GEOLeGIC MAP OF THE PINTURA QUADRANGLE, WASHINGTON COUNTY, UTAH

by

Hugh A. Hurlow and Robert F. Biek

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ABSTRACT

This report describes selected aspects of the geology of the Pintura quadrangle. The quadrangle includes Permian through early Tertiary sedimentary rocks, middle Tertiary intrusive and volcanic rocks, and Quaternary volcanic rocks and surficial deposits. Mesozoic to early Cenozoic compressional deformation in the Utah-Idaho-Wyoming section of the Sevier orogenic belt, followed by Cenozoic magmatism and extensional faulting, created complex structural relations within the quadrangle. These structures are the main focus of this report.

Five major structures, including the Pintura anticline, parts of the Virgin and Kanarra anticlines, an intervening buried syncline, and the Hurricane fault, formed during Mesozoic to Cenozoic tectonism. In addition, large masses of mid-Tertiary-age quartz monzonite porphyry of the Pine Valley Mountains are at structurally and topographically low elevations in the quadrangle. This structural complexity, coupled with the fact that critical relationships are concealed by late Tertiary to Quaternary deposits in the hanging wall of the Hurricane fault, has led to conflicting structural interpretations of the area. The principal controversies concern the existence of the Pintura anticline and the timing and magnitude of displacement on the late Tertiary Hurricane fault. Stratigraphic units important to interpreting these structures include the late Campanian to early Paleocene Canaan Peak Formation, which unconformably overlies the Jurassic Navajo Sandstone in the suspected hinge zone of the Pintura anticline, and Quaternary basalt exposed on either side of the trace of the Hurricane fault.

Our mapping provides detailed field data and observations that help constrain and focus, but not necessarily resolve, these debates. We conclude that an important structural culmination occupies the suspected hinge zone of the Pintura anticline, but reinterpret this feature as a composite fold that formed first during late Mesozoic to early Cenozoic contractual deformation, then was modified during Tertiary time by extensional faulting and large-scale reverse drag in the hanging wall of the Hurricane fault.

INTRODUCTION

The Pintura quadrangle is in Washington County, southwestern Utah, about 20 miles (32 km) northeast of St. George and 30 miles (48 km) southwest of Cedar City (figures 1 and 2). Although no large towns lie within the quadrangle, it is bisected by Interstate 15 and is affected by the 86 percent population increase experienced by Washington County between 1990 and 2000 (Utah Governor’s Office of Planning and Budget, 2001). This population increase has resulted in dramatically greater demand for local natural resources, especially ground water, and the location of residential developments in areas of moderate to high geologic hazards. The climate in the Pintura quadrangle is semiarid; mean annual precipitation varies from less than 12 inches (30 cm) near Anderson Junction to about 20 inches (50 cm) in the eastern foothills of the Pine Valley Mountains (Cordova, 1978). Several perennial streams flow through the quadrangle, including Ash Creek, Wet Sandy, and Leeds Creek, whose sources are in the eastern Pine Valley Mountains, and LaVerkin Creek, whose source is east of the quadrangle (figure 3).

This pamphlet describes selected aspects of the geology of the Pintura quadrangle, including major structures; the field relations, ages, and geochemistry of Quaternary basalt; and some natural resources. Discussion of these and other aspects of the geology of the Pintura quadrangle and surrounding area - including stratigraphic units, geologic hazards, and geologic resources - can be found in Dobbin (1939), Gregory and Williams (1947), Cook (1957, 1960), Kurie (1966), Watson (1968), Rowley and others (1979), Stewart and others (1997), Hurlow (1998), Pearthree and others (1998), Lund and others (2001), and Biek (2003a, 2003b).

TECTONIC SETTING

The Pintura quadrangle is in the transition zone between the Basin and Range and Colorado Plateau physiographic
Figure 1. Generalized geologic map of southwestern Utah in the vicinity of the Pintura quadrangle, after Hintze and others (2000). Towns: CC = Cedar City; E = Enterprise; P = Pintura; and SG = St. George.
provinces (figures 1 and 2) (Heylmu, 1963; Best and Hamblin, 1978; Scott and Swadley, 1995; Maldonado and Nealey, 1997). The Basin and Range Province in southwest Utah is characterized by superposition of Cenozoic volcanism and normal faulting on Mesozoic to early Cenozoic contractional structures. The Mesozoic structures are part of the Utah-Idaho-Wyoming section of the Cordilleran fold and thrust belt, characterized by deformed Paleozoic and Mesozoic carbonate and siliciclastic strata (Armstrong, 1968; Royse and others, 1975; Allmendinger, 1992; Willis, 1999). The Colorado Plateau is underlain by strata deposited east of the Cordilleran hinge line, and is structurally simpler than the Basin and Range Province. The transition zone contains structural and stratigraphic characteristics of both provinces.

During the Sevier orogeny, uplift and erosion in eastern Nevada and western Utah associated with thrust faulting and folding led to fluvial deposition of the Iron Springs Formation in southwestern Utah during Late Cretaceous time (Fillmore, 1991; Goldstrand, 1994). Contractual deformation migrated eastward into southwestern Utah during latest Cretaceous to early Paleocene time, forming: (1) in the Pinta quadrangle, the Pinta and Kanarra anticlines, an intervening syncline (not exposed), and thrust faults that cut the east limb of the Kanarra anticline (cross section A-A') (Gregory and Williams, 1947; Cary, 1963; Kurie, 1966; Watson, 1968); (2) the Virgin anticline southwest of the Pinta quadrangle (figure 1) (Dobbin, 1939; Higgins and Willis, 1995; Biek, 2003a, 2003b; Higgins, 1998); and (3) several thrust faults and folds in the Cedar City area north and northeast of the quadrangle (figure 1) (Threet, 1963; van Kooten, 1988; Maldonado and Williams, 1993a). As explained below, the existence of the Pinta anticline and related syncline is controversial. The timing of Late Cretaceous to early Cenozoic contractual deformation is constrained in part by strata exposed in the Pinta quadrangle. Fluvial strata of the late Campanian to early Paleocene Canaan Peak Formation record the waning stages of contractual deformation, whereas the Paleocene-Eocene Claron Formation was deposed after that deformation had ceased (Taylor, 1993; Goldstrand, 1994). In the Pinta quadrangle, the Canaan Peak Formation comprises fluvial conglomerate deposited on the suspected hinge zone of the Pinta anticline; this formation was only recently identified in the eastern Pine Valley Mountains (R.E. Anderson, written communication to P.M. Goldstrand in Goldstrand, 1992), and is more extensively exposed in south-central Utah (Bowers, 1972; Goldstrand, 1994).

During Oligocene to Quaternary time, volcanism and extension occurred throughout southwestern Utah. Oligocene to early Miocene calc-alkaline ash-flow tuff, volcanic mudflow breccia, and lava flows covered most of southwestern Utah; their source areas were primarily the Indian Peak and Caliente caldera complexes in western Utah and eastern Nevada, though local sources were also active in the Bull Valley Mountains about 25 miles (40 km) west-northwest of Pinta, and other local areas (figure 1) (Cook, 1960; Mackin, 1960; Rowley and others, 1979; Rowley and others, 1995; McKee and others, 1997). Relatively minor normal faulting and crustal extension accompanied the eruption of these volcanic rocks (Best and Christiansen, 1991; Rowley and others, 1995).

Quartz monzonite porphyry laccoliths of the "iron axis" were emplaced around 21 million years ago, including the Pine Valley laccolith, part of which crops out in the Pinta quadrangle (figure 1) (Cook, 1957, 1960; Blank and others,
Figure 3. Geographic and hydrologic features of the Pintura quadrangle.

1992; McKee and others, 1997; Hacker, 1998). The Pine Valley laccolith chiefly intruded the middle part of the Claron Formation parallel to bedding (Cook, 1957, 1960; Hacker, 1998), but also locally intruded the lower part of the Iron Springs Formation in the Pintura quadrangle (see below). Intrusion of the Pine Valley laccolith rapidly uplifted the land surface, resulting in large landslides off the uplifted roof of the intrusion (Cook, 1957; Blank and others, 1992; Hacker, 1998; Hacker and others, 2002). These landslides consist of megabreccia deposits now exposed north and west of the Pine Valley Mountains (Cook, 1957; Blank and others, 1992; Hacker, 1998); such deposits presumably once covered much of the Pintura quadrangle, but have largely been removed by erosion or are now covered by younger deposits. A small erosional remnant of one of these megabreccia deposits is present in the northwestern part of section 2, T. 40 S., R. 13 W. in the Pintura quadrangle. Viscous, autobrec­ciated lava flows erupted from the areas evacuated by the landslides (Cook, 1957; Hacker, 1998); small outcrops of such flows are in the northern part of the Pintura quadrangle.

Basin and Range extension on steeply dipping normal faults accompanied by bimodal basaltic and rhyolitic volcan­ism began in southwestern Utah (at least north of the Pintura quadrangle) during late Miocene time, after emplacement of the iron-axis intrusions (Anderson and Mehnert, 1979). Two generations of normal faults formed in the Pintura quadrangle during Basin and Range extension, as described below; the older set is pre-Quaternary age, and the younger set includes the late Tertiary-Quaternary Hurricane fault and associated faults in its hanging wall.
GEOLOGIC STRUCTURES IN THE PINTURA QUADRANGLE

The Pintura quadrangle contains five major structural features, including the Pintura anticline and parts of the Virgin and Kanarra anticlines and associated thrust faults, an intervening buried syncline, and the Hurricane fault. As discussed below, the existence of the Pintura anticline and the syncline between the Pintura and Kanarra anticlines is uncertain. In addition, large blocks of the quartz monzonite porphyry of the Pine Valley Mountains are present at a structurally and topographically low elevation compared to the main mass of the intrusion. Because some of this structure is “hidden” in the cross-bedded Navajo Sandstone, and because late Tertiary and Quaternary deposits in the hanging wall of the Hurricane fault conceal critical structures, interpretations of the area differ. Although much remains speculative, our new geologic mapping further constrains structural interpretations of this area.

Pintura Anticline

The existence of the Pintura anticline has long been debated in the literature. Because the age of this structure provides important constraints on the timing of Sevier-age folding in southwestern Utah, a short review of previous work is in order. Huntington and Goldthwait (1904, 1905) and Gardner (1941, 1952) depicted the Pintura anticline in the north-central part of the Pintura quadrangle. Neighbor (1952) briefly described the structure and a dry oil-explo­ration hole (Sun Oil Company No. 1 Pintura Unit; see table 3) drilled in the hinge zone of the Pintura anticline; he estimated the anticline had about 1,400 feet (430 m) of closure. Cook (1957) doubted the presence of the Pintura anticline, and correctly noted that its existence involves deciphering the attitude of the Navajo Sandstone, which is difficult to determine given its large-scale cross-beds. Cook noted that the easternmost outcrop of the Carmel-Navajo contact - in Leap Creek drainage in the adjacent New Harmony quadrangle (see also Grant, 1995) - dips northwest and is overlain in angular unconformity by the Claron Formation. He also noted that when the Claron is rotated back to horizontal, the Carmel-Navajo contact dips even more steeply northwest. Cook (1957) thus saw no evidence of a fold axis or east limb and therefore doubted the Pintura anticline is a Sevier-age fold. We agree with Cook’s assessment that direct evidence of the Pintura anticline as a Sevier-age structure lies hidden in the great, sweeping cross-beds of Navajo Sandstone, and that when the Claron is rotated back to horizontal the Carmel everywhere dips to the northwest.

To more accurately map the axial plane of the fold, Cary (1963) used a color break in the Navajo Sandstone as a proxy for a paleohorizontal surface by contouring the interval between the color break and the base of the Carmel (figure 4). He determined that the Pintura anticline was doubly plunging with about 2,000 feet (600 m) of closure on the Navajo Sandstone, but did not take a position as to the origin of the fold.

Figure 4. View to the northwest of the west-central part of the Pintura quadrangle from southern Black Ridge. The quartz monzonite porphyry of the Pine Valley Mountains (unit Tip) west of Interstate 15 is about 3,000 feet below the main mass of the laccolith (visible in the background), and may be a satellitic intrusion or an erosional remnant of a once-continuous sheet. The structurally low position of this quartz monzonite porphyry is due to the combined effects of (1) normal faults bounding either side of the body (shown by solid lines where visible; the trace of the western fault is concealed behind the main body; the arrow shows its position), and (2) reverse drag in the hanging wall of the Hurricane fault and other west-side-down normal faults. The base of the quartz monzonite porphyry here is discordant with bedding in the underlying Claron Formation, indicating faulting during or prior to intrusion. Qafo = early Quaternary alluvial-fan deposits; Tip = quartz monzonite porphyry of the Pine Valley Mountains; Tc = Claron Formation (Oligocene-Eocene); Kis = Iron Springs Formation (Cretaceous); Jc = Carmel Formation (Jurassic); Jn = Navajo Sandstone (Jurassic).
Our mapping reveals the following evidence regarding the controversy over the Pintura anticline.

1. In the north-central Pintura quadrangle, the Claron Formation depositionally overlies the Navajo Sandstone and Canaan Peak Formations in sections 27, 28, 33, and 34, T. 39 S., R. 13 W., but overlies the Carmel Formation both northeast and west of this area. The Claron Formation was, therefore, deposited above an angular unconformity developed on an erosionally beveled structural culmination. Where the Canaan Peak and Claron Formations unconformably overlie the Navajo Sandstone, erosion has removed more than 4,000 feet (1,220 m) of stratigraphic section, including all of the Upper Cretaceous Iron Springs Formation. This unconformity establishes the age of the structural culmination as between early and late Campanian time (about 84 to 72 Ma), the youngest known age of the Iron Springs Formation and the oldest known age of the Canaan Peak Formation, respectively (Goldstrand, 1992, 1994), but both dates are poorly constrained and are derived from outside the quadrangle. This culmination most likely formed either in the hinge zone of an anticline or along the trace of a reverse fault, and continued at least 5 miles (8 km) south to section 28, T. 40 S., R. 13 W., the southernmost exposure of the Canaan Peak Formation.

2. The Carmel Formation presently shows a reverse in dip direction in the north-central part of the Pintura quadrangle (plate 1) and the southern part of the New Harmony quadrangle (Grant, 1995). In the Pintura quadrangle the western limb, hinge zone, and eastern limb of the Pintura anticline are exposed in three distinct outcrop areas. In the western exposure area, in the NW1/4 of section 28 and the NE1/4 and south-central parts of section 29, T. 39 S., R. 13 W., the Carmel dips about 14 to 34 degrees west to west-northwest. In the central exposure area, in the N1/4 of section 28, T. 39 S., R. 13 W., the Carmel dips 10 to 35 degrees north-northwest to north-northeast, with considerable local variation in attitude. We interpret these exposures as the broad hinge zone of the Pintura anticline; this hinge zone contains several open parasitic folds but generally dips gently to the north. In the eastern outcrop area, in the NW1/4 of section 27, T. 39 S., R. 13 W., the Carmel dips about 10 to 12 degrees east to east-southeast, with local variations in attitude not shown on plate 1. High-angle normal faults cut both Jurassic and Tertiary units, accounting for some of the local structural variation in all three outcrop areas. As noted above, when the Claron Formation is rotated to horizontal, bedding in the exposed Carmel Formation everywhere restores to westward dips. If a pre-Hurricane fault Pintura anticline existed, its hinge is concealed beneath younger deposits east of present exposures of Mesozoic rocks.

3. The Claron Formation dips 15 to 30 degrees east and is cut by numerous normal faults, complicating the restoration of the Pintura anticline’s early Tertiary configuration.

Considering the evidence listed above, we are left with two plausible interpretations for the original configuration of the Pintura anticline during late Cretaceous to early Tertiary time. (1) The Pintura anticline was actually a west-facing homoclinal fold, formed as a reverse fault ramp or splay. This thrust fault flattened east of the homoclinal, then ramped upward again to form the Kanarra anticline. (2) The Pintura anticline was a broad anticline whose east limb formed the west limb of a syncline that separates the Pintura and Kanarra anticlines. We favor the second interpretation, mainly on the presence of the Late Cretaceous to early Paleocene structural culmination described above and lack of evidence of an associated reverse fault. Cross section A-A’ (plate 2) reflects this interpretation; in that section, the dip of the east limb of the Pintura anticline is poorly constrained and was modified from its original configuration by an unknown amount of reverse drag in the hanging wall of the Hurricane fault.

On the map we place the axial trace of the Pintura anticline along the present dip reversal in the Carmel Formation in the north-central part of the Pintura quadrangle, and continue it south along the outcrop belt of Canaan Peak Formation, recognizing that these features occupy a broad, poorly defined, composite hinge zone. Our axial trace is about 0.5 to 1 mile (0.8-1.6 km) east of that shown by Cary (1963). This hinge zone formed as a late Cretaceous-early Eocene contractional fold, and then was modified in the axis of a large-scale reverse-drag fold in the hanging wall of the Hurricane fault. This large-scale reverse drag is to us the most likely explanation for the eastward tilting of the Claron Formation.

**Kanarra Anticline**

The Kanarra anticline strikes northeast parallel to the Hurricane Cliffs in the east-central part of the Pintura quadrangle where it folds exposed Permian and Triassic units; the fold continues 30 miles (48 km) north to Cedar City (figure 1) (Gregory and Williams, 1947; Threet, 1963; Kurie, 1966; Averitt and Threet, 1973). Grant and others (1994) depicted the Kanarra anticline as a fault-propagation fold, related to an east-directed thrust fault in the subsurface.

The Hurricane fault truncates the Kanarra anticline just northeast of Anderson Junction (figure 5). The east limb and part of the crest of the fold are well exposed in the Hurricane Cliffs and in the LaVerkin Creek drainage. Near the top of the cliffs, Fossil Mountain strata generally dip 20 to 30 degrees east. Dips increase considerably down the east limb of the fold and beds are locally overturned. Only part of the west limb of the Kanarra anticline is preserved in the footwall of the Hurricane fault; near the fault, normal fault drag accentuates dips on the west limb. The axial plane of the Kanarra anticline probably dips steeply west.

The west-directed Taylor Creek thrust fault cuts the east limb of the Kanarra anticline and, in its best exposures at the
south end of Black Ridge, places the Lower Permian Fossil Mountain Member of the Kaibab Formation over the Lower Triassic lower red member of the Moenkopi Formation (figure 6). In the hanging wall of the Taylor Creek thrust fault in the eastern half of section 13, T. 40 S., R. 13 W., the lower Moenkopi and Kaibab Formations are overturned, and the middle red member of the Moenkopi Formation is tightly folded into northeast-trending anticlines and synclines. Several smaller east- and west-directed thrust faults displace the Virgin Limestone and middle red members of the Moenkopi Formation in the hanging wall of the Taylor Creek thrust fault. We interpret this overturning and small-scale folding as the result of deformation in the footwall of a small, east-directed thrust fault (cross section A-A’).

Older Tertiary Normal Faults

Older normal faults generally strike north to northeast, have relatively short traces, and include both southeast- and northwest-side-down displacement senses. The older normal faults cut pre-Quaternary units but are concealed by Quaternary surficial deposits. Most of the older faults are likely younger than about 21 million years, the age of the quartz monzonite porphyry of the Pine Valley Mountains, but some may be older (see following discussion in “Interpretation of the Quartz Monzonite Porphyry of the Pine Valley Mountains”). Older-generation faults in the east-central part of the quadrangle that cut the Jurassic Carmel Formation and Navajo Sandstone form a complex array, and the displacement on some of these faults may have included transcurrent and/or scissors-like motion. North-northeast-striking normal faults in the north-central part of the quadrangle include both west- and east-side-down displacement senses, and continue northward into the New Harmony quadrangle (Grant, 1995).

The largest and tectonically most important of the older normal faults is in the south-central part of the quadrangle, about 1 to 2 miles (1.5-3 km) northwest of Interstate 15, along the southeastern margin of the foothills of the Pine Valley Mountains (figure 4). This down-to-the-east fault is mostly concealed; it may comprise a single, continuous trace with subsidiary splays, or a fault zone consisting of several en echelon and roughly co-linear faults. On the map the fault is illustrated as a single trace and is dotted where concealed.

This fault or fault zone strikes north in its northernmost extent, and gradually curves to an east-northeast strike in its...
southwesternmost exposure; its trace length is about 6 miles (10 km). The northern part of the fault (in section 9, T. 40 S., R. 13 W.) juxtaposes a hanging wall composed of the upper part of the Navajo Sandstone, the overlying Canaan Peak and Claron Formations, and quartz monzonite porphyry of the Pine Valley Mountains against a footwall composed of the lower part of the Navajo Sandstone; this represents a stratigraphic separation of about 500 to 1,500 feet (150-460 m). A southern splay of this part of the fault displaces map unit Qafo (pre-Holocene) by approximately 100 to 150 feet (30-45 m), indicating continued motion or reactivation during Pleistocene time (figure 4). A small exposure at about 4,120 feet (1,255 m) elevation in an unnamed wash in section 21, T. 40 S., R. 13 W., juxtaposes a hanging wall of Claron Formation overlying the Canaan Peak Formation with a footwall of Navajo Sandstone. Stratigraphic displacement on this fault is difficult to determine given complex faulting of Navajo, Temple Cap, and Carmel strata 1 to 2 miles (1.5-3 km) to the west, absence of these beds east of the fault, and pre-Canaan Peak paleotopography developed on the Navajo Sandstone. Displacement is probably between a few hundred feet and 1,500 feet (up to 460 m).

This fault and another, subparallel but down-to-the-west fault about one mile (1.5 km) to the east together form a graben that bounds a large block of quartz monzonite porphyry of the Pine Valley Mountains in the center of the quadrangle, in the W1/2 sections 10 and 15, T. 40 S., R. 13 W. (figure 4). The eastern fault is exposed in an excavation (labeled a prospect near the center of section 15) where it places the quartz monzonite porphyry down on the west against the lower Claron Formation; farther north, the fault places the Claron Formation against the Navajo Sandstone.

Another fault is exposed in a gully east of the latter fault described in the preceding paragraph and immediately west of Interstate 15, in the west-central part of section 15, T. 40 S., R. 13 W. (plate 1). This east-side-down fault juxtaposes a hanging wall of quartz monzonite porphyry of the Pine Valley Mountains against a footwall of upper Claron Formation. Whereas the previously described faults have brittle deformation fabrics where exposed, the "gully fault" is a 3- to 4-foot-thick (1-3 m) mylonitic zone developed in the Claron Formation. The gully fault likely formed relatively shortly after intrusion of the quartz monzonite porphyry of the Pine Valley Mountains, accounting for the mylonitic crystal-plastic deformation fabrics. The extent and tectonic significance of the gully fault are uncertain.

**Hurricane Fault**

The Hurricane fault is a late Tertiary-Quaternary, west-side-down normal fault that strikes north to northeast and extends for about 160 miles (250 km) from the Grand Canyon, Arizona, to Cedar City, Utah (figure 1) (Huntington and Goldthwait, 1904; Dobbin, 1939; Gardner, 1941; Hamblin, 1965; Kurie, 1966; Anderson and Mehnert, 1979; Hamblin and others, 1981; Anderson and Christenson, 1989; Stewart and Taylor, 1996; Pearthree and others, 1998; Lund and others, 2001). The Hurricane fault lies near the base of the rugged Hurricane Cliffs. The Hurricane fault consists of
The bends, referred to as geometric-segment boundaries by Lund and Everitt, 1998; Higgins, reverse drag flexure is cut by numerous normal faults. Stewart and Taylor (1996) and as sections by straight sections were referred to as geometric segments by others (1998); Lund and others (2001) presented evidence that suggests that at least some of these segments/sections are true seismogenic segments. These geometric segments/sections are about 6 to 25 miles (10-40 km) long and consist of closely spaced, steeply dipping, sub-parallel normal faults. The bends, referred to as geometric-segment boundaries by Stewart and Taylor (1996) and section boundaries by Pearthree and others (1998), consist of broad, structurally complex zones of faulting and folding (Stewart and Taylor, 1996; Stewart and others, 1997). The Pintura quadrangle contains the southern part of the Ash Creek geometric segment of the Hurricane fault and part of its southern geometric-segment boundary (Stewart and Taylor, 1996; Lund and Everitt, 1998; Lund and others, 2001; Biek, 2003b).

Estimates of the timing and amount of displacement on the Hurricane fault differ, although it is generally accepted that stratigraphic separation increases from south to north (Gardner, 1941; Kurie, 1966; Anderson and Mehnert, 1979; Stewart and others, 1997). Most workers think that motion on the Hurricane fault began no earlier than early Miocene time, and Anderson and Mehnert (1979) suggested that motion did not begin until Pliocene or Pleistocene time.

Attempts to estimate tectonic throw on the Hurricane fault are greatly complicated by deformation near the fault trace, and because the fault cuts and modifies the hinge zone and west limb of the Kanarra anticline (Hamblin, 1965; Kurie, 1966; Anderson and Mehnert, 1979; Anderson and Christenson, 1989). In the Pintura quadrangle, Stewart and Taylor (1996) measured about 1,480 feet (450 m) of stratigraphic separation of geochemically correlated Quaternary basalt exposed in the hanging wall and footwall (figure 5). For pre-Tertiary rocks, Stewart and Taylor (1996) estimated about 8,250 feet (2,520 m) of stratigraphic separation and Hurlow (1998) illustrated about 2,800 to 5,000 feet (850-1,500 m) of stratigraphic separation on the southern part of the Ash Creek segment of the Hurricane fault. Based on our new mapping, projection of the footwall geology to the Hurricane fault above the present land surface on cross section A-A' indicates throw of about 10,000 feet (3,000 m) on the base of the Navajo Sandstone, due to the combined effects of displacement on the Hurricane fault and reverse drag and normal faulting in its hanging wall. This estimate depends strongly on assumptions about the geometry of eroded parts of the Kanarra anticline, the subsurface shape of the Hurricane fault, and the subsurface geometry of the hanging wall.

Deformation of the hanging wall of the Hurricane fault in the Pintura quadrangle is extensive. Quaternary basalt exhibits reverse drag along the length of the fault, as demonstrated by map relations and by paleomagnetic data discussed below. The basalt is thus folded into an asymmetric anticline whose ill-defined axis parallels the Hurricane fault. This reverse drag flexure is cut by numerous normal faults. Anderson and Christenson (1989) and Lund and Everitt (1998) documented several east-side-down fault scarps in Quaternary basalt and Pleistocene alluvial fans between the Hurricane fault and the eastern Pine Valley Mountains, and named this region the Ash Creek graben (figure 4).

Stewart and Taylor (1996) described a small reverse fault and anticline in Quaternary basalt within the segment boundary in the southern part of the Pintura quadrangle. As noted above, we interpret the east dip of the Claron Formation as evidence for large-scale reverse drag in the hanging wall of the Hurricane fault. Reverse drag forms in response to curvature of the fault plane, and the greater magnitude and extent of this folding in the Claron Formation than in the basalt is due to protracted, pre-Quaternary motion on the Hurricane fault.

**Interpretation of the Quartz Monzonite Porphyry of the Pine Valley Mountains**

Several masses of quartz monzonite porphyry of the Pine Valley Mountains lie 0.5 to 3 miles (0.8-5 km) west of Interstate 15 in the Pintura quadrangle. These outcrops are enigmatic because: (1) their basal contacts are about 3,000 feet (900 m) lower than the basal contact of the main body of the Pine Valley laccolith, (2) their basal contacts are structurally discordant with bedding in underlying sedimentary rocks, and (3) one of these masses locally overlies the lower part of the Iron Springs Formation. In contrast, the main mass of the Pine Valley laccolith, exposed about 5 miles (8 km) to the west in the Pine Valley Mountains, consistently intrudes the middle part of the Claron Formation parallel to bedding, which dips gently toward the center of the laccolith everywhere the intrusive contact is exposed (Cook, 1957, 1960; Hacker, 1998).

Three plausible interpretations explain these anomalous masses of the Pine Valley laccolith: (1) they are gravity-slide blocks, (2) they represent local, satellite intrusions of the Pine Valley laccolith, or (3) they are erosional remnants of the once-continuous laccolith, which originally extended at least as far east as the present location of Interstate 15. We do not believe that these masses are gravity-slide blocks, due to the absence of brecciation of the quartz monzonite porphyry along its basal contact except near known faults, and because subjacent sedimentary rocks locally display low-grade contact metamorphism similar to that observed along the base of the main laccolith body. Interpretations (2) and (3) seem equally plausible. Anderson and Mehnert (1979) first reported, and coauthor Biek mapped, deeply weathered blocks of quartz monzonite porphyry of the Pine Valley Mountains caught in the Hurricane fault near the Kolob Canyons (Biek, 2002a). Whether these blocks, and those in the Pintura quadrangle, were once part of a much larger laccolith, or are satellite intrusions, is unknown.

We interpret the angular discordance between the intrusive base and bedding in the underlying Claron Formation, and the local intrusion into the Iron Springs Formation, to reflect pre-intrusion faulting and related tilting. The best candidates for pre-quartz monzonite porphyry faults are in the west-central part of the quadrangle (see discussion of “Older Tertiary Normal Faults” above); one of these faults cuts the Claron, Iron Springs, and Carmel Formations but is truncated by the quartz monzonite porphyry, in section 18, T. 40 S., R. 13 W. There, the Claron Formation dips about 20 to 30 degrees northeast below the subhorizontal intrusive contact. The base of the large mass of quartz monzonite porphyry just west of Interstate 15 in the central part of the quadrangle dips gently southeast to south and is discordant.
with bedding in the underlying Claron Formation, which dips about 20 to 40 degrees east to southeast (section 15, T. 40 S., R. 13 W.). A pre-intrusion, west-side-down normal fault may be responsible for the dip of the Claron Formation and the repetition of section on either side of the quartz monzonite body; this fault was either covered (laccolith interpretation) or intruded (satellite intrusion interpretation) by the quartz monzonite porphyry.

If the masses of quartz monzonite porphyry of the Pine Valley Mountains are indeed in place, they owe their low structural position to the combined effects of post-intrusion faulting and large-scale reverse drag in the hanging wall of the Hurricane fault. Another possibility, difficult to prove, is that these masses intruded at lower structural levels than the main laccolith. As noted above, the largest mass occupies a graben between two older normal faults; the western fault accommodated about 500 feet (150 m) of throw.

**Discussion of Cross Section**

Cross section A-A' illustrates many aspects of the structure of the Pintura quadrangle described above, including the Kanarra and Pintura anticlines and a postulated intervening buried syncline, the Taylor Creek thrust and related faults, and the Hurricane fault with associated faulting and reverse drag in its hanging wall. Several features in cross section A-A' are poorly constrained. The curved geometry of the Hurricane fault is based on requirements of reverse drag as shown in cross sections drawn by Hamblin (1965). The dip of the fault near the surface is based on a single fault-plane exposure immediately southeast of Pintura, and by numerous exposures in the Hurricane quadrangle to the south, all of which indicate the fault dips 65 to 75 degrees near the surface (Biek, 2003b). The geometry of the eastern limb of the Pintura anticline and of the adjacent syncline are largely unknown, because no outcrops or subsurface data are available to constrain their location, shape, or magnitude.

All folds in cross section A-A' were constructed using the kink-band method (Suppe and Medwedeff, 1990), maintaining constant stratal thickness. The dip of Tertiary rocks in the hanging wall of the Hurricane fault is based on down-dip projection of the Claron Formation, which dips about 30 degrees east in its easternmost exposures. This approach creates up to about 2,800 vertical feet (850 m) of “space” between the top of the Claron Formation and the base of Quaternary basalt in the subsurface. We therefore assume that quartz monzonite porphyry of the Pine Valley Mountains, associated megabreccia deposits, and late Tertiary clastic deposits overlie the Claron Formation in the subsurface along the line of section. Several water-well logs (table 1 and figure 3) provide minimum estimates of the subsurface thickness of unconsolidated deposits and Quaternary basalt in the hanging wall of the Hurricane fault.

**QUATERNARY BASALT**

Quaternary basalt exposed on the hanging wall and footwall of the Hurricane fault in southwestern Utah and northwestern Arizona is useful in analyzing the displacement history and style of the Hurricane fault and the geomorphic evo-

<p>| Table 1. Water wells in the Pintura quadrangle. |</p>
<table>
<thead>
<tr>
<th>ID²</th>
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<th>Sec³</th>
<th>T³</th>
<th>R³</th>
</tr>
</thead>
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<td>25</td>
<td>39 S</td>
<td>13 W</td>
</tr>
<tr>
<td>2</td>
<td>S 500 W 500 E4</td>
<td>25</td>
<td>39 S</td>
<td>13 W</td>
</tr>
<tr>
<td>3</td>
<td>N 130 W 450 S4</td>
<td>26</td>
<td>39 S</td>
<td>13 W</td>
</tr>
<tr>
<td>4</td>
<td>S 1290 W 420 NE</td>
<td>2</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>5</td>
<td>S 510 W 550 E4</td>
<td>2</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>6</td>
<td>S 1553 E 800 W4</td>
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<td>13 W</td>
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<tr>
<td>7</td>
<td>S 1680 E 836 W4</td>
<td>1</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>8</td>
<td>S 1824 E 800 W4</td>
<td>1</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>9</td>
<td>N 5160 E 1390 SW</td>
<td>11</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>10</td>
<td>N 1948 E 135 SW</td>
<td>23</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>11</td>
<td>N 575 E 620 S4</td>
<td>22</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>12</td>
<td>S 235 E 135 N4</td>
<td>27</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>13</td>
<td>S 1135 W 825 N4</td>
<td>27</td>
<td>40 S</td>
<td>13 W</td>
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<tr>
<td>14</td>
<td>S 138 W 1188 N4</td>
<td>27</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>15</td>
<td>N 795 E 425 S4</td>
<td>28</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>16</td>
<td>N 428 E 540 S4</td>
<td>28</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>17</td>
<td>N 172 E 1137 SW</td>
<td>33</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>18</td>
<td>S 44 E 1151 NW</td>
<td>4</td>
<td>41 S</td>
<td>13 W</td>
</tr>
<tr>
<td>19</td>
<td>S 203 E 193 NW</td>
<td>4</td>
<td>41 S</td>
<td>13 W</td>
</tr>
<tr>
<td>20</td>
<td>S 605 W 183 NE</td>
<td>5</td>
<td>41 S</td>
<td>13 W</td>
</tr>
<tr>
<td>21</td>
<td>S 1180 E 505 NW</td>
<td>4</td>
<td>41 S</td>
<td>13 W</td>
</tr>
<tr>
<td>22</td>
<td>S 1650 W 125 NE</td>
<td>5</td>
<td>41 S</td>
<td>13 W</td>
</tr>
<tr>
<td>23</td>
<td>S 1131 W 375 N</td>
<td>5</td>
<td>41 S</td>
<td>13 W</td>
</tr>
<tr>
<td>24</td>
<td>S 1059 E 1863 N4</td>
<td>5</td>
<td>41 S</td>
<td>13 W</td>
</tr>
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<td>S 1345 E 1776 N4</td>
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<td>N 2513 W 1444 SE</td>
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<td>13 W</td>
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<td>28</td>
<td>N 2308 W 1526 SE</td>
<td>32</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>29</td>
<td>S 1000 E 1100 NW</td>
<td>32</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>30</td>
<td>S 541 E 217 NW</td>
<td>32</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>31</td>
<td>S 136 W 1364 E4</td>
<td>31</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>32</td>
<td>S 618 E 486 NW</td>
<td>5</td>
<td>41 S</td>
<td>13 W</td>
</tr>
<tr>
<td>33</td>
<td>S 1133 W 1062 NW</td>
<td>5</td>
<td>41 S</td>
<td>13 W</td>
</tr>
<tr>
<td>34</td>
<td>N 2958 E 1124 SW</td>
<td>31</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>35</td>
<td>S 132 W 1554 NE</td>
<td>1</td>
<td>41 S</td>
<td>14 W</td>
</tr>
</tbody>
</table>

**Notes:**

1. Data from Utah Division of Water Rights (http://waterrights.utah.gov).
2. Corresponds to number on figure 3.
3. Location is given in “Point of Diversion” (POD) notation.

NW, NE, SW, and SE refer to the northwest, northeast, southwest and southeast section corners, respectively.

N4, S4, E4, and W4 = midpoint of northern, southern, eastern, and western section boundary lines, respectively.

Sec = Section, T = midipoint of northern, southern, eastern, and western section boundary lines, respectively.

Example: well 1 is located 590 feet south and 129 feet west of the midpoint of the east boundary line of section 25 in T. 39 S., R. 13 W., relative to the Salt Lake Base Line and Meridian.
olution of the region (Hamblin, 1963, 1965; Anderson and Mehnert, 1979; Hamblin and others, 1981; Anderson and Christenson, 1989; Stewart and Taylor, 1996; Pearthree and others, 1998; Willis and others, 1999; Lund and others, 2001; Willis and Biek, in press). Lund and others (2001) used geochemical, geochronologic, and paleomagnetic investigations of Quaternary basalt adjacent to the Hurricane fault to calculate long-term slip rates, which we briefly summarize here.

Minor and trace element geochemistry shows that the basaltic flows in the Pintura quadrangle consist of three distinct geochemical groups, each of which is widely distributed and present on both sides of the Hurricane fault. These flows are part of the Pintura volcanic field, whose eruptive center is just west of Interstate 15 and just north of the Pintura quadrangle (Grant, 1995; Lund and Everitt, 1998). Smaller vents from outside of the flows yielded 40Ar/39Ar plateau ages of 0.04 Ma (Lund and others, 2001; Willis and others, 1999; Lund and others, 2001; Christenson, 1989; Stewart and Taylor, 1996; Biek, 2003b). Lund and others (2001) used geochemically correlated, dated basalt flows, and accounting for the effects of hanging-wall deformation, Lund and others (2001) determined a long-term slip rate for the Hurricane fault at the south end of Black Ridge of 0.018 inches/year (0.45 mm/yr); farther north, near Exit 36 on Interstate 15, they calculated a long-term slip rate of 0.023 inches/year (0.57 mm/yr).

**ECONOMIC RESOURCES**

Water is perhaps the most important and valuable resource in the Pintura quadrangle, considering the rapid population growth and arid climate of Washington County. Wells and springs in the quadrangle are shown on figure 3 and are listed in tables 1 and 2. Toquerville Springs provide culinary water to several public-supply entities. A well drilled by Washington County Water Conservancy District southwest of Anderson Junction in section 28, T. 40 S., R. 13 W. (well 15, table 1) produces water from the Navajo Sandstone. An aquifer test conducted by the U.S. Geological Survey yielded transmissivity estimates of 18,000 square feet per day (1,670 m^2/d) and 900 square feet per day (85 m^2/d) from two observation wells, each about 380 feet (115 m) deep, but in different directions, from the pumping well (Heilweil and others, 2000). Their results indicate strongly anisotropic hydraulic conductivity in the Navajo Sandstone, resulting from a dense array of joints and faults that cut the

---

**Table 2. Springs in the Pintura quadrangle.**

<table>
<thead>
<tr>
<th>ID</th>
<th>Name</th>
<th>CFS³</th>
<th>Point of Diversion⁴</th>
<th>Sec⁴</th>
<th>T⁴</th>
<th>R⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Deer Spring</td>
<td>0.013</td>
<td>N 4000 E 2400 SW</td>
<td>28</td>
<td>39 S</td>
<td>13 W</td>
</tr>
<tr>
<td>2</td>
<td>Blue Spring</td>
<td>0.015</td>
<td>N 2000 W 300 SE</td>
<td>19</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>3</td>
<td>Unnamed Spring</td>
<td>0.018</td>
<td>N 2600 W 2900 SE</td>
<td>31</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>4</td>
<td>Unnamed Spring</td>
<td>0.089</td>
<td>S 3070 W 1833 NE</td>
<td>5</td>
<td>41 S</td>
<td>13 W</td>
</tr>
<tr>
<td>5</td>
<td>Unnamed Spring</td>
<td>0.089</td>
<td>S 3145 W 1790 NE</td>
<td>5</td>
<td>41 S</td>
<td>13 W</td>
</tr>
<tr>
<td>6</td>
<td>Unnamed Spring</td>
<td>0.089</td>
<td>S 3210 W 1783 NE</td>
<td>5</td>
<td>41 S</td>
<td>13 W</td>
</tr>
<tr>
<td>7</td>
<td>Danish Ranch Domestic Spring/Stream</td>
<td>1.5</td>
<td>S 20 E 340 NW</td>
<td>4</td>
<td>41 S</td>
<td>13 W</td>
</tr>
<tr>
<td>8</td>
<td>Danish Ranch Domestic Spring/Stream</td>
<td>1.5</td>
<td>N 345 W 2120 E4</td>
<td>33</td>
<td>40 S</td>
<td>13 W</td>
</tr>
<tr>
<td>9</td>
<td>Toquerville Springs</td>
<td>1.97</td>
<td>N 2125 E 735 S4</td>
<td>35</td>
<td>40 S</td>
<td>13 W</td>
</tr>
</tbody>
</table>

Notes:
1. Data from Utah Division of Water Rights (http://nrwt1.nr.state.ut.us).
2. Corresponds to number on figure 3.
3. Water right in cubic feet per second.
4. Location is given in “Point of Diversion” (POD) notation.
   - NW, NE, SW, and SE refer to the northwest, northeast, southwest and southeast section corners, respectively.
   - N4, S4, E4, and W4 = midpoint of northern, southern, eastern, and western section boundary lines, respectively.
   - Sec = Section, T = Township, R = Range.
   - Example: spring 1 is located 4,000 feet north and 2,400 feet east of the southwest corner of section 28 in T. 39 S., R. 13 W., relative to the Salt Lake Base Line and Meridian.
unit (Cordova, 1978; Hurlow, 1998; Heilweil and others, 2000). Fractures are abundant in the Navajo Sandstone throughout the Pintura quadrangle, and likely formed during both Cretaceous and Tertiary-Quaternary deformation.

Several oil-test wells in the Pintura quadrangle tested Paleozoic and Mesozoic units along anticlinal folds (figure 3; table 3); none produced significant shows of oil or natural gas. Numerous gravel pits are in alluvial fans derived from the Pine Valley Mountains and Hurricane Cliffs. The Navajo Sandstone was quarried for local use as dimension stone in section 28, T. 40 S., R. 13 W., near Anderson Junction. The old town site and part of the White Reef mining district are in the southwest corner of the quadrangle. Biek (2003a, 2003b) reviewed the geology and history of the Silver Reef mining district. He also provided a more complete treatment of the geologic resources and geologic hazards of the Hurricane quadrangle to the south - much of that discussion is relevant to the Pintura quadrangle.

ACKNOWLEDGMENTS

This project was jointly funded by the Utah Geological Survey (UGS) and U.S. Geological Survey (USGS) under STATEMAP agreement No. 99HQAG0138. Hurlow mapped areas west of Interstate 15 and Utah Highway 17; Biek mapped areas to the east. Ernie Anderson (USGS) graciously shared his knowledge of the area, and spent a day in the field discussing structurally complex parts of the quadrangle. We also thank Bill Lund (UGS) and Ben Everitt (Utah Division of Water Resources) for sharing their knowledge of the Hurricane fault and Pintura basalt flow. We appreciate the very thorough reviews of Ernie Anderson (USGS), Pete Rowley (USGS), Doug Sprinkel (UGS), and Mike Hylland (UGS); Sandy Eldredge, Bill Lund, Bryce Tripp, and Janae Wallace, each with the UGS, also reviewed portions of the report.
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APPENDIX

Radiometric ages for basalt samples AC-1 and ACG-1

Introduction

In this appendix we report radiometric-age data for two whole-rock samples of Quaternary basalt in the Pintura quadrangle. Lund and Everitt (1998) reported the ages, but not the analytical data, for these samples. The New Mexico Geochronology Research Laboratory (NMGRL) in Socorro, New Mexico, performed the analyses on samples provided by W.R. Lund of the Utah Geological Survey. The methods, descriptions, interpretations, data tables, and diagrams presented below are reproduced from reports submitted by the NMGRL to Lund and Ben Everitt of the Utah Division of Water Rights. The two reports had slightly different formats, reflected in the sections below.

Sample AC-1

Summary

Results for sample AC-1 were reported to Everitt by Lisa Peters of the NMGRL on June 10, 1998. The interpreted age for a groundmass concentrate sample is 0.84 ± 0.03 Ma from a nearly concordant age spectrum with -96% of the 39Ar released to define the plateau.

Methods

The basalt samples were crushed, sieved, treated with HCl, washed in distilled water and hand-picked to remove phenocrysts, alteration, and other extraneous material. The groundmass concentrates were then placed in machined Al discs along with interlaboratory standard Fish Canyon Tuff (Age = 27.84 Ma) as the neutron flux monitor. After sealing stacked Al discs in an evacuated quartz tube, samples and monitors were irradiated for 3 hours (N-83) in the L-67 position of the Ford Reactor at the Phoenix Memorial Laboratory, Ann Arbor, Michigan.

Following irradiation, samples and monitors were placed within an automated ultra-high vacuum extraction system where they were heated using resistance-furnace or laser methods to extract argon. Individual crystals of monitor sanidine were placed in a copper planchet and fused with a 10W Synrad CO2 continuous laser. Evolved gases were purified of reactive species for two minutes using two GP-50 SAES getters, one operated at ~450°C, the other operated cold. The groundmass concentrates were step-heated in a double-vacuum Mo resistance furnace. Evolved gases were purified during heating with a SAES GP-50 getter operated at ~450°C for seven minutes, followed by ten minutes of cleanup using two additional GP-50 getters, one operated at ~450°C and the other operated cold. Argon isotopic compositions were analyzed by a MAP 215-50 mass spectrometer operated in static mode. Argon isotopes were detected by an electron multiplier with an overall sensitivity of about 1 x 10^6 moles/pA for the furnace. Extraction systems and mass spectrometer blanks and backgrounds were measured numerous times throughout the course of the analyses. Typical furnace blanks [were] 2 to 5 x 10^-18 moles at masses 40, 39, 38, 37, and 36. J-factors were determined to a precision of ± 0.1% (2σ) by analyzing 4 single crystal aliquots from each of 6 radial positions around the irradiation vessel. Correction factors for interfering nuclear reactions were determined using K- and Ca-rich glasses and salts (Table A.1). The reported ages are calculated by using the inverse variance as the weighting scheme and the errors are calculated using the method of Samson and Alexander (1987). All errors are reported at the two-sigma confidence level. The decay constant and isotopic abundances are those suggested by Steiger and Jäger (1977).

Results

Results are detailed in Table A.1 and are presented graphically in figure A.1. The furnace incremental heating data are displayed in figure A.1. The age spectrum is constructed using the assumption that trapped argon has the isotopic composition of modern atmosphere (40Ar/36Ar = 295.5). Age spectra plot apparent age of each incrementally heated gas fraction versus the cumulative %39Ar released, with steps increasing in temperature from left to right. Where appropriate, other parameters for each of the heating steps are also plotted versus the cumulative %39Ar released. These auxiliary parameters, which aid interpretation of age spectra, include radiogenic yield (percent of 40Ar which is not atmospheric) and K/Ca (determined from measured Ca-derived 37Ar and K-derived 39Ar). Interpretation of age spectra can be complicated due to such problems as excess argon, alteration, contamination, 39Ar recoil, and argon loss. An entirely or partially flat spectrum, in which apparent ages are the same within analytical error, may indicate that the sample is homogeneous with respect to K and Ar and has had a simple thermal and geological history. Some geochronologists use the term "plateau" to describe such flat age segments. Here we define "plateau" as three or more contiguous incrementally heated gas fractions that agree within error and together contain at least 50% of the total 39ArK released (Fleck and others, 1977). We calculate the "plateau age" by weighting each step on the plateau by the inverse of its variance (Samson and Alexander, 1987). This ensures that the heating steps with the lowest analytical error will dominate the final age calculation. Some inhomogeneous and/or hydrous samples such as hornblende and micas may yield relatively flat spectra that fail to meet strict plateau criteria. In these cases, a preferred age is calculated for the indicated steps using the same method used for the plateau age determinations.

Sample ACG-1

Summary

Results for sample ACG-1 were reported to Lund by Richard Esser of the NMGRL on July 5, 2000. The interpreted age for a groundmass concentrate sample is 0.81 ± 0.10 Ma from a nearly concordant age spectrum with nearly 100% of the cumulative 39ArK released defining the plateau. Table A.2 describes the analytical methods, and table A.3 and figure A.2 present the results.
Table A.1. Furnace isotopic data for AC-1.

<table>
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<tr>
<th>ID</th>
<th>Temp (°C)</th>
<th>40Ar/39Ar</th>
<th>37Ar/39Ar</th>
<th>36Ar/39Ar</th>
<th>39ArK</th>
<th>K/Ca</th>
<th>40Ar*</th>
<th>39Ar</th>
<th>Age (Ma)</th>
<th>±2σ (Ma)</th>
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</thead>
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Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interfering reactions. Individual analyses show analytical error only; mean age errors also include error in J and irradiation parameters. Analyses in italics are excluded from mean age calculations.

Correction factors:

\[
\frac{\text{Ar}_{38}}{\text{Ar}_{37}}_{\text{K}} = 0.0003 \pm 0.0002
\]

\[
\frac{\text{Ar}_{36}}{\text{Ar}_{37}}_{\text{K}} = 0.0119
\]

\[
\frac{\text{Ar}_{40}}{\text{Ar}_{39}}_{\text{K}} = 0.0340 \pm 0.0100
\]

Table A.2. Methods for laser fusion and laser step-heating analyses.

Sample preparation and irradiation:

Samples provided by William Lund.

Groundmass concentrate prepared using standard techniques (crushing, sieving, magnetic separation, and hand-picking).

Samples packaged and irradiated in machined Al discs for 1 hour in D-3 position. Texas A&M Research Reactor.

Neutron flux monitor Fish Canyon Tuff sanidine (FC-1). Assigned age = 27.84 Ma (Deino and Potts, 1990) relative to Mmhb-1 at 520.4 Ma (Samson and Alexander, 1987).

Instrumentation:

Mass Analyzer Products 215-50 mass spectrometer on line with automated all-metal extraction system.

Bulk aliquots of groundmass concentrate were step-heated by a 50-watt CO₂ laser using a beam integrator lens.

Reactive gases removed during a 10 minute reaction with 2 SEAS GP-50 getters, 1 operated at −450°C and 1 at 20°C. Gas also exposed to a W filament operated at −2000°C and a cold finger operated at −140°C.

Analytical parameters:

Electron multiplier sensitivity averaged 1.5 x 10⁻⁶ moles/pA.

Total system blank and background averaged 478, 0.6, 0.4, 0.4, 2.3 x 10⁻⁷ moles.

J-factors determined to a precision of ±0.1% by CO₂ laser-fusion of 4 single crystals from each of 6 radial positions around the irradiation tray.

Correction factors for interfering nuclear reactions were determined using K-glass and CaF₂ are as follows:

\[
\frac{\text{Ar}_{40}}{\text{Ar}_{39}}_{\text{K}} = 0.0002 \pm 0.0003; \quad \frac{\text{Ar}_{36}}{\text{Ar}_{37}}_{\text{K}} = 0.00026 \pm 0.000007; \quad \text{and } \frac{\text{Ar}_{39}}{\text{Ar}_{37}}_{\text{K}} = 0.0007 \pm 0.00005.
\]

Age calculations:

Weighted mean age calculated by weighting each age analysis by the inverse of the variance.

Weighted mean error calculated using the method of Taylor (1982).

Decay constants and isotopic abundances following Steiger and Jäger (1977).

All final errors reported at ±2σ, unless otherwise noted.
### Table A.3. Analytical results for ACG-1 groundmass concentrates.

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### Notes:
- Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interfering reactions.
- Individual analyses show analytical error only; plateau and total gas age errors include error in J and irradiation parameters.
- Analyses in italics are excluded from final age calculations.

**AC-1**

- **Integrated Age**: 0.84±0.03
- **K/Ca**
- **Apparent Age Ma**
- **Cumulative % 39Ar Released**

**Figure A.1.** $^{40}$Ar/$^{39}$Ar age spectrum for sample AC-1.
Figure A.2. $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum and inverse isochron for groundmass concentrate ACG-1. The plateau age ($0.81 \pm 0.10 \text{ Ma}$) is the preferred age for the sample.