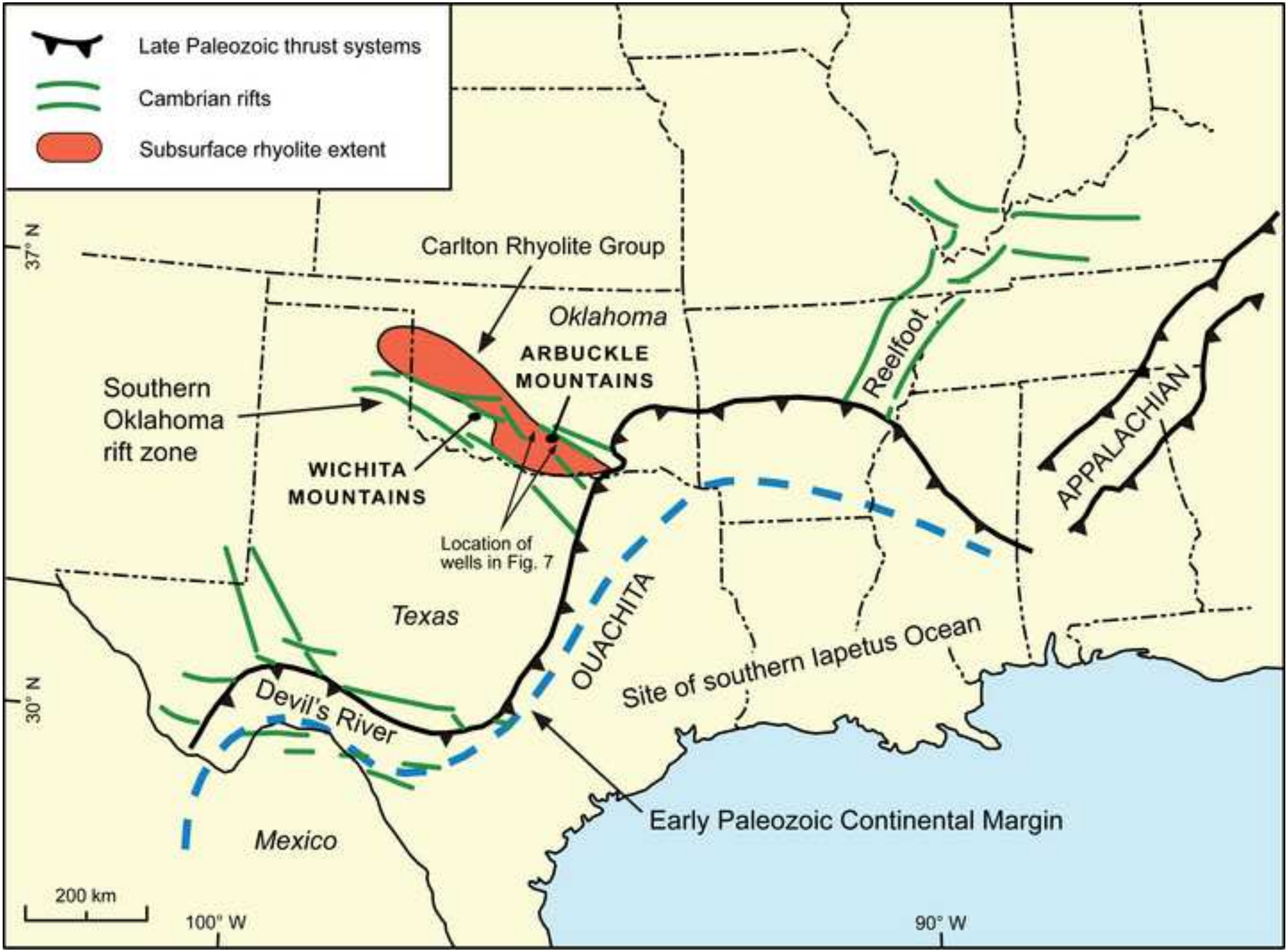

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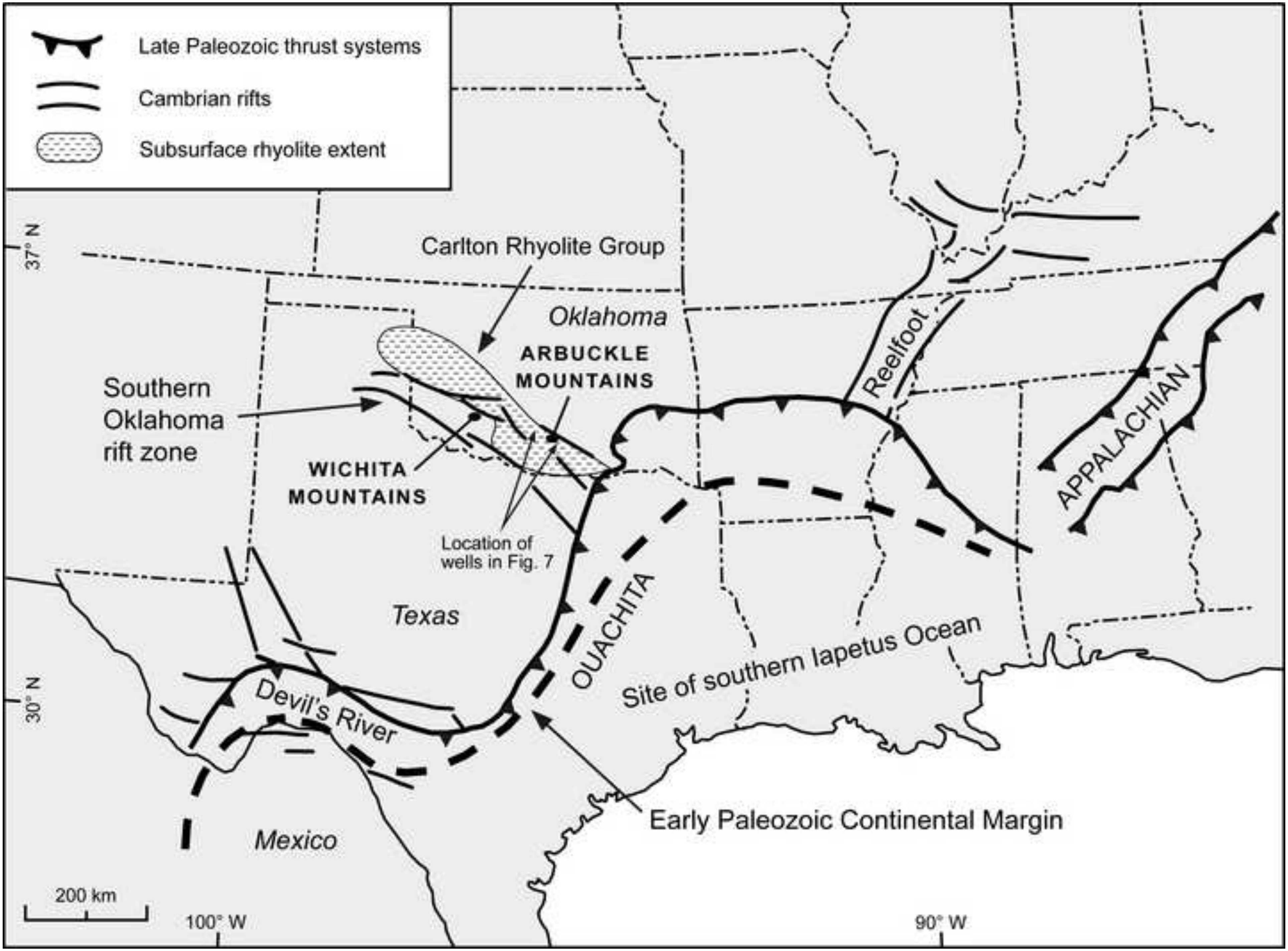

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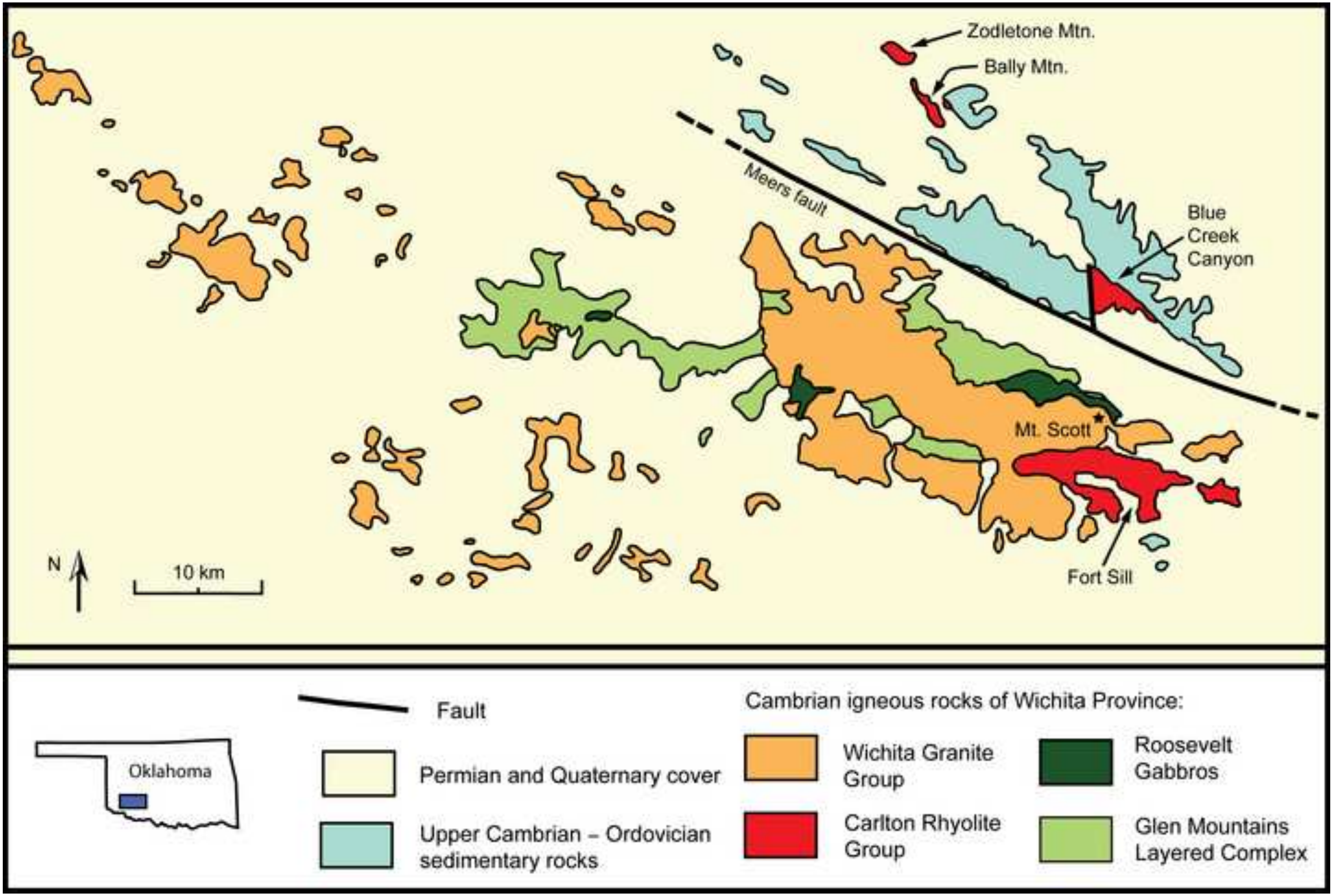

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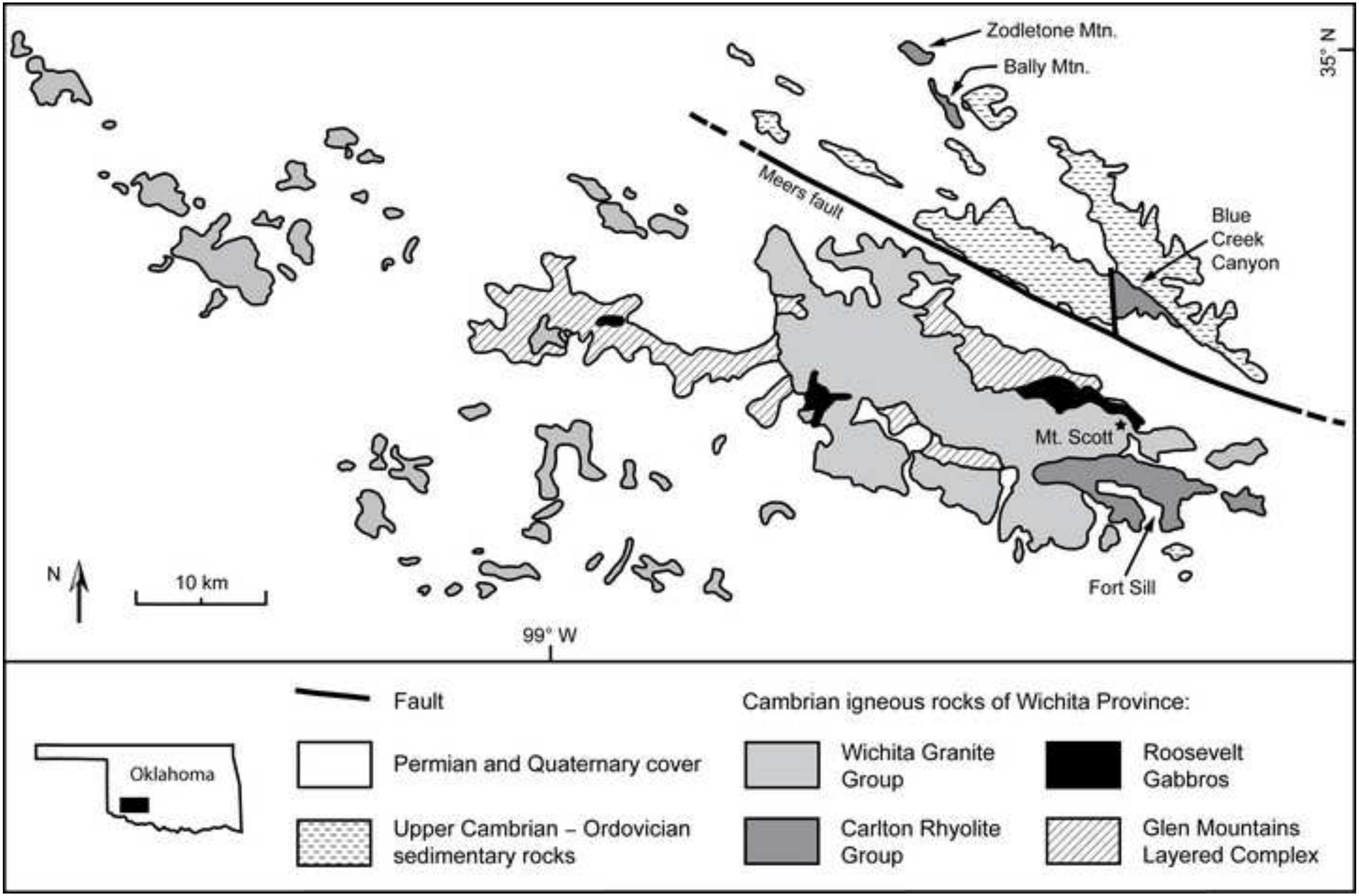

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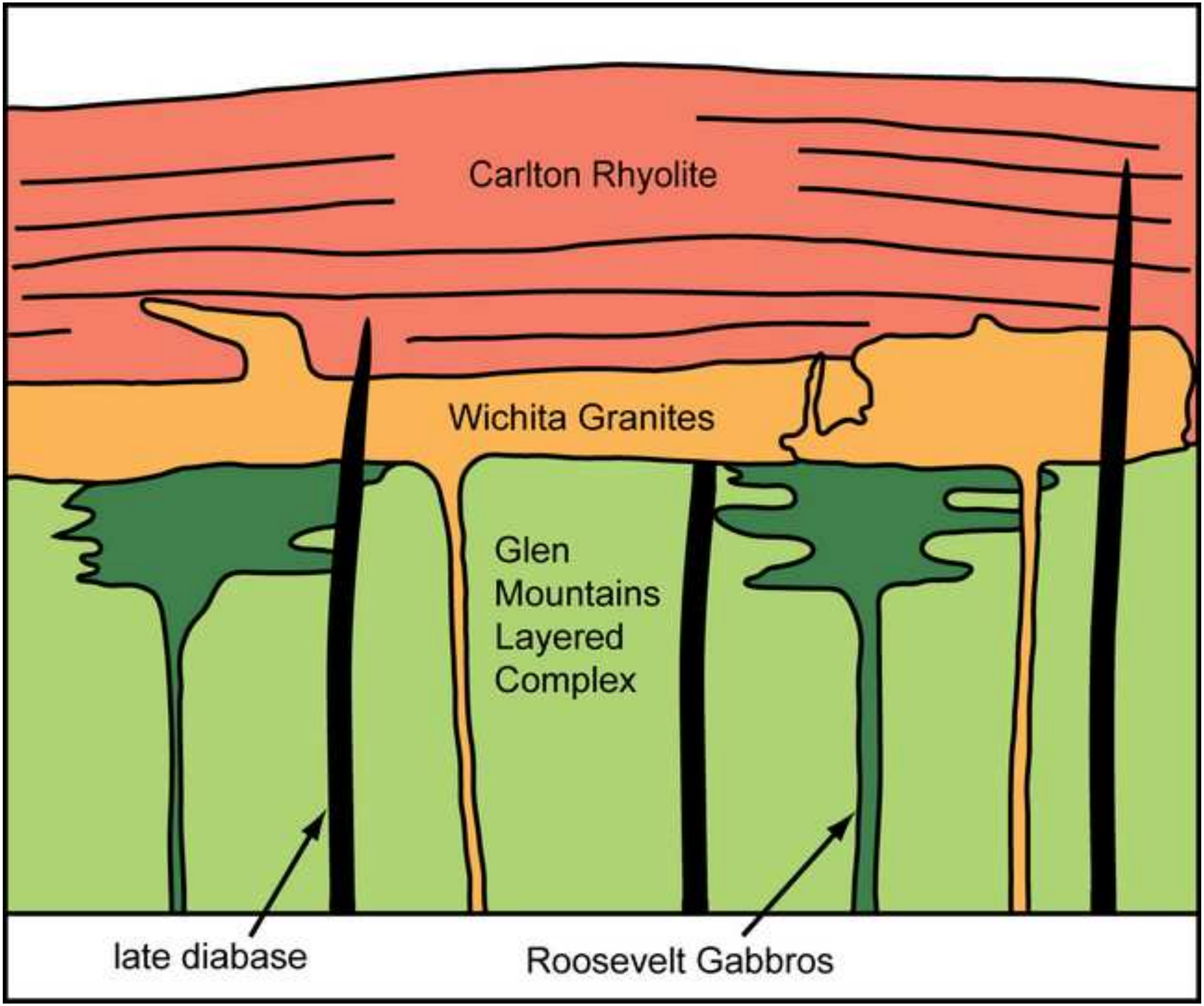

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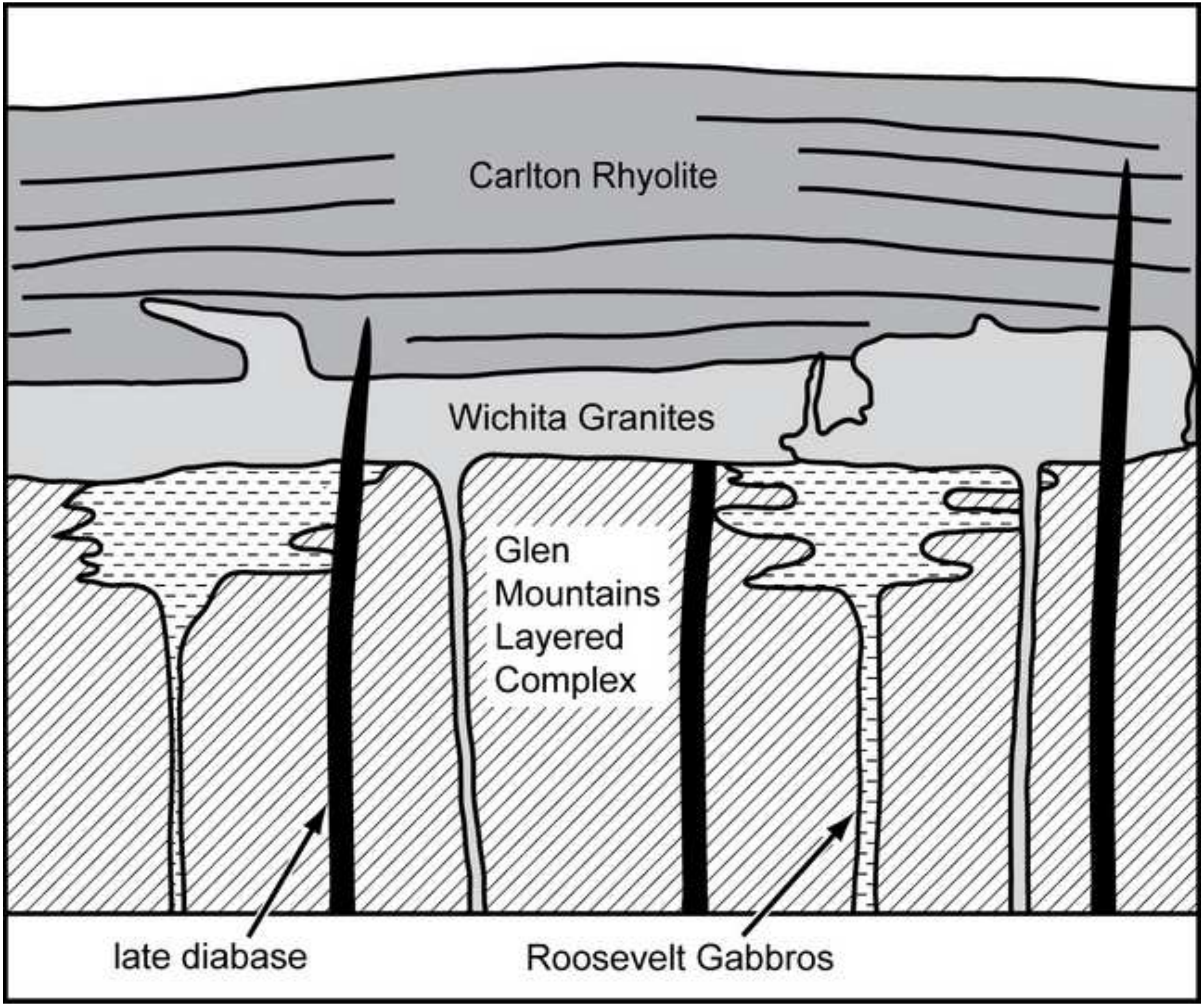

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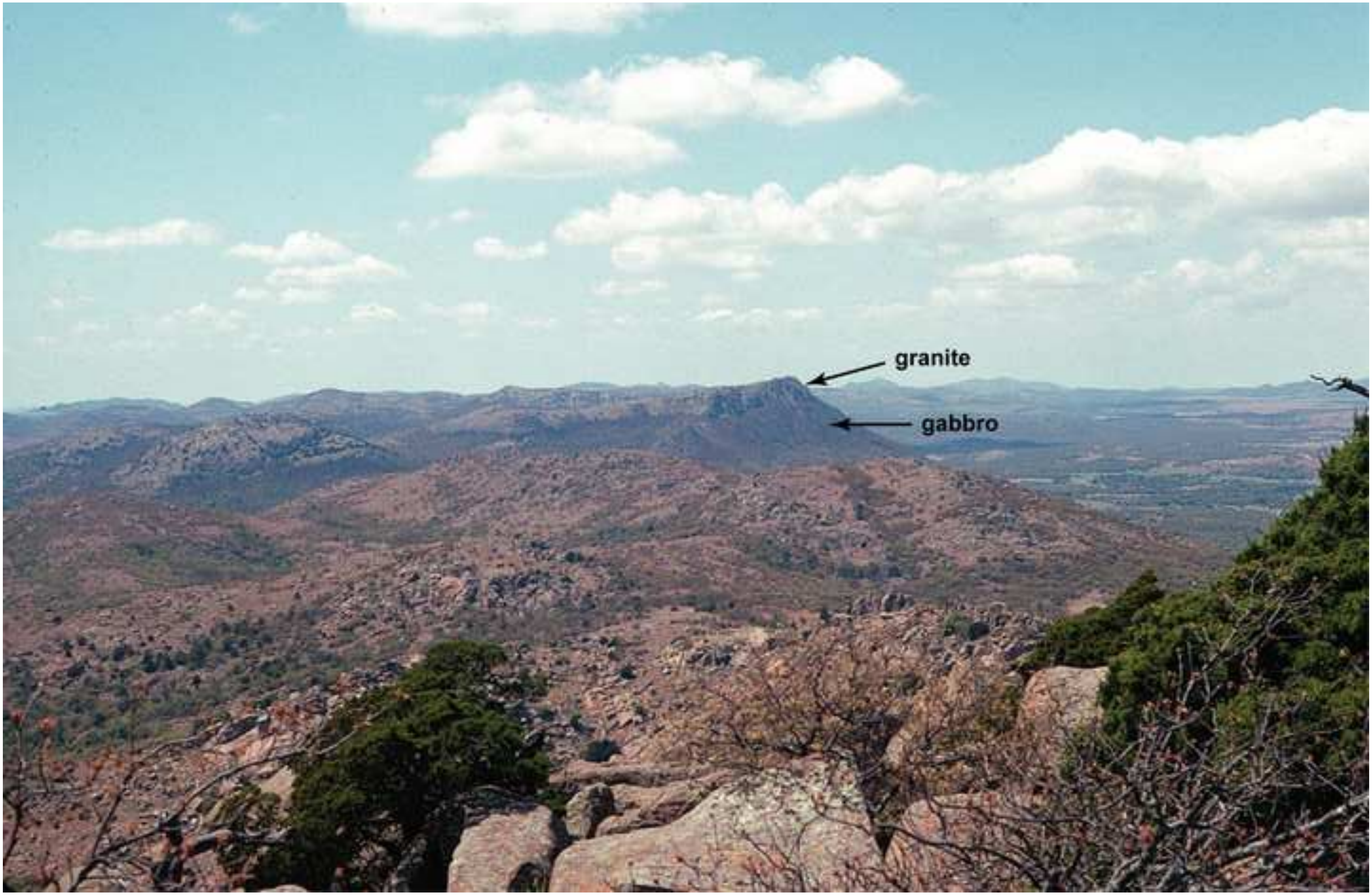

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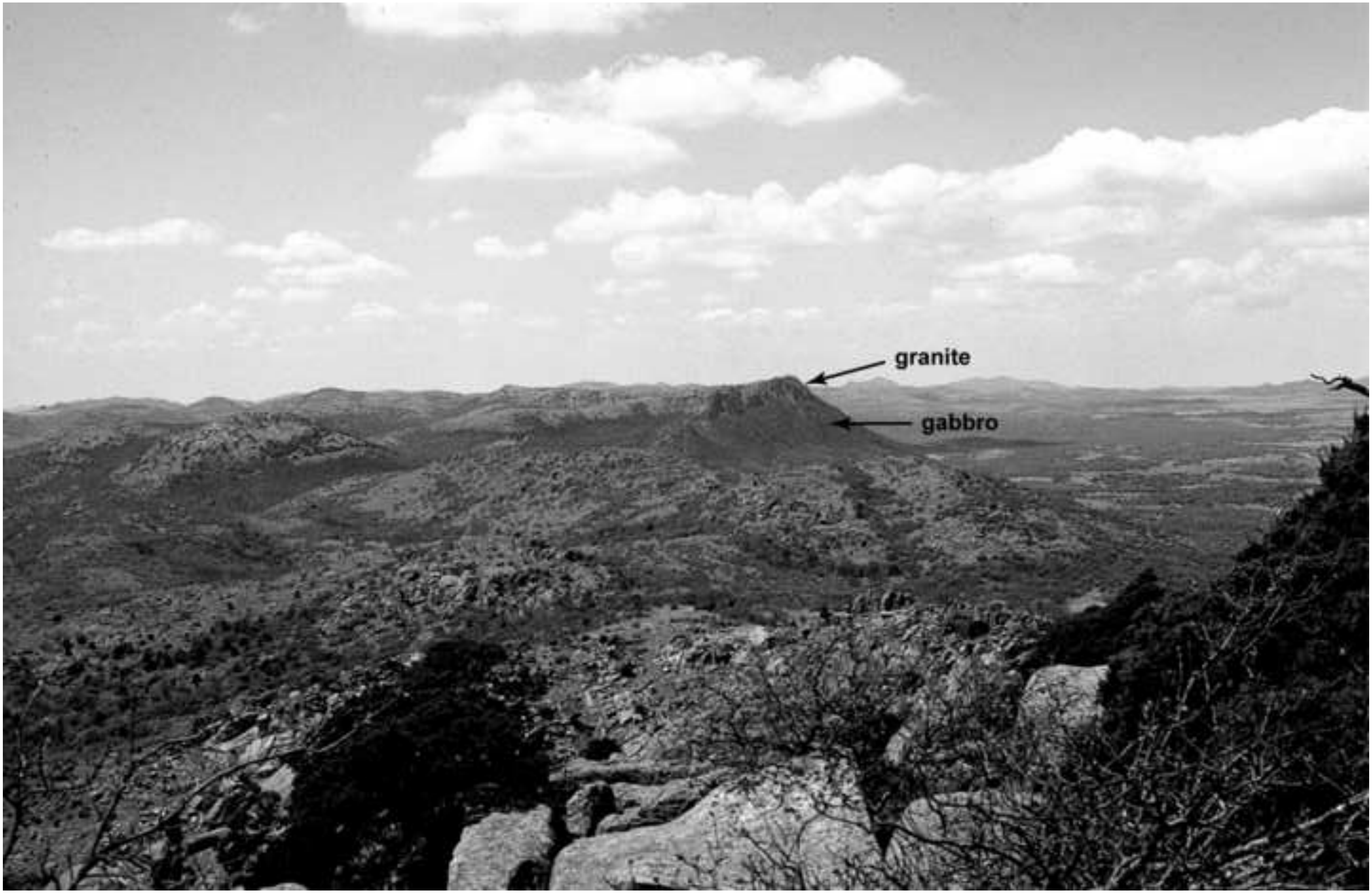

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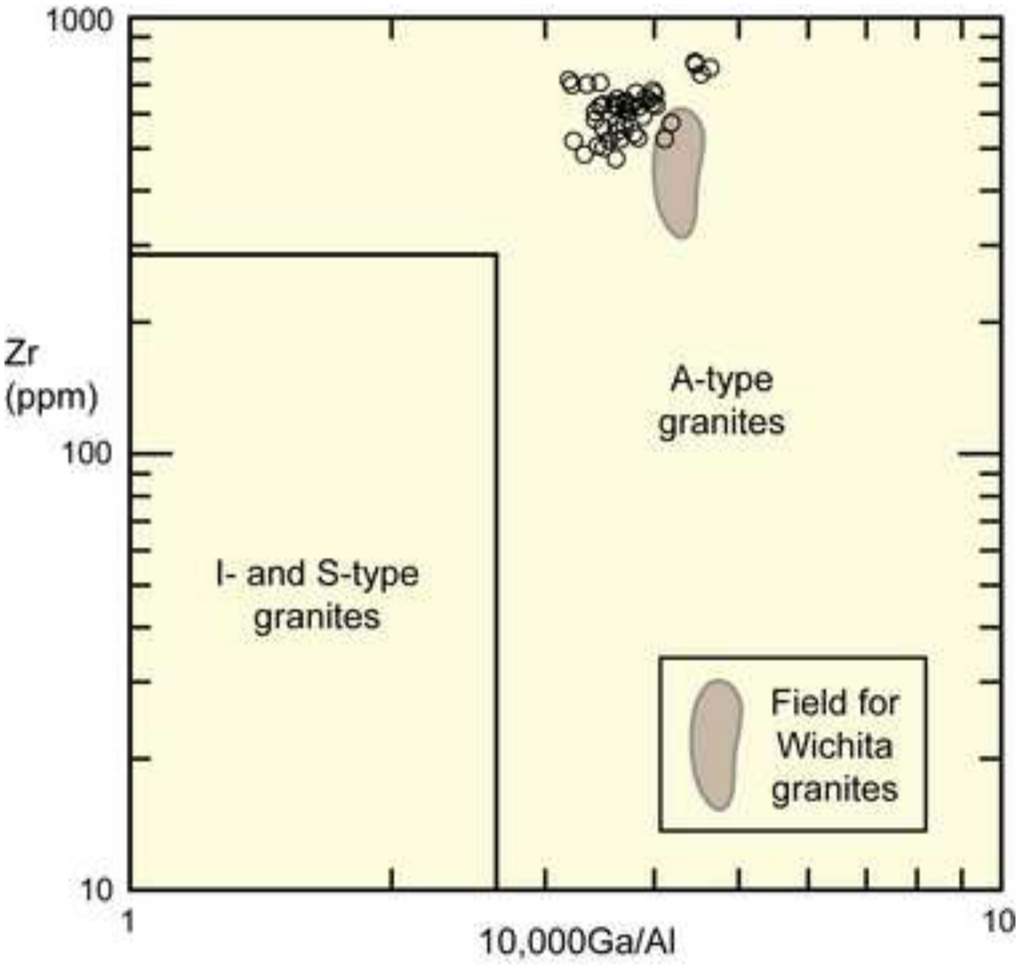

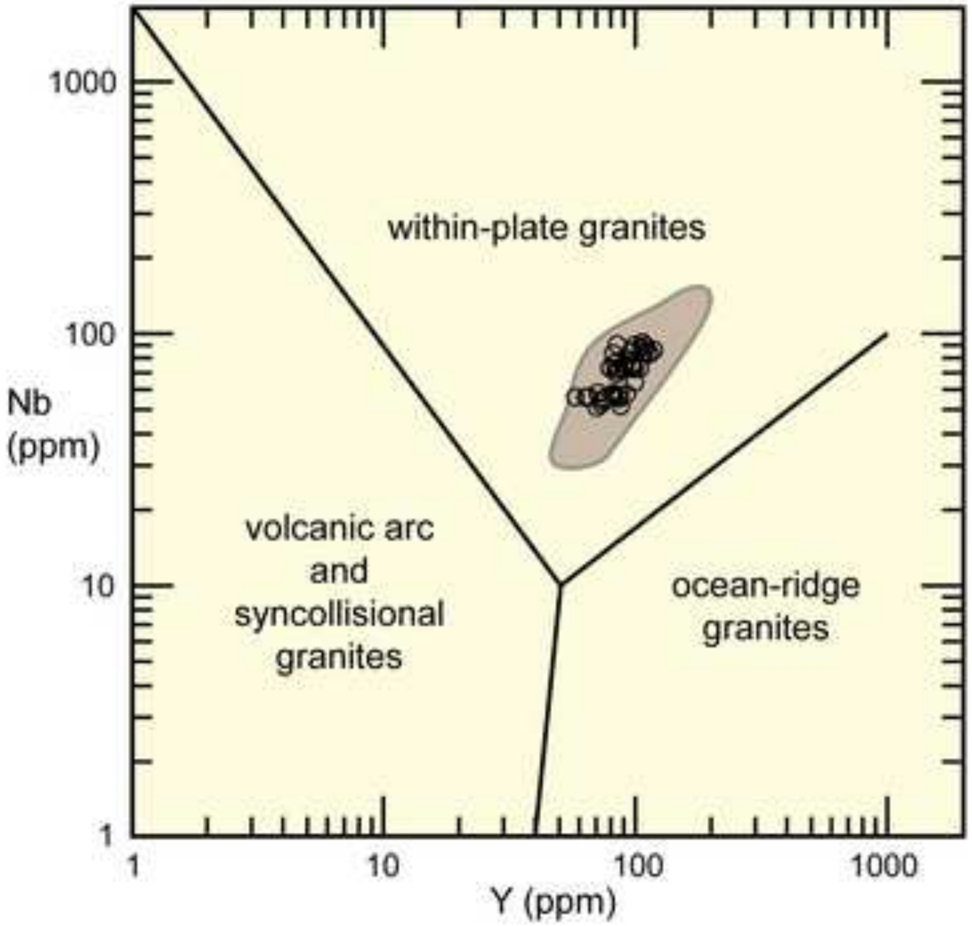

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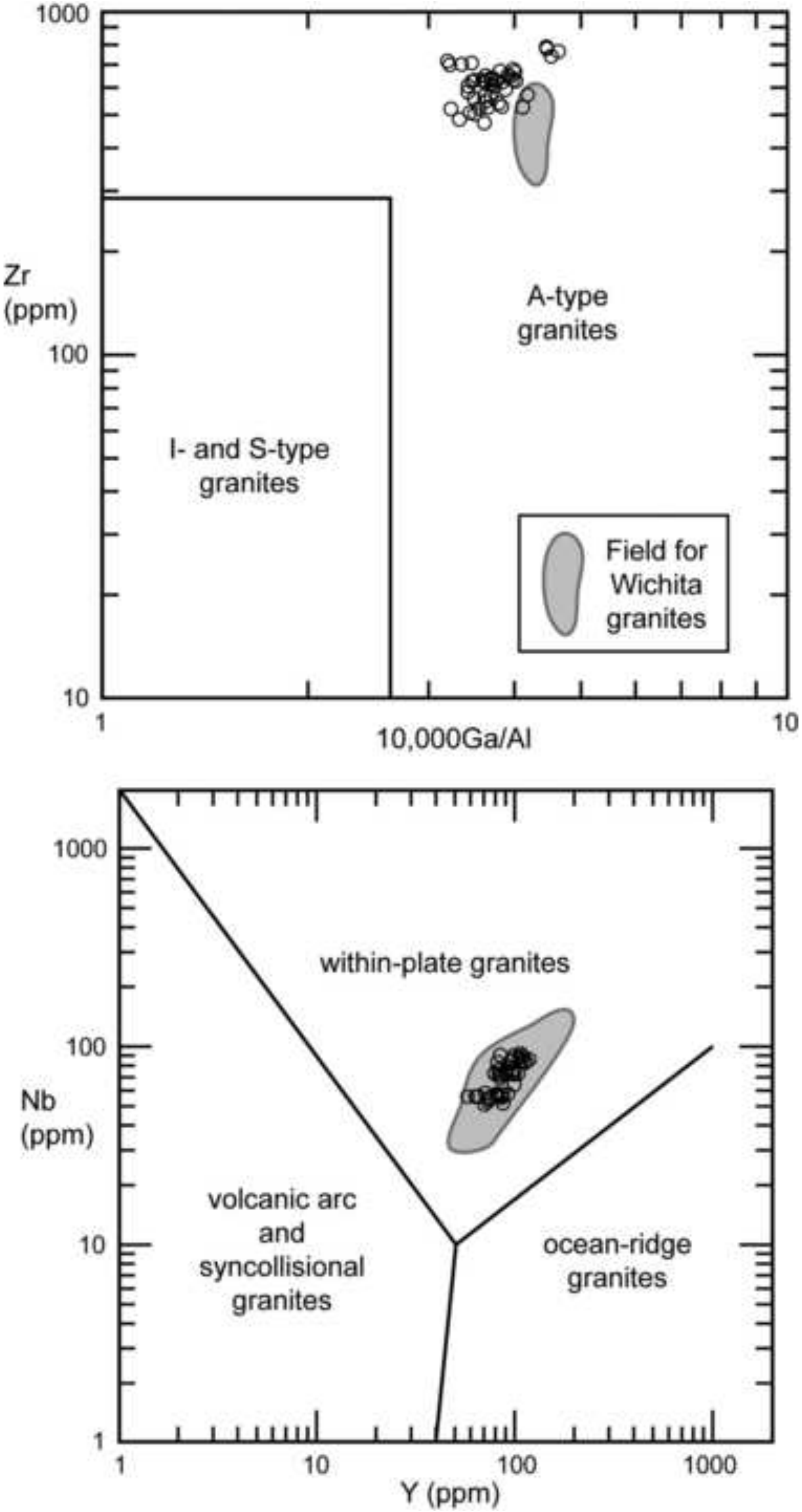

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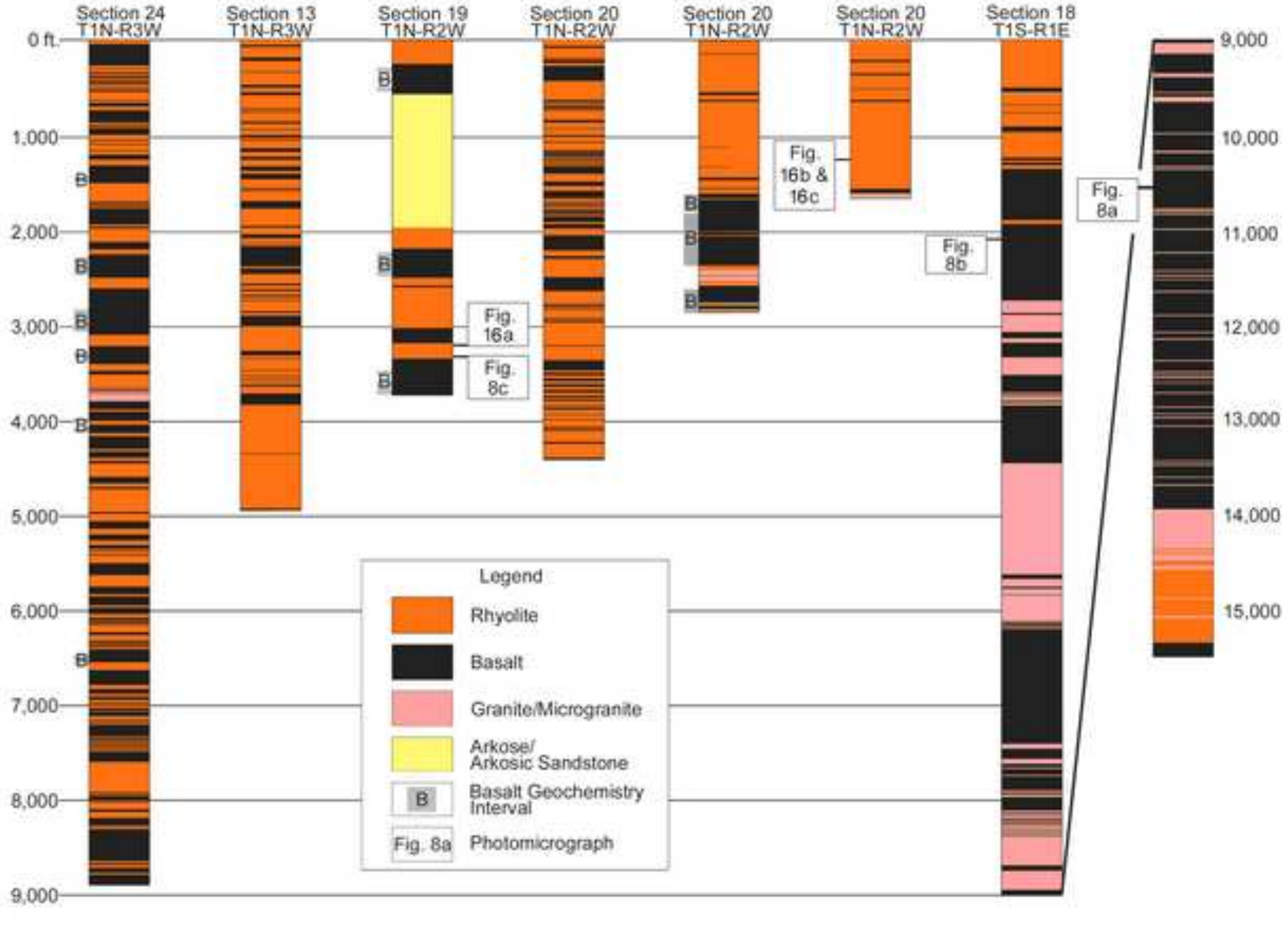

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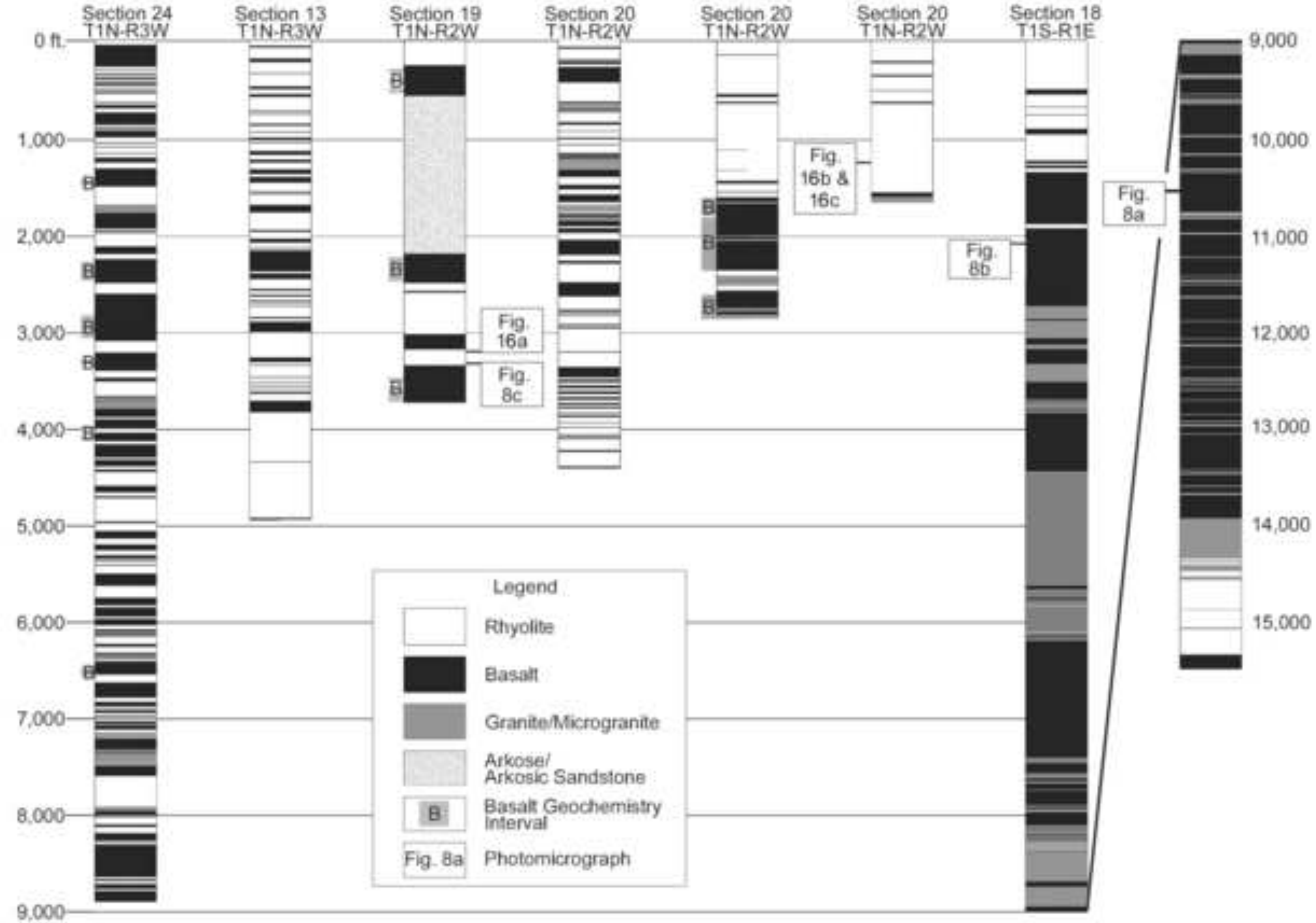

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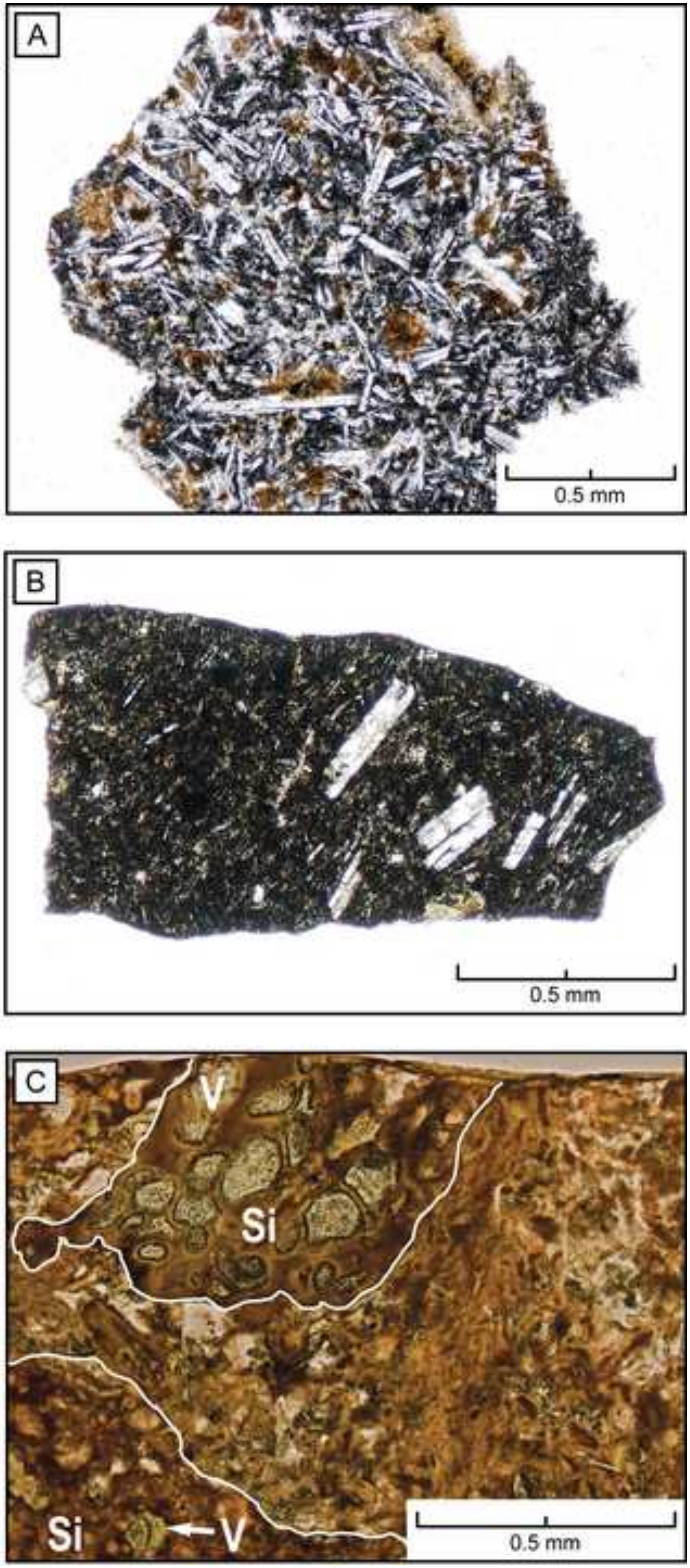

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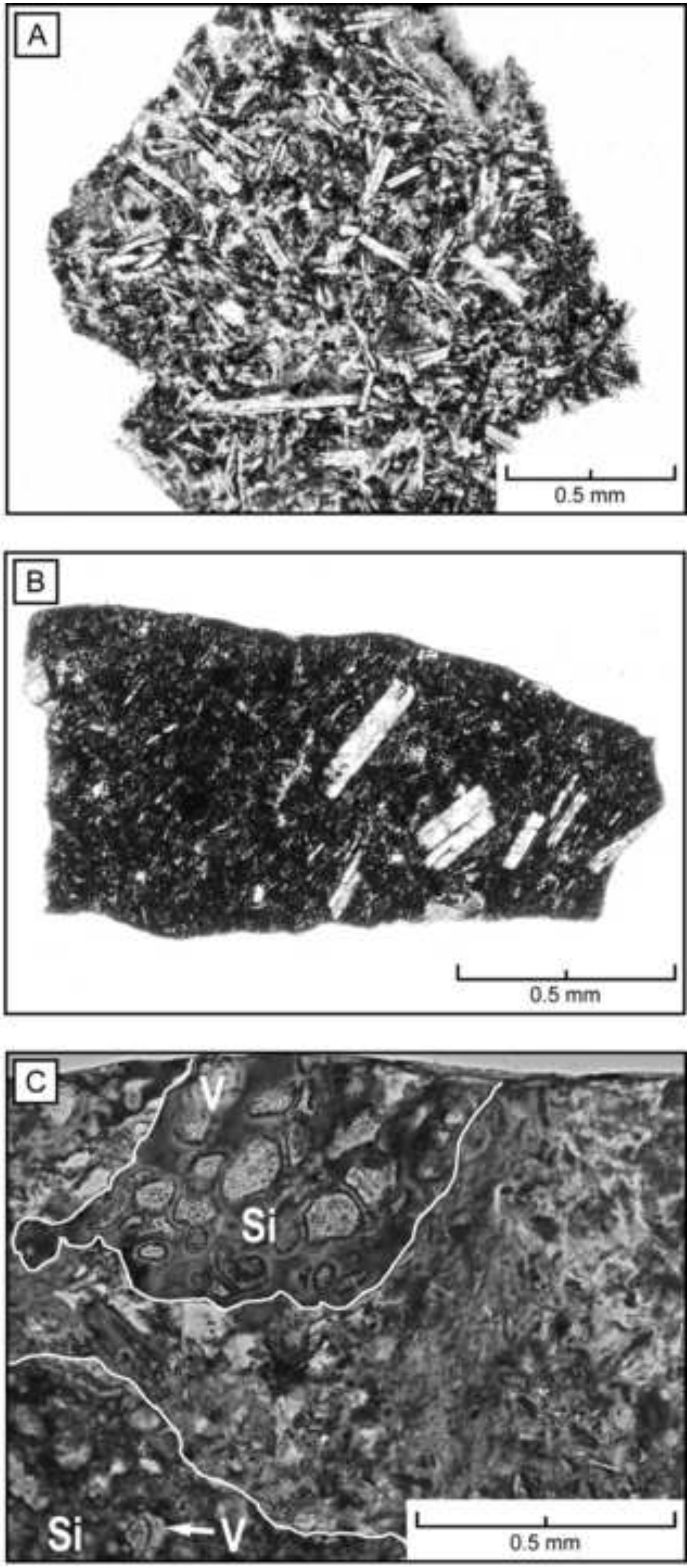

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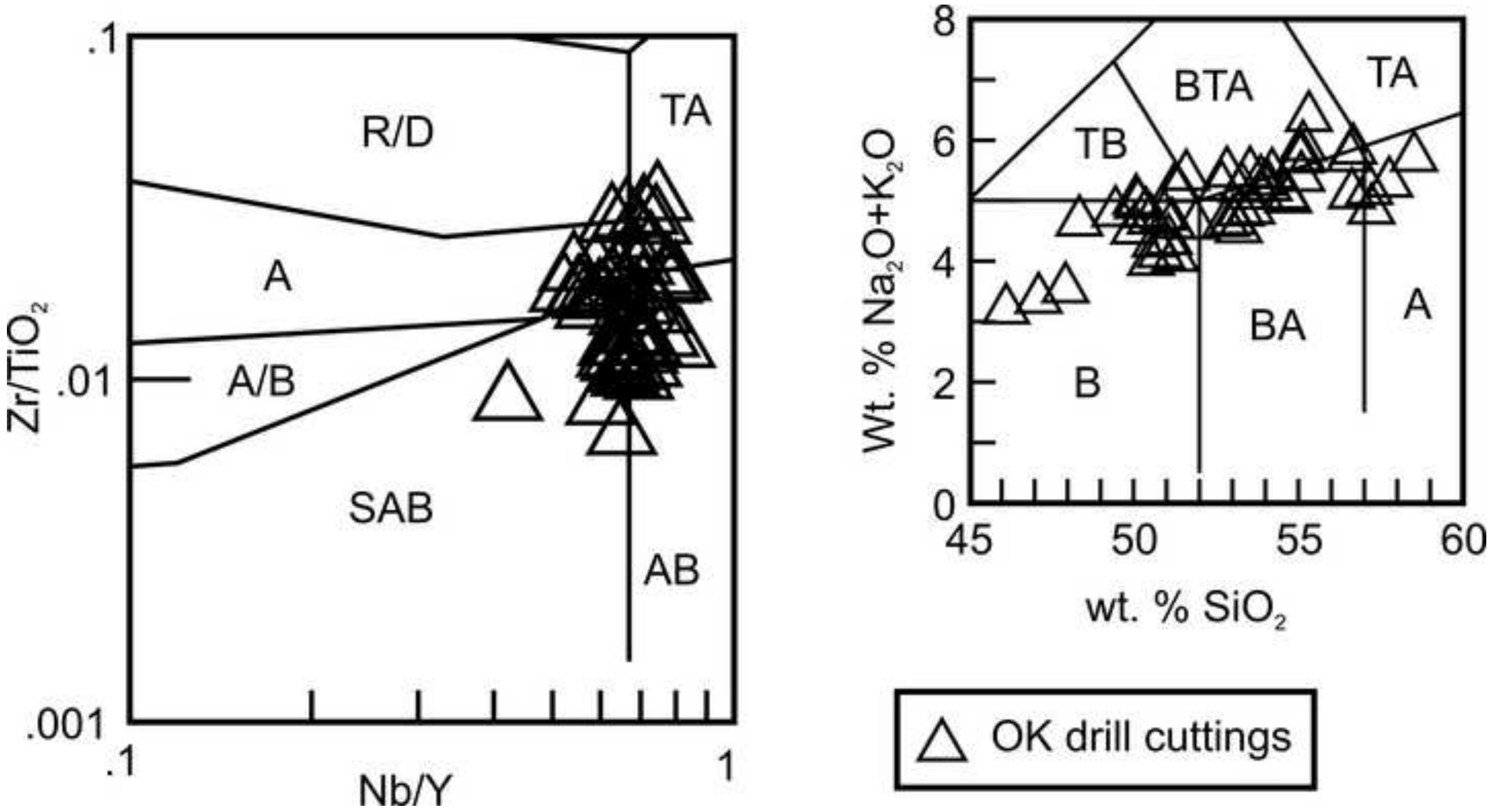

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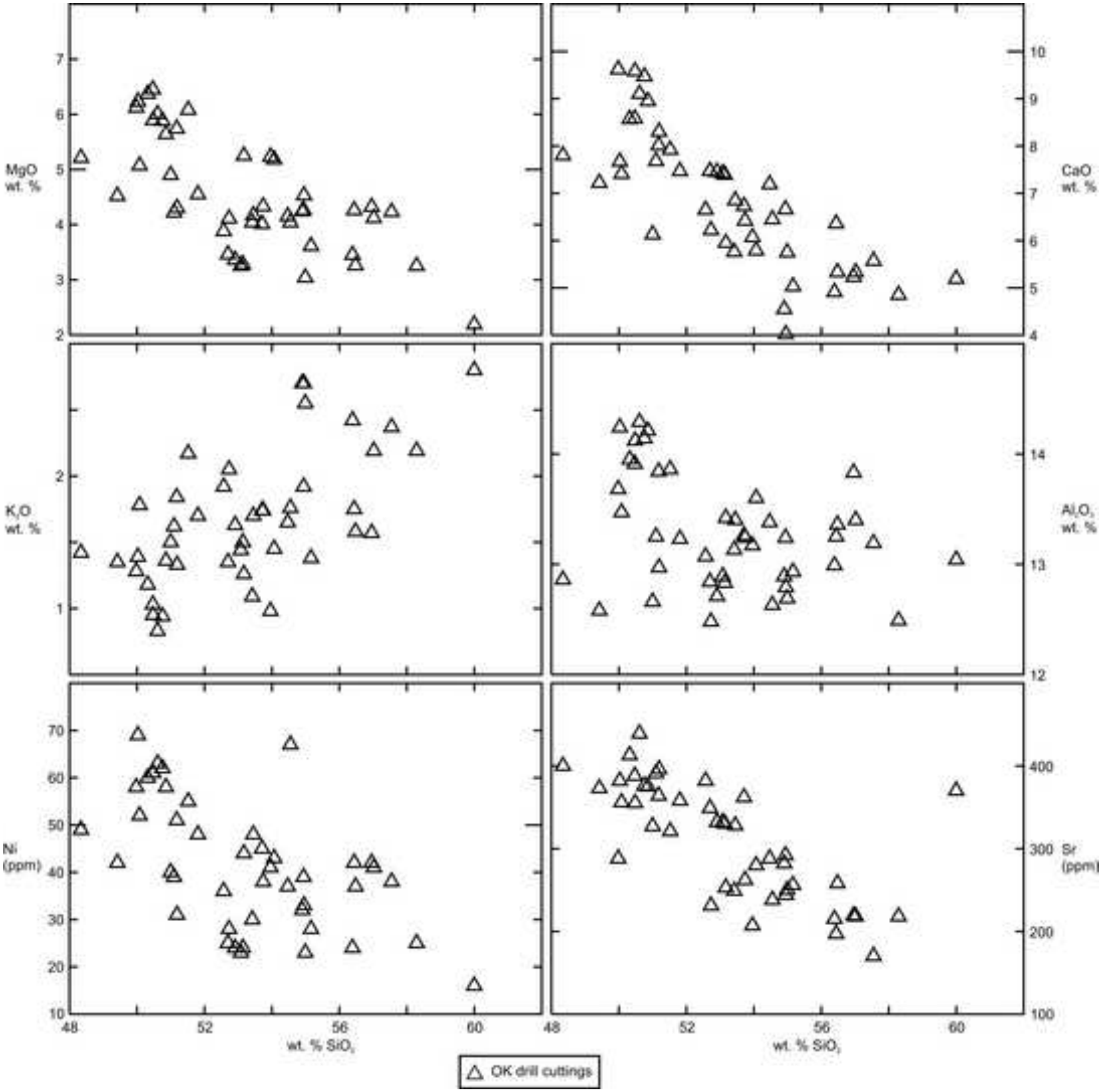

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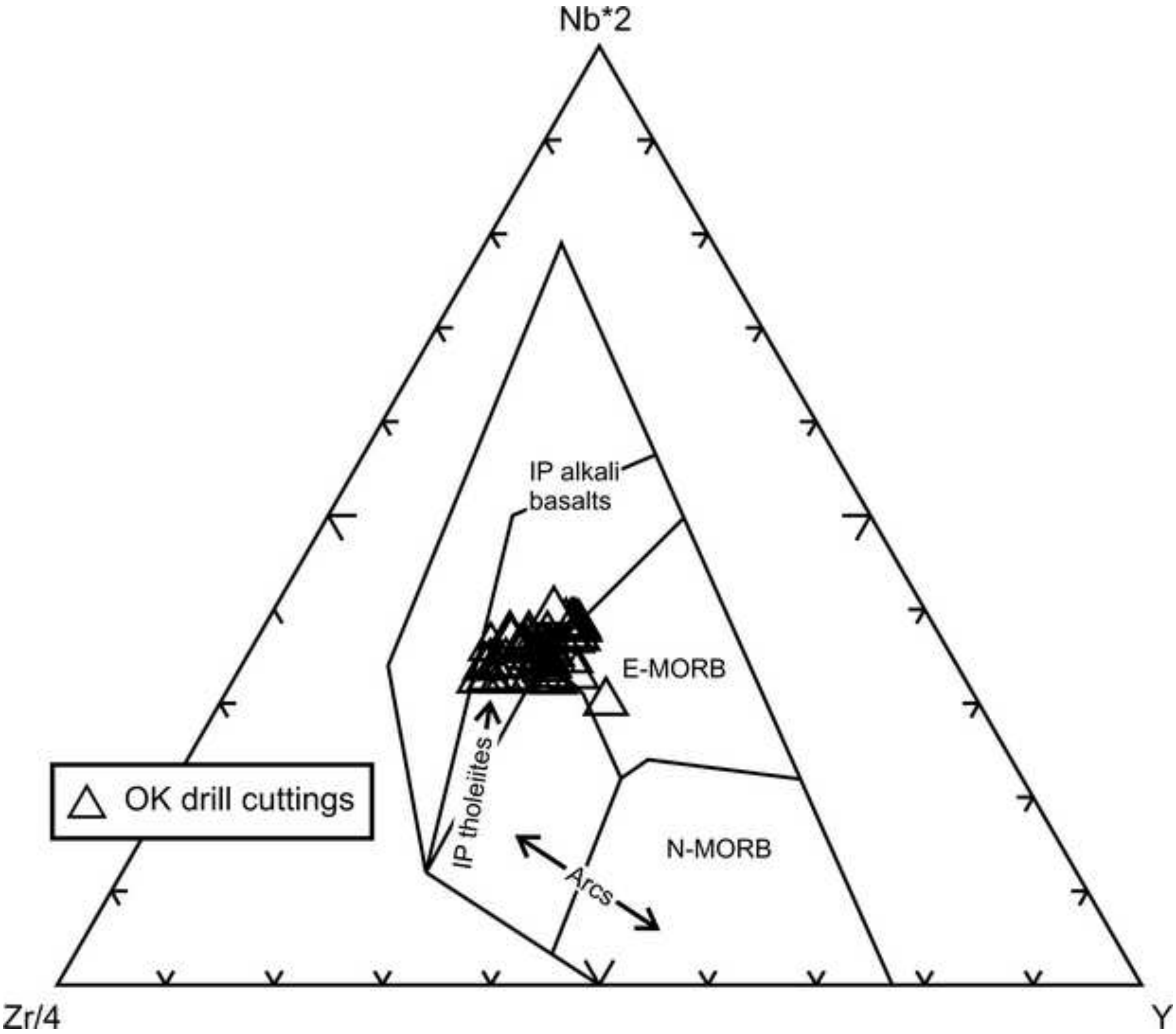

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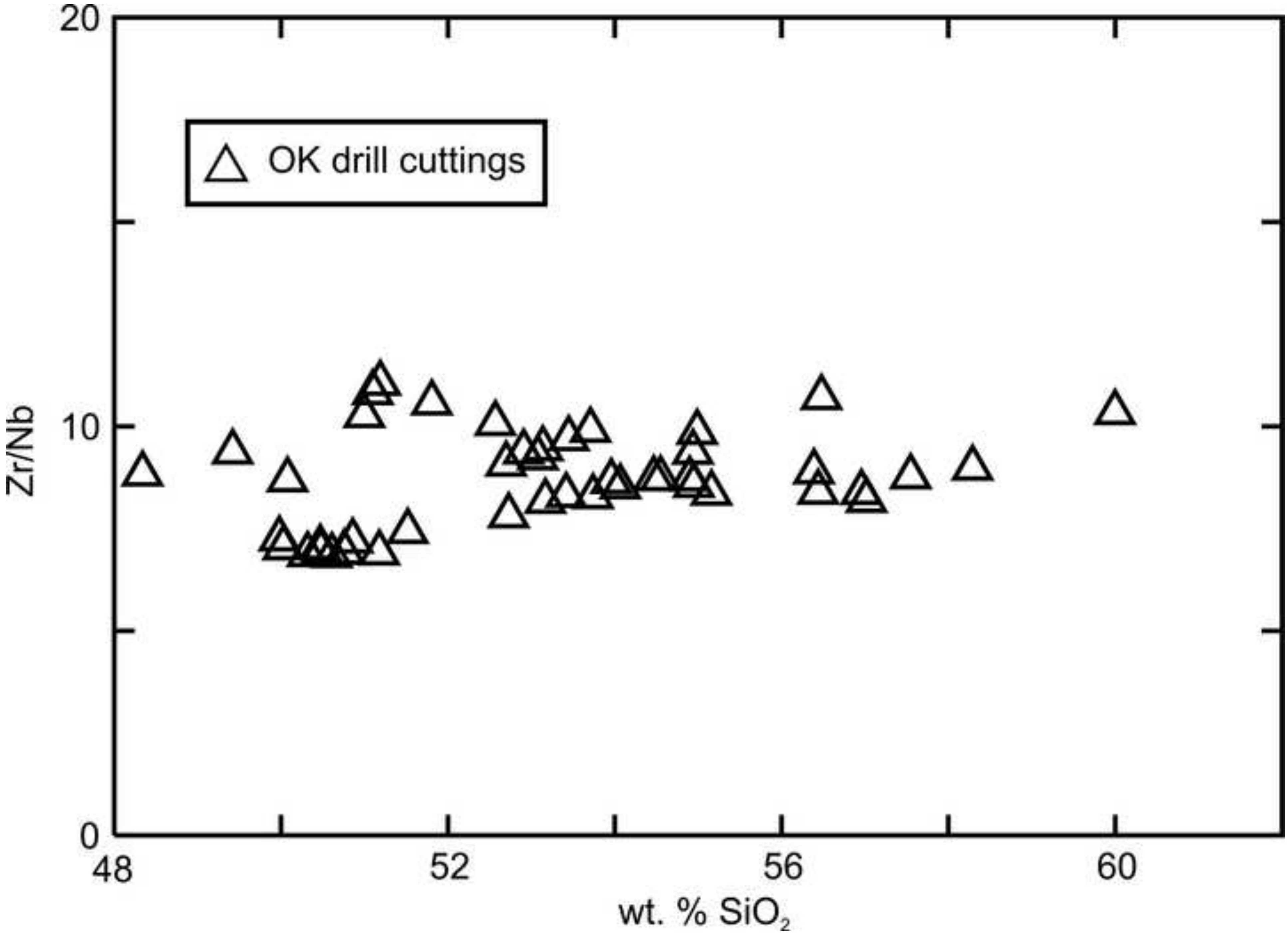

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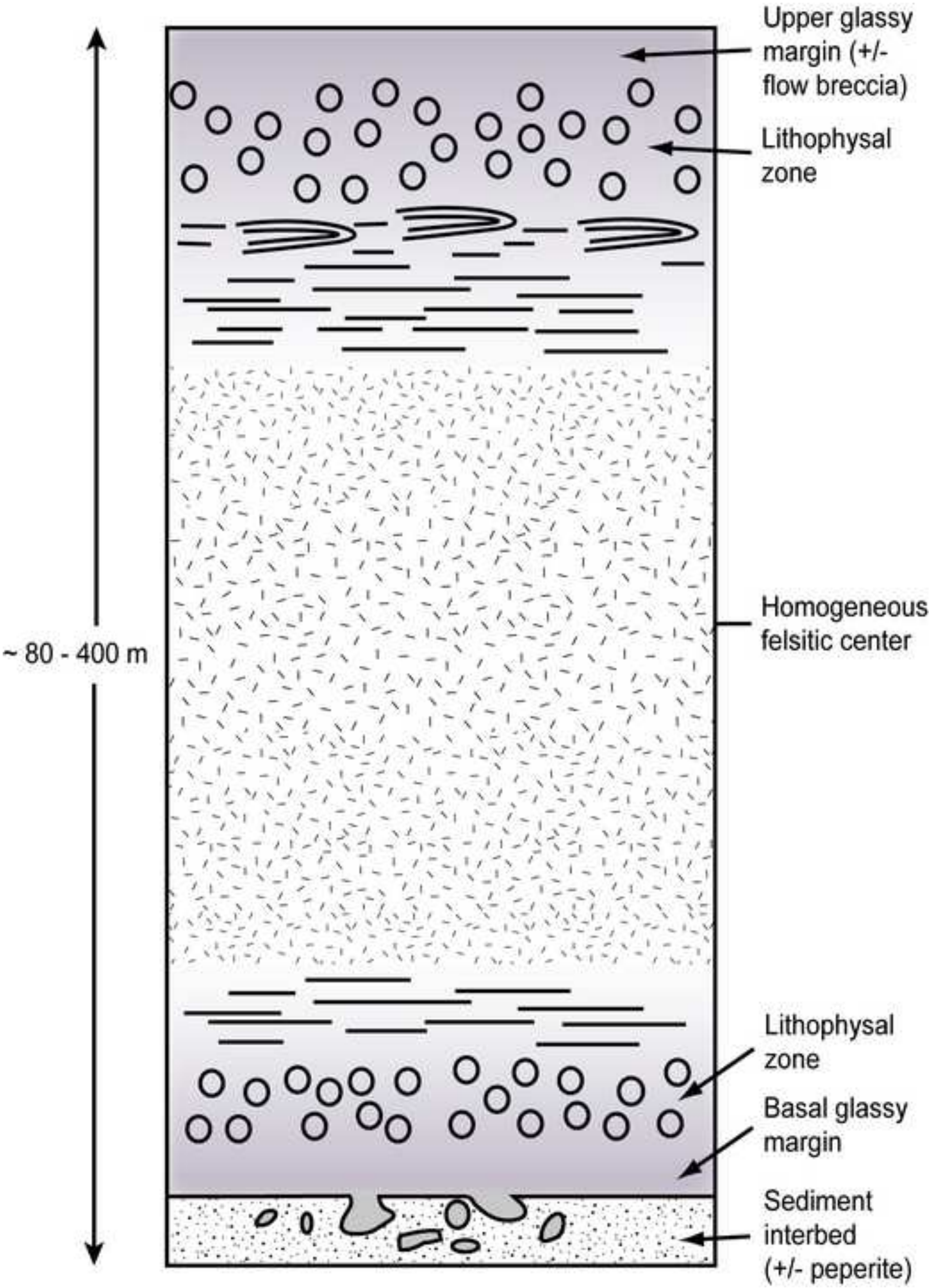

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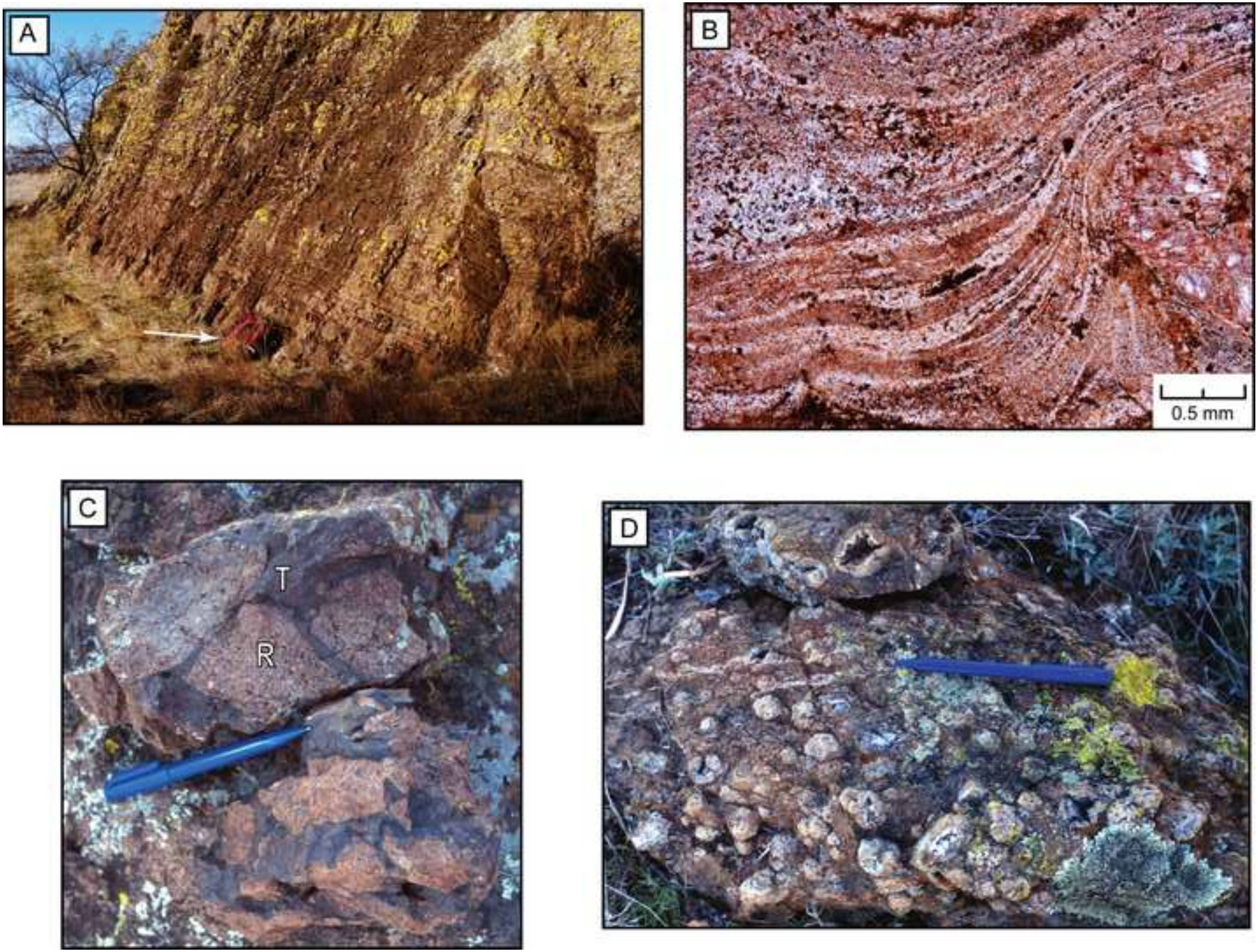

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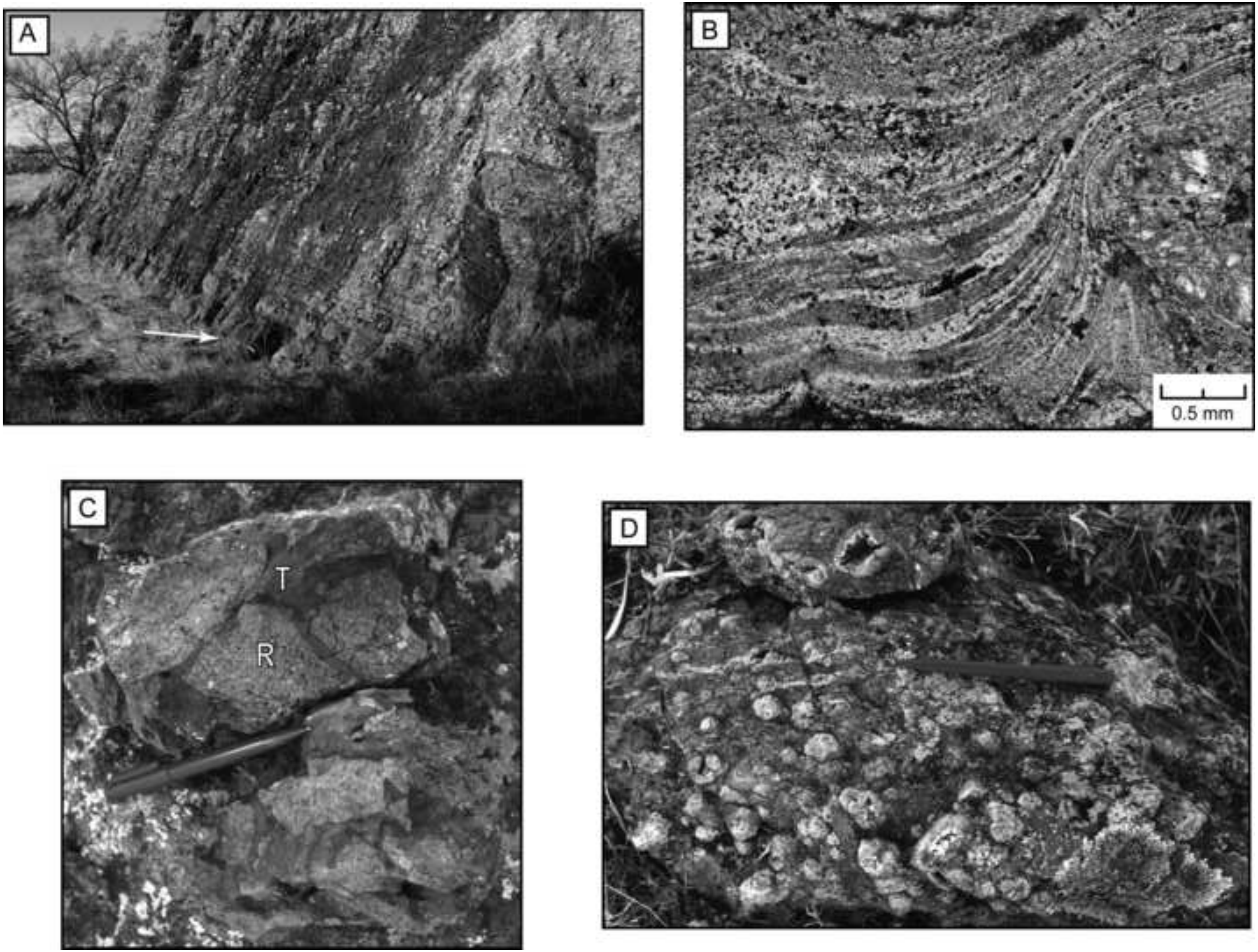

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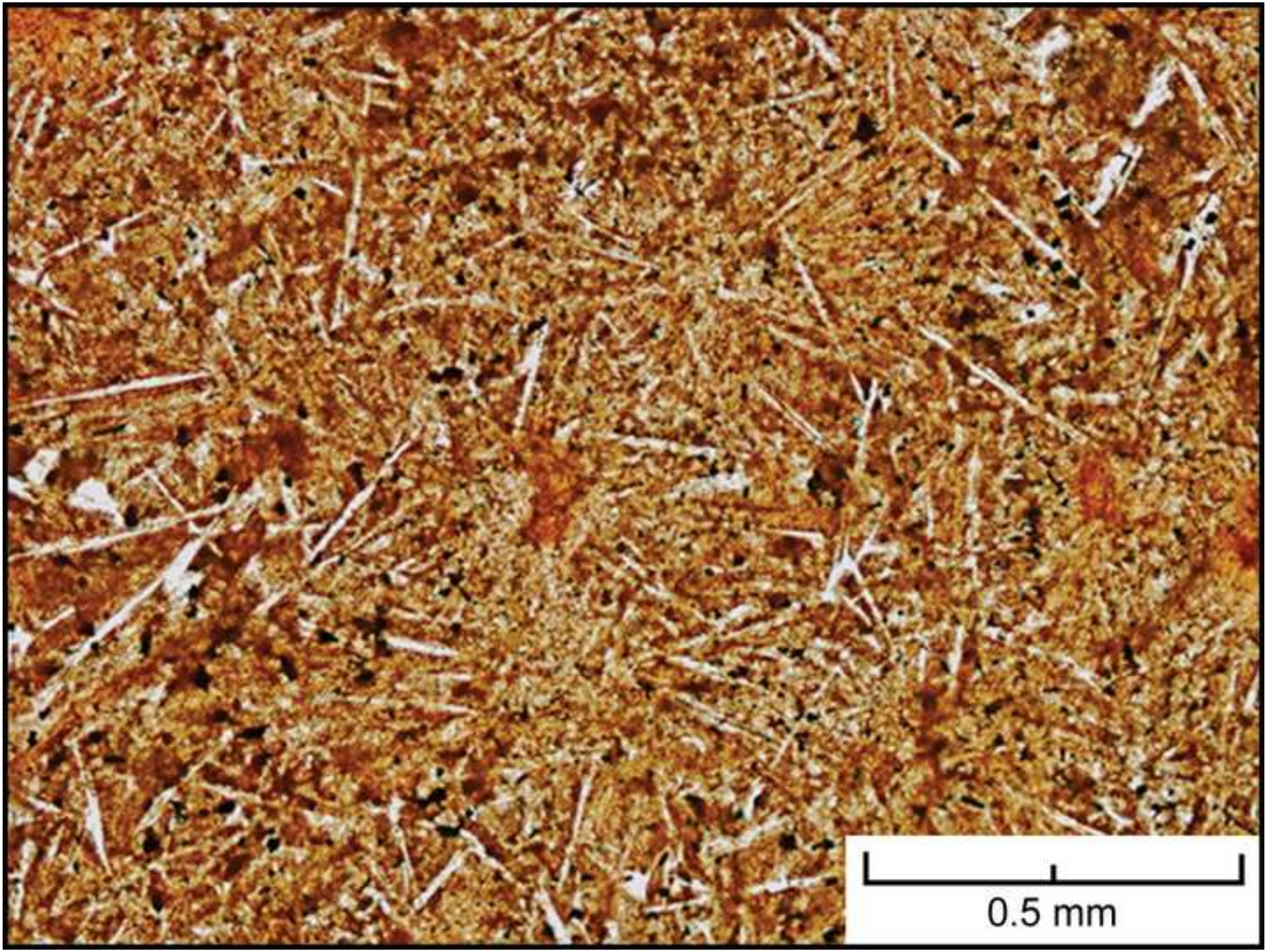

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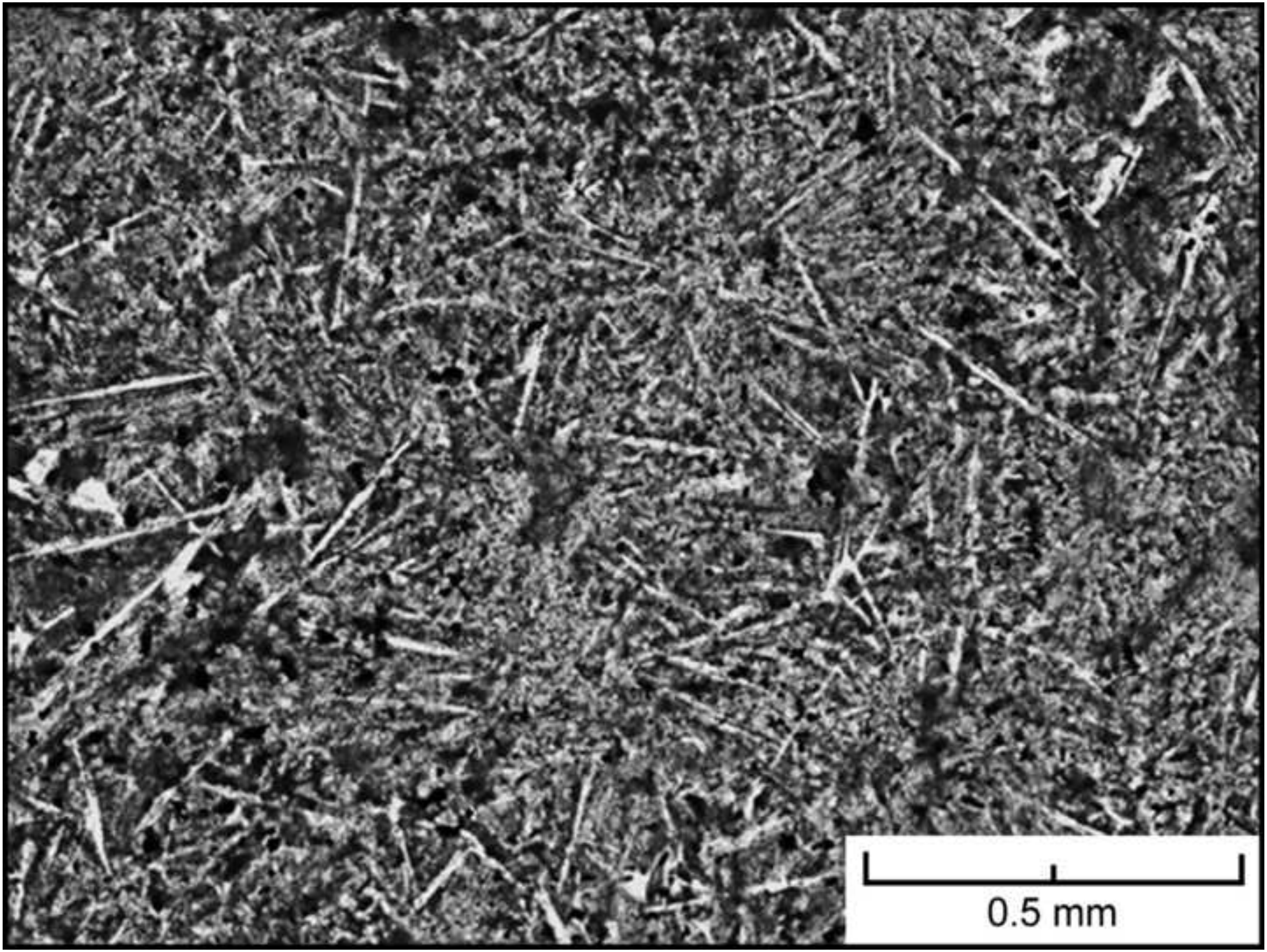

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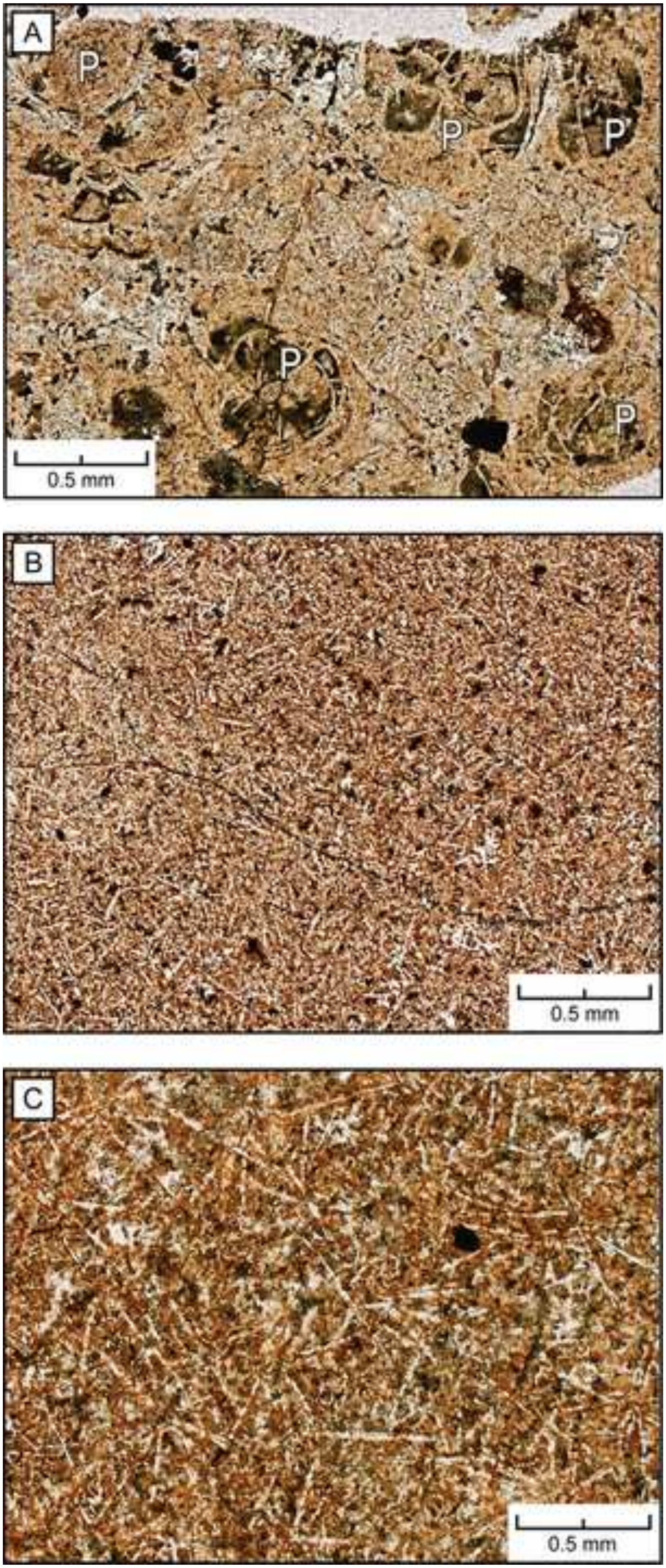

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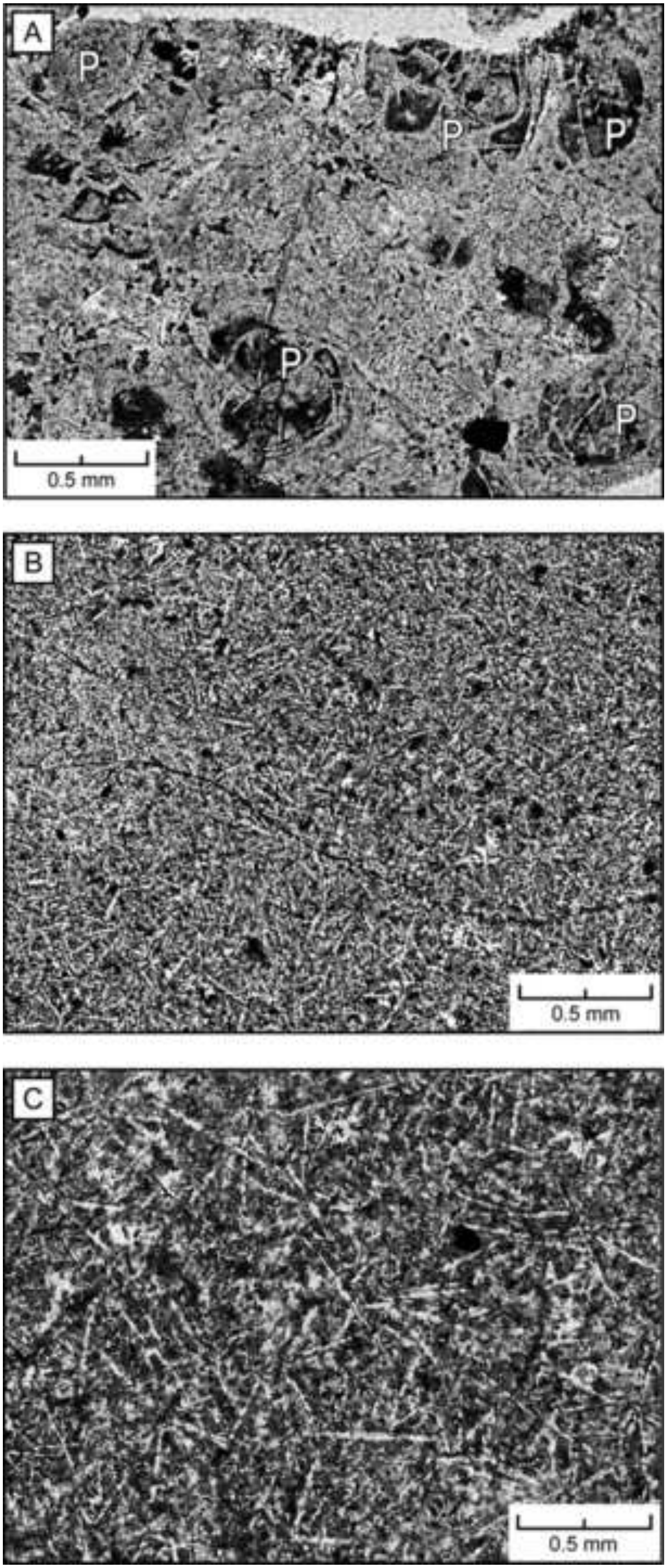

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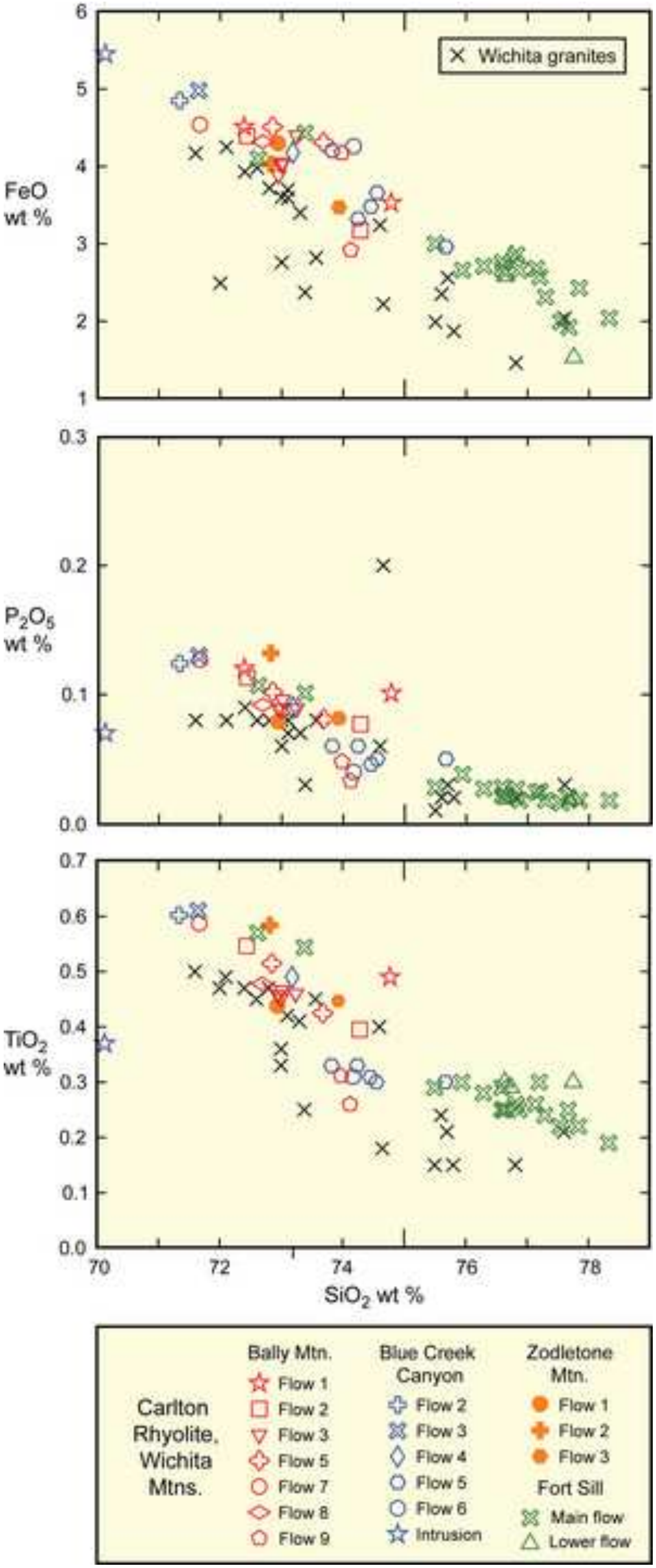

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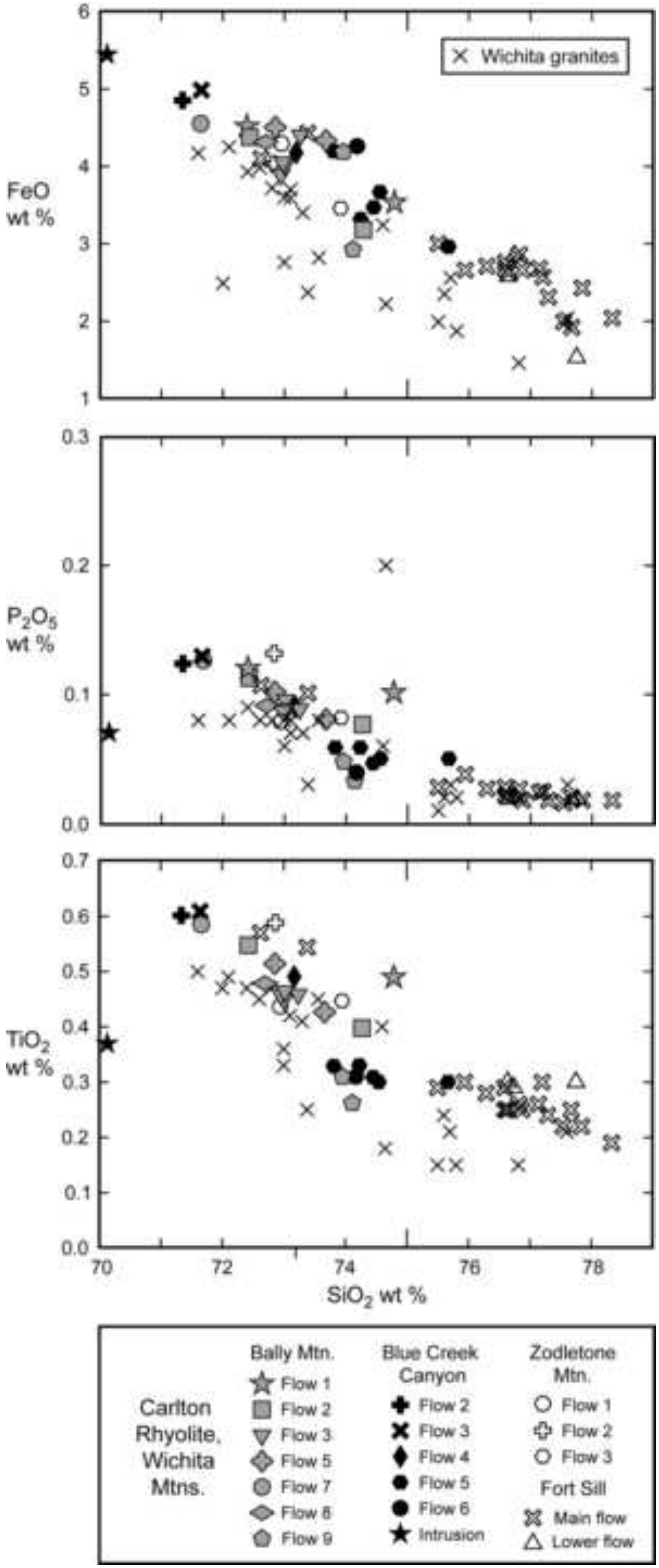

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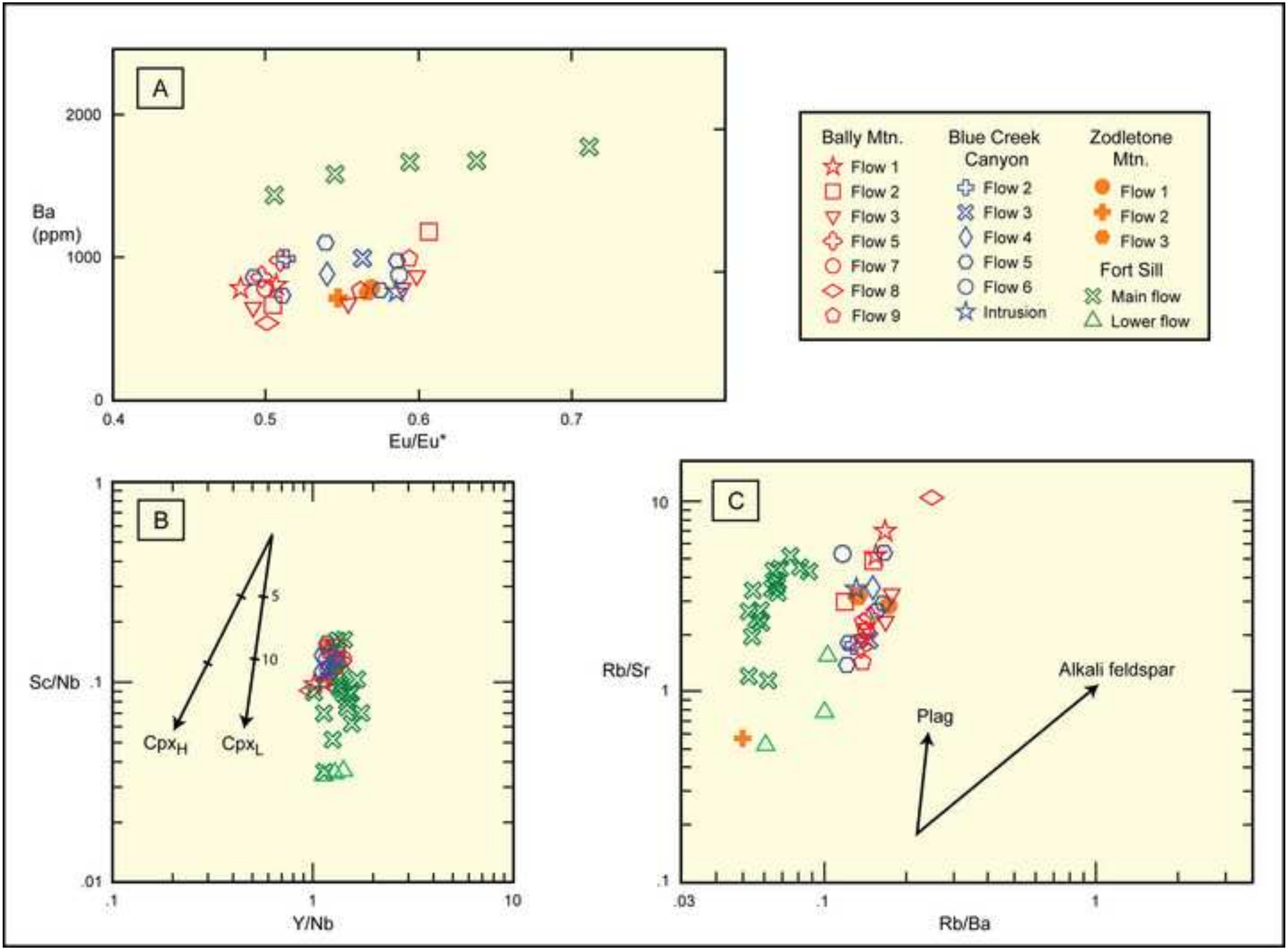

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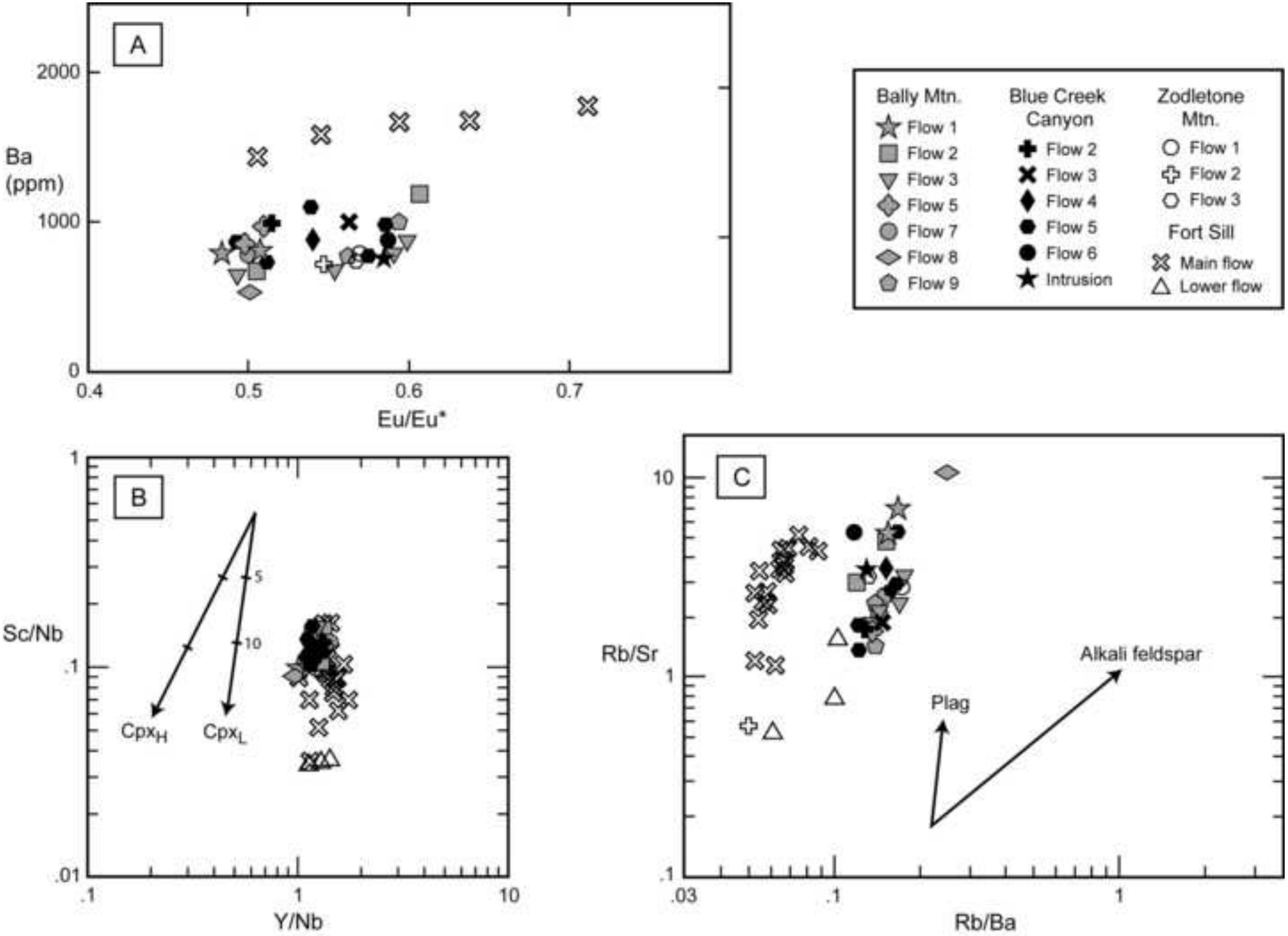

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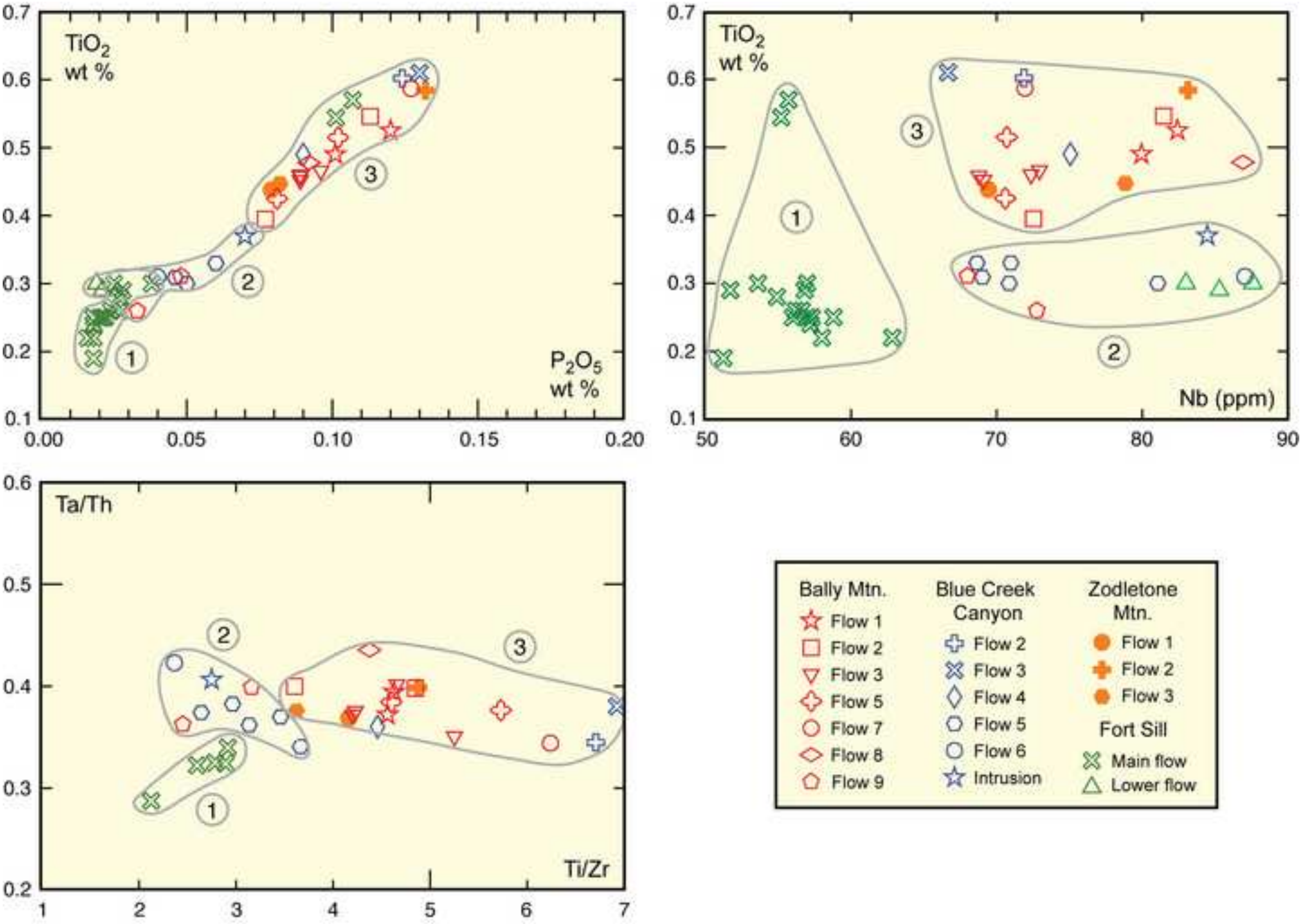

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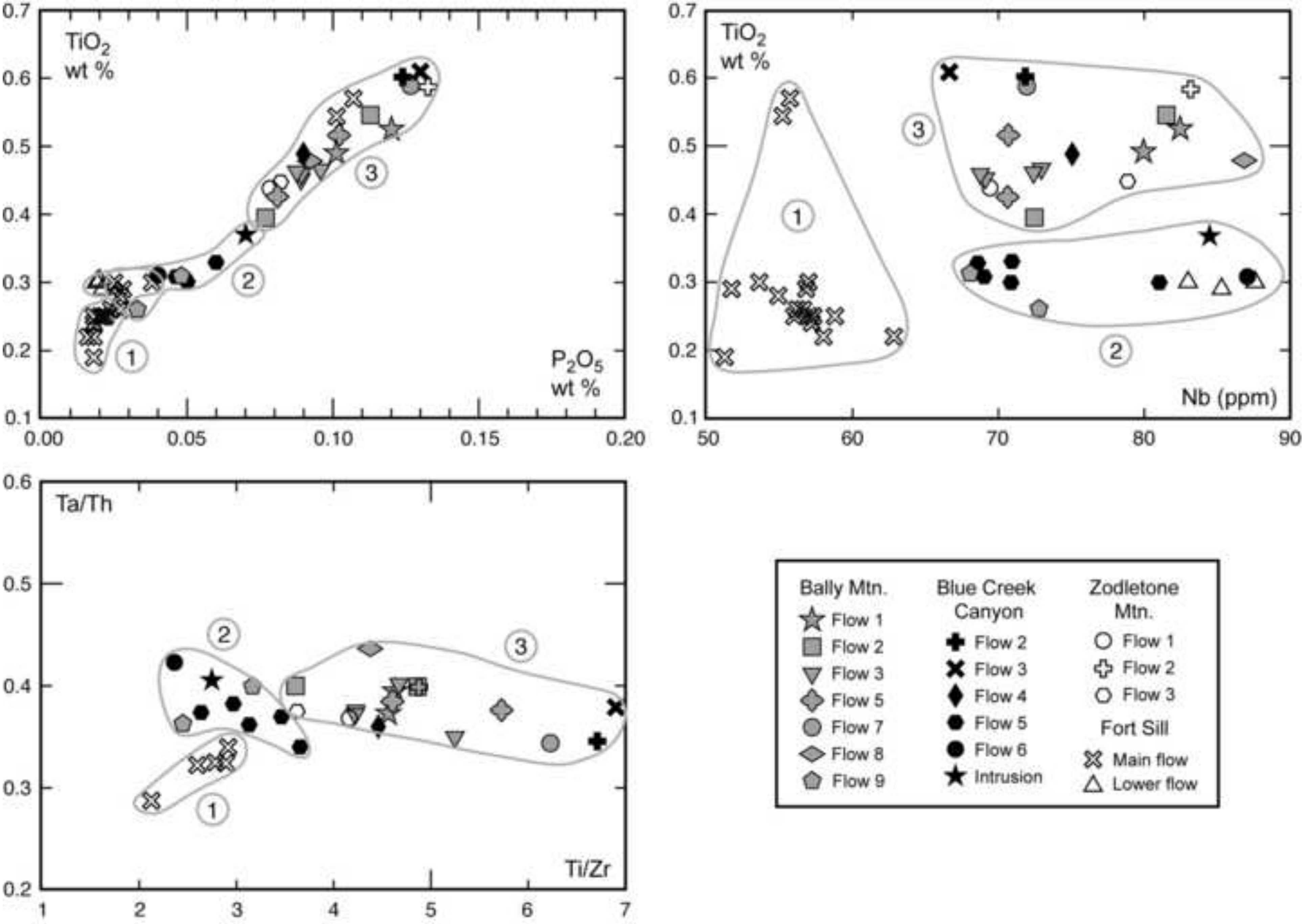

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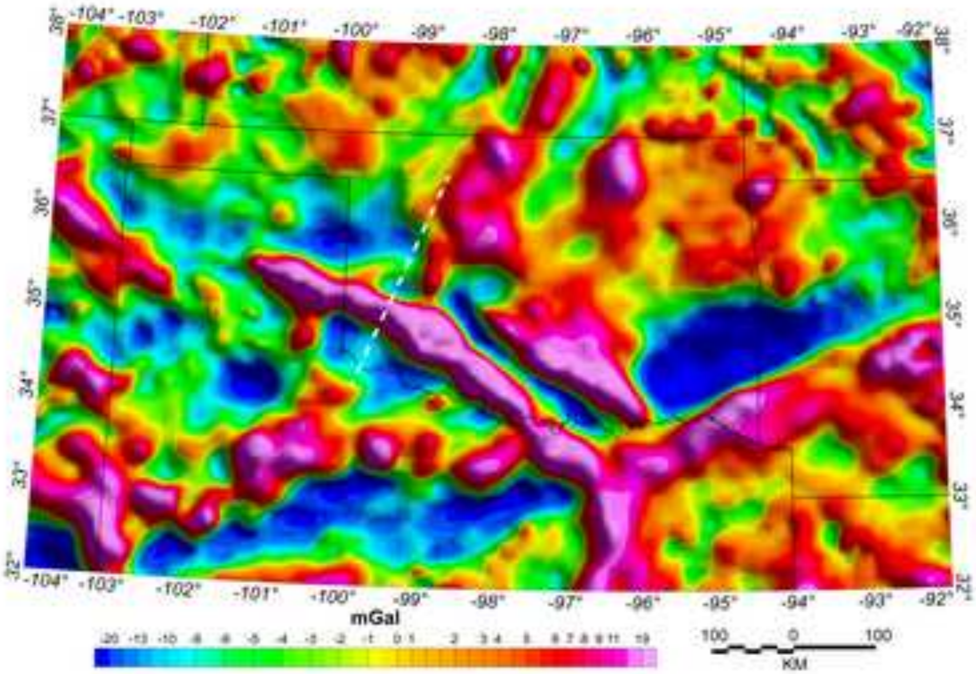

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