Characterization and Correlation of Lava Flows in Wupatki National Monument, Northern Arizona

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Introduction

Wupatki National Monument (NM), located in a high desert in northern Arizona, has excellent exposures of the Permian Kaibab and Triassic Moenkopi Formations. Many of the mesas are capped with basalt from volcanic centers of varying ages. These volcanics are part of the San Francisco Volcanic Field (SVSF), one of several late Cenozoic volcanic fields located along the southern margin of the Colorado Plateau. Volcanic activity in the SFVF began approximately 6 million years ago in the western portion of the field and continued intermittently, culminating with the eruption of Sunset Crater Volcano in the eastern portion of the field approximately 900 years ago. Throughout this time, the locus of activity progressed eastward producing over 600 volcanoes. Wupatki NM is located along the northeastern edge of the SFVF.

Previous Work

Moore and Wolfe (1987) and Ulrich and Bailey (1987) completed cursory examinations of basalt flows in the eastern and northeastern portions of the SFVF respectively. In Wupatki NM, individual lava flows were mapped on the basis of lithology and morphology and grouped into individual map units based on superposition and physiographic relationships, supplemented by sparse magnetic polarity and four K-Ar determinations. These authors show seven larger individual flows composed of 5 different rock types in Wupatki NM.

Relative and absolute ages of these flows are summarized in Figure 1. Note that caution should be exercised when interpreting these K-Ar ages as basalt often yields ages older than the time of their eruption because they contain mantle source region ^{40}Ar (excess Ar) trapped in the glassy groundmass or in fluid inclusions in crystals (Dalrymple and Hirooka, 1965; Damon et al. 1967; Laughlin et al. 1994, Dalrymple and Hamblin, 1998; Fenton, 2002). This problem is exacerbated in basalt younger than 0.5 Ma because the half-life of ^{40}Ar is so long (1.25×10^{9}yr) and the basalt contains so little potassium. Duffield et al. (2006) suggest that the problem of excess Ar in basaltic lavas of the SFVF may be widespread as Ar could be inherited from incompletely degassed magma from the mantle source region and/or contamination contained in xenocrysts.

Lava flows in Wupatki NM, shown in Figure 2, are subdivided into eight flows and include three named flows: the Arrowhead Sink, Gem City, and Black Point flows. The second lobe of the Black Point flow will be treated as a separate flow, the Citadel flow, a name given to the flow that caps the mesas near Citadel Ruin by (Cooley, 1962). The remaining flows have been assigned names for ease of discussion and include: the Doney Crater (several flows), Woodhouse Mesa, Red House Basin and Wukoki flows. The flow at Black Falls Crossing is the northern terminus of the flow referred to as the Grand Falls Flow by Duffield et al. (2006).

Petrography

In general, the lava flows are vesicular near the top and become massive toward the center. The individual flows differ from one another in size, percentage and type of phenocrysts present. In general, they are slightly to strongly porphyritic aphanitic with a fine grained to microcrystalline groundmass. They are holocrystalline to hypocrystalline, with little to no glass in the groundmass. Phenocryst percentages range from 1-30% and are composed of anhedral to euhedral olivine crystals a few millimeters in size, several mm euhedral to anhedral augite, and less than 1 mm plagioclase laths. Olivine phenocrysts exhibit normal zoning with average Fo contents ranging from 70 to 40. Plagioclase exhibits oscillatory zoning and is compositionally andesine to laboradorite. Aphanitic ground mass material is poorly to strongly aligned to the direction of flow and is composed of euhedral to subhedral plagioclase, pale green augite and unexolved ilmenite. Rock type was determined using the total alkali vs. silica (TAS) diagram modified from LeBas and Streckeisen (1991) and ranges in composition from tephrite to trachyandesite (Figure 3).

Geochemistry

A total of thirty samples were selected, based on lack of weathering and absence of calcite deposition in vesicles, for whole rock geochemical analyses. SiO_2 in Wupatki basalt varies from 43.69% to 48.71% with more restricted compositional variations within each flow (Figure 3). Variation diagrams (Figures 4 and 5) for major and trace elements versus MgO can be used to evaluate whether lava flows are genetically related to one another by fractional crystallization of olivine ± clinopyroxene. Linear trends suggest that a genetic relationship, thus a single magma source, <u>may</u> be the source for all of the volcanic products. Non-linear trends suggest that either the events are unrelated, mixing between two magma types occurred, or there was some degree of contamination of the magma by crustal material.

In general, Al_2O_3, CaO, Na_2O, Ni, Cr, Y and, with some scatter, SiO_2 exhibit linear trends suggesting that these volcanics may be related by fractional crystallization of olivine ± pyroxene from a single melt source. However, the several of the diagrams exhibit more complex patterns suggesting that this is not the only process occurring. For example, Ba, La, Th, and to a lesser extent, P_2O_5, are enriched in the Doney Mountain flow and, to a lesser extent, the Grand Falls flow. Elements typically not affected by crustal contamination such as Cr, Ni and TiO_2 generally exhibit linear trends. This suggests that the Doney Mountain and Grand Falls flows may have undergone a greater degree of crustal contamination .

Ratios of select trace elements can be used to evaluate the degree of partial melting of the asthenospheric mantle and whether crustal contamination has affected melt composition (Menzies et al., 1991). On a plot of K_2O versus La/Ta (Figure 6a) all of the samples, with the exception of Doney Mountain basalt, lie in the range of no substantial crustal contamination suggested by Menzies et al. (1991). Doney Mountain flows, with a much lower K_2O and greater La/Ta ratio, lie along a trend Menzies et al. (1991) attributes to contamination by lower crustal material. In figure 6b, the higher Th/Ta for Doney Mountain basalt is consistent with crustal contamination. Higher Zr/Y for the Grand Falls flow suggests that this melt was produced by a smaller amount of partial melting (Menzies et al., 1991).

Average chemical compositions were normalized to estimates of their abundance in the primordial Earth as given by Thompson et al. (1984) and are shown on a chondrite normalized diagram (Figure 7). Elevated high field strength (HFSE) such as Nb, Zr, REE and Y and large ion lithophile (LILE) elements such as Ba and Th as well as a lower heavy rare-earth–element (HREE) all suggest a moderately enriched, mantle derived ocean island basalt (OIB) source. The Doney Mountain basalt is enriched in Ba, Th, Rb and the LREE and depleted in Ta relative to other Wupatki lava flows. This is consistent with a higher degree of crustal contamination of the parental melt. Additionally, the Wukoki and Red House Basin flows lie slightly below other Wupatki flows suggesting that the source melt may have been produced by either a greater degree of partial melting or underwent a lesser amount of crustal contamination. The Woodhouse Mesa flow exhibits characteristics intermediate to the western and the central flows although it is generally more like the western Black Point, Citadel and Arrowhead Sink flows.

A chondrite normalized REE diagram (Figure 8) shows that Wupatki basalt is light-rare-earth-element (LREE) enriched. This is consistent with an OIB-like mantle source for the melts. Additionally, basalt from Doney Mountain is significantly enriched in LREE and the Red House Basin and Wukoki flows are slightly depleted in LREE relative to other Wupatki flows. This is consistent with the variable degrees of crustal contamination described above.

Discussion

SFVF melts are anorogenic and have been attributed to shear heating at the base of the lithosphere (Tanaka *et al.*, 1986) in a process similar to that describing the origin of volcanism in the Yucca Mountain Volcanic Field (Smith and Keenan, 2005). An abrupt change in crustal thickness below the Yucca Mountain Volcanic Field (Smith et al., 2003) perturbs the flow of the mantle along this boundary and may lead to the formation of eddies or rolls that stir up the mantle close to melting temperatures (Smith and Keenan 2005). This upward movement of mantle material results in a pressure reduction producing basaltic melts. Mantle eddies traveling within the lithosphere can produce long-lived, geographically restricted magmatism (Humphreys et al. 2000). This process can be invoked to generate melts in the SFVF because there is an abrupt change in crustal thickness below the SFVF as it lies in the Transition Zone between thick crust of the Colorado Plateau province to the north and thin crust of the Basin and Range province to the south.

The large compositional range of rock types, from basalt to rhyolite, within the SFVF have been attributed to variable amounts of mixing between primary mantle material with that generated from crustal melting and mixing with K-rich rhyolitic magmas (Bloomfield and Arculus 1989; Arculus and Gust1995). Few studies have attempted to quantify the relative input of the above sources to the mantle derived melts. Blaylock and Smith (1996) used isotopic evidence to evaluate the source of the eruptive products at Sunset Crater Volcano, approximately 30 km to the south of Wupatki NM. These authors suggest that the melt source is an OIB-like parental melt with ~ 20 - 30% crustal contamination by lower crustal mafic granulites for the fissure eruption and Sunset Crater Volcano respectively. This melt was subsequently modified by fractional crystallization of olivine and pyroxene.

All of the flows in Wupatki can be attributed to partial melting of an OIB-like parental material. Variation between the flows is attributed to varying degrees of assimilation and fractional crystallization (AFC processes). The effects of these processes were superimposed on at least five individual partial melting events that ultimately produced melts for the Wupatki lava flows.

Western Wupatki hosts the oldest flows, the Black Point (2.4 Ma) and Citadel flows, and the younger Arrowhead Sink flow. The Black Point and Citadel flows are mineralogically, texturally and geochemically similar yet the Citadel flow is a slightly more evolved trachyandesite. Ulrich and Bailey (1987) suggest that these flows represent two separate lobes from a single flow. However this cannot be evaluated as the origin of these flows is covered by the younger flows to the south. The Arrowhead Sink flow, the most evolved flow in western Wupatki, is much younger but lies on a similar trend with the Black Point and Citadel flows. Thus, it may represent a younger event resulting from fractional crystallization of Black Point and Citadel magma. Ulrich and Bailey, (1987) suggested, based on major element chemistry and flow direction, that the Arrowhead Sink flow originated from Vent 3705 southwest of the monument. Furthermore, flow directions for the Black Point and Citadel flows suggest that they may be related to the activity to the southwest as well. A single major element analysis for this vent is given by Ulrich and Bailey (1987) and is shown on Figure 4. Although it is slightly more fractionated, the major element chemistries are similar suggesting that a genetic relationship is permissible. More detailed petrographic and major and trace element studies from the volcanic vents to the southwest of Wupatki are needed before any vent source for the western flows can be confirmed.

The Red House Basin and Wupatki flows in central Wupatki exhibit similar characteristics to the western flows. However, chondrite normalized compositions and trace element ratios suggest that the source melt for these flows may be the result of either a slightly greater degree of partial melting or a lesser degree of crustal contamination.

The Woodhouse Mesa flow exhibits characteristics similar to both the western and the central flows. However, higher Ti values this flow suggests that it may represent a discrete melting event. This flow occurs on an eroded mesa top giving no indication of flow direction and is significantly older so that the vent from which this flow effused has either eroded away or is covered by younger volcanics. Thus, a geomorphic comparison to nearby flows is impossible.

The younger flows in eastern Wupatki, the Doney Mountain and Grand Falls (20,000a) flows are moderately evolved and appear to be unrelated to each other as well as to other magmatic events in Wupatki. The Doney Mountain flow has undergone significantly more crustal contamination whereas the Grand Falls flow was generated by a lesser amount of partial melting. Moore and Wolfe (1987) suggested that both of these events were related to activity at Merriam Crater and/or The Sproul, 25 km to the south-southwest. Geochemical and physiographic relationships show that the Grand Falls flow originated from Merriam Crater, The Sproul or one of the two smaller vents at the east base of Merriam Crater (Moore and Wolfe, 1987; Duffield, 2006). These four vents are distributed along two en-echelon northwest trends suggesting that volcanoes of this cluster were active at about the same time. It is possible that all four may have erupted during a single brief period to feed the Grand Falls lava flow (Duffield et al., 2006). A single major element analysis for The Sproul (Moore and Wolfe, 1987) and a major and trace element analysis for Merriam Crater (Hooten et al., 2001) are shown for comparison on the geochemical diagrams (Figures 3-8). Based on major element analyses, The Sproul appears to be a better candidate for the source of the Grand Falls flow. The relationship of these vents to the Doney Mountain cinder cones is less clear. A comparison these data to the Doney Mountain lava flows suggest the magma source for The Sproul cannot be the same as that for Doney Mountain. Additionally, although the magma source for the Merriam Crater eruption exhibits a significant amount of crustal contamination, it is less than that exhibited by the Doney Mountain cinder cones. Thus, the Doney Mountain cinder cones cannot be related exclusively to this volcano. More detailed petrographic, major and trace element geochemical studies from Merriam Crater and adjacent vents as well as from The Sproul are needed before the relationship between these vents and the Grand Falls and Doney activity can be understood. Regardless, the younger Grand Falls and Doney Mountain flows, although similar in age, represent discrete events and are likely unrelated to other flows in Wupatki NM.

Conclusions

Lava flows in Wupatki NM were produced by varying amounts of partial melting of an OIB-like mantle source which underwent variable degrees of contamination from lower crustal material. These melts were subsequently modified by fractional crystallization of olivine ± clinopyroxene. Finally, the presence of xenoliths, xenocrysts, and unexolved Fe-Ti oxides in these lava flows is consistent with a rapid transport to the surface and rapid cooling. Thus, these melts were not stored in a low level magma chamber prior to eruption. At least 9 individual eruptions (8 if the Black Point and Citadel flows represent a single flow) produced the lava flows in Wupatki NM. These flows are moderately enriched and represent at least five separate melting events. The first group includes the Black Point and Citadel flows as well as the younger, more fractionated Arrowhead Sink flow. The eruptive center that produced these flows is likely one or more of the cinder cones located southwest of the monument. The Red House Basin and Wukoki flows represent a separate melting event which resulted from either a slightly larger amount of partial melting or slightly lower amount of crustal contamination than the western flows. The vents for these flows have not been determined and may have eroded away or been covered by later volcanic events. The Woodhouse Mesa flow, although in close proximity to these two flows, is significantly older and enriched in Ti, thus most likely represents a separate melting event. The Grand Falls flow erupted from a melt that was produced by a significantly smaller degree of partial melting than that from which other Wupatki lava flows originated. Field relations show that the Grand Falls flow effused from cinder cones centered south-southeast of the monument and include Merriam Crater, The Sproul, and two cones along the east base of Merriam Crater. Based on major element compositions, The Sproul is a better candidate for the source of the Grand Falls flow. The Doney Mountain volcanics represent another discrete melting event which involved greater degrees of contamination from lower crustal material. Moore and Wolfe (1987) suggested that the Doney Mountain cinder cones are also related to Merriam Crater and the nearby events. While Merriam Crater exhibits a higher degree of crustal contamination as compared to other Wupatki melts, it is still less contaminated than the Doney Mountain melt. Thus, it is unlikely that it alone produced this flow. More petrographic and geochemical data for Merriam Crater and nearby cinder cones are needed to evaluate their relationship to both the Grand Falls flow and the Doney Mountain volcanics.

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Other publications resulting from this work:

Hanson, S.L. (2006) Correlation of Lava Flows at Wupatki National Monument, Northern Arizona. GSA Abstracts with Programs. v. 38, no.7, p. 36

A manuscript is currently being prepared and will be submitted to a professional journal upon completion.

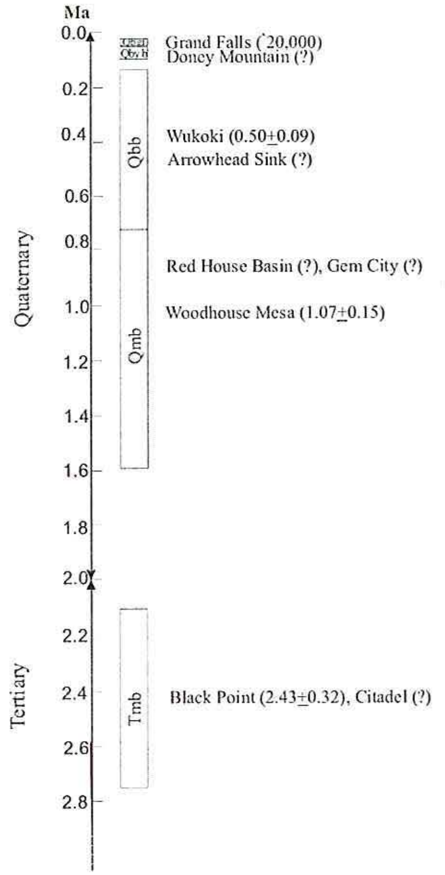

Figure 1. Correlation of volcanic units in Wupatki National Monument. Map units based on relative age are from Moore and Wolfe (1987) and Ulrich and Bailey (1987). Radiometric ages are shown in parenthesis and flows lacking age dates are shown with a question mark. All ages are K-Ar dates from Moore and Wolfe (1987) and Ulrich and Bailey (1987) with the exception of the Doney Mountain age which is from Duffield et al. (2006).

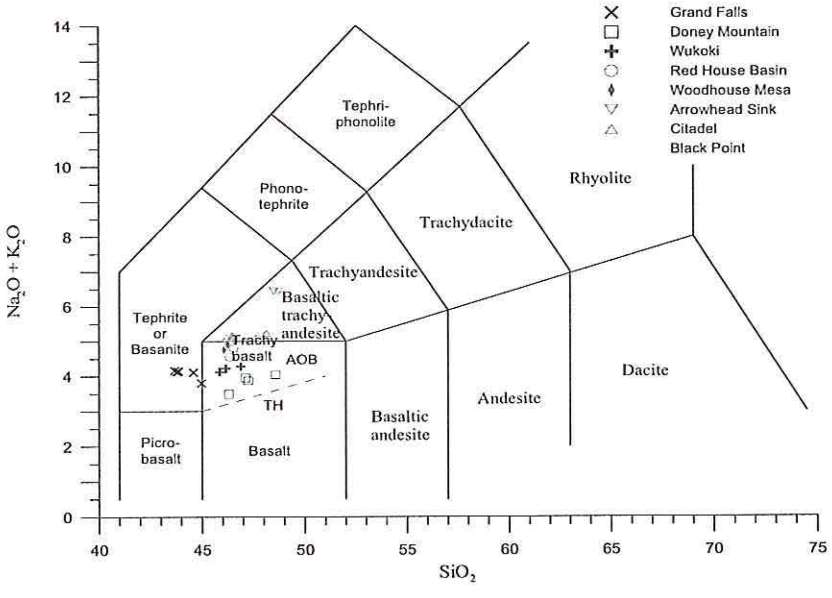

Figure 3. Total alkali versus silica diagram for Wupatki NM lava flows (after LeBas and Streckeisen, 1991)

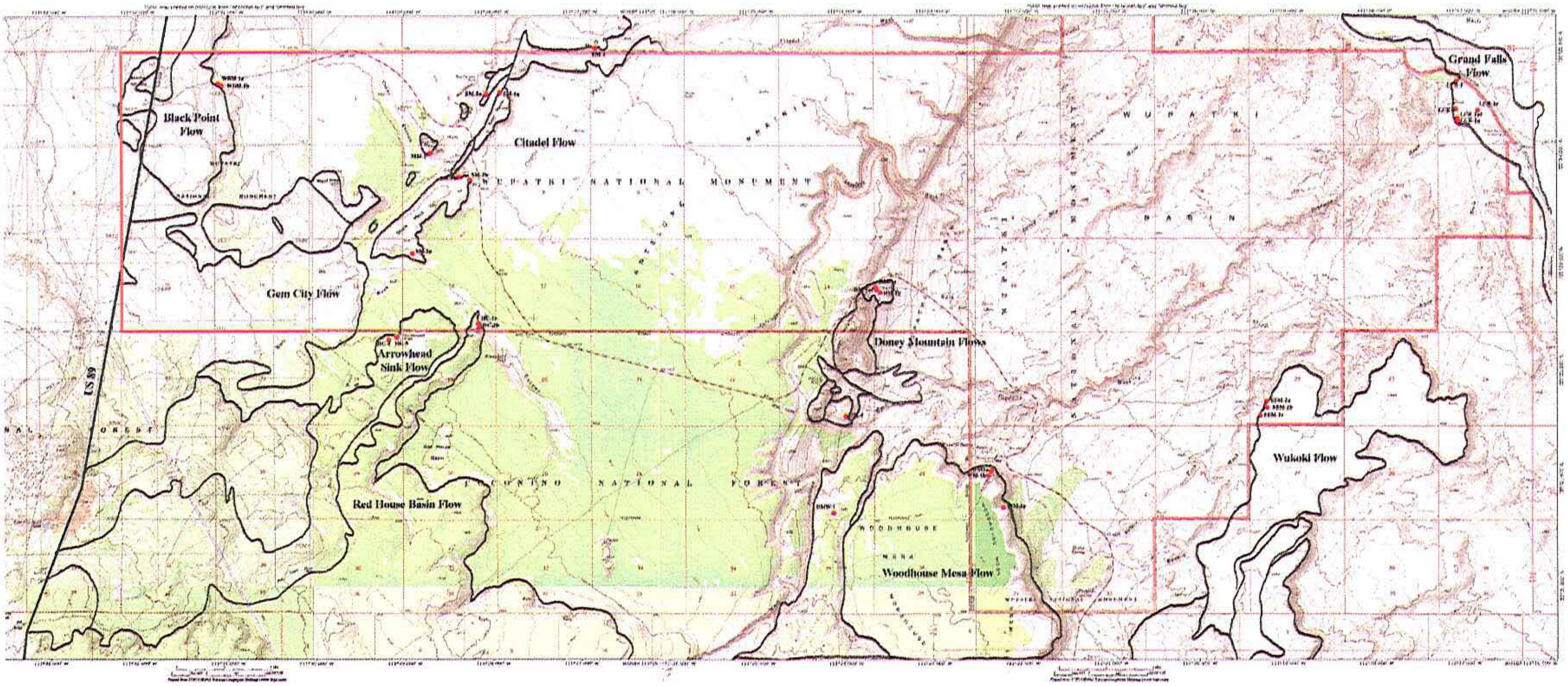

Figure 2. Topographic map of Wupatki NM showing sample locations and lava flows as mapped by Moore and Wolfe (1987) and Ulrich and Bailey (1987). Flows are distinguished on the basis of geochemical analyses (this study). Base topographic map was created using TOPO, a program produced by National Geographic.

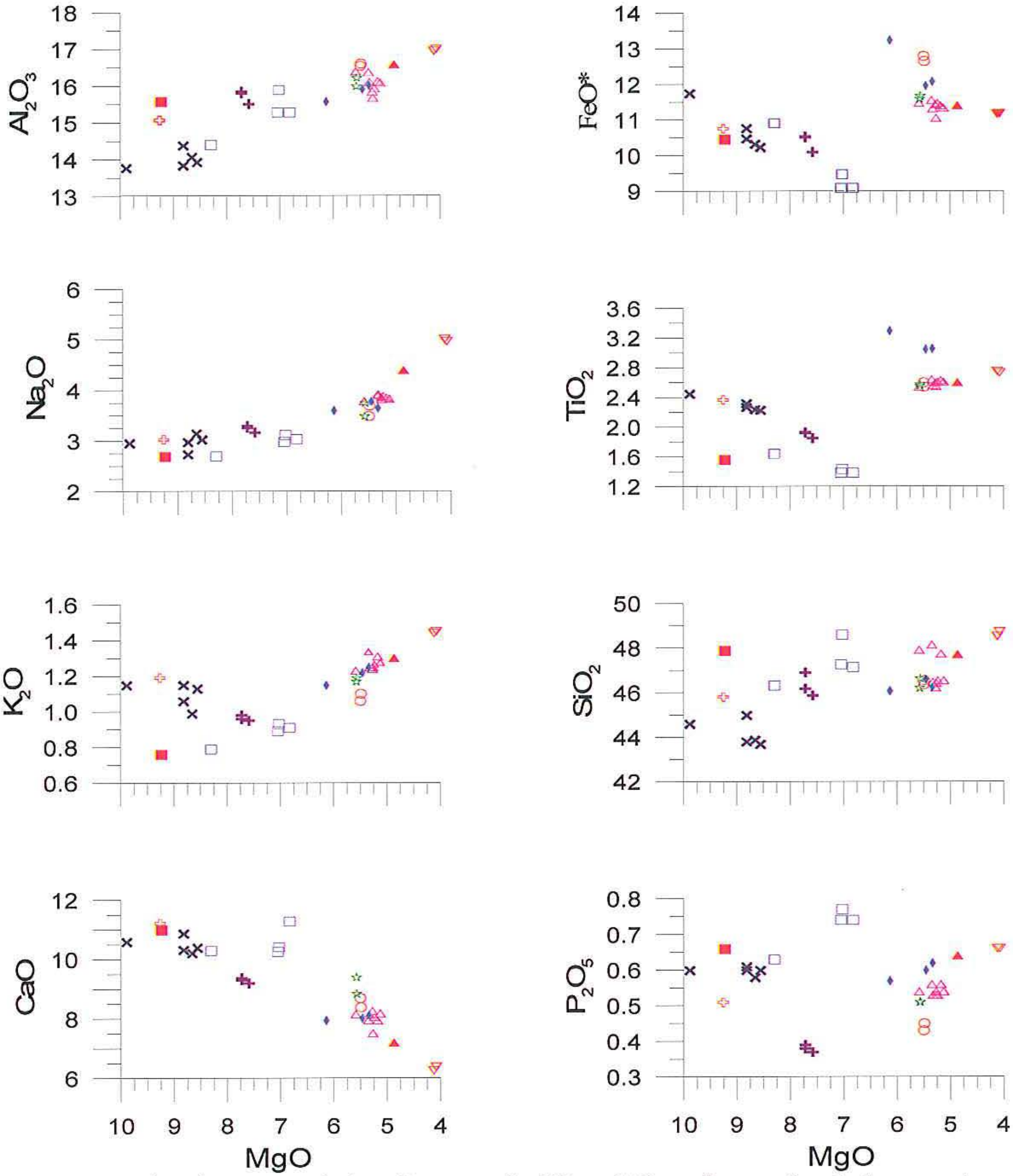

Figure 4. Major element variation diagrams for Wupatki lava flows. Symbols are as in Figure 3 with the following additions: Merrian: solih squares; The Sproul: hollow crosses; Vent 3705: solid triangle.

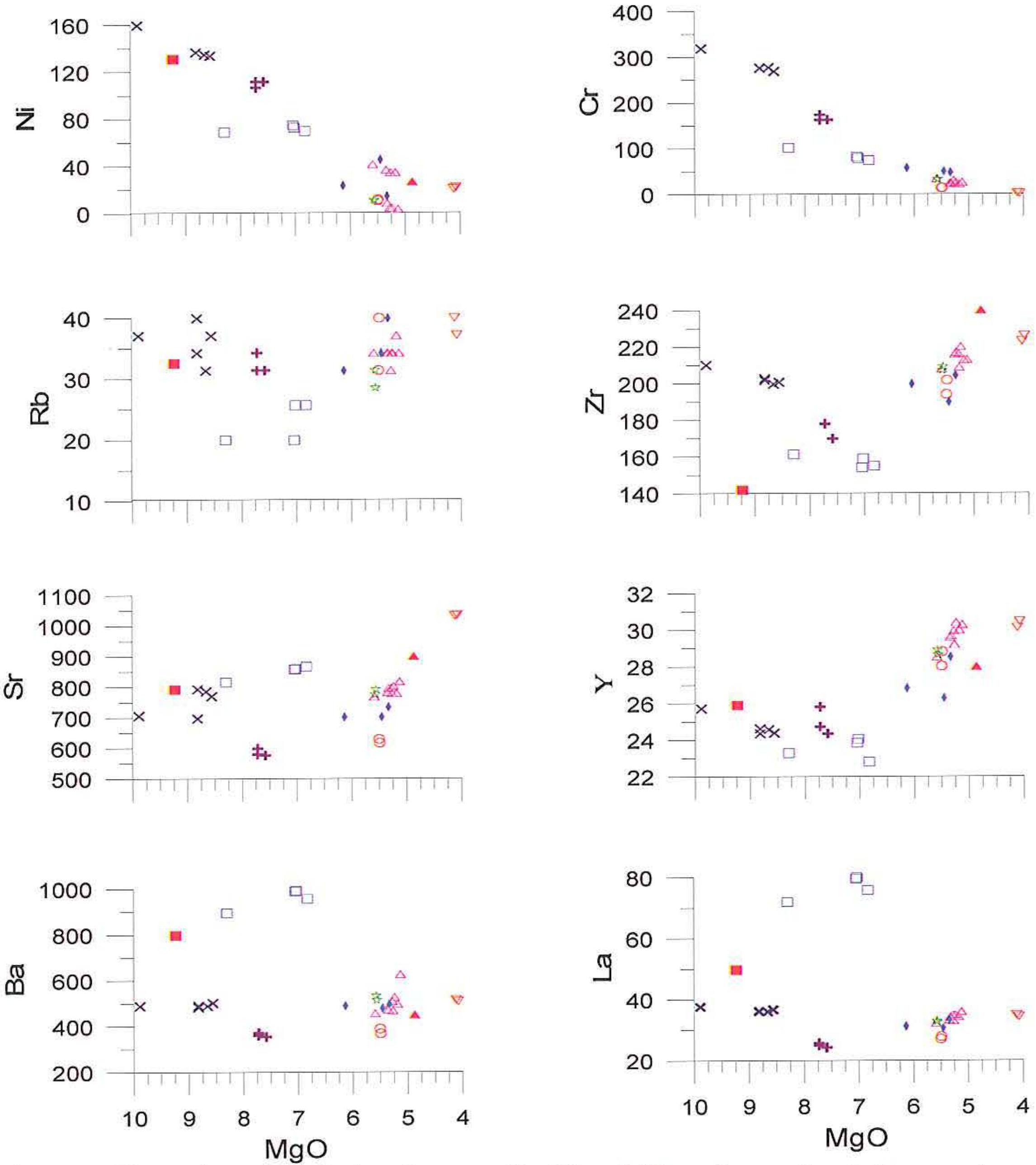

Figure 5. Trace element variation diagrams for Wupatki lava flows. Symbols are as in Figure 4.

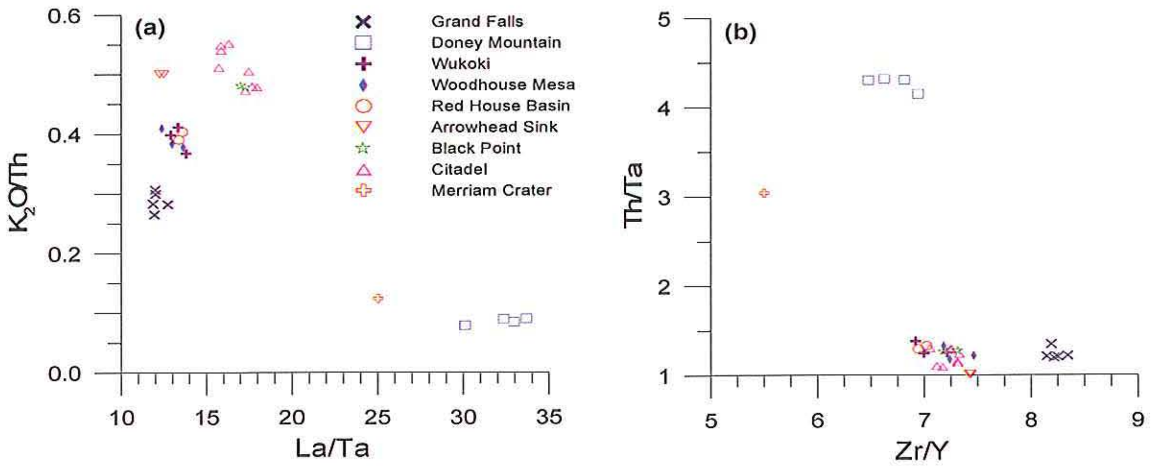

Figure 6. Trace element ratios for Wupatki lava flows.

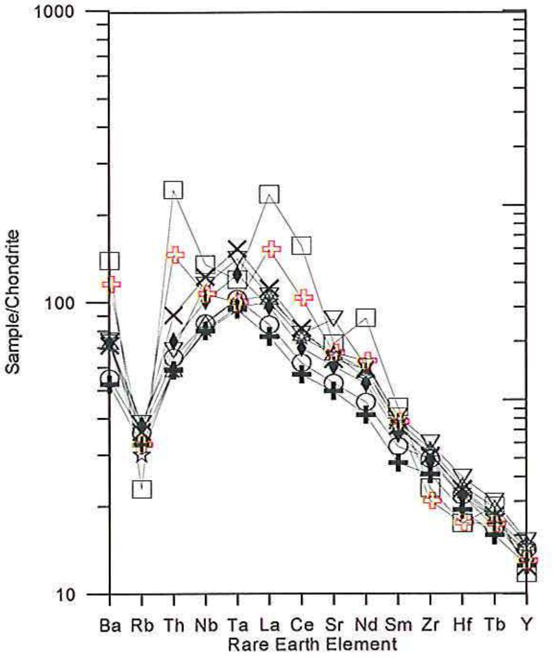

Figure 7. Chondrite normalized trace element diagram for Wupatki lava flows. Symbols as in Figure 8.

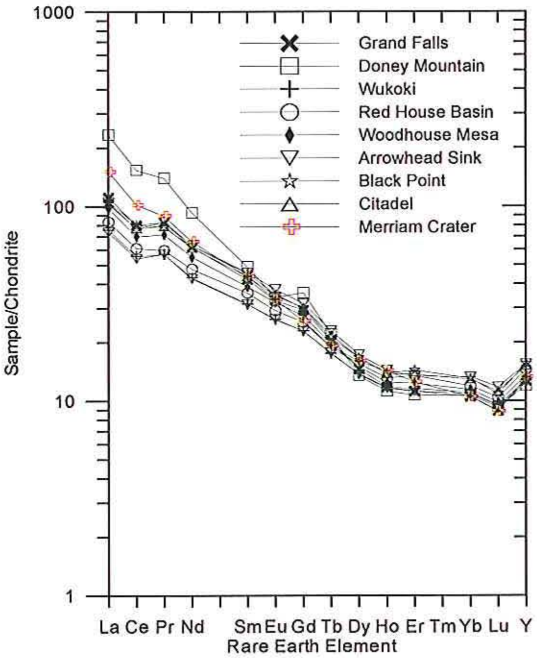

Figure 8. Chondrite normalized rare-earth-element diagram for Wupatki lava flows.