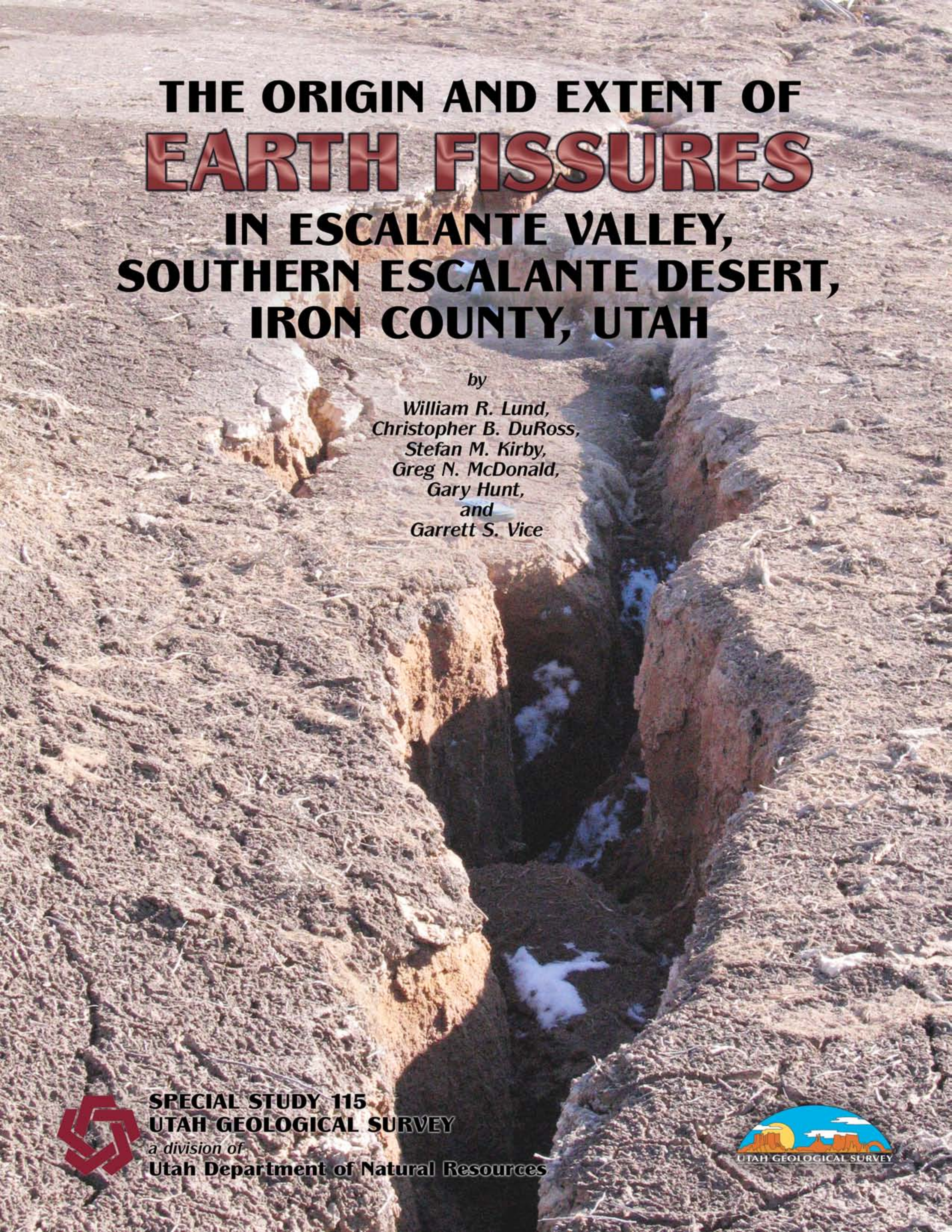

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SPECIAL STUDY 115
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[1]Utah Geological Survey, Cedar City
[2]Utah Geological Survey, Salt Lake City
[3]Southern Utah University, Cedar City

ISBN 1-55791-730-2

SPECIAL STUDY 115
UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources
2005

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1/05

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THE ORIGIN AND EXTENT OF EARTH FISSURES IN ESCALANTE VALLEY, SOUTHERN ESCALANTE DESERT, IRON COUNTY, UTAH

by

William R. Lund[1], Christopher B. DuRoss[2], Stefan M. Kirby[2], Greg N. McDonald[2], Gary Hunt[3], and Garrett S. Vice[1]

ABSTRACT

The Utah Geological Survey investigated five earth fissures that formed in Escalante Valley in southwestern Utah. The fissures were discovered after a warm winter storm on January 8-12, 2005 caused flooding in the valley, and infiltrating floodwater and sheetwash enlarged the fissures. The fissures range in length from about 100 meters (330 ft) to more than 400 meters (1300 ft), and form a discontinuous nine-kilometer-long (5.6 mi) generally north-trending zone roughly centered on the community of Beryl Junction. In places, the floodwater eroded gullies along the fissures that were up to three meters (10 ft) wide and two meters (6.6 ft) deep. Local residents reported that floodwater flowed into the fissures for a period of a day or more during the height of the flooding, and that vortices formed in the floodwater over some fissures.

Bouguer gravity data show that Escalante Valley is a sediment-filled basin, the deepest part of which lies just east of Beryl Junction. Escalante Valley is an agricultural area, and ground-water pumping from the basin-fill aquifer began in the 1920s. Monitoring shows that ground-water levels have declined steadily since the late 1940s, and that the rate of decline has increased in recent years due to drought conditions. The area of greatest ground-water decline is south of Beryl Junction.

Our investigation showed that the physical characteristics of the earth fissures are typical of similar fissures that have formed in other western states as a result of ground-water pumping and water-level decline. Length-to-width ratios are high, the fissures extend for considerable distances in a mostly linear fashion across a variety of material types, and the fissures appear to extend to great depth (perhaps the ground-water table) based on the volume of floodwater that entered the fissures. Other possible causes for the fissures (i.e., desiccation cracking, hydrocompaction, surface faulting) typically produce cracks with different characteristics, are limited to clay-rich deposits, or require a large (>M 6.5) earthquake to form. Additionally, high-resolution GPS surveying of benchmarks and the ground surface across Escalante Valley indicates that the ground surface has subsided locally as much as four feet (1.2 m) since 1941 to 1972 in a zone centered near Beryl Junction and the area of maximum ground-water-level decline.

Based on current evidence, we conclude that the most likely explanation for the formation of earth fissures in Escalante Valley is ground-water withdrawal, which has caused a significant drop in the ground-water level, permanent compaction of fine-grained units in the Escalante Valley aquifer, and ground subsidence near Beryl Junction. We infer that the earth fissures are the surface expression of horizontal tension in the Escalante Valley aquifer formed in response to differential aquifer compaction (and ground subsidence) near western Escalante Valley. To better understand the origin and possible future extent of additional fissuring, we recommend additional studies including (1) satellite interferometry to quantify subsidence across the Escalante Valley, (2) further investigation of the geology and hydrogeology of Escalante Valley to determine their relation to earth-fissure formation, (3) a search for additional earth fissures, and (4) a valley-wide analysis of well-casing and wellhead deformation.

INTRODUCTION AND PURPOSE

On January 8-12, 2005 a warm winter storm moved into southwestern Utah from southern California, causing widespread flooding and damage. The flooding extended northward into Escalante Valley in western Iron County about 56 kilometers (35 mi) west of Cedar City (figure 1). Erosion by floodwaters revealed a large (>400 meters [1300 ft] long) earth fissure near the small community of Beryl Junction. The fissure intercepted Utah State Route 56 (SR-56) and displaced the road surface several inches down-to-the-east. In addition, floodwaters draining into the fissure quickly eroded the fissure walls creating a gully that in places was as much as three meters (10 ft) wide and two meters (6.5 ft) deep.

Dennis Stowell, Iron County Commissioner, contacted the Utah Geological Survey's Southern Utah Office on January 20, 2005, and requested an investigation to determine the nature and extent of the fissure. Lund responded to the Commissioner's request that afternoon and met with Steve Platt

[1]*Utah Geological Survey, Cedar City*
[2]*Utah Geological Survey, Salt Lake City*
[3]*Southern Utah University, Cedar City*

(Iron County Engineer), Ron Gardner (Iron County Deputy Sheriff), and Beth England and James Holt (local residents) at the site of the fissure in Beryl Junction. Deputy Gardner and Ms. England reported the existence of two additional earth fissures, one southwest and the other northwest of Beryl Junction. Following an initial examination of the Beryl Junction fissure, the other two fissures were located and briefly examined prior to nightfall.

The following day, Lund mapped (with a hand-held GPS unit), measured, and photographed the three fissures. DuRoss and Kirby visited the earth fissures on February 9 and 10, 2005; investigated an additional earth fissure within a state-owned gravel pit north of Beryl Junction; revisited ground cracks along the eastern margin of the valley (originally studied by Christenson, 1991); and made a visual examination of 70 irrigation wells within Escalante Valley for evidence of ground subsidence. McDonald and Hunt performed a high-resolution Global Positioning System (GPS) survey on February 9 and 10, 2005. Hunt investigated the Bossardt earth fissure on March 30, 2005.

In this report, we use the term earth fissure to indicate a long, linear ground crack, or series of subparallel cracks having a high surface-trace length-to-width ratio (e.g., more than 5-10:1), as defined by the length and width of a rectangle encompassing the entire crack trace. Conversely, we use the term "ground crack" to describe less continuous cracks, or networks of cracks, having a smaller length-to-width ratio (i.e., less than 5:1). Measurements of distances and fissure dimensions are given in metric units with English-unit equivalents; water-level and surveyed ground elevations are given in their original English units with metric equivalents.

In addition to the field reconnaissance and mapping, the scope of this investigation included a review of geologic and hydrologic literature and maps pertaining to the study area, construction of a geologic cross section in the vicinity of the fissures, interviews with local residents who observed the fissures during the flooding, GPS surveying of benchmarks in the vicinity of the earth fissures, and review of an extensive set of digital photographs of the flooding taken from both the air and ground by a local landowner.

BACKGROUND

Physical Setting and Geology

For purposes of this report, we consider Escalante Valley to comprise the southernmost portion of the Escalante Desert, a 40-kilometer-wide (25 mi) by 100-kilometer-long (60 mi) northeast-trending mountain-bordered basin typical of the Basin and Range Province (figure 1). Escalante Valley is bordered on the east by the Antelope Range and Pine Valley Mountains, on the south by the Bull Valley Mountains, and on the west by a series of low hills. The valley is approximately 5 to 18 kilometers (3 to 11 mi) wide by 25 kilometers (16 mi) long, opening to the northeast into the Escalante Desert. Bedrock exposures in the surrounding mountains consist chiefly of Tertiary and Cretaceous sedimentary rocks and Tertiary volcanic rocks (Hintze, 1980). Mower and Sandberg (1982) state that basin fill in Escalante Valley consists of unconsolidated to semi-consolidated layers of gravel, sand, silt, and clay deposited in stream, lake, and wind-blown environments. They estimate the thickness of the basin fill to be greater than 300 meters (1000 ft) in the deeper parts of the basin. A review of drillers' well logs showed that the upper 60 meters (200 ft) of basin fill typically consists of less than 25% sand and gravel (Mower and Sandberg, 1982).

Beryl Junction is near the center of Escalante Valley, and the *Complete Bouguer Gravity Anomaly Map of Utah* (Cook and others, 1989) shows that the community is on the western edge of a strong northeast-trending gravity low that parallels the long axis of Escalante Valley (figure 2). The gravity low is indicative of a deep sediment-filled basin. Depth to bedrock within the low is unknown, but a detailed gravity survey performed to help define a geothermal system near Newcastle (Blackett and Shubat, 1992) indicated that depth to bedrock within the Newcastle graben west of the community of Newcastle and east of Beryl Junction (figure 1) is about 1.6 kilometers (1.0 mi).

Escalante Valley was settled in the 1860s and has been an area of intensive agricultural cultivation since that time. Over time, alfalfa has replaced potatoes as the principal crop, and dairies and feedlots have become increasingly important in recent years. Initially, water for irrigation came from perennial streams draining nearby mountains, but beginning in the 1920s and continuing to the present the principal source of irrigation water is wells; by 1982 ground water supplied 93% of the water used in Escalante Valley (Mower and Sandberg, 1982). Since 1950, ground-water levels have declined steadily and consistently in Escalante Valley and show no recovery during periods of above-average precipitation (Christiansen, 2003).

Ground Water

Ground water is generally present in an unconfined basin-fill aquifer in Escalante Valley, although confining beds exist locally (Fix and others, 1950; Mower and Sandberg, 1982). Principal recharge to Escalante Valley takes place along the southern end of the valley near Enterprise where Shoal Creek enters the valley (figure 1). Along the southeast margin of the valley near Newcastle, Pinto Creek provides the primary recharge (Fix and others, 1950; Mower and Sandberg, 1982). Mower and Sandberg (1982) estimate total recharge for the entire Escalante Desert at 48,000 acre-feet (59 cubic hectometers [hm^3]) per year. Total recharge within Escalante Valley is likely a large portion of this total (Mower and Sandberg, 1982). Monitoring wells in Escalante Valley indicated that the 2002 potentiometric surface, or ground-water table in the unconfined aquifer, sloped gently inward from the valley margins and southward from the northern part of Escalante Valley toward a north-south-trending kidney-shaped zone of maximum depression extending south from Beryl Junction along SR-18 (Beryl Highway) (figure 3; U.S. Geological Survey Water Resources, 2005).

The 2002 potentiometric surface is significantly different from the potentiometric surface dating from the late 1940s, which shows a north-northwest-sloping ground-water table across Escalante Valley prior to major ground-water withdrawal (Fix and others, 1950). Over about six decades, from the late 1940s to 2002, water levels in monitoring wells have fallen as much as 105 feet (32 m), with the level in many wells dropping 85 feet (26 m) (figure 4; table 1; USGS

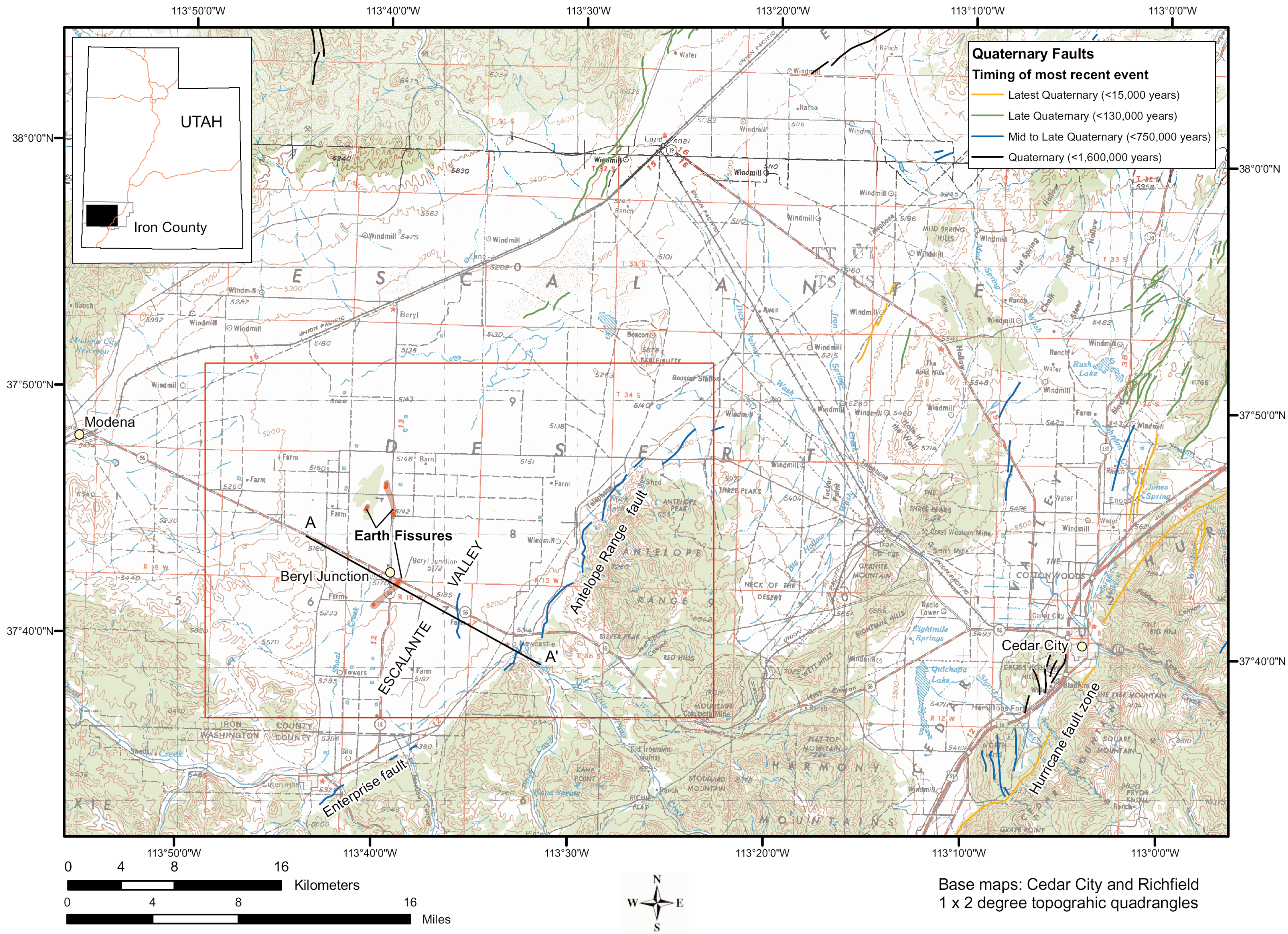

Figure 1. *Regional map of the Escalante Desert, showing location of earth fissures in western Escalante Valley. Fault traces and timing from Black and others (2003). Red box indicates extent of figure 2. Cross section A-A′ shown on figure 5.*

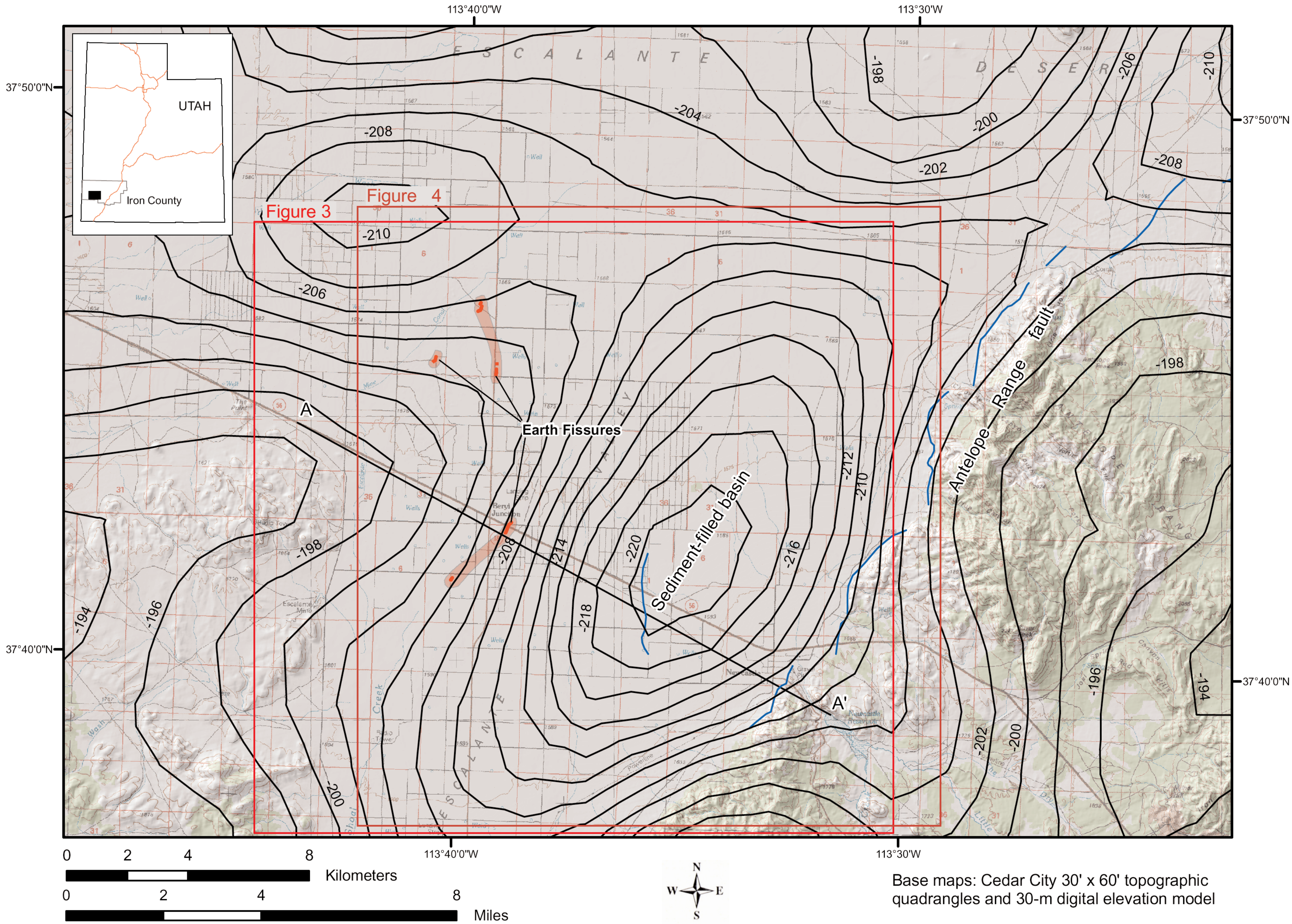

Figure 2. Complete Bouguer gravity anomaly map for the southern Escalante Desert, showing the location of earth fissures relative to the gravity low east of Beryl Junction. Contours (2 milligal) interpolated from 5 km square grid. Solid black line indicates location of cross section A-A′ (figure 5). Blue lines are mid- to late Quaternary faults.

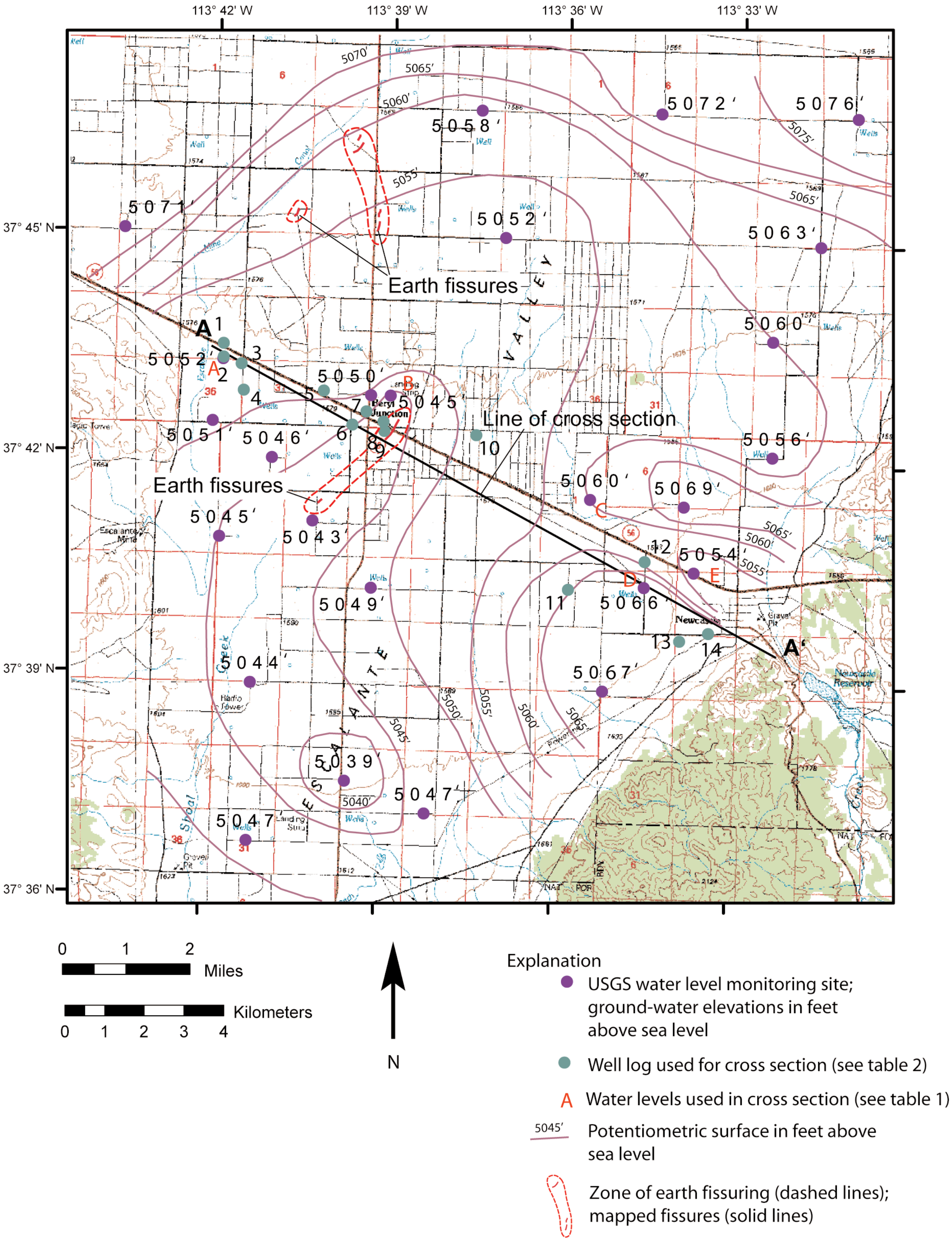

Figure 3. *Potentiometric surface in Escalante Valley, based on 2002 water-level elevations (U.S. Geological Survey Water Resources, 2005). All water-level elevations are in feet. Base map: Cedar City 30′ x 60′ topographic quadrangle. Solid black line indicates location of cross section A-A′ (figure 5).*

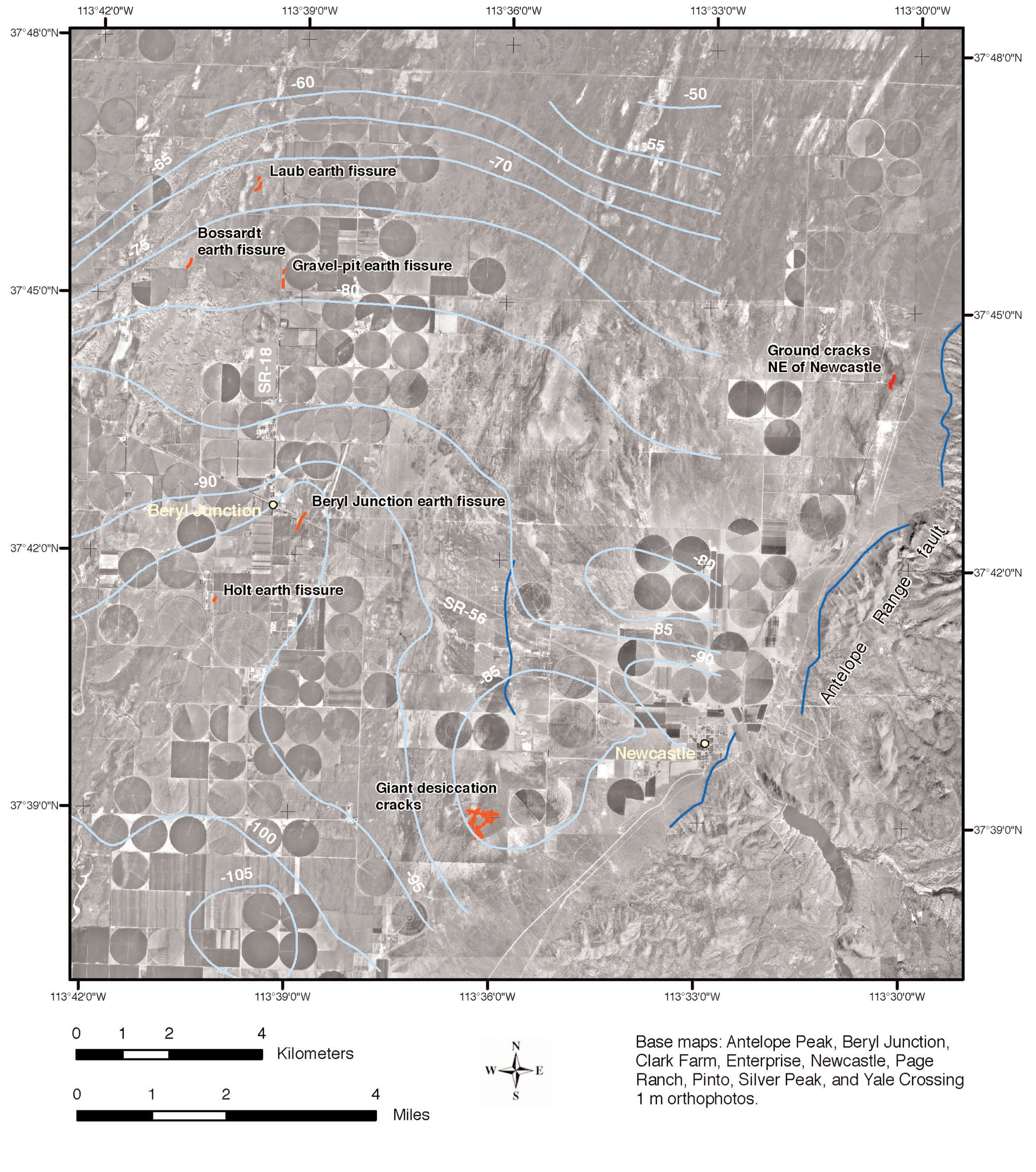

__Figure 4.__ Change in ground-water level (light blue contours, in feet; negative value indicates decline) from 1949 to 2002 in the Escalante Valley, and locations of Beryl Junction, Holt, gravel-pit, Bossardt, and the Laub earth fissures; ground cracks northeast of Newcastle; and giant desiccation cracks southwest of Newcastle.

Table 1. *Depth to ground water for monitoring wells shown on figure 3.*

Monitoring well	**1960 water level (ft)**	**1980 water level (ft)**	**2002 water level (ft)**	**Total drawdown (ft)**
A	63	88	128	65
B	No data	86	131	45
C	No data	105	147	42
D	95	123	173	78
E	No data	154	203	49

Data are from U.S. Geological Survey Water Resources (2005). All levels are in feet below the ground surface. Total drawdown is over the period of record (1960-2002 or 1980-2002).

Table 2. *Water-well locations and depth to bedrock.*

Well reference number[a]	UTM location (easting, northing)[b]	Depth to bedrock (ft)[c]
1	262233, 4178577	>300
2	262233, 4178230	>315
3	262691, 4178059	>375
4	262738, 4177390	>400
5	264767, 4177360	>200
6	265495, 4176501	>283
7	265850, 4176837	>300
8	266279, 4176572	>262
9	266303, 4176335	>300
10	268635, 4176229	>405
11	270947, 4172320	>496
12	272895, 4173022	>500
13	273763, 4171003	>513
14	274501, 4171224	>500

[a] Numbers correspond to water-well labels on figure 3.
[b] All locations in NAD 27, UTM Zone 12N coordinate system.
[c] Estimated depth to bedrock based on well drillers' logs. Logs are available from the Utah Division of Water Rights at <http://www.waterrights. utah.gov>.

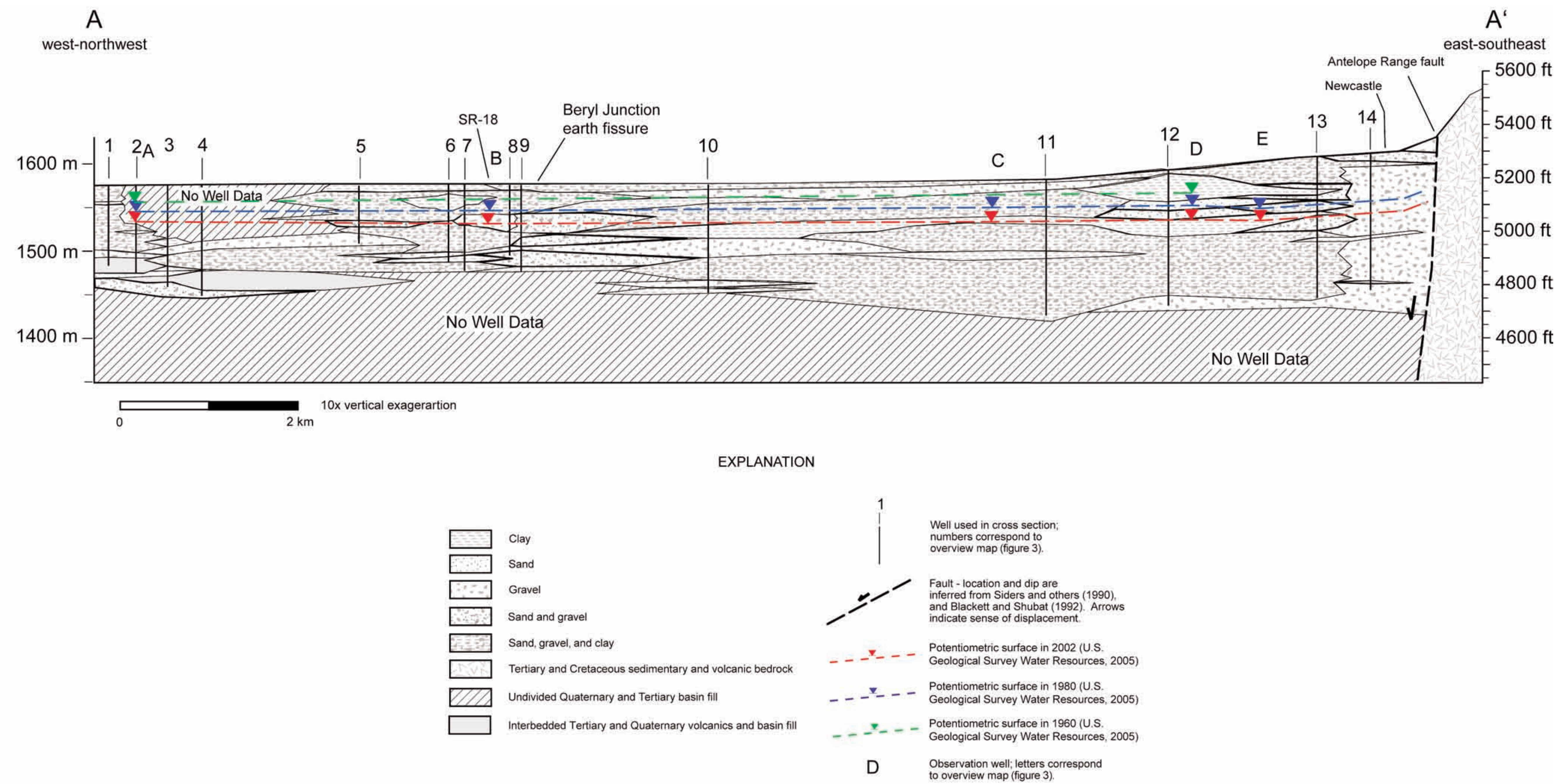

Figure 5. *Geologic cross section A-A′ from water-well logs, oriented west-northwest to east-southeast across Escalante Valley south of SR-56. Water-level data are from U.S. Geological Survey Water Resources (2005). Location of cross section shown on figures 1, 2, and 3. Well numbers and letters correspond to figure 3 and tables 1 and 2.*

Water Resources, 2005; Christiansen, 2003). Ground-water decline decreases north of Beryl Junction, where total decline is 60 feet (18 m). Two of the earth fissures investigated during this study are in a zone of high drawdown shown in figure 4, which has declined over 95 feet (29 m) since the late 1940s. For the year 2002, the total volume of ground water withdrawn in the entire Escalante Desert was approximately 99,000 acre-feet (122 hm^3; Christiansen, 2003). Total withdrawal within Escalante Valley is likely a large but undocumented portion of this total.

We examined 70 agricultural wells along SR-18 and to the east near Newcastle for evidence of ground subsidence at the wellhead. None of the wells showed evidence of ground deformation or subsidence.

A west-northwest to east-southeast cross section constructed from water-well logs shows a relatively complex basin-fill stratigraphy, which is composed of intermixed clay, sand, and gravel across much of Escalante Valley (figure 5; table 2). Near the earth fissure that intercepts SR-56, well logs show sand, gravel, and clay in the upper 46 meters (150 ft) of the basin fill, which overlies dominant sand and gravel in the lower portions of these wells (figure 5). Well logs suggest that the basin fill increases in clay content to the north and east toward the center of Escalante Valley.

January Flood

The January 2005 flood in Escalante Valley resulted from much greater than normal flows in Shoal and Spring Creeks, which enter the valley at its south end near the town of Enterprise (figure 1). Neither creek has a stream gage, so maximum stream flows during the flood are unknown. Both drainages are ephemeral, flowing only in response to increased precipitation or snowmelt. Typically, water flowing in the drainages quickly infiltrates into the coarse alluvial-fan deposits that have accumulated where the streams enter Escalante Valley, but during periods of high flow, the water continues down gradient to the north and spreads across the valley. Mower and Sandberg (1982) documented flood conditions on Shoal Creek in 1975 that exceeded 5.5 cubic meters per second (200 cfs), and floodwaters extended as far north as Beryl Junction, approximately 16 kilometers (10 mi) north of where the creek enters the valley. The extent of flooding in January 2005 exceeded that of 1975, with floodwaters reaching at least 7 kilometers (4.4 mi) north of Beryl Junction (figure 6).

Once floodwaters enter Escalante Valley, they quickly spread out and typically are only inches to a few feet deep. However, the valley is crisscrossed by a complex system of raised roadbeds, canals, ditches, and other impediments to flow that preferentially direct and concentrate the water into some areas while leaving other areas dry (figure 6). The result is a complex pattern of flooding and flood damage.

DESCRIPTION

This investigation identified five earth fissures in Escalante Valley following the flood of January 8-12, 2005 (figure 7). The longest fissure is near Beryl Junction near the center of Escalante Valley, and other fissures are 2.4 kilometers (1.5 mi) southwest (Holt fissure), 5.0 kilometers (3.1 mi) north (gravel-pit fissure), 5.5 kilometers (3.5 mi) northwest (Bossardt fissure), and 7.0 kilometers (4.4 mi) north (Laub fissure) of Beryl Junction (figure 7). In addition, we include a brief description of two separate zones of ground cracking, located 8.5 kilometers (5.3 mi) northeast and 5.0 kilometers (3.1 mi) west-southwest of Newcastle (figure 4).

Beryl Junction Earth Fissure

The Beryl Junction earth fissure is in section 33, T. 35 S., R. 16 W. and section 4, T. 36 S., R. 16 W., Salt Lake Base Line and Meridian, in the Beryl Junction 7.5-minute quadrangle. The fissure is a minimum of 410 meters (1345 ft) long (trace length) and may be as long as 460 meters (1510 ft; figure 8). From near its south end, the fissure generally trends N. 25° E. until reaching a point just north of SR-56 (figure 8, station 23), where the fissure bends and trends N. 45° E. for the remainder of its length. The fissure crosses SR-56 about 0.65 kilometers (0.4 mi) east of the SR-56/SR-18 intersection at Beryl Junction, and displaced the asphalt road surface several inches down-to-the east (Scott Munson, Utah Department of Transportation, verbal communication, 2005). The road was quickly repaired, and no known photographs exist of the pre-repair damage. The Beryl Junction earth fissure traverses distal alluvial-fan deposits of ancestral Shoal Creek (Siders, 1985), mapped by Ulrich (1960) as silt-loam and fine sandy loam soil types at the surface. Material exposed in the eroded fissure and within a gravel-pit exposure west of the Beryl Junction airport is predominantly cross-bedded silt, sand, and pebble gravel, with significant pedogenic carbonate.

At its south end in an alfalfa field, the Beryl Junction fissure is a centimeter or less wide and exhibits no vertical displacement (BJ-1, appendix). Proceeding north, the fissure increases in width to a few centimeters and exhibits as much as 10 centimeters (4 in) of down-to-the-east displacement (BJ-2, appendix). Two piping holes created by infiltrating floodwater formed along the fissure at stations 8 and 9 (BJ-3, appendix). Due to the complex path followed by the floodwater through the valley, the alfalfa field was only partially flooded and the fissure was not inundated at its south end (Klayton Holt, landowner, verbal communication, 2005). However, as the fissure exited the field to the north and approached SR-56, floodwater ponding on the south side of the highway was directed westward until it encountered the fissure. The floodwater flowed into the fissure and quickly eroded the fissure walls. In places, the resulting gullies were up to 3 meters (10 ft) wide and 2 meters (6.5 ft) deep (BJ-4, appendix). Down-to-the-east displacement across the fissure in this area was 20 to 30 centimeters (8-12 in) (BJ-5, appendix).

Minimal or no floodwater reached the fissure north of SR-56, although sheetwash during periods of heavy precipitation likely did occur. North of SR-56, the fissure was typically a few centimeters or less wide and exhibited no vertical displacement (BJ-6, appendix). An exception occurred where the fissure crossed a graded dirt road (BJ-7, appendix; figure 8, station 23) and expanded to several centimeters wide. We do not know what part traffic on the road may have played in enhancing the width of the fissure. At its north end (figure 8, station 26), the fissure was again a centimeter or

***Figure 6.** Aerial view showing the January 2005 flooding north of Beryl Junction at the intersection of SR-18 and 1200 North.*

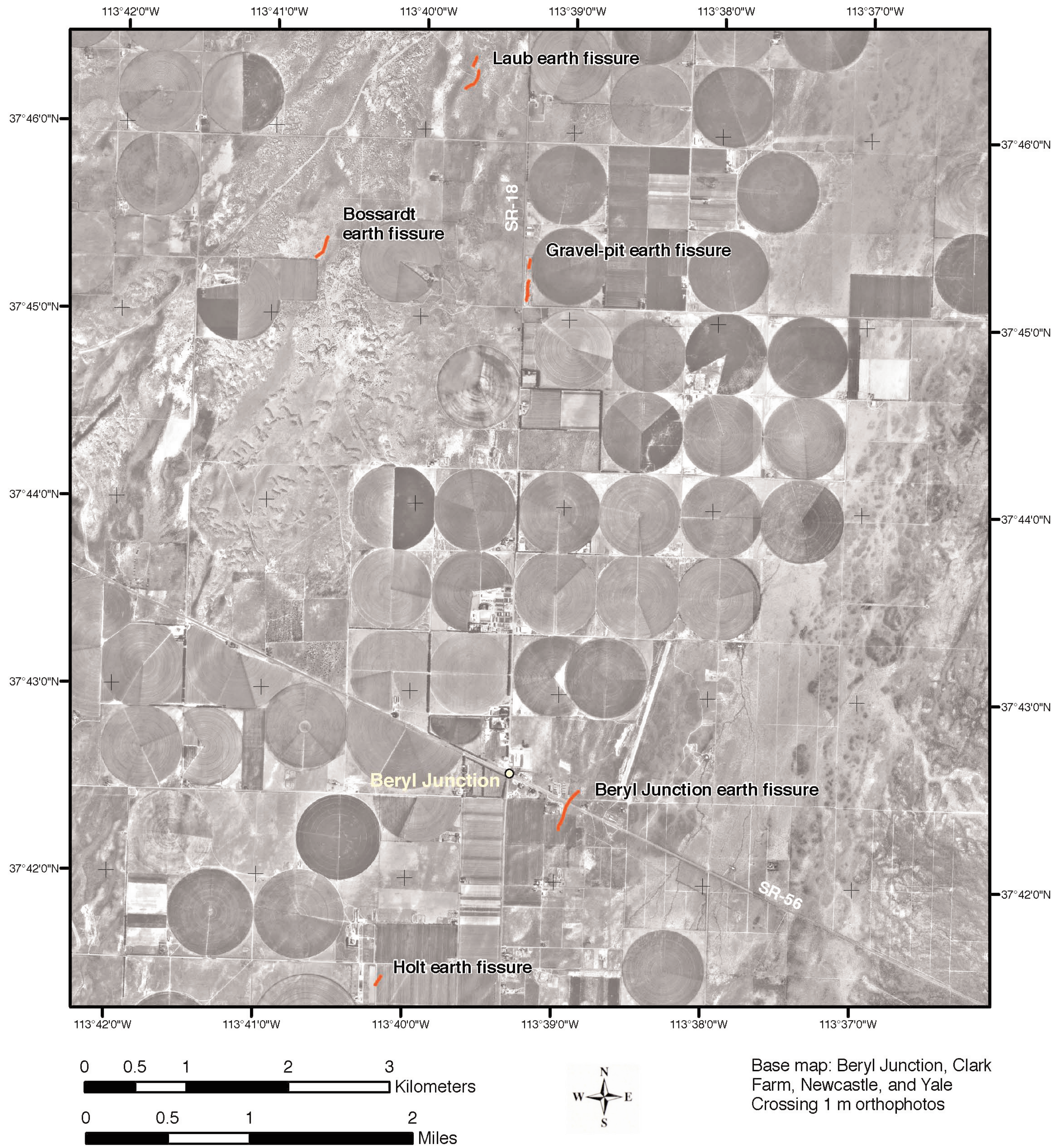

Figure 7. *Location of the Beryl Junction, Holt, gravel-pit, Bossardt, and Laub earth fissures.*

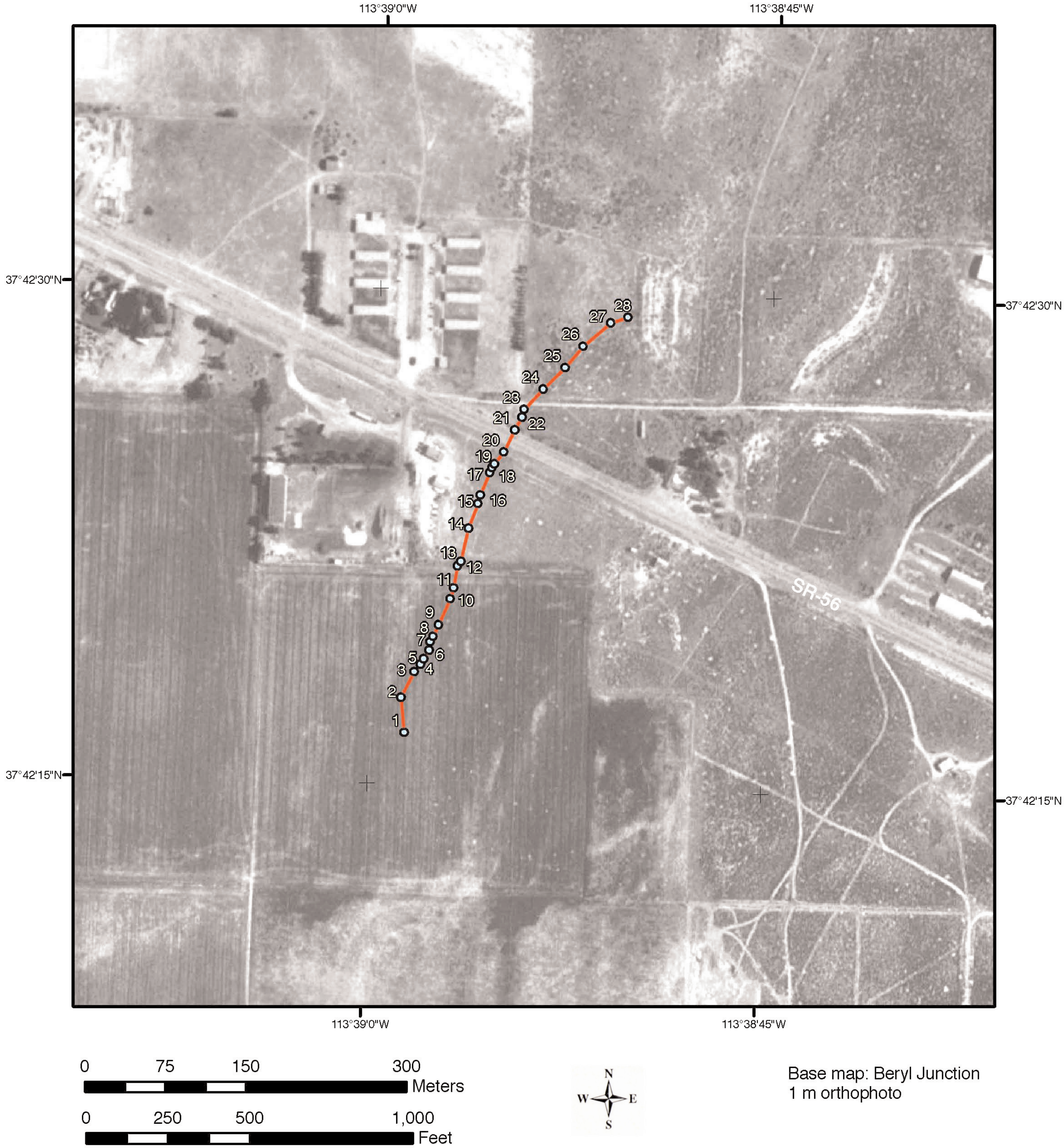

Figure 8. *Map of the Beryl Junction earth fissure, showing GPS stations.*

less wide before terminating (BJ-8, appendix). Between stations 26 and 27 (figure 8), no evidence of fissuring was evident. Between stations 27 and 28 a linear hairline crack marked what might be the northern extent of fissuring. However, this area was covered by an extensive system of polygonal mud cracks that obscured evidence of fissuring.

Klayton Holt, the farmer who owns the pivot-irrigated alfalfa field in which the southern part of the Beryl Junction earth fissure is located, stated that the earth fissure displaced SR-56 on the evening of Wednesday, January 12 at the height of the flood, and that floodwater entered the fissure for the remainder of that night and into the following day. Mr. Holt also indicated that a dip in the surface of SR-56 existed at the point where the fissure crossed the road for a number of years prior to the roadbed failure. Mr. Holt further stated that portions of his alfalfa field have subsided noticeably south of the southern terminus of the Beryl Junction fissure since the flood, and that surface water is now ponding where it formerly drained away. Mr. Holt installed a pivot irrigation system and began raising alfalfa in the field two years ago; prior to that time the field was a sprinkler-irrigated pasture. Finally, Mr. Holt stated that in 2000 his irrigation well at the southwest corner of the field (750 meters [2460 ft] southwest of the fissure's southern terminus) failed when the well casing sheared and displaced sideways. Attempts to verify other instances of well failures were unsuccessful and no other landowners contacted had experienced similar well failures.

Holt Earth Fissure

The Holt earth fissure is in section 5, T. 36 S., R. 16 W., Salt Lake Base Line and Meridian, in the Beryl Junction 7.5-minute quadrangle, about 2.4 kilometers (1.5 mi) southwest of Beryl Junction (figure 7). The fissure is 120 meters (395 ft) long and trends N. 30° E (figure 9). The fissure's southern terminus is near a fence bordering the east side of a cattle feedlot. The fissure extends from the fence northeastward across 500 West Street (a dirt road) into an agricultural field (figure 9). The fissure crosses the road approximately 160 meters (530 ft) south of the intersection of 800 South and 500 West Streets. We did not observe evidence of fissuring south of the fence during the field reconnaissance, and a feedlot employee reported finding no evidence of the fissure on the feedlot property (Fred Woods, verbal communication, 2005). The Holt earth fissure traverses distal alluvial-fan deposits of ancestral Shoal Creek (Siders, 1985), mapped by Ulrich (1960) as sandy clay loam and sandy loam soil types at the surface.

At its south end, the Holt earth fissure was a few centimeters wide and showed no evidence of vertical displacement (H-1, appendix; figure 9, station 1). A short distance to the north, infiltrating floodwater increased the fissure width to several centimeters. The floodwater-enhanced fissure damaged 500 West Street (H-2, appendix; figure 9, station 3), causing the landowner to repair the road with sand, thus indicating that the fissure was sufficiently wide and/or deep to impair vehicle traffic. Upon entering the field, the fissure exhibited a few centimeters of down-to-the-east vertical displacement, and at station 5 (figure 9), floodwater draining into the fissure created a piping hole that measured 3.1 meters (10.2 ft) long, 1.5 meters (4.9 ft) wide, and 1.2 meters (3.9 ft) deep (H-3, appendix). The feedlot employee reported that a vortex formed in the floodwater above the hole (Fred Woods, verbal communication, 2005). Before entering the fissure, the floodwater passed through the feedlot, likely becoming charged with animal waste.

Beyond the piping hole, the fissure was typically a few centimeters wide, and locally consisted of two or more subparallel strands that created a zone up to 2 meters (6.5 ft) wide (H-4, appendix). The fissure showed little or no evidence of vertical displacement, and before terminating at its north end was reduced to a narrow crack a centimeter or less wide (H-5, appendix; figure 9, station 10).

Gravel-Pit Earth Fissure

The gravel-pit earth fissure is in section 16, T. 35 S., R. 16 W., Salt Lake Base Line and Meridian, in the Yale Crossing 7.5-minute quadrangle, about 5 kilometers (3.1 mi) north of Beryl Junction (figure 7). The fissure follows the long axis of a gravel pit, northeast of the intersection of SR-18 and 2400 North Street (figure 10). The fissure consists of two strands separated by 109 meters (358 ft) of unfissured ground and is aligned in a N. 5° E. direction. The fissures have a cumulative trace length of 314 meters (1030 ft), and a total length (tip to tip) of 420 meters (1378 ft). Based on the map pattern and field investigation, we presume that a crack, uneroded by surface water, connects the two fissures. We found no evidence for vertical displacement across the fissures. The gravel-pit earth fissure traverses distal alluvial-fan deposits of ancestral Shoal Creek (Siders, 1985), mapped by Ulrich (1960) as a fine sandy loam soil type at the surface. Material exposed in the eroded fissure and within the gravel-pit exposure is predominantly silt, sand, and pebble gravel.

The southern gravel-pit earth fissure is 214 meters (702 ft) long and is expressed as isolated and interconnected centimeter-scale depressions along its northern half, and as a continuous, linear, eroded crack, up to 1.5 meters (4.9 ft) wide and several decimeters deep along its southern half. In the deepest part of the gravel pit, floodwater infiltrated and eroded the fissure, locally forming piping holes and areas of ground collapse up to 1.5 meters (4.9 ft) wide (GP-1 and GP-2, appendix). The south end of the fissure bends to the southwest and continues up the eroded gravel pit wall for 11 meters (36 ft) (figure 10, station 1), as evidenced by centimeter-scale depressions (GP-3, appendix). The aligned depressions extend to a few meters below the approximate elevation of floodwater that filled the gravel pit during the January storm. At the north end of the south fissure, a moderately eroded crack less than about 2-15 centimeters (0.8-6 in) wide and up to several centimeters deep extends across the gravel pit floor and along the flank of a gravel mound within the pit (GP-4, appendix; figure 10, station 11). The crack is remarkably linear, with the exception of a minor Y-shaped branch toward the southeast, approximately 65 meters (213 ft) north of the southern end of the fissure (figure 10, stations 5 and 7). At this location, a minor, 25-meter-long (82 ft) crack oriented N. 45° W. intersects the main crack system. The subsidiary crack is a few centimeters wide and is expressed as centimeter-scale depressions at its southwest end.

The northern gravel-pit earth fissure is 100 meters (328 ft) long and is expressed as isolated centimeter-scale depressions in sandy artificial fill along the south half of the fissure

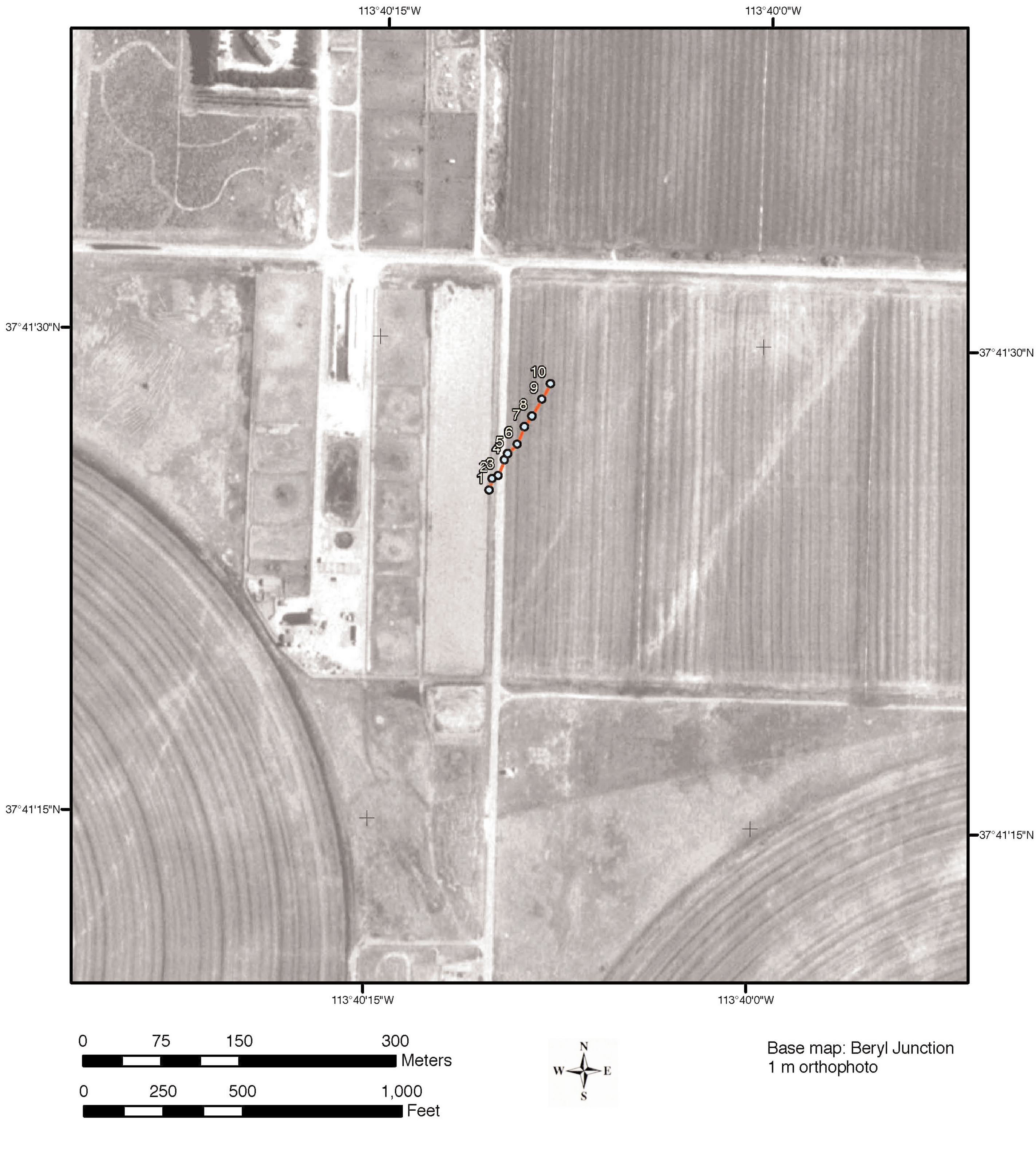

Figure 9. *Map of the Holt earth fissure, showing GPS stations.*

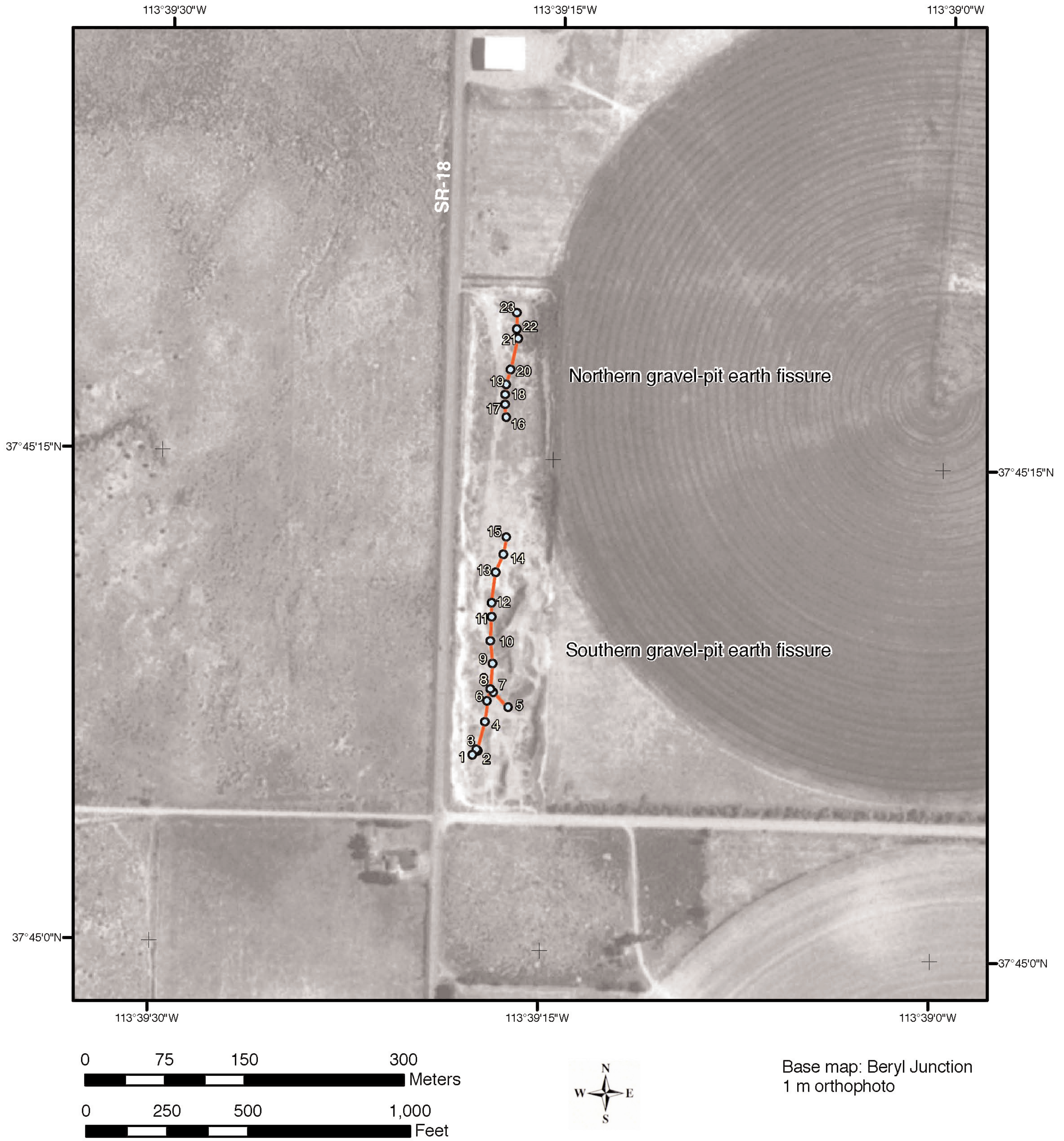

Figure 10. *Map of the gravel-pit earth fissure, showing GPS stations.*

(GP-5, appendix; figure 10, station 16) and as a continuous crack extending across a deeper part of the gravel pit along the remainder of its length (GP-6, appendix; figure 10, station 20). Floodwater has eroded the crack to a depth of approximately 1 meter (3.3 ft) where the fissure continues northward across a north-facing, approximately 2- to 3-meter-high (6.6-10 ft) embankment within the gravel pit (GP-6 and GP-7, appendix). The northernmost part of the fissure consists of a 5- to 10-centimeter-wide (2-4 in) parallel-sided crack at least a meter deep (GP-8, appendix), transitioning to isolated centimeter-scale depressions along the northernmost wall of the gravel pit. In a manner similar to the southern fissure, the depressions do not continue above the estimated high-water mark of floodwater in the gravel pit. West of the main fissure in the deepest part of the gravel pit, desiccation cracks less than 5 centimeters (2 in) wide by 5 centimeters (2 in) deep form polygons approximately 2 meters (6.6 ft) wide in clay-rich deposits along an eroded east-facing embankment within the gravel-pit (GP-9, appendix). Based on a lack of erosion by floodwater and their limited extent, we conclude that the desiccation cracks formed post-flooding and are unrelated to the earth fissures extending across the entire gravel pit.

Bossardt Earth Fissure

The Bossardt earth fissure is in section 18, T. 35 S., R. 16 W., Salt Lake Base Line and Meridian, in the Yale Crossing 7.5-minute quadrangle. The site is approximately 5.5 kilometers (3.5 mi) northwest of Beryl Junction, and is the farthest west of the known fissures in Escalante Valley (figure 7). The fissure is 257 meters (843 ft) long, a minimum estimate as wind-blown sand has obscured the northern terminus (figure 11). The south part of the fissure trends N. 40° E. for 90 meters (295 ft), changing to N. 20° E. for the remainder of its visible length. An irrigated alfalfa field 25 meters (80 ft) south of the southern fissure terminus shows no evidence of fissuring. The Bossardt earth fissure crosses distal alluvial-fan deposits and wind-blown silt and sand dunes, mapped by Ulrich (1960) as fine sandy loam and dune-land soil types at the surface.

At its southern end, the Bossardt fissure is less than 3 centimeters (1.2 in) wide and exhibits no vertical displacement. Highly desiccated clay-rich soils near its south end made the fissure difficult to identify. The fissure width gradually increases to the northeast; at 70 meters (230 ft) north of the south end of the fissure, near the intersection of two minor graded dirt roads (figure 11, north of station 2), floodwater has eroded the fissure, forming a piping hole measuring 0.5 meters (1.6 ft) long, 0.5 meters (1.6 ft) wide, and 0.3 meters (1.0 ft) deep (BF-1, appendix). Small-scale grabens 0.5 to 0.75 meters (1.6-2.5 ft) wide also formed at this location. North of the change in fissure direction (figure 11, station 3), the fissure increases in width and depth, achieving an average width of 0.30 meters (1 ft) and a maximum depth of 1.5 meters (4.9 ft; BF-2, appendix). One hundred meters (330 ft) from its south end the fissure has 3-4 centimeters (1.2-1.6 inches) of down-to-the-east vertical displacement. Infiltrating floodwater formed a piping hole measuring 2.0 meters (6.6 ft) long, 1.5 meters (4.9 ft) wide, and 1.0 meters (3.3 ft) deep about 190 meters (620 ft) from the south end of the fissure (BF-3, appendix). At 210 meters (690 ft) from its south end, the fissure crosses another graded dirt road and then quickly narrows before disappearing into sand dunes 15 meters (50 ft) north of the road (BF-4, appendix).

Laub Earth Fissure

The Laub earth fissure is in section 8, T. 35 S., R. 16 W., Salt Lake Base Line and Meridian, in the Yale Crossing 7.5-minute quadrangle, about 7 kilometers (4.4 mi) northwest of Beryl Junction (figure 7), and is the farthest of the five fissures from areas of pump-irrigated agriculture. The fissure consists of two subparallel strands offset approximately 70 meters (230 ft) in a northwest-southeast direction: the southern and northern Laub earth fissures (figure 12). The total length of the fissure (cumulative length along both strands) is 363 meters (1191 ft). The Laub earth fissure crosses distal alluvial-fan deposits and wind-blown silt and sand dunes, mapped by Ulrich (1960) as fine sandy loam and dune-land soil types at the surface.

The southern Laub earth fissure is 256 meters (840 ft) long and shows three distinct changes in trend along its length. From its south end to station 6 (figure 12) the fissure trends N. 55° E. The fissure bends to the north at station 7 and then trends N. 30° E. between stations 8 and 13. From station 13 to the north end of the fissure at station 19 (figure 12) the fissure trends N. 5° E. The fissure crosses a two-wheel dirt track at station 12 (figure 12). From the dirt track/fissure intersection, it is 645 meters (2120 ft) to the southeast along the track to SR-18 (figure 7). The northern Laub earth fissure is 107 meters (351 ft) long, trending N. 25° E. along the southernmost 87 meters (285 ft) and north-south along the northernmost 20 meters (66 ft) (figure 12). The southern termination of the northern fissure (station 20, figure 12) is approximately 70 meters (230 ft) northwest of the northern termination of the southern fissure (station 19, figure 12).

At its south end, the southern Laub earth fissure began as a narrow crack that was difficult to distinguish from numerous desiccation cracks formed in the clay-rich soils of the area (L-1, appendix). Continuing northeastward, the fissure remained difficult to recognize to station 3 (figure 12), where infiltrating floodwater began to erode and enlarge the fissure (L-2, appendix). From that point northward the effect of floodwater on the fissure became increasingly pronounced (L-3, appendix), until at station 12 (figure 12), where the fissure crossed the dirt track, the fissure was 0.7 meters (2.3 ft) wide and 0.7 meters (2.3 ft) deep (L-4, appendix). Between stations 14 and 17 (figure 12), floodwater eroded three piping holes along the fissure; the largest hole measured 3.9 meters (12.9 ft) long, 0.8 meters (2.6 ft) wide, and 1.0 meters (3.3 ft) deep (L-5, appendix). Beyond station 17, the fissure showed progressively fewer effects of infiltrating floodwater until eventually terminating in an area of extensive polygonal mud cracks (L-6, appendix).

The northern Laub earth fissure consists of isolated, centimeter-scale depressions forming a linear trend. Near the center of the fissure, surface water infiltrated and eroded the crack, forming piping holes up to 0.4 meters (1.3 ft) long, 0.1 meters (0.3 ft) wide, and 0.7 meters (2.2 ft) deep (L-7, appendix; figure 12, station 25). Approximately 15 meters (49 ft) from the north end of the fissure, centimeter-scale depressions continue across the western end of an active sand dune,

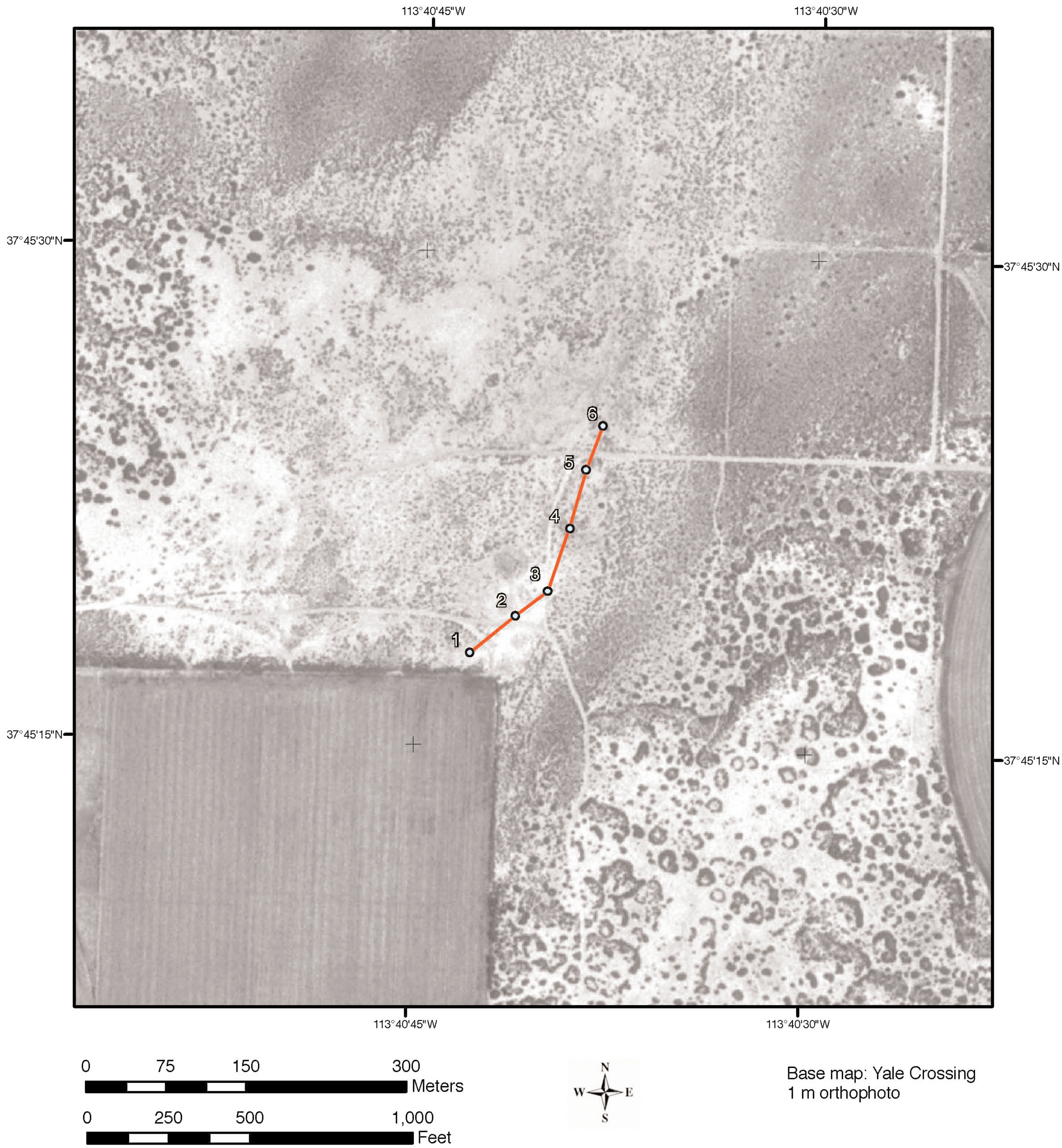

Figure 11. *Map of the Bossardt earth fissure, showing GPS stations.*

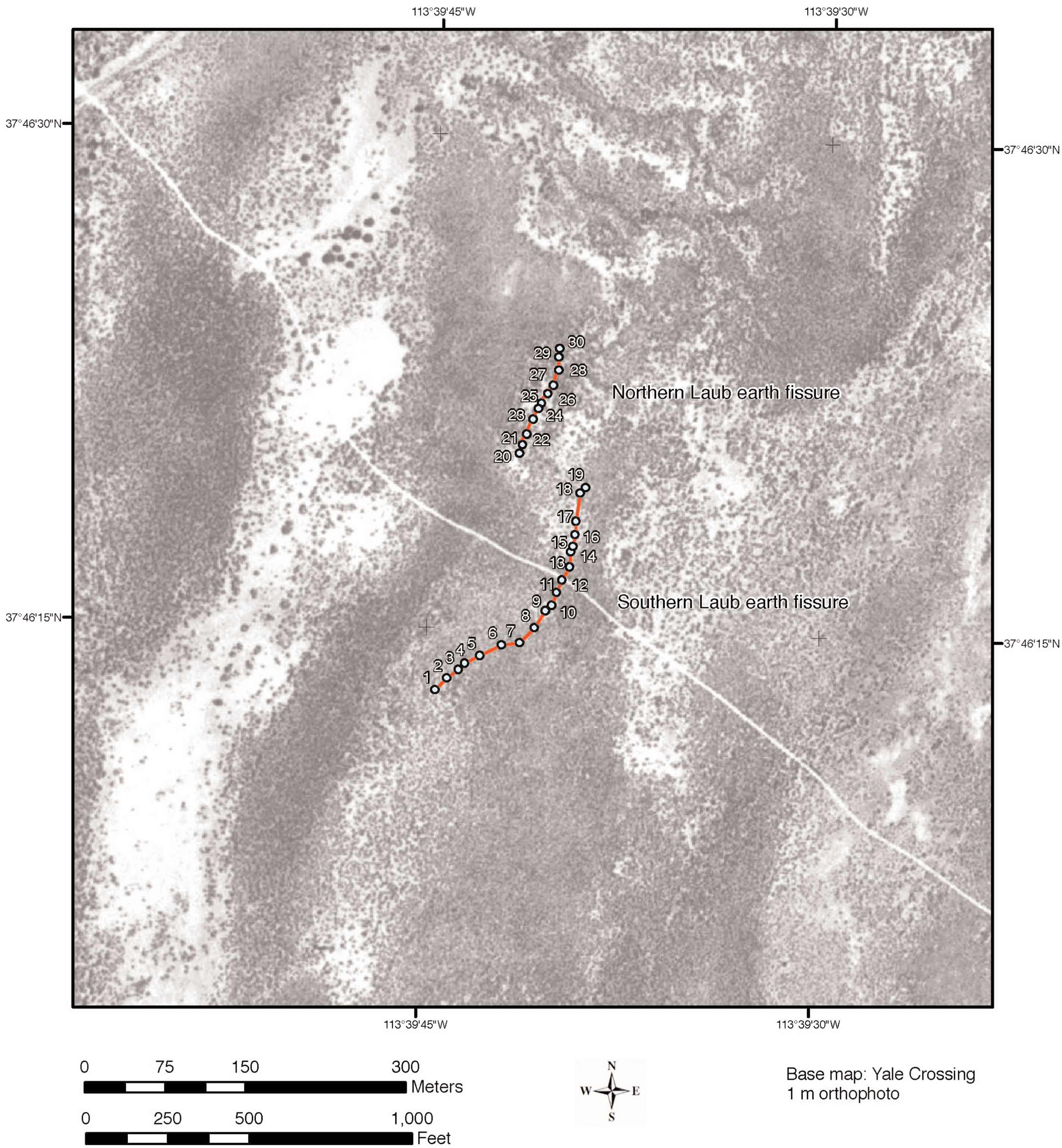

Figure 12. *Map of the Laub earth fissure, showing GPS stations.*

indicating erosion by surface water (L-8, appendix; figure 12, station 29). The north and south ends of the fissure were difficult to identify due to the abundance of wind-blown silt and sand that likely mask potential hairline cracks. We found no evidence for vertical displacement across the fissure.

Ground Cracks Northeast of Newcastle

The ground cracks northeast of Newcastle are in sections 23 and 26, T. 35 S., R. 15 W., Salt Lake Base Line and Meridian, in the Newcastle 7.5-minute quadrangle, approximately 8.5 kilometers (5.3 mi) northeast of Newcastle (figure 4). The ground cracks form a zone of cracking approximately 277 meters (910 ft) long by 60 meters (200 ft) wide, with the long axis trending N. 25° E (figure 13). The cracks formed in clay-rich sediment in a minor depression at the east edge of the Pinto Creek alluvial fan near the toes of several coalesced alluvial fans extending from the Antelope Range to the east (Siders and others, 1990). Ulrich (1960) mapped the area as having a silt-loam soil type.

The ground cracks have multiple segments and intersections, which are most apparent on the U.S. Geological Survey (USGS) Newcastle orthophoto quadrangle compiled from 1999 aerial photographs (figure 13), but are difficult to trace on the ground (GC-1, appendix). At one locality, the ground cracks cross and parallel a dirt track (GC-2, appendix). Christenson (1991) described the cracks as consisting of shallow, elongate closed depression, which may channelize local surface-water flow. Generally, the cracks have eroded shapes, and are up to 0.3 meters (1.0 ft) wide but only a few centimeters deep. Minor evidence of more recent erosion by surface water (perhaps during the flood of January 8-12, 2005) exists near the center of the zone of cracks, where depressions are up to 0.3 meters (1.0 ft) deep (GC-3, appendix). We found no evidence for vertical displacement across the cracks.

Brad Hewlett (landowner) and Evan Hansen (Escalante Valley resident, verbal communication in Christenson, 1991) stated that the cracks have been present for at least 20-30 years. For a detailed description of the ground cracks, see Christenson (1991).

Giant Desiccation Cracks Southwest of Newcastle

Giant desiccation cracks exist in sections 13, 14, 23, and 24, T. 36 S., R. 15 W., Salt Lake Base Line and Meridian, in the Newcastle 7.5-minute quadrangle, approximately 5.0 kilometers (3.1 mi) west-southwest of Newcastle (figure 4). The cracks form a 0.3-square-kilometer (0.1 mi^2) triangular-shaped zone along the east edge of the Shoal Creek alluvial fan and the toes of several coalesced alluvial fans (figure 14) extending from the Antelope Range to the southeast (Siders and others, 1990). Ulrich (1960) mapped the area containing the cracks as having a silty clay loam soil type. We mapped the desiccation crack traces on 1:20,000-scale, 1967 aerial photographs; the cracks were not apparent on the USGS Newcastle orthophoto quadrangle. We did not investigate the cracks in the field.

The giant desiccation cracks have 10- to 90-meter-long (30-300 ft) linear and intersecting traces that form an extensive network of polygons (figure 14). Most polygons are composed of four to seven linear crack segments. We mapped 22 polygons that are completely closed or open on only one side, having an average width of 38 meters (125 ft) and a minimum-maximum range in width of 20 to 80 meters (65-260 ft). Based on our analysis of aerial photographs, we infer that as of 1967 the cracks had been eroded by surface water and covered with vegetation. Prior to 1999, the cracks may have been plowed, as they are not apparent on the USGS Newcastle orthophoto quadrangle.

RESULTS OF GEODETIC SURVEYING

We performed high-resolution Global Positioning System (GPS) surveying of the ground surface, Utah Department of Transportation (UDOT) right-of-way markers, and National Geodetic Survey (NGS) and USGS benchmarks using a Trimble 5800 real-time kinematic GPS system having accuracy specifications of ±0.01 meters horizontal and ± 0.02 meters vertical. Our survey included a 32-kilometer-long (20 mi) northwest to southeast transect along SR-56, a north-south transect along SR-18 from 11 kilometers (7 mi) south to 8 kilometers (5 mi) north of Beryl Junction, and a 12-kilometer-long (7.5 mi) north-south transect in a farmed area north of SR-56 between Modena and Beryl Junction. The data were compared to older elevations for benchmarks, 1972 USGS 7.5-minute topographic quadrangles, and UDOT surveys performed in 1941 and 1955. Figure 15 shows GPS stations surveyed for this study with elevation differences between our GPS survey results and older elevation data, rounded to the nearest foot. The changes in elevation represent different time periods, depending on the date of the initial survey, so values in figure 15 do not necessarily represent the total decline in ground-surface elevations since subsidence began. In addition, these data should be considered approximate because the older elevation data available for comparison are limited and are based on dated, less accurate surveying methods compared to modern GPS techniques. Our GPS surveying was done strictly for scientific purposes and does not represent the work of a Utah licensed surveyor.

The GPS survey data indicate a zone of ground subsidence centered near Beryl Junction, where the ground-surface elevation decreased by as much as 4 feet (1.2 m) since 1941 to 1972, yielding an average subsidence rate of about 0.1 feet (0.03 m) per year at Beryl Junction, the area of maximum measured subsidence. Our data also suggest the zone of subsidence may extend beyond our northernmost survey point along SR-18. Our north-south GPS transect surveyed in the west part of Escalante Valley between Modena and Beryl Junction suggests little or no subsidence has occurred there.

DISCUSSION

Earth fissures and ground cracks can result from one of several processes, including (1) aquifer compaction and associated ground subsidence resulting from ground-water withdrawal, (2) desiccation of fine-grained surficial deposits forming giant desiccation cracks, (3) hydrocompaction of alluvial-fan deposits due to flooding, and (4) ground-surface deformation due to active fault movement. Other possible

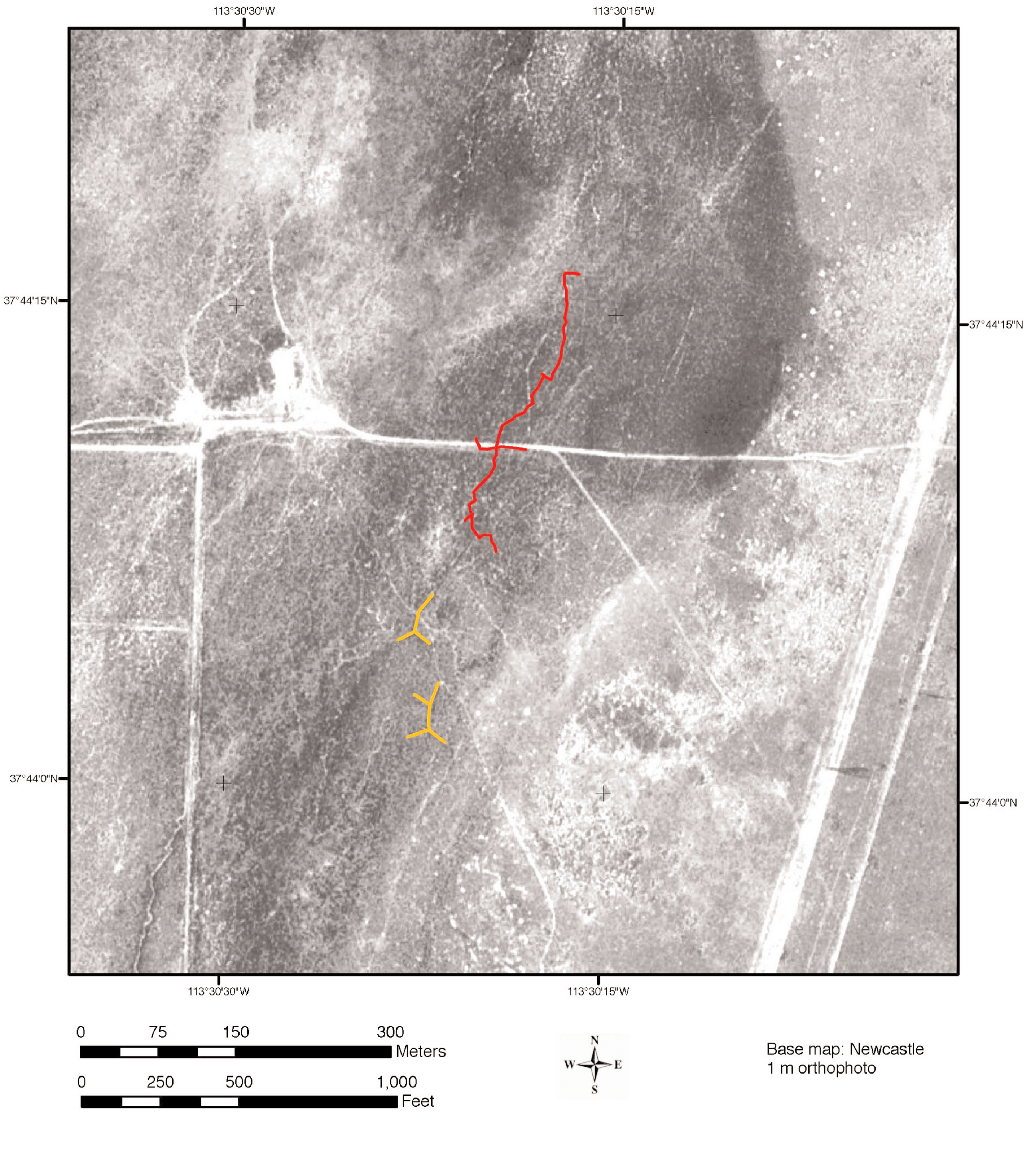

Figure 13. Map of ground cracks northeast of Newcastle. Red lines denote ground cracks investigated in field; orange lines are ground cracks inferred from 1 m aerial photography.

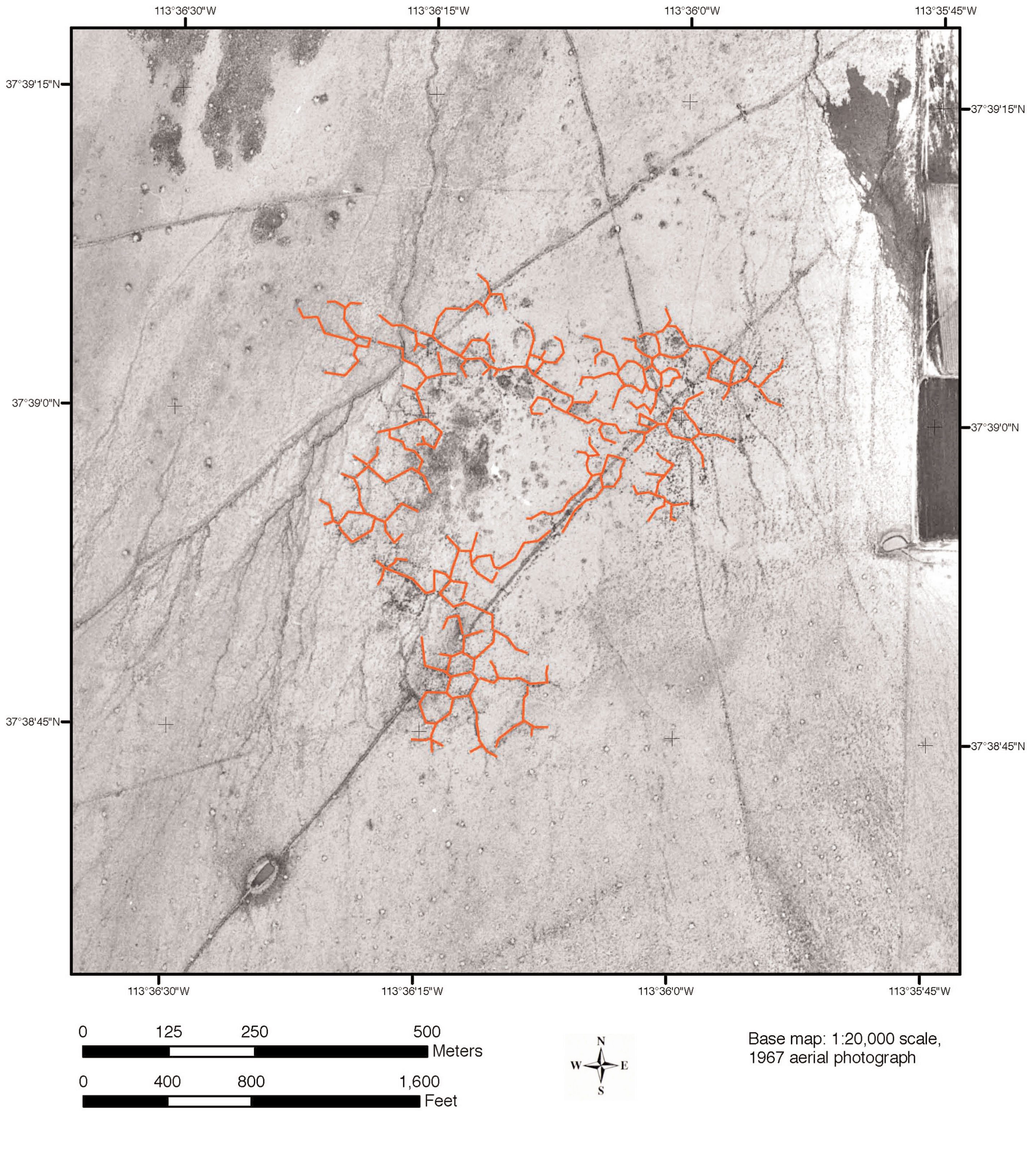

Figure 14. *Map of giant desiccation cracks southwest of Newcastle.*

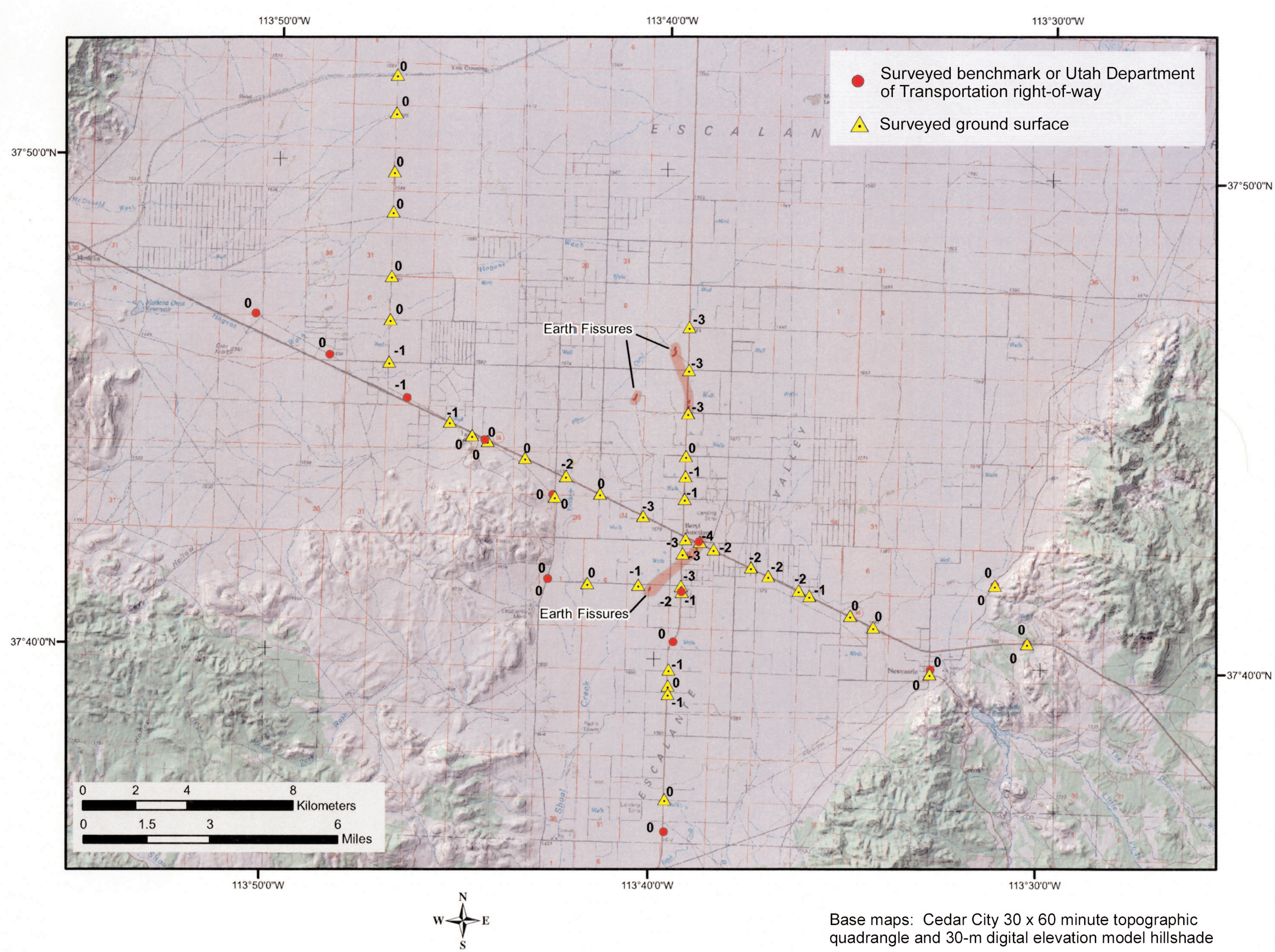

Figure 15. *GPS survey points with measured subsidence (feet) since initial surveys were performed (1941, 1955, and 1972).*

causes include the draining of organic soils, earthquake-induced liquefaction, sinkholes, and underground mining; however, we do not consider these to be viable explanations for the origin of earth fissures and ground cracks in Escalante Valley.

Compaction of the Escalante Valley Aquifer

Aquifer compaction is the irreversible consolidation of fine-grained, low-permeability aquifer units (aquitards) due to an increased load on the aquifer following ground-water withdrawal (Gelt, 1992; Galloway and others, 2004) (figure 16). Within the aquifer below the ground-water level, the pore-fluid pressure and aquifer skeleton (solid grains) balance the total weight of the overlying rocks and water. Following a significant drop in the ground-water level, the pore-fluid pressure in the aquifer decreases and the weight of the overlying material is transferred to the aquifer skeleton, causing consolidation (pore-space reduction) in the more compactible aquitard units (Galloway and others, 2004). Compaction within the aquifer is commonly expressed as permanent land subsidence, which may result in the development of long, linear, and deep tension cracks (earth fissures). Earth fissures form due to differential compaction of the aquifer across changes in sediment thickness or lithology. The fissures generally initiate at depth, propagate toward the ground surface with time, and are observed at the ground surface following precipitation or continued compaction due to ground-water withdrawal (Sheng and others, 2003). To reduce future aquifer compaction, increased recharge and/or decreased ground-water pumping is necessary; however, residual compaction (at a reduced rate) may occur for several decades after ground-water levels are stabilized or restored (Galloway and others, 2004). Subsidence due to aquifer compaction resulting from ground-water pumping has been recorded in five of the six states bordering Utah (Arizona, Nevada, Idaho, Colorado, and New Mexico), and in 19 different locations within California (Galloway and others, 2004).

Earth fissures related to aquifer compaction and land subsidence induced by ground-water pumping are often confused with cracks related to desiccation of shallow clay-rich sediment, as the cracks have similar morphologies when young (R.C. Harris, Arizona Geological Survey, verbal communication, 2005). However, we use several physical, geological, and hydrological lines of evidence to differentiate between the two crack types.

Earth fissures related to ground-water pumping have the following characteristics that set them apart from giant desiccation cracks (Galloway and others, 2004; R.C. Harris, Arizona Geological Survey, verbal communication, 2005):

1. Formation related to ground-water decline, aquifer compaction, and land subsidence, initiated by ground-water pumping.
2. Linear, continuous, deep-seated (tens of meters [hundreds of feet] deep) cracks, forming a zone of fissuring usually greater than 0.8 to 1.6 kilometers (0.5-1.0 mi) long.
3. Long life cycle, continually developing and eroding to form large cavernous cracks, as ground-water pumping continues.
4. Complex crack traces, often with branching and en echelon patterns.
5. May develop on any type of unconsolidated material.
6. Vertical displacement may develop across the fissures due to differential compaction of aquifer units across changes in aquifer thickness or lithology.

The following characteristics distinguish giant desiccation cracks from aquifer-compaction-related earth fissures (Harris, 2004; R.C. Harris, Arizona Geological Survey, verbal communication, 2005):

1. Formation related to dewatering of clay-rich sediment resulting from drought or ground-water pumping.
2. Linear cracks having intersections and forming extensive networks of polygons up to 180 meters (590 ft) across (Harris, 2004).
3. Short life cycle, generally not remaining active over a long period; however, the cracks may show cyclic periods of short-lived activity.
4. Limited depth of about 6 to 9 meters (20-30 ft), and generally are eroded to a depth of less than a meter.
5. Occur in shallow clay-rich deposits (minimum of 1.5-3.0 meters [5-10 ft] thick), commonly at local depressions at the toes of alluvial fans where sheet flooding intercepts and erodes the cracks.
6. No vertical displacement across the cracks.

Compaction of the Escalante Valley aquifer due to ground-water pumping provides a good explanation for the earth fissures near Beryl Junction. The locations of the Beryl Junction and Holt earth fissures coincide with an area of significant ground-water decline (greater than 95 feet [29 m]) in Escalante Valley since the late 1940s (figures 3 and 4). Ground-water decline decreases to the north, but is still significant (70-80 feet [21-24 m]) in the area of the gravel-pit, Bossardt, and Laub earth fissures. The geometry of the Beryl Junction, Holt, gravel-pit, Bossardt, and Laub earth fissures is consistent with an aquifer-compaction origin. The fissures are linear and long (length-to-width ratio up to 30:1), individually over 100 to 400 meters (330-1300 ft) long, and cumulatively form a north-trending zone of fissuring over 9 kilometers (5.6 mi) long. Although our field mapping documented branching and step-over patterns, the fissures do not form extensive polygons. The fissures' physical characteristics and the fact that they consumed large volumes of floodwater, which did not reappear, suggest deep-seated cracks that likely extend to the ground-water table. The fissures formed on several different kinds of surficial deposits at numerous locations, and floodwater eroded the fissures to several meters depth. Displacement across the Beryl Junction, Holt, and Bossardt earth fissures, although localized, is important as it indicates both tension and down-to-the-east movement across the fissures, typical of an aquifer-compaction origin for the fissure. Also, the coincidence of the area of ground-surface subsidence with the area of signifi-

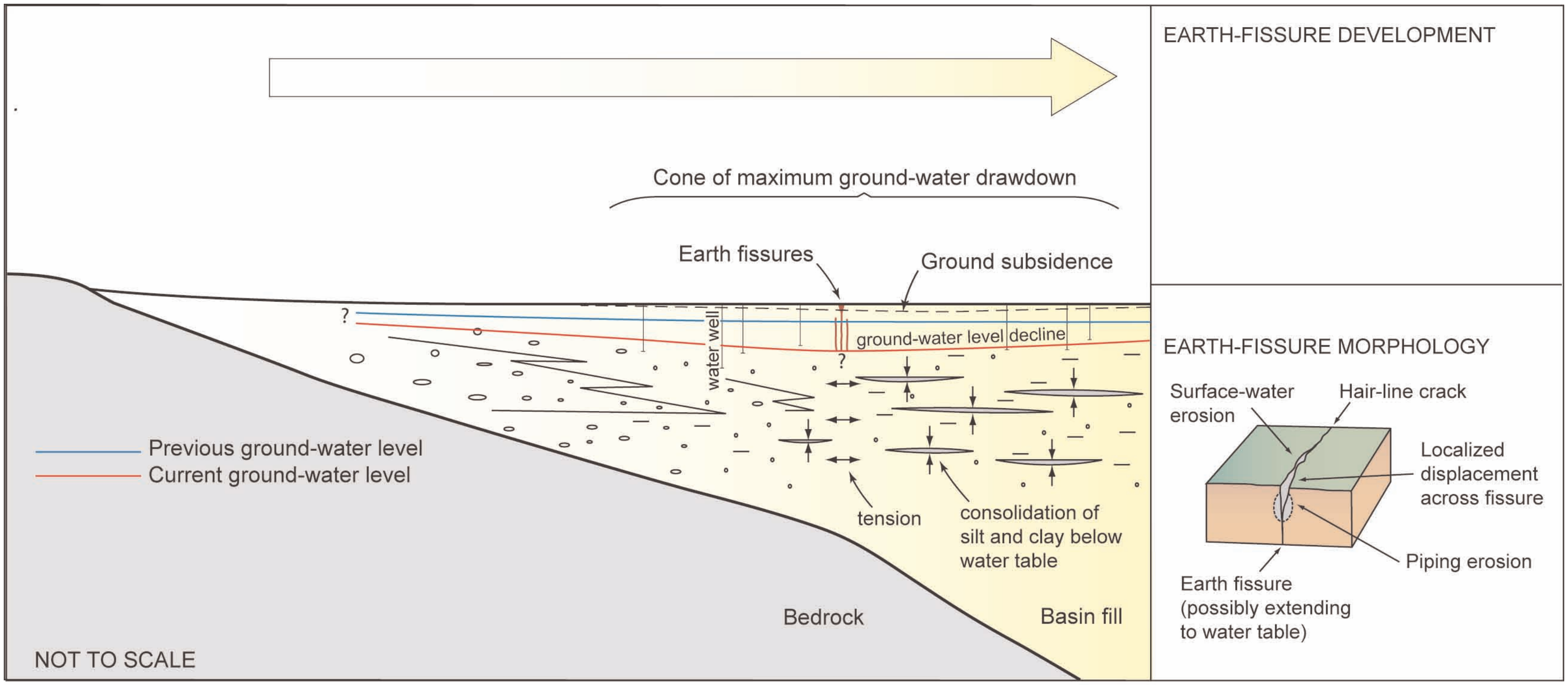

Figure 16. *Schematic representation of earth-fissure formation, illustrating (a) differential compaction of an aquifer as a possible cause for earth-fissure development, and (b) the morphology of earth fissures at the ground surface.*

cant ground-water-level decline supports the aquifer-compaction origin. The lack of subsidence in the area of maximum decline about 10 kilometers (6.2 mi) south-southwest of Beryl Junction is probably due to the coarser grained nature of the deposits in the area. The actual pattern of subsidence depends on both the amount of ground-water withdrawal and thickness of fine-grained basin fill.

Earth fissures form in response to horizontal tension that develops between parts of an aquifer that compact by different amounts following ground-water decline, for example, due to a lateral change in aquifer thickness or lithology (figure 16). The Escalante Valley earth fissures are aligned along the western edge of a large gravity low that defines a deep basin beneath Escalante Valley. The fissures are oriented subparallel to the gravity contours, which indicate an east-west increase in the gravity gradient and a relative shallowing of bedrock (and thinning of basin-fill alluvium) along the western flank of the basin. Thus, the Escalante Valley earth fissures may have formed due to the differential compaction of the Escalante Valley aquifer across the western margin of the basin. Differential compaction due to an east-west change in lithology may also have contributed to the earth-fissure development.

Desiccation of Escalante Valley Surficial Deposits

The dewatering of silt- and clay-rich surficial deposits creates tension in the deposits and produces polygonal desiccation cracks (i.e., mudcracks). The cracks are commonly a few to tens of centimeters in diameter but in some cases may be tens to hundreds of meters across (i.e., giant desiccation cracks; Harris, 2004). Formation of large desiccation cracks may result from both drought- and ground-water-pumping-related declines in ground-water levels. Giant desiccation cracks may develop due to pumping of shallow ground water, but are generally not influenced by ground-water decline once ground-water levels are more than 50 to 100 feet (15-30 m) below the ground surface (Harris, 2004).

Giant desiccation cracks have formed at several locations in Arizona (Harris, 2004), and are a possible explanation for ground cracks investigated near Parowan Gap, Utah (DuRoss and Kirby, 2004). Giant desiccation cracks and earth fissures related to ground-water pumping may occupy the same locality, although several lines of evidence can be used to differentiate between them (see previous section on compaction of the Escalante Valley aquifer). Although desiccation cracks may extend several meters below the surface, they are distinguished from earth fissures by their characteristic intersecting traces that often form multiple polygons. In addition, desiccation cracks are shallower and have shorter life cycles than ground-water-pumping-related earth fissures. Desiccation cracks also typically form in clay-rich deposits, often within localized depressions (Harris, 2004), whereas earth fissures may develop in any type of unconsolidated surficial deposit.

We do not consider the earth fissures in Escalante Valley to be giant desiccation cracks. Basin-fill deposits containing clay do exist locally (figure 5) and have been dewatered in the past 20 to 40 years due to ground-water decline; however the existing fissures are not limited to clay-rich deposits, but rather extend across silt-, sand- and pebble-gravel-rich alluvial, fluvial, and wind-blown deposits (Siders, 1985). In addition, the linearity and nonintersecting traces of the fissures, local displacement across the Beryl Junction, Holt, and Bossardt earth fissures, and both eroded and inferred subsurface depths indicate that desiccation is not the formative mechanism behind the Escalante Valley earth fissures. Also, the current ground-water level is greater than 100 feet (30 m) below the surface near Beryl Junction, likely too deep to produce giant desiccation cracks.

In contrast, the ground cracks northeast of Newcastle along the eastern margin of Escalante Valley are likely giant desiccation cracks. The crack traces are linear, segmented, intersecting, and continuous in a north-south direction (length-to-width ratio less than 4:1). In addition, the cracks are limited to clay-rich deposits within a local depression along Pinto Creek near the toes of alluvial fans derived from the Antelope Range. The varying physical properties of the cracks and landowner reports indicate cyclic behavior. In addition, the ground cracks exhibit no vertical displacement and have not evolved into large, continually eroding, linear crack systems. Rather, a network of subdued cracks generally less than a few centimeters deep has developed since the cracks were first noticed, possibly in the mid-1970s (Christenson, 1991). The initial drop in ground-water level due to pumping may have contributed to the formation of the ground cracks, as ground-water levels were relatively shallow (approximately 20 to 38 feet [6-11.5 m] during the late 1940s) prior to pumping. However, the current ground-water level (100-110 feet [30-33.5 m] during 2002) likely has no impact on the formation of the giant desiccation cracks due to its significant depth.

We consider the ground cracks southwest of Newcastle to be giant desiccation cracks. The crack traces form an extensive zone of 20- to 80-meter-wide (65-260 ft) polygons in a distal alluvial-fan environment, mapped as having fine-grained (silty clay loam) soil (Ulrich, 1960). The initial drop in ground-water level following significant withdrawal may have contributed to the formation of the ground cracks, due to a relatively shallow ground-water level (approximately 48-62 feet [15-19 m] during the late 1940s). However, the current ground-water level likely has no impact on the formation of the giant desiccation cracks due to its significant depth (133-143 feet [40.5-43.5 m] during 2002).

Hydrocompaction

Hydrocompaction occurs when near-surface deposits containing significant void space (e.g., alluvial-fan deposits or wind-blown dust and sand) are thoroughly wetted for the first time since deposition. The addition of water causes the material to compact and concentric cracks to form around areas of localized subsidence. We do not consider hydrocompaction a viable mechanism for the formation of the earth fissures near Beryl Junction, due to the linearity of the fissures, their semi-regional extent along the western margin of Escalante Valley, and their location in an area that is periodically wetted by flooding from Shoal Creek (Mower and Sandberg, 1982) and that has been extensively irrigated for decades. Hydrocompaction may also occur along the margin of playa deposits; however, no such deposits are recognized near Beryl Junction.

Surface Faulting

We do not consider movement on faults to be a plausible explanation for the earth fissures near Beryl Junction. Mapped faults bordering Escalante Valley include the range-bounding Antelope Range and Enterprise faults, both of which are normal faults having down-to-the-west displacement and a north to northeast orientation. The Enterprise fault, in the southernmost part of Escalante Valley, has a short, 8-kilometer-long (5 mi) surface trace, and has not been active since at least the mid-Holocene (>5,000 years), and more likely not since the middle to late Quaternary (<750,000 years) based on the age of the deposits the fault displaces (Black and others, 2003). The Antelope Range fault has a more continuous, 24-kilometer-long (15 mi) surface trace, but likewise has not been active since the middle to late Quaternary based on the age of the displaced geologic units. A north-south-trending, east-dipping fault, 5 kilometers (3.1 mi) west of the Antelope Range (Siders and others, 1990) may be related to the Antelope Range fault. The fault has a limited surface trace and shows no evidence for young (Holocene) displacement.

Based on the location, geometry, and estimated timing of most recent fault displacement, we do not consider movement along the Enterprise or Antelope Range faults to be a viable explanation for earth-fissure formation in Escalante Valley. The presence of concealed north- to northeast-trending faults near Beryl Junction cannot be precluded; however, if present, the faults could locally influence ground-water flow and aquifer compaction, but not directly cause earth-fissure formation in the absence of a large earthquake.

Catalogs of historical earthquakes indicate a scarcity of magnitude >4 earthquakes in Escalante Valley or the Escalante Desert. Only one earthquake of magnitude >4.5 has occurred in the Escalante Desert-Cedar City area since 1962. Earthquakes of magnitude <3 have occurred, but such small events are not associated with ground deformation, and generally can only be detected with sensitive instrumentation. Earthquakes of magnitude <3 to 6 may generate discernable seismic shaking; however, events of such magnitude typically do not result in surface faulting. Generally, an earthquake of magnitude >6.5 is necessary to produce a surface-fault rupture, and none have been reported historically in or near Escalante Valley. Only one such event has occurred in Utah during the historical record: the 1934 magnitude 6.5 Hansel Valley earthquake north of Great Salt Lake, which had a surface rupture of less than 22 kilometers (14 mi) (Black and others, 2003). Also, a magnitude ~6 earthquake occurred in 1902 near Pine Valley, around 32 kilometers (20 mi) southeast of Enterprise; seismic shaking was felt from St. George to Enterprise, but no surface faulting was reported.

SUMMARY

We investigated the origin and extent of earth fissures within Escalante Valley, in the southern part of the Escalante Desert, that were enlarged by infiltrating floodwater during the flood of January 8-12, 2005. The earth fissures form a north- to northeast-oriented zone, described separately from south to north as the Holt, Beryl Junction, gravel-pit, Bossardt, and Laub earth fissures. The fissures are long and continuous (individually over 100 to 400 meters [330-1300 ft] long), and are formed on several different unconsolidated surficial deposits chiefly dominated by silt, sand, and pebble gravel. At the ground surface, the earth fissures are typically expressed as hairline to centimeter-scale-wide cracks having several centimeters of localized down-to-the-east vertical displacement (BJ-2, appendix). In places, surface and subsurface ground-water flow (piping) has eroded the fissures, forming linearly aligned centimeter- to decimeter-scale depressions and piping holes up to 3 meters (10 ft) wide by 2 meters (6.6 ft) deep (BJ-4, appendix).

Ground-water pumping for agricultural purposes in Escalante Valley during the past half century has significantly lowered (70-100 feet [21-31 m]) the ground-water potentiometric surface, and produced a north-to-south gradient change near Beryl Junction. Although field investigations uncovered no visual evidence of subsidence at water wells in Escalante Valley, high-resolution GPS survey data indicate that several feet of ground subsidence has occurred in a zone centered around Beryl Junction since ground-water pumping began.

We consider aquifer compaction and land subsidence related to ground-water pumping to be the most likely explanation for the formation of the earth fissures and pattern of subsidence in Escalante Valley. The fissures have high length-to-width ratios, are continuous and deep seated, locally exhibit vertical displacement, occur on disparate geologic units, and coincide with an area of measured ground subsidence and significant ground-water decline near Beryl Junction. Although ground-water decline is also great south of Beryl Junction, the amount of subsidence is less because the relatively coarser geologic units there are less susceptible to consolidation and compaction. Thus, the earth fissures are likely tensional cracks that formed in response to aquifer compaction and land subsidence east of Beryl Junction, resulting from ground-water pumping.

We conclude that the ground cracks northeast and southwest of Newcastle along the eastern margin of Escalante Valley are related to the desiccation of clay-rich deposits, within local depressions near the toes of alluvial fans derived from the Antelope Range. Although ground-water pumping may have influenced the initial formation of the desiccation cracks, natural causes (e.g., drought) likely influence the continued development and cyclic nature of these features.

CONCLUSIONS AND RECOMMENDATIONS

Based on current evidence, we conclude that the most likely explanation for the formation of the earth fissures in Escalante Valley is ground-water pumping that has resulted in a permanent decline in ground-water levels. Dewatering of the upper portion of the basin-fill aquifer allowed the aquifer to compact, and the resulting subsidence of the ground surface over the western margin of the basin beneath Escalante Valley or lateral change in lithology created horizontal tension that caused the ground surface to crack.

To better understand the origin and possible future extent of additional fissuring we recommend the following:

- Application of satellite interferometry (InSAR) to quantify subsidence across the entire Escalante Valley combined with continued and expanded monitoring of subsidence using high-resolution GPS surveying.

- Further investigation of the geology and hydrogeology of Escalante Valley to determine the relation between earth-fissure formation and basin-fill stratigraphy, aquifer heterogeneity, and local and regional geology and structure.
- Completion of a thorough search for additional earth fissures and ground cracks using both ground and aerial surveying techniques; investigation of parallel surface lineaments in the area of earth-fissure development.
- Completion of a valley-wide analysis of well casing and wellhead deformation.
- Continued monitoring of existing and new earth fissures.
- Continued monitoring of ground-water-level declines and pumping rates in Escalante Valley.

A geologic investigation of the Escalante Valley earth fissures that includes excavating trenches across the cracks and drilling to determine soil types and ground-water levels would further assist in understanding the formation and evolution of the earth fissures.

ACKNOWLEDGMENTS

We thank James and Klayton Holt, Beth England, the Bossardt family, LaDel Lamb, Escalante Valley Water Users Assoc. and Brad Hewlett (Escalante Valley residents) for discussions and land access; and Ron Gardner (Iron County Deputy Sheriff) and Robert Twitchell (Iron County Road Department) for identifying earth-fissure and ground-crack locations. Thanks to Gary Christenson and Mike Lowe (Utah Geological Survey), and Boyd Clayton and Bill Schlothauer (Utah Division of Water Rights) for reviews of this manuscript. We also thank Jerry Olds (Utah Division of Water Rights) and Mike Suflita (Utah Division of Water Resources) for valuable comments on this work, and Raymond Harris (Arizona Geological Survey) for insights into giant-desiccation-crack and earth-fissure formation.

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APPENDIX

Photographs of Escalante Valley earth fissures

File Name	Description
BJ-1.jpg	South end of Beryl Junction earth fissure in an alfalfa field; note mechanical pencil for scale.
BJ-2.jpg	Down-to-the-east displacement across the Beryl Junction earth fissure.
BJ-3.jpg	Piping hole formed by floodwater on the Beryl Junction earth fissure in the alfalfa field.
BJ-4.jpg	Floodwater-enhanced Beryl Junction earth fissure immediately south of SR-56.
BJ-5.jpg	Floodwater-enhanced Beryl Junction earth fissure, showing down-to-the-east vertical displacement; view is to the north toward SR-56.
BJ-6.jpg	Beryl Junction earth fissure north of SR-56 in an area that did not flood.
BJ-7.jpg	Beryl Junction earth fissure crossing a dirt road north of SR-56.
BJ-8.jpg	North end of the Beryl Junction earth fissure.
H-1.jpg	South end of the Holt earth fissure adjacent to a cattle feedlot fence.
H-2.jpg	Repairs to the roadway where the Holt earth fissure crosses 500 West Street.
H-3.jpg	Piping hole formed by floodwater on the Holt earth fissure in an agricultural field; a feedlot employee reported see ing a vortex form in the floodwater above this hole.
H-4.jpg	Subparallel cracks along a portion of the Holt earth fissure.
H-5.jpg	North end of the Holt earth fissure.
GP-1.jpg	Southern gravel-pit earth fissure; view is to the north.
GP-2.jpg	Eroded crack and collapsed ground along the southern gravel-pit earth fissure; note hand-held GPS unit for scale.
GP-3.jpg	South end of the southern gravel-pit earth fissure. Note high-water mark of floodwater that filled the gravel pit in upper half of image.
GP-4.jpg	Centimeter-scale depressions and ground cracks along the southern gravel-pit earth fissure; note hand-held GPS unit for scale.
GP-5.jpg	Centimeter-scale depressions along the south end of the northern gravel-pit earth fissure.
GP-6.jpg	Erosion of north-facing embankment along the northern gravel-pit earth fissure.
GP-7.jpg	Centimeter-scale depressions and eroded embankment; north end of northern gravel-pit earth fissure.
GP-8.jpg	Centimeter-scale desiccation cracks and eroded north part of the northern gravel-pit earth fissure; note hand-held GPS unit for scale.
GP-9.jpg	Meter-scale desiccation cracks within the gravel pit.
BF-1.jpg	Floodwater-enhanced south part of the Bossardt earth fissure.
BF-2.jpg	Southern part of the Bossardt earth fissure.
BF-3.jpg	Large piping hole formed from infiltrating floodwater on the Bossardt earth fissure; note field notebook for scale.
BF-4.jpg	Centimeter-scale crack at the northern end of the Bossardt earth fissure; stake marks north end of fissure.
L-1.jpg	South end of the southern Laub earth fissure.
L-2.jpg	Southern Laub earth fissure where initially enlarged by floodwater.
L-3.jpg	Progressive enlargement of the southern Laub earth fissure by floodwater.
L-4.jpg	Southern Laub earth fissure crossing dirt track.
L-5.jpg	Large piping hole formed by floodwater on the southern Laub earth fissure.

L-6.jpg	North end of the southern Laub earth fissure.
L-7.jpg	Center of the northern Laub earth fissure; note hand-held GPS unit for scale.
L-8.jpg	North end of the northern Laub earth fissure; note hand-held GPS unit for scale.
GC-1.jpg	Ground cracks northeast of Newcastle, showing intersection of separate linear crack segments and centimeter-scale desiccation cracks; note hand-held GPS unit for scale.
GC-2.jpg	Ground cracks northeast of Newcastle, showing eroded depressions and cracks along dirt track; note hand-held GP unit for scale.
GC-3.jpg	Recent erosion of the ground cracks northeast of Newcastle due to surface water; note hand-held GPS unit for scale.