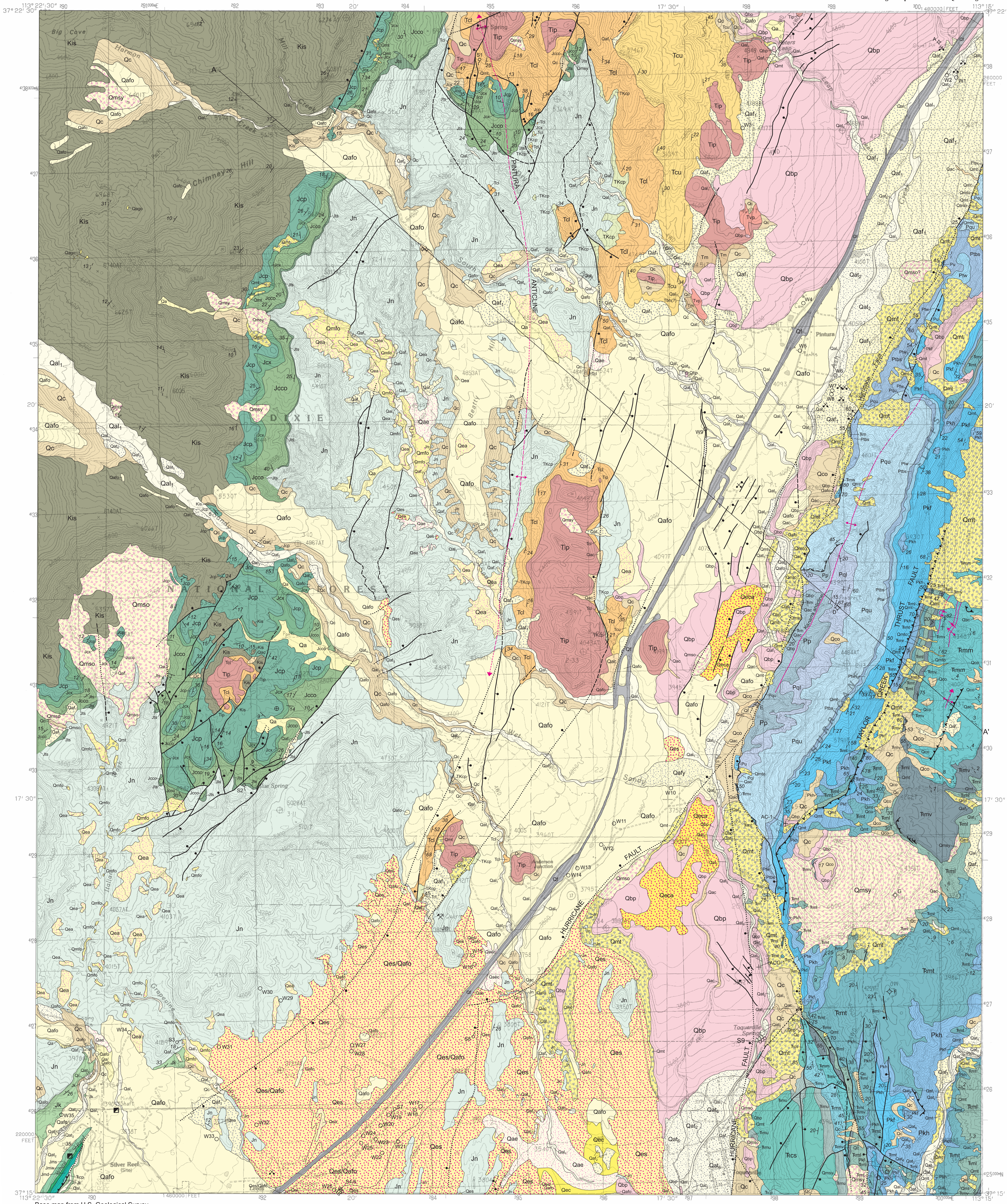
UTAH GEOLOGICAL SURVEY
a division of the
Utah Department of Natural Resources



Base map from U.S. Geological Survey
Pintura 7.5' Quadrangle, 1986

Lori J. Douglas, cartographer

SCALE 1 : 24,000
1 1/2 0 1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 .5 0 1 KILOMETER
CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

13°
231 mils
2003 MAGNETIC DECLINATION
AT CENTER OF SHEET

UTAH
QUADRANGLE LOCATION

1	2	3
4		5
6	7	8

1 Grass Valley
2 New Harmony
3 Kolob Arch
4 Signal Peak
5 Smith Mesa
6 Harrisburg Junction
7 Hurricane
8 Virgin

ADJOINING 7.5' QUADRANGLE NAMES

Research funded by the Utah Geological Survey and the U.S. Geological Survey National Cooperative Geologic Mapping Program, through USGS STATEMAP award number 99HQAG0138.

GEOLOGIC MAP OF THE PINTURA QUADRANGLE, WASHINGTON COUNTY, UTAH

by

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and
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2003

DESCRIPTION OF MAP UNITS

QUATERNARY

Qa Alluvial deposits - *Poorly to well-sorted boulder to pebble gravel, sand, silt, and clay deposited in stream channels and flood plains and on alluvial fans at the mouths of small tributary drainages. Mapped on the flanks of the Pine Valley Mountains where stream and alluvial-fan deposits are too small to differentiate. Up to 15 feet (5 m) thick.*

Qal_1 Stream deposits - *Moderately to well-sorted gravel, sand, silt, and clay; includes channel, flood-plain, local small alluvial-fan and colluvial deposits, and stream-terrace deposits less than 10 feet (<3 m) above modern base level. Up to 25 feet (8 m) thick.*

Qat_{2-6} Stream-terrace deposits - *Moderately to well-sorted alluvial gravel, sand, silt, and clay that form level to gently sloping surfaces above modern drainages. Subscript denotes relative age and height above modern drainages: level 2 deposits (youngest) are about 10 to 30 feet (3-9 m), level 3 deposits are about 30 to 55 feet (9-17 m), level 4 deposits are about 55 to 95 feet (17-29 m), level 5 deposits are about 95 to 130 feet (29-40 m), and level 6 deposits (oldest) are over 130 feet (40 m) above adjacent streams. Level 6 deposits near Toquerville are based on mapping in the adjacent Hurricane quadrangle and therefore do not correspond to this numbering scheme. Individual terrace levels are not necessarily correlative in age with those same levels across the Hurricane fault. Deposited principally in stream-channel and flood-plain environments. Up to 30 feet (9 m) thick; deposits near Toquerville may be somewhat thicker.*

Qago Older stream gravel - *Well-sorted pebble gravel exposed as small erosional remnants at about 6,700 feet (2,040 m) elevation in the northwestern part of the quadrangle. Clasts are rounded and include quartzite, chert, and quartz monzonite porphyry of the Pine Valley Mountains. Correlation with other alluvial deposits uncertain. Probably deposited in stream-channel environment. Up to about 10 feet (3 m) thick.*

Qaf_{1-2} Alluvial-fan deposits - *Poorly sorted, boulder- to clay-size sediment deposited at the base of the Hurricane Cliffs and locally at the mouths of active drainages. Clast composition differs widely and reflects lithologies of local upstream drainage basins. Subscript denotes relative age and height above modern drainages: level 1 fan deposits (youngest) form active depositional surfaces, whereas level 2 fan deposits (oldest) are deeply incised and now lie up to 50 feet (15 m) above modern channels. Up to about 50 feet (15 m) thick.*

Qafy Younger alluvial-fan deposits - *Poorly sorted, subangular to subrounded boulders, gravel, sand, and silt. Mapped at the distal end of Wet Sandy Wash where it likely includes sediment equivalent to both level 1 and level 2 alluvial-fan deposits. Up to several tens of feet thick.*

Qafo Older alluvial-fan deposits - *Poorly sorted, subangular to subrounded boulders, gravel, sand, and silt. Most clasts are derived from the quartz monzonite porphyry of the Pine Valley Mountains and are as much as 20 feet (6 m) in diameter; other clast types include rounded, iron-stained quartzite pebbles, and clasts from Claron, Iron Springs, Carmel, and Navajo strata. Deposited on broad, gently east- to southeast-sloping surfaces at the base of the Pine Valley Mountains that are deeply incised by modern drainages. Equivalent to map units Qaf_5 and Qaf_6 as mapped in the Hurricane quadrangle (Biek, 2003b). Up to about 150 feet (45 m) thick.*

Qf Artificial fill - *Engineered fill used to create the roadbed of Interstate 15 and, locally, adjacent frontage roads, and a single exposure of general borrow material used to create a level drilling platform. Although we mapped only the larger deposits, fill should be anticipated in all built-up areas, many of which are shown on the topographic base map. Up to several tens of feet thick.*

Qc, Qco Colluvial deposits - *Poorly to moderately sorted, locally derived gravel, sand, and soil obscuring bedrock and older Quaternary units; locally includes talus and alluvial deposits. Deposited principally by slope wash and soil creep on moderate slopes. Where present below unit Qafo, contains Pine Valley monzonite boulders up to 20 feet (6 m) in diameter. Older colluvial deposits (Qco) are deeply incised, and both units are each generally less than 10 feet (3 m) thick.*

Qes Eolian sand deposits - *Well- to very well-sorted, fine- to medium-grained quartz sand typically deposited by wind at the base of steep outcrops or in areas of extensive exposures of Navajo Sandstone, from which the sand is derived. May include slopewash and colluvial deposits composed of locally derived, reworked eolian sand and coarser sediment from nearby outcrops. Generally less than about 15 feet (5 m) thick.*

Qmt, Qmto Talus deposits - *Poorly sorted, angular boulders and lesser fine-grained interstitial sediments deposited principally by rock fall on and at the base of steep slopes. Locally includes and is gradational with colluvial deposits. Older talus deposits (Qmto) are deeply incised and largely inactive. Both units are each generally less than about 40 feet (12 m) thick.*

Qmsy, Qmso Landslide deposits - *Poorly sorted, clay- to boulder-sized, locally derived material deposited by rotational and translational downslope movement. Younger deposits (Qmsy), including landslides that may have historical movement, are characterized by hummocky topography, numerous subdued internal scarps, and chaotic bedding attitudes. Older deposits (Qmso) are deeply incised by active stream channels and their main scarps and hummocky topography have been extensively modified by erosion. Slip surfaces of both units are principally in the Moenkopi, Chinle, and Iron Springs Formations. Thickness highly variable.*

Qmfo Debris-flow deposits - *Poorly sorted, chaotic mixture of gravel and boulders in clay- to sand-size matrix. Extensively modified by erosion, deeply dissected by modern stream channels, and locally overlain by younger alluvial and eolian deposits. Deposits in Dry Sandy wash are up to 50 feet (15 m) thick and are composed entirely of Iron Springs Formation clasts; deposits in Grapevine Wash are about 3 to 10 feet (1-3 m) thick and are composed entirely of Carmel Formation clasts.*

Qac Alluvial and colluvial deposits - *Poorly to moderately sorted, clay- to boulder-size sediments deposited in swales and small drainages. Gradational with both alluvial and colluvial deposits. Generally less than about 20 feet (6 m) thick.*

Qae, Qaec Alluvial and eolian deposits – *Poorly to moderately sorted, clay- to boulder-size sediment with well-sorted eolian sand and reworked eolian sand. Younger (Qae) deposits are in active drainages and broad depressions; older (Qaec) deposits have white to pale gray caliche up to 3 feet (1 m) thick. Generally less than 20 feet (6 m) thick.*

Qea Eolian and alluvial deposits - *Well-sorted, fine- to medium-grained eolian sand forming dunes, and poorly to moderately sorted gravel, sand, and silt deposited in fans and channels. Eolian deposits are dominant. Mapped where deposits are either gradational or interbedded at too fine a scale to map individually. Ranges from about 10 to 30 feet (3-10 m) thick.*

Qec Eolian and colluvial deposits – *Well-sorted eolian sand that overlies and is intermixed with colluvium derived from reworking of older alluvial-fan deposits. Generally less than 20 feet (6 m) thick.*

Qeca Eolian and alluvial deposits with thick carbonate soil on basalt flow - *Thin cover of ancestral Ash Creek gravels on top of Pintura lava flows (Qbp), partly concealed by eolian silt and sand; includes well-developed pedogenic carbonate. Generally less than a few feet thick.*

Qes/Qafo Eolian sand over older alluvial-fan deposits - *Well-sorted eolian sand over older alluvial-fan deposits. Mapped where eolian deposits are too thin or too small to show separately, or otherwise conceal underlying older alluvial-fan deposits. May include considerable slopewash deposits adjacent to Navajo outcrops.*

Qa/Qafo Alluvium over older alluvial-fan deposits - *Moderately to well-sorted stream and alluvial-fan deposits derived principally from reworking of older alluvial-fan deposits. Mapped in the Leeds Creek drainage where younger alluvial channels are too small to show individually.*

Qbp Pintura flows - *Medium- to dark-gray basalt with fine- to medium-grained phenocrysts of olivine and plagioclase; geochemically divisible into three groups: basalt, trachybasalt, and borderline basaltic trachyandesite to basaltic andesite. Groundmass contains microscopic plagioclase, pyroxene, olivine and glassy to microcrystalline material. Flow units typically have highly vesicular tops and brecciated bases. Erupted principally from the Pintura volcanic center, north of the Pintura quadrangle in sections 24 and 25, T. 39 S., R. 13 W. Yielded $^{40}Ar/^{39}Ar$ whole-rock ages of 0.89 ± 0.02 Ma, 0.84 ± 0.03 Ma, 0.88 ± 0.05 Ma, 0.81 ± 0.10 Ma, and 0.87 ± 0.04 Ma (appendix) (Lund and others, 2001; Biek, 2003b). Individual flow units are generally 3 to 20 feet (1-6 m) thick, with total accumulations up to 1,140 feet (350 m) thick.*

unconformity

TERTIARY

Tvp Pine Valley latite – *Medium- to pale-gray volcanic mudflow breccia composed of angular clasts of latite in highly brecciated, glassy groundmass of same composition. Latite clasts contain medium- to coarse-grained phenocrysts of plagioclase, sanidine, and pyroxene. The latite overlies the monzonite of the Pine Valley Mountains in section 35, T. 39 S., R. 13 W. Approximately 100 feet (30 m) thick.*

Tip Quartz monzonite porphyry of the Pine Valley Mountains - *Medium-gray, ranging to orange-, lavender-, and green-gray, quartz monzonite porphyry with medium- to coarse-grained phenocrysts of plagioclase, clinopyroxene, biotite, sanidine, and orthopyroxene. Groundmass is composed of fine-grained to microscopic plagioclase and pyroxene crystals and cryptocrystalline material. Locally flow layered. Forms sills intruding the middle part of Claron Formation and, in sections 13 and 19, T. 40 S., R. 13 W., the upper part of Iron Springs Formation. Also forms a brecciated dike discordantly intruding a gravity-slide megabreccia deposit composed of mid-Tertiary volcanic rocks (map unit Tm) in the northwest part of section 2, T. 40 S., R. 13 W. Up to 450 feet (135 m) thick in map area; upper contact is not exposed. West of the Pintura quadrangle in the Pine Valley Mountains, the quartz monzonite porphyry of the Pine Valley Mountains forms a laccolith up to 3,330 feet (1,000 m) thick that intruded the Claron Formation (Cook, 1957, 1960; Hacker, 1998). McKee and others (1997) reported a concordant, early Miocene K-Ar age of 20.9 ± 0.6 Ma on biotite for a sample from the central part of the laccolith, located about 6 miles (9 km) west-northwest of Pintura. Hacker (1998) reported $^{40}Ar/^{39}Ar$ ages of 20.66 ± 0.13 Ma on biotite and 20.47 ± 0.04 Ma on potassium feldspar from the basal glass zone, and 20.53 ± 0.07 Ma on biotite and 20.32 ± 0.08 Ma on sanidine from the brown zone.*

unconformity

Tm Megabreccia - *Faulted and locally brecciated, chaotically distributed masses of Harmony Hills Tuff, Bauers Tuff Member of the Condor Canyon Formation, Leach Canyon Formation, and Claron Formation, undivided. Formed as a gravity slide derived from the actively uplifting roof of the 21 million-year-old Pine Valley laccolith (Cook, 1960; Blank and others, 1992; Hacker, 1998). Bauers Tuff Member of the Condor Canyon Formation is resistant, reddish-brown to pinkish-red, densely welded ash-flow tuff, with fine- to medium-grained phenocrysts of plagioclase, sanidine, biotite, and magnetite. Matrix is microcrystalline to cryptocrystalline devitrified glass shards with conspicuous pale-gray fiamme. Derived from the Caliente caldera complex (Rowley and others, 1995). McKee and others (1997) reported an early Miocene K-Ar age of 22.6 ± 0.6 Ma on biotite from a sample of the Bauers Tuff Member from the Bull Valley Mountains, about 14 miles (22 km) west of Pintura. About 40 feet (12 m) thick. Leach Canyon Formation is pale-pink to pinkish-gray, poorly welded ash-flow tuff with medium- to coarse-grained phenocrysts of plagioclase, quartz, sanidine, and biotite. Matrix is microcrystalline to cryptocrystalline devitrified glass shards. Contains angular fragments of red, gray, and pale-green flow rock with fine-grained phenocrysts of plagioclase, quartz, sanidine, biotite, and magnetite. Flattened pumice lenticles are lined with white secondary minerals and surrounded by pale-gray to white alteration halos. Rowley and others (1995) summarize K-Ar ages of the formation; the most likely age is 23.8 Ma based on preliminary $^{40}Ar/^{39}Ar$ ages (Best and others, 1993). About 100 feet (30 m) thick. Harmony Hills Tuff is light-tan to medium-gray, welded crystal-rich ash-flow tuff containing plagioclase, biotite, hornblende, quartz, pyroxene, and minor magnetite; yielded a K-Ar age of 20.5 Ma (Armstrong, 1970).*

unconformity

Tbh(?) Brian Head Formation(?) - *Interbedded sandstone, shale, and tuff. Sandstone is medium-gray to greenish-gray, fine- to medium-grained, tuffaceous litharenite to sublitharenite; mudstone and shale are pale olive gray to pale gray to reddish brown, with moderately to poorly defined lamination; tuff is moderately indurated with orange-pink, microcrystalline to cryptocrystalline groundmass and fine- to medium-grained sanidine, plagioclase, quartz, and biotite phenocrysts. About 30 feet (9 m) thick. A single outcrop of these rocks is present in a stream-cut bank of Dry Wash in section 34, T. 39 S., R. 13 W. These rocks are tentatively correlated with the Brian Head Formation based on their position above the Claron Formation, and on their similarity to exposures in the west-central Red Hills, about 22 miles (35 km) north-northeast of Cedar City, and on Brian Head, about 13 miles (21 km) east of Cedar City. The rocks in the Red Hills were mapped by Maldonado and Williams (1993a, 1993b) as the informally named "sedimentary and volcanic rocks of Red Hills," and they were incorporated into the Brian Head Formation (revised) by Sable and Maldonado (1997). The Brian Head Formation (revised) is late Eocene to middle Oligocene in age, based on isotopic ages of ash-flow tuffs from the upper part of the formation and overlying units, and on palynological ages from the underlying Claron Formation (Sable and Maldonado, 1997).*

Claron Formation

Tcu Upper member - *White to pale-gray, resistant limestone interbedded with pale-gray to pinkish-gray, clay-rich mudstone; limestone has moderately well- to poorly defined bedding, and includes unfossiliferous micrite, fine-grained bioclastic calcarenite, and pelletal calcarenite; calcite-filled veins are common. Deposited in fluvial and lacustrine environments, possibly extensively modified by post-depositional bioturbation and pedogenic processes (Mullet and others, 1988a, 1988b; Mullet, 1989; Taylor, 1993). The contact between the lower and upper members is mapped where gray to pinkish-gray mudstone of the upper member overlies bright red-orange mudstone of the lower member. The Claron Formation is late Paleocene to late Eocene(?) or early Oligocene in age based on paleontological and palynological data (Goldstrand, 1994). About 520 feet (160 m) thick.*

Tcl Lower member - *Interbedded mudstone, siltstone, sandstone, conglomerate, and limestone. Mudstone is orange-red to red-brown and clayey to silty, and contains thin beds of resistant, reddish-brown siltstone. Sandstone is tan to brown, medium- to coarse-grained, cross-bedded to structureless litharenite; sandstone grades into, or is locally incised by, limestone-quartzite-chert-clast pebble conglomerate that is clast supported, very thick bedded, and in discrete channels up to 3 feet (1 m) thick. The lower to middle part of the lower member contains very resistant micrite with sparse shell fragments that is stained orange, pink, tan, lavender, and yellow; bedding is poorly defined and 2 to 5 feet (0.6-1.5 m) thick. This micrite contains vugs about 0.5 to 1 inch (1.3-2.5 cm) in diameter filled with coarse crystalline calcite and surrounded by a yellow alteration halo. The upper part of the lower member contains medium-gray, resistant micrite to calcarenite with moderately to well-defined, medium to thin bedding; bivalve shell fragments are common, and many layers contain pellets, oncolites, and calcite-filled veins and vugs. The base of the lower member is late Paleocene in age (Goldstrand, 1994). About 1,090 feet (330 m) thick.*

TERTIARY-CRETACEOUS

TKcp Canaan Peak Formation - *Conglomerate with minor interbedded sandstone and mudstone. Conglomerate is reddish brown, contains pebble- to cobble-sized, rounded clasts of quartzite, welded dacitic to andesitic volcanic tuff, chert, and sandstone, is clast supported, and is typically structureless although faint pebble imbrication is locally present. Clasts include tan, purple, gray, rusty brown, and black, structureless to cross-bedded quartzite; sandstone that is pale gray to tan gray, fine to medium grained, and well cemented; and welded tuff containing medium- to fine-grained feldspar (altered) and quartz phenocrysts in a gray, pale-green, orange-tan, or purple-brown, devitrified groundmass. Goldstrand (1992) correlated the volcanic clasts with Jurassic volcanic rocks exposed in southeastern California. The sandstone is reddish-brown, medium- to coarse-grained, structureless to weakly laminated litharenite in 0.5- to 1-foot-thick (0.2-0.3 m) beds. The mudstone is present near the base and top of the formation, and is reddish brown and finely laminated. Preserved in paleochannels on the Navajo Sandstone (Goldstrand, 1992) along a structural culmination interpreted here as the hinge zone of the Pintura anticline. Palynomorphs collected from the Canaan Peak Formation on the Table Cliff plateau in south-central Utah indicate a late Campanian to early Paleocene age (Goldstrand, 1994). Thickness ranges from 0 to 119 feet (0-36 m).*

unconformity

CRETACEOUS

Kis Iron Springs Formation - *Interbedded mudstone, sandstone, conglomerate, and thin sandy coquina beds, in order of decreasing abundance. The lower approximately 100 feet (30 m) of the formation consists of red to gray mudstone with a single, 1- to 30-foot-thick (0.3-10 m) layer of conglomerate and coarse sandstone; the remainder of the formation consists of interbedded sandstone and mudstone, with rare beds of conglomerate and sandstone-matrix coquina. The mudstone ranges from tan, medium gray, greenish gray, reddish gray, to reddish brown, and is weakly laminated to structureless. The sandstone is tan to brown, locally altered to white or reddish brown, fine to coarse grained, and weakly laminated to planar or trough cross-bedded, with highly contorted laminations and small petrified wood fragments; composition ranges from quartz arenite to litharenite (Fillmore, 1991; Goldstrand, 1992). The conglomerate contains rounded to subrounded, moderately to well-sorted pebble- to cobble-size clasts of quartzite, limestone, lithic fragments, and chert, in decreasing order of abundance. The coquina beds are tan to medium brown, 0.5 to 1 foot (0.2-0.3 m) thick, and contain disarticulated, broken bivalve and gastropod shells in a medium-grained sand matrix. The Iron Springs Formation was deposited in a sandy braidplain environment (Fillmore, 1991), and is Cenomanian to Santonian or early Campanian in age (Goldstrand, 1994). It is up to 3,500 feet (1,070 m) thick in the southeastern Pine Valley Mountains (Cook, 1960); the lower 3,200 feet (975 m) is exposed in the northwest part of the Pintura quadrangle.*

K unconformity

JURASSIC

Carmel Formation

Jcp Paria River Member - *Interbedded, pale- to medium-gray, platy weathering, thin- to medium-bedded, silty to clayey micrite to fine-grained calcarenite with sparse bivalve fossils; pale-gray to greenish-gray, massive to poorly laminated silty micrite; and pale-yellowish-gray, calcareous mudstone. Deposited in a shallow-marine environment (Imlay, 1980). Upper contact is defined by hard, platy, calcareous siltstone overlain by reddish-brown, weakly consolidated mudstone of the Iron Springs Formation. Ranges from about 360 to 680 feet (110-210 m) thick.*

Jcx Crystal Creek Member - *Poorly exposed brown to reddish-brown, locally gypsiferous mudstone that contains sparse bivalve fossils. Typically covered by talus of platy, clayey limestone of the Paria River Member. Deposited in coastal sabkha and tidal-flat environments (Imlay, 1980). Upper contact corresponds to the top of red-brown, typically poorly exposed, gypsiferous mudstone, which is overlain by hard, platy, calcareous siltstone of the Paria River Member. Ranges from about 100 to 190 feet (30-60 m) thick.*

Jcco Co-op Creek Limestone Member - *Interbedded, pale-greenish-gray calcareous mudstone to siltstone and clayey micrite, and tan, sandy bioclastic limestone to calcareous sandstone containing disarticulated bivalve mollusks, including oyster shells, and, locally,* Isocrinus *sp. (formerly* Pentacrinus*) crinoid columnals. Siltstone and micrite have moderately to poorly defined bedding and are resistant; mudstone forms slopes and is poorly exposed; and tan, sandy, bioclastic limestone to calcareous sandstone marks the top of the member. Deposited in a shallow-marine environment (Imlay, 1980). Ranges from about 300 to 450 feet (90-135 m) thick.*

J-2 unconformity

Temple Cap Formation

Jts Sinawava Member - *Lower part is reddish-brown gypsiferous mudstone interbedded with sandstone and siltstone and local massive gypsum; upper part is pale-pinkish-gray, gypsiferous mudstone to siltstone. Deposited in coastal-sabkha and tidal-flat environments (Blakey, 1994; Peterson, 1994). Ranges from about 10 to 50 feet (3-15 m) thick. Shown as a line where too thin to map separately.*

J-1 unconformity

Jn Navajo Sandstone - *Pale-reddish-orange, reddish-brown, or white, fine- to medium-grained eolian sandstone (quartz arenite). Characterized by large-scale cross-bedding and well-rounded quartz grains that have frosted surfaces. The lower 100 to 150 feet (30-45 m) is composed of interbedded, fine-grained sandstone, siltstone, and shale that vary from internally structureless to moderately laminated, with gently wavy to flaser-like laminae and soft-sediment deformation features including flame and load structures; reddish-brown, fissile to very thick-bedded siltstone and fine-grained sandstone; and 1- to 3-foot-thick (0.3-1 m) beds of eolian sandstone. Sansom (1992) interpreted this part of the Navajo to have been deposited in a sabkha, representing a transition from fluvial deposition of the underlying Kayenta Formation to eolian deposition of the main part of the Navajo Sandstone. Upper contact characterized by orange to pale-gray, cross-bedded eolian sandstone overlain by deep-reddish-brown, structureless to poorly bedded sandstone and gypsiferous siltstone of the Temple Cap Formation. About 2,300 feet (700 m) thick.*

Jk Kayenta Formation - *Interbedded, reddish-brown to orange-red, thin- to medium-bedded, fine-grained sandstone, siltstone, and mudstone with planar and ripple laminae; a thin, pale gray-weathering dolomite bed is also present. Deposited in distal river, playa, and minor lacustrine environments (Sansom, 1992; Blakey, 1994; Peterson, 1994). Only the upper 455 feet (140 m) is exposed in section 1, T. 41 S., R. 12 W., in the southwest part of the quadrangle. The Kayenta Formation is 925 feet (282 m) in the adjacent Harrisburg Junction quadrangle (Biek, 2003a).*

Moenave Formation

Jm Moenave Formation, undivided - *shown on cross section only.*

Jms Springdale Sandstone Member – *Medium- to very thick-bedded, fine-grained or rarely medium-grained sandstone, with planar and low-angle cross-stratification, and minor, thin, discontinuous lenses of intraformational conglomerate and thin interbeds of moderate-reddish-brown or greenish-gray mudstone and siltstone; contains locally abundant petrified and carbonized fossil plant remains. Forms rounded cliffs and ledges at the northwest end of White Reef and is host to the ore deposits of the Silver Reef mining district. Deposited in braided-stream and minor flood-plain environments (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998). The upper contact is conformable and corresponds to the first appearance of thin-bedded, reddish-brown, fine-grained silty sandstone that overlies very thick-bedded, rounded-weathering Springdale Sandstone. About 100 feet (30 m) thick.*

Jmw Whitmore Point Member - *Interbedded, pale-reddish-purple, greenish-gray, and blackish-red mudstone and claystone, lesser moderate-reddish-brown, very fine- to fine-grained sandstone and siltstone, and uncommon dark-yellowish-orange micaceous siltstone and very fine- to fine-grained, very pale-orange sandstone. Contains several 3- to 18-inch-thick (8-45 cm), bioturbated, cherty, dolomitic limestone beds with algal structures and fossil fish scales of* Semionotus kanabensis *(Hesse, 1935; Schaeffer and Dunkle, 1950); the dolomitic limestones range in color from light greenish gray to very light gray and yellowish gray, and weather to mottled colors of pale yellowish orange, white, yellowish gray, and pinkish gray, commonly with green copper-carbonate stains. The lower 25 feet (8 m) of the member consists of reddish-brown sandstones similar to those of the Dinosaur Canyon Member. The Whitmore Point Member weathers to poorly exposed, brightly colored slopes at the northeast end of White Reef. The Whitmore Point Member is unconformably overlain by the Springdale Sandstone, with local channeling and mudstone rip-up clasts present at the contact. Deposited in flood-plain and lacustrine environments (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998). About 60 feet (18 m) thick.*

Jmd Dinosaur Canyon Member - *Interbedded, generally thin-bedded, moderate-reddish-brown to moderate-reddish-orange, very fine- to fine-grained sandstone, very fine-grained silty sandstone, and lesser siltstone and mudstone with planar, low-angle, and ripple cross-stratification. Forms a slope at the northeast end of White Reef. The contact with the Whitmore Point Member is conformable and gradational and corresponds to the base of a 6- to 18-inch-thick (16-46 cm), light-gray, bioturbated, dolomitic limestone with algal structures and reddish-brown chert blebs. About 25 feet (8 m) of brown sandstone typical of the Dinosaur Canyon Member overlies the dolomitic limestone and is included in the Whitmore Point Member. Deposited in fluvial and flood-plain environments (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998). About 200 feet (60 m) thick.*

J-0 unconformity

TRIASSIC

Ɍu Chinle and Moenkopi Formations, undivided – *May include Petrified Forest, or lower, middle, or upper red strata caught in the Hurricane fault near Toquerville Springs.*

Chinle Formation

Ɍcp Petrified Forest Member - *Variably colored mudstone, claystone, siltstone, lesser sandstone and pebbly sandstone, and minor chert and nodular limestone. Swelling bentonitic mudstones and claystones are common throughout and although typically poorly exposed, their bright purple, grayish-red, dark-reddish-brown, light-greenish-gray, brownish-gray, olive-gray, and similar hues locally show through to the surface. Bentonitic mudstones weather to a "popcorn" surface and are responsible for numerous foundation problems in the region. The member commonly forms slumps, especially along steep hillsides. Only the lower part of the member is exposed east of Toquerville, and the upper part at White Reef. The upper contact corresponds to the first appearance of reddish-brown, non-bentonitic siltstone and fine-grained sandstone, below which lies brightly colored swelling mudstones with nodular limestone. Deposited in a variety of fluvial, flood-plain, and lacustrine environments (Stewart and others, 1972; Dubiel, 1994; DeCourten, 1998). About 400 feet (120 m) thick.*

Ɍcs Shinarump Conglomerate Member - *Laterally and vertically variable sequence of cliff-forming, fine- to very coarse-grained sandstone, pebbly sandstone, and lesser pebbly conglomerate; clasts are subrounded quartz, quartzite, and chert. Mostly thick to very thick bedded with both planar and low-angle cross-stratification, although thin, platy beds with ripple cross-stratification occur locally. Predominantly pale- to dark-yellowish orange, but pale-red, grayish-red, very pale-orange, and pale-yellow-brown hues are common; locally stained by iron-manganese oxides, forming "picture stone." Contains poorly preserved petrified wood and plant debris, commonly replaced in part by iron-manganese oxides. Exposed in the southeast corner of the quadrangle east of Toquerville. The upper contact corresponds to the first appearance of varicolored, swelling mudstone. Deposited in braided streams that flowed north and northwest (Stewart and others, 1972; Dubiel, 1994; DeCourten, 1998). About 120 feet (37 m) thick.*

TR-3 unconformity

Moenkopi Formation

Ɍm Moenkopi Formation, undivided - *West-dipping, fault-bounded blocks of lower, middle, or upper red member strata along the Hurricane fault. Also used for the entire formation on the west part of cross section A-A'.*

Ɍmu Upper red member - *Interbedded, mostly thin- to medium-bedded, moderate-reddish-orange to moderate-reddish-brown siltstone, mudstone, and very fine- to fine-grained sandstone with planar, low-angle, and ripple cross-stratification; well-preserved ripple marks are common. Forms ledgy slopes and cliffs in fault-bounded blocks east of Toquerville. The upper, unconformable contact shows minor channeling at the base of the Shinarump Conglomerate. Deposited in a tidal-flat environment (Stewart and others, 1972; Dubiel, 1994). About 200 feet (60 m) thick.*

Ɍms Shnabkaib Member - *Forms "bacon-striped," ledgy slopes of laminated to thin-bedded, gypsiferous, pale-red to moderate-reddish-brown mudstone and siltstone, resistant, white to greenish-gray gypsum, and lesser thin, laminated, light-gray dolomite beds. Gypsum is present as laterally continuous, structureless beds, finely laminated, commonly silty or muddy beds, and nodular intervals that range from less than one inch to about 9 feet (0.01-3 m) thick; gypsum also is present as secondary cavity fillings and cross-cutting veins. The member weathers to soft, punky, gypsiferous soils, and is present in fault-bounded blocks east of Toquerville. Upper, conformable and gradational contact corresponds to the top of the highest thick gypsum bed. Deposited in a variety of supratidal, intertidal, and subtidal environments on a broad, coastal shelf of very low relief (Lambert, 1984). About 350 feet (110 m) thick.*

Ɍmm Middle red member - *Interbedded, laminated to thin-bedded, moderate-reddish-brown to moderate-reddish-orange siltstone, mudstone, and very fine-grained sandstone; white to greenish-gray gypsum beds and veins are common, and lower part includes several thick gypsum beds. Forms slopes along the east side of the Hurricane Cliffs. Upper, conformable and gradational contact corresponds to the base of the first thick gypsum bed. Deposited in a tidal-flat environment (Stewart and others, 1972; Dubiel, 1994). About 200 feet (60 m) thick.*

Ɍmv Virgin Limestone Member - *Very pale-orange to yellowish-gray, finely crystalline limestone and silty limestone; light-gray to light-olive-gray, coarsely crystalline, fossiliferous limestone with locally abundant circular and five-sided crinoid columnals, gastropods, and brachiopods; and siltstone and mudstone. Mudstone and siltstone have variable gray, yellowish-gray, and grayish-purple hues. Forms three limestone ledges separated by poorly exposed mudstone slopes on the east side of the Hurricane Cliffs. Upper, conformable contact corresponds to the top of the uppermost Virgin limestone bed. Deposited in a variety of shallow-marine environments (Dubiel, 1994). About 120 to 270 feet (37-82 m) thick.*

Ɍml Lower red member - *Interbedded, laminated to thin-bedded, moderate-reddish-brown mudstone and siltstone with local, thin, laminated, light-olive-gray gypsum beds and veinlets. Forms slopes on the east side of the Hurricane Cliffs and fault blocks east of Toquerville. Upper, unconformable contact corresponds to the base of the first Virgin limestone bed. Deposited in a tidal-flat environment (Stewart and others, 1972; Dubiel, 1994). About 250 to 315 feet (75-95 m) thick.*

Ɍmt Timpoweap Member - *Lower part consists of light-brown-weathering, light-gray, thin- to thick-bedded limestone and cherty limestone; chert occurs as small disseminated blebs, thus giving weathered surfaces a very rough texture. Upper part consists of grayish-orange, thin- to thick-bedded, slightly calcareous, very fine-grained sandstone, siltstone, and mudstone. Both parts weather to low cliffs and ledges and form a gently undulating surface on top of the Permian-Triassic unconformity. Exposed along the east side of the Hurricane Cliffs. Upper contact is conformable and gradational and corresponds to a change from yellowish-brown, fine-grained sandstone, siltstone, and minor limestone below to reddish-brown siltstone and mudstone above. Deposited in a shallow-marine environment (Nielson and Johnson, 1979; Dubiel, 1994). Ranges from 50 to 180 feet (15-55 m) thick (Nielson, 1981).*

Ɍmr Rock Canyon Conglomerate Member - *Consists of two main rock types: a pebble to cobble, clast-supported conglomerate with rounded chert and minor limestone clasts derived from the Harrisburg Member of Kaibab Formation, which was deposited in paleovalleys and is 0 to about 100 feet (0-30 m) thick; and a thin, unmapped but widespread angular breccia 0 to 10 feet (0-3 m) thick, which probably formed as a regolith deposit on Harrisburg strata (Nielson, 1991). Conformably and gradationally overlain by limestone of the Timpoweap Member.*

TR-1 unconformity

PERMIAN

Pu Kaibab Formation, Toroweap Formation, and Queantoweap Sandstone, undivided - *Fault-bounded, highly fractured and brecciated blocks of Kaibab, Toroweap, and Queantoweap strata along the Hurricane fault.*

Kaibab Formation

Pkh Harrisburg Member - *Thin- to thick-bedded limestone and cherty limestone and minor medium- to very thick-bedded, laminated gypsiferous mudstone; forms ledgy slopes that enclose a resistant, cliff- and ledge-forming medial white chert and limestone interval. The medial limestone includes medium-gray cherty limestone breccia and coarsely crystalline limestone; laminated, thin-bedded, brown-weathering, medium-gray, slightly fetid limestone; grayish-orange-pink intraformational limestone conglomerate; grayish-orange-pink to pinkish-gray oncolitic limestone; and fine- to medium-crystalline limestone with abundant light-brown to moderate-reddish-brown weathering, light-gray chert nodules and lenticular beds with sparse silicified fenestrae bryozoans. Typically forms steep slopes on the east side of the Hurricane Cliffs. Unconformably overlain by Rock Canyon Conglomerate river-channel and breccia deposits. Deposited in a complex sequence of shallow-marine and sabkha environments (McKee, 1938; Nielson, 1981, 1986; Sorauf and Billingsley, 1991). Ranges from 120 to 180 feet (37-55 m) thick (Nielson, 1981).*

Pkf Fossil Mountain Member - *Lithologically uniform, light-gray, thick- to very thick-bedded, fossiliferous limestone and cherty limestone; fossils are whole brachiopods, broken bryozoans, and disarticulated crinoids. The member is "black-banded" due to abundant reddish-brown, brown, and black chert; ribbon chert and irregular chert nodules locally make up 30 to 40 percent of the rock. Forms prominent cliff at or near the crest of the Hurricane Cliffs. Conformable contact with Harrisburg strata corresponds to a sharp break in slope. Deposited in a shallow-marine environment (McKee, 1938; Nielson, 1981, 1986; Sorauf and Billingsley, 1991). About 240 to 280 feet (73-85 m) thick (Nielson, 1981).*

Toroweap Formation

Ptw Woods Ranch Member - *Laterally variable, interbedded, yellowish-gray to light-gray, laminated to thin-bedded dolomite, black chert, massive gypsum, gypsiferous mudstone, and limestone; contains local intraformational conglomerate and collapse breccia. Forms steep slope just below top of the Hurricane Cliffs. Contact with Fossil Mountain strata corresponds to a sharp break in slope with slope-forming, gypsiferous siltstone and thin limestone beds below and cliff-forming cherty limestone above. Deposited in a complex sequence of shallow-marine and sabkha environments (McKee, 1938; Rawson and Turner-Peterson, 1979; Nielson, 1981, 1986). About 120 to 250 feet (37-75 m) thick (Nielson, 1981).*

Ptbs Brady Canyon and Seligman Members, undivided - *The Brady Canyon Member is lithologically uniform, light- to medium-gray, medium- to coarse-grained, thick- to very thick-bedded fossiliferous limestone and cherty limestone; fossils are broken brachiopods, bryozoans, and crinoids. Ribbon chert and irregular chert nodules locally make up 30 to 40 percent of the rock. Forms prominent gray cliff, similar to that developed in Fossil Mountain strata, in the upper part of the Hurricane Cliffs. Contact with Woods Ranch strata is unconformable and corresponds to a sharp break in slope, with cliff-forming cherty limestone below and slope-forming, gypsiferous siltstone and thin limestone beds above. Deposited in a shallow-marine environment (McKee, 1938; Rawson and Turner-Peterson, 1979; Nielson, 1981, 1986). About 220 to 255 feet (67-78 m) thick (Nielson, 1981). The Seligman Member forms slopes of yellowish-brown to grayish-orange, very thin- to thin-bedded, planar-bedded, very fine- to medium-grained sandstone and minor siltstone with brown-weathering nodular chert. The contact with the Brady Canyon Member corresponds to a sharp break in slope, with slope-forming, thin-bedded sandstone below and cliff-forming cherty limestone above. Deposited in shallow-marine and beach environments (McKee, 1938; Rawson and Turner-Peterson, 1979; Nielson, 1981, 1986). About 30 feet (9 m) thick.*

Queantoweap Sandstone

Pqu Upper member of Queantoweap Sandstone - *Yellowish-brown to grayish-orange, very thick-bedded, cross-bedded, fine-grained noncalcareous sandstone (quartz arenite). Forms the bulk of the Hurricane Cliffs with a conspicuous stair-step topography. The contact with the Seligman Member corresponds to a subtle break in slope, with ledge- and cliff-forming cross-bedded sandstone below and slope- and ledge-forming, planar-bedded sandstone above. Deposited in shallow-marine, beach, and dune environments (Nielson, 1981). About 1,300 to 1,630 feet (400-500 m) thick.*

Pql Lower member of Queantoweap Sandstone - *Consists of three main parts of approximately equal thickness: (1) lower slope-forming, brown-weathering, brownish-gray, thin- to medium-bedded, very fine-grained sandy dolomite; (2) middle cavernous- and vuggy-weathering, very thick-bedded, yellowish-brown calcareous sandstone - these vuggy beds are locally reddish brown, include sedimentary and karst-like breccias, and weather to a prominent ledge; and (3) upper slopes of yellowish-brown, and minor reddish-brown, thin- to medium-bedded, very fine- to fine-grained calcareous sandstone and silty sandstone. The contact with the upper member of the Queantoweap Sandstone is sharp and corresponds to the first appearance of very thick-bedded, cross-bedded, noncalcareous sandstone. Probably deposited in a shallow-marine environment. About 120 feet (37 m) thick near the south end of the Pintura quadrangle. The thickness to the north is uncertain due to structural complexity along the axis of the Kanarra anticline; outcrop patterns there suggest a thickness of up to 800 feet (245 m).*

Pp Pakoon Formation - *Light- to medium-gray, thin- to very thick-bedded dolomite, dolomitic limestone, and minor limestone, all with local, yellowish-brown-weathering, light-gray to white, irregularly shaped chert nodules. Contains sparse macrofossils in upper beds, including crinoid columnals, and a thin bed of white chert near the top of the formation. Forms ledges in the lower part of the Hurricane Cliffs. Upper contact appears sharp and corresponds to the first appearance of thin-bedded, yellowish-brown-weathering, sandy dolomite beds. Deposited in a shallow-marine environment. Only the upper 250 feet (75 m) exposed.*

Subsurface Units

PIPc Callville Limestone - *shown only on cross section.*

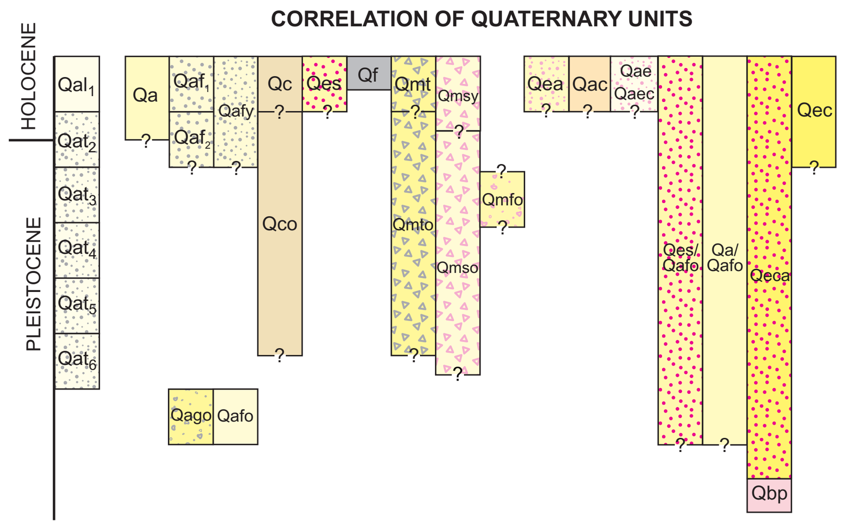
Mr Redwall Limestone - *shown only on cross section.*

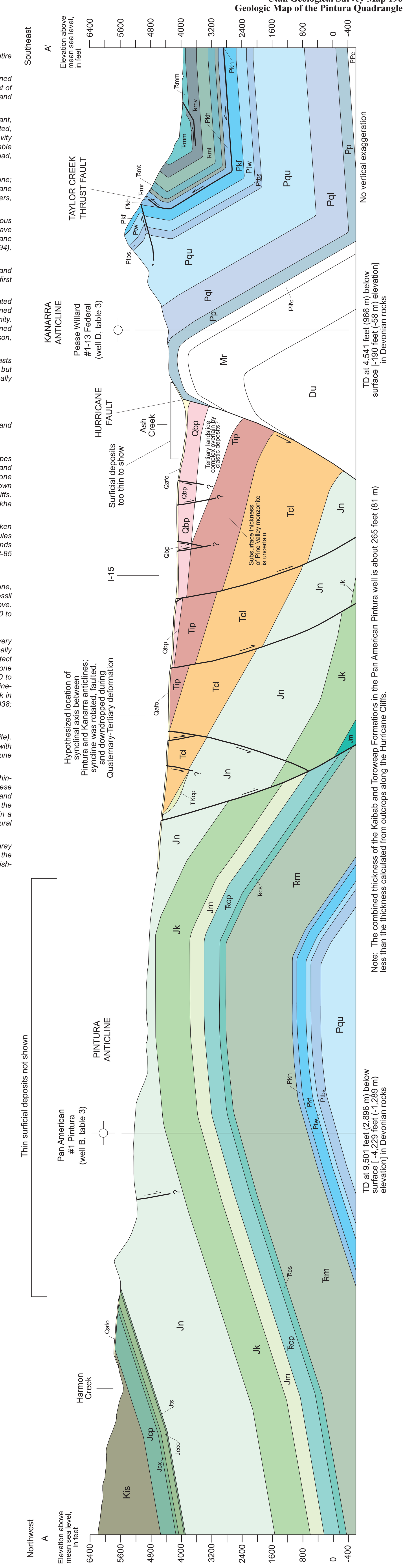
Du Devonian, undivided - *shown only on cross section.*

MAP SYMBOLS

Contact	
65	High-angle normal fault, dashed where approximately located, dotted where concealed; bar and ball on down-thrown side; arrow indicates dip of exposed fault surface
	Low-angle normal fault; open teeth on upper plate
?	Thrust fault, dotted where concealed, queried where uncertain; teeth on upper plate
	Axial trace of anticline, showing direction of plunge; dashed where approximately located, dotted where concealed
	Axial trace of syncline
	Axial trace of overturned syncline
35	Strike and dip of inclined bedding
13	Approximate strike and dip of inclined bedding determined from aerial photography
	Approximate strike and dip direction of inclined bedding
	Strike of vertical bedding
20	Strike and dip of overturned bedding
	Pit - sand and gravel
	Quarry
X	Prospect
	Mine shaft
	Spring (see also figure 3 and table 2)
W32	Water well (see also figure 3 and table 1)
A	Petroleum exploration drill hole - plugged and abandoned (see also table 3)
	Sinkhole
ACG-1	Sample location and number

CORRELATION OF QUATERNARY UNITS





LITHOLOGIC COLUMN

TIME STRAT. UNIT		FORMATION		SYMBOL	THICKNESS feet (m)	LITHOLOGY
Quaternary		Surficial deposits		Q	0-150+ (0-45+)	
Quaternary		Pintura flows		Qbp	0-1,140 (0-350)	0.81-0.89 Ma (see appendix)
Miocene	Lower	Pine Valley latite		Tvp	~100 (~30)	K-feldspar megacrysts
Miocene	Lower	Quartz monzonite porphyry of the Pine Valley Mountains		Tip	450+ (135+)	20.32-20.66 Ma
Miocene	Lower	Megabreccia		Tm	~150 (~45)	fault-bounded, brecciated Tertiary volcanic rocks
Oligocene		Brian Head Formation (?)		Tbh?	~30 (~9)	
Eocene		Claron Formation	upper	Tcu	520 (160)	
Eocene		Claron Formation	lower	Tcl	1,090 (330)	intruded by Pine Valley Mtns. quartz monzonite porphyry
Paleocene		Canaan Peak Formation		TKcp	0-119 (0-36)	quartzite and volcanic clasts
Cretaceous	Upper	Iron Springs Formation		Kis	3,200+ (975+)	intruded by Pine Valley Mtns. quartz monzonite porphyry; soft-sediment deformation; cross-bedding
Jurassic	Middle	Carmel Formation	Paria River Member	Jcp	360-680 (110-210)	
Jurassic	Middle	Carmel Formation	Crystal Creek Member	Jcx	100-190 (30-60)	
Jurassic	Middle	Carmel Formation	Co-op Creek Limestone Member	Jcco	300-450 (90-135)	
Jurassic	Lower	Temple Cap Formation		Jts	10-50 (3-15)	gypsum

TIME STRAT. UNIT			FORMATION		SYMBOL	THICKNESS feet (m)	LITHOLOGY
Jurassic	Lower		Navajo Sandstone		Jn	~2,300 (~700)	high-angle cross beds; transition zone
Jurassic	Lower		Kayenta Formation		Jk	~455+ (~140+)	
Jurassic	Lower		Moenave Formation	Springdale Sandstone Member	Jms	~100 (~30)	Silver Reef mining district
Jurassic	Lower		Moenave Formation	Whitmore Point Member	Jmw	~60 (~18)	*Semionotus kanabensis*
Jurassic	Lower		Moenave Formation	Dinosaur Canyon Member	Jmd	~200 (~60)	
Triassic	Upper	Ɍu Chinle and Moenkopi Formations, undivided	Chinle Formation	Petrified Forest Member	Ɍcp	~400 (~120)	swelling, brightly colored clays
Triassic	Upper	Ɍu Chinle and Moenkopi Formations, undivided	Chinle Formation	Shinarump Conglomerate Member	Ɍcs	~120 (~37)	
Triassic	Middle	Ɍu; Ɍm Moenkopi Formation, undivided	Moenkopi Formation	upper red member	Ɍmu	~200 (~60)	
Triassic	Lower	Ɍu; Ɍm Moenkopi Formation, undivided	Moenkopi Formation	Shnabkaib Member	Ɍms	~350 (~110)	"bacon-striped" gypsum
Triassic	Lower	Ɍu; Ɍm Moenkopi Formation, undivided	Moenkopi Formation	middle red member	Ɍmm	~200 (~60)	
Triassic	Lower	Ɍu; Ɍm Moenkopi Formation, undivided	Moenkopi Formation	Virgin Limestone Member	Ɍmv	120-270 (37-82)	3 limestone ledges
Triassic	Lower	Ɍu; Ɍm Moenkopi Formation, undivided	Moenkopi Formation	lower red member	Ɍml	250-315 (75-95)	
Triassic	Lower	Ɍu; Ɍm Moenkopi Formation, undivided	Moenkopi Formation	Timpoweap Member	Ɍmt	50-180 (15-55)	
Triassic	Lower	Ɍu	Moenkopi Formation	Rock Canyon Conglomerate Member	Ɍmr	0-100 (0-30)	
Permian	Lower	Pu Kaibab Formation, Toroweap Formation, and Queantoweap Sandstone, undivided	Kaibab Formation	Harrisburg Member	Pkh	120-180 (37-55)	gypsum
Permian	Lower	Pu	Kaibab Formation	Fossil Mountain Member	Pkf	240-280 (73-85)	white chert "black-banded"
Permian	Lower	Pu	Toroweap Formation	Woods Ranch Member	Ptw	120-250 (37-76)	
Permian	Lower	Pu	Toroweap Formation	Brady Canyon & Seligman Members	Ptbs	250-285 (76-87)	
Permian	Lower	Pu	Queantoweap Sandstone	upper member	Pqu	1,300-1,630 (400-500)	forms stairstep topography
Permian	Lower	Pu	Queantoweap Sandstone	lower member	Pql	120-800 (37-245)	
Permian	Lower		Pakoon Formation		Pp	250+ (75+)	
Pennsylvanian			Callville Limestone		PIPc	285 (85)	Subsurface, shown only on cross section A-A'
Mississippian			Redwall Limestone		Mr	1,220 (370)	Subsurface, shown only on cross section A-A'
Devonian			Devonian, undivided		Du	570+ (175+)	Subsurface, shown only on cross section A-A'

Research funded by the Utah Geological Survey and the U.S. Geological Survey National Cooperative Geologic Mapping Program, through USGS STATEMAP award number 99HQAG0138.

GEOLOGIC MAP OF THE PINTURA QUADRANGLE, WASHINGTON COUNTY, UTAH

by

Hugh A. Hurlow and Robert F. Biek

This geologic map was funded by the Utah Geological Survey and the U.S. Geological Survey, National Cooperative Geologic Mapping Program through STATEMAP Agreement No. 99HQAG0138

ISBN 1-55791-596-2

MAP 196
Utah Geological Survey
a division of
Utah Department of Natural Resources

2003

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by

Hugh A. Hurlow and Robert F. Biek

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 contractional 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

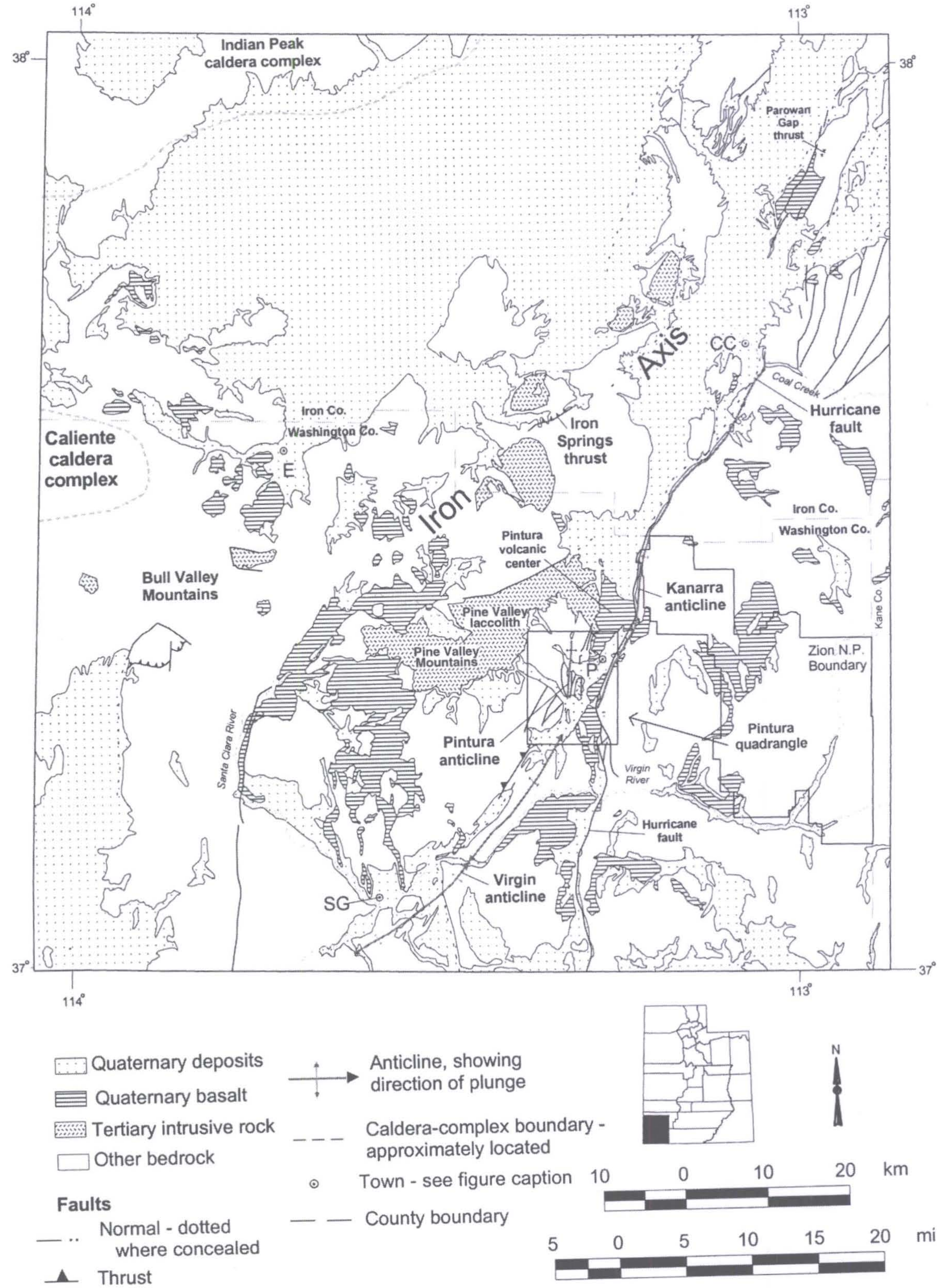

Figure 1. Generalized geologic map of southwestern Utah in the vicinity of the Pintura quadrangle, after Hintze and others (2000). Towns: CC = Cedar City; E = Enterprise; P = Pintura; and SG = St. George.

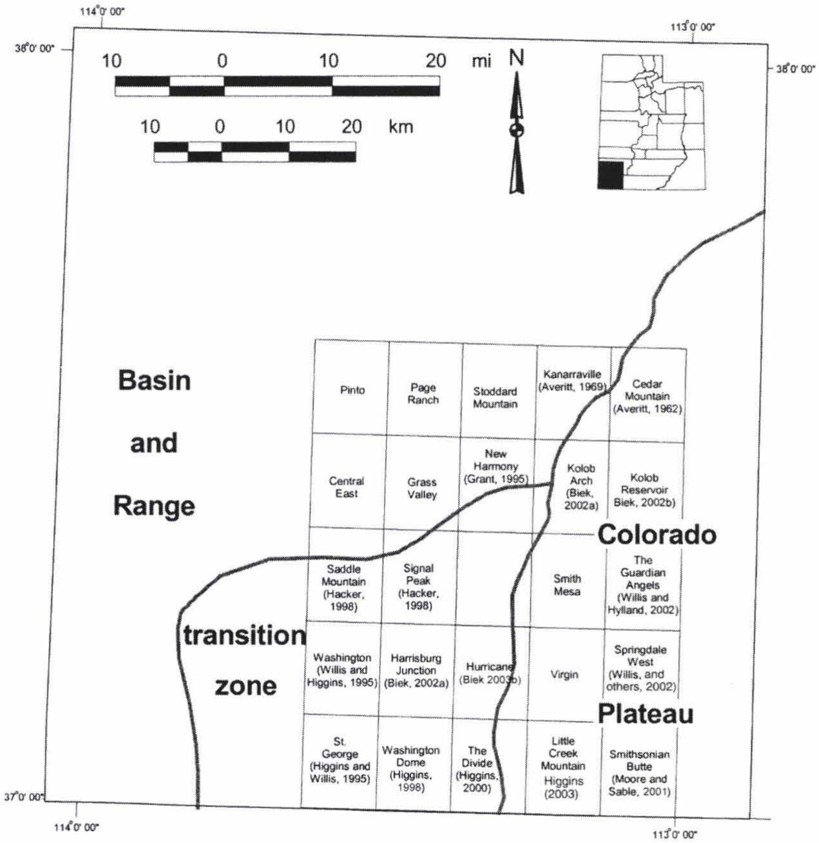

Figure 2. *Locations of Basin and Range, Colorado Plateau, and transition zone physiographic provinces, and of the Pintura and surrounding quadrangles, in southwestern Utah. Published geologic maps shown with author reference.*

provinces (figures 1 and 2) (Heylmun, 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). Contractional deformation migrated eastward into southwestern Utah during latest Cretaceous to early Paleocene time, forming: (1) in the Pintura quadrangle, the Pintura 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 Pintura 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 Pintura anticline and related syncline is controversial. The timing of Late Cretaceous to early Cenozoic contractional deformation is constrained in part by strata exposed in the Pintura quadrangle. Fluvial strata of the late Campanian to early Paleocene Canaan Peak Formation record the waning stages of contractional deformation, whereas the Paleocene-Eocene Claron Formation was deposited after that deformation had ceased (Taylor, 1993; Goldstrand, 1994). In the Pintura quadrangle, the Canaan Peak Formation comprises fluvial conglomerate deposited on the suspected hinge zone of the Pintura 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 Pintura, 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 Pintura quadrangle (figure 1) (Cook, 1957, 1960; Blank and others,

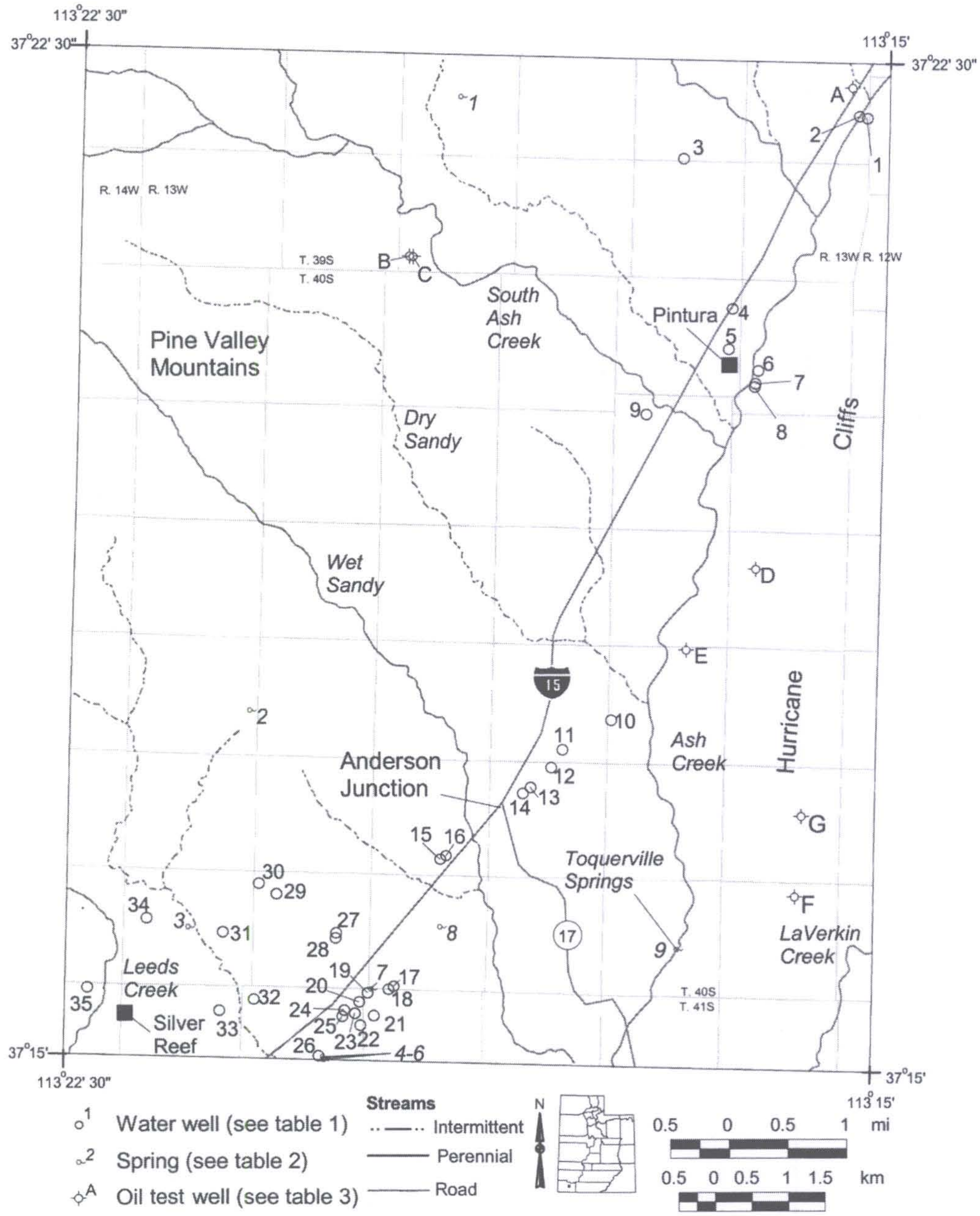

Figure 3. Geographic and hydrologic features of the Pintura quadrangle.

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.

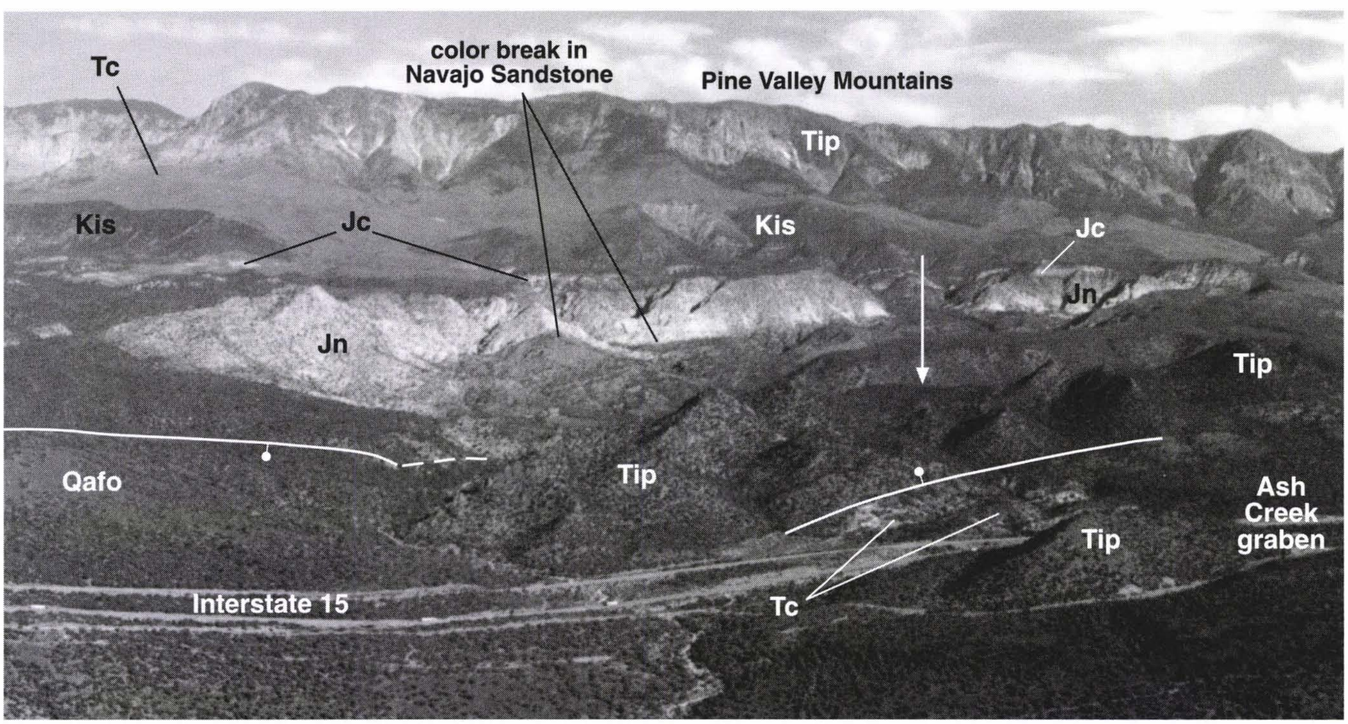

Figure 4. View to the northwest of the west-central part of the Pintura quadrangle from southern Black Ridge. The quartz monzonite porphyry of the Pine Valley Mountains (unit Tip) west of Interstate 15 is about 3,000 feet below the main mass of the laccolith (visible in the background), and may be a satellitic intrusion or an erosional remnant of a once-continuous sheet. The stucturally 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/or 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 Quarternary 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 Sandsone (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 reversal 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 latest Cretaceous to early Tertiary time. (1) The Pintura anticline was actually a west-facing homocline formed above a thrust-fault ramp or splay. This thrust fault flattened east of the homocline, 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 Mesozoic-early Cenozoic 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

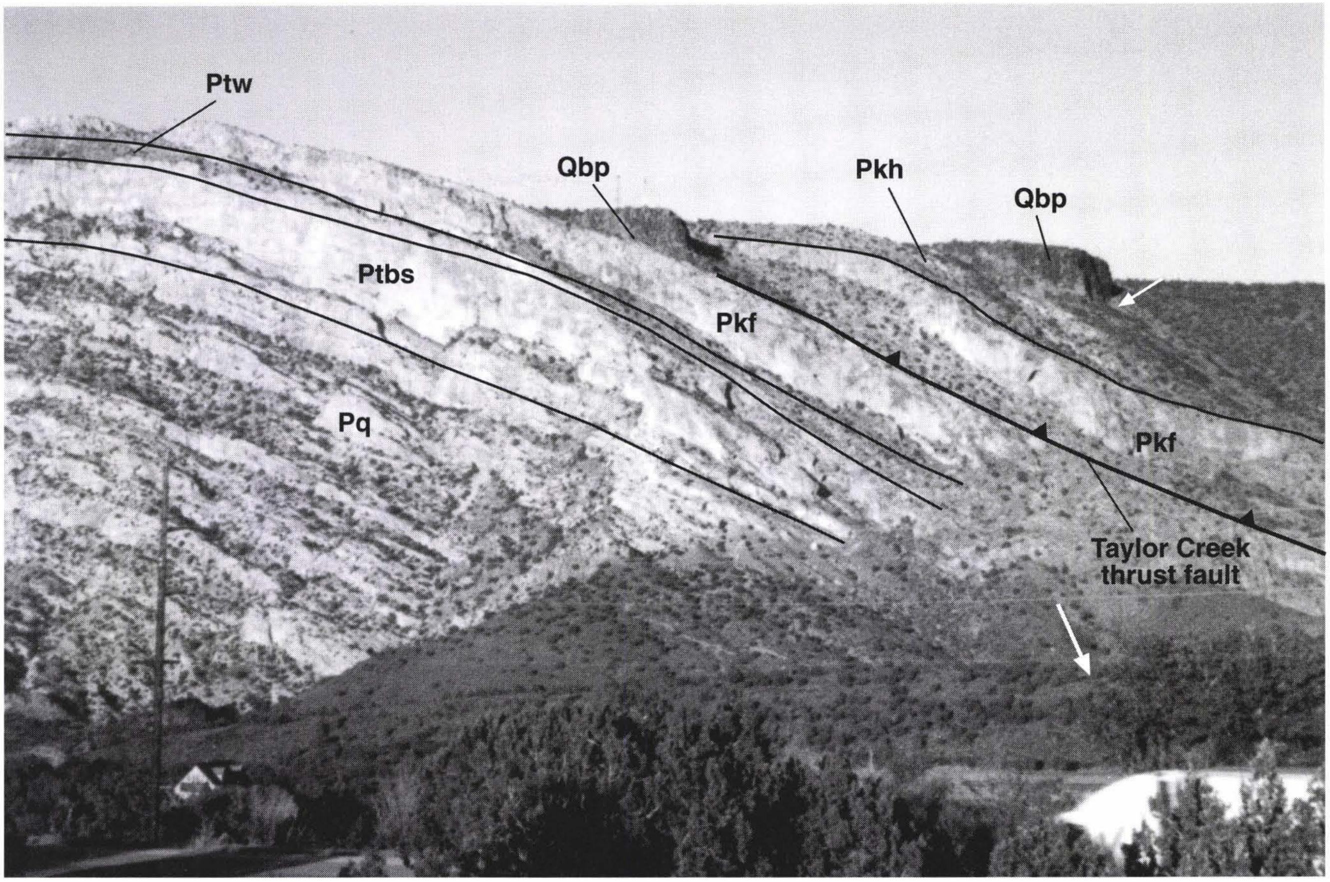

Figure 5. View to the east of the Hurricane Cliffs at the southern edge of Black Ridge, sections 23, 24, 25, 26, T. 40 S., R. 13 W. The trace of the Hurricane fault is along the slope break at the base of the cliffs. The cliffs are composed of Permian strata of the Queantoweap Sandstone (Pq), the Brady-Seligman (Ptbs) and Woods Ranch (Ptw) Members of the Toroweap Formation, and the Fossil Mountain (Pkf) and Harrisburg (Pkh) Members of the Kaibab Formation. Beds dip about 20 to 35 degrees southeast on the east limb of the Kanarra anticline. The Fossil Mountain Member is repeated by the west-directed Taylor Creek thrust fault. Quaternary basalt of the Pintura flow (Qbp) overlies the Permian strata on the southern margin of the cliffs, and is also exposed at the base of the cliffs. Stewart and Taylor (1996) correlated basalt outcrops on the hanging wall and footwall of the Hurricane fault based on geochemistry (white arrows show approximate locations of the samples), indicating about 1,480 feet (450 m) of stratigraphic separation across the fault since the basalt erupted about 880,000 years ago.

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

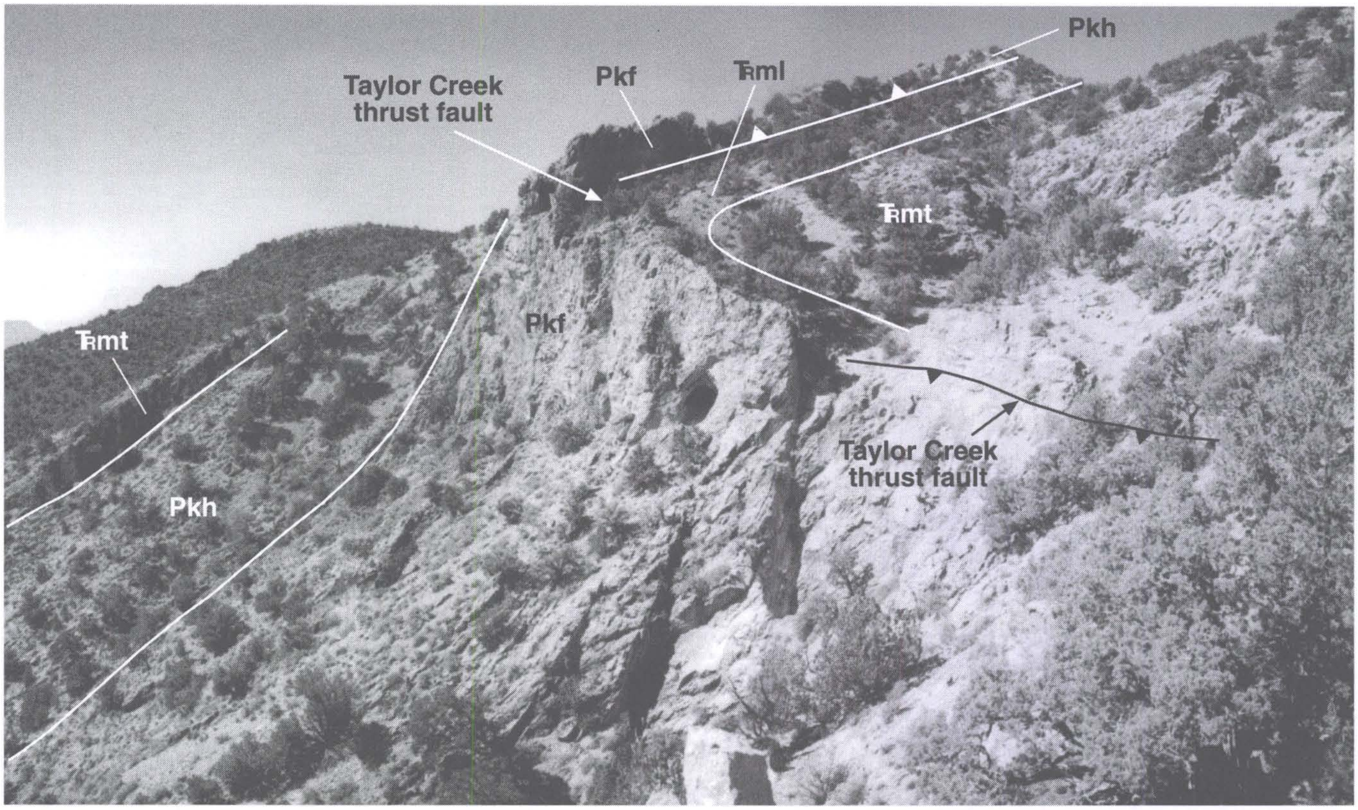

Figure 6. *View southwest to the Taylor Creek thrust fault in the SW1/4 section 24, T. 40 S., R. 13 W. The thrust here is folded and dips very steeply east and southeast; it is partly hidden from view by the Fossil Mountain cliffs. It places steeply east-southeast-dipping Kaibab strata (Fossil Mountain [Pkf] and Harrisburg [Pkh] Members) over the lower red (TRml) and Timpoweap (TRmt) Members of the Moenkopi Formation.*

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 relatively straight sections separated by relatively sharp bends (Stewart and Taylor, 1996; Stewart and others, 1997; Lund and Everitt, 1998; Higgins, 2000; Biek, 2003b). The straight sections were referred to as geometric segments by Stewart and Taylor (1996) and as sections by Pearthree and 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, satellitic 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 intrusion 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 (satellitic 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-

Table 1. *Water wells in the Pintura quadrangle[1].*

ID[2]	Point of diverson[3]	Sec[3]	T[3]	R[3]
1	S 590 W 129 E4	25	39 S	13 W
2	S 500 W 500 E4	25	39 S	13 W
3	N 130 W 450 S4	26	39 S	13 W
4	S 1290 W 420 NE	2	40 S	13 W
5	S 510 W 550 E4	2	40 S	13 W
6	S 1553 E 800 W4	1	40 S	13 W
7	S 1680 E 836 W4	1	40 S	13 W
8	S 1824 E 800 W4	1	40 S	13 W
9	N 5160 E 1390 SW	11	40 S	13 W
10	N 1948 E 135 SW	23	40 S	13 W
11	N 575 E 620 S4	22	40 S	13 W
12	S 235 E 135 N4	27	40 S	13 W
13	S 1135 W 825 N4	27	40 S	13 W
14	S 138 W 1188 N4	27	40 S	13 W
15	N 795 E 425 S4	28	40 S	13 W
16	N 428 E 540 S4	28	40 S	13 W
17	N 172 E 1137 SW	33	40 S	13 W
18	S 44 E 1151 NW	4	41 S	13 W
19	S 203 E 193 NW	4	41 S	13 W
20	S 605 W 183 NE	5	41 S	13 W
21	S 1180 E 505 NW	4	41 S	13 W
22	S 1650 W 125 NE	5	41S	13 W
23	S 1131 W 375 N	5	41 S	13 W
24	S 1059 E 1863 N4	5	41 S	13 W
25	S 1345 E 1776 N4	5	41 S	13 W
26	S 3111 E 699 N4	5	41 S	13 W
27	N 2513 W 1444 SE	32	40 S	13 W
28	N 2308 W 1526 SE	32	40 S	13 W
29	S 1000 E 1100 NW	32	40 S	13 W
30	S 541 E 217 NW	32	40 S	13 W
31	S 136 W 1364 E4	31	40 S	13 W
32	S 618 E 486 NW	5	41 S	13 W
33	S 1133 W 1062 NW	5	41 S	13 W
34	N 2958 E 1124 SW	31	40 S	13 W
35	S 132 W 1554 NE	1	41 S	14 W

Notes:
1. Data from Utah Divsion 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 = Township, R = Range.
   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.

lution 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 are known atop Black Ridge at "Mystery Hill" in the Smith Mesa quadrangle, (Ben Everitt, Utah Division of Water Resources, written communication, 2000) and co-author Biek mapped cinder deposits near Ash Creek Reservoir dam in the Kolob Arch quadrangle (Biek, 2002a). The Pintura flows yielded $^{40}Ar/^{39}Ar$ plateau ages of 0.84 ± 0.03 Ma and 0.81 ± 0.10 Ma from samples within the quadrangle (appendix; Lund and others, 2001). Samples of Pintura flow rocks from outside of the Pintura quadrangle yielded $^{40}Ar/^{39}Ar$ plateau ages of 0.89 ± 0.02 Ma, 0.88 ± 0.05 Ma, and 0.87 ± 0.04 Ma (Lund and others, 2001; Biek, 2003b).

Paleomagnetic data indicate that basalt in the hanging wall of the Hurricane fault, in sections 14, 23, and 26 of T. 40 S., R. 13 W., has been tilted about 10 to 25 degrees toward the fault (M. Hozik in Lund and Everitt, 1998). These results agree with the conclusions of Hamblin (1965) that reverse drag, related to the curvature of the Hurricane fault, is an important aspect of deformation of its hanging wall and complicates estimates of tectonic throw on the fault. Using 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[1].*

ID[2]	Name	CFS[3]	Point of Diversion[4]	Sec[4]	T[4]	R[4]
1	Deer Spring	0.013	N 4000 E 2400 SW	28	39 S	13 W
2	Blue Spring	0.015	N 2000 W 300 SE	19	40 S	13 W
3.	Unnamed Spring	0.018	N 2600 W 2900 SE	31	40 S	13 W
4.	Unnamed Spring	0.089	S 3070 W 1833 NE	5	41 S	13 W
5.	Unnamed Spring	0.089	S 3145 W 1790 NE	5	41 S	13 W
6.	Unnamed Spring	0.089	S 3210 W 1783 NE	5	41 S	13 W
7.	Danish Ranch Domestic Spring/Stream	1.5	S 20 E 340 NW	4	41 S	13 W
8.	Danish Ranch Domestic Spring/Stream	1.5	N 345 W 2120 E4	33	40 S	13 W
9.	Toquerville Springs	1.97	N 2125 E 735 S4	35	40 S	13 W

Notes:
1. Data from Utah Division of Water Rights (http://nrwt1.nr.state.ut.us).
2. Corrsponds 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.

***Table 3.** Petroleum-test wells in the Pintura quadrangle[1].*

ID[2]	Operator	Well Name	Spot[3]	Sec[3]	T[3]	R[3]	API Number[4]	Year	Elevation (feet)	Total Depth (feet)	Formation Tops[5]
A	Neptune Explor. Co.	1-25 FEDERAL	2060 FNL 721 FEL	25	39 S	13 W	4305330024	1976	4250	2610	Log not available
B	Pan American Co.	1 PINTURA UNIT	675 FSL 505 FWL	33	39 S	13 W	4305310879	1962	5272	9501	TRcp 915; TRcs 2635; TRmu 2800; Pkh 4585; Pqu 5390; Pp 6730; Mc 7470; Mr 8140; Du 8925
C	Sun Oil Co.	1 UNIT	398 FSL 872 FWL	33	39 S	13 W	4305311164	1951	5250	5496	TRcp 905; TRcs 2550; TRmu 2727; Pkh 4998
D	Pease Oil & Gas Co.	1-13 FEDERAL	1625 FNL 1140 FWL	13	40 S	13 W	4305330007	1972	4351	3171	Mr 1466; Du 3995
E	McCulloch Oil Co.	1 GOVT-WOLF	90 FNL 3515 FWL	23	40 S	13 W	4305310704	1964	3799	7315	Fault 375; Mr 792; Du 1742; Fault 3375; TD in Cambrian strata
F	Titan Oil Co.	36-C1 STATE	660 FNL 1980 FEL	36	40 S	13 W	4305330003	1969	4200	4124	Pq 1620; Pp 3180; Mc 3784
G	Buttes Oil & Gas Co.	Pease Federal #1	3050 FSL 1725 FEL	25	40 S	13 W	4305320318	1967	4340	5236	Log not available

Notes:

1 Data from U.S. Bureau of Reclamation.
2 Corresponds to letter on figure 3.
3 Location is given as distance in feet from section lines. FNL = from north line, FSL = from south line, FEL = from east line, FWL = from west line, Sec = Section, T = Township, R = Range, relative to Sale Lake Base Line and Meridian.
4 American Petroleum Institute Petroleum information (PI) database number.
5 Data from UGS unpublished records. Formation tops are in feet. Unit abbreviations are same as on map and in Explanation of Map Units.

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 portion of the Silver 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 $^{39}Ar_K$ 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 CO_2 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 ($^{40}Ar/^{36}Ar$ = 295.5). Age spectra plot apparent age of each incrementally heated gas fraction versus the cumulative %$^{39}Ar_K$ 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 %$^{39}Ar_K$ released. These auxiliary parameters, which aid interpretation of age spectra, include radiogenic yield (percent of ^{40}Ar which is not atmospheric) and K/Ca (determined from measured Ca-derived ^{37}Ar and K-derived ^{39}Ar). Interpretation of age spectra can be complicated due to such problems as excess argon, alteration, contamination, ^{39}Ar 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 $^{39}Ar_K$ 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 $^{39}Ar_K$ 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.

ID	Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_K$ (x 10^{-15} mol)	K/Ca	$^{40}Ar^*$ (%)	^{39}Ar (%)	Age (Ma)	±2σ (Ma)
Ash Creek #1, C3:83,145.49 mg, groundmass, J=0.000518106, D=1.0024, NM-83, Lab#=8765-01										
A	*625*	*147.9*	*0.8825*	*500.8*	*2.08*	*0.58*	*0.0*	*0.9*	*-0.04*	*1.74*
B	*700*	*15.66*	*2.060*	*51.23*	*8.47*	*0.25*	*4.1*	*4.5*	*0.60*	*0.17*
C	750	7.095	2.180	21.57	6.07	0.23	12.0	7.1	0.80	0.14
D	800	3.588	1.808	9.470	23.0	0.28	24.9	16.9	0.84	0.04
E	875	2.316	1.201	5.004	44.2	0.42	38.7	35.8	0.84	0.02
F	975	1.993	0.9438	3.770	72.1	0.54	46.0	66.6	0.86	0.01
G	1075	2.650	1.077	6.082	30.4	0.47	34.0	79.5	0.84	0.04
H	1250	16.52	2.864	53.97	33.8	0.18	4.6	94.0	0.71	0.12
I	1650	17.74	13.73	59.77	14.1	0.037	6.2	100.0	1.04	0.20
total gas age			n=9		234.1	0.38			0.82	0.08
plateau			n=7	steps C-I	223.6	0.39		95.5	0.84	0.03

Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interferring reactions.
Individual analyses show analytical error only; mean age errors also include error in J and irradiation parameters.
Analyses in italics are excluded excluded from mean age calculations.
Correction factors:

$(^{39}Ar/^{37}Ar)_{Ca}$ = 0.00070±0.00005

$(^{36}Ar/^{37}Ar)_{Ca}$ = 0.00026±0.00002

$(^{38}Ar/^{39}Ar)_K$ = 0.0119

$(^{40}Ar/^{39}Ar)_K$ = 0.0340±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 CO_2 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^{-16} moles/pA.
Total system blank and background averaged 478, 0.6, 0.4, 0.4, 2.3 x 10^{-17} moles.
J-factors determined to a precision of ±0.1% by CO_2 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 CaF_2 are as follows:
$(^{40}Ar/^{39}Ar)K$ = 0.0002±0.0003; $(^{36}Ar/^{37}Ar)_{Ca}$ = 0.00026±0.000007; and $(^{39}Ar/^{37}Ar)Ca$ = 0.0007±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.*

Table A.3. Analytical results for ACG-1 groundmass concentrates.

ID	Power (watts)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ ($\times 10^{-3}$)	$^{39}Ar_K$ ($\times 10^{-16}$ mol)	K/Ca	$^{40}Ar^*$ (%)	^{39}Ar (%)	Age (Ma)	±1σ (Ma)
ACG-1,26.39 mg groundmass, J=0.0001140±0.11%, D=1.00394±0.00121, NM-126, Lab#=51401-01										
A †	*2*	*12172*	*4.223*	*40709*	*0.016*	*0.12*	*1.2*	*0.1*	*29*	*912*
B	3	342.0	5.688	1129.5	0.356	0.090	2.5	1.9	1.8	1.5
C	5	60.03	5.257	189.5	1.19	0.097	7.4	7.9	0.92	0.22
D	6	27.93	4.190	81.53	1.91	0.12	14.9	17.5	0.86	0.13
E	9	20.04	3.377	53.95	4.32	0.15	21.7	39.2	0.90	0.06
F	12	16.89	2.486	45.35	3.43	0.21	21.8	56.5	0.76	0.07
G	15	21.08	2.216	59.19	2.69	0.23	17.8	70.0	0.77	0.07
H	23	40.88	2.633	127.6	3.47	0.19	8.2	87.5	0.69	0.10
I	30	95.90	5.219	310.7	1.63	0.098	4.7	95.7	0.93	0.21
J	40	214.0	26.30	733.4	0.857	0.019	-0.3	100.0	-0.15	0.57
total gas age			n=10		19.9	0.16			0.82	1.76*
plateau		MSWD=1.0	n=9	steps B-J	19.9	0.16		99.9	0.81	0.10*
isochron		MSWD=1.0	n=10		$^{40}Ar/^{36}Ar$=294±5*				0.83	0.10*

Notes:

Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interferring 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.

n= number of heating steps

†= analyses excluded from weighted mean age.

K/Ca = molar ratio calculated from reactor produced $^{39}Ar_K$ and $^{37}Ar_{Ca}$.

* 2σ error

** MSWD outside of 95% confidence interval

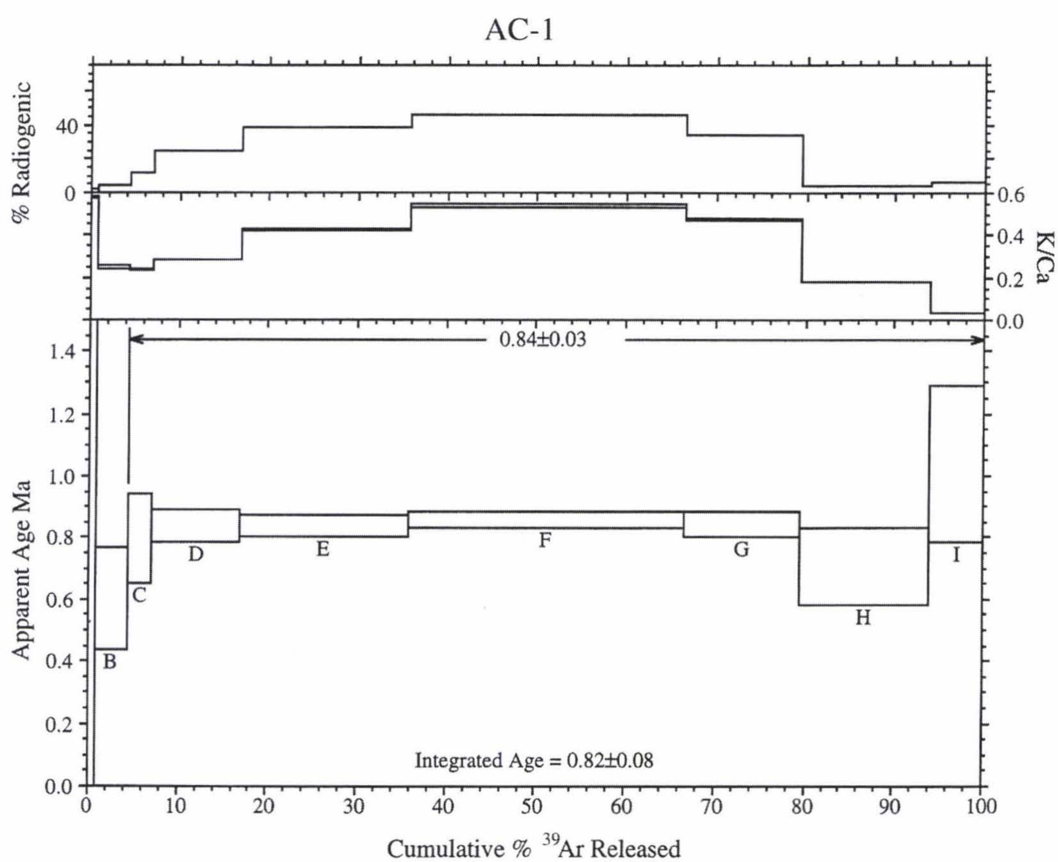

Figure A.1. *$^{40}Ar/^{39}Ar$ age spectrum for sample AC-1.*

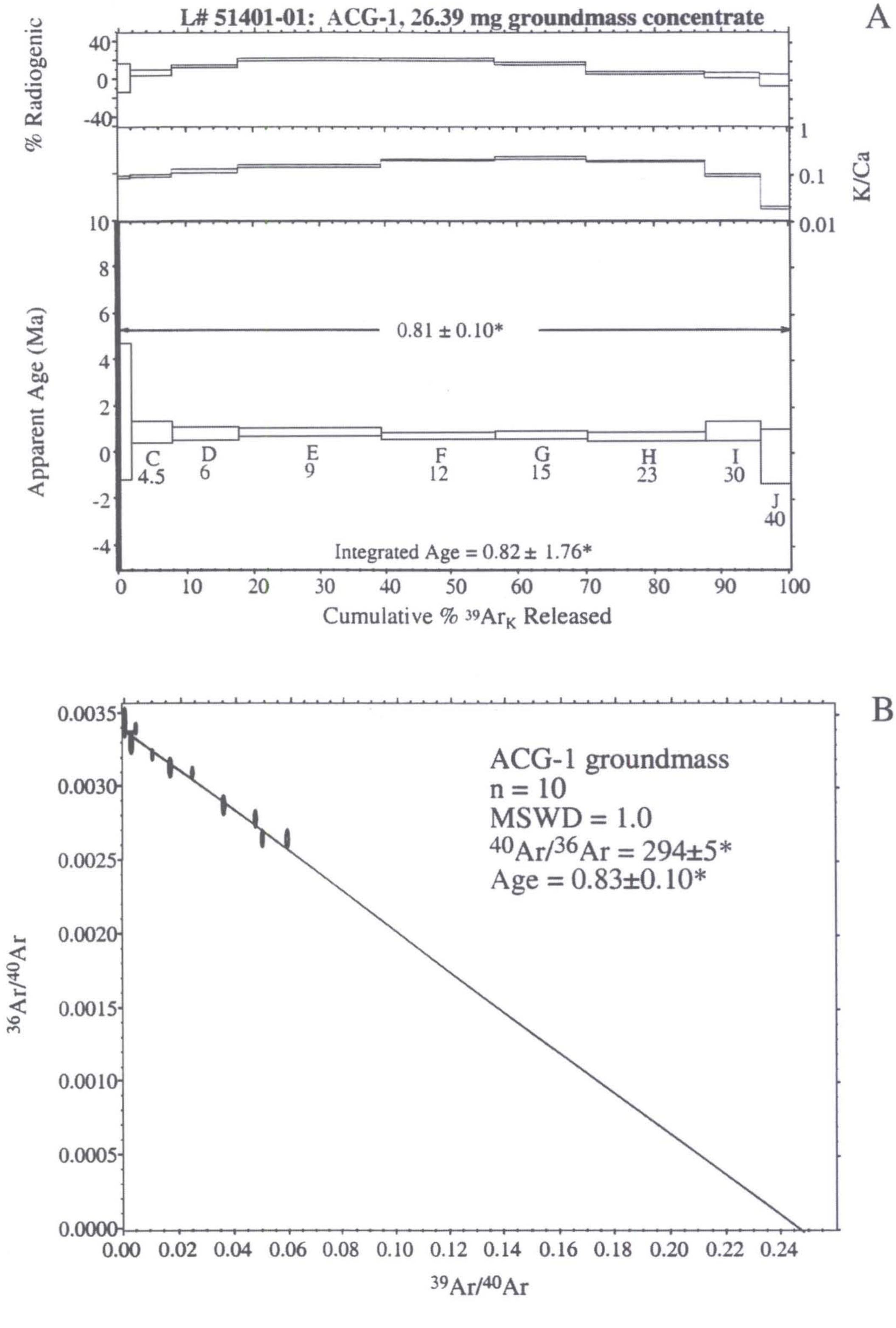

Figure A.2. *$^{40}Ar/^{39}Ar$ age spectrum and inverse isochron for groundmass concentrate ACG-1. The plateau age (0.81 ± 0.10 Ma) is the preferred age for the sample.*