Estimated Depth to Bedrock in Arizona

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INTRODUCTION

The Arizona Basin and Range Province consists of broad alluvial valleys that separate low but rugged mountain ranges. The broad expanses of dry alluvial deposits and ephemeral streams that characterize the basin areas belie their importance as water sources and their geologic complexity. These basins are geologically interesting as the record of late Cenozoic deformation in southwestern North America. They are economically interesting because of contained salt, anhydrite, manganese, uranium, clay, and zeolite resources, as well as the potential for metallic mineral deposits concealed beneath their sedimentary fill. The alluvial basins contain reservoirs of groundwater that are a vital resource for human occupants. An accurate geologic framework model of these basins is fundamental to scientific understanding of geologically recent continental tectonics, and to the discovery and managed development of the resources contained in the basins. This report provides a snapshot of current understanding of the subsurface geometry of the boundaries of Tertiary basin fill, which is a major component of the necessary geologic framework model.

Definition of Bedrock and Basin

For the purposes of this report, bedrock is thought of in hydrogeologic terms—that is rock that has sufficiently low bulk permeability that it could not be an aquifer. Basin fill is the term used to refer to the sedimentary (and locally volcanic) materials that fill Basin and Range basins, and is generally younger than about 15 million years in the southern part of the state and about 12 million years in the northwestern part of the state. This distinction is quite clear in situations in which non-consolidated alluvial material (sandy gravel) overlies indurated pre-Tertiary rock. It becomes much less clearly defined when the basin fill material in question is consolidated to some degree or contains volcanic layers, and the physiographic basin is bordered by Tertiary volcanic and sedimentary rocks that may not be well consolidated.

The term basin is used with several meanings that need to be clearly distinguished for hydrogeologic purposes.

1. Physiographic basin. “a large or small depression in the surface of the land or ocean floor” (definition 3a, http://www.m-w.com/dictionary/basin, Mirriam-Webster Online Dictionary). This is the sense used in the phrase ‘Basin and Range’.
2. Drainage basin. “the entire track of country drained by a river and its tributaries” (definition 3b, http://www.m-w.com/dictionary/basin, Mirriam-Webster Online Dictionary). These are commonly referred to as ‘surface-water basins’ or watersheds.
3. Groundwater basin. “A hydrologic unit of groundwater storage defined as an area more or less separate from neighboring groundwater storage areas.” (http://ag.arizona.edu/AZWATER/reference/glossary/grndbasn.html), or “an area underlain by permeable materials capable of furnishing a significant supply of groundwater to wells or storing a significant amount of water. A groundwater basin is three-dimensional and includes both the surface extent and all of the subsurface fresh water yielding material.” (http://www.groundwater.water.ca.gov/bulletin118/basin_maps/definition.cfm)
4. Structural basin. “areas where the dip of strata is towards the center of the basin” (Neuendorfer et al., 2005), “a broad area of the earth beneath which the strata dip usually from the sides towards the center” (definition 4, http://www.m-w.com/dictionary/basin, Mirriam-Webster Online Dictionary).

5. Sedimentary basin. “any geographical feature exhibiting subsidence and consequent infilling by sedimentation” (Wikipedia, 6/7/2006, http://en.wikipedia.org/wiki/Sedimentary_basin). Denotes a region of sediment accumulation.

The purpose of this map is to delineate sedimentary basins a portion of which contain low-density, relatively permeable sedimentary material. In the Basin and Range Province sedimentary basins are closely related to groundwater basins because the sedimentary basin fill-material forms aquifers that contain large amounts of stored water. The boundaries between groundwater basins and sedimentary basins are closely related because the geologic structures that form the boundaries of sediment accumulation zones commonly separate aquifer from non-permeable bedrock.

Because the boundary between bedrock and basin fill is directly observable only in outcrops at the edges of a sedimentary basin or in relatively sparse point locations where boreholes penetrate the boundary, remote sensing methods are used to infer the depth to this boundary in almost all cases. Borehole data are used to constrain geophysical models that are mostly based on gravity data, supplemented in some areas by magnetic field data, seismic reflection, or other geophysical data.

Surveys of slight variations in the local acceleration of gravity provide information about density differences in subsurface materials. In general, unconsolidated sedimentary fill in late Tertiary basins is less dense than consolidated sediments and crystalline basement rocks. The measured variations in the acceleration of gravity can be compared with predicted variation based on models of subsurface geology and measured rock densities (see Sharma, 1976, chapter 3). This procedure is used to generate a subsurface model that is consistent with measured gravity variations, known rock distribution, and geologic reasoning. Gravity-based subsurface models only constrain the depth to bedrock within a range of possible values. Consequently, the depth to bedrock map does not give exact depths. Other data are required to better constrain the interpretations, for instance drilling logs, cuttings and core, surface mapping, and other geophysical data such as seismic refraction or magnetic field anomaly data.

Geologic Setting

The Tertiary geologic history of the Basin and Range Province includes a major pulse of volcanism in late Oligocene and Miocene time that preceded or accompanied a major crustal extension event (Spencer and Reynolds, 1989). Formation of many of the present basins is due to faulting subsequent to this volcanism and extension (Eberly and Stanley, 1978; Shafiqullah et al., 1980; Houser et al., 2004), but it is not unusual for volcanic rocks to be interbedded in a basin fill sequence, particularly in the older parts. In some cases, such as the San Bernardino and Sentinel volcanic fields, young basalt lava flows apparently cover older basins that are otherwise similar to basins without the young volcanic cover.

In the Basin and Range Province, the pre-basin fill geologic sequence typically consists of pre-Tertiary rocks, overlain by interbedded Oligocene through middle Miocene volcanic and sedimentary rocks that were intricately faulted and tilted during early to middle Miocene extension. The Oligocene to middle Miocene extension event is characterized by extensive volcanism and large-scale low-angle normal faulting with closely spaced faults cutting and tilting volcanic and sedimentary rocks (Spencer and Reynolds, 1989). Hydrothermal activity associated with high thermal gradients and volcanic activity resulted in alteration and thorough cementation of sedimentary rocks accumulated in basins during this episode (e.g. Hollocher et al., 1994). In many areas, erosion and sedimentation during extensional deformation resulted in rapid changes in the thickness of Tertiary units (e.g. Dickinson, 1991). In some parts of a basin, the late Miocene and younger basin fill may be stratigraphically conformable with early Miocene sedimentary and volcanic rocks, whereas on nearby buried horst blocks, the late Miocene and younger sequence may be considerably thinner and overlie pre-Tertiary rocks directly. Between about 12 and 15 million years ago, the style of deformation and volcanism changed to a pattern of high-angle, more widely spaced faults that largely control the present basin-and-range physiography and formed the sedimentary basins that are the focus of this report (see Menges and Pearthree, 1989).

METHODS, PROCEDURES, ASSUMPTIONS, AND CAVEATS

Production of this data set began with a digitized version of contours for depths greater than or equal to 400 feet from a depth to bedrock map published by Oppenheimer and Sumner (1980). This data set was digitized from the published paper map by the U. S. Geological Survey (USGS) at the Southwest Field Office (SWFO) in Tucson, Arizona. No metadata are available on this original data automation activity. Depth to bedrock contours for this original map were obtained by extrapolating between 336 gravity profiles (about 22000 stations) along which 2-D models were constructed using a 2-layer geologic model to estimate the depth of the boundary between bedrock with a density greater than 2.67 g/cc and basin fill with a density varying between about 2.05 and 2.42 g/cm^3 (Oppenheimer and Sumner, 1981).

Depth to bedrock contours on the Oppenheimer and Sumner (1980) map were also constrained by 321 wells that either penetrated bedrock, or did not penetrate bedrock but are deep enough to constrain the depth to bedrock contours. The well locations and depths shown on Oppenheimer and Sumner (1980) were correlated where possible with permitted wells in the Arizona Oil and Gas Conservation Commission database of oil and gas wells (Rauzi and Richard, 2005). Oppenheimer (1980) reports that data for these wells are from well logs in U.S. Geological Survey files. Some of these wells appear to be included in the Arizona Department of Water Resources well database (Arizona Department of Water Resources, 2005), based on reported well depth matches.

For gravity-modeling purposes, Oppenheimer and Sumner (1980, 1981) defined bedrock as "rock having a density of greater than 2.67 g/cc ". Oppenheimer (1980) argues that although the density of basin fill increases with depth, it "does not approach" the average density of bedrock (2.67 g/cc), and thus the density definition of bedrock does not differ greatly from the geologic definition of bedrock. In the gravity models used by Oppenheimer and Sumner (1980), the density of basin fill was inferred to vary inversely with the magnitude of the measured (negative) residual Bouguer gravity value (Fig. 6 in Oppenheimer and Sumner, 1981) between about 2.04 and 2.42 g/cm^3. This assumption was based on the observation that more negative residual Bouguer gravity values are associated with thicker basin fill, and that the density of basin fill increases uniformly with thickness of overlying sediment (Tucci et al., 1982), thus the average density of a thicker basin-fill column is higher. The gravity modeling procedure of Oppenheimer and Sumner (1980), which assumes increasing average density with increasing basin fill thickness, will tend to overestimate the thickness of low-density basin fill.

Saltus and Jachens (1995) also published a depth to bedrock map for the Basin and Range Province. The 'bedrock' on their map is apparently defined as pre-Cenozoic rock. Thus, basins depicted on the Saltus and Jachens (1995) map include accumulations of volcanic rock that are considered bedrock on the Oppenheimer and Sumner (1980) map. Saltus and Jachens' (1995) analysis used gravity stations on bedrock to estimate a bedrock gravity anomaly, and gravity anomalies related to lower-density basin fill were then calculate with respect to this basement gravity field. The analytical technique also uses well control to constrain the calculation (see Saltus, 1991). Difference in analytical technique and definition of bedrock produces the obvious discrepancies between the maps in the Castle Dome Mountains, Ajo area, Superstition Mountains, and Peloncillo Mountains, among others. The basins shown by Saltus and Jachens (1995) in the Mohon Mountains, San Francisco Peaks area, and White Mountains are also thought to be due to the presence of voluminous Tertiary volcanic rocks. The basin depth map from Saltus and Jachens (1995) (Map C) was scanned at 150 dpi, and georeferenced to overlay with the other data sets for this update.

A variety of additional sources of information were used to update the depth to bedrock contours from the Oppenheimer and Sumner (1980) map. Additional well control was added, including wells from the Oil and gas wells in the State of Arizona database (Rauzi and Richard, 2005) and files of the Arizona Oil and Gas conservation Commission (unpublished, Arizona Geological Survey), the Arizona Department of Water Resources Wells 55 (Arizona Department of Water Resources, 2005) and Groundwater Site Inventory (GWSI, see http://www.azwater.gov/dwr/Content/Find_by_Program/Hydrology/Basic_Data.htm) databases, an Arizona well inventory (Peirce and Scurlock, 1972), and from consultants' reports and journal articles. No well logs, cuttings, or cores were studied as part of this project. All depth to bedrock interpretations for drilling data are based on written data associated with the wells. Bedrock intercepts reported in water wells are generally the boundary into hard rock, but in some wells may be to pre-Tertiary bedrock.

The surface outcrop of bedrock is from the Geologic Map of Arizona (Richard et al., 2000). Other major sources of depth to bedrock information for this update are a variety of published basin studies (e.g. Bultman, 1999; Earman et al., 2003). These are cited in the reference list (below) and in the feature-level metadata (tracking records) linked to each contour line segment in the digital data file.

Contour lines from Oppenheimer and Sumner (1980) were revised or, in places, replaced with new interpretations based on all the available information using map overlays in an ESRI ArcMap project. The greatest changes are in the interpretation of basin geometry away from the gravity profiles constructed by Oppenheimer and Sumner (1980), where the Saltus and Jachens (1995) or other more recent basin studies were considered more accurate depictions of subsurface geometry. Where bedrock outcrops were intersected by contours showing significant basin depth, the contour lines have been adjusted to be consistent with the bedrock outcrop. In some areas of generally flat-lying or gently tilted late Tertiary to Quaternary volcanic rocks, basin contours have been drawn to indicate suggested basin-fill accumulations beneath the volcanic rocks.

Definition of a hydrologic depth to bedrock, i.e. thickness of potential aquifer, is complicated by a number of factors. Depth-to-bedrock interpretations based on density contrast must be reconciled with interpretation of the contact between Tertiary sandstone and conglomerate and mostly Tertiary volcanic rocks or pre-Tertiary rocks based on well log information. Many basins contain interbedded volcanic rocks, making definition of a single depth impossible. In some cases, such as the San Bernardino and Sentinel volcanic fields, young basalt lavas apparently cover older basins that are otherwise similar to basins without the young volcanic cover. In these cases, geologic bedrock is the indurated and denser rock that underlies sedimentary basin fill. In some basins (e.g. lower Gila River area, San Pedro Valley, Cienega Gap area), relatively thick, well indurated Oligocene to early Miocene sedimentary sequences are present. From a hydrologic point of view, such strata are more akin to bedrock and their density may be quite close to that of the bedrock, with a gradational transition into low-density basin fill. In well log descriptions, it may be quite difficult to distinguish the older, Oligocene to early Miocene sedimentary strata from flat lying basin fill. In basins within the Transition Zone (e.g. Verde Valley, Tonto Basin), which are undergoing deep dissection, definition of depth to bedrock is complicated by the fact that the thickness of basin fill may vary dramatically in different parts of the basin depending on the depth of dissection. Note that because of the presence of fine-grained, clay-rich (aquitard) facies in many basins, the potential yield of basin fill is not simply related to the basin fill thickness contoured on this map. Further refinement of this map will require a basin by basin analysis (see Ostenaa et al. (1993), Gettings and Houser (2000), and Langenheim et al. (2005) for examples). More refined modeling could be done using seismic, electromagnetic, and aeromagnetic data, as well as more sophisticated gravity modeling.

DIGITAL DATA

This digital package includes an Adobe Acrobat document (pdf) containing this text, an Adobe Acrobat document containing an image of the depth to bedrock map, an ESRI shape file with line features representing depth to bedrock contours, and an ESRI point shape file containing collar locations for boreholes used to constrain depth to bedrock. The line feature shapefile, DTB_Contours.shp, represents estimated depth to bedrock contours for the state of Arizona. Except for depths based on bedrock penetrations reported in bore holes, determination of depth to bedrock is based on interpretation of geophysical data, and solutions for bedrock depth are in general poorly constrained. As discussed above the definition of 'bedrock' is subject to interpretation. These contours should be considered qualitative. Horizontal accuracy of depth to bedrock contours cannot be rigorously quantified, but is estimated to be in the range of +/- 1-3 km. Depth estimates are poorly constrained and should be considered highly uncertain, in the range of +/- 20-30 percent, except in the vicinity of wells penetrating bedrock. Depths are reported and contoured in feet, following common practice in virtually all of the available source data.

The U.S. Geological Survey Southwest Field Office (USGS SWFO) in Tucson originally digitized the Oppenheimer and Sumner (1980) depth to bedrock map. No metadata are available on original digitizing procedure. The digital data were obtained by AZGS from USGS, and have been edited and updated as discussed. The TextDescription field in the shape-file data table contains more information on processing and data sources for individual contours. Citations in the feature level source information reference the bibliography at the end of this report. The 'MapHorizon' attribute of line features in the shape file represent depth to bedrock in feet beneath ground surface. See the metadata files associated with the shape files for more information on data structure. Digital data are in Universal Transverse Mercator projection (UTM Zone Number 12, North American Datum of 1927, ellipsoid of Clarke, 1866).

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