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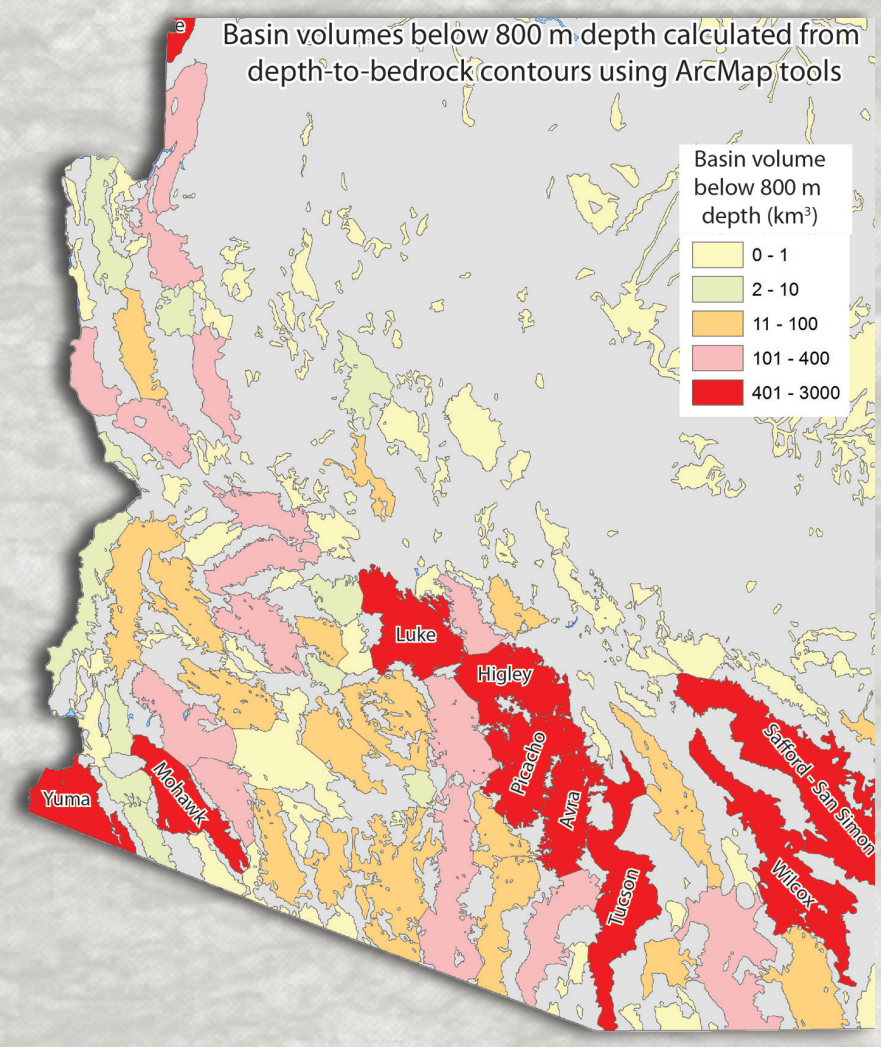

PRELIMINARY EVALUATION OF CENOZOIC BASINS IN ARIZONA FOR CO2 SEQUESTRATION POTENTIAL

May 2011

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ARIZONA GEOLOGICAL SURVEY

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Arizona Geological Survey, Open-File Report OFR-11-05, 15 p.

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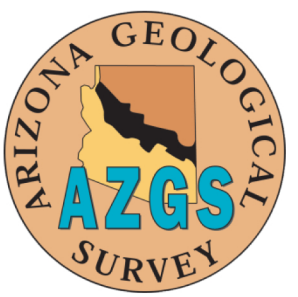

Introduction

The U.S. Department of Energy (DOE), through its National Engineering and Technology Laboratory (NETL), established a national program to evaluate the feasibility of separating carbon dioxide (CO_2) from industrial sources and pumping it underground for long-term storage or disposal. This program was established in response to concerns that CO_2 emissions from fossil-fuel combustion, and from other industrial processes such as cement production from limestone, are increasing atmospheric CO_2 concentration and solar-energy absorption, thereby causing global warming. Carbon dioxide removal from industrial sources and storage in geologic reservoirs is known as "geologic sequestration." A major aspect of the DOE program is to evaluate subsurface geology to determine the potential of underground rock formations for long-term CO_2 sequestration.

WESTCARB (West Coast Regional Carbon Sequestration Partnership) is a consortium of seven western U.S. States and one Canadian Province that is one of seven regional North American partnerships established to evaluate technical aspects of high-volume CO_2 capture and sequestration. Collaborative WESTCARB research programs have included more than 90 public agencies, private companies, and non-profit organizations. The Arizona Geological Survey began work in 2010 on *WESTCARB Phase III – Arizona Geological Characterization*. This report represents an initial WESTCARB assessment of CO_2 storage potential in Arizona's Cenozoic basins, and is part of Task 2 of Arizona WESTCARB Phase III (California Energy Commission Agreement Number 500-10-024).

The focus of this study is Cenozoic basin volume and volume below 800m depth, with the purpose of reducing the number of basins subjected to further carbon-sequestration evaluation. Basin volume below 800m depth is important because CO_2 will remain in a liquid state at pressures corresponding to rock overburden at such depths. Successful sequestration requires both adequate permeability and porosity for large-volume CO_2 injection, and an impermeable cap rock that will prevent movement of CO_2 to shallower depth and escape to the atmosphere. Basin stratigraphy and sediment characteristics are not the subject of this report, however, but will be evaluated for a subset of basins identified in this study that are both large and deep.

Basin and Range Physiographic and Tectonic Province

Southern and western Arizona are part of the Basin and Range tectonic and physiographic province, which is characterized by numerous small mountain ranges and intervening basins. This region extends southward to central Mexico and northward through southeastern California, Nevada, western Utah, and southern Idaho (Dickinson, 2002). The numerous basins and ranges are commonly separated by normal faults, although in almost all of Arizona, the faults are

inactive and largely or entirely buried. Normal faulting and crustal extension occurred in two phases, although distinction between the two is not everywhere clear. The early phase, beginning at about 30 Ma, was associated with low-angle normal faulting and uplift of metamorphic core complexes such as the Harcuvar core complex in western Arizona and the Catalina-Rincon complex in southeastern Arizona (Spencer and Reynolds, 1989; Dickinson, 1991). This phase was accompanied by voluminous felsic magmatism that ended at about 15-18 Ma. The second phase is represented by moderate- to high-angle normal faulting, produced most of the modern range fronts, and was accompanied by minor, dominantly basaltic magmatism (e.g., Davis et al., 2004). Furthermore, whereas the earlier phase of extension was generally oriented WSW-ENE in Arizona, the later phase was oriented approximately E-W.

The area that is now the Basin and Range province in Arizona was a topographic highland in early Cenozoic time, and contains no known sedimentary rock with ages between ~55 and 30 Ma. This highland area was largely the result of Laramide crustal thickening due to crustal shortening and magmatism. All easily eroded Laramide sedimentary rocks were eroded off of the highland, and surviving strata are indurated and typically affected by low grade metamorphism and alteration. Thus, all pre-extension strata are essentially rock, with corresponding high physical density.

Middle to late Cenozoic extension broke apart the bedrock surface, uplifting some fault blocks and down dropping others. Many blocks were tilted, so that one side became a mountain range and the other became a basin floor. In most cases, the geometry of fault blocks is poorly known because the faults are now buried. Voluminous volcanic rocks, erupted during early extension, form many ranges. In some areas, these volcanic rocks overlie initial basin-filling clastic sediments. As volcanism waned and was replaced by relatively minor basaltic volcanism, coincident with the transition to dominantly high-angle normal faulting, deep basins were formed and filled with sediments. Most of these sediments are poorly lithified, porous and permeable sand and gravel, but also include silt and clay, limestone, basalt, and the evaporites halite, gypsum, anhydrite.

Depth to bedrock

Gravity surveys are effective in determining approximate depth to bedrock in the Basin and Range province because the upper Cenozoic basin-filling sediments are less dense than the bedrock that makes up underlying basin floors and adjacent ranges. Gravity surveys done largely by University of Arizona faculty and students, with a total of ~22,000 measurement stations, were utilized to make a depth-to-bedrock map (Oppenheimer and Sumner, 1980, 1981). Depth-to-bedrock contours determined from gravity modeling were modified by incorporating information derived from 321 deep drill holes, few of which penetrated to depths greater than 500m. The greatest uncertainties in basin contours are for deep basins because small variations in estimates of basin or bedrock density can have an especially large influence on calculated depth

of deep basins. As a consequence, depths greater than approximately 1000m are especially uncertain.

The contours on the depth-to-bedrock map of Oppenheimer and Sumner (1980, 1981) were digitized by the U.S. Geological Survey and incorporated into a geodatabase for a new depth-to-bedrock map by the Arizona Geological Survey (Richard et al., 2007). These contours were modified to incorporate additional drill-hole data and gravity modeling studies (see references in Richard et al., 2007) as well as improved representation of basin margins on the updated Geologic Map of Arizona (Richard et al., 2000). Numerous sources of uncertainty include the unmodeled gravitational signature of volcanic rocks interbedded with, or overlying, basin sediments, complex surface topography in incised basin fill not incorporated into gravity models or bedrock depth estimates, and variable bedrock density that produces overestimates of basin depth where bedrock density is low and underestimates basin depth where bedrock density is high (see discussion in Richard et al., 2007).

Basin-volume calculations - procedure

To a first-order approximation, basin-fill sediments in the Arizona Basin and Range province are porous and permeable while bedrock is not. Hence, voluminous groundwater is derived from basin-fill sediments but little is derived from bedrock. Groundwater quality generally declines with depth in Arizona's Cenozoic basins, with higher total dissolved solids at greater depth. Thus, the deeper parts of Cenozoic basins are potential targets for CO_2 sequestration, both because they are porous and permeable and because contained groundwater is typically too saline for human consumption or agriculture. Furthermore, and as noted above, effective CO_2 sequestration must be done at depths greater than 800m because associated pressures at such depths will keep CO_2 in a high density, essentially liquid state, which results in a much more efficient use of pore space.

The purpose of this study is to evaluate basin-sediment volumes and volumes below 800m depth. No consideration was given to the presence of an impermeable cap rock that would prevent upward CO_2 diffusion and escape to the atmosphere. Basin volumes were estimated using ESRI® ArcMap™ version 10 software, as follows:

(1) The margins of the Cenozoic basins were derived from the Geologic Map of Arizona (Richard et al., 2000) and used to represent the zero-depth contour for the Cenozoic basins. All Quaternary sedimentary units were included in basin areas. These were modified so that young Tertiary sedimentary rocks (map unit Tsy) were also included with basin sediments, and in a small number of areas, basaltic lavas that overlie the basin-fill units were included in basin areas (QTb in the Sentinel and San Bernardino volcanic fields, and Tby in Grand Wash Trough). Some Oligo-Miocene sedimentary rocks were also included in basin areas (Tsm in Tucson, Northern San Pedro, and Cienega basins). Digitized depth-to-bedrock contours from Richard et al. (2007,

1600-foot contour interval, plus contours at 400 and 800 feet), were combined with the basin-margin, zero-depth contour to construct the depth-to-bedrock contour map used for this study.

(2) In a raster representation of a contour map, a surface is constructed that interpolates between contours. The surface has a depth value at evenly spaced points. The contour map of Cenozoic basins was used to build a raster representation of basin depths using the ArcMap "Topo to raster" tool in the "Raster interpolation" tool set in the "3D Analyst" toolbox. The raster representation has depth values at 200m spacing (in map view). A single raster representation was created for all of Arizona incorporating all contours. This raster was then used to create a contour map of basin depths with an 800m contour interval (Figure 1).

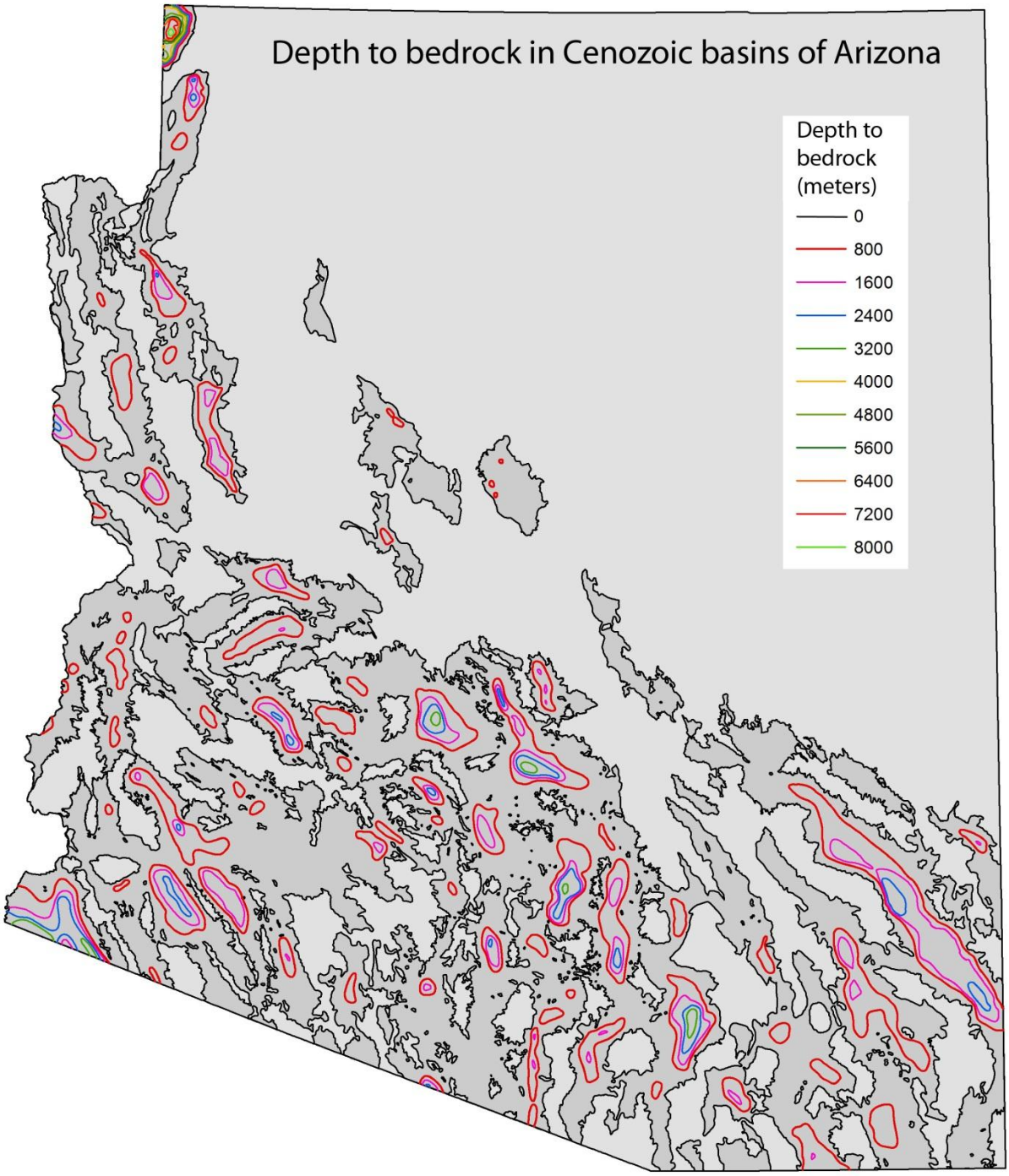

Figure 1. Cenozoic sedimentary basins in Arizona (dark gray) and depth-to-bedrock contours with 800m contour interval. Shallow basins and sediment veneers were excluded from basins.

(3) The zero-depth contour was used to create polygons for all of the basin areas. Using the other (deeper than zero) depth-to-bedrock contours to evaluate the morphology of basin floors, the

basin-area polygons were, in most areas, cut into smaller polygons, each representing a single named basin (the “Tucson basin” polygon, for example, was cut to separate it from the adjacent “Avra basin” and “Altar basin” polygons). This resulted in division of the basin-area polygons into 88 named basins. Shallow basins and sediment veneers that do not include a 400 foot contour, and small basins that did not include an 800 foot contour, were excluded from the basin-area polygon set.

(4) The 200-m-pixel, statewide raster representation of depth-to-bedrock was then divided into 88 separate rasters using the “Extract by mask” tool of the “Extraction” tool set within the “Spatial Analyst” toolbox, with one raster for each Cenozoic basin. This was done one basin at a time.

(5) Each basin raster was then used to calculate total basin volume, and volume below 800m depth, using the “Surface volume” tool from the “Functional surface” tool set in the “3D Analyst” toolbox (Figure 2).

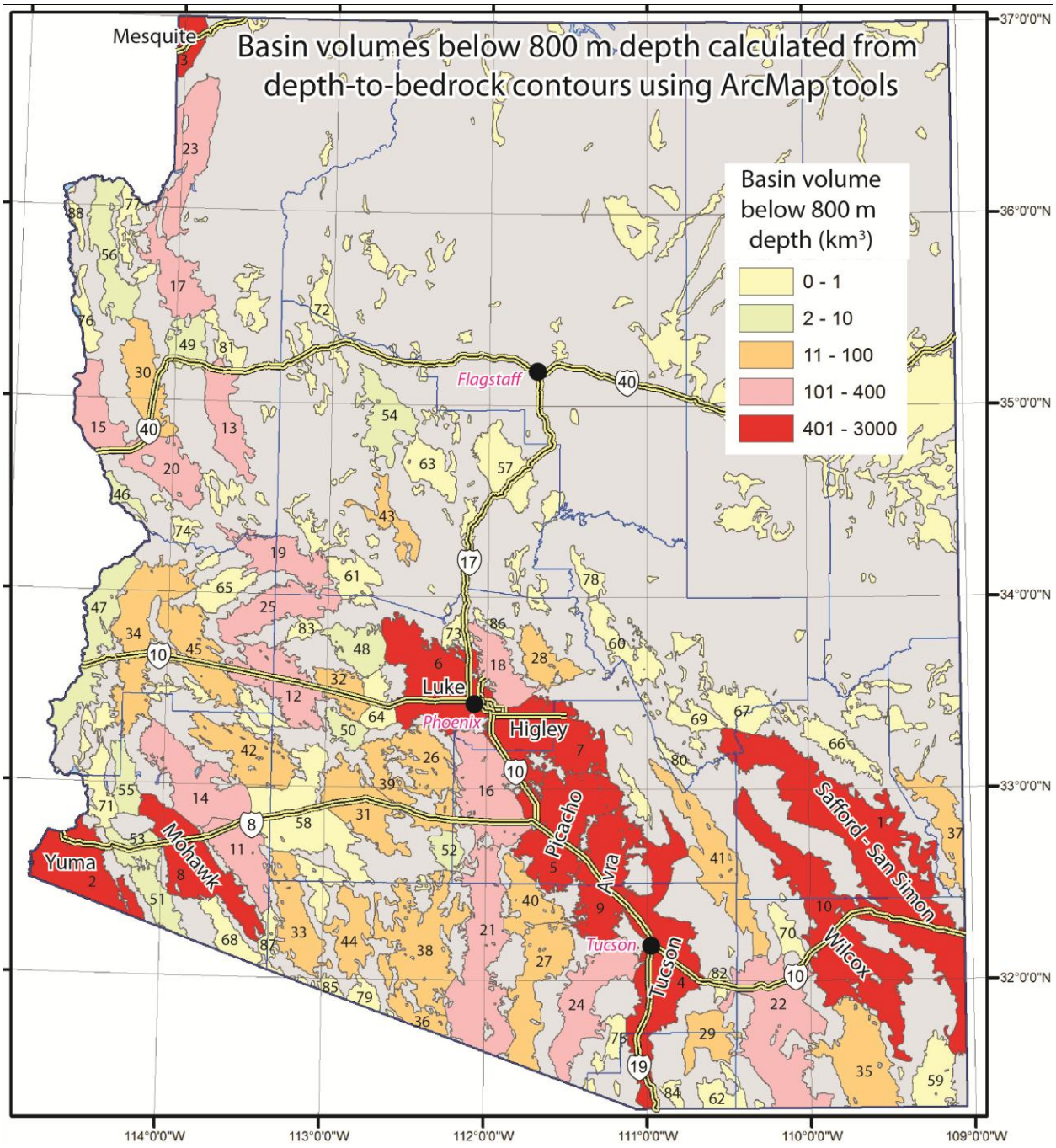

Figure 2. This map shows the 88 Cenozoic basins for which volume calculations were done. Contiguous basins were divided at areas of shallow bedrock. The ten basins with the greatest basin volume below 800m depth are shown in red with basin names. Basin numbers correspond to basin numbers in Table 1.

(6) To test the precision of ArcMap basin-volume calculations, basin volume was also calculated using Excel for 19 basins, as follows: Where basins are contiguous, contours were cut and drawn along boundaries between basins so as to create closed contours for each basin. Each closed contour was then converted to a polygon, and surface area was determined. Volumes were determined for each pair of adjacent, stacked polygons (as in a stack of pancakes). This was done by calculating the average area of the two contour polygons forming a pair of adjacent contour polygons, and multiplying that average by the thickness of the pancake (difference in depth between each adjacent contour in a pair) to yield volume between each pair of contours. The deepest contour was paired with a point to represent the depth of the next deepest contour. These volume determinations were summed to determine basin volume. Basin volumes derived using each method are quite similar, at least for the larger basins (Figure 3). The use of a point for the bottom of a polygon where a deeper contour did not exist was determined to introduce the greatest discrepancy with the raster-based volume determinations, but this was only apparent for some of the smallest basins.

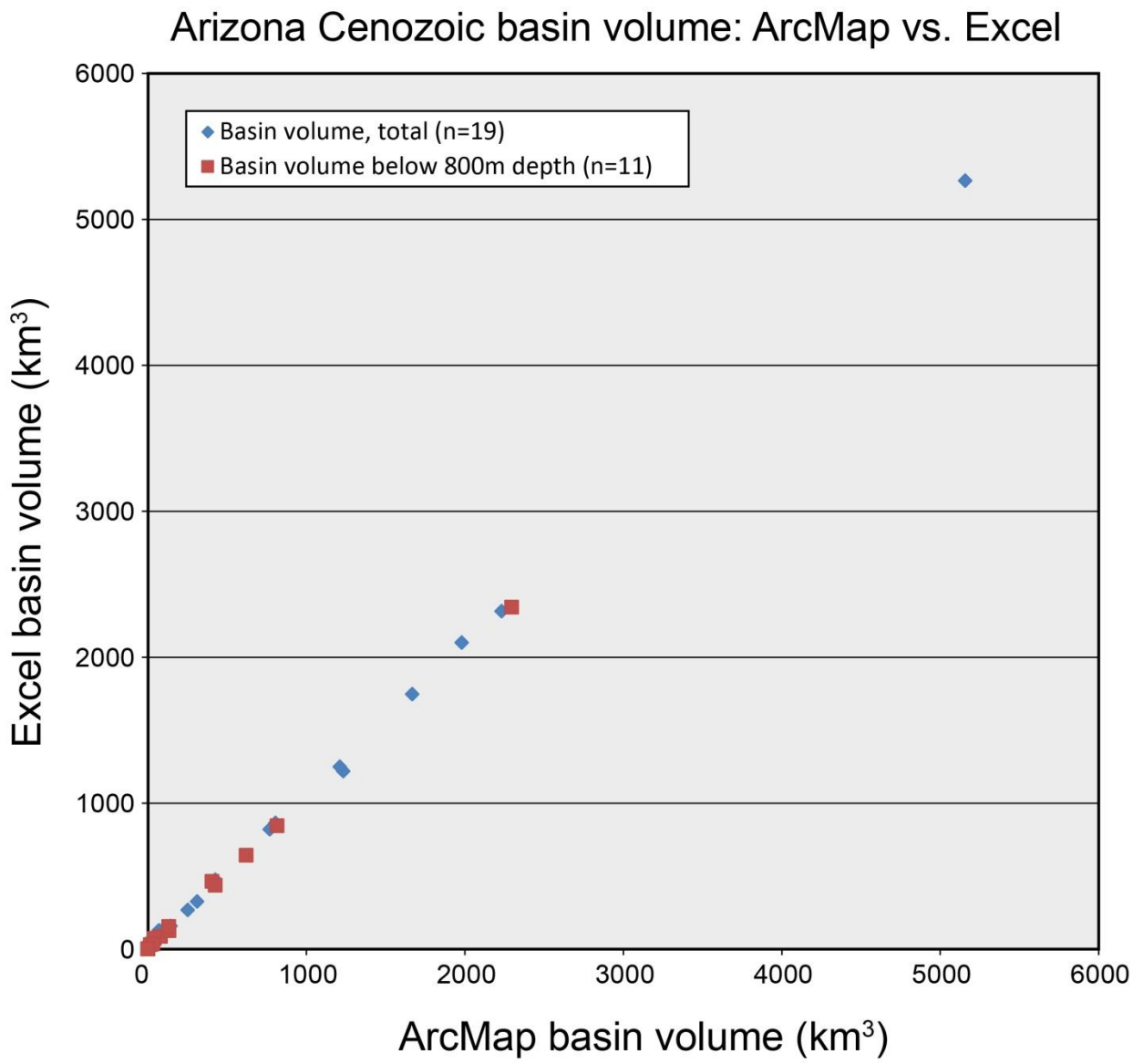

Figure 3. Comparison of basin volumes determined from depth-top-bedrock contours by two different methods (see text). Volumes determined by each method are similar, which indicates that complex ArcMap calculation methodology is consistent with results from relatively simple Excel calculations. While this supports the precision of calculation methodology, it does nothing to evaluate the accuracy of depth-to-bedrock contour placement and, ultimately, of calculated basin volumes.

Basin-volume calculations - results

A plot of total basin volume versus basin volume below 800m reveals some differences in basin morphology (Figure 4). Basins in the lower right, especially Wilcox, have large basin volume but

proportionately little volume below 800m depth. In contrast, basins in the upper left, particularly Mesquite and Yuma, appear deep, with a high ratio of deep basin fill to total basin fill. This characteristic for these two basins may be fallacious, however, because both basins are truncated, for basin analysis purposes, by the Arizona State border, which is represented as a vertical basin boundary. The ten basins with the greatest volume below 800m are named.

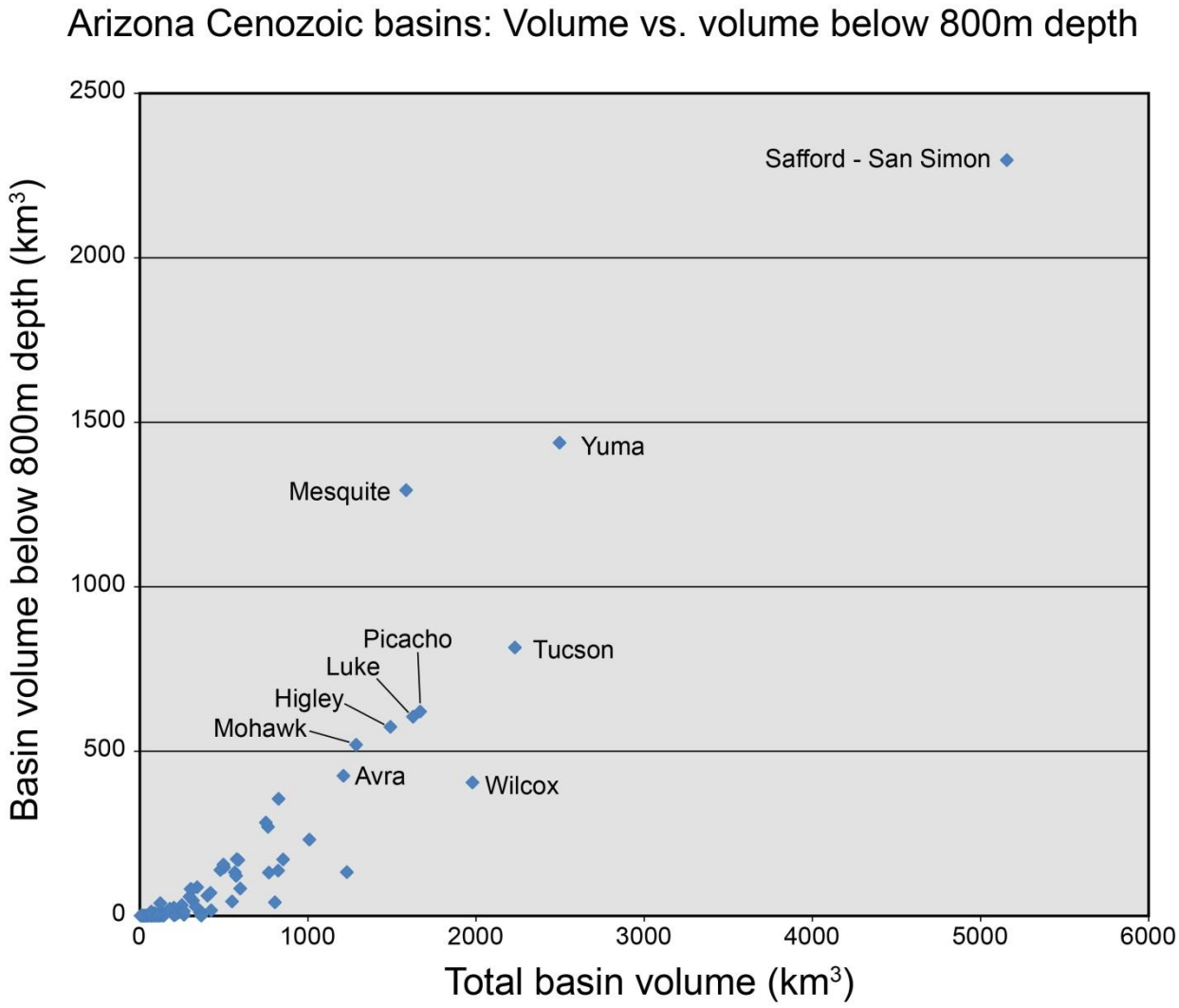

Figure 4. Total basin volume versus basin volume below 800m. The ten largest basins, targeted for additional study, are labeled.

The sediment volume in the 88 Cenozoic basins in Arizona evaluated for this study totals 42,247 km^3, with 49% of the sediment volume in the largest ten basins (Figure 5, Table 1). Fifty-seven basins were determined to extend below 800m depth, with a total basin volume of 12,655 km^3 below 800m depth (Figure 6, Table 1). Ten of these basins, shown in red in figure 2, contain 71% of this deep-basin volume.

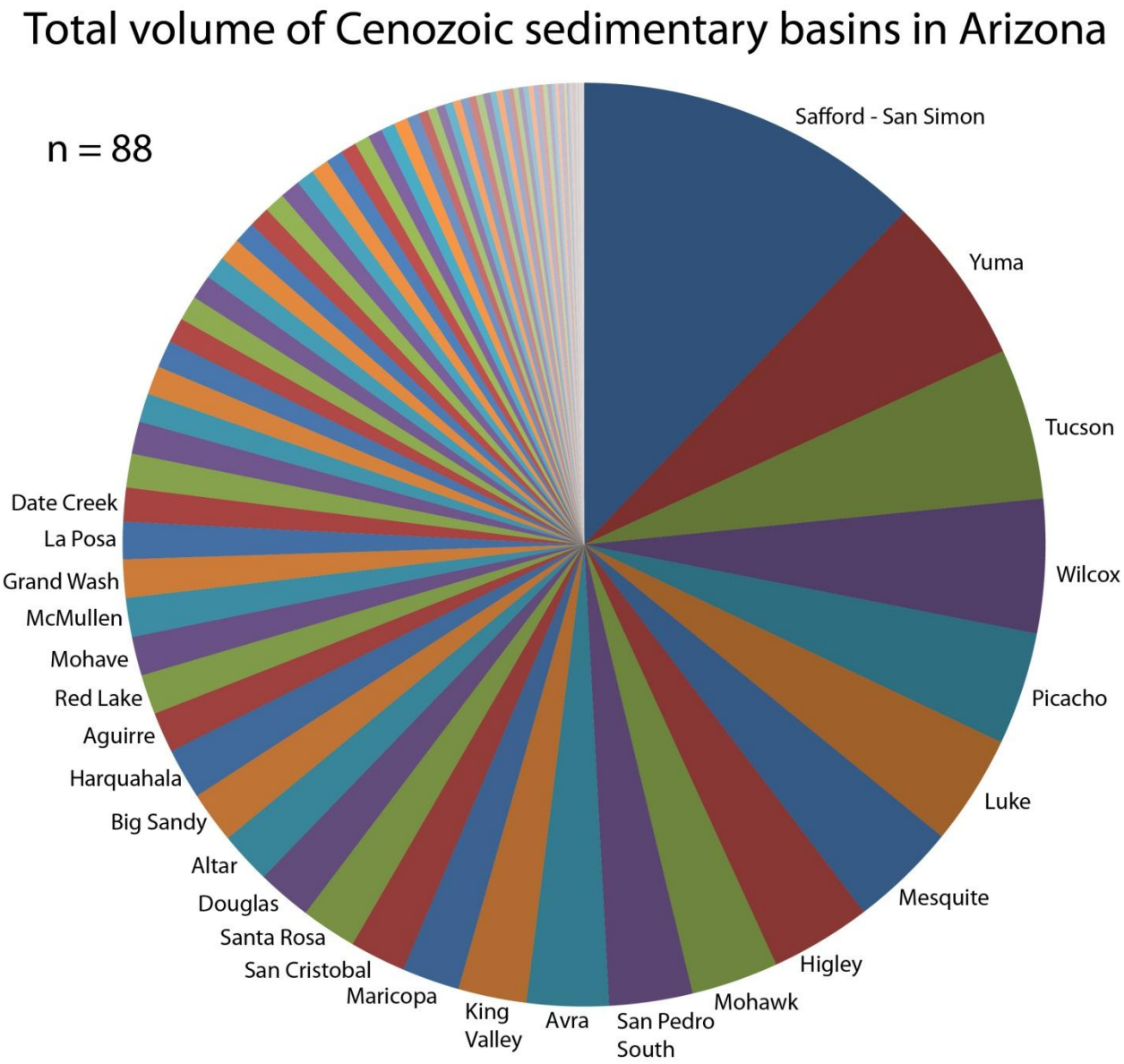

Figure 5. Calculated volume of Cenozoic sedimentary basins in Arizona.

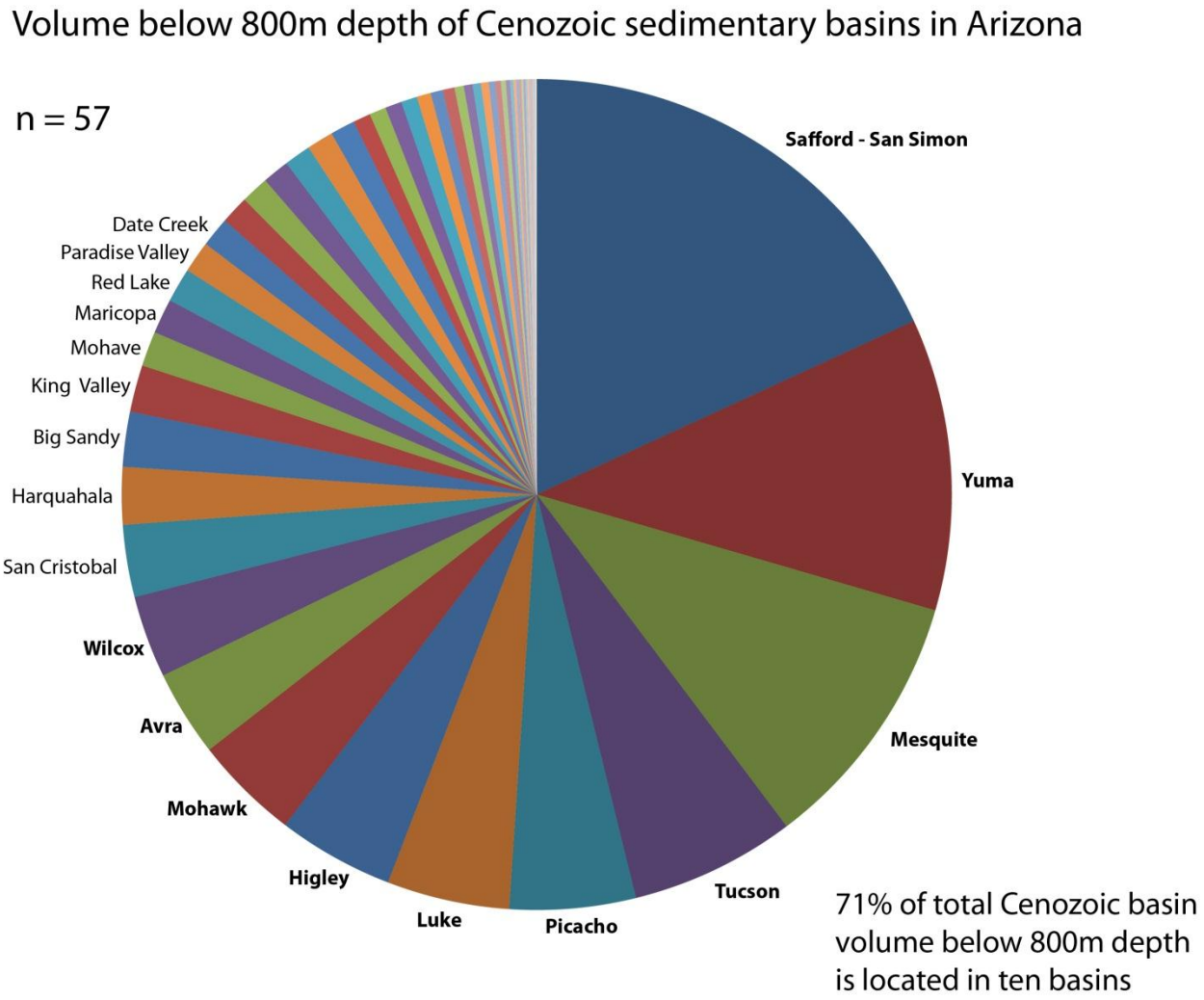

Figure 6. Calculated volume below 800m depth for Cenozoic sedimentary basins in Arizona that extend below 800m depth.

Table 1. Volume of Cenozoic basins in Arizona

Basin no.	Basin	Area (km^2)	volume (km^3)	volume (km^3) below 800 m depth
1	Safford-San_Simon	5694.4	5157.6	2296.0
2	Yuma	1730.3	2497.1	1437.1
3	Mesquite	434.4	1585.1	1293.4
4	Tucson	3141.1	2232.0	814.9
5	Picacho	2411.6	1668.4	620.5
6	Luke	2511.7	1625.6	604.5
7	Higley	2282.7	1491.6	573.6
8	Mohawk	1837.3	1288.1	519.3
9	Avra	1792.0	1211.5	424.9
10	Wilcox	3738.1	1980.1	404.8
11	San_Cristobal	1012.5	825.9	355.1
12	Harquahala	1324.9	750.5	282.7
13	Big_Sandy	948.3	763.4	270.0
14	King_Valley	1700.2	1009.5	231.4
15	Mohave	924.6	577.7	171.9
16	Maricopa	1816.5	852.9	171.1
17	Red_Lake	994.2	586.4	169.3
18	Paradise_Valley	829.0	498.0	155.5
19	Date_Creek	965.7	501.6	146.8
20	Dutch_Flat	1067.7	479.6	139.0
21	Santa_Rosa	2613.9	823.2	137.2
22	San_Pedro_South	2810.0	1232.9	132.2
23	Grand_Wash	1424.7	566.5	131.7
24	Altar	1596.3	768.9	131.2
25	McMullen	1142.8	573.8	121.2
26	Rainbow	851.0	341.6	86.2
27	Aguirre	1482.0	598.5	82.6
28	Fort_McDowell	618.1	303.9	81.5
29	Sonoita	670.5	310.7	79.5
30	Sacramento	1046.7	421.7	69.3
31	Gila_Bend	1289.2	403.6	60.7
32	Tonopah	541.0	297.2	57.7
33	Growler	1102.2	317.4	45.9
34	La_Posa	1929.9	549.5	43.4
35	Douglas	1650.7	804.7	40.8
36	La_Quituni	354.2	123.0	38.2
37	Duncan	846.7	251.4	31.8
38	San_Simon	2059.7	333.4	27.6
39	Gillespie	775.8	203.0	24.1
40	Tat_Momoli	715.3	178.6	20.8
41	San_Pedro_North	1704.9	424.8	16.2
42	Palomas	1106.0	262.4	13.6
43	Skull	486.9	68.7	12.7
44	Ajo	765.2	218.4	11.8

45	Ranegras	1254.0	367.4	10.6
46	Lake_Havasu	192.8	73.8	9.3
47	Blythe	1438.9	360.3	9.3
48	Hassayampa	672.8	231.5	9.0
49	Kingman	535.3	135.2	8.9
50	Arlington	309.4	91.1	8.2
51	Lechuguilla	534.6	118.8	4.0
52	Vekol	285.7	73.8	3.5
53	Wellton	456.7	106.1	3.3
54	Big_Chino	909.3	213.1	3.0
55	Castle_Dome	480.0	75.1	2.8
56	Detrital	1131.2	263.8	2.3
57	Verde_Valley	956.3	205.3	1.4
58	Sentinel	2280.9	366.1	0.0
59	San_Bernardino	747.6	143.4	0.0
60	Roosevelt	678.0	128.9	0.0
61	Congress	522.7	115.6	0.0
62	San_Rafael	390.3	112.9	0.0
63	Prescott	636.6	105.8	0.0
64	Buckeye	459.9	92.6	0.0
65	Butler	509.5	85.1	0.0
66	Ash_Flat	515.5	73.9	0.0
67	San_Carlos	779.4	73.2	0.0
68	Tule	476.6	69.8	0.0
69	Globe	432.9	67.7	0.0
70	Allen_Flat	314.7	62.7	0.0
71	Laguna	492.5	49.8	0.0
72	Aubrey	328.6	49.3	0.0
73	Pleasant_Valley	206.0	42.8	0.0
74	Castaneda	176.8	39.6	0.0
75	Sierrita_South	262.3	34.6	0.0
76	Cottonwood	287.3	31.0	0.0
77	Hualapai	321.1	27.9	0.0
78	Tonto	215.1	26.6	0.0
79	Sonoyta	223.1	26.2	0.0
80	Dripping_Spring	158.2	22.8	0.0
81	Peacock	292.7	22.1	0.0
82	Cienega	131.1	18.9	0.0
83	Eagle_Eye	158.7	17.6	0.0
84	Patagonia	122.0	16.0	0.0
85	Abra	109.3	15.6	0.0
86	Cave_Creek	90.2	15.2	0.0
87	Antelope	220.6	11.3	0.0
88	Willow_Beach	104.8	6.3	0.0
	TOTAL	88543	42247	12655
	TOTAL for top ten*	25574	20737	8989

*top ten basins by volume >800m depth

References cited

Davis, G.H., Constenius, K.N., Dickinson, W.R., Rodíguez, E.P., and Cox, L.J., 2004, Fault and fault-rock characteristics associated with Cenozoic extension and core-complex evolution in the Catalina-Rincon region, southeastern Arizona: Geological Society of America Bulletin, v. 116, n. 1/2, p. 128-141.

Dickinson, W.R., 1991, Tectonic setting of faulted Tertiary strata associated with the Catalina core complex in southern Arizona: Geological Society of America, Special Paper 264, 106 p.

Dickinson, W.R., 2002, The Basin and Range province as a composite extensional domain: International Geology Review, v. 44, p. 1-28.

Oppenheimer, J.M., and Sumner, J.S., 1980, Depth-to-bedrock map, Basin and Range province, Arizona: Tucson, University of Arizona, Department of Geosciences, Laboratory of Geophysics, 1 sheet, scale 1:1,000,000 (available as Arizona Geological Survey publication NP-14).

Oppenheimer, J.M., and Sumner, J.S., 1981, Gravity modeling of the basins in the basin and Range Province, Arizona, *in* Stone, Claudia, and Jenny, F.P., eds.: Tucson, Arizona Geological Society Digest 13, p. 111-116.

Richard, S.M., Reynolds, S.J., Spencer, J.E., and Pearthree, P.A., 2000, Geologic map of Arizona: Arizona Geological Survey Map 35, scale 1:1,000,000.

Richard, S.M., Shipman, T.C., Greene, L.C., and Harris, R.C., 2007, Estimated depth to bedrock in Arizona: Arizona Geological Survey, Digital Geologic Map DGM-52, layout scale 1:100,000, with 9 p. text.

Spencer, J.E., and Reynolds, S.J., 1989, Middle Tertiary tectonics of Arizona and the Southwest, in Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest, v. 17, p. 539-574.