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ARIZONA'S EARTH FISSURE MAPPING PROGRAM: PROTOCOLS, PROCEDURES AND PRODUCTS

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ARIZONA GEOLOGICAL SURVEY

Executive Summary

In 2006, Arizona enacted legislation that directed the Arizona Geological Survey (AZGS) to map earth fissures in the state, required that the presence of earth fissures be disclosed in real estate transactions, and that the resultant earth fissure maps be made publicly available. The Arizona State Land Department (ASLD) serves the fissure maps online as part of the their responsibility for the state's geospatial data clearinghouse, giving the public easy access to the digital maps. Funding was appropriated for geologic staff and for high-precision Global Positioning System (GPS) equipment, so that the mapped earth fissure locations would be both precise and accurate.

In order to meet these statutory requirements, AZGS developed, for the first time, standards, procedures, and criteria for identifying, mapping, and characterizing earth fissures. The Arizona Land Subsidence Group (ALSG) served as an advisory and review body for technical aspects of the earth fissure mapping program. Because the AZGS earth fissure maps are to be used as definitive documentation in real estate transactions, the State Geologist appointed an external Earth Fissure Advisory Group to advise the mapping program from an end-user's perspective to ensure the maps meet societal needs in a clear and easy to understand manner.

AZGS geologists identified earth fissures through a review of publications and reports, air photo analysis, and field reconnaissance. Using GPS, we collected relatively high-precision locations and descriptive data along the length of earth fissure surface exposures, and categorized them as either continuous or discontinuous. If we were not able to find and map previously reported fissures, we used the "reported, unconfirmed" category. GPS location information is refined using differential corrections from base station data, and we filter the locations by only using satellites above a certain angle from the horizon and within defined tolerances for signal to noise ratios. Data stations with corrected location information are then loaded into ArcGIS software as an ESRI ArcGIS shape file. AZGS provides the information to ASLD for publishing online at http://azmap.org/fissures, as the official source of these data. AZGS also provides the same published ESRI ArcGIS shape file on our website (www.azgs.az.gov/EFC) for download as support data. The largest scale to which information is accurate is the 1:12,000 scale, with earth fissures accurate to 4 meters in width. AZGS also produces fixed maps for each study area completed, which are available as downloads from our website.

Introduction

In June 2006, a new Arizona law tasked the Arizona Geological Survey (AZGS) with comprehensive mapping of earth fissures throughout the state. The passage of Arizona Revised Statute ARS 27-152.01.11 reflects a growing concern that earth fissure hazards represent a risk to the people and infrastructure of Arizona. The State's first earth fissures, reported in the 1920's near the Picacho Mountains of Pinal County (Leonard, 1929), were confined to agricultural lands, where they were merely a nuisance to local farmers. The proliferation of earth fissures through the last half of the 20th century, particularly in Maricopa and Pinal Counties, coincided with exponential growth, juxtaposing expanding population centers and earth fissures. As a result, the impact of earth fissures on the people of Arizona, their property and infrastructure, is on the rise. Detailed mapping of earth fissures is the first best strategy for mitigating the risks associated with the hazards of earth fissures (Strange, 1983).

AZGS's first efforts to identify and map earth fissures in Arizona were largely reconnaissance in nature, yielding several small-scale regional reconnaissance maps with accompanying reports (Schumann and Genualdi, 1986). In the late 1980's the AZGS map strategy shifted to detailed studies of local earth fissures, but there was no consistent funding support for fissure mapping so studies were completed as opportunities arose (Slaff *et. al.*, 1989; Slaff, 1991; Harris, 1994; Harris, 1995). In 2007, Shipman (2007a; 2007b; 2007c; 2007dcompiled earlier published maps, reports and imagery, and supplemented those with new aerial reconnaissance analysis to construct 1:250,000 scale earth fissure planning maps for Cochise, Maricopa, Pima, and Pinal counties (Allison and Shipman, 2007). These planning maps identified 23 study areas in the four counties for prioritized detailed mapping as part of the AZGS's formal Earth Fissure Mapping Program. This report serves to document the procedures and protocols adopted by AZGS geoscientists as part of our program to map and report on all of Arizona's earth fissures.

Importantly, while AZGS is responsible for mapping earth fissures, it is the responsibility of the Arizona State Land Department (ASLD), as laid out by statute (ARS 27-152.01.11), to make those data initially available to the public. When AZGS staff finalize map construction in a study area, they provide the resultant dataset to ASLD. Following the transfer of map data, ASLD, in its role as the central clearinghouse for all State geospatial data, has 90 days to make the data available to the public digitally on the Internet. In conjunction with ALSD's public release of the digital earth fissure maps online, AZGS makes the map data available as GIS shape files and printed maps. Maps are available both on the AZGS website (www.azgs.az.gov/EFC) and in analog (i.e., "paper") format. The intent is to ensure that ALSD is the single primary earth fissure data source, with the other materials serving as ancillary, supporting resources. The website at http://azmap.org/fissures is the official website for the most up-to-date maps of earth fissure study areas.

Earth Fissures: Physical Attributes

Earth fissures are fractures or cracks that form in alluvial basins due to substantial groundwater overdrafts that produce local subsidence (Holzer, 1976; Jachens and Holzer, 1979; Larson and Péwé, 1986). Four counties in Arizona are especially prone to fissuring; in order from greatest to least number of reported fissures, they are: Pinal, Maricopa, Cochise, and Pima Counties (Shipman, 2007).

The surface expression of earth fissures vary greatly from cracks, to small circular depressions, to gullies that are difficult to distinguish from natural drainages and washes (Fig. 1). Cracks are narrow, with sharp, steep sides, and a hidden, or ill-defined fissure floor. Circular depressions may be shallow or deep, with gently sloping, rounded edges, or steep, sharp edges, and may occur as a discontinuous linear series. Gullies developed along fissures are enlarged due to erosion of sidewalls during capture of surface runoff. Newly formed or younger fissure-induced gullies tend to have steep and well-defined sidewalls, while older fissure gullies present more rounded, gently sloping sidewalls produced by erosion and widening of the cavity. A fissure may exhibit any combination of surface expressions along its length. A common sequence along fissures, however, is crack - circular depression - gully - circular depression - crack.

Earth fissures are expressed continuously or discontinuously at the surface. Discontinuous earth fissures at the surface are incipient expressions of earth fissures that are likely continuous at some depth below the surface. Incipient earth fissures are expressed at the surface by circular depressions and punctuated cracks or gullies. Continuous earth fissures are expressed at the surface as connected openings, which in some cases have captured surface drainage creating gullies.

In the field, earth fissures may be confused with giant desiccation cracks (Harris, 2004). We distinguish earth fissures from giant desiccation cracks by differences in surface expression. Desiccation cracks commonly form polygons, whereas fissures tend to form linear fractures. Earth fissures extend deeper in the subsurface than giant desiccation cracks, which are confined to the near surface. Nonetheless, distinguishing fissures from desiccation cracks by visual inspection alone is sometimes difficult, and requires more in-depth investigation to make the classification. Trenching is a common and successful approach because giant desiccation cracks typically are less than several meters deep, whereas earth fissures may continue for as much as hundreds of meters into the subsurface.

Methodology and Data Collection

Earth Fissure Mapping Procedures

The chief goal of the AZGS Earth Fissure Mapping Program is to document the location, geometry and context of earth fissures in Arizona. The completed map data are provided to ASLD for presentation to the public at no larger than 1:12,000-scale. Our map strategy is based on earlier reconnaissance mapping, which relied heavily on analysis of aerial photographs and limited field investigations. The earth fissure mapping process is subdivided into four phases: 1) preliminary investigation (initial data compilation); 2) field mapping of earth fissures; 3) post-processing and reduction of GPS data; and 4) map interpretation and production (including GIS shape files) and transfer of the finished map product to ASLD.

Phase 1: Preliminary Investigation

In the preliminary investigation, we compiled information related to previously reported earth fissures in Arizona. This involved an extensive review of published and unpublished reports, images, maps, and anecdotal information. Data that included a spatial component (i.e., the location of fissures) were incorporated into a comprehensive geographic information system (GIS) database. This database includes more than 250 known or reported earth fissures from Cochise, Maricopa, Pinal, and Pima counties. Grouping proximal earth fissures together, we delineated 23 study areas (named for nearby topographic or geographic features) that encompass the entire suite of previously reported fissures (Table 1). From this database, we constructed planning maps with approximate and preliminary fissure locations and the locations of the study areas for those four counties to serve as the basis for field investigations (Shipman, 2007; Allison and Shipman, 2007).

As part of our effort to develop a robust procedural approach to mapping, we sought input from individuals and groups outside AZGS with expertise in earth fissure mapping or analysis. These individuals and groups critiqued early drafts of the planning earth fissure maps. Their recommendations improved the map products and, importantly, enhanced our field mapping strategy. Reviewers who have completed site-specific geotechnical reports within the study areas may submit their work to verify, document, or repudiate reported earth fissures.

During the preliminary phase, the AZGS fissure mapping team learned how to use aerial photographs to differentiate earth fissures from other lineaments, such as cow trails, washes, underground pipelines, jeep trails, and giant desiccation cracks. The mapping team visited earth fissures and deliberated and codified the array of characteristics observed at incipient, well-developed, and gullied fissures.

While historical photographs may help verify the presence or identify the locations of earth fissures, we cannot physically map or verify fissures whose surface expression has been substantially modified or obscured (typically by farming or development). Aerial photographs alone are not sufficient evidence to positively identify a feature as a fissure. Phase 2 involves rigorous field verification of all reported and potential earth fissures observed on aerial photographs or reported elsewhere.

This preliminary phase culminated in June 2007 with the release of earth fissure planning maps in both analog and digital form. Between June 2007 and December 2007, more than 45,000 copies of the planning maps and accompanying report (Allison and Shipman, 2007) were downloaded from azgs.az.gov. Importantly, the maps were designed as an interim tool to assist the public, civil authorities, real estate agents and developers in better understanding the distribution of earth fissures in Arizona. The rough approximation of actual fissure locations and the coarse map scale, 1:250,000, precludes using the maps for high-resolution (i.e., site-specific) analysis.

Table 1. Breakdown by county of the 23 study areas identified for fissure mapping.

Earth Fissure Study Areas			
Cochise County		**Pinal County**	
Sulphur Springs North	Bowie-San Simon	Apache Junction	Heaton
Three Sisters Buttes	Dragoon Road	Picacho	Signal Peak
Maricopa County		White Horse Pass	Greene Wash
Wintersburg	Luke	Tator Hills	Pete's Corner
Harquahala Plain	Mesa	Sacaton Butte	
Scottsdale/NE Phoenix		Santa Rosa Wash	
Chandler Heights	Apache Junction	Chandler Heights	
Pima County		Friendly Corners	
Marana		Toltec Buttes	

Phase 2: Field Mapping of Earth Fissures

The AZGS earth fissure mapping team adopted field protocols to standardize the mapping process and to ensure a consistently high-precision, high-quality, and accurate map product. The protocols reflect the overarching goal of documenting the location, geometry, and context of earth fissures. Additionally, these protocols, manifested as a suite of measurable parameters (Table 2), provide baseline data against which future changes in fissure geometry can be measured. Earth fissure mapping is confined to surface expressions defined within this document. For land that has been disturbed or where development obscures earth fissure traces, we cannot use the AZGS protocols to map them; they are identified on the fissure maps as "reported, unconfirmed."

In the field, we use a Trimble 2005 GeoXH GPS receiver and Terrasync Pro software for collecting and processing spatial and ancillary data (e.g., width, depth, vegetation type and abundance) at multiple locations along earth fissures. GeoXH is a single frequency GPS receiver incapable of real-time differential data reduction. To standardize mapping, members of the AZGS mapping team use the same data dictionary. That data dictionary (Table 2) comprises the chief physical parameters used to describe each earth fissure (see the following section). Along each fissure, the full suite of measurable parameters is collected every 2 to 4 meters – yielding between 250 to 500 measurements per kilometer of fissure. When mapping curvilinear earth fissures, we increase the density of stations per unit length so that the arc can be more accurately depicted during map construction. For earth fissures with a discontinuous character (i.e., gullies or circular depressions separated by unbroken ground), measurements are made at each surface expression.

Table 2. The earth fissure station data dictionary used by AZGS geoscientists in the field.

Station Data Dictionary	
Attributes	**Menu**
Waypoint Type	Endpoint, Vertices
Date of the Visit	Day-Month-Year
Time of the Visit	24 Hour Format
Surface Expression	Pot Hole, Surface crack, Gully, Displacement
Displacement	Increments of 0.1 meter
Location with Respect to the Fissure	Center line; NSWE of the fissure
Surface Width	Increments of 0.1 meter
Fissure Depth	Increments of 0.1 meter
Vegetation Density	Medium, Light, Heavy, No Vegetation
Vegetation Type	Bush, Grass, Large Tree, etc.
Fissure Shape	Sharp, Flat Bottom; Rounded, Flat Bottom; Sharp, Crack Bottom; Rounded, Crack Bottom
Line Continuity	Continuous, Discontinuous

Map Parameters. The physical parameters used by the AZGS earth fissure mapping team to characterize earth fissure geometry and context include: location, width, depth, morphology, vegetation, vertical displacement (i.e., displacement across the axis of the fissure), and location with respect to the fissure (i.e. orientation) (Table 2). Wherever feasible and safe, we collect physical parameters along the centerline of each individual earth fissure. The presence of dense vegetation, an unstable fissure floor, or collapsing sidewalls, however, frequently preclude data collection along the centerline. Whenever this occurs, we note the physical offset from the perimeter in the data file and then resolve it in the post-processing phase.

Figure 1. Earth fissure surface expressions are classified into four categories A) circular depressions "potholes", B) surface cracks, C) gullies, and D) displacement.

The Trimble GeoXH receiver simultaneously captures UTM location coordinates with 2-m horizontal resolution, and the date and time of data collection. We manually enter the remaining data, beginning with the relative type of each data station, delineated as either the endpoint or vertex of an earth fissure. The overall surface expression is characterized as displacement, circular depression ("pothole"), surface crack, or gully (Fig. 1).

Surface expressions classified in Figure 1 can also show displacement, which is recorded in the data at each station (Table 2). Measurements of fissure width and depth are estimated to the nearest tenth of a meter. In measuring width, we estimate the distance perpendicular to the long axis of the fissure, scrupulously avoiding areas of headward erosion. Depth is a measure of the vertical distance from the surrounding ground surface to the floor of the fissure. Where depth cannot be ascertained with confidence, either because the fissure is too narrow to provide a view of the floor, or because sidewall instability and the threat of further collapse precludes a clear view of the fissure floor, we assign a depth of 100 meters. Since this number is much larger than any possible recorded earth fissure depth, it could not be confused with a real measurement.

Vegetation presents an especially important quantitative parameter. The amount, type, age, and condition of vegetation in and immediately adjacent to a fissure yield clues to the age and activity of that fissure. We classify vegetation as light, moderate, or heavy, and identify vegetation by name (e.g., juniper) or by character (e.g., grass). The age of the vegetation can be a proxy for fissure age, as older and more developed vegetation implies that the earth fissure has existed for a longer time.

We classify the geometry of the sidewalls and floor of a fissure as either sharp, crack bottom; sharp, flat bottom; rounded, crack bottom; or, rounded, flat bottom (Fig. 2). The terms round and sharp refer to the sidewall-land surface intersection of the fissure (fissure edges), and the bottom is the floor of the fissure. The term "crack bottom" refers to fissures whose floor is not visible from the surface. We are collecting these data for future research into the change and development of earth fissures over time.

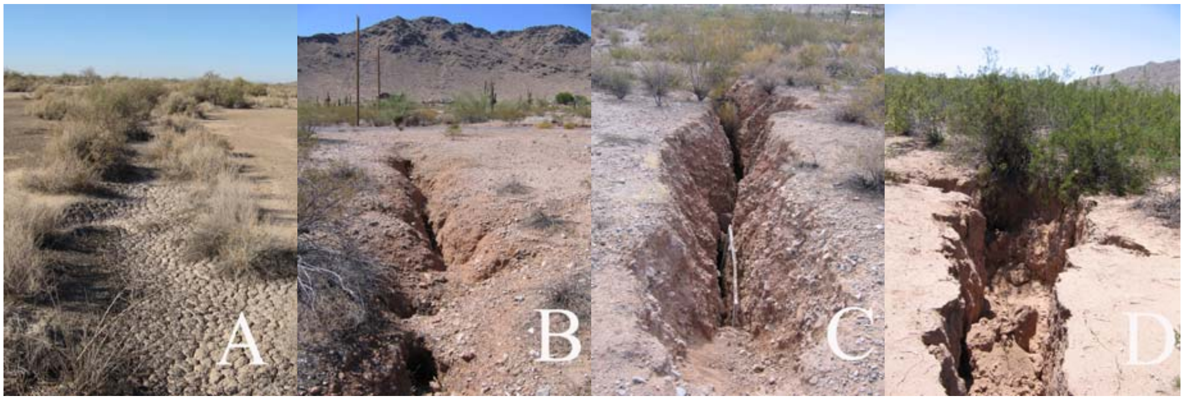

Figure 2. Earth fissures interior geometries are grouped into four categories. A) Rounded edges with a flat bottom, B) rounded edges with a crack bottom, C) sharp edges with a crack bottom, and D) sharp edges with a flat bottom.

We also record at each station whether the surface expression is directly connected to adjacent stations along the fissure (continuous) or if the features are disconnected on the surface (discontinuous) (Fig. 3). The first data station collected along any earth fissure will not have a defined continuity, because earth fissure continuity is defined between successive data station

Figure 3. The surface expression of the earth fissures varies from A) continuous to B) discontinuous.

Mapping an Earth Fissure. The first step in the field mapping process is to ascertain whether the feature on the county-scale planning map is indeed an earth fissure. Once that is established, we walk the length of the fissure to locate the fissure termini. This requires careful examination of the ground surface because earth fissures commonly transition from easily recognized features to obscure incipient fissures (characterized by small fractures or lineations of small discontinuous circular shaped depressions or surface cracks). We include this incipient component within the fissure envelope, which extends the map length to the last surficial expression.

Once we establish the existence and extent of the earth fissure, we collect data as we walk its length, addressing each of the parameters noted in Table 2. We collect a minimum of 10 GPS locations at each station as we fill out our data dictionary.

Phase 3: Post-processing and reduction of the GPS data

The penultimate phase involves reduction (i.e. post-processing) of the GPS data, which includes: 1) differential correction of locations; and 2) transferring the data to a GIS (geographic information system) database for map production.

Post-processing chiefly involves differential correction of GPS locations using three base stations. Base stations are selected by proximity to the fissure, integrity, and orientation, and thus the base stations use vary from study area to study area. The log of each base station for the appropriate time-window is downloaded from a source directory. The log contains the GPS locations over time from a base station with a known location. Using the change in the GPS location, a correction can then be calculated for the other measured GPS locations. For best results, we use a minimum of three widely-spaced base stations within a 100-km radius and at varied distances from the study area. We use GPS Pathfinder Office software to calculate the differential correction. Following data correction, we produce a shape file that can be imported into a GIS database. Filtering of poor quality data occurs during collection and within GPS Pathfinder Office program. Collected data is filtered at the source by only using satellites at certain angles above the horizon and certain sound to noise ratio filters.

Phase 4: Map Interpretation and Production Phase

Post-processed data are brought directly into AZGS's Earth Fissure GIS Database via an ESRI ArcGIS shape file. Individual vertices and endpoints, termed node or point data, are synthesized into lines or arcs using a snapping lines function within ArcMap GIS software. Within the GIS database, each line is stamped with a date of origin (e.g., 02/21/2008); this provides for temporal control and baseline data for ongoing monitoring. The map expression of each line is reviewed to ensure that it accurately depicts the earth fissure. Lines on AZGS maps are accurate within 4 meters horizontally at 1:12,000-scale. Last, we define the extent of our study area investigation by constructing a study area boundary to include on maps.

In the AZGS Earth Fissure GIS database, and on subsequent analog and digital map products, mapped earth fissures are classified as *continuous*, *discontinuous*, or *reported, unconfirmed*. Lines are interpreted based upon data collected at each data station.

Discontinuous and continuous lines are plotted from data station to data station based classification in the data dictionary. Reported, unconfirmed lines are interpreted from scanned and rectified images with unknown accuracy.

Three categories of earth fissures are represented on map products: continuous fissures, discontinuous fissures, and previously reported but unconfirmed fissures. Each fissure is represented as a line or arc of a prescribed color, and geometry (i.e., continuous versus dashed)

(Fig. 4). Continuous fissures are manifested on the ground surface by an unbroken, and easily traced, surface expression. On our maps, we denote continuous fissures with a solid, black line, discontinuous fissures with a red line, and reported, unconfirmed with a dashed green line (Fig. 4). Discontinuous fissures, those with a broken or non-continuous surface expression such as lines of potholes, are denoted by a dashed red line on map products. (While the surface expression is broken, we believe, and we strongly recommend that map users assume that the fissure is continuous in the subsurface.)

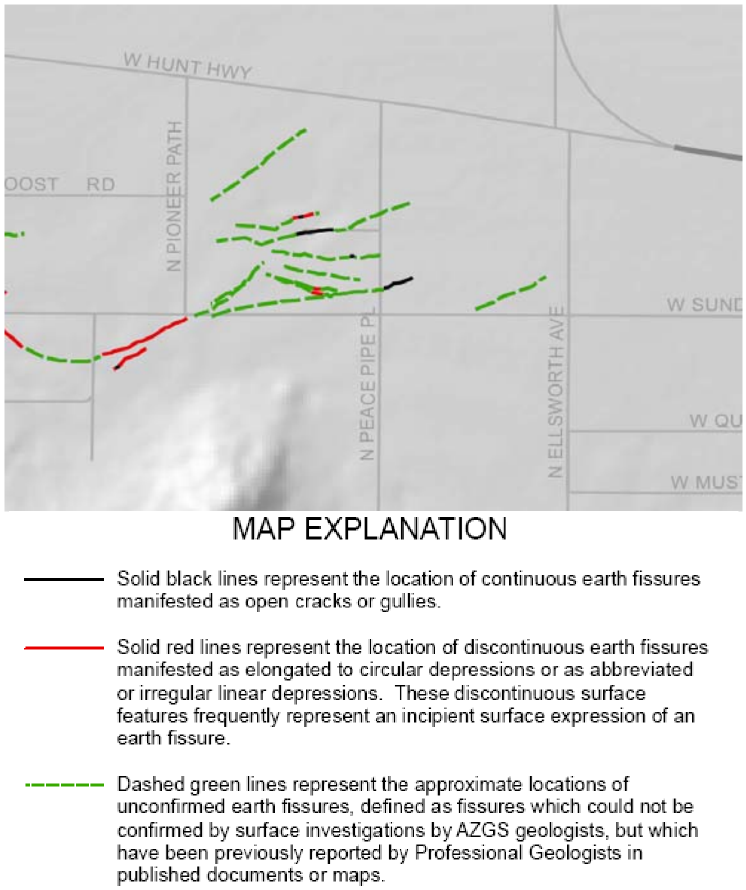

Figure 4. Example of an earth fissure map showing the hierarchy of fissure lines, street network, and shaded relief.

Reported, unconfirmed fissures represent earth fissures previously documented in published papers or maps, but which we were unable to confirm during fieldwork. Two principal reasons for not confirming earlier reported fissures are 1) backfilling or severe disturbance of the fissure, such as plowing or grading, such that all surface manifestations were obliterated or otherwise obscured; and, 2) we were physically unable to access the land hosting the fissure.

Study area boundaries expressed on maps demarcate the areal extent of the investigation; we have neither mapped nor investigated areas outside the boundary. All areas inside the study area boundaries are investigated by performing an aerial photography survey, physically walking them, or both. It should be noted, however, that, due to the dynamic nature of earth fissures, areas within the boundary lacking any surface expression of earth fissures could still potentially develop fissures in the future. Agriculturally developed lands within the study area boundaries are difficult to identify earth fissure surface expressions, due to constant disturbance of the surface. Although we have investigated these areas, it is difficult to determine if earth fissure have developed, without using geophysical techniques or trenching of the property. Suspected earth fissures on developed property can usually not be confirmed in the field and are only shown on the map if they have been previously reported (Fig. 4).

Earth Fissure Map Products

As AZGS completes the digital earth fissure file for each study area, the final map data, in the form of an ESRI ArcGIS shape file, is handed off to ASLD. ASLD has 90 days following delivery to release the data and to maintain the official, sole-source web-based maps. The final Internet map product includes a road network, showcasing highways and major roads, superimposed on a shaded relief base that accentuates local topography. The ASLD earth fissure website, which is hosted by Arizona Department of Real estate, has a maximum resolution of 1:12,000-scale to prevent the appearance of higher accuracy by zooming in on a given area.

AZGS produces and sells paper copies of the map as Digital Map Series (DM)-Earth Fissure (EF), with a number corresponding to each study area (e.g., DM-EF-1 is Chandler Heights). As ASLD makes the earth fissure data public through their website, AZGS will make PDF versions available free at azgs.az.gov/EFC. AZGS paper maps are produced at either the 1:24,000- or 1:12,000-scale, depending on the size of the study area. As AZGS completes work on a study area, ASLD will update the earth fissure map on their website. AZGS will provide the same shape file that is sent to ASLD for their website as a download on our website. The number at the end of each version of the shape file corresponds to the date of publication and older versions will be archived for comparison.

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