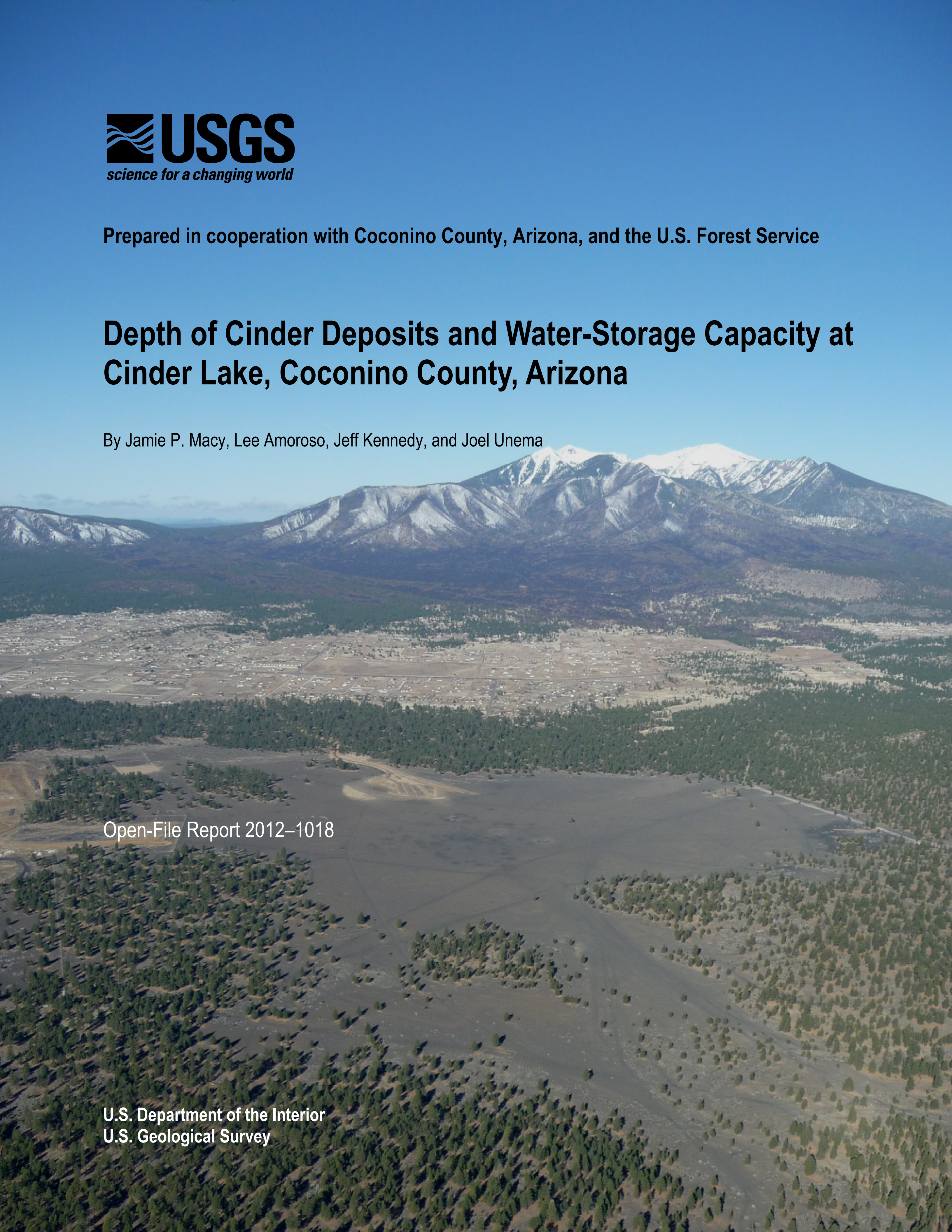

Prepared in cooperation with Coconino County, Arizona, and the U.S. Forest Service

Depth of Cinder Deposits and Water-Storage Capacity at Cinder Lake, Coconino County, Arizona

By Jamie P. Macy, Lee Amoroso, Jeff Kennedy, and Joel Unema

Open-File Report 2012–1018

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

COVER:
Photograph of San Francisco Mountain, nearby neighborhoods, and Cinder Lake area, Coconino County, Arizona. (USGS photograph taken by Jon Mason.)

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KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2012

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Conversion Factors and Datums

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
liter (L)	61.02	cubic inch (in^3)
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Time	
Second (s)	0.001	millisecond (msec)
Second (s)	0.000001	microsecond (µsec)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32.
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8.
Electrical resistivity ρ in ohm-meters [ohm-m] can be converted to electrical conductivity σ in siemens per meter [S/m] as follows: $\sigma = 1/\rho$.
Electrical resistivity ρ in ohm-meters [ohm-m] can be converted to electrical conductivity σ in millisiemens per meter [mS/m] as follows: $\sigma = 1{,}000/\rho$.
Electrical resistivity ρ in ohm-meters [ohm-m] can be converted to electrical conductivity σ in microsiemens per centimeter [µS/cm] as follows: $\sigma = 10{,}000/\rho$.

Datums

Vertical coordinate information is referenced to theNorth American Vertical Datum of 1988 (NAVD 88).
Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).
Altitude, as used in this report, refers to distance above the vertical datum.

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Abstract

The 2010 Schultz fire northeast of Flagstaff, Arizona, burned more than 15,000 acres on the east side of San Francisco Mountain from June 20 to July 3. As a result, several drainages in the burn area are now more susceptible to increased frequency and volume of runoff, and downstream areas are more susceptible to flooding. Resultant flooding in areas downgradient of the burn has resulted in extensive damage to private lands and residences, municipal water lines, and roads. Coconino County, which encompasses Flagstaff, has responded by deepening and expanding a system of roadside ditches to move flood water away from communities and into an area of open U.S. Forest Service lands, known as Cinder Lake, where rapid infiltration can occur. Water that has been recently channeled into the Cinder Lake area has infiltrated into the volcanic cinders and could eventually migrate to the deep regional groundwater-flow system that underlies the area. How much water can potentially be diverted into Cinder Lake is unknown, and Coconino County is interested in determining how much storage is available. The U.S. Geological Survey conducted geophysical surveys and drilled four boreholes to determine the depth of the cinder beds and their potential for water storage capacity. Results from the geophysical surveys and boreholes indicate that interbedded cinders and alluvial deposits are underlain by basalt at about 30 feet below land surface. An average total porosity for the upper 30 feet of deposits was calculated at 43 percent for an area of 300 acres surrounding the boreholes, which yields a total potential subsurface storage for Cinder Lake of about 4,000 acre-feet. Ongoing monitoring of storage change in the Cinder Lake area was initiated using a network of gravity stations.

Introduction

The 2010 Schultz fire northeast of Flagstaff, Arizona, burned more than 15,000 acres on the east side of San Francisco Mountain from June 20 to July 3 (fig. 1). As a result, several drainages in the burn area are now more susceptible to runoff and flooding events of greater frequency and volume. Despite a rapid response from the U.S. Forest Service (USFS) to mitigate some of the expected flooding and debris effects of the fire, one of the largest flood events associated with the Schultz Fire burn area occurred on July 20, 2010. Massive damage to private lands and residences, municipal waterlines, and roads in and downgradient of the burn areas have occurred, and greater than expected flooding persists. Although the fire occurred on USFS lands, there are a number of subdivisions located on unincorporated lands in Coconino County within drainage basins downgradient of the burn area, including the communities of Timberline Estates, Fernwood Estates, Pine Mountain Estates, and Wupatki Trails (fig. 1). In response to the flooding effects, the County deepened and expanded a system of roadside ditches to move flood water away from these communities and into open USFS lands where rapid infiltration can occur. The Copeland, Campbell, and Girl's Ranch Ditches were designed to safely reroute the runoff from two of the largest drainages originating in the burn area through developed lands and distribute the water into the Cinder Lake area (fig. 2). The Copeland, Campbell, and Girl's Ranch ditches are designed to carry about 1,600, 1,200, and 500 ft^3/s of water, respectively.

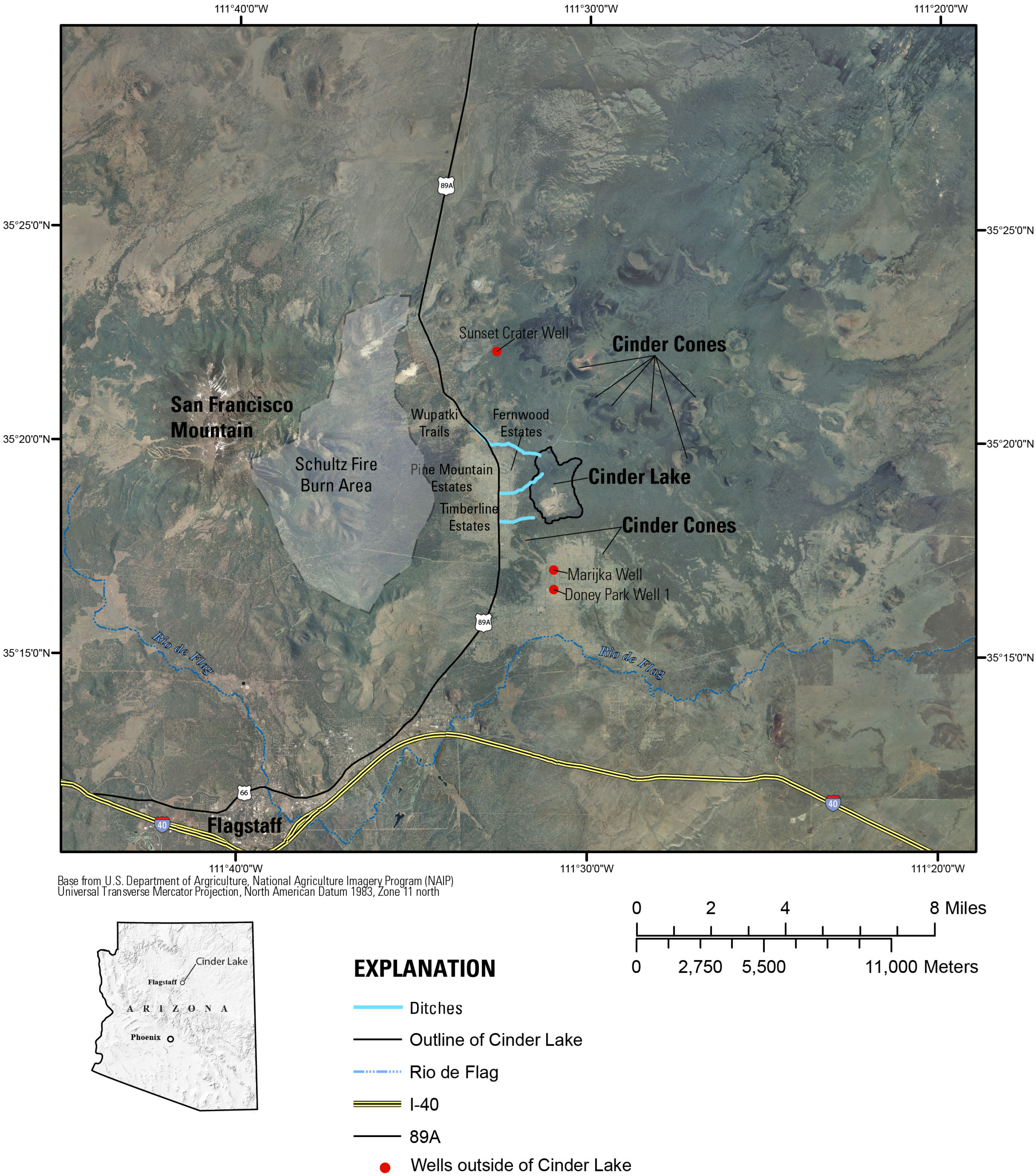


Figure 1. Map of Flagstaff, Arizona, and area north of Flagstaff, including Cinder Lake.

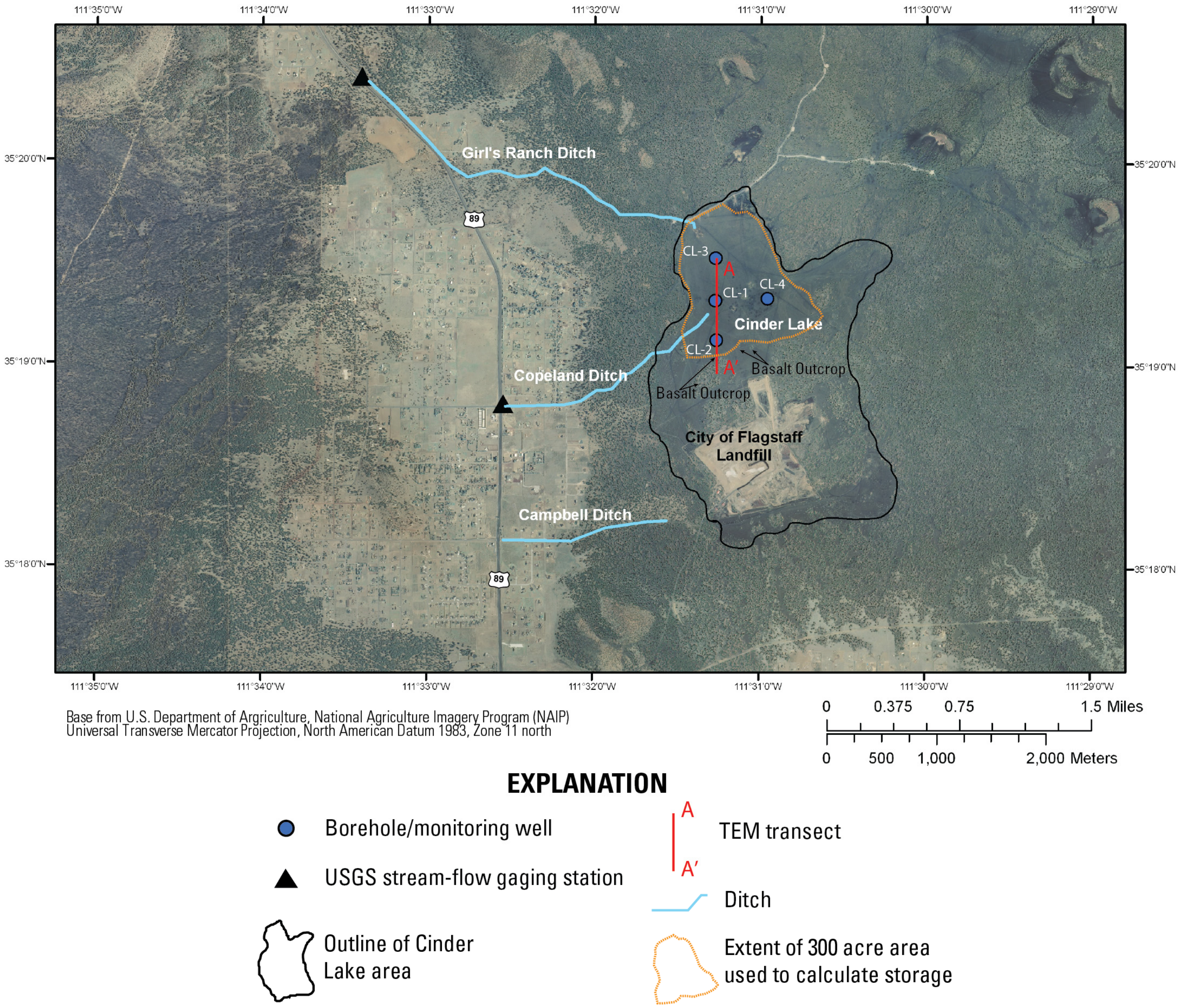


Figure 2. Map of the study area, Cinder Lake, Coconino County, Arizona, including borehole locations, USGS stream-flow gages, transient electromagnetic transect, ditches, and the extent of the area used to calculate total storage.

Cinder Lake is a dry cinder bed located on USFS land surrounded by cinder cones to the north, east, and south and alluvial fans at the base of San Francisco Mountain to the west. Water that has been channeled into the Cinder Lake area infiltrates into the volcanic cinders and alluvium and could follow three flowpaths out of the Cinder Lake area, including: (1) recharging the deep regional groundwater-flow system that underlies the area, (2) development of a perched aquifer that discharges to the Rio de Flag through the subsurface by moving laterally along confining layers such as basalt or clay, or (3) accumulating in the subsurface to the point where the cinders and alluvium are filled to capacity, forming a surface lake discharging to the Rio de Flag outside of the area to the southeast (fig. 1). The third flowpath could potentially impact the City of Flagstaff's unlined landfill, which is downgradient and to the southeast of Cinder Lake.

The ultimate flow path for the runoff may be largely determined by the lithology and storage capacity of near-surface materials in the Cinder lake area. Although a cinder bed occurs at the surface, little is known about the thickness or potential water storage capacity of those highly porous materials and underlying materials. Therefore in 2010, Coconino County entered into a cooperative program with the U.S.Geological Survey (USGS) to determine the depth and storage capacity of cinder deposits in the Cinder Lake area for distributing and infiltrating water from flow events associated with the Schultz Fire burn area.

Purpose and Scope

The purpose of this report is to describe and define the depth of interbedded cinders and alluvial deposits to the uppermost basalt layer in the study area, and to provide estimates of potential water storage in the interbedded deposits above the basalt in the Cinder Lake area. The scope of the report includes a description of methods used to determine the depth of the interbedded deposits to the top of the basalt layer and calculate water storage for the Cinder Lake study area.

Methods

Surface geophysical surveys were conducted and four boreholes were drilled to assess the near-surface materials and collect lithologic information, to provide control for the geophysical surveys, and to monitor for possible water storage following infiltration events. Surface geophysics are nonintrusive methods that can indicate changes in electrical properties and characteristics of the subsurface. Transient Electromagnetics (TEM) surveys were made to determine the total depth of cinders to basalt. Drill cores from the boreholes were used to estimate storage capacity of the cinder deposits. In addition to the subsurface investigations, a network of gravity monuments were established to monitor changes in subsurface water storage.

Local Hydrogeology

Flagstaff is located on the southern edge of the Colorado Plateau in north-central Arizona. The eastern part of the San Francisco volcanic field covers most of the area and provides much of the topographic relief. Cinder cones and hills, basalt flows, and San Francisco Mountain are the principal features superimposed onto the consolidated sedimentary rocks of the Colorado Plateau (Bills and others, 2000). In northern Arizona, the Colorado Plateau is composed of Cambrian through Mesozoic sedimentary rocks overlain by Tertiary and Quaternary volcanic and sedimentary rocks.

Volcanic rocks of Miocene to Quaternary age overlie sedimentary strata of the Colorado Plateau and are prevalent near Flagstaff and Cinder Lake. These volcanic rocks are aphanitic basalt and cinder cones; dacite flows and domes; dacite pyroclastic-flow breccias; andesite flows, flow breccias, and tuff breccia; and benmoreitic flows, cinder cones, and domes. These rocks range in thickness from zero to more than 5,000 ft beneath San Francisco Mountain. The average thickness of the volcanic rocks is about 150 ft (Bills and others, 2000). The hills surrounding Cinder Lake primarily are basalt cinder cones (Moore and Wolfe, 1976; figs. 1 and 3). Remnant basalt flows also are exposed to the north, east, and south of Cinder Lake (Moore and Wolfe, 1976; fig. 3). There are a few exposures of basalt within Cinder Lake that resemble push-up features where basalt is exposed at the surface (figs. 2 and 3). These basalt features could be remnants of basalt flows or eroded basalt flows. On the southern edge of Cinder Lake, basalt exposures form a ridge-like feature.

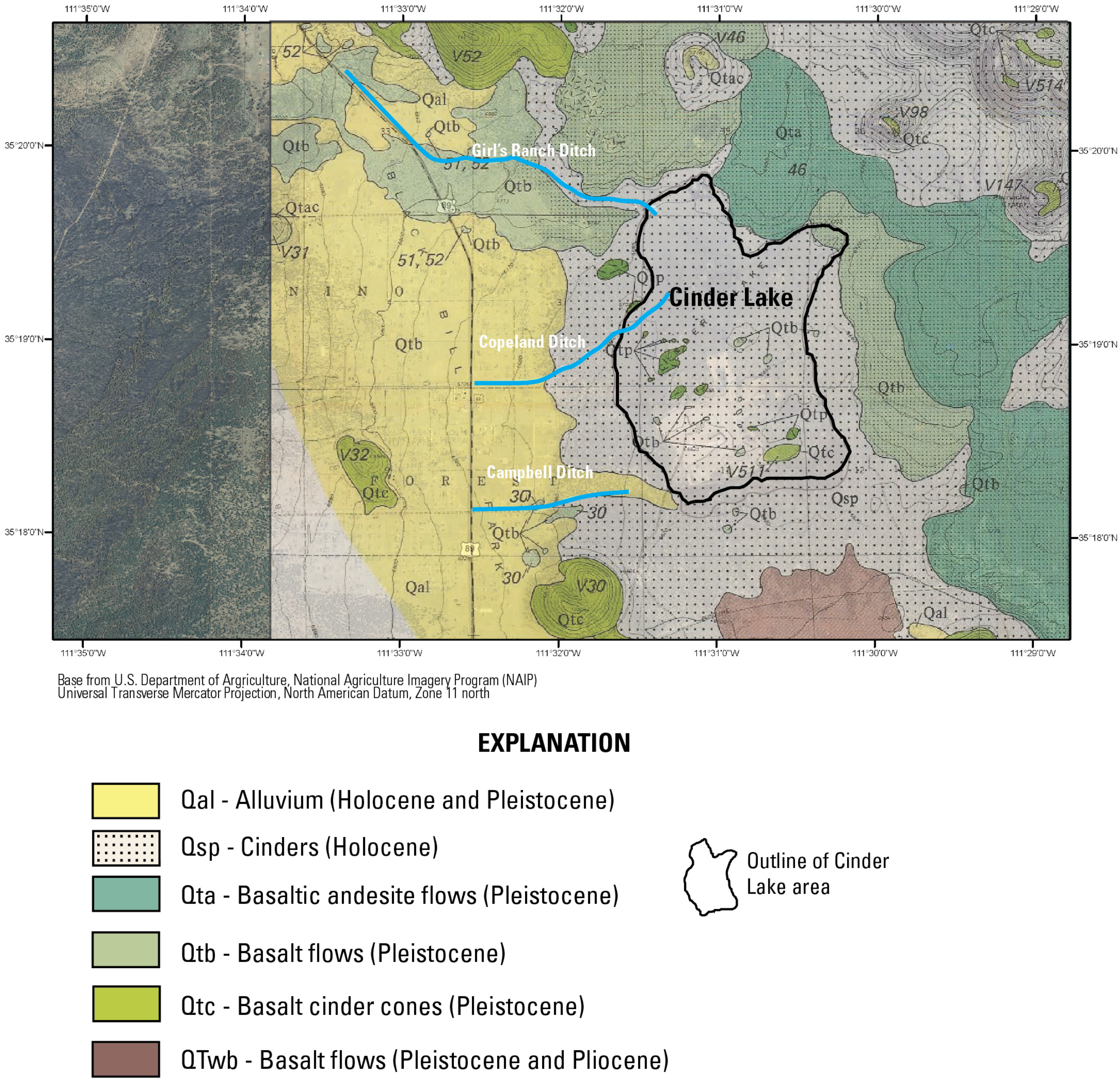


Figure 3. Geologic map of the study area, Cinder Lake, Coconino County, Arizona.

Information from three deep groundwater wells developed in the Cinder Lake area provide a context for the regional aquifer near Flagstaff and for what is to be expected in the subsurface near Cinder Lake. Those wells include the Sunset Crater Well, the Marijka Well, and the Doney Park Well 1 (DPW1) (fig. 1). All three wells were developed for groundwater withdrawal, but driller's logs from the wells provide information about the subsurface and the depth of the regional aquifer. The regional aquifer near Flagstaff typically is 1,200 to 1,400 ft below land surface. The regional aquifer is composed of the Kaibab Formation, Toroweap Formation, Coconino Sandstone, Schnebly Hill Formation, and Upper and Middle Supai Formation. The regional aquifer is heterogeneous and anisotropic and has a complex groundwater-flow system. The most productive water-bearing material tends to be fine- to medium-grained sandstone, and groundwater flow and potential well yields are related to geologic structure. Static water in wells around Flagstaff typically is in the Schnebly Hill Formation or the Upper Supai Formation.

The driller's log for the Sunset Crater Well (fig. 1) shows an interval of 700 ft of volcanic material at the surface. The Kaibab Limestone underlies volcanic material and extends to a depth of 1,000 ft below land surface. An 830-ft interval of Coconino Sandstone is beneath the Kaibab Limestone. Then from 1,830 to 2,200 ft below land surface, the well is completed in the Supai Formation.

Another well with similar characteristics in the area is the Marijka Well (fig. 1). Alluvium and cinder material extend from the surface to a depth of about 210 ft below land surface. Basalt continues another 90 ft to the top of the Kaibab Limestone. Kaibab Limestone extends from 300 to 740 ft below land surface. The Coconino Sandstone is found in this well from 740 to 1,400 ft, where it contacts the Schnebly Hill Formation and upper Supai Formation.

A third well in the area is well DPW-1 (fig. 1). The driller's log from well DPW-1 showed basaltic sand, basalt fragments, and basaltic scoria to a depth of 55 ft below land surface and an interval of basalt from 55 to 205 ft. An interval of Moenkopi Formation from 205 to 260 ft is beneath the basalt. Driller's logs from the Sunset Crater and Marijka Wells in the area do not show an interval of Moenkopi Formation. In DPW-1, the Moenkopi Formation overlies Kaiaba Formation from 260 to 480 ft and the Coconino Sandstone extends from 560 to 1,740 ft beneath the Kaibab Formation. The Schnebly Hill Formation is at a depth of 1,740 ft, and the well is completed in this unit. The stratigraphy described in three wells near Cinder Lake provides background information that was used to determine possible depth of study for geophysical techniques and what would be expected from a borehole drilled from the surface to the water table near Cinder Lake.

Transient Electromagnetics (TEM) Surveys

A TEM sounding is made by transmitting an intermittent electrical signal through an ungrounded wire that is laid in a square loop on the surface of the earth. The transmitter loop (Tx) is energized periodically at regular intervals at frequencies of 4 to 32 hertz and creates a time-varying magnetic field in the earth below it through Ampere's law (Fitterman and Stewart, 1986). According to Faraday's Law of Induction (Fitterman and Stewart, 1986), rapidly switching the electric signal on and off produces a primary electromagnetic field that diffuses into the ground and causes (induces) eddy currents in the ground and in nearby buried conductors (Sharma, 1997). The eddy currents create secondary magnetic fields, some portion of which travel back to the surface (Nabighian and Macnae, 1987) where they can be measured as a decaying magnetic field. This usually is done by using a receiver composed of a smaller secondary loop or a vertical coil of highly conductive material. Although the secondary magnetic field can be measured anytime, many instruments focus on detecting the fields after the instrument stops transmitting. This gives the instrument greater sensitivity than other electrical methods because the decay of these currents occurs when there is no primary field to interfere with detection (Nabighian and Macnae, 1987).

Measurements of the decaying secondary field are made at the land surface by sampling the field during multiple short time windows. Measurements for this survey are made with the receiver coil inside of the transmitter loop to provide a 1-dimensional (1-D) sounding of the subsurface response to the primary field. The depth of investigation of a TEM sounding is dependent on the size of the primary loop, the amount of current excited into the loop, and the ability of the subsurface to conduct an electrical field. A general guideline is that the depth of investigation is about two to three times the size of the transmitter loop of wire. In conductive areas, the depth of investigation may only be equivalent to the size of the loop; and in more resistive areas, the depth of investigation may be more than three times the size of the primary loop (Zonge, 1992). Each TEM sounding is comparable to a single drilled borehole, although the sample volume is significantly larger because of the size of the transmitter loop and the outward spreading of the primary field with depth (smoke-ring effect). The results of an individual TEM sounding can be modeled and plotted as resistivity values with depth. Multiple TEM soundings adjacent to or near each other can be plotted together as a TEM profile or cross section.

Raw TEM data were collected and then processed, and 1-D layered earth resistivity models were developed using Zonge Engineering's DATPRO (Zonge Engineering, Tucson, Arizona) suite of software. Raw TEM data were averaged using Zonge's TEMAVG program. Averaged data were imported into Zonge's STEMINV inversion software to produce a 1-dimensional model of subsurface resistivity for each sounding.

A Zonge Engineering NanoTEM system (Zonge Engineering, Tucson, Arizona) was used for this investigation. The system was set up in a configuration that consisted of a Zonge ZT-20 transmitter connected to a transmitter loop (Tx) that was excited with between 3.0 and 3.5 amps for each sounding. The receiver consisted of a smaller loop of wire located in the center of the transmitter loop used in conjunction with a Zonge GDP-32II multifunction receiver (Rx). Thirty-two hertz data were collected for each sounding. Thirty-one time windows of data were collected at each sounding from 0.0 μsec to 2.859 msec. Measured data were observed in the field as averaged normalized returns for each time window that were then graphed for visual inspection of irregularities. Three repetitions of each sounding were measured and averaged together.

TEM soundings were conducted at Cinder Lake during May and June 2011. Although different TEM loop sizes were tested to determine which size would most appropriately profile the depth to basalt, a 60 ×60 ft transmitter loop with a 15 ×15 ft receiver loop showed the best results and was therefore used for the survey. A north-south profile, A–A′, of 49 adjacent TEM soundings were made from borehole CL-3 in the north to about 600 ft south of borehole CL-2 (figs. 2 and 4).

TEM data can be influenced negatively by nearby metal conductors, such as fences, pipes, underground wires, overhead or buried power lines, and train tracks. There were no cultural interferences such as these in the vicinity of Cinder Lake.

Borehole Drilling

Boreholes were drilled at Cinder Lake to provide control for geophysical techniques and to characterize the subsurface materials found above the first basalt layer (fig. 1). Four boreholes were drilled by Boart Longyear™ (2010), using sonic drilling methods. The sonic drilling method produces a continuous, relatively undisturbed core sample and is beneficial for investigative studies where information is needed about subsurface lithology. Sonic drilling uses an outer steel casing and an inner, smaller diameter steel drill pipe connected to a hollow pipe that fits inside the outer steel casing. High-frequency vibrations are sent down the drill stem as it rotates into the subsurface. As the outer case advances into the subsurface, the inner casing forms a sleeve around the subsurface material that can be extracted as a core. The sleeve is removed from the core and core materials are loaded into clear plastic sleeves and described. Each bag typically holds about 2.5 ft of core sample and the clear bags are laid on a tarp in sequential order where they can be described and documented. Borehole cores were initially described on-site and further described in the laboratory (Schoeneberger and others, 2002; Birkeland and others, 1991).

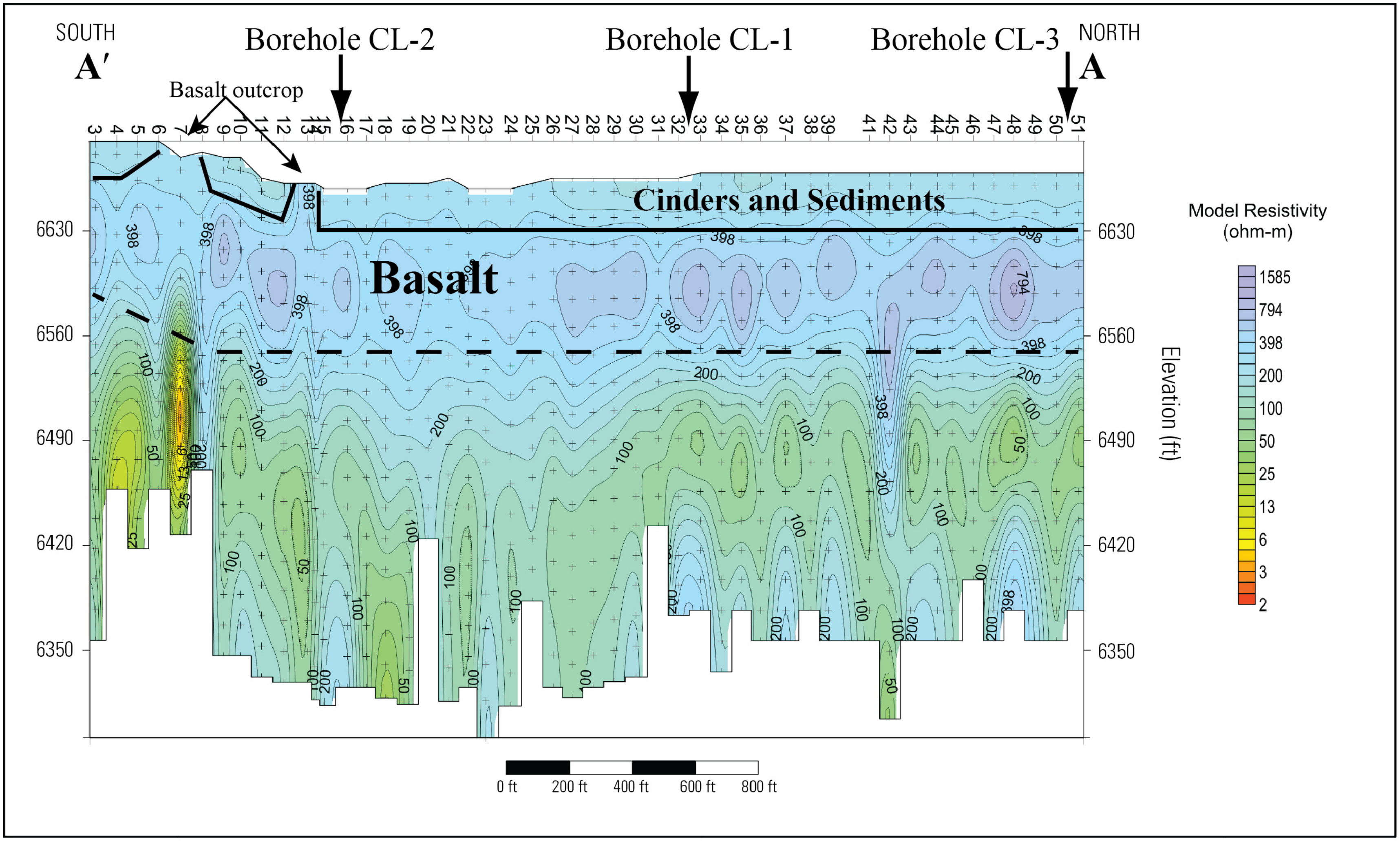


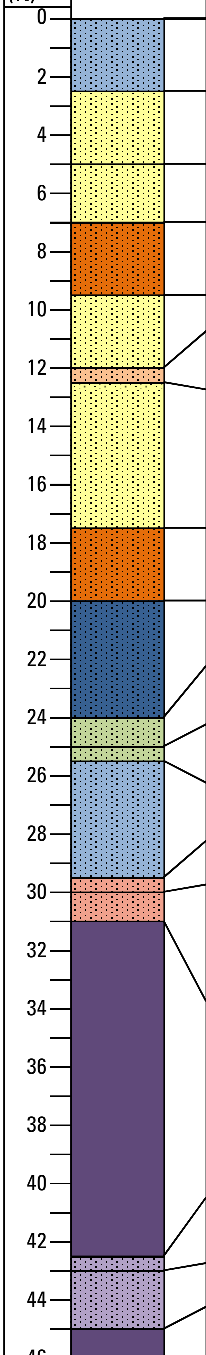
Figure 4. Subsurface lithologic and electrical profile A' to A (fig. 2). Results of 51 one-dimensional transient electromagnetic smooth-model inversions are contoured at irregular resistivity intervals. Numbers across the x-axis indicate the TEM station number.

A total of four boreholes were drilled to depths of 40–45 ft between June 3 and June 6. Three of the boreholes were drilled in a north to south line across Cinder Lake and named from north to south CL-3, CL-1, and CL-2 (fig. 2). The fourth borehole was drilled offset to the east from borehole CL-1 and CL-4 (fig. 2). The boreholes were completed into the top 5 ft of the uppermost basalt layer using 4-in. polyvinyl chloride (pvc) casing with perforations in the bottom 10 ft. The perforated casings are intended to provide a means to measure future water accumulation that may occur following runoff and infiltration events.

Porosity Calculations

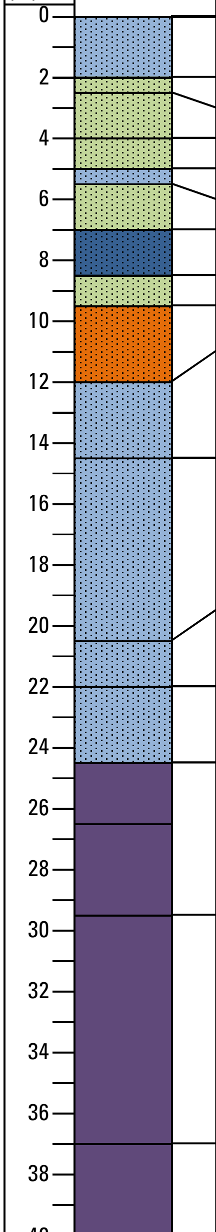
A component of the study was to determine the total porosity of subsurface materials and to calculate the total potential subsurface storage capacity beneath Cinder Lake. The total porosity of the major lithologic units from the cores of wells CL-1, CL-2, CL-3, and CL-4 were estimated using a direct water saturation technique (Yu and others, 1993; Nimmo, 2004). Plastic bags containing the cores were cut open and allowed to partially dry. Samples of 2–3 Lwere collected from six or seven individual units within each core (labeled porosity sample number) and air-dried for several hours. Each sample was divided into two test samples of 1,000 mL each, which were placed in an 80°C oven on an aluminum baking sheet until completely dry. Each dry sample was added to a 1,000 mL glass beaker and compacted by shaking the beaker by hand. Compaction often reduced the volume from the original 1,000 mL test sample, so the post-compaction sediment volume of each sample was recorded. Volumes ranged from 870 to 1,000 mL. Water was added to each test sample from a 1,000 mL graduated cylinder until the sediment was saturated to the bottom of the container and the water level rose to the level of the top of the sediment. Saturation occurred in a few minutes for coarse-grained cinder samples but required several hours in finer grained units including clay- and silt-sized particles. The total amount of water added to each test sample was recorded and divided by the test sample sediment volume to estimate the porosity of each test sample. The porosities estimated from the two test samples were averaged for each unit.

The water-saturation technique for estimating porosities provides an estimate for total porosity minus the micro-pore space for the sampled sediments. The time allowed for sample saturation was limited, and therefore small-scale pores may have remained filled with air and could contribute to an underestimate of total porosity. An average total porosity for each core section was determined by an average of the porosity of each layer weighted by layer thickness. Layers in each core were either measured or assigned an estimated minimum total porosity based on the measured values of similar layers. The products of the total porosity and thickness of each layer within a core were summed and divided by the total thickness of the cinder deposits above the basalt to calculate the weighted average total porosity. This calculation was performed for all cores (figs. 5–8).



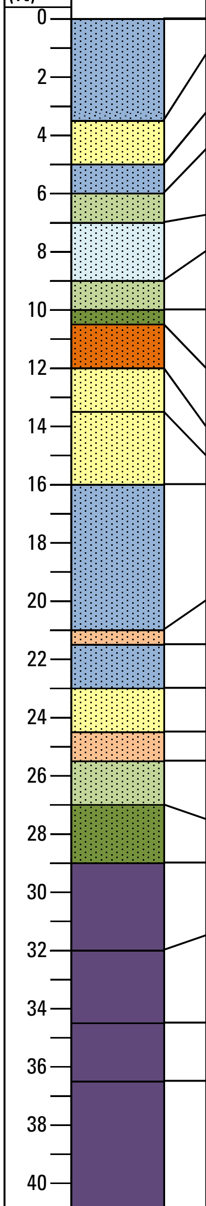
Description	Munsell color	Porosity sample number	Total porosity (blue shaded cells estimated from similar units of other Cinder Lake boreholes)
Basalt cinders and clasts to 1.5-4 inches with some clayey fine to medium sand	7.5YR 4/3 (moist)	1	55%
Clayey, slightly consistent fine to medium sand	7.5YR 4/3, (moist)	2	40%
Loose fine to medium sand with ~2% coarse-grained quartz sand	7.5YR 6/3 (moist)		
Loose, very fine to fine well-sorted sand	10YR 4/4 (moist)		
Loose, fine to medium sand		3	40%
Moderately well-sorted, loose fine to medium sand with some coarse mafic volcanic fragments	7.5YR 4/4 (moist)		30%
Moderately well-sorted fine to medium sand with some soil development and clay films	7.5YR 4/6 (moist)	4	38%
Clayey fine to medium sand	10YR 4/4 (moist)		
Basalt clasts up to 6 inches diameter, gravels, and cinders with very little sand-size material	N4 to N2 (moist)	5	49%
Loose, moderately sorted medium to coarse quartz, feldspar, and lithic sand with some clay films on grains	7.5YR 3/2 (moist)		40%
Dense, soft, plastic, clayey, moderately sorted medium to coarse sand	7.5YR 4/3 (moist)		
Basalt cinders with some sand-size material	5R 2/2 (moist)	6	44%
Loose fine sand and silt	7.5YR 6/4 (moist)	7	39%
Basalt clasts 1 to 4 inches in diameter (some weathered) with a matrix of finer basalt fragments and cinders	Clasts: 2.5Y 7/1 (dry) Matrix: 5YR 4/1 (dry)		
Competent vesicular (0.15-0.3 inch) basalt bedrock with sub-vertical fractures with weathering rinds and sub-vertical voidsup to 1 inch wide and 4 inches long	Basalt: N6 (dry) Weathering rind: 5Y 6/1 (dry)		minimal
Basalt rubble and fine material with discontinuity; possible flow base	N3 (dry)		minimal
Basalt bedrock becoming less vesicular	N4 (dry)		
Basalt bedrock, increasingly vesicular	N3 (dry)		minimal
Average Column Porosity (weighted average of upper 31 ft)			42.2%

Figure 5. Lithologic Log of Borehole CL-1



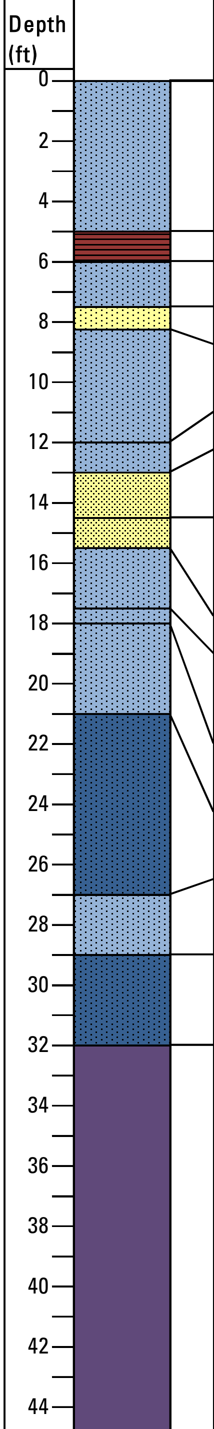
Description	Munsell color	Porosity sample number	Total porosity (blue shaded cells estimated from similar units of other Cinder Lake boreholes)
Basalt cinders and fine basalt fragments 0.1 to 0.25 inch in diameter.	N2 (dry)	1	51%
Loose medium to coarse sand with silt and cinders	10YR 5/6 (dry)	2	39%
Medium to coarse clayey sand	7.5YR 4/3 (moist)		
Medium to coarse sand	7.5YR 4/4 (moist)		
Upper 3 inches loose basalt cinders.	N3 to N1 (moist)		50%
Clayey loose coarse sand with volcanic fine gravels	7.5YR 4/4 (moist)	3	46%
Basal cinders and clasts up to 5 inches in diameter	N2 to N1 (moist)	4	51%
Clayey medium to coarse sand with 5% basalt cinders	10YR 4/5 (moist)	5	46%
Fine to medium clayey sand	10YR5/3 (dry)		
Basalt cinders 0.2 to 0.6 inches in diameter with clasts to 1.8 inches	10R 5/4 (moist)		
Basalt cinders 0.10 to 0.25 inches in diameter, a few clasts to 1 inch	5R 3/4 to 10R 4/3 (moist)		
Basalt cinders up to 1.5 inches in diameter with overlying basaltic rubble	10R 3/4 (moist)		
Basalt cinders 0.15 to 0.4 inch in diameter	5R 4/6 to 5R 3/4 (moist)	6	28%
Basalt bedrock, upper part of core appears abraded by drilling, no fractures	5YR 4/1 (moist)		minimal
Basalt bedrock, slightly vesicular, no fractures	N7 (dry)		minimal
Basalt bedrock with 0.15 to 0.25 inch diameter vesicles, no fracturing	N5 (dry)		minimal
Average Column Porosity (weighted average of upper 24.5 ft)			44.1%

Figure 6. Lithologic Log of Borehole CL-2



Description	Munsell color	Porosity sample number	Total porosity (blue shaded cells estimated from similar units of other Cinder Lake boreholes)
Basalt cinders 0.1 to 0.5 inches in diameter	N3 (moist)	1	56%
Loose, moderately well-sorted medium to coarse sand with basalt cinders throughout	10YR 7/6 to 10YR 4/4 (moist)	2	58%
Basalt cinders 0.1 to 0.25 inches in diameter	N2 (moist)		50%
Loose medium to coarse, slightly clayey sand with fine gravels (0.2-0.4 inches in diameter)	7.5YR 3/3 (moist)	3	34%
Weathered basalt cinders with poorly-sorted sand	7.5 YR 3/4 (moist)		
Loose, moderately well sorted medium to coarse sand with some gravel-sized cinders	10YR 3/4 (moist)		
Basalt clasts, 0.2-0.5 diameter, up to 1 inch with a matrix of fine sand and cinders	10YR 3/4 to 10YR 4/4 (moist)		
Loose, well sorted very fine to fine sand with fine gravel-sized lithic clasts at base	7.5YR 5/4 to 7.5YR 3/3 (moist)		
Clayey fine to medium sand	10YR 6/6 (dry)	4	38%
Loose, well sorted fine to medium sand	10YR 4/4 (dry)		
Basalt cinders 0.15 to 0.4 inches in diameter	N2 (moist)	5	53%
Moderately sorted medium to coarse clayey sand	10YR 4/3 (moist)		40%
Loose basalt cinders, average 0.1 inches in diameter	N2 (moist)		50%
Loose, well-sorted fine sand	10YR 4/4	6	38%
Soft, clayey medium to coarse sand	10YR 5/6 (moist)		
Soft, slightly clayey medium to very coarse sand with some basalt cinders throughout.	10YR 4/2 (moist)		
Coarse sand with basaltic cinders.	7.5YR 3/4 (moist)	7	43%
Basalt bedrock, fine vesicles 0.1 to 0.15 inches in diameter, no fractures	N3 (dry)		minimal
Basalt bedrock, few vesicles 0.1 to 0.2 inches in diameter, no fractures other than those induced by drilling	N3 (moist)		
Basalt cinders	5YR 4/4 (dry) to N6 (dry)		
Vesicular basalt bedrock with some sub-vertical fracturing	N3 (moist)		
Average Column Porosity (weighted average of upper 29 ft)			43.3%

Figure 7. Lithologic Log of Borehole CL-3



Description	Munsell color	Porosity sample number	Total porosity (blue shaded cells estimated from similar units of other Cinder Lake boreholes)
Loose basalt cinders up to ½ inches in diameter	N2 (dry)	1	53%
Cinders mixed with waxy plastic clay	7.5YR 4/3 (moist)	2	49%
Basalt cinders, average 0.1 inches in diameter	N2 (dry)		50%
Moderately well-sorted very fine to fine sand	7.5YR 5/4-3/3 (moist)	3	50%
Loose basalt cinders, average 0.2 inches in diameter with clasts to 1 inch	N2 (moist)	4	60%
Loose basalt cinders, average 0.1 inches in diameter	N2 (moist).		
Loose, well sorted fine to very fine sand with rare basalt cinders up to ¾ inches in diameter.	7.5YR 4/3 (moist)	5	44%
Well sorted fine to very fine sand with weak soil development. Grades into sand and basalt cinders at base of interval.	7.5YR 4/4 (moist)		
Loose basalt cinders, average ¼ inches in diameter	N2 (moist)	6	57%
Basalt cinders up to 3 inches in diameter in a loose matrix of well-sorted fine sand	7.5YR 4/3 (moist)		
Basalt cinders up to 2 ¾ inches in diameter, some are highly weathered	7.5YR 4/4 (moist)		
Basalt cinders to 6 ½ inches in diameter, some very well weathered, with matrix of finer cinders	7.5YR 6/8 (moist)	7	35%
Basalt cinders to 1 ¼ inches in diameter with a trace of very fine-grained sand.	N3 (moist)		
Angular basalt clasts, some clasts show strong weathering	10YR 7/1 (dry)		
Hard and dense basalt			minimal
Average Column Porosity (weighted average of upper 32 ft)			47.5%

Figure 8. Lithologic Log of Borehole CL-4

Gravity

Gravity data are a measure of mass below the measurement location. Changes in gravity over time, determined from repeat measurements at the same location, indicate changes in subsurface mass when elevation change and other sources of subsurface mass change are negligible. At Cinder Lake, the dominant source of any measurable gravity change would be due to a change in water storage in the subsurface. As stormwater enters the basin, water storage and gravity increase. Over time, if stormwater moves deeper and spreads laterally, gravity would decrease because the distance between infiltrated stormwater and the gravimeter has increased (following Newton's law of gravitation, gravity decreases as $1/r^2$, where r is the radial distance to the mass under consideration). The Cinder Lake area is well suited to gravity monitoring because of the unsaturated-zone storage change by introducing large amounts of infiltration and unconfined aquifer conditions, both of which result in a large-magnitude signal. To quantify the spatial extent of water storage change, a network of 19 gravity stations has been established. An initial round of gravity measurements was made in June 2011, prior to the summer monsoon season. Subsequent measurements were made over the course of the summer of 2011. Measurements are made using both an absolute gravimeter, which determines gravity by measuring the acceleration of a falling mass in a vacuum, and a spring-based relative gravimeter, which measures the difference in gravity between stations by measuring the difference in length of a mechanical spring among the stations. The absolute gravimeter provides reference values at a small number of stations, much like benchmarks in a leveling network; the relative gravimeter, with which measurements can be collected more quickly, is used to measure the relative gravity difference between the absolute gravity stations and the remaining stations throughout the study area. As with leveling surveys, the two types of measurements are combined in a least-squares network adjustment to take full advantage of redundant observations.

Results

Transient Electromagnetics (TEM) Surveys

TEM soundings at Cinder Lake were useful in determining the lateral continuity of materials found at depths of 40–45 ft in boreholes and in estimating the thickness of the basalt layer. Adjacent TEM soundings were made every 60 ft from north to south along a transect between wells CL-3, CL-1, and CL-2 (fig. 2). TEM modeling consisted of calculating a 1-D, smooth-model inversion of resistivity versus depth for each sounding. The 1-D inversions are then interpolated to form a cross section of estimated resistivity with depth. Inversion results from the 60-ft loops produced models with three distinct layers (fig. 4). The uppermost layer is a moderately resistive unit with resistivity values between 200 and 300 ohm-m (blue) that extends from the surface to a depth of about 30 ft (fig. 4). The uppermost layer corresponds to the overlying cinder, sand, silt, and clay material observed in the boreholes at Cinder Lake. The second layer is a highly resistive unit between 300 and 1,000 ohm-m (purple) that extends from about 30 to about 90 ft in depth (fig. 4). This layer corresponds with the basalt layer found in the boreholes and is consistently observed along the geophysical cross section. The basalt layer crops out in two areas near the southern end of the TEM profile, which is consistent with observed basalt exposures at Cinder Lake. Along the basalt layer there are areas near TEM soundings 17, 20, and 21 where the resistivity is about 300 ohm-m compared to the more typical 400 ohm-m throughout the rest of the layer. The slightly lower resistivity could indicate that the basalt near these soundings is more fractured and has some component of saturation. Water infiltrates into the ground from the Copeland Ditch near this area and could provide the additional water found in the fractured basalt. The third layer of this inverse model begins at a depth greater than 90 ft and is characterized by resistivity values ranging from 50 to 300 ohm-m (green; fig. 4). There is no supporting borehole data for the layers beneath the basalt and therefore no interpretation of this layer is made, although it represents a lithology with much lower resistivity values than cinders and sediments or basalt.

Borehole Drilling

Drilling in all four boreholes encountered interbedded cinders, sand, silt, and clay overlying hard, fractured basalt at depths between 29 and 32 ft. Many high-angle fractures were observed in basalt samples recovered during the drilling process, which implies that the basalt layer is not a confining layer. Interbedded cinders, sand, silts, and clays were above the basalt. Diagrams of the boreholes describe the cinder deposits and illustrate the interbedded relationship of the cinders and sediments (figs. 5–8). Intervals of clay in each of the boreholes could indicate a layer that could potentially cause perching conditions. Layers of clay are found in borehole CL-1 at depths of 2.5, 15, and 25 ft; in borehole CL-2 at depths of 5 and 9 ft; in borehole CL-3 at depths of 12 and 25 ft; in borehole CL-4 at a depth of 5 ft.

Moore and Wolfe (1976) reported the age of basalt and pyroclastic deposits in the Cinder Lakes area as Middle Pleistocene. The fact that basalt, scoria, and cinders were found in the boreholes below a depth of about 15 ft shows some evidence of weathering, as these deposits were subaerially exposed for perhaps 500 k.y.

The alluvium (medium- to coarse-grained sand and clayey sand) found in the cores above the Middle Pleistocene volcanic rocks shows that waterborne sediments were transported to the Cinder Lake area by water, hyper-concentrated flow, or debris flow during and between episodes of volcanic activity. Lithic clasts and mafic volcanic rocks with an andesite affinity are a minor component of the alluvial deposits. Upgradient from Cinder Lake, there are multiple andesite flows on the eastern side of San Francisco Mountain (Wolfe and others, 1987) and a small andesite cinder cone (Moore and Wolfe, 1987) about 3.5 km upslope that might have been the source of the andesite clastic material. The clays may have been transported by fluvial action, although some of the clay might be the result of soil development based on clay films and bridging between sand grains seen in some samples that resulted from pedogenesis. The degree of pedogenesis corroborated by the minor clay and carbonate accumulation seen in the samples suggests that alluvial deposition occurred during the middle Holocene to perhaps the latest Pleistocene.

The fine-grained to very fine grained sand and silt suggests that there was some eolian activity that deposited thin sand sheets on the volcanic deposits. Small calcareous nodules found within these fine-grained sands appear to be Stage I pedogenic carbonate (Machette, 1985). In the southern Colorado Plateau region, Stage I soil carbonates have been found to form within 2–10 k.y. (L. Amoroso, unpub. data, 2012), so there may have been a hiatus in deposition after the mid- to early Holocene. The eruptions from Sunset Crater began about A.D. 1040 and continued to about A.D. 1180 (Smiley, 1958; Ort and others, 2002); pyroclastic materials from these eruptions are found at the surface and to a depth of about 15 ft in the cores.

No radiocarbon-datable organic material or charcoal was found in the samples that could constrain the age of the alluvial deposits.

Estimates of Total Porosity and Storage

The amount of water that can be accommodated in the cinders and sediments during a given time interval is a function of not only the volume of available storage (capacity) of the deposits, but also the volume of groundwater inflow and outflow. Water-storage capacity for this study refers to the total available water storage in the deposits and does not take into consideration inflows and outflows from the system.

Porosity estimates were calculated for each borehole. The weighted average porosity for cores from boreholes CL-1, CL-2, CL-3, and CL-4 are 42.2, 44.1, 43.3, and 47.5 percent, respectively (tables 1– 4; figs. 5–8). An overall average porosity for the 30 ft of material above the uppermost basalt flow is 44 percent. The estimated porosity values for these cores are within the reported range for these types of unconsolidated deposits, which are between 25 and 50 percent (Todd, 1964; Freeze and Cherry, 1979; Driscoll, 1986).

Porosity sample number	Test	Sediment Volume (mL)	Water Volume (mL)	Estimated porosity (percent)	Porosity sample number average (percent)	Thickness (ft)
CL-1-1	1	1000	550	55.0	54.5	2.5
	2	1000	540	54.0		
CL-1-2	1	1000	400	40.0	40.0	7.0
	2	1000	400	40.0		
CL-1-3			395	39.5	40.0	2.5
	2	1000	405	40.5		
CL-1-4	1	1000	400	40.0	38.0	7.5
	2	1000	360	36.0		
CL-1-5	1	1000	500	50.0	48.5	4.0
CL-1-5	2	1000	470	47.0		
CL-1-6						
CL-1-6						
CL-1-7						
CL-1-7						

Table 1. Estimated total porosity values for samples from borehole CL-1

Porosity sample number	Test	Sediment volume (mL)	Water volume (mL)	Estimated porosity (percent)	Porosity sample number average (percent)	Thickness (ft)
CL-2-1	1	1050	525	50.0	50.8	2.0
	2	1000	515	51.5		
	1	1000	430	43.0	38.5	3.0
	2	1000	340	34.0		
CL-2-3	1	1000	460	46.0	46.0	1.5
	2	1000	460	46.0		
CL-2-4						
CL-2-4						
CL-2-5						
CL-2-5						
CL-2-6						
CL-2-6						

Table 2. Estimated total porosity values for samples from borehole CL-2

Porosity sample number	Test	Sediment volume (mL)	Water volume (mL)	Estimated porosity (percent)	Porosity sample number average (percent)	Thickness (ft)
CL-3-1	1	1000	579	57.9	56.4	3.5
	2	1000	548	54.8		
CL-3-2	1	950	360	37.9	37.8	1.5
CL-3-2	2	940	355	37.8		
CL-3-3	1	1000	340	34.0	34.2	6.0
CL-3-3	2	1000	343	34.3		
CL-3-4						
CL-3-4						
CL-3-5						
CL-3-5						
CL-3-6						
CL-3-6						
CL-3-7						
CL-3-7						

Table 3. Estimated total porosity values for samples from borehole CL-3

Porosity sample number	Test	Sediment volume (mL)	Water volume (mL)	Estimated porosity (percent)	Porosity sample number average (percent)	Thickness (ft)
CL-4-1	1	1000	520	52.0	52.5	5.5
	2	1000	530	53.0		
CL-4-2	1	1000	490	49.0	48.7	0.5
	2	950	460	48.4		
CL-4-3	1	1000	480	48.0	50.0	1.0
CL-4-3	2	1000	520	52.0		
CL-4-4	1	1000	600	60.0	59.5	4.5
CL-4-4	2	1000	590	59.0		
CL-4-5						
CL-4-5						
CL-4-6						
CL-4-6						
CL-4-7						
CL-4-7						

Table 4. Estimated total porosity values for units from borehole CL-4

The lateral extent of the area used to calculate storage at Cinder Lake is about 300 acres (fig. 2), and the cinder deposits are about 30 ft deep with an average total porosity of 44 percent. These dimensions and average porosity yield a total storage for Cinder Lake of 3,960 acre-ft or about 4,000 acre-ft.

Gravity

Gravity measurements are ongoing at Cinder Lake, and results from gravity measurements will not be available until data have been collected through multiple infiltration events and multiple quiescence periods during fiscal year 2012.

Conclusions

The U.S. Geological Survey drilled four boreholes and conducted geophysical surveys to determine the depth of the cinder beds and their potential for water storage capacity. Results indicate that the uppermost basalt layer at Cinder Lake is approximately 30 ft below land surface in an area that has little topography. Total porosity for the upper 30 ft of sediments was estimated as 43 percent, which yields a total storage for the 300-acre extent of Cinder Lake of about 4,000 acre-ft.

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