USGS
science for a changing world

Prepared in cooperation with the National Park Service

Characterization of the Sevier/Toroweap Fault Zone in Kane County, Utah, Using Controlled-Source Audio-Frequency Magnetotelluric (CSAMT) Surveys

Scientific Investigations Report 2022–5071

U.S. Department of the Interior
U.S. Geological Survey

Characterization of the Sevier/Toroweap Fault Zone in Kane County, Utah, Using Controlled-Source Audio-Frequency Magnetotelluric (CSAMT) Surveys

By Casey J.R. Jones, Michael J. Robinson, and Jamie P. Macy

Prepared in cooperation with the National Park Service

Scientific Investigations Report 2022–5071

U.S. Department of the Interior
U.S. Geological Survey

U.S. Geological Survey, Reston, Virginia: 2022

Suggested citation:
Jones, C.J.R., Robinson, M.J., and Macy, J.P., 2022, Characterization of the Sevier/Toroweap Fault Zone in Kane County, Utah, using controlled-source audio-frequency magnetotelluric (CSAMT) surveys: U.S. Geological Survey Scientific Investigations Report 2022–5071, 14 p., https://doi.org/10.3133/sir20225071.

Associated data for this publication:
Robinson, M.J., and Macy, J.P., 2022, Controlled source audio-frequency magnetotellurics (CSAMT) data from the Sevier fault near Red Knoll, Kane County, Utah: U.S. Geological Survey data release, https://doi.org/10.5066/P9QF9PFR.

ISSN 2328-0328 (online)

Contents

Figures

Table

Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)

U.S. customary units to International System of Units

Multiply	By	To obtain
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)

Datum

Latitude and longitude values are referenced to World Geodetic System 1984 (WGS 84).

Vertical coordinate information is referenced to North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above vertical datum.

Abbreviations

Ω•m	ohm meter
bls	below land surface
CSAMT	controlled-source audio-frequency magnetotelluric
GPS	global positioning system
Hz	hertz
MT	magnetotelluric
NPS	National Park Service
NWIS	National Water Information System
USGS	U.S. Geological Survey
WRA	Water Rights Area

Characterization of the Sevier/Toroweap Fault Zone in Kane County, Utah, Using Controlled-Source Audio-Frequency Magnetotelluric (CSAMT) Surveys

By Casey J.R. Jones, Michael J. Robinson, and Jamie P. Macy

Abstract

The Sevier/Toroweap Fault Zone is a major north-south-striking fault located in northern Arizona and southwestern Utah. In partnership with the National Park Service, the U.S. Geological Survey conducted two geophysical controlled-source audio-frequency magnetotelluric (CSAMT) surveys that transected the Sevier/Toroweap Fault Zone at Clay Flat, Utah, a potential pull-apart basin, west of a site of proposed groundwater pumping to evaluate the subsurface hydrogeology. The goal of the surveys was to enhance understanding of the interconnectedness of the Navajo aquifer, the region's primary groundwater source, across two groundwater basins to the east and west of the fault zone, Water Rights Area (WRA) 81 and WRA 85.

In the Kane County, Utah, area, the Sevier/Toroweap Fault Zone consists of the Sevier section (to the north) and the northern Toroweap section (to the south). Two survey lines totaling 7 kilometers (km) of CSAMT survey data were collected. The CSAMT survey line SV1 transected both the Sevier section and the northern Toroweap section of the fault zone; survey line SV2 transected only the Sevier section. Although offset of the Navajo Sandstone, the main component of the Navajo aquifer, by the Sevier/Toroweap Fault Zone is generally accepted as the geologic reason that the Navajo aquifer is disconnected in the study area, results of the CSAMT surveys suggest that vertical offset of the Navajo Sandstone of the Glen Canyon Group across the Sevier/Toroweap Fault Zone is insufficient to completely disconnect the aquifer in the study area. The effects of faulting on groundwater north and south of the study area, where offset of water-bearing layers may be greater, requires further study. A clearer understanding of groundwater movement across the Sevier /Toroweap Fault Zone will aid water-resource managers in making informed decisions concerning groundwater rights.

Introduction

The waters of Zion National Park are protected under a water-rights settlement agreement between the National Park Service (NPS) and the State of Utah. The agreement covers groundwater withdrawals from Utah's Water Rights Area (WRA) 81. Current understanding of the geohydrology in the area is incomplete; it is unknown if groundwater withdrawals in an adjacent basin (WRA 85) could potentially affect groundwater quantity in WRA 81. These two groundwater basins are divided by the Sevier/Toroweap Fault Zone, with WRA 81 to the east and WRA 85 to the west (fig. 1) (Hayden, 2008). The Sevier/Toroweap Fault Zone is a major north-south-striking fault located in northern Arizona and southwestern Utah. This study was designed to enhance understanding of the connectedness of the regionally extensive Navajo aquifer across the Sevier/Toroweap Fault Zone in Kane County, Utah, near Red Knoll, a local surface feature and the site of proposed well construction. It is unknown whether the geologic structure of the fault plays a role in restricting groundwater flow between WRA 81 and WRA 85. Offset of the Navajo Sandstone of the Glen Canyon Group, the main component of the Navajo aquifer, by the fault zone is generally accepted as the geologic reason for the Navajo aquifer to be disconnected in the study area (Heilweil and Freethey, 1992; Truini, 1999; Billingsley and others, 2004). In this area, an en echelon left step between two sections of the Sevier/Toroweap Fault Zone—the Sevier section to the north and the northern Toroweap section to the south—forms Clay Flat, a small (1 square kilometer [km^2]), closed potential pull-apart basin, further complicating the geology and groundwater movement (Lund and others, 2008).

The Navajo aquifer supplies groundwater for municipal, domestic, and agriculture uses in southwestern Utah, and it contributes baseflow for the North and East Forks Virgin River, located in WRA 81 (Heilweil and Freethey, 1992). Although the study area is in a remote location that has very little development, the presence of the Navajo aquifer makes the area attractive for future water development. To address potential concerns and make informed decisions in the future, water-resource managers need a clearer understanding of the groundwater movement across the Sevier/Toroweap Fault Zone.

Purpose and Scope

This report describes two controlled-source audio-frequency magnetotelluric (CSAMT) electromagnetic profiles across the Sevier/Toroweap Fault Zone at Clay Flat near Red Knoll, in Kane County, Utah. Groundwater levels from nearby wells and springs are also reviewed. By surveying the electrical properties of the subsurface, using

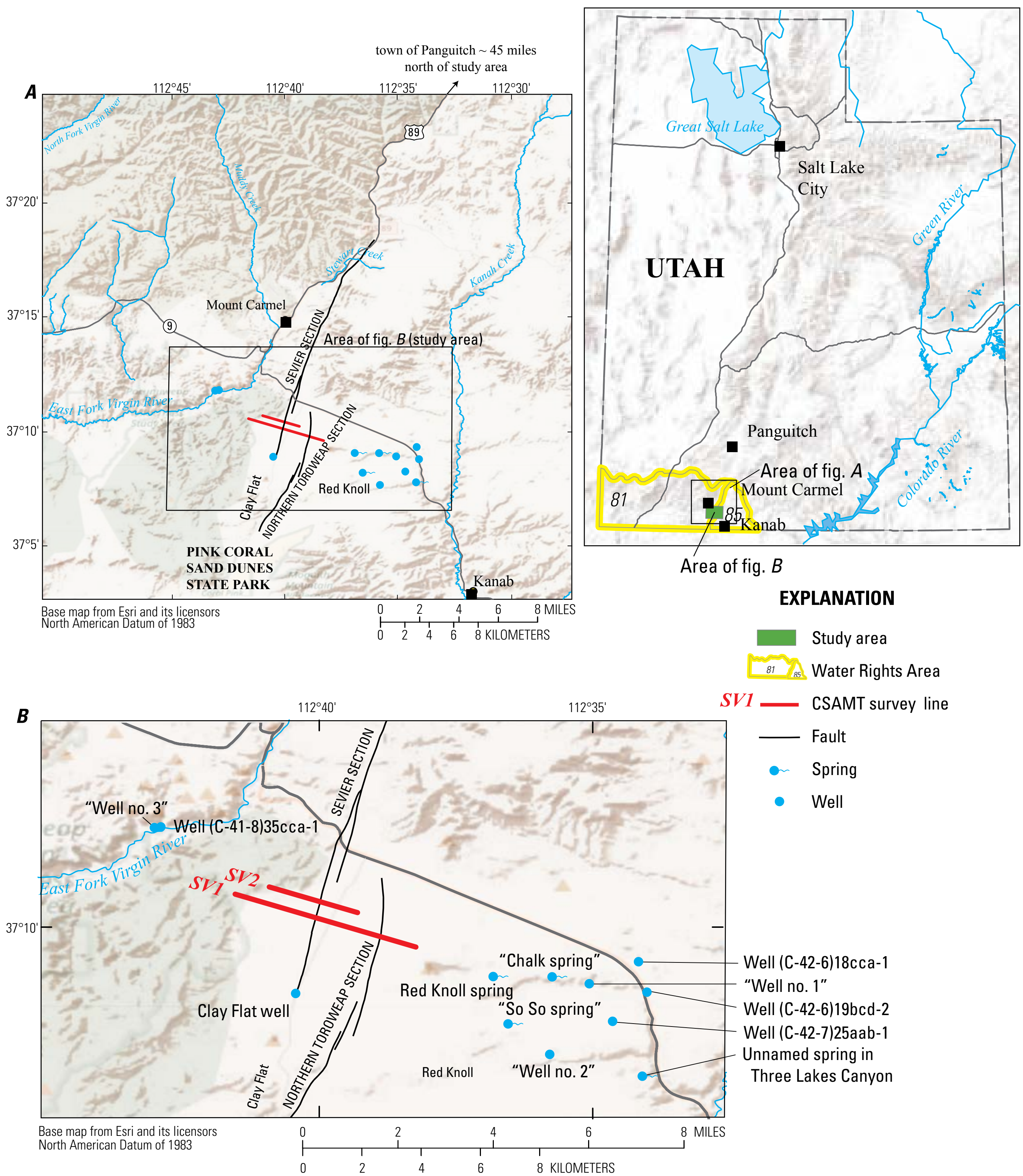


Figure 1. Shaded-relief maps showing (*A*) location of, and areas surrounding, study area (*B*) in Kane County, Utah. Also shown are locations of wells and springs from which hydrogeologic data were acquired, two controlled-source audio-frequency magnetotelluric (CSAMT) surveys (lines SV1 and SV2), and northern Toroweap and Sevier sections of Sevier/Toroweap Fault Zone. Faults modified from U.S. Geological Survey [USGS] (2021). Well and spring locations from USGS (2020).

the geophysical CSAMT surveys, and collecting groundwater data, the stratigraphic and structural characteristics of the Sevier/Toroweap Fault Zone can be inferred. Insights gained will improve the understanding of the hydrogeology of this complex area, and it will help determine if the section of the Sevier/Toroweap Fault Zone in the study area acts as a natural geologic barrier between WRA 81 and WRA 85 near the proposed groundwater drilling site at Red Knoll, or if the two groundwater basins are hydrologically connected by juxtaposed blocks of the Navajo Sandstone across the fault zone. This information will be useful in understanding the effects of groundwater development in southwestern Utah and for potential future groundwater-modeling efforts. A stronger understanding of groundwater movement across the Sevier/Toroweap Fault Zone will also aid water-resource managers in making informed decisions concerning groundwater rights.

Study Area

The study area is located about 15 kilometers (km) northwest of Kanab, Utah, in Kane County (fig. 1). Included in the study area is Clay Flat, a small (1 km^2), closed, potential pull-apart basin at the step-over between two sections of the Sevier/Toroweap Fault Zone (Lund and others, 2008); also included is Red Knoll, a local surface feature and the site of proposed groundwater drilling, about 4 km east of Clay Flat.

Physiography

The study area is in a zone of structural and geologic transition known as the High Plateaus of Utah Section of the physiographic province Colorado Plateaus Province. The High Plateaus of Utah Section, which lies in northwestern Arizona and southwestern Utah, is considered a transition zone between the core Colorado Plateaus Province to the east and the core Great Basin Section of the Basin and Range Province to the west (Davis, 1999; Lund and others, 2008, Ford and others, 2010). The subparallel Sevier/Toroweap Fault Zone is located between the Hurricane Fault and the Paunsaugunt Fault, two major north-south-striking faults, and it extends nearly 250 km, from south of the Colorado River in the Grand Canyon region of Arizona northward to north of Panguitch, Utah (Black and Hecker, 1997). The Sevier/Toroweap Fault Zone is the result of extensional stresses that caused downward motion of the downthrown strata on its west side relative to the upthrown strata on its east side. Normal displacement along the fault generally increases to the north, ranging from 300 meters (m) near the Grand Canyon in the south to 900 m in Red Canyon, southeast of Panguitch, at the north end of the fault (Pearthree, 1998). Nearly 500 m of displacement has occurred along the fault north of the Utah-Arizona border (Black and Hecker, 1997).

Previous authors have used different nomenclature to describe the Sevier/Toroweap Fault Zone and its individual fault sections. This report uses nomenclature in USGS's Quaternary fault and fold database (Black and Hecker, 1997; U.S. Geological Survey [USGS], 2021). Although this fault is traditionally known as the Sevier Fault in Utah and the Toroweap Fault in Arizona, here in the study area, the Toroweap Fault and the southern part of the Sevier Fault are considered to be the same fault (Black and Hecker, 1997).

The Sevier/Toroweap Fault Zone is divided into four distinct sections; the two northernmost sections (the northern Toroweap and Sevier sections) are located in the study area. The southernmost part of the late Quaternary northern Toroweap section begins in Arizona, and its northern part terminates about 20 km north of the Utah-Arizona border, in Clay Flat. The late Quaternary Sevier section begins west of the northern Toroweap section via a 2.5-km-long step in the fault zone at Clay Flat, and it extends northward to Panguitch (Black and Hecker, 1997).

This en echelon left step between the northern Toroweap section on the east and the Sevier section on the west forms a small (1 km^2), closed, potential pull-apart basin (Clay Flat). Clay Flat is a depocenter for a much larger drainage area of about 70 km^2 (Anderson and Christenson, 1989; Lund and others, 2008). Although not many studies have been completed in this location, it is thought that Clay Flat may be a seismogenic segment boundary on the basis of the differing frequencies of scarps and earthquake epicenters in the area. North of Clay Flat, scarps are present and more earthquake epicenters have been recorded; to the south, scarps are absent and fewer epicenters exist (Lund and others, 2008).

Geology

The stratigraphic layers in the Colorado Plateaus Province regionally dip from 1° to 5° to the north-northeast (Heilweil and Freethey, 1992). Locally, the geology in the study area consists of the Triassic Chinle Formation, the Triassic to Jurassic Moenave Formation of the Glen Canyon Group (hereafter referred to as the Moenave Formation), the Lower Jurassic Kayenta Formation of the Glen Canyon Group (hereafter referred to as the Kayenta Formation) (including the Tenney Canyon Tongue), and the Lower Jurassic Navajo Sandstone of the Glen Canyon Group (hereafter referred to as the Navajo Sandstone) (including the Lamb Point Tongue). Quaternary sediments overlie the Navajo Sandstone (fig. 2).

The Chinle Formation consists of mudstone and interbedded sandstone in its upper strata and sandstone and conglomerate in its lower strata (Martz and others, 2017). The Moenave Formation consists of fine-grained sandstone and siltstone; an unconformity is present within lower strata of the formation (Ford and others, 2010). The Kayenta Formation, which is a mixture of calcareous mudstone, siltstone, and sandstone, ranges in thickness from an average of 61 m in the area of Zion National Park, west of the study area, to 122 m near the Moccasin Mountains, south of the study area (Gates, 1965; Billingsley and others, 2004). The Kayenta Formation is dark red to light-reddish brown, as is its Tenney Canyon Tongue in this region. The Tenney Canyon Tongue intertongues with the underlying Lamb Point Tongue of the Navajo Sandstone. The Tenney Canyon Tongue is 67 m thick in the Moquith Mountains area, also located south of the map area, just southeast of Coral Pink Sand Dunes State Park. The Navajo Sandstone is a fine-grained, well-sorted quartz sandstone cemented with calcite (Heilweil and Freethey, 1992). Deposited under eolian conditions, the Navajo Sandstone is commonly cliff forming and contains medium to thick crossbedding (Heilweil and others, 2000; Billingsley and others, 2004). Its color varies from white, generally in its upper parts, to red, generally in its lower parts (Billingsley and others, 2004). Near Zion National Park, the thickness of the Navajo Sandstone is as much as 549 m (Heilweil and Freethey, 1992).

In the study area, the Tenney Canyon Tongue of the Kayenta Formation may lie above the main body of the Navajo Sandstone and below the Lamb Point Tongue of the Navajo Sandstone, splitting the Lamb Point Tongue from the main body of the Navajo Sandstone (Heilweil and Freethey, 1992; Blakey, 1994). The Lamb Point Tongue is a grayish-white to orangeish-brown quartz sandstone. Near Kanab, southeast of the study area, the Lamb Point Tongue is about 122 m thick and thins to the south and west (Heilweil and Freethey, 1992; Billingsley and others, 2004). The Navajo Sandstone is overlain by unconsolidated sandy deposits in many places in the study area.

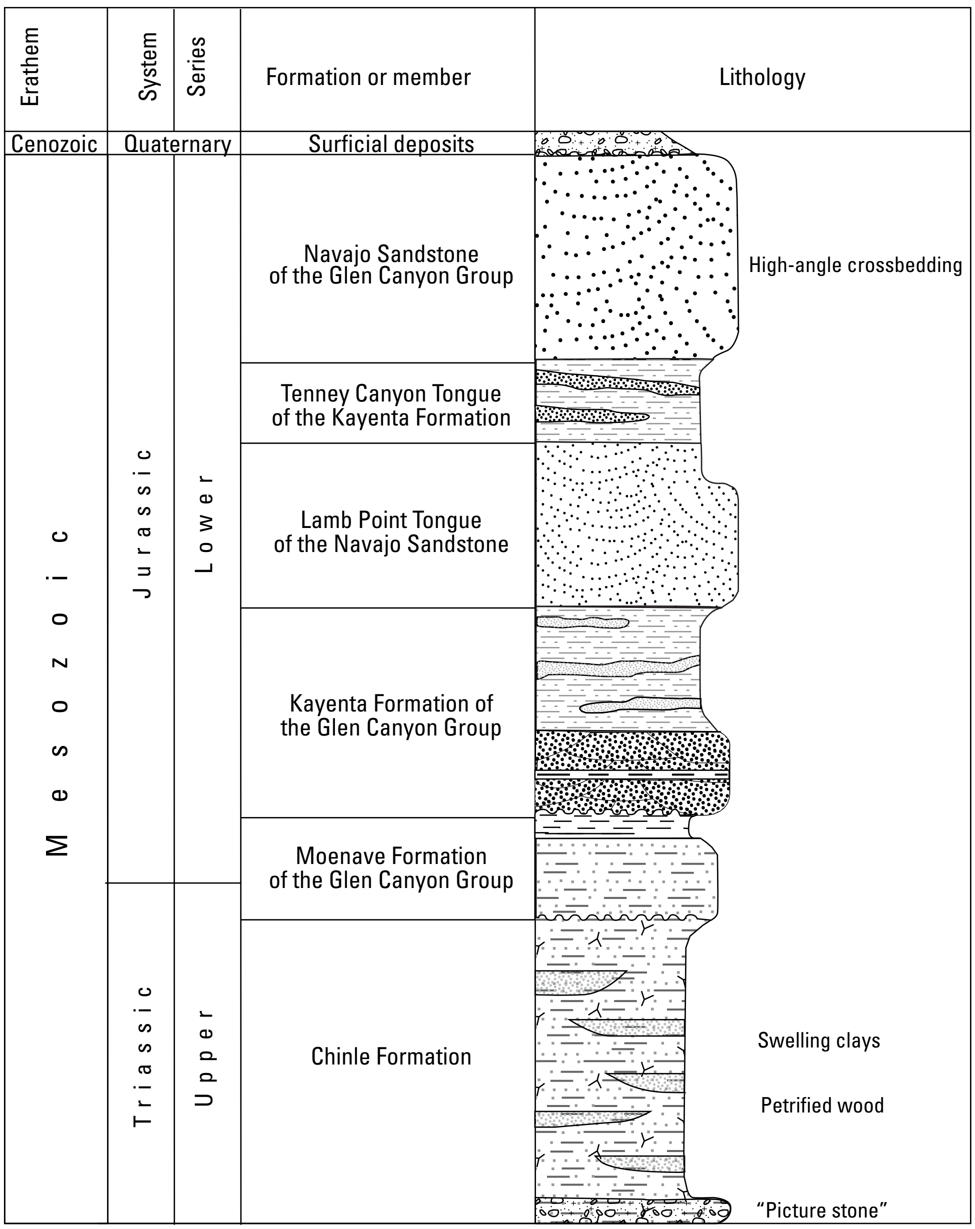


Figure 2. Generalized stratigraphic column showing ages and lithologies of rock units in study area (modified from Hayden, 2011).

Aquifer Characteristics

The Navajo aquifer is an expansive regional aquifer located in Arizona, Colorado, Nevada, New Mexico, and Utah. It is a valuable source of water for municipal, domestic, stock, and agricultural uses (Heilweil and Freethey, 1992). The aquifer is considered confined where it is overlain by either the Carmel Formation of the San Rafael Group or the Temple Cap Sandstone of the San Rafael Group, both of which are present to the west, north, and south of the study area (Doelling, 2008; Ford and others, 2010). Where it reaches the surface, the Navajo aquifer is considered unconfined, and direct groundwater recharge occurs. In the study area, the Navajo Sandstone is divided by the Tenney Canyon Tongue of the Kayenta Formation, which impedes vertical movement of water, potentially splitting the aquifer vertically; the lower part of the aquifer is the Lamb Point Tongue of the Navajo Sandstone. Near the Sevier/Toroweap Fault Zone, the Lamb Point Tongue is estimated to be about 60 m thick, and it is generally fully saturated. In the study area, the upper part of the Navajo Sandstone is not expected to be fully saturated owing to its unconfined conditions. Freethey (1988) stated that, west of Johnson Wash, a major north-south-trending drainage located about 25 km east of the study area, 45 to 60 m of the upper part of the Navajo Sandstone is thought to be saturated.

Between the Hurricane Fault, about 55 km west of the study area, and the Paria River, about 65 km east of the study area, as much as 68,180 acre-feet of water recharges the Navajo aquifer annually (Heilweil and Freethey, 1992). Groundwater in the Navajo aquifer generally moves from high altitudes, where recharge occurs, to springs and gaining streams in deep canyons, where discharge occurs. On the west side of the Sevier/Toroweap Fault Zone, groundwater moves from higher elevations down to the canyons of Zion National Park and East Fork Virgin River. On the east side of the Sevier/Toroweap Fault Zone, groundwater moves from the higher elevation bodies of the Navajo Sandstone down to the canyon systems of Kanab Creek, Cottonwood Creek, and Johnson Wash (Heilweil and Freethey, 1992).

Previous Studies of Groundwater Movement

Several previous studies have looked at groundwater flow around and across the Sevier/Toroweap Fault Zone, but no detailed studies have been conducted in the study area. Heilweil and Freethey (1992) analyzed groundwater flow in southwestern Utah and northwestern Arizona using steady-state groundwater models. They hypothesized that groundwater flow is restricted across the south half of the Sevier/Toroweap Fault Zone but is unrestricted in the north half.

More comprehensive studies of the Navajo aquifer have been conducted just south of the Utah-Arizona border. Truini (1999) studied the geohydrology of Pipe Spring National Monument, located about 35 km south of the study area, using drillers logs, depth-to-water measurements, and chemical analyses of water samples to ascertain the general direction of groundwater flow in the monument. Truini (1999) concluded that groundwater flow moved predominantly north to south along the west side of the Sevier/Toroweap Fault Zone and not laterally across it. Billingsley and others (2004) similarly interpreted the Sevier/Toroweap Fault Zone in Pipe Spring National Monument as a partial barrier for groundwater movement across the fault, owing to the high-angle, west-dipping fault plane that places impermeable strata of the older Chinle Formation, as well as that of the older Moenkopi Formation (not in the study area), east of the fault against the younger, water-bearing Navajo Sandstone and Kayenta Formation on the west side. Truini and others (2004) used seismic refraction and frequency-domain electromagnetic-induction geophysical surveys in and around Pipe Spring National Monument to gain information about the subsurface geologic structures, including the northern Toroweap section of the Sevier/Toroweap Fault Zone. Truini and others (2004) stated that the data suggest that groundwater movement and discharge to springs in the monument are controlled by geologic structures, including the northern Toroweap section of the Sevier/Toroweap Fault Zone, although they acknowledged that more information is needed to determine this definitively. Sabol (2005) suggested that a groundwater divide caused by a topographic high exists near the Arizona-Utah border: south of the divide, groundwater flows southward toward Pipe Spring National Monument; north of the divide, groundwater flows to the north-northwest toward the East Fork Virgin River, ultimately falling under the water rights of Zion National Park.

Vander Vis (2017) expanded these studies northward, conducting geophysical analyses of the Navajo aquifer from Pipe Spring National Monument northward through the Kaibab-Paiute Reservation and into Utah to determine where the regional groundwater divide is located. Transient electromagnetic techniques that measure the resistivity structure of the subsurface were used to collect resistivity data related to depth located below the point of data acquisition. Vander Vis (2017) concluded that the groundwater divide is located about 1,500 m south of the Arizona-Utah border and assumed that the Sevier/Toroweap Fault Zone is a restricting geologic structure that hinders groundwater flow.

Methods

Our study used surface geophysical surveys and groundwater data gathered from various sources to develop a better understanding of the geologic structures that control the hydrogeology of the Sevier/Toroweap Fault Zone. The CSAMT methods were used because of their relatively fast data acquisition, their ability to survey large areas, and their ability to identify faults and stratigraphic units to the depths necessary for this study. Existing well logs, water-level data, and other hydrogeologic information were used to constrain the subsurface electrical models. Locations of wells and springs that have water-level data described in this report are provided in table 1 (see also, USGS' National Water Information System (NWIS) database [USGS, 2020; https://waterdata.usgs.gov/nwis/gw] or Utah's Division of Water Rights website [Utah Division of Water Rights, 2020; https://waterrights.utah.gov/]).

Controlled-Source Audio-Frequency Magnetotelluric (CSAMT) Survey Methodology

The CSAMT method is an electromagnetic sounding technique that has proven useful for hydrogeological and groundwater studies. It is low impact and nonintrusive, and it has been used extensively by the mineral-, geothermal-, hydrocarbon-, and groundwater-exploration industries since 1978 when CSAMT equipment systems first became commercially available (Zonge, 1992). The CSAMT methods can provide electrical-resistivity information from the near-subsurface to depths of about 3,000 m below the surface. Resistivity is a measure of a material's opposition to the flow of electrical current, and it typically is measured in ohm meters (Ω•m). Because electrical resistivity varies with rock type and water content, this method can provide an indication of subsurface structures (for example, strata, faults, fractures) and the presence of groundwater (Simpson and Bahr, 2005). Resistivity in rocks such as carbonates typically ranges from 100 to 2,000 Ω•m; in shales and claystones, from 1 to 100 Ω•m; in sandstones, from 20 to 1,000 Ω•m; and in igneous rocks such as basalts, from 200 to 1,000 Ω•m (Sumner, 1976; Palacky, 1988; Nabighian and Macnae, 1991; Yungul, 1996). The resistivity of a rock is also dependent on saturation, porosity, fracturing, conductivity of fluids within the rock, and mineral composition (Zohdy and others, 1974). Saturated rocks have lower resistivity values than do unsaturated dry rocks. In addition, the same lithologic layer can have different resistivity values when saturated or unsaturated owing to void space. If unsaturated, the void space in a rock is filled with air and, thus, acts as an electrical resistor. Once saturated, the void space is filled with electrically conductive water, lowering the resistivity.

Description of Method

The CSAMT method provides information on the electrical resistivity of the subsurface along a receiver profile by measuring the electric and magnetic fields that are transmitted from a controlled current at several frequencies and at a specified distance away (fig. 3). Grounded dipoles at the receiver site detect the electric field parallel to the transmitter, and a magnetic-coil antenna senses the magnetic field perpendicular to the transmitter (fig. 3). The ratio of the orthogonal and horizontal electric-field magnitudes to the magnetic-field magnitudes yields the apparent resistivity, which would be the true resistivity if the subsurface were homogeneous and isotropic.

Table 1. Hydrogeologic data locations, water-surface elevations, and Utah Water Right numbers in and around the study area in Kane County, Utah.

[U.S. Geological Survey (USGS) site identifications (USGS site ID) are from USGS' National Water Information System database (U.S. Geological Survey, 2020). Latitude and longitude values (in decimal degrees) are referenced to World Geodetic System 1984 (WGS 84). Water-level elevations (in meters above mean sea level [m AMSL]) are referenced to North American Vertical Datum of 1988 (NAVD 88). Water Right numbers are from Utah Division of Water Rights (Utah Division of Water Rights, 2020). Other abbreviations: --, not applicable; ° N., degrees north; no., number; ° W., degrees west; yr, year]

Site name	USGS site ID	Site type	Latitude (° N.)	Longitude (° W.)	Water-level elevation (m AMSL)	Date of well water level (yr)	Water Right no.
East of the Sevier/Toroweap Fault Zone							
Well (C-42-7)25aab-1	370809112344001	well	37.1358	112.578	1,683	2021	85-978
"Well no. 1"	--	well	37.147	112.585	1,610	2008	85-946
Well (C-42-6)18cca-1	370915112341301	well	37.154	112.570	1,662	2021	--
Well (C-42-6)19bdc-2	370843112340602	well	37.145	112.568	1,666	1977	--
"Well no. 2"	--	well	37.1262	112.597	1,625	2006	85-1081
Red Knoll spring	--	spring	37.1497	112.613	1,816	--	85-565
"So So Spring"	--	spring	37.1351	112.608	1,793	--	85-827
Unnamed spring in Three Lakes Canyon	--	spring	37.1295	112.566	1,660	--	85-725
"Chalk spring"	--	spring	37.1495	112.595	1,771	--	85-828
Between the Sevier and northern Toroweap sections of the Sevier/Toroweap Fault Zone							
Clay Flat well	--	well	37.1466	112.675	1,552	1956	81-333
West of the Sevier/Toroweap Fault Zone							
Well (C-41-8)35cca-1	371146112430101	well	37.1954	112.718	1,512	1975	81-1155
"Well no. 3"	--	well	37.1961	112.717	1,516	2009	81-4703

The CSAMT method uses a remote, grounded, electric-dipole transmitter as an artificial signal source. Unlike natural-source audio-frequency magnetotelluric soundings in which the source of telluric current (for example, distant lightning strikes or atmospheric interaction with solar winds) is considered infinitely distant and nonpolarized, the CSAMT source is finite in distance and distinctly polarized (Sharma, 1997). The transmitter source provides a stable signal, resulting in higher precision and faster measurements than what can be obtained from natural-source audio-frequency magnetotelluric methods. Typically, the source for a CSAMT survey is separated from the survey line by a distance greater than three times the depth of investigation (Zonge, 1992). For this study, the maximum depth of investigation was about 1,100 m below the surface (fig. 4).

The CSAMT measurements typically are made at frequency ranges from about 1 to 8,000 hertz (Hz), in binary incremental steps. The frequencies used for the surveys in this report were 2, 4, 8, 16, 32, 64, 128, 256, 512, 1,024, 2,048, 4,096, and 8,192 Hz. The CSAMT measurements consist of orthogonal and parallel components of the electric (E) and magnetic (H) fields at a separation of 4 to 10 km from the source (Sharma, 1997). The measurements can be taken in several different arrays, depending on the type of information desired. This study used what is termed a “reconnaissance” type of CSAMT array, which consists of one electric (E_x) and one magnetic (H_y) component for each measurement (Zonge, 1992), as opposed to a more involved survey that collects vector and tensor measurements by measuring two electric-field components (E_x and E_y) and three magnetic-field components (H_x, H_y, and H_z). Multiple electric fields are measured concurrently during reconnaissance CSAMT surveys. This study used a six-channel receiver, with the capability of simultaneously measuring five electric fields for every one magnetic field. Because the magnetic field does not change significantly over the same distance that substantial electric-field changes occur, fewer magnetic-field measurements are required. The magnetic-field measurement is used to normalize the electric fields and calculate the apparent resistivity and phase difference (Zonge, 1992). Grounded dipoles at the receiver site measure the electric field parallel to the transmitter (E_x), and a magnetic-coil antenna measures the perpendicular magnetic field (H_y). The ratio of the E_x and H_y magnitudes yields the apparent resistivity (eq. 1; Zonge, 1992; Simpson and Bahr, 2005):

$$\rho_a = \frac{1}{5} f \left| \frac{E_x}{H_y} \right|^2 , \qquad (1)$$

where

ρ_a = the measured apparent ground resistivity, in Ω•m;

f = the signal frequency, in Hz (Zonge, 1992; Simpson and Bahr, 2005);

E_x = the parallel electrical-field strength, in volts/meter; and

H_y = the perpendicular magnetic-field intensity, in amps/meter.

The penetration of CSAMT into the subsurface and the depth of investigation are determined by the skin depth (eq. 2):

$$S = 503\sqrt{\rho_a \div f}, \qquad (2)$$

where

S = the skin depth, in m.

The skin depth is the depth at which the amplitude of a plane-wave signal has dropped to 37 percent of its value at the surface (Zonge, 1992). The skin depth is pertinent because CSAMT survey data are most commonly interpreted using simplified magnetotelluric (MT) equations that are based on the assumption that the electric and magnetic fields can be approximated as plane waves.

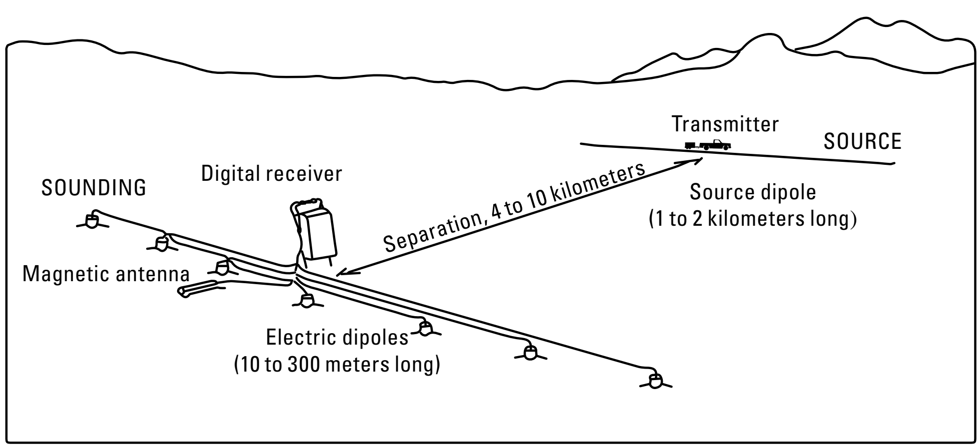
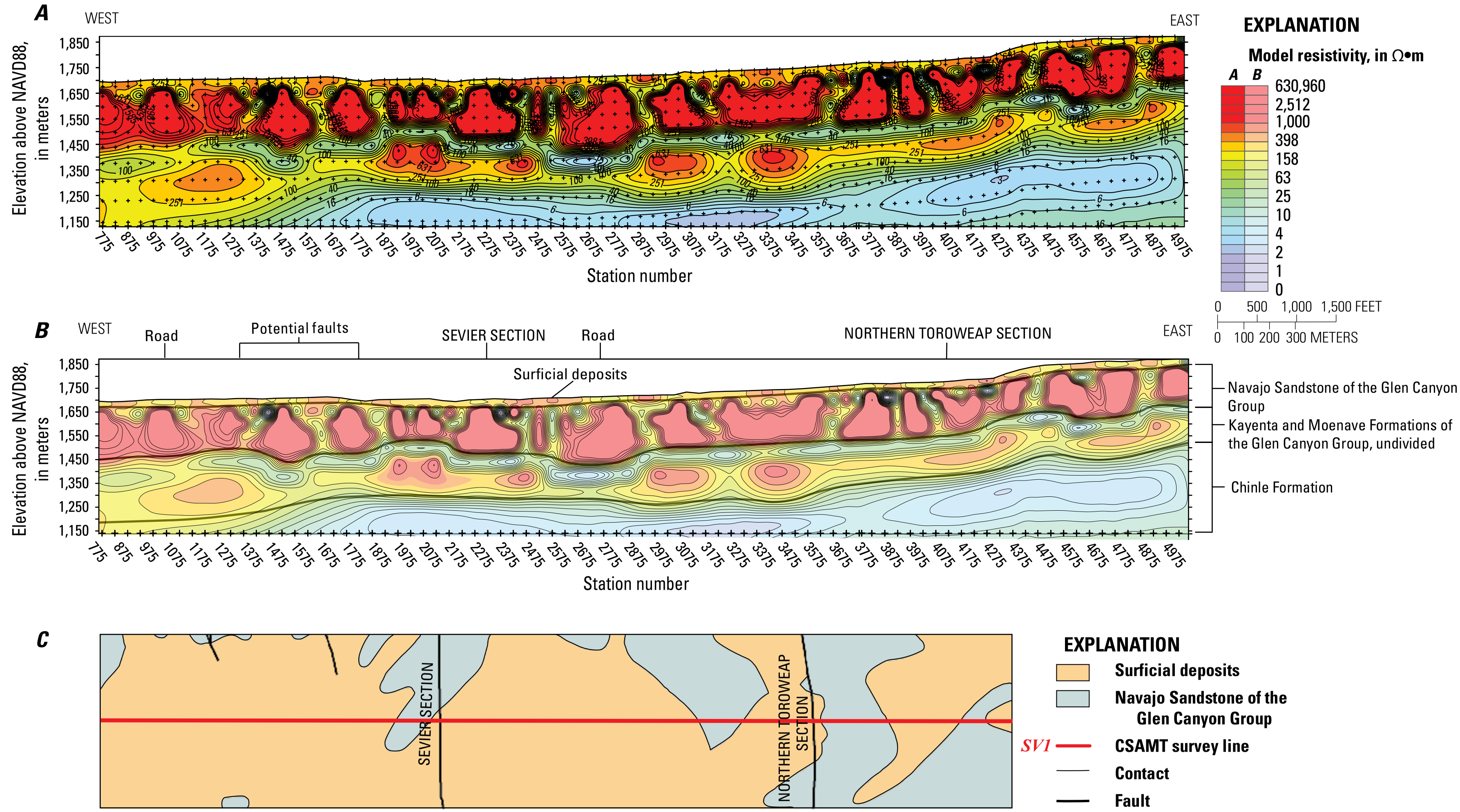


Figure 3. Diagram showing layout of controlled-source audio-frequency magnetotelluric (CSAMT) survey (modified from Zonge, 1992).



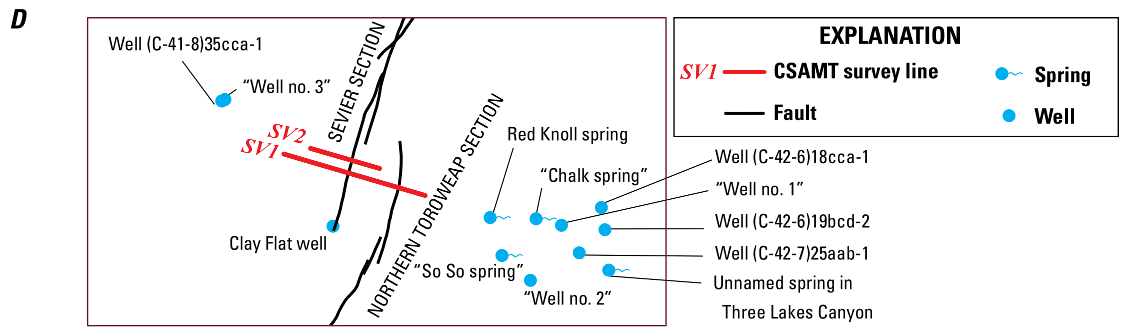


Figure 4. Cross sections (*A*, *B*) and maps (*C*, *D*) showing west-to-east-trending controlled-source audio-frequency magnetotelluric (CSAMT) survey line SV1. *A*, Smooth model-inversion results for line SV1. *B*, Interpretation of inversion results shown in *A*. *C*, Simplified geologic map (plan view) of area surrounding line SV1 (red line). Geology modified from Doelling (2008). Note that scale differs from that of *A* and *B*; length of line SV1 is 5 kilometers (km). *D*, Location map showing study area and location of survey lines SV1 and SV2 (see figure 5 for smooth model-inversion results for line SV2 and interpretation of those results). Note that scale differs from that of *A* and *B*; width of location map is about 19 km. Faults modified from U.S. Geological Survey [USGS] (2021). Well and spring locations from USGS (2020). Other abbreviations: Ω•m, ohm meter; NAVD88, North American Vertical Datum of 1988.

The separation between the transmitter and receiver for CSAMT surveys must be greater than three skin depths for the current driven into the ground to behave like plane waves (termed "far field"). When the separation is less than three skin depths at the frequency being measured, the electric and magnetic fields no longer behave as plane waves and become curved (termed "near field"), such that the equation for apparent resistivity (eq. 1) no longer applies (Zonge, 1992). All data from this study used for modeling are measured in the far field. The minimum distance between the source and receiver was 4.7 km, yielding a separation of greater than three skin depths.

When the separation between the receiver and transmitter is greater than three skin depths, the following equation (eq. 3) for depth of investigation (D) applies (Zonge, 1992):

$$D = 356\sqrt{\rho_a \div f}, \tag{3}$$

The depth of investigation of a CSAMT survey can range from 20 to 3,000 m, depending on the resistivity of the ground and the frequency of the signal. Lower frequency signals have a greater depth of investigation than do higher frequency signals. Equations 2 and 3 are used as a guideline to estimate the separation and depth of investigation rather than as a firm rule. During data analysis, plotting of the apparent resistivity versus the frequency for a given set of soundings was used to determine the lowest far-field frequency. The bearing of the receiving line must be parallel to the transmitting line and must be within the useable cone of measurement, which is ±30° (Zonge and Hughes, 1991).

Data Collection and Analysis

The CSAMT survey data were collected along two survey lines across sections of the Sevier/Toroweap Fault Zone west of Red Knoll from May 2020 to January 2021 (fig. 1). A total of 7 km of CSAMT survey data were collected. A Zonge GGT-30 geophysical transmitter, powered by and connected to a 25-kilowatt, trailer-mounted generator, and a Zonge XMT-32 transmitter controller were used to transmit the electrical source through a 1-km-long dipole. A Zonge GDP-32II multichannel geophysical receiver was connected to six porous pot electrodes, which were filled with a copper-sulfate solution and arranged in 50-m-long dipoles. A Zonge ANT6 high-gain mu-metal[1] core magnetic antenna was used to measure the Earth's response to the transmitted signal. Each CSAMT survey field measurement consisted of one magnetic-field measurement (H_y) and five accompanying electric-field measurements (E_x).

The CSAMT survey data can be influenced by nearby metal conductors such as fences, pipes, underground wires, overhead or buried power lines, and train tracks. Cultural interferences such as these were noted in the study area and then avoided when possible. Notch filters for 60, 180, 300, and 540 Hz were used for all CSAMT surveys in this study to reduce noise.

Two CSAMT survey lines, SV1 and SV2, were surveyed over the Sevier and northern Toroweap sections of the Sevier/Toroweap Fault Zone near Clay Flat, west of Red Knoll (fig. 1). The separation between transmitter and receiver locations ranged from 4.7 to 5.5 km. Global positioning system (GPS) locations were marked for each receiver station using a handheld GPS unit.

Once the surveys were complete, data were processed and analyzed using Zonge International's DATPRO suite of software. Raw CSAMT survey data were first averaged using Zonge International's CSAVG-W software (version 1.2; Zonge International, 2015a). Averaged data were reviewed for near-field and far-field effects by plotting the apparent resistivity versus the frequency (eq. 2) for a given set of soundings. The lowest far-field frequency was determined on the basis of these plots, and data below that frequency were not used in the analysis. For the surveys in this study, 8 Hz typically was the lowest far-field frequency used for analysis. After determining the lowest far-field frequency, the data for each distinct frequency, from 8 to 8,192 Hz, were averaged individually. The averaged data were inverted by Zonge's SCS2D software (version 3.40.h; Zonge International, 2015b), which employs a two-dimensional finite-element algorithm and finite-element mesh draped over an along-line topographic profile, to provide a two-dimensional resistivity profile for each survey line. The profiles were then examined for errors and adjusted as appropriate.

Although water-level data are included in this report, no water-level or other borehole data exist in the immediate vicinity of the survey lines. Owing to a lack of applicable data from well logs, no adjustments were made to the inversion models on the basis of hydrogeologic data. However, lithologic logs from wells about 4.5 to 6.5 km east of the study area indicate a similar sequence of geologic stratigraphy as interpreted in the inversion models. For inversion purposes, a one-dimensional "layer-cake" resistivity structure was assumed. Final inversion models (presented in the "Results" section below) represent the best fit to subsurface resistivity. All data collected and used in this report are provided in the data release (Robinson and Macy, 2022) associated with this report.

Hydrogeologic Methodology

Hydrologic data for this study consist of one water-level measurement taken by USGS at a preexisting well, made in accordance with methodologies in USGS' prescribed groundwater technical procedures (Cunningham and Schalk, 2011). Surface elevations of springs were recorded (table 1) (USGS, 2017). Lithologic logs and historical depth-to-water levels of wells were acquired from the Utah Division of Water Rights (Utah Division of Water Rights, 2020; www.waterrights.utah.gov) and USGS National Water Information System (NWIS) (USGS, 2020).

[1]Mu-metal is a nickel-iron, soft ferromagnetic alloy that has very high permeability, which is used for shielding sensitive electronic equipment against static or low-frequency magnetic fields.

Results

Geophysical Data

The data collected in the two CSAMT survey lines that transect the Sevier/Toroweap Fault Zone were inverted and modeled to display vertical cross sections of subsurface resistivity. Combined, about 7 km of data were collected across the two CSAMT survey lines. The CSAMT survey line SV1 (figs. 1, 4) runs roughly perpendicular to both the Sevier and the northern Toroweap sections of the Sevier/Toroweap Fault Zone. The CSAMT survey line SV2 is located 550 m north of SV1 and is perpendicular to the Sevier section of the fault zone (figs. 1, 5).

Note that data from stations 0 to 775 were not incorporated in the two-dimensional smooth model for survey line SV1 (fig. 4) because they did not fall within approved field methodology; that is, they were outside of the ±30° usable cone of measurement (Zonge and Hughes, 1991). Data below 1,100 m were also not included in the model owing to diminished resolution and accuracy at depth.

Survey Line SV1

The inverted resistivity model for survey line SV1 indicates four different layers (fig. 4). At the surface is a layer that has moderately high resistivity, having values that range from about 200 to 700 Ω•m. Consistent with unconsolidated sandy deposits, this layer extends to a depth of less than 50 m below the surface, or to about 1,850 m on its southeast end (station 4,975) and to about 1,650 m elevation on the northwest end of survey line SV1 (station 775). The second layer is a resistor, having resistivity values greater than 550 Ω•m, that extends from about 1,850 to 1,450 m elevation, and it is interpreted as saturated and unsaturated bodies of the Navajo Sandstone. Vertical and near-vertical conductive features in this resistive layer are likely fracture locations. Below the Navajo Sandstone, from 1,660 to 1,175 m elevation, is a less resistive lithologic layer that has resistivity values ranging from about 5 to 500 Ω•m; this layer is interpreted as the Moenave and Kayenta Formations, undivided. The electrical properties of the Triassic to Jurassic Moenave Formation and the Jurassic Kayenta Formation can be difficult to differentiate from one another; however, the less resistive area nearer the surface is likely the Kayenta Formation (Zonge International, 2015b). From 1,525 m elevation to the lower extent of the resistivity cross section (at 1,125 m elevation), a more conductive layer is present that has resistivity values ranging from about 0 to 50 Ω•m; this layer is likely the Chinle Formation.

Survey Line SV2

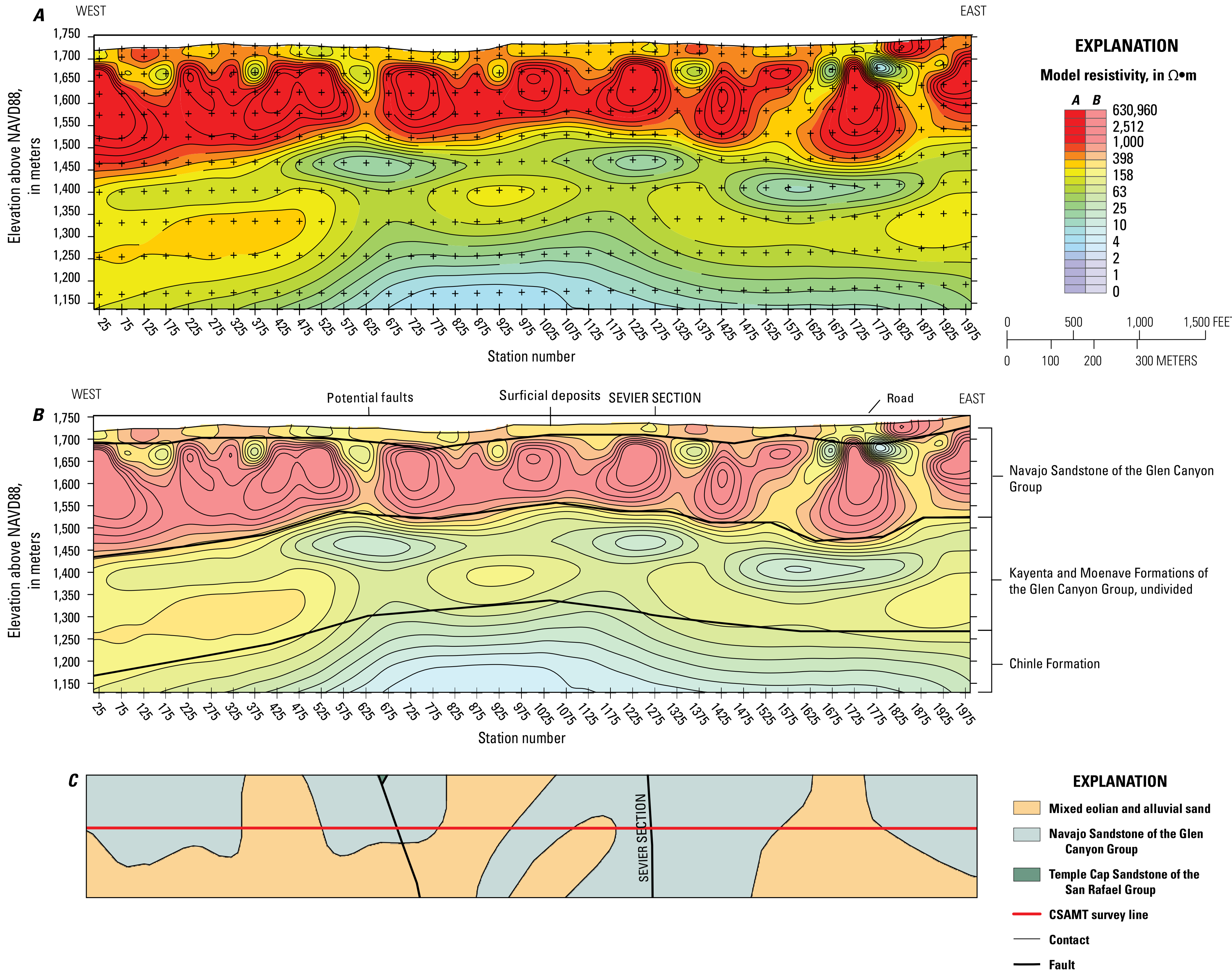
The general lithology interpreted in CSAMT survey line SV2 (figs. 1, 5), which is 0.55 km north of line SV1 and follows the same bearing as line SV1 (figs. 1, 4), applies to survey line SV2. The vertical cross section from the surface to depth is consistent with unconsolidated sandy surficial deposits, followed by the Navajo Sandstone, the undivided Kayenta and Moenave Formations, and the Chinle Formation.

The thicknesses, contact locations, and resistivity values of strata of the surveys correlate well with those from previous studies in nearby areas (Billingsley and others, 2004; Hayden, 2008; Macy and others, 2012; Vander Vis, 2017). Alternative interpretations are possible for the distinct, thin conductive layer that lies below the primary uppermost resistive layer: (1) the thin conductive layer may represent saturation in the Navajo Sandstone, and the underlying Kayenta Formation begins with the resistive layer in the center of the cross section; or (2) it could represent the Tenney Canyon Tongue of the Navajo Sandstone, with the lower parts of Navajo Sandstone extending into the resistive layer in the center. This second interpretation implies that nearly the entire thickness of the Navajo Sandstone is present. Regardless, the major conductive layer in the bottom parts of the cross sections (figs. 4, 5) is most likely the Chinle Formation.

The Sevier section of the Sevier/Toroweap Fault Zone approximately bisects survey line SV1 at station 2300 and line SV2 at station 1275 (figs. 4, 5) (Hayden, 2008). The Sevier section is not well constrained in the study area; however, both survey lines show little to no offset around these stations. The northern Toroweap section the Sevier/Toroweap Fault Zone bisects only survey line SV1. At SV1 station 4175 (fig. 4), about 50 m of offset is apparent (Hayden, 2008).

Several other anomalies are apparent in the resistivity models of both survey lines SV1 and SV2. These anomalies can be interpreted as either normal faults or cultural interference. County Road 43, also called Coral Pink Sand Dunes Road, crosses both survey lines SV1 at station 2775 and SV2 at station 1750, causing interference in the model. Road K1445 crosses line SV1 between SV1 stations 1025 and 1075. Stairstep features present in the model at SV1 stations 1375 to 1525, SV1 stations 1775 to 1875, and SV2 stations 575 to 675 (figs. 4, 5) may be areas of potential normal faulting and may correspond to faults previously mapped north of the survey lines (Hayden, 2008). Other vertical anomalies could be faults or cultural interference, or they could be artifacts from the inversion, depending on the horizontal and vertical smoothing coefficients chosen for the inversion.

Figure 5 (page 11). Cross sections (*A*, *B*) and map (*C*) showing west-to-east-trending controlled-source audio-frequency magnetotelluric (CSAMT) survey line SV2 (see figures 1*B* and 4*D* for location of line SV2 in study area). *A*, Smooth model-inversion results for line SV2. *B*, Interpretations of inversion results shown in *A*. *C*, Simplified geologic map (plan view) of area surrounding line SV2 (red line). Geology modified from Doelling (2008). Note that scale differs from that of *A* and *B*; length of line SV2 is 2 kilometers. Other abbreviations: Ω•m, ohm meter; NAVD88, North American Vertical Datum of 1988.


A
WEST
EAST
Elevation above NAVD88, in meters
1,750
1,700
1,650
1,600
1,550
1,500
1,450
1,400
1,350
1,300
1,250
1,200
1,150
Station number
EXPLANATION
Model resistivity, in Ω•m
A B
630,960
2,512
1,000
398
158
63
25
10
4
2
1
0
0 500 1,000 1,500 FEET
0 100 200 300 METERS
B
Potential faults
Surficial deposits
SEVIER SECTION
Road
Navajo Sandstone of the Glen Canyon Group
Kayenta and Moenave Formations of the Glen Canyon Group, undivided
Chinle Formation
C
SEVIER SECTION
EXPLANATION
Mixed eolian and alluvial sand
Navajo Sandstone of the Glen Canyon Group
Temple Cap Sandstone of the San Rafael Group
CSAMT survey line
Contact
Fault

The CSAMT survey line data indicate minimal offset in the Clay Flat area on both the Sevier and northern Toroweap sections, consistent with the area being a local transition between more prominent fault segments to the north and south (Lund and others, 2008). No vertical offset of the Navajo Sandstone that is large enough to hydrologically disconnect the unit east and west of the Sevier/Toroweap Fault Zone is apparent in the study area. Thus, the potential exists for groundwater to move across the fault zone. Other potential barriers to groundwater flow such as the presence of fault gouge are unknown. The significance of faulting on groundwater north and south of the study area, where offset of water-bearing layers may be greater, requires further study.

Hydrogeologic Data

Available hydrogeologic data, which include lithologic well records, historical water-level measurements, current water-level measurements, and locations of surface-water expressions (springs) of the Navajo aquifer, were acquired to further describe the hydrogeological character of the study area. Although no water-level or other borehole data exist in the immediate vicinity of the survey lines, several springs and wells exist east of the study area. Available data west of the study area are sparser.

In the study area, springs in the Navajo aquifer east of the northern Toroweap section of the Sevier/Toroweap Fault Zone include Red Knoll spring, "Chalk spring," "So So spring," and another unnamed spring in Three Lakes Canyon (fig. 1). One depth-to-water measurement was obtained during this study at well (C-42-7)25aab-1, a private well 5.8 km east of line SV1's station 5000 (table 1). Another well, well (C-42-6)18cca-1, located about 6.2 km east of line SV1's station 5000, has water-level data from 1977 to present; table 1 shows its most recent (2021) water-level elevation, but its water level has been trending downward, dropping about 6 m since 1988. Table 1 also contains historical water-level elevations for "well no. 1," "well no. 2," and well (C-42-6)19bdc-2 (fig. 1) (USGS, 2017, 2020; Utah Division of Water Rights, 2020).

When available, lithologic logs from wells east of the study area indicate a similar sequence of geologic stratigraphy as interpreted in the inversion models. "Well no. 1" has a depth of 216 m: 0 to 1.5 m depth below land surface (bls) consists of sand; 1.5 to 213 m depth bls, fractured bodies of the Navajo Sandstone; and 213 to 216 m depth bls, a red siltstone, possibly consistent with the Kayenta Formation. Lithologic logs for well (C-42-7)25aab-1 and "well no. 2" also show bodies of the Navajo Sandstone overlain by sand (Utah Division of Water Rights, 2020).

South of the survey lines, between the northern Toroweap and the Sevier sections of the Sevier/Toroweap Fault Zone (fig. 1), is Clay Flat well. Because of access restrictions, a current water-level measurement could not be acquired for this well, and so a historical (1956) measurement is included in table 1 (USGS, 2017; Utah Division of Water Rights, 2020). No lithologic log was available for this well.

Few wells exist west of the Sevier section, and hydrogeologic data are nearly nonexistent. Well (C-41-8)35cca-1 and the nearby "well no. 3" are both located about 200 m northwest of the East Fork Virgin River and 8.2 km northwest of station 5000 of CSAMT survey line SV1 (fig. 1). Again, access was restricted, and so historical (1975 and 2009, respectively) depth-to-water measurements are included in table 1 (USGS, 2020; Utah Division of Water Rights, 2020). Lithologic logs for both wells show bodies of the Navajo Sandstone overlain by 1.5 to 2.5 m of sand (Utah Division of Water Rights, 2020).

The water-level elevations of the hydrogeologic data points (table 1) on the east side of the Sevier/Toroweap Fault Zone indicate that, in this area, the water-level elevations in the Navajo aquifer decrease from west to east-southeast. The groundwater appears to flow from the high hydraulic head just east of the fault zone, downward along this gradient toward Three Lakes Canyon, and Kanab Creek.

West of the Sevier section of the Sevier/Toroweap Fault Zone and between the Sevier and northern Toroweap sections, no hydrogeologic data were available in the immediate vicinity of the CSAMT survey lines. Clay Flat well, 2.4 km south of survey line SV1, has a historical (1956) groundwater-level elevation of 1,552 m (table 1). West of the survey lines, well (C-41-8)35cca-1 has a historical (1975) groundwater-level elevation of 1,512 m, and "well no 3" has a historical (2009) groundwater-level elevation of 1,516 m (table 1). Additional borehole lithology data, geophysical logging, and water-level data are required to better constrain the interpretation of the CSAMT survey-line sections.

Summary

The Navajo aquifer is a regional aquifer located in Arizona, Colorado, Nevada, New Mexico, and Utah. The Navajo aquifer supplies groundwater for municipal, domestic, and agriculture uses in southwestern Utah, and it contributes baseflow for the North and East Forks Virgin River. The goal of this study was to enhance understanding of the interconnectedness of the Navajo aquifer across two groundwater basins to the east and west of the fault zone, Water Rights Area (WRA) 81 and WRA 85, in Kane County, Utah. The Sevier/Toroweap Fault Zone acts as the natural boundary between these two WRAs (fig. 1). West of Red Knoll, two sections of the Sevier/Toroweap Fault Zone, the Sevier section and the northern Toroweap section, are separated by a 2.5-kilometer (km)-long, left-lateral oblique slip fault, potentially forming a pull-apart basin known as Clay Flat. The extent of significant faulting at Clay Flat is unclear. One or both sections of the Sevier/Toroweap Fault Zone could serve as either a barrier or a conduit to flow.

To identify how these fault sections connect and what the extent of fault displacement is, U.S. Geological Survey (USGS) ran two controlled-source audio-frequency magnetotelluric (CSAMT) surveys. The CSAMT survey is a low-impact, nonintrusive electrical-resistance geophysical technique. The CSAMT survey line SV1 crossed both the

Sevier and the northern Toroweap sections of the Sevier/Toroweap Fault Zone; CSAMT survey line SV2 crossed only the Sevier section. Data were inverted to provide a two-dimensional resistivity profile for each survey line. Although borehole data in the area are sparse, lithologic logs from nearby wells support the stratigraphic interpretations of the inversion models. Unconsolidated sandy deposits are present at the surface and are underlain by a resistive layer interpreted as the Navajo Sandstone. Below the Navajo Sandstone, the less resistive Kayenta and Moenave Formations, undivided, are present. The lower extent of the inversion models is likely the Chinle Formation.

The CSAMT survey results indicate minimal offset on both fault sections of the Sevier/Toroweap Fault Zone, and they also suggest the presence of several small faults, thereby supporting the hypothesis that Clay Flat is a pull-apart basin. Minimal offset indicates that a significant barrier to flow likely is not present. Further investigations into the characteristics of the groundwater-flow system in the area—in particular, additional data from boreholes—are needed in the Kane County, Utah, area to aid water-resource managers in making informed decisions concerning groundwater rights.

References Cited

Anderson, R.E., and Christenson, G.E., 1989, Quaternary faults, folds, and selected volcanic features in the Cedar City 1°×2° quadrangle, Utah: Utah Geological and Mineral Survey Miscellaneous Publication 89–6, 29 p.

Billingsley, G.H., Priest, S.S., and Felger, T.J., 2004, Geologic map of Pipe Spring National Monument and the Western Kaibab-Paiute Indian Reservation, Mohave County, Arizona: U.S. Geological Survey Scientific Investigations Map 2863, scale 1:24,000, p. 7, https://doi.org/10.3133/sim2863.

Black, B.D., and Hecker, S., comps., 1997, Fault number 997b, Sevier/Toroweap fault zone, northern Toroweap section, *in* Quaternary fault and fold database of the United States: U.S. Geological Survey database, accessed March 11, 2021, at https://earthquake.usgs.gov/cfusion/qfault/show_report_AB_archive.cfm?fault_id=997&section_id=b.

Blakey, R.C., 1994, Paleogeographic and tectonic controls on some lower and middle Jurassic erg deposits, Colorado Plateau, *in* Caputo, M.V., Peterson, J.A., and Franczyk, J.J., eds., Mesozoic systems of the Rocky Mountain region, USA: Society of Economic Paleontologists and Mineralogists, Rocky Mountain section, p. 273–298.

Cunningham, W.L., and Schalk, C.W., 2011, Groundwater technical procedures of the U.S. Geological Survey: U.S. Geological Survey Techniques and Methods, book 1, chap. A1, 151 p., https://pubs.usgs.gov/tm/1a1/.

Davis, G.H., 1999, Structural geology of the Colorado Plateau region of southern Utah, with special emphasis on deformation bands: Geological Society of America Special Paper 342, 157 p.

Doelling, H.H., 2008, Geologic map of the Kanab 30′×60′ quadrangle, Kane and Washington Counties, Utah, and Coconino and Mohave Counties, Arizona: Utah Geological Survey Miscellaneous Publication 08–2DM, 2 plates, scale 1:100,000.

Ford, R.L., Gillman, S.L., Wilkins, D.E., Clement, W.P., and Nicoll, K., 2010, Geology and geomorphology of Coral Pink Sand Dunes State Park, Utah, *in* Sprinkel, D.A., Chidsey, T.C., Jr., and Anderson, P.B., eds., Geology of Utah's parks and monuments: Salt Lake City, Utah Geological Association Publication 28 (3d ed.), p. 379–403.

Freethey, G.W., 1988, Geohydrology of the Navajo Sandstone in western Kane, southwestern Garfield, and southeastern Iron Counties, Utah: U.S. Geological Survey Water-Resources Investigations Report 88–4040, 49 p.

Gates, J.S., 1965, Ground water in the Navajo Sandstone at the east entrance of Zion National Park, *in* Goode, H.D., and Robison, R.A., eds., Geology and resources of south-central Utah—Resources for power: Salt Lake City, Utah Geological Association Publication 19, p. 151–160.

Hayden, J.M., 2008, Interim geologic map of the Mount Carmel quadrangle, Kane County Utah: Utah Geological Survey Open-File Report 531, p. 1–15.

Hayden, J.M., 2011, Geologic map of the Kanab 7.5′ quadrangle, Kane County, Utah and Coconino and Mohave Counties, Arizona: Utah Geological Survey Map 248DM, 2 plates, scale 1:24,000.

Heilweil, V.M., and Freethey, G.W., 1992, Simulation of ground-water flow and water-level declines that could be caused by proposed withdrawals, Navajo Sandstone, southwestern Utah and northwestern Arizona: U.S. Geological Survey Water-Resources Investigation Report 90–4105, 51 p.

Heilweil, V.M., Freethey, G.W., Wilkowski, C.D., Stolp, B.J., and Wilberg, D.E., 2000, Geohydrology and numerical simulation of groundwater flow in the central Virgin River Basin of Iron and Washington Counties, Utah: Utah Department of Natural Resources Technical Publication 116, p. 139.

Lund, W.R., Knudsen, T.R., and Vice, G.S., 2008, Paleoseismic reconnaissance of the Sevier fault, Kane and Garfield Counties, Utah, volume 16 *of* Paleoseismology of Utah: Utah Geological Survey Special Study 122, 31 p.

Macy, J.P., Gungle, B., and Mason, J.P., 2012, Characterization of Big Chino subbasin hydrogeology near Paulden, Arizona, using controlled source audio-frequency magnetotelluric surveys: U.S. Geological Survey Scientific Investigations Report 2019–5082, 39 p., https://doi.org/10.3133/sir20195082.

Martz, J.W., Kirkland, J.I., Milner, A.R.C., Parker, W.G., and Santucci, V.L., 2017, Upper Triassic lithostratigraphy, depositional systems, and vertebrate paleontology across southern Utah: Geology of the Intermountain West, v. 4, p. 99–180.

Nabighian, M.N., and Macnae, J.C., 1991, Time domain electromagnetic prospecting methods, chap. 6 *of* Nabighian, M.N., ed., Electromagnetic methods in applied geophysics, Volume 2—Applications part A: Tulsa, Okla., Society of Exploration Geophysicists, Investigations in Geophysics Series, p. 427–520.

Palacky, G.J., 1988, Resistivity characteristics of geologic targets, chap. 3 *of* Nabighian, M.N., ed., Electromagnetic methods in applied geophysics—Volume 1, Theory: Tulsa, Okla., Society of Exploration Geophysicists, Investigations in Geophysics Series, p. 52–129.

Pearthree, P.A., 1998, Quaternary fault data and map for Arizona: Arizona Geological Survey Open-File Report 98–24, scale 1:750,000, 122 p.

Robinson, M.J., and Macy, J.P., 2022, Controlled source audio-frequency magnetotellurics (CSAMT) data from the Sevier fault near Red Knoll, Kane County, Utah: U.S. Geological Survey data release, https://doi.org/10.5066/P9QF9PFR.

Sabol, T.A., 2005, Delineation of wellhead and springhead protection areas for the Kaibab Paiute Indian Reservation, Arizona: Flagstaff, Northern Arizona University, M.S. thesis, 181 p.

Sharma, P.V., 1997, Environmental and engineering geophysics: Cambridge, U.K., Cambridge University Press, 475 p.

Simpson, F., and Bahr, K., 2005, Practical magnetotellurics: Cambridge, U.K., Cambridge University Press, 254 p.

Sumner, J.S., 1976, Principles of induced polarization for geophysical exploration: Amsterdam, Elsevier, 277 p.

Truini, M., 1999, Geohydrology of Pipe Springs National Monument area, northern Arizona: U.S. Geological Survey Water-Resources Investigations Report 98–4263, 25 p., https://doi.org/10.3133/wri984263.

Truini, M., Fleming, J.B., and Pierce, H.A., 2004, Preliminary investigation of structural controls of ground-water movement in Pipe Spring National Monument, Arizona: U.S. Geological Survey Scientific Investigations Report 2004–5082, 17 p., https://pubs.usgs.gov/sir/2004/5082/.

U.S. Geological Survey [USGS], 2017, The National Map—Elevation point query service: U.S. Geological Survey website, accessed September 7, 2021, at https://ned.usgs.gov/epqs/.

U.S. Geological Survey [USGS], 2020, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessed February 2020 at https://doi.org/10.5066/F7P55KJN.

U.S. Geological Survey [USGS], 2021, Quaternary fault and fold database of the United States: U.S. Geological Survey database, accessed January 2021 at https://earthquake.usgs.gov/cfusion/qfault/query_main_AB.cfm.

Utah Division of Water Rights, 2020, Utah Division of Water Rights: Utah Division of Water Rights website, accessed February 2020 at https://waterrights.utah.gov/.

Vander Vis, T., 2017, A transient electromagnetic analysis of groundwater on the Utah-Arizona border: Flagstaff, Northern Arizona University, M.S. thesis, 91 p.

Yungul, S.H., 1996, Electrical methods in geophysical exploration of deep sedimentary basins: Dordrecht, Netherlands, Springer Netherlands, 218 p.

Zohdy, A.A.R., Eaton, G.P., and Mabey, D.R., 1974, Application of surface geophysics to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 2, chap. D1, 116 p.

Zonge International, 2015a, CSAVG-W CSAMT Processing Tools, version 1.2: Zonge International software, http://zonge.com/instruments-home/software/data-processing/cs-avg/.

Zonge International, 2015b, SCS2D Two-dimensional, smooth-model CSAMT inversion, version 3.40.h: Zonge International software, http://zonge.com/instruments-home/software/modeling-amt/.

Zonge, K., 1992, Broadband electromagnetic systems, *in* Van Blaricom, R., ed., Practical geophysics II for the exploration geologist: Spokane, Wash., Northwest Mining Association, 96 p.

Zonge, K.L., and Hughes, L.J., 1991, Controlled source audio-frequency magnetotellurics, chap. 9 *of* Nabighian, M.N., ed., Electromagnetic methods in applied geophysics, Volume 2—Applications part B: Tulsa, Okla., Society of Exploration Geophysicists, Investigations in Geophysics Series, p. 713–810.

Moffett Field Publishing Service Center, California
Manuscript approved for publication July 5, 2022
Edited by Taryn A. Lindquist
Layout and design by Kimber Petersen

Jones and others—**Characterization of the Sevier/Toroweap Fault Zone in Kane County, Utah, Using CSAMT Surveys**—Scientific Investigations Report 2022–5071

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20225071