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Geologic Framework

By Ed DeWitt, Victoria E. Langenheim, and Laurie Wirt

Chapter B

Geologic Framework of Aquifer Units and Ground-Water Flowpaths, Verde River Headwaters, North-central Arizona

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Geologic Framework

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Abstract

The basins underlying by Big and Little Chino Valleys developed in late Tertiary time (10 Ma to the present) by crustal extension in central Arizona and in the Basin-and-Range province to the south. Big Chino Valley, which is the larger of the two basins, is a northwest-trending, 45-km-long graben bordered by the Quaternary Big Chino Fault on the northeast side of the valley. Big Chino Valley contains at least 700 m of Quaternary and late Tertiary sediment near the deepest part of the basin. Fine-grained carbonate sediment, containing analcime and bloedite(?), indicates that the central part of the basin was a playa. Alluvial fans contributed sediment to the margin of the playa from the south and west. Basalt flows entered the valley from the north, west, and southeast from 6.0 to 4.5 Ma.

The basin underlying Little Chino Valley is smaller and contains a thinner sequence of Quaternary and late Tertiary sediment. The deepest part of the basin trends northwest and is 18 km long. Maximum sediment thickness is about 200 m. Alluvial fans contributed sediment from the west, south, and southeast. The valley lacks any proven playa deposits. No young (4-6 Ma) basalt flows are known in the valley. Beneath the Quaternary and late Tertiary sediments are abundant flows, domes, and intrusive centers of 24-Ma lati-andesite, and some extensive basalt flows of the 10-15-Ma Hickey Formation. These volcanic rocks formed an irregular topographic surface on which the Quaternary and late Tertiary sediment was deposited. Consequently, isopachs of sediment thickness in Little Chino Valley are complex and mirror the underlying relief on the Tertiary volcanic rocks.

Introduction

Tertiary basins in north-central Arizona formed as the Basin-and-Range province was extended to the southwest, away from the Colorado Plateau. Within the Transition Zone, Big and Little Chino Valleys are the northernmost of such valleys that were formed from 10 Ma to the present (fig. B1). Although not as extensive nor as deep as Basin-and-Range basins, the basins underlying Big and Little Chino Valleys share common characteristics, such as fault-bounded margins, incorporation of volcanic material in the basin fill, and facies variations within the sediment fill. Knowledge of the geologic material in the basin, deposited over space and time, is necessary for an understanding of the evolution of the basin.

Studies of the geology of Big Chino Valley include regional reconnaissance mapping (Krieger, 1965; 1967a; 1967b; 1967c), investigations of water resources in the western and southeastern part of the valley (Water Resource Associates, 1989), and an integrated study of water resources (Ostenaa and others, 1993a, 1993b; Ewing and others, 1994). Geologic mapping since the 1970's has been limited to the far western end of the valley (Goff and others, 1983) and the far southeastern end (Tyner, 1984 and Ward, 1993), where Tertiary volcanic rocks were studied. The geology of Little Chino Valley has been studied in less detail than Big Chino Valley. Mapping includes detailed work in the far northern and southern ends of the valley (Krieger, 1965) and reconnaissance investigations in Little Chino and Lonesome Valleys (Schwalen, 1967).

Detailed knowledge of the geology of the mountains and basins is necessary in order to determine aquifer boundaries, hydraulic characteristics, and the ground-water flow paths, which are discussed in Chapter D (this volume). This investigation builds on previous ones and includes new mapping in parts of the two valleys, chemical analysis and X-ray diffraction studies of Tertiary sedimentary and volcanic units, compilation and synthesis of well logs in both valleys, and construction of preliminary longitudinal and cross sections in parts of the valleys. Mapping was compiled at 1:100,000 scale and is part of a regional map of the Prescott National Forest-Verde headwaters region (DeWitt and others, in press).

Acknowledgments

John Hoffmann, D.A. Lindsey, Keith Nelson, Frank Corkhill, Pat O'Hara, Dean Ostenaa, and William Wellendorf, provided constructive criticism of the manuscript. Dean Ostenaa provided drill cuttings of the three Bureau of Reclamation wells in Big Chino Valley. William Wellendorf provided drill cuttings of wells from northern Little Chino Valley. Discussions with Pat O'Hara, Steve Reynolds, Dean Ostenaa, and William Wellendorf improved the first author's understanding of the Tertiary volcanic rock units and geometry of basins in the Chino Valley area.

Rock Units

Early and Middle Proterozoic plutonic and metamorphic rocks constitute the basement to the mountains and valleys in the region. Exposures of the basement are limited in the study area, but are abundant in the Bradshaw Mountains to the south and the Black Hills to the southeast (fig. B1). Paleozoic sedimentary rocks overlie the basement and are exposed throughout the area except where removed by erosion during Tertiary time. Rocks include sandstone, limestone, dolomite, and minor shale. Tertiary volcanic rocks are locally abundant both in mountain ranges and within the basins. Tertiary to Quaternary sediments and rocks are abundant in both basins and include fanglomerate, other alluvial deposits, and playa deposits, all of which interfinger in complex patterns.

Proterozoic Rocks

Proterozoic rocks are well exposed west of the town of Chino Valley and along Granite Creek, northeast of Chino Valley (fig. B2). Other exposures of these units throughout the area are smaller and discontinuous, including some near the confluence of Granite Creek and the Verde River (fig. B2), near Table Mountain southwest of Chino Valley, (fig. B2), and west of Sullivan Buttes (fig. B3). Metabasalt (unit Xb) that includes minor metaandesite and iron-formation forms a prominent outcrop west of Chino Valley and a much smaller outcrop east of Del Rio Springs. Metatuff and associated volcaniclastic rocks (unit Xt) are exposed southeast of Lower Granite Spring in a faulted sliver of bedrock. Metamorphosed pelitic sediments and wacke (unit Xp) crops out west of the metabasalt (fig. B2) and underlies much of the Sullivan Buttes (DeWitt and others, in press). Similar metapelitic rocks are present in cuttings from wells north of Paulden (logs by E.D. McKee of well in B(18-2)20 CA, as supplied by Tom McGarvin, written commun., 2000).

These three rock units have been regionally metamorphosed to greenschist facies and deformed, and possess a northeast-striking foliation that dips steeply. Zones of high strain are locally apparent in the metamorphic rocks. Rocks of similar composition, metamorphic grade, and fabric development are exposed in the Bradshaw Mountains, south of Prescott (Krieger, 1965; Anderson and Blacet, 1972a; DeWitt and others, in press) and in the Black Hills, west of Jerome (Anderson and Creasey, 1958; 1967). Although an isotopic age for these rock units has not been determined in the study area, similar metabasalt and metatuff to the south in the Bradshaw

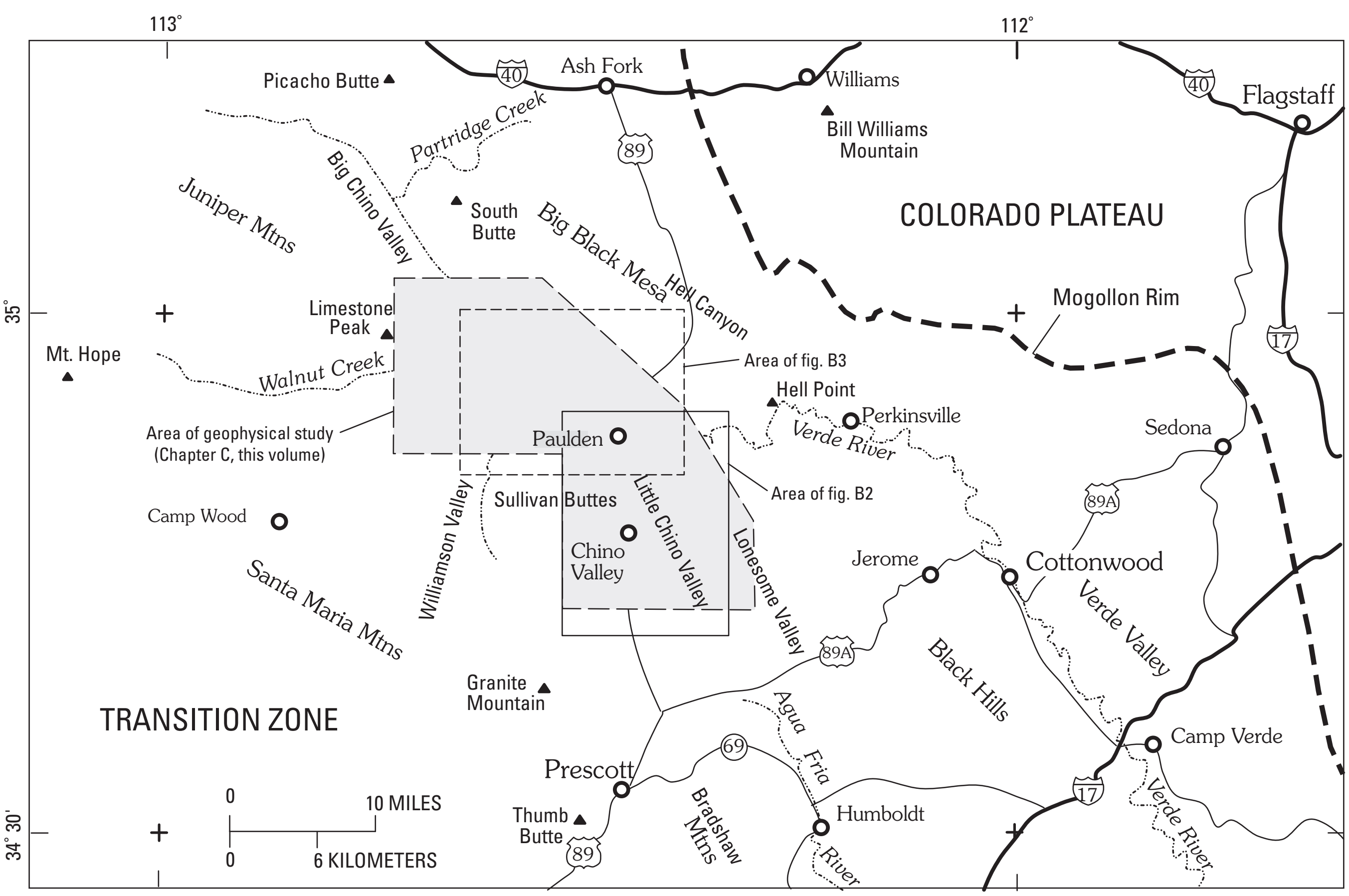


Figure B1. Location map of north-central Arizona showing location of study area and location of figures B2 and B3.

Mountains are as old as 1.76 Ga and metapelitic rocks are about 1.76-1.74 Ga (DeWitt and others, in press). Regional magnetic patterns (Langenheim and others, 2000; Langenheim and others, Chapter C, this volume) reveal that the foliation and rock units strike north in the eastern part of the study area (fig. B2) and northeast in the western part (fig. B3). Therefore, much of Little Chino Valley is probably underlain by metabasalt and metatuff. Much of the far southeastern end of Big Chino Valley is probably underlain by metapelitic rocks.

Four Proterozoic plutonic units intrude the metavolcanic and metasedimentary rocks, but none forms large outcrops. Gabbro (unit Xgb) is recognized east of Table Mountain (fig. B2). Coarse-grained gabbro, cumulate-texture gabbro, and ultramafic rocks are present as inclusions in Tertiary latiandesite throughout the eastern Sullivan Buttes (Arculus and Smith, 1979; Tyner, 1984; Ward, 1993). Gravity data (Langenheim and others, 2000; Langenheim and others, this volume) suggest that abundant gabbro and associated ultramafic rocks may underlie the western side of Little Chino Valley. The long-wavelength nature of the gravity anomaly suggests that the gabbro is deeply buried. The gabbro is similar in composition to abundant gabbro in the central Bradshaw Mountains (Anderson and Blacet, 1972a; 1972b), and probably is 1.74-1.76 Ga (DeWitt and others, in press).

The Williamson Valley Granodiorite (unit Xwv; DeWitt and others, in press) intrudes metabasalt and metapelitic rocks west of Chino Valley (fig. B2) and is medium grained, equigranular, undeformed in most outcrops, and contains distinctive yellow-stained quartz grains (DeWitt, 1989). A mixture of aplite and pegmatite dikes and irregularly shaped bodies (unit Xap) intrudes metapelitic rocks west of Sullivan Buttes (fig. B3). The aplite-pegmatite is medium to coarse grained and highly variable, texturally. Pegmatite bodies in drill cuttings from a well north of Paulden probably are from this unit (logs by E.D. McKee of well in B(18-2)20 CA, as supplied by Tom McGarvin, written commun., 2000).

Small bodies mapped as Prescott Granodiorite (Krieger, 1965) east of Table Mountain and east of Granite Creek (fig. B2) contain variably foliated biotite granodiorite (unit Xpr). The Prescott Granodiorite is about 1.68 Ga (DeWitt and others, in press). Magnetic and gravity data (Langenheim and others, 2000; Langenheim and others, this volume) suggest that much of southern Little Chino Valley may be underlain by Prescott Granodiorite. Some well logs from the area of Sullivan Lake area (fig. B2) report "granite" at depth, but it cannot be proven if this "granite" is equivalent to the Prescott Granodiorite, Williamson Valley Granodiorite, or other known plutonic units in the Prescott-Jerome area.

The Mazatzal Group (unit Xq) unconformably overlies metabasalt and metatuff along lower Granite Creek (fig. B2), at the northern end of Little Chino Valley (Krieger, 1965; Bradshaw, 1974). Abundant quartzite and lesser conglomerate and argillite are deformed about northeast-striking axial planes into open anticlines and synclines. The Mazatzal Group east of Del Rio Springs could be slightly younger (Chamberlain and others, 1991) than the type Mazatzal Group in central Arizona (Silver and others, 1986). Quartzite of the Mazatzal Group extends to the north, in isolated outcrops, to the Verde River. Magnetic data (Langenheim and others, 2000; Langenheim and others, this volume) suggests that the quartzite probably extends to the south, in the subsurface, beneath the northern end of Little Chino Valley.

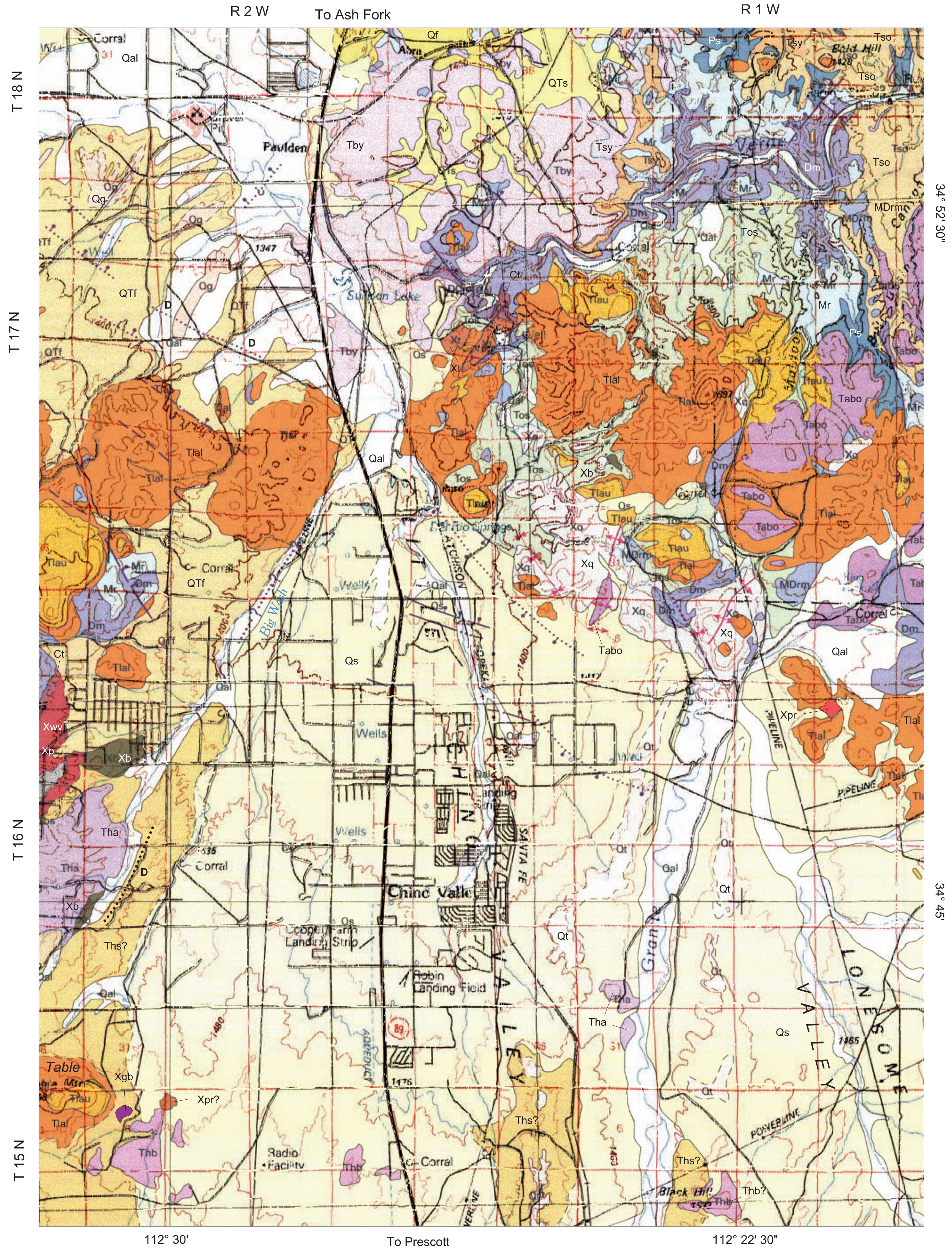
A fifth plutonic unit, the granite of Chino Valley (DeWitt and others, in press) underlies much of central Big Chino Valley (fig. B3), but is exposed only northwest of the study area near South Butte and Partridge Creek (fig. B1). The granite is medium to coarse grained, slightly to strongly porphyritic, and contains potassium-feldspar phenocrysts. Undeformed in many outcrops, the granite is deformed in zones of high strain that strike northeast and dip steeply. The granite coincides with an aerially extensive high-amplitude magnetic anomaly centered over Big Black Mesa.

A simplified depiction of the basement rocks, from west to east, is: (1) a large body of granite underlies much of central Big Chino Valley, northwest of figure B3; (2) metasedimentary rocks contact the granite to the east in a northeast-striking belt that extends from the western Sullivan Buttes to north of Paulden (fig. B3); (3) metavolcanic rocks contact the metasedimentary rocks to the east and may be present throughout much of Little Chino Valley (fig. B2); (4) a large body of gabbro and ultramafic rocks is present in the upper crust beneath the western part of Little Chino Valley; (5) small bodies of granite to granodiorite cut the metavolcanic rocks in the far southern part of Little Chino Valley and may form a large pluton farther to the south; and (6) quartzite of the Mazatzal Group locally overlies the metavolcanic rocks in an irregularly shaped belt that extends from the Verde River, southwest, to beneath the northern end of Little Chino Valley.

Paleozoic rocks

Cambrian Tapeats Sandstone (unit Ct) is the basal Paleozoic rock unit in the area, lying unconformably on Proterozoic rocks west of the town of Chino Valley and in fault contact with the Proterozoic rocks along lower Granite Creek (fig. B2). Farther down the Verde River the Tapeats crops out beneath the Devonian Martin Formation (fig. B2). Outcrops of Tapeats are tentatively identified north of the Big Chino Fault, along the base of Big Black Mesa. Rocks in that area could be part of the Devonian Chino Valley Formation, as discussed below. The Tapeats consists of a basal quartz-pebble conglomerate, strongly cemented sandstone and quartzite, and minor dolomitic sandstone (Krieger, 1965). Near topographic highs created by erosion-resistant basement rocks such as the quartzite of the Mazatzal Group, the Tapeats was not deposited. Thickness of the Tapeats ranges from 30 to 50 meters and increases to the west (Krieger, 1965).

Cambrian Bright Angel Shale is exposed west of the study area, in western Big Chino Valley, at the base of the Juniper Mountains (Krieger, 1967a; fig. B1). There the unit is composed of shale, dolomitic shale, and unusual K_2O-rich rocks that are 10-20-m thick and that underlie the Martin


R 2 W
To Ash Fork
R 1 W
T 18 N
T 17 N
T 16 N
T 15 N
34° 52' 30"
34° 45'
112° 30'
To Prescott
112° 22' 30"
Paulden
Big Wash
Chino Valley
Cooper Farm Landing Strip
Robin Landing Field
Radio Facility
Black Hill
Bald Hill
Table Mtn
LONESOME VALLEY
PIPELINE
POWERLINE
SANTA FE
Corral
Wells
Qal
Qg
QTf
Qf
QTs
Tby
Tsy
Tso
Ps
Mr
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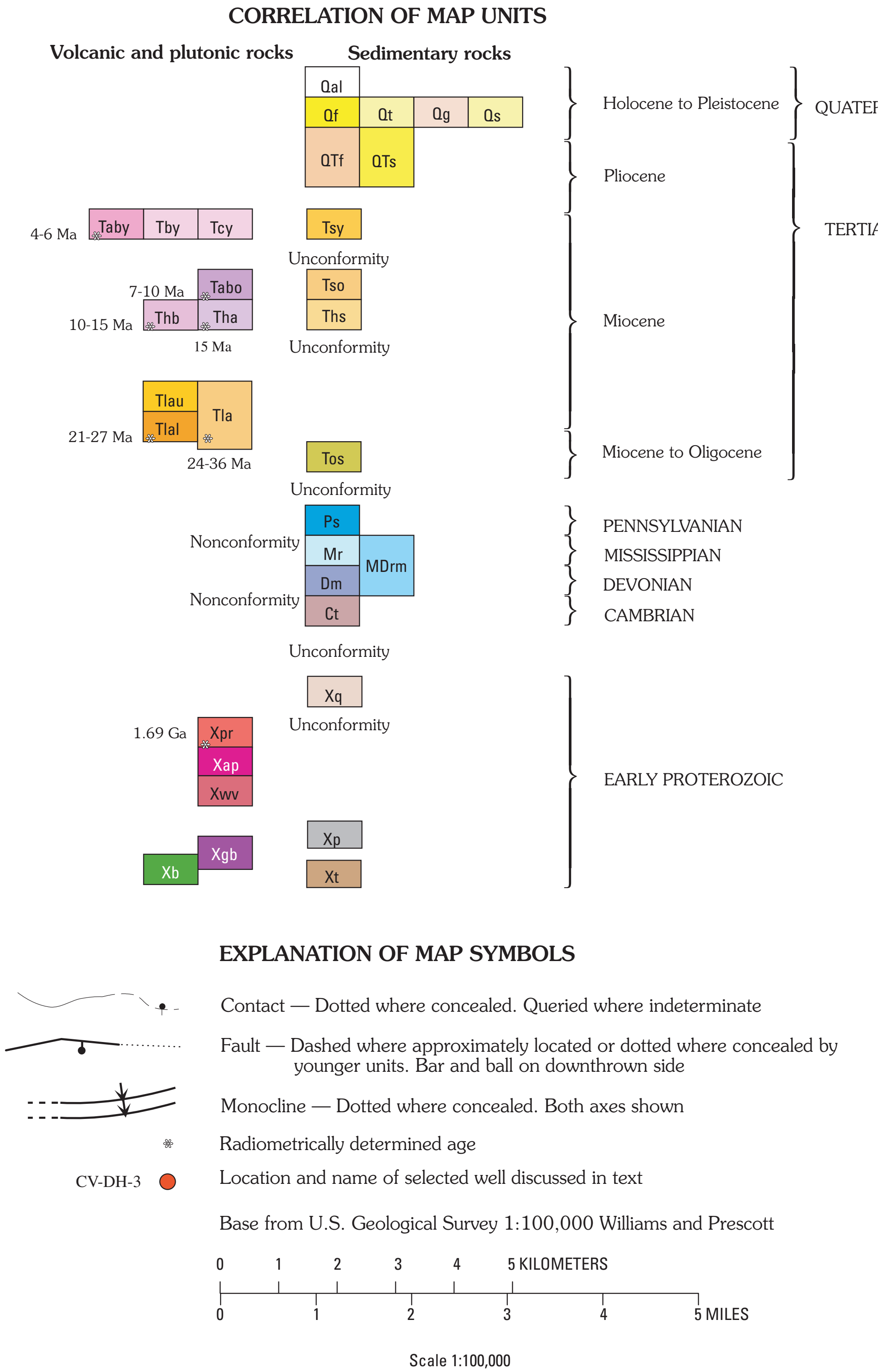


Figure B2 (above and facing page). Geologic map of the northern part of Little Chino Valley. Geology from DeWitt and others (in press).

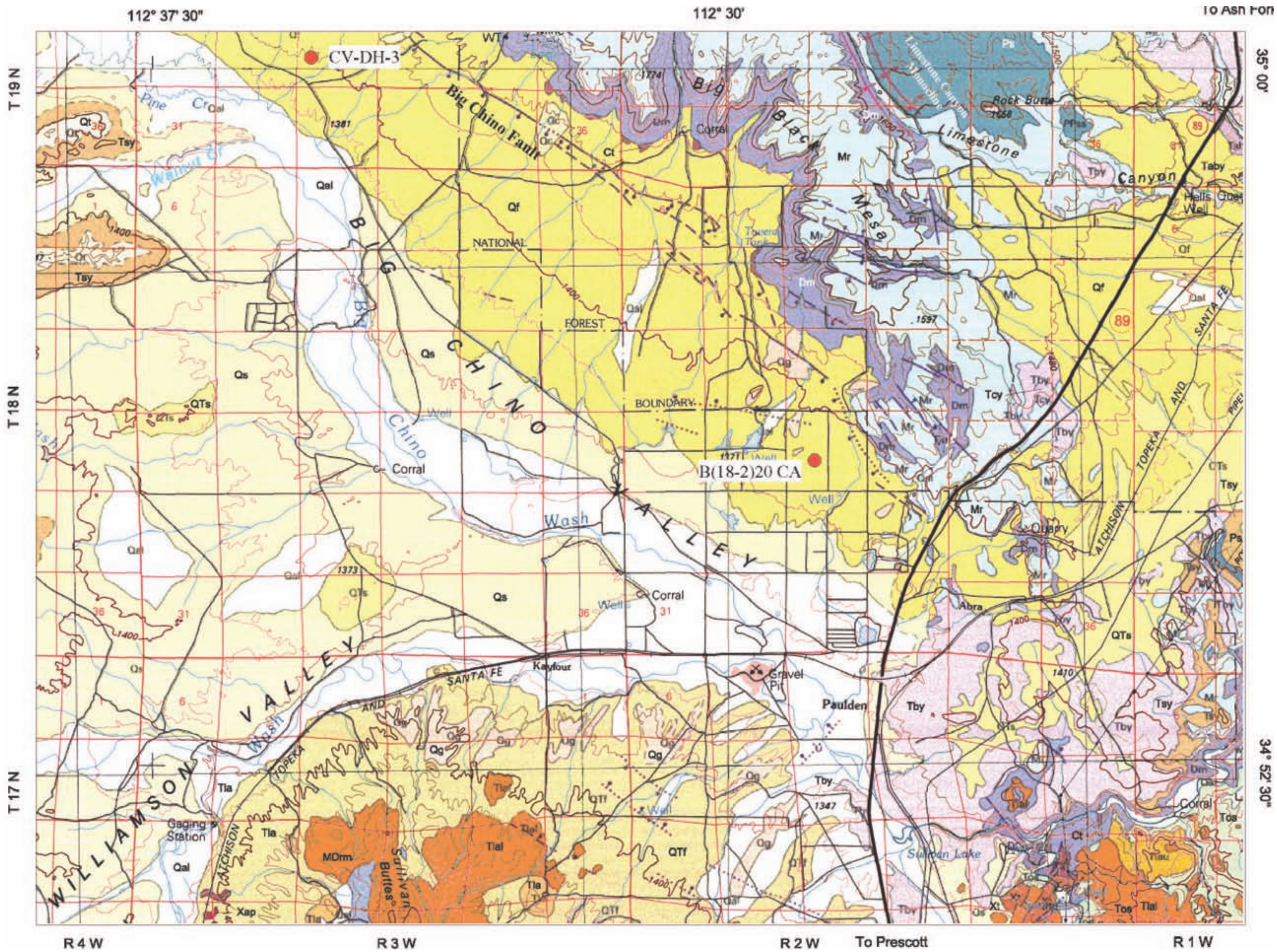


Figure B3. Geologic map of the southeastern part of Big Chino Valley. Geology from DeWitt and others (in press).

Formation. K_2O concentrations as high as 10.0 weight percent and boron concentrations as high as 280 ppm (Miesch, unpub. data in Baedecker and others, 1998) suggest that the Bright Angel Shale may contain a component of felsic tuff that was deposited in a shallow-water marine setting (Bowie and others, 1966, 1967; Hutcheon and others, 1998). However, rocks of such unusual chemical composition have not been documented in regional geologic mapping of Big Chino Valley (DeWitt, this study).

The Devonian Martin Formation (unit Dm) is extensively exposed on Big Black Mesa north of the Big Chino Fault (fig. B3), and east of Granite Creek and along the Verde River (fig. B3). The Martin is composed of thickly bedded dolomite and minor impure limestone that are about 130-m thick (Krieger, 1965). Karst features are noted near the base of the Martin, along northwest-striking, high-angle fractures (this study). For purposes of this study, the Chino Valley Formation (Hereford, 1975) is grouped within the basal Martin Formation. The Chino Valley consists of sandstone, conglomerate, and dolomitic shale (Beus, 1989) that are 5-10-m thick near Jerome (Wolfe, 1983). Aluminous rocks in the Chino Valley Formation have an unusual chemical composition characterized by K_2O concentrations as high as 8.5 weight percent (Hereford, unpub data in Baedecker and others, 1998). These aluminous rocks are similar, compositionally, to shale-rich rocks in the Bright Angel Shale and probably were formed by felsic tuff deposition in a marine basin ((Bowie and others, 1966, 1967; Hutcheon and others, 1998).

Mississippian Redwall Limestone (unit Mr) overlies the Martin Formation and is exposed extensively on the top of Big Black Mesa (fig. B3) and to a lesser extent east of Muldoon Canyon and north of the Verde River (fig. B2). The Redwall is a high-calcium limestone (contains less than 1.1% equivalent MgO) containing variable amounts of chert in thin, discontinuous beds. Karst features, including interconnected caves, are well developed in the Redwall, particularly in the middle part of the unit. Thickness of the Redwall varies according to the amount of karst and collapse in the unit, but averages about 80 m.

The Pennsylvanian Supai Formation (unit Ps), a predominantly quartz-rich clastic rock that contains minor amounts of conglomerate, limestone, and evaporite beds (unit Ps), overlies the Redwall and is exposed north of Big Black Mesa (fig. B3), and north of the Verde River and east of Muldoon Canyon (fig. B2). Much of the Supai is poorly cemented and weathers to recessive outcrops. Regionally the Supai is as much as 180 m thick (Krieger, 1965); only about 40 m of Supai is exposed in the study area. The upper part has been removed by erosion prior to Tertiary time.

Tertiary rocks

The oldest Tertiary rock unit is a distinctive and important sequence of fluvial gravels and alluvial fan deposits (unit Tos) that were derived from a regional uplift to the southwest. These gravels contain cobbles of Early Proterozoic rock units common in the Bradshaw Mountains to the south, and of Paleozoic carbonate rocks and sandstone (Krieger, 1965). Imbrication directions show northeast transport, toward the present-day Mogollon Rim. The gravels are poorly to moderately well sorted and poorly cemented, and crop out in a paleochannel, about 6.5 km wide, that extends from near Highway 89 at Del Rio Springs on the west to Muldoon Canyon on the east. The paleochannel coincides with map unit Tos in fig. B2. Maximum thickness of the unit is about 75 m (Krieger, 1965). The gravel deposits extend beneath Little Chino Valley and the town of Chino Valley and form part of the productive artesian aquifer (Schwalen, 1967). The extent of the channel north of the Verde River cannot be determined because of erosion and cover by younger gravel deposits. Because the gravels are preserved beneath 24-Ma lati-andesite flows, the unit is Oligocene or older. The Tertiary tectonic history of the Basin-and-Range province south of the Bradshaw Mountains suggests that the channel deposits are probably no older than 34 Ma (Spencer and Reynolds, 1989).

No other gravel of this age is known in the study area, but other similar deposits are exposed farther west in Big Chino Valley, near South Butte (fig. B1). There, conglomerate containing clasts of Early Proterozoic gabbro and metasedimentary rocks, and Middle Proterozoic granite, as well as Paleozoic sandstone and carbonate rocks, unconformably overlies Martin Formation and Redwall Limestone. Clast imbrications indicate transport to the northeast. Streams in that area eroded Proterozoic basement and Paleozoic strata on the south side of present-day Big Chino Valley and transported the clasts across the site of the future valley to the northeast. Locally, lati-andesite flows cap South Butte at an elevation higher than the Tertiary conglomerate. The extent of this paleochannel and associated gravels cannot be determined due to extensive erosion of the conglomerate.

Lati-andesite

Lati-andesite (a rock composition intermediate between latite and andesite) and associated volcanic rocks (units Tla, Tlal, Tlau) are exposed northeast and northwest of Little Chino Valley (fig.2) and in the Sullivan Buttes area, south of Big Chino Valley (fig. B3). Eruptions began with formation of mafic cones and flows (part of unit Tlal); younger flows, domes, and breccias of intermediate composition followed (also part of unit Tlal); late eruptions were of locally thick mafic flows (unit Tlau). Both extrusive sheets and intrusive necks and plugs are well preserved, some in large ring dikes (Krieger, 1965; Tyner, 1984; Ward, 1993). Individual eruptive centers produced extrusive sheets whose partially eroded remnants are less than 1,500 m in diameter and less than 200 m thick. Preserved plugs are less than 300 m in diameter.

The most mafic rock types are alkali-calcic alkali basalt; least mafic rock types are alkali-calcic dacite (fig. B4A). Very low A/CNK ratios (fig. B4B), potassic to very potassic nature (fig. B4C), and very Mg-rich to Mg-rich nature (fig. B4D) allow the lati-andesite to be distinguished from Miocene and

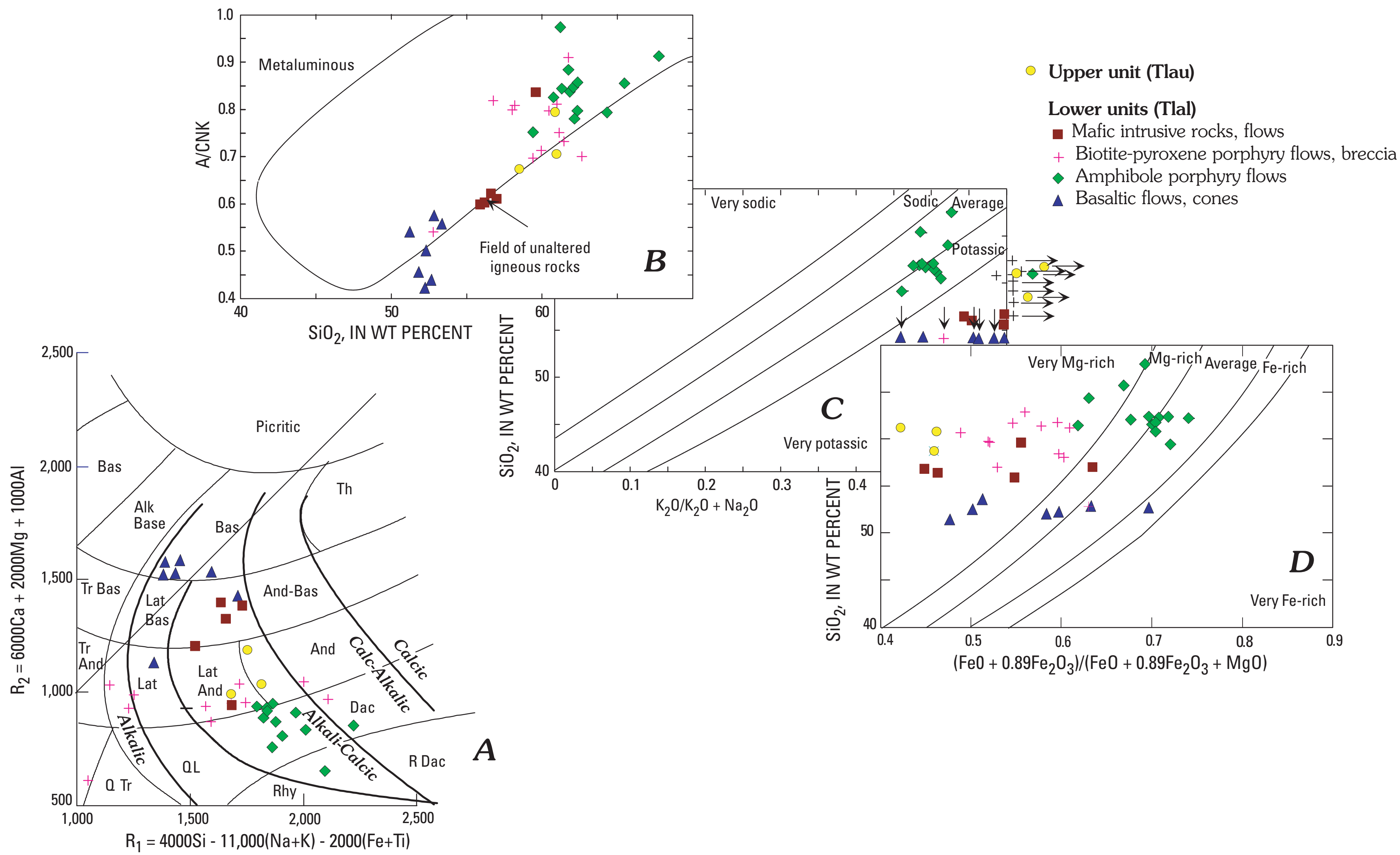


Figure B4. Major-element classification diagrams for 21-27-Ma volcanic rocks in the Sullivan Buttes volcanic field (units Tlal, Tlau, and Tla) near Chino Valley. Data from Tyner (1984), Ward (1993), and this study. *(A)*, R_1R_2 major-element classification diagram (De la Roche and others, 1980). Picritic, ultramafic composition; Bas, basinite; Alk Bas, alkali basalt; Bas, basalt; Th, tholeiite; Tr Bas, trachybasalt; Lat Bas, lati-basalt; And-Bas, andesitic basalt; Tr And, trachyandesite; Lat, latite; Lat And, lati-andesite; And, andesite; Q Tr, quartz trachyte; QL, quartz latite; Dac, dacite; Rhy, rhyolite; R Dac, rhyodacite. Fields of alkalinity from Fridrich and others (1998). *(B)*, Alumina saturation diagram (SiO_2 versus A/CNK). A, molar Al_2O_3; C, molar CaO; N, molar Na_2O; K, molar K_2O. Field of unaltered igneous rocks from DeWitt and others (2002). *(C)*, Alkali classification diagram ($K_2O/(K_2O + Na_2O)$ versus SiO_2). Field boundaries from Fridrich and others (1998). Samples with horizontal arrows plot far to the right of the outline of (C). Samples with vertical arrows plot in the very potassic field, below the outline of (C). *(D)*, Iron enrichment classification diagram ($(FeO + 0.89*Fe_2O_3)/(FeO + 0.89*Fe_2O_3 + MgO)$ versus SiO_2. Field boundaries from DeWitt and others (2002).

younger basaltic rocks. Lati-andesite and associated rocks have elevated Th and U concentrations, and are easily distinguished from other Tertiary volcanic rocks on radiometric maps (Langenheim and others, 2000). Although the youngest flows physically resemble Miocene and younger basalts, elevated Th and U concentrations allow differentiation from Miocene and younger basalt. Remnants of the oldest basaltic latites, recognized by elevated Th and U concentrations, were remapped (this study) in areas previously thought to be covered by younger basalt, especially in the area northeast of Granite Creek (fig. B2).

The lati-andesite forms a volcanic field that overlies a dissected surface underlain by rocks ranging in age from the Early Proterozoic Mazatzal Group through the Permian Supai Formation. Much of the lati-andesite was erupted onto the Martin Formation. The age of volcanism appears to be about 24 Ma, as determined by limited K-Ar dating of hornblende and biotite (Krieger and others, 1971). The original extent of the volcanic field was larger than the remnant preserved in the study area. The volcanic field extended into the northern part of Little Chino and Lonesome Valleys and occupied a considerable part of the southeastern part of Big Chino Valley as evidenced by magnetic data (Langenheim and others, 2000; Langenheim and others, this volume). Intrusive centers are consistently reversely magnetized, leading to a pattern of conspicuous magnetic lows on magnetic maps (Langenheim and others, this volume). Locations of such lati-andesite centers buried beneath basin fill can be accurately determined (fig. B5A and B). Outcrops of lati-andesite and related rocks to the west of Big Chino Valley, in the Camp Wood area (Ash, 1997), suggest continuity of the volcanic field across much of Williamson Valley Wash and some of southern Big Chino Valley.

In Bureau of Reclamation drillhole CV-DH-3, located in central Big Chino Valley (fig. B3), biotite-rich volcanic rock was encountered at about 698 m (2290 ft) depth, but was identified as basalt (Ostenaa and others, 1993b). X-ray diffraction data corroborate the presence of biotite and indicate significant potassium feldspar. Chemical data confirm that the rock is a lati-andesite, we tentatively correlate it with lati-andesite in the Sullivan Buttes area.

Hickey Formation and Older Basalt and Sedimentary Rocks

The Miocene Hickey Formation, consisting of regionally extensive basalt flows and less extensive sedimentary rocks, crops out in the surrounding mountain ranges, especially in the Black Hills, and in the Bradshaw Mountains (fig. B1). Basalt flows in the Hickey Formation that erupted from the northern Black Hills are present just east of Lonesome Valley and probably underlie much of eastern Lonesome Valley. No flows of Hickey age are recognized in the Big Chino Valley area.

West of the town of Chino Valley, a locally thick hornblende-bearing trachyandesite to trachybasalt (unit Tha) overlies Early Proterozoic basement rocks. This hornblende-rich rock is mineralogically similar to trachyandesite at Thumb Butte, west of Prescott, which has a $^{40}Ar/^{39}Ar$ groundmass date of 14.8 Ma (Nichols Boyd, 2001). Rocks of similar mineralogy are exposed along Granite Creek southeast of the town of Chino Valley (Krieger, 1965) and are included in the Hickey Formation for this report. Samples of this rock contain calcite and plot above the field of those at Thumb Butte (fig. B6A), but the sample containing the least calcite has similar A/CNK ratio (fig. B6B) and Fe/Fe+Mg ratio (fig. B6D) to the Thumb Butte rocks. The top surface of the trachyandesite flow can be traced using interpreted well logs toward the town of Chino Valley for a distance of about 5.5 km (fig. B7), and probably extended farther northeast before formation of the basin in northeastern Little Chino Valley after about 7 Ma.

Discontinuously exposed basalt flows (unit Thb), thought to be in the Hickey Formation (Krieger, 1965), extend from Table Mountain to Black Hill. Chemistry of one sample from Black Hill is similar to many samples in the Prescott area (fig. B6). The upper surface of the flow(s) can be traced toward the town of Chino Valley by the interpretation of well logs (fig. B7). Prior to development of the basin in northeastern Little Chino Valley, the flow(s) could have extended farther northeast.

Sedimentary rocks tentatively assigned to the Hickey Formation (unit Ths) crop out between Black Hill and Table Mountain (fig. B2). Rock types include poorly sorted conglomerate, fluvial sandstone, and minor clay-rich beds. East of Granite Creek these sedimentary rocks underlie the basalt flow on Black Hill. The base of the sedimentary rocks is not exposed. A partial thickness in excess of 35 m is indicated.

One distinctive and extensive basalt flow (unit Tabo) extending from King Tank to Muldoon Canyon (fig. B2) is believed to be younger than the Hickey Formation (< 10 Ma), but older than younger basalt flows (4-6 Ma). This basalt is extremely magnetic (about 10 volume- percent magnetite-equivalent), crops out over a large area, and extends to the northeast of Bull Basin Canyon (fig. B2). Originally considered a part of the lati-andesite (Krieger, 1965), this basalt is characterized by its low eU (equivalent uranium) and Th concentrations (Langenheim and others, 2000) and alkalic chemistry (fig. B6), and is presumed to be unrelated to the lati-andesite. Its present topographic position, at an elevation lower than the Hickey Formation, but higher than younger basalt flows, suggests an intermediate age of 7-10 Ma, but the flow could be within the range of the Hickey Formation.

Beneath the magnetic basalt flow along Bull Basin Canyon (fig. B2) are sedimentary rocks consisting of distal fanglomerate, fluvial conglomerate, and minor sandstone (unit Tso). Clasts in the conglomerate were derived, predominantly, from the southwest, as indicated by clast imbrication and composition. Originally mapped as sedimentary rocks beneath lati-andesite (Krieger, 1965), we interpret the rocks to be filling an 7-10-Ma channel that cut down to the present-day elevation of the Verde River southeast of Bald Hill, near the Paulden gage (fig. B2). Similar rocks crop out on the north side of the river, but some of them may have been derived from the northwest or were locally reworked. Thickness of the sedimentary rocks along the northern part of Bull Basin Canyon is as much as 90 m.

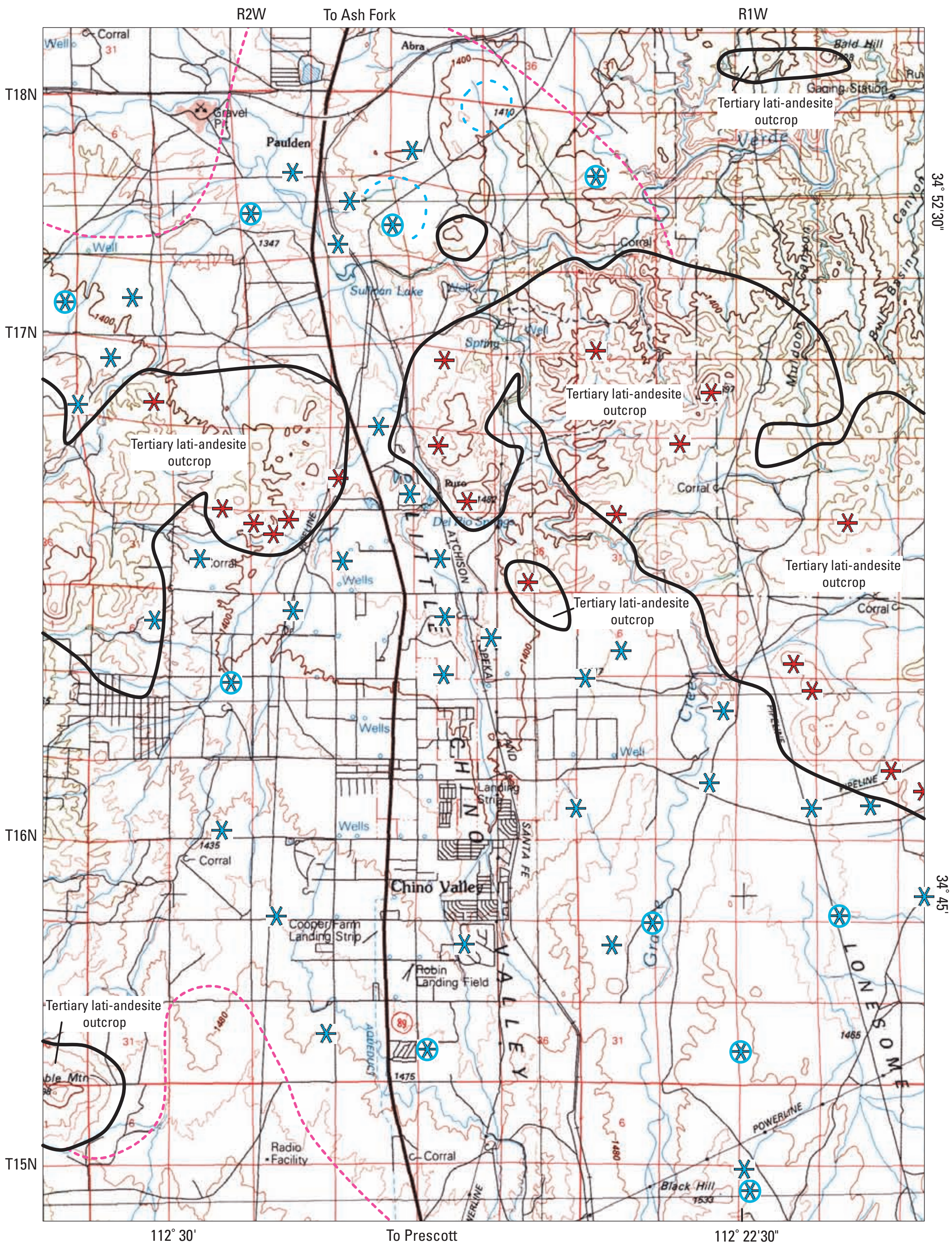
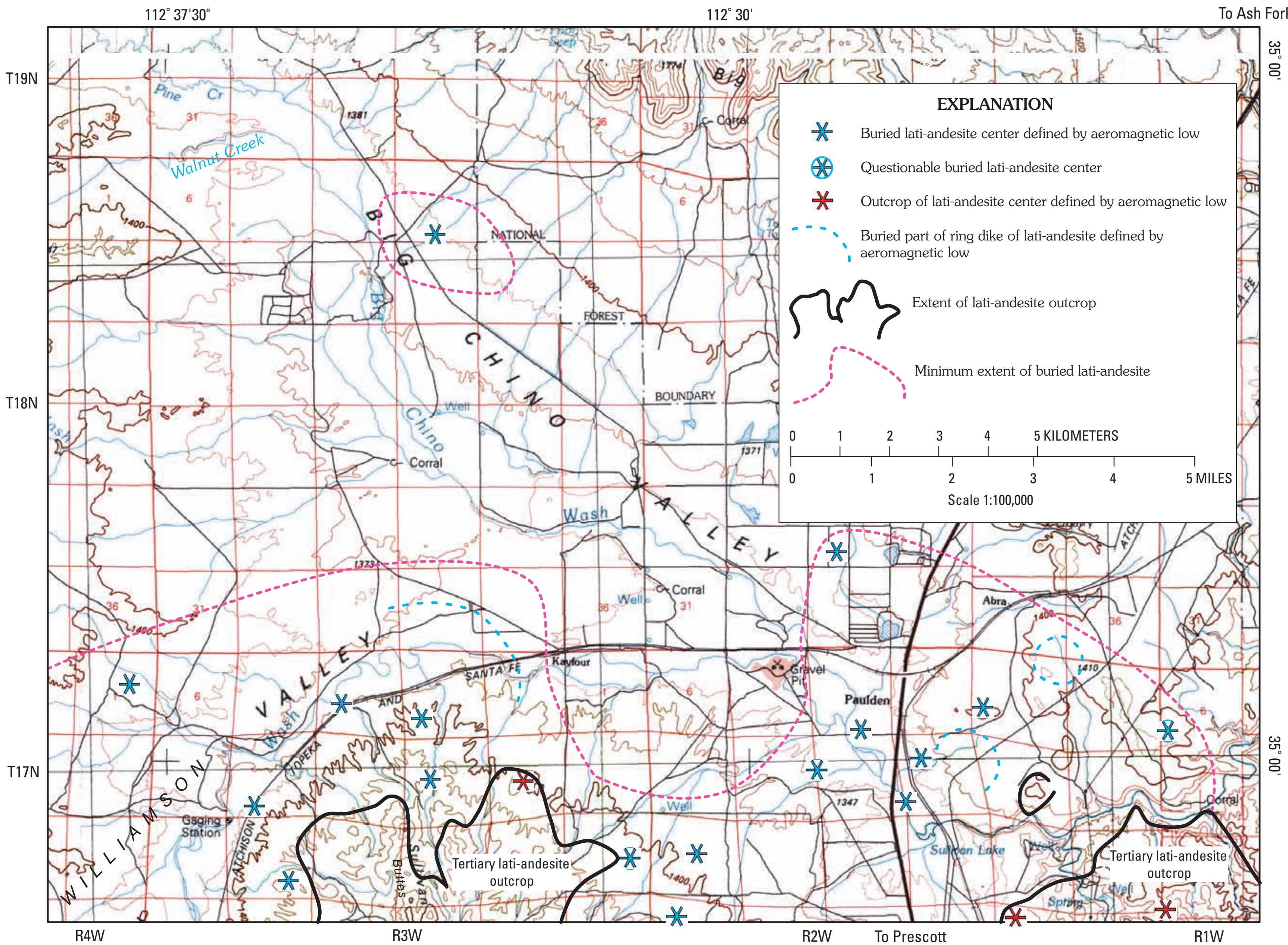


Figure B5 (above and facing page). Maps showing location of buried lati-andesite centers. *(A)*, Little Chino Valley; *(B)*, Big Chino Valley.



112° 37'30"
112° 30'
To Ash Fork
35° 00'
T19N
T18N
T17N
R4W
R3W
R2W
R1W
To Prescott
EXPLANATION
Buried lati-andesite center defined by aeromagnetic low
Questionable buried lati-andesite center
Outcrop of lati-andesite center defined by aeromagnetic low
Buried part of ring dike of lati-andesite defined by aeromagnetic low
Extent of lati-andesite outcrop
Minimum extent of buried lati-andesite
0 1 2 3 4 5 KILOMETERS
0 1 2 3 4 5 MILES
Scale 1:100,000
Tertiary lati-andesite outcrop
Tertiary lati-andesite outcrop
BIG CHINO VALLEY
WILLIAMSON VALLEY
Walnut Creek
Pine Cr
NATIONAL
FOREST
BOUNDARY
Corral
Well
Kayfour
SANTA FE
Gravel Pit
Paulden
Abra
Sullivan Lake
Gaging Station
Spring

Younger Basalt and Sedimentary Rocks

Extensive basalt flows (units Tby and Taby), derived primarily from eruptive centers on the Colorado Plateau to the north, flowed over the Mogollon Rim and into Big Chino Valley and the present-day area of the Verde River east of Paulden from about 4 to 6 Ma (fig. B2). Cinder cones (unit Tcy), such as the one northeast of Paulden (fig. B3) provided local sources for some of the flows. These flows are part of the Miocene Perkinsville Formation (Lehner, 1958), defined to the east of the map area. Northeast of Hells Well (fig. B3), a flow near the Drake railroad siding is 6.0 Ma (K-Ar whole rock, McKee and Anderson, 1971). This flow probably extends southeast toward Hell Point (fig. B1). Extensive basalt flows (unit Tby) east and south of Paulden are 4.5 Ma (K-Ar whole rock, McKee and Anderson, 1971) and provide important limitations on the configuration of basin fill beneath the basalt.

The 4.5-Ma basalt outcrop east and south of Paulden consists of three flows, two of which fill a paleocanyon in the gorge of the Verde River east of Sullivan Lake. An arcuate paleocanyon (fig. B8A), having a steep southeastern wall, is partially filled by the lowest flow, which is a minimum of 30-m thick. The middle flow, which is about 40- m thick, fills the rest of the paleocanyon and is separated from the lowest flow by less than 1 m of conglomerate derived from lati-andesite to the south. This middle flow has the 4.5-Ma age determination. The top flow is exposed north of the gorge; its eroded thickness is less than 10 m. A 1-m-thick conglomerate containing clasts of lati-andesite separates the top flow from the middle flow. Location of the paleocanyon can be determined to the west, beneath Quaternary and Tertiary valley fill in Big Chino Valley, by the greatest thickness of basalt (fig. B8B). Well logs document the presence of buried basalt at least 8 km northwest of Paulden, at a depth of greater than 175 m (570 ft). Magnetic data (Langenheim and others, 2000; Langenheim and others, this volume) confirms the presence of basalt in the subsurface slightly farther to the northwest. The thickest accumulation of basalt, in excess of 125 m (400 ft) south of Abra, fills the paleocanyon cut into Paleozoic bedrock. This thick section of basalt was interpreted to result from a narrow, buried graben (Water Resource Associates, Inc., 1991). To the northeast, location of the paleocanyon is approximately indicated by logs of water wells; the canyon appears to curve to the north and northwest, and may have drained Limestone Canyon during the time of basalt eruptions.

Basalt in the paleocanyon and beneath Big Chino Valley to the west of Paulden may have been derived, in part, from the cinder cone northeast of Paulden along Highway 89 (fig. B2), but much of the basalt south of Paulden could have had local, concealed sources, most likely northwest-striking, high-angle feeder dikes. Abundant cinders noted in well logs southwest of Sullivan Lake (Arizona Department of Water Resources, 2003) suggest a buried cinder cone that could have fed some of the flows from the south. The present dip of the top surface of the flows beneath Big Chino Valley, to the northwest, averages only one degree (fig. B8B). Subsidence since 4.5-Ma must account for part of that dip, leaving a dip surface of less than one degree down the valley during basalt eruption. A local source for the basalt would aid flow down a surface of such minimal dip.

North of Abra (fig. B3) basalt flowed over Paleozoic strata and into the basin of Big Chino Valley. A small, sinuous canyon may have been cut in Paleozoic bedrock north of Abra where basalt is locally more than 30- m thick (fig. B8B). East of Paulden the basalt flowed over Paleozoic bedrock before encountering Tertiary sediments in Big Chino Valley. In DRM-2 (fig. B8A), a well west of Paulden (B17-2)4 CAD, basalt overlies 75 m of Tertiary fine-grained sediment that is part of the valley fill in Big Chino Valley (Water Resource Associates, Inc., 1990). Given the thickness and fine grain size of sediment beneath the basalt at this location, the margin of the Big Chino basin must be east of Highway 89 and be buried by basalt. South of Sullivan Lake, basalt flows thin against a buttress of lati-andesite flows. Decreasing thickness to the south (fig. B8B), in the region 2 km north of Del Rio Springs (fig. B3), suggests that the basalt flows never reached Little Chino Valley, but were deflected to the west into the deeper part of Big Chino Valley (fig. B8B). Logs from wells are lacking north of Del Rio Springs, but wells south of Del Rio Springs show no evidence of 4-6-Ma basalt flows in northern Little Chino Valley.

Chemistry of all the younger basalt flows in the area is similar (fig. B9). The middle and top flows of the 4.5-Ma sequence near Paulden are identical, within uncertainty, to the cinder cone northeast of Paulden. Magnetic susceptibility measurements of all three flows are similar, and are higher than basalt from the cinder cone. The 6.0-Ma flows near Drake and Hell Point also are chemically similar to the flows near Paulden (fig. B9).

These 4.5-Ma basalt flows are present, at the same elevation, on both sides of the present-day Verde River downstream from Sullivan Lake (fig. B2). An ancestral Verde River was not present in that area at 4.5 Ma. Similarly, the flow at Hell Point (fig. B1; Krieger, 1965) extends across the Verde River, indicating that neither the river nor Hell Canyon were developed in that area at 6.0 Ma. Stream cobbles found on top of the 4.5-Ma basalt flow on the north side of the Verde River north of Lower Granite Spring were derived from the south, in the Bradshaw Mountains, not from the west in the Juniper and Santa Maria Mountains (DeWitt, this study). Therefore, after 4.5 Ma, the ancestral Verde River appears to have flowed to the north from the Bradshaw Mountains to the present-day confluence of Granite Creek and the Verde River. The location of present-day Granite Creek may have been the site of the ancestral Verde River.

Basalt-cobble conglomerate and limestone-cobble conglomerate (unit Tsy) are locally interbedded with the basalt flows, especially in the area 7 km south of Hells Well (Krieger, 1965). Regionally, such fluvial systems were flowing from north to south, off the Mogollon Rim (McKee and McKee, 1972). Locally, fluvial systems were draining uplifts such as Big Black Mesa, where limestone-cobble conglomerate was

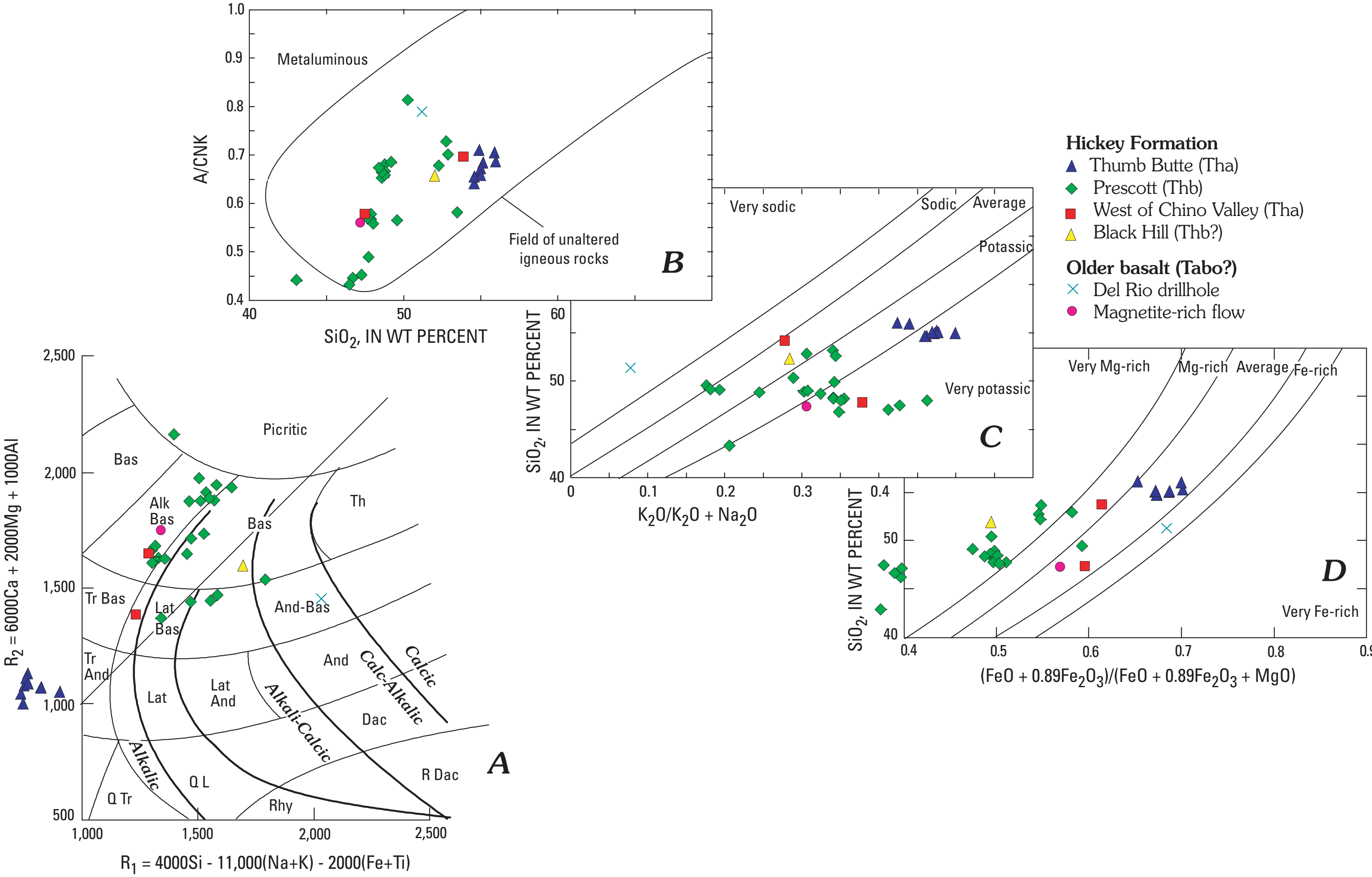


Figure B6. Major-element classification diagrams for 10-15 Ma volcanic rocks of the Hickey Formation (units Thb, and Tha) and 8-10 Ma volcanic rocks (unit Tbo) near Prescott and Chino Valley. Data from this study, McKee and Anderson (1971), and Nichols Boyd (2001). Rock abbreviations and field boundaries defined in figure B4. Samples from Thumb Butte are in the trachyandesite field, and are plotted correctly, but are to the left of the outline of (A). Samples from near Prescott are in the very Mg-rich field, and are plotted correctly, but are to the left of the outline of (D).

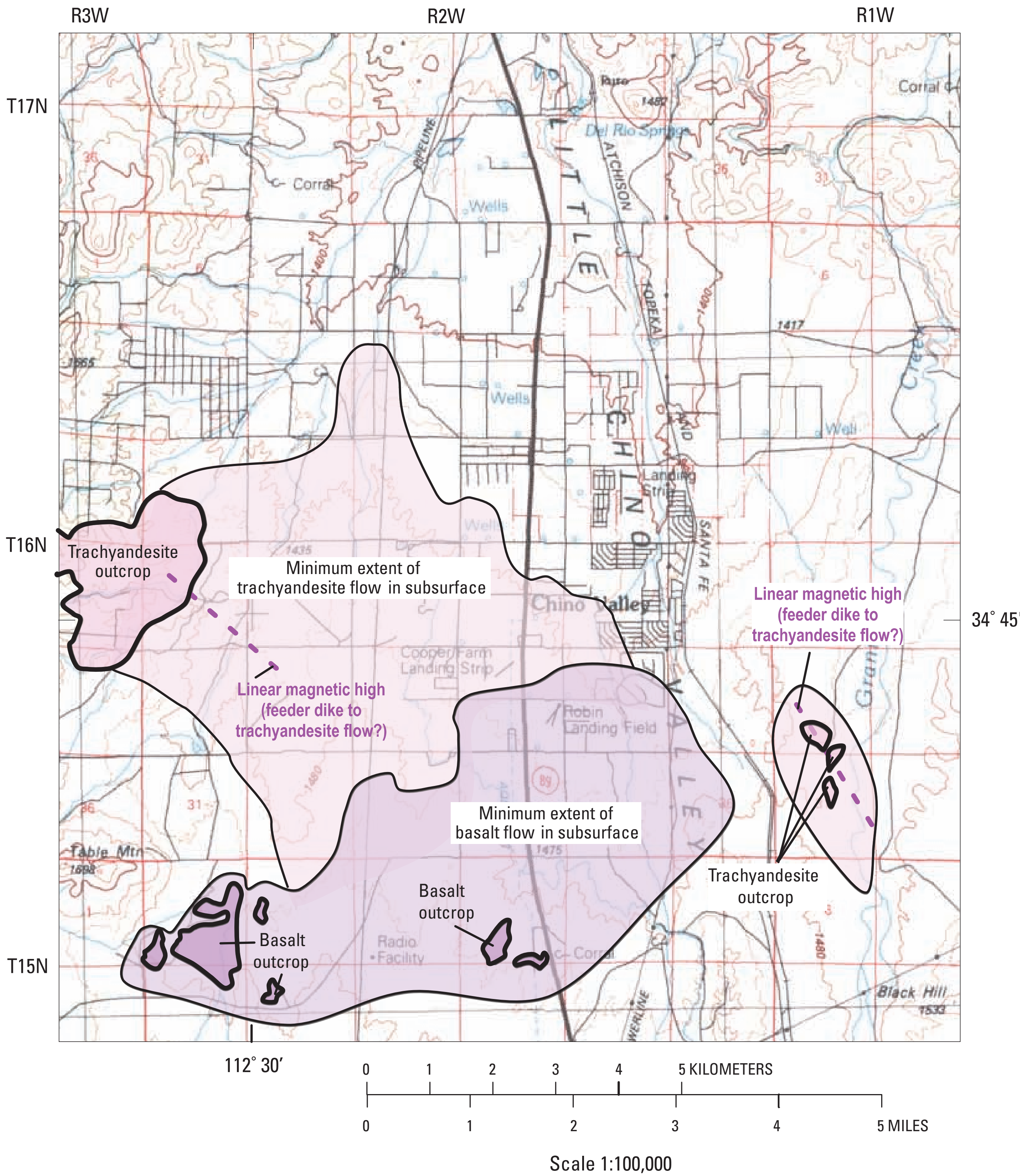


Figure B7. Map showing extent of 10-15-Ma flows in the Hickey Formation, Little Chino Valley.

shed to the southeast and was intermixed with the basalt flows. These younger sedimentary rocks are discernible from the sedimentary rocks older than the lati-andesite by virtue of the abundance of basalt cobbles and virtual lack of Early Proterozoic basement clasts.

Tertiary and Quaternary sediment in Big and Little Chino Valleys

Tertiary and Quaternary sediments consist of proximal and distal alluvial fan deposits (units Qf, QTf), fine-grained alluvial sediments (units Qs, QTs), terrace gravels (unit Qt), thin sheet-like deposits of gravel (unit Qg), and alluvial material in present-day streams (unit Qal). Alluvial fans are most abundant in Big Chino Valley where they extend away from Big Black Mesa and radiate from the Sullivan Buttes (fig. B3). Fine-grained alluvial sediments are common in the central parts of Little and Big Chino Valleys (figs. B2 and B3). Terrace gravels are common along Granite Creek in Little Chino Valley (fig. B2) and Walnut Creek in Big Chino Valley (fig. B3). Sheets of gravel (unit QTf) are restricted to the area radiating away from the Sullivan Buttes (figs. B2 and B3). Alluvial material is present in the modern drainages of Granite Creek (fig. B2), Big Chino Wash, and Williamson Valley Wash (fig. B3). The distribution of surficial deposits shown in figures B2 and B3 has been simplified from previous investigations (Ostenaa and others, 1993b, plate 1).

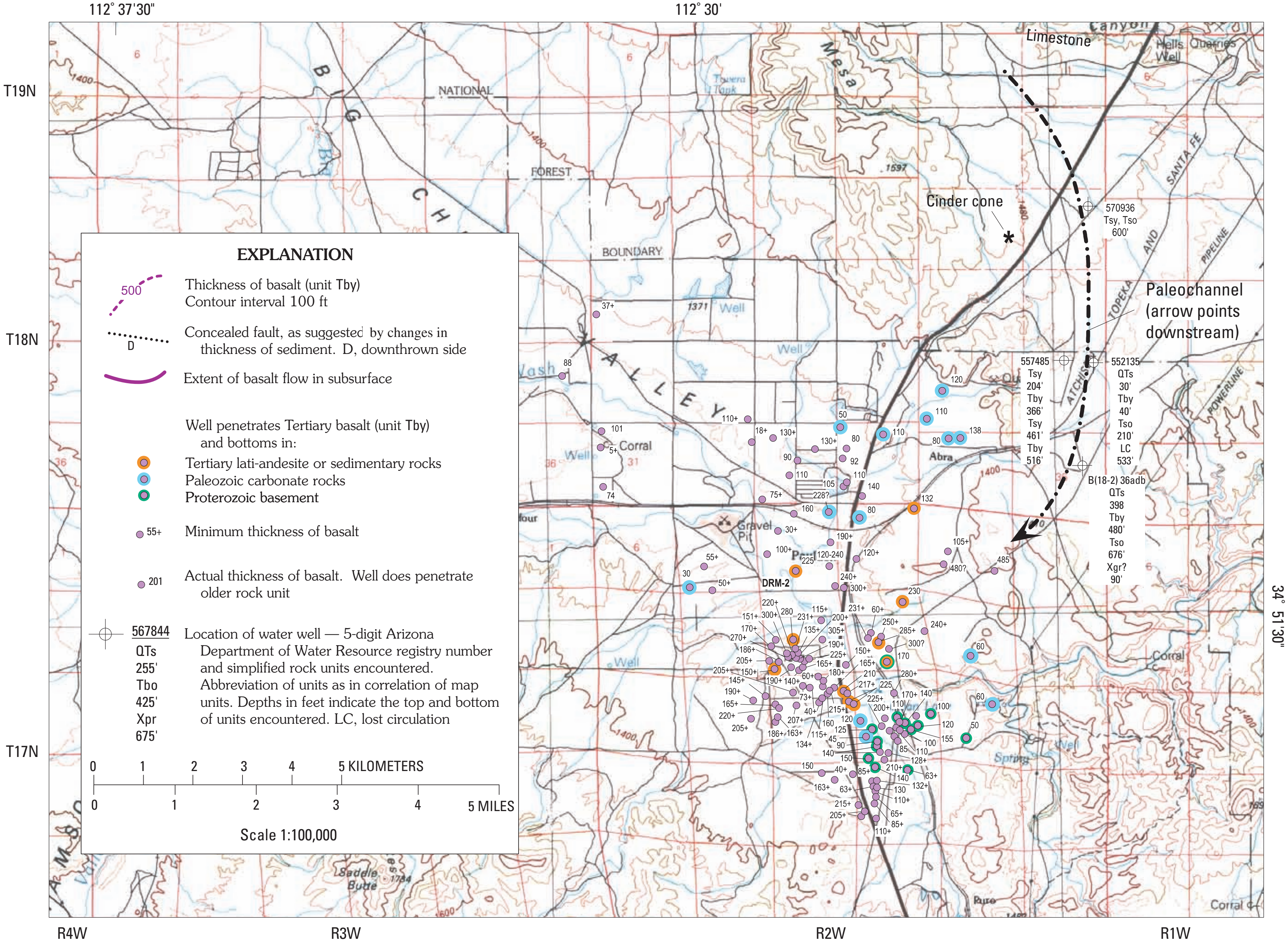
Extensive alluvial fans composed primarily of carbonate clasts and detritus extend away from outcrops of Paleozoic carbonate rocks along Big Black Mesa (fig. B3). Fans are of low slope, but extend as much as 5 km into Big Chino Valley. Cobbles as large as 1 m near the mountain front give way to pebble-size clasts near the bottom of the fans. These carbonate-rich fans are recognized on eU and Th radiometric maps (Langenheim and others, 2000) by their very low concentrations of radioactive elements. Distal parts of the fans may contain a significant amount of fine-grained basin fill. Fans are thickest near the mountain front. About 150 m (500 ft) of alluvial fan sediment overlies playa sediments in the Bureau of Reclamation drill hole CV-DH3 near the Big Chino Fault (Ostenaa and others, 1993b) in Big Chino Valley (fig. B10).

Alluvial fans composed primarily of clasts of lati-andesite and minor Paleozoic carbonate rock radiate from Sullivan Buttes (fig. B3). These fans have moderate slope and extend as much as 3.5 km away from outcrop in the Sullivan Buttes. Cobble- to pebble-size clasts of lati-andesite are common along the length of the fans, as the lati-andesite is more resistant to transport than carbonate material. Because of the abundance of lati-andesite, the alluvial fans have high concentrations of eU and Th, and stand out on radiometric maps (Langenheim and others, 2000) as distinct from fans containing abundant carbonate clasts. Radiometric logs of a well north of Sullivan Buttes (Ostenaa and others, 1993b) indicate that the fans extend into southeastern Big Chino Valley to depths of greater than 220 m. Fans of this nature are not recognized at the northern margin of Little Chino and Lonesome Valley, and probably were never formed in that area. Remnants of such fans would be preserved in some of the valleys draining south into present-day Lonesome Valley if they had formed in Quaternary to Tertiary time.

Fine-grained alluvial sediment in the centers of Big and Little Chino Valleys is diverse in composition. Material in western Big Chino Valley and Williamson Valley contains pebbles of Proterozoic basement rocks, lati-andesite, and basalt in a carbonate-poor to carbonate-rich matrix. Clasts decrease in abundance toward the central part of Big Chino Valley, where sediment at the surface is carbonate rich and fine grained. The western side of Little Chino Valley contains sediment similar in composition to that in Williamson Valley, as it was derived from bedrock of similar composition in the eastern Sullivan Buttes and the Bradshaw Mountains to the southwest (fig. B1). Eastern Little Chino Valley and Lonesome Valley contain carbonate-rich fine-grained sediments derived from weathering of Paleozoic strata in the Black Hill to the east (fig. B1). Beds containing high concentrations of clay minerals are more common in Lonesome Valley than in the western part of Little Chino Valley.

Playa deposits in Big Chino Valley. In order to understand the mineralogy and distribution of sediments in central Big Chino Valley, archived samples from Bureau of Reclamation drillholes (Ostenaa and others, 1993b) were analyzed by x-ray diffraction techniques. Samples were analyzed at 30-m (100-ft) intervals in the three drillholes; selected qualitative mineral abundances are shown for various depths (fig. B10). Caution is urged in the interpretation of the results because the holes were drilled using muds containing clay minerals, and only chips are available from the drilling. Although care was exercised in washing drilling mud from the chips, some could have adhered to the chips (Ostenaa and others, 1993b). Also, chips may circulate up and down the hole during drilling, creating a sample that is a composite of an interval of sediment. Grain size of the sediment cannot be determined from the chips because of the small size of the chips and because dissolution of carbonate-cemented and sulfate-bearing materials could take place during drilling. Depths and thicknesses are noted in feet (meters in parentheses) in the following discussion because original depths, thicknesses, and descriptions of the drillholes are in feet (Ostenaa and others, 1993b).

Two minerals were found in deposits interpreted to have been deposited in a playa environment in Big Chino Valley. Analcime, a zeolite mineral, is recognized in all three drillholes. Bloedite, a sodium sulfate mineral, is tentatively identified from selected samples from the three drillholes. Other minerals, predominantly feldspars, interfere with a positive identification of bloedite(?). Chemical analyses or scanning electron imaging may be needed to corroborate the presence of bloedite(?). From 500 foot depth (150 m) to 2300 foot depth (700 m) in CV-DH-3 both minerals are noted and analcime is abundant. In CV-DH-1 an interval from 50 foot depth (15 m) to 850 foot depth (260 m) contains both minerals. Only one sample in CV-DH-2 contains the minerals, at about 220 foot depth (67 m). Analcime can be formed by the diagenetic



112° 37'30"
112° 30'
T19N
T18N
T17N
R4W
R3W
R2W
R1W
34° 51'30"
EXPLANATION
500
Thickness of basalt (unit Tby)
Contour interval 100 ft
D
Concealed fault, as suggested by changes in thickness of sediment. D, downthrown side
Extent of basalt flow in subsurface
Well penetrates Tertiary basalt (unit Tby) and bottoms in:
Tertiary lati-andesite or sedimentary rocks
Paleozoic carbonate rocks
Proterozoic basement
55+
Minimum thickness of basalt
201
Actual thickness of basalt. Well does penetrate older rock unit
567844
QTs
255'
Tbo
425'
Xpr
675'
Location of water well — 5-digit Arizona Department of Water Resource registry number and simplified rock units encountered. Abbreviation of units as in correlation of map units. Depths in feet indicate the top and bottom of units encountered. LC, lost circulation
0 1 2 3 4 5 KILOMETERS
0 1 2 3 4 5 MILES
Scale 1:100,000
Limestone
Hells Quarries Well
Cinder cone
570936
Tsy, Tso
600'
Paleochannel
(arrow points downstream)
557485
Tsy
204'
Tby
366'
Tsy
461'
Tby
516'
552135
QTs
30'
Tby
40'
Tso
210'
LC
533'
B(18-2) 36adb
QTs
398
Tby
480'
Tso
676'
Xgr?
90'
DRM-2
NATIONAL
FOREST
BOUNDARY
Corral
Gravel Pit
Abra
SANTA FE
AND
TOPEKA
PIPELINE
POWERLINE

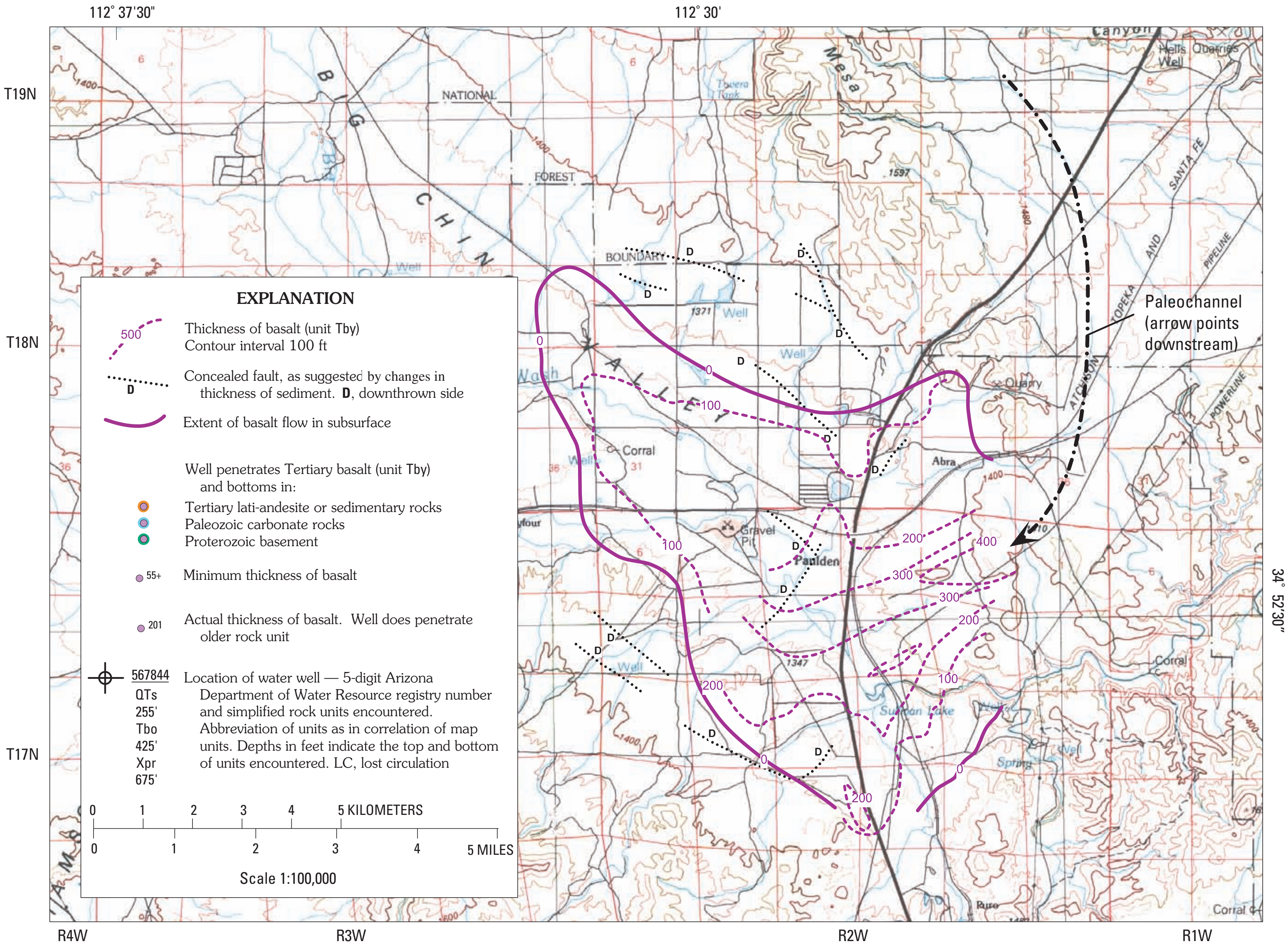


Figure B8 (above and facing page). *(A),* Maps showing thickness of 4-6-Ma basalt flows in southeastern Big Chino Valley. (A) Well locations and thickness determinations. *(B),* Isopachs of basalt thickness and locations of buried faults.

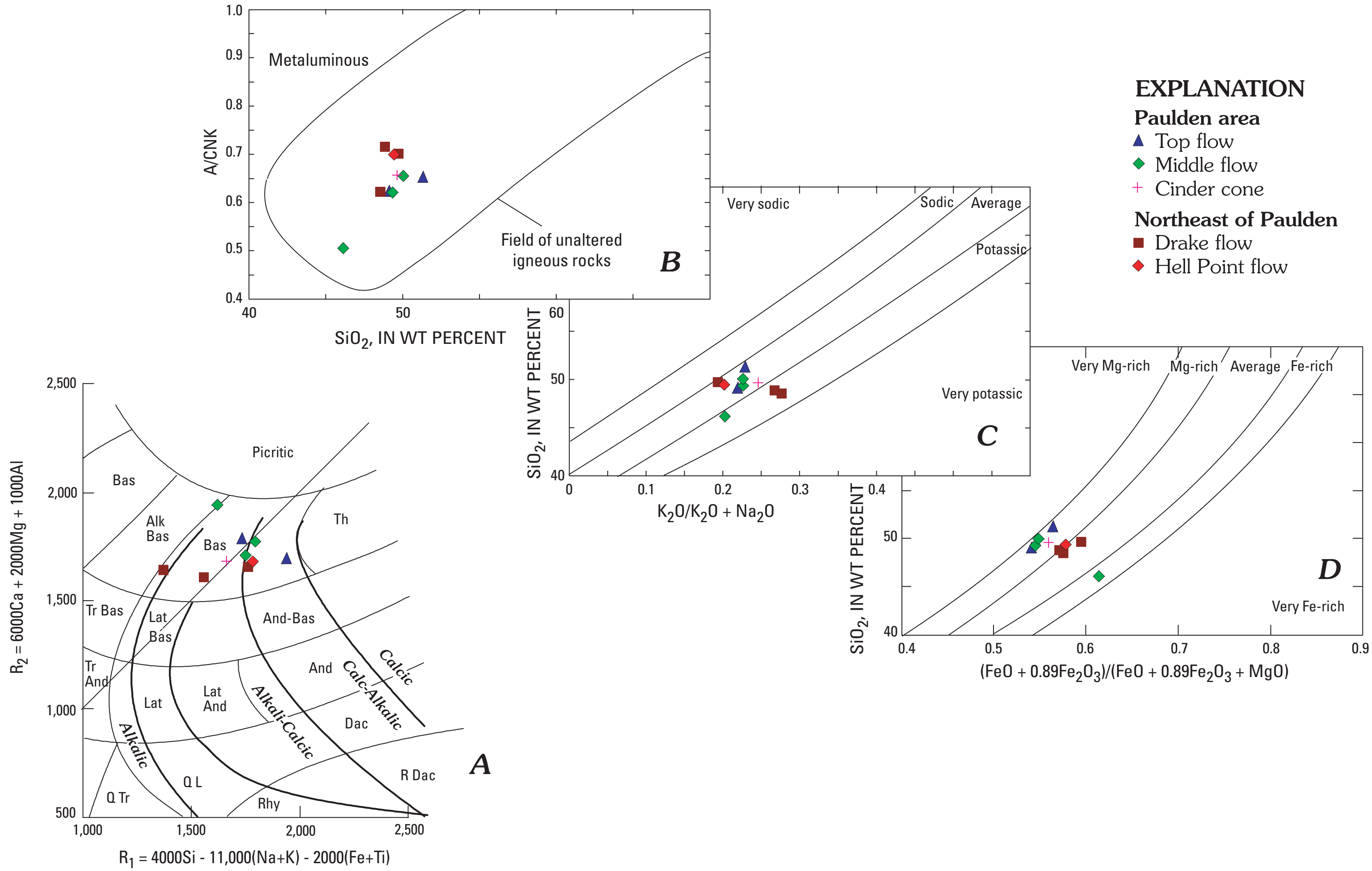


Figure B9. Major-element classification diagrams for 4-6-Ma volcanic rocks (unit Tby) near Paulden. Data from this study, McKee and Anderson (1971), and Witke and others (1989). Rock abbreviations and field boundaries defined in figure B4.

breakdown of albite at elevated pH, or can be a primary mineral deposited in alkaline lakes such as those that formed the Green River Formation in Wyoming and Utah (Meddaugh and Salotti, 1983; Remy and Ferrell, 1989). Bloedite(?) forms from evaporation of dilute brines in marine, playa, or closed-basin settings (Palache and others, 1957; Rosen, 1994). The presence of both minerals, coupled with the fine grain size of the sediment (Ostenaa and others, 1993b), and the predominance of calcite and dolomite in all analyzed sediments, is evidence of deposition in a playa setting.

Thickness of the playa deposits decreases from 1800 feet (550 m) near the Big Chino Fault (CV-DH-3) to 800 feet (244 m) near the axis of the valley, farther southeast (CV-DH-1), to less than 100 feet (30 m) on the southwest side of Big Chino Wash (CV-DH-2). Calcareous siltstone interrupts the playa sediments in CV-DH-1 over an interval of 150 feet (46 m). From CV-DH-3, the playa sediments are interpreted to interfinger with siltstone and silty dolomite to the southeast. This interfingering probably is the result of fluctuating shoreline of the playa and periodic flooding of the playa by alluvial fan sediment from the south and southeast. From CV-DH-1 to CV-DH-2, the interval of playa sediments thins to less than 100 feet (30 m). Alluvial sediment from Williamson Valley, including calcareous siltstone and calcareous sand and gravel were shed onto the margins of the playa, restricting its growth to the south and west.

An approximate timeline within the basin can be determined from the thickness of sediment overlying the 4.5-Ma basalt flow northwest of Paulden (figs. B11A and B11B). The top surface of the basalt flow dips uniformly to the northwest at 1 degree. North-northeast of Kayfour, in the center of the valley, the 500-foot isopach of sediment above the basalt flow is well located. From that point to CV-DH-3 is a distance of 6.5 miles. Given a drop of 100 feet per mile (approximately 1 degree dip), the projected top surface of the basalt (a 4.5-Ma timeline) would be found in CV-DH-3 at a depth of 1150 feet (350 m). Because the rate of subsidence in the deepest part of the basin is probably greater than that near Kayfour, the projected depth of the 4.5-Ma timeline at CV-DH-3 is probably a minimum. Therefore, at least the upper 1000 feet of sediment in CV-DH-3 could be younger than 4.5 Ma.

Preliminary qualitative ranking, based on X-ray diffraction peaks of minerals in the playa sediments, shows, in general, carbonate minerals greater in concentration than analcime, which is greater in concentration than clay minerals, which are greater in concentration than bloedite(?) and quartz (fig. B10). Exceptions are noted to this general order. Only a qualitative estimation of mineral concentrations was undertaken due to the nature of the chip samples. Relative order of the four most abundant minerals could be amended by further investigations, primarily by chemical analyses. An altered illite is the predominant clay mineral identified in the playa sediments. Potassium appears to be deficient in the illite, resulting in peaks of reduced intensity and broadened width at low 2-theta measurements. A comparison of the qualitative abundance of clay minerals in non-playa sediments to that in playa sediments suggests greater concentration of clay minerals in the playa sediments, in agreement with previous work (Ostenaa and others, 1993b, Water Resource Associates, Inc., 1989, 1990, and 1991)., Carbonate minerals and analcime are more abundant than clay minerals in the playa sediments. Dolomite-to-calcite ratios vary in the playa, dolomite being more abundant at depth and calcite being more abundant shallower in the playa (fig. B10). This variation could be primary or it could reflect dolomitization of the lower parts of the playa sediments.

Sediment in Little Chino Valley. Compared to central and northwestern Big Chino Valley, Little Chino Valley contains much thinner Quaternary and Tertiary sediment that is younger than the youngest volcanic rocks (fig. B12A). Significantly, the pattern of isopachs of sediment is very irregular compared to those in southeastern Big Chino Valley (fig. B12B). Sediment in Little Chino Valley was deposited on an irregular topography created by underlying lati-andesite flows, domes, and intrusive necks, and by valleys partially filled by flows of the Hickey Formation. In general, sediment increases in thickness from southwest to northeast, and exceeds 600 feet (180 m) only south of Del Rio Springs. Between Table Mountain and Black Hill, thickness of sediment younger than the youngest volcanic rocks is less than 20 m. Areas of least sediment fill coincide with resistant intrusive centers of lati-andesite (fig. B12B). Topography on the eroded lati-andesite surface locally exceeds 70 m, especially at inferred buried intrusive centers (fig. B12B). East of Granite Creek there are too few drillholes to define thickness of the sediment.

Structural Features

The Limestone Canyon monocline, exposed on Big Black Mesa (fig. B3), is believed to be of Laramide (60-80 Ma) age because of its similarity in structure to monoclines on the Colorado Plateau (Davis, 1978). This monocline strikes northwest and faces northeast; the Martin Formation and Redwall Limestone are present on the southwestern side of the monocline and the Supai Formation crops out on the northeast (Krieger, 1965). Structural relief along the monocline ranges from 70 to 120 m; the monocline dies out to the southeast near the mouth of Limestone Canyon (fig. B3). A small, north-striking monocline along Bull Basin Canyon (Krieger, 1965; fig. B2) probably is a Laramide structure. The monocline is truncated and overlain by undeformed Tertiary volcanic rocks, chiefly older(?) Tertiary basalt (unit Tabo) and is therefore older than about 10 Ma.

The regional dip of Paleozoic strata on Big Black Mesa and the area north of the Verde River is gently to the northeast, and probably is the result of deformation related to monocline formation. Such deformation resulted in a series of basement-cored blocks that dipped gently to the northeast and that were bounded by the northwest-striking monoclines. Northwest-striking normal faults having displacement down to the south were formed between monoclines, but none are recognized in the study area. The combination of monocline formation and

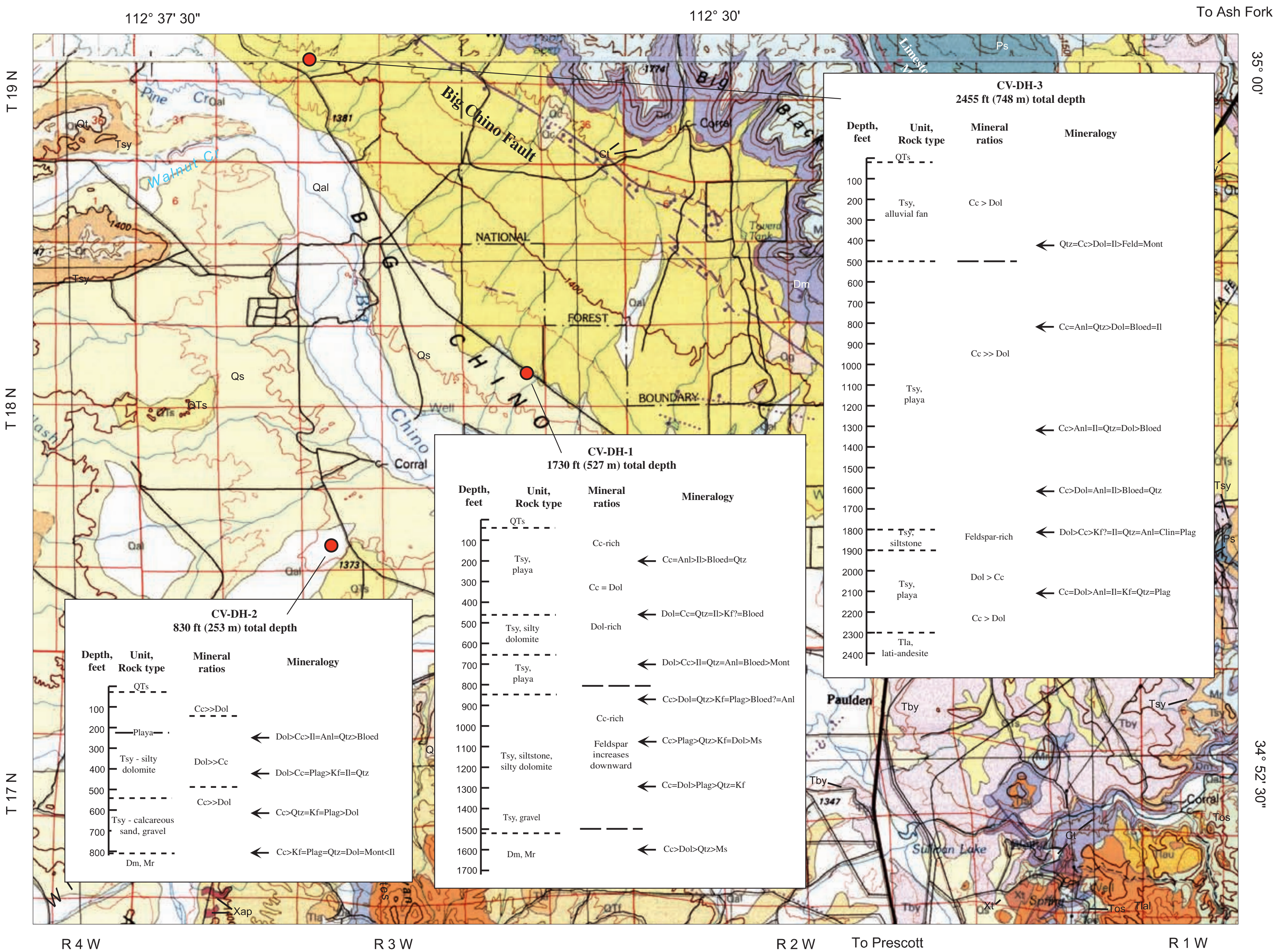


Figure B10. Lithologic logs showing mineralogy of playa deposits and other basin-fill units, Big Chino Valley. Location of Bureau of Reclamation drill holes (Ostenaa and others, 1993b) shown. Abbreviation of units as in figures 2 and 3. Cc, calcite; Dol, dolomite; Il, illite; Anl, analcime; Qtz, quartz; Bloed, bloedite(?); Plag, plagioclase; Kf, potassium feldspar; Mont, montmorillonite; Ms, muscovite; Feld, feldspar; Clin, clinoptilolite.

normal faulting created a dip slope of Paleozoic strata that rose gently to the southwest, away from the Colorado Plateau. Paleozoic rocks therefore were stripped from the basement in the southern part of the study area.

A northeast-striking pair of high-angle reverse faults cuts the Paleozoic rocks and Proterozoic basement between Lower Granite Spring and the Verde River (Krieger, 1965). The faults project beneath undeformed Tertiary lati-andesite to the northeast, and must, therefore, be older than about 24 Ma. The extent of these faults to the southwest is unknown. A concealed normal fault having displacement down to the east is suggested west of the town of Chino Valley, along or slightly east of Big Wash (fig. B2). On the northwestern side of the fault, trachyandesite of the Hickey Formation rests on Proterozoic basement. On the southeastern side of the fault, logs of water wells suggest a minimum of 70 m of sediment and lati-andesite separating the trachyandesite from underlying basement. The fault would be pre-Hickey in age, as the trachyandesite does not appear to be offset.

Quaternary to Late Tertiary Faults

Big Chino Valley is a northwest-trending late Tertiary graben that is bordered on the northeast by the Big Chino Fault. Only about one-third of the total length of the fault is in the study area. At the northern margin of the study area, near CV-DH-3, the fault has at least 1100 m of displacement (fig. B3). The fault decreases in displacement to the southeast and dies in a series of horsetail splays north of Paulden. Latest movement on the fault is pre-Holocene (Menges and Pearthree, 1983; Pearthree, 1998). At the surface, the Big Chino Fault displaces alluvial fan material 8-10 m down toward the basin over a length of more than 45 km.

The Big Chino Fault is only 1.6 km northeast of CV-DH-3, but there is little evidence of fault-related sediments in the well log (fig. B10). From the base of lati-andesite to the covering alluvial fan, there are no conglomerates such as would be expected from erosion of the uplifted block along a normal fault. Instead, the entire interval contains fine-grained playa sediments. In the Verde Valley to the southeast, conglomeratic sediments shed from the uplifted block of the Verde Fault are numerous in the basin sediments near the fault (Anderson and Creasey, 1967; Nations and others, 1981). Perhaps displacement on the Big Chino Fault during the time of playa development did not produce a significant topographic block on the upthrown side. Rather, uplift on the northeastern side may have kept pace with subsidence on the southwestern side. Significant topographic relief on the upthrown side of the fault is signaled by the appearance of alluvial fan deposits overlying the playa sediments, at a depth of about 150 m (fig. B10).

The southwestern side of the valley north of Sullivan Buttes contains a number of small faults having various senses of displacement (fig. B11B). The southernmost of these faults increases in displacement from about 100 m (in T17N, R2W, Sec. 7) to the northwest. Northwest of Kayfour the presumed northwestern extension of the fault has a minimum of 300 m of offset, as determined from displacement of lati-andesite in drillhole B(18-3) 35DA, drilled to a depth of 260 m (Ostenaa and others, 1993b). Across Williamson Valley to the northwest, a lack of deep water wells hinders interpretation of buried faults. Northwest of the study area, near Limestone Peak (fig. B1), displacement on a concealed normal fault that may border the basin on the south is about 220 m, as calculated from displacement of the Redwall Limestone.

The inception and duration of normal faulting in Big Chino Valley and along the Big Chino Fault is difficult to determine. Regional extension took place after deposition of the youngest flows in the Hickey Formation at 10 Ma. The Big Chino basin probably started to form at about 8-10 Ma. By 6 Ma, parts of the basin had a topographic form similar to its present-day shape, with cliffs of Paleozoic strata on the north side. Basalt flowed over these cliffs and into the valley northeast of the map area, south of Picacho Butte (fig. B1), by about 6 Ma. At 5.5 Ma basalt flowed into the northwestern end of the valley from sources in the northeastern Juniper Mountains (Goff and others, 1983; Arney and others, 1985), and at 4.5 Ma, basalt flowed into the southeastern end of the basin. Central parts of the valley may have continued to subside slowly and form playa deposits after 4.5 Ma. The first significant topographic relief across the fault is indicated by thick alluvial fan material that overlies the playa deposits.

The northern end of Little Chino Valley, south of outcrops of the Mazatzal Group, likely is bounded by a largely concealed normal fault(s) that strikes northwest (fig. B2). Part of the fault(s) is mapped southeast of Del Rio Springs and has displacement down to the west, as would be expected for a basin-bounding fault. The fault(s) may step to the south, away from bedrock exposures (fig. B12B), as suggested by logs of water wells near Granite Creek. Displacement across the fault segments is difficult to determine, as no wells are drilled deep enough to penetrate both sediment fill and lati-andesite, but may exceed 180 m near Del Rio Springs. Farther southeast, near Granite Creek, displacement appears to be less, about 100 m. A concealed normal fault that forms part of the southwestern side of the basin is suggested by logs of water wells (fig. B12B). The northwest-striking fault, which may have less than 50 m of displacement, passes beneath the town of Chino Valley and extends toward Lonesome Valley.

Two small, northwest-striking faults that are exposed south of Del Rio Springs (fig. B2) have displacement, determined from surface ruptures (Pearthree, 1998), of down to the north, opposite to that of the basin-bounding fault(s). Although this opposing sense of displacement could suggest formation of a local graben, groundwater withdrawal in far northern Little Chino Valley (Schwalen, 1967) also could be causing surface ruptures that have displacement down to the north.

The western side of northern Little Chino Valley west of Del Rio Springs may not be bounded by a laterally continuous late Tertiary fault, as suggested by some previous work (Ostenaa and others, 1993b). Rather, alluvial fans extend away from lati-andesite flows and intrusive rocks and thicken into Little Chino Valley. A buried normal fault could be concealed

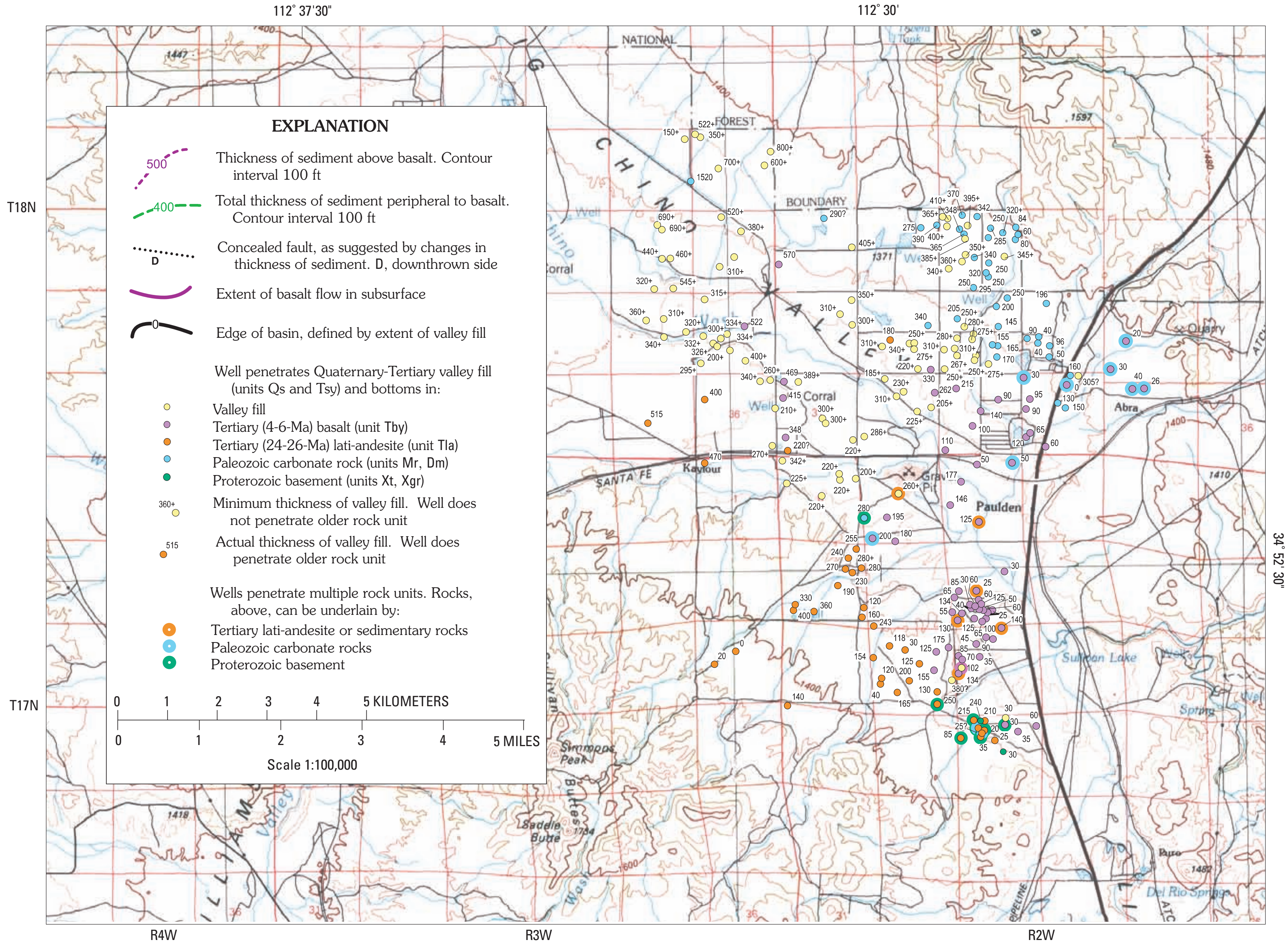
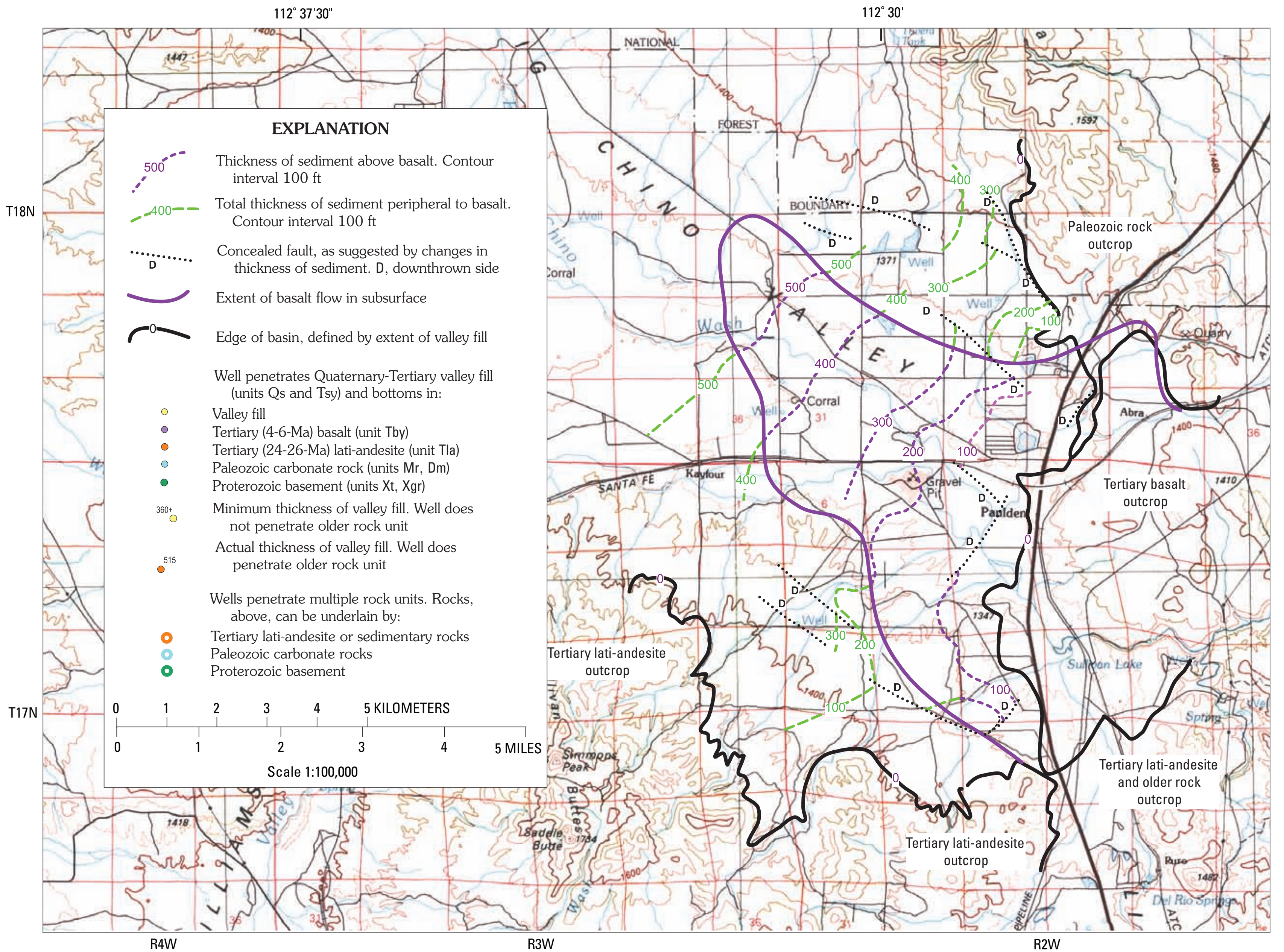


Figure B11 (above and facing page). *(A),* Map showing thickness of Quaternary and Tertiary basin fill above 4-6-Ma basalt flows in southeastern Big Chino Valley. (A) Locations of wells and thickness determinations. *(B),* Isopachs of sediment thickness above basalt and locations of buried faults.



112° 37'30"
112° 30'
T18N
T17N
34° 52' 30"
R4W
R3W
R2W
EXPLANATION
Thickness of sediment above basalt. Contour interval 100 ft
Total thickness of sediment peripheral to basalt. Contour interval 100 ft
Concealed fault, as suggested by changes in thickness of sediment. D, downthrown side
Extent of basalt flow in subsurface
Edge of basin, defined by extent of valley fill
Well penetrates Quaternary-Tertiary valley fill (units Qs and Tsy) and bottoms in:
Valley fill
Tertiary (4-6-Ma) basalt (unit Tby)
Tertiary (24-26-Ma) lati-andesite (unit Tla)
Paleozoic carbonate rock (units Mr, Dm)
Proterozoic basement (units Xt, Xgr)
Minimum thickness of valley fill. Well does not penetrate older rock unit
Actual thickness of valley fill. Well does penetrate older rock unit
Wells penetrate multiple rock units. Rocks, above, can be underlain by:
Tertiary lati-andesite or sedimentary rocks
Paleozoic carbonate rocks
Proterozoic basement
0 1 2 3 4 5 KILOMETERS
0 1 2 3 4 5 MILES
Scale 1:100,000
Paleozoic rock outcrop
Tertiary basalt outcrop
Tertiary lati-andesite outcrop
Tertiary lati-andesite and older rock outcrop
Tertiary lati-andesite outcrop
CHINO VALLEY
Abra
Paulden
Kaufour
Gravel Pit
Corral
Quarry
Sullivan Lake
Simmons Peak
Saddle Butte

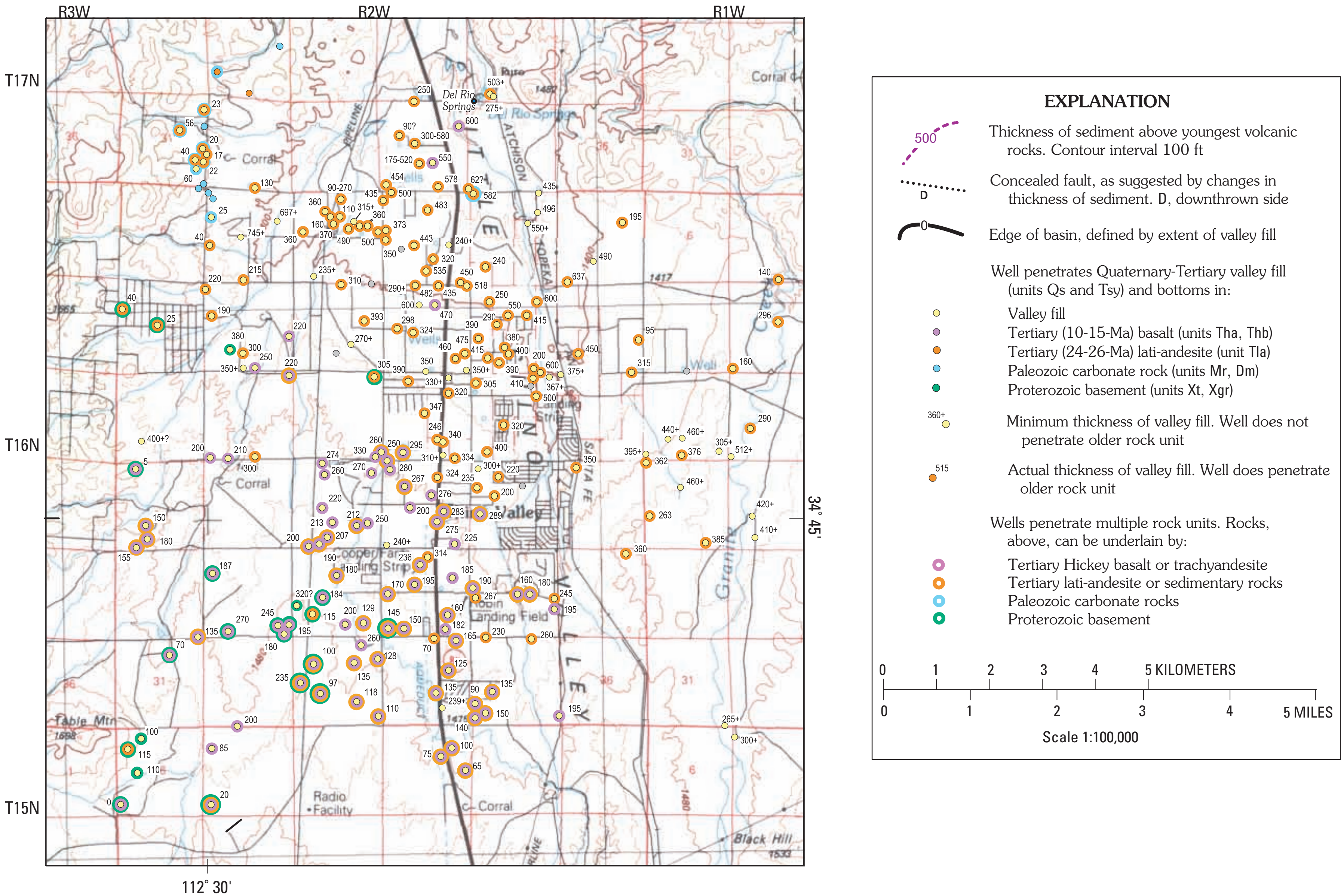
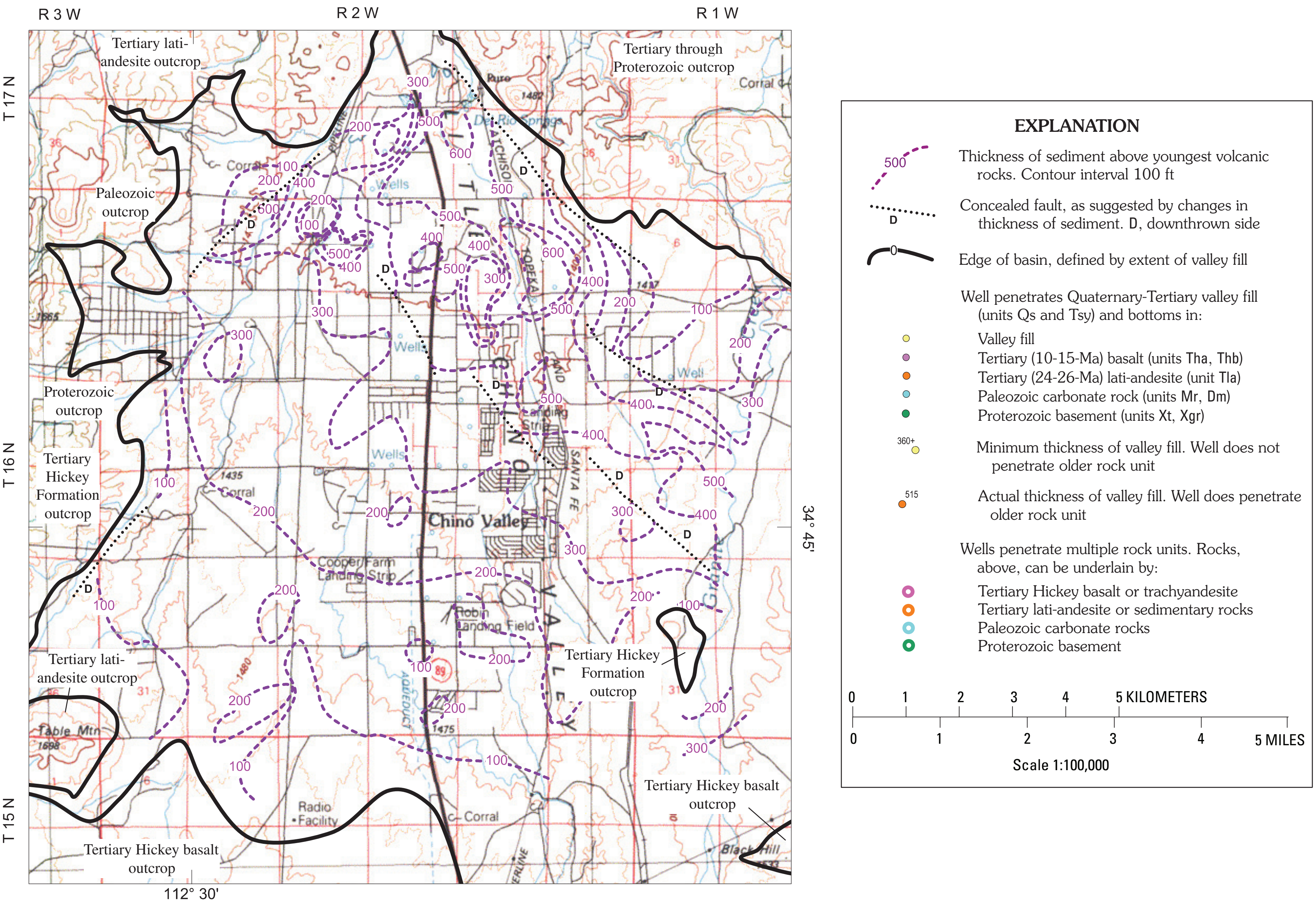


Figure B12 (above and facing page). Maps showing thickness of Quaternary and Tertiary basin fill above youngest Tertiary volcanic units in northern Little Chino Valley. *(A)*, Location of wells and schematic logs showing thickness of Quaternary and Tertiary basin fill above youngest Tertiary volcanic units. *(B)*, Isopachs of thickness of Quaternary and late Tertiary basin fill above youngest Tertiary volcanic units, and locations of buried faults, northern Little Chino Valley



R 3 W
R 2 W
R 1 W
T 17 N
T 16 N
T 15 N
112° 30'
34° 45'
Tertiary lati-andesite outcrop
Tertiary through Proterozoic outcrop
Paleozoic outcrop
Proterozoic outcrop
Tertiary Hickey Formation outcrop
Tertiary lati-andesite outcrop
Tertiary Hickey basalt outcrop
Tertiary Hickey Formation outcrop
Tertiary Hickey basalt outcrop
Chino Valley
Cooper Farm Landing Strip
Robin Landing Field
Radio Facility
Table Mtn
Black Hill
Del Rio Springs
Wells
Corral
EXPLANATION
Thickness of sediment above youngest volcanic rocks. Contour interval 100 ft
Concealed fault, as suggested by changes in thickness of sediment. D, downthrown side
Edge of basin, defined by extent of valley fill
Well penetrates Quaternary-Tertiary valley fill (units Qs and Tsy) and bottoms in:
Valley fill
Tertiary (10-15-Ma) basalt (units Tha, Thb)
Tertiary (24-26-Ma) lati-andesite (unit Tla)
Paleozoic carbonate rock (units Mr, Dm)
Proterozoic basement (units Xt, Xgr)
Minimum thickness of valley fill. Well does not penetrate older rock unit
Actual thickness of valley fill. Well does penetrate older rock unit
Wells penetrate multiple rock units. Rocks, above, can be underlain by:
Tertiary Hickey basalt or trachyandesite
Tertiary lati-andesite or sedimentary rocks
Paleozoic carbonate rocks
Proterozoic basement
0 1 2 3 4 5 KILOMETERS
0 1 2 3 4 5 MILES
Scale 1:100,000

beneath the fans, toward the center of the basin, but drillhole data are lacking to prove the continuity of such a fault. To the south, Big Wash is a linear, north-northeast striking feature that has been suggested to be underlain by a fault. North of Table Mountain, along Big Wash, a pre-Hickey, northeast-striking normal fault is present (fig. B12B). Because of the presence of this fault, we cannot dismiss the possibility that the northern part of Big Wash could be underlain by a pre-Hickey fault.

Conclusions

Synthesis of the geology, geochemistry, and geophysics of rock units in the area resulted in significant additions to understanding of how Miocene basins formed in both Big and Little Chino valleys. Geologic mapping enabled Proterozoic basement rocks to be projected beneath the basins from surrounding outcrops. Geochemical investigations and aerial radiometric data allowed the separation of Oligocene lati-andesite from Miocene and younger basalt. X-ray diffraction data substantiated the presence of playa deposits containing fine-grained carbonate-rich sediments rich in analcime and possibly containing bloedite(?) in the deepest part of Big Chino Valley. Aerial magnetic data revealed the location of buried Proterozoic basement rocks. Synthesis of data from well logs enabled mapping of buried Oligocene lati-andesite and Miocene and younger basaltic rocks beneath basin fill in Big and Little Chino valleys. Locations of probable concealed normal faults in the two basins were interpreted from rapid apparent thickness changes of sediment. Data from aerial magnetic surveys revealed the location of buried intrusive centers of lati-andesite and basalt.

Within the study area, the basin underlying Big Chino Valley contains at least 700 m of Miocene and younger basin fill that rests regionally on Paleozoic strata, and locally on Oligocene lati-andesite. Much of the deepest part of the basin contains sediment deposited in a playa. Alluvial fans supplied clastic sediment to the playa from the west and south. The basin probably had internal drainage from its inception at about 8-10 Ma through 4-5 Ma, when basalt flows from the Colorado Plateau entered the valley from the west, north, and southeast. Continued subsidence in the central part of the basin after 4-5 Ma resulted in deposition of additional playa sediments. Coarse-grained fanglomerate deposited adjacent to the Big Chino Fault overlies the playa sediment and indicates significant topographic relief across the fault only late in its movement history.

The basin underlying northern Little Chino Valley contains less than 200 m of Miocene and younger basin fill that rests on a buried volcanic field of Oligocene lati-andesite and Miocene and younger basalt. The complex pattern of buried lati-andesite and basalt reveals paleovalleys and topographic highs concealed by the Miocene and younger basin fill. No playa sediments are documented in the basin fill, which is characterized by fanglomerate and finer-grained alluvial sediment derived from the south, west, and southeast. Formation of the basin is believed to have taken place during the same interval as the basin in Big Chino Valley, but direct geochronologic data are lacking. No 4.5-6-Ma basalt flows are known in the northern part of the valley. A normal fault along the northeast margin of the basin has at least 180 m of displacement, and probably was active during formation of the basin.

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