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PRELIMINARY GROUND SUBSIDENCE AND EARTH FISSURE EVALUATION REEMS ROAD CHANNEL AND BASIN MARICOPA COUNTY, ARIZONA

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Submitted to:

Flood Control District of Maricopa County
Phoenix, Arizona

Submitted by:

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Tempe, Arizona

Registered Professional Engineer (Civil)
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LAWRENCE A. HANSEN
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ARIZONA, U.S.A.

November 30, 2007

AMEC Job No. 7-117-001074
Contract FCD 2006C020
Work Assignment 1

November 30, 2007
AMEC Job No. 7-117-001074

Flood Control District of Maricopa County
2801 West Durango Street
Phoenix, Arizona 85009-6399

Attn: Bobbie Ohler, P.E.

Re: Preliminary Ground Subsidence and Earth Fissure Evaluation
Reems Road Channel and Basin
Contract FCD 2006C020
Work Assignment 1
Maricopa County, Arizona

Transmitted herewith is the final version of our report for the referenced project. This report presents the findings of a preliminary assessment of the potential impact of earth fissuring and ground subsidence on the future design and operation of the, Reems Road Channel and Basin.

Please feel free to contact the undersigned should you have any questions.

Respectfully submitted,

AMEC Earth & Environmental, Inc.

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EXECUTIVE SUMMARY

The investigation detailed in the following report was completed to evaluate the potential impact of earth fissuring and ground subsidence on the future design and operation of the Reems Road Channel and Basin (Project). The Project, as planned by the Flood Control District of Maricopa County (District), includes a channel and basin system for storm water conveyance along Reems Road between Peoria Avenue and Falcon Dunes Golf Course, a half mile north of Northern Avenue. The investigative approach included four basic components: 1) compilation and review of existing data; 2) acquisition and analysis of synthetic aperture radar interferometry; 3) analysis of project-specific high resolution aerial digital imagery; and 4) ground reconnaissance of the project site.

Available subsidence data indicates that the Reems Road Channel and Basin are located in an area that has seen significant subsidence due to groundwater withdrawal, with approximately 19 feet of subsidence occurring since the 1950s. No known earth fissures are present along the alignment of the proposed channel or basin and the closest documented earth fissure is located approximately 1 mile to the northeast and east. No new earth fissures were documented as part of this investigation. The proposed channel and basin are located in an area where subsidence has likely created compressional stresses in the ground; therefore, the formation of earth fissures in the past or future is unlikely.

The potential for future differential subsidence to affect future grades of the proposed channel does exist and may pose a risk for the proposed structures. Subsidence profiles indicate that past subsidence north of the proposed basin declines to the north. If future subsidence were to occur, it is anticipated that this trend would continue, indicating that grades along this portion of the proposed channel would likely be steepened by future subsidence. Subsidence profiles to the south of the proposed basin show that the magnitude of past subsidence declines south of Olive Avenue. If future subsidence were to occur in the project area, it is anticipated that this trend would also continue, indicating that grades along this portion of the proposed channel would likely be lessened by future subsidence.

The groundwater history of the study area indicates that in the past 30 years, groundwater levels have increased by 50 to 150 feet. As this has occurred, subsidence rates have significantly decreased from their maximum rates of at least 0.5 ft/yr between 1957 and 1992 to about 0.03 ft/yr from 1992 to 2007. If current groundwater trends extend into the future, it is anticipated that subsidence rates will continue to decline. If groundwater trends reverse and groundwater levels begin to fall in the future, it is anticipated that subsidence rates would increase, possibly significantly if groundwater withdrawal is equally significant.

It is recommended that the District monitor groundwater trends in the area of the proposed Reems Road Basin and Channel. It is also recommended that the District directly monitor subsidence trends through the use of periodic surveys of the channel and basin profiles, and the use of InSAR. Recommendations are provided for the conceptual design of a monitoring system and design considerations for the proposed channel.

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1.0 INTRODUCTION

The investigation detailed herein was completed to evaluate the potential impact of earth fissuring and ground subsidence on the future design and operation of the Reems Road Channel and Basin (Project). The Project, as planned by the Flood Control District of Maricopa County (District), includes a channel and basin system for storm water conveyance along Reems Road between Peoria Avenue and Falcon Dunes Golf Course, a half mile north of Northern Avenue. This location is an area of known ground subsidence due to past groundwater level declines resulting from agricultural and municipal groundwater pumping. This subsidence is also responsible for the formation of earth fissures located along the fringe of the Luke Salt Body, located approximately 1 mile east and northeast of the project area.

This report contains a detailed assessment of the potential impact of earth fissuring and ground subsidence on the future design and operation of the Project components. This investigation involved research, compilation, and interpretation of existing technical data, including aerial photography and satellite-based synthetic aperture radar interferometric (InSAR) data, and a limited ground reconnaissance of the project area.

This study was authorized by the District in August of 2007 under the terms and conditions of Contract FCD 2006C0020, with the scope defined as Work Assignment No. 1. This work was performed by AMEC Earth & Environmental, Inc. (AMEC) for the sole use of the District in evaluating ground subsidence and earth fissure risks for the Reems Road Channel and Basin. AMEC is not responsible for any peripheral use of this information, or of the interpretations presented herein, by parties other than the District.

2.0 PROJECT DESCRIPTION

The extent of the study area covered in this investigation is shown on Figure 1. The local project site is presented on Figure 2. This region is located on a broad alluvial basin to the east of the White Tanks Mountains. This surface appears to be comprised of distal alluvial fan surfaces coalescing towards the Agua Fria River to the east. The terrain gently slopes to the southeast, ranging in elevation from about 1400 to 1000 feet above MSL. The Project area is immediately surrounded by agricultural farmland. Numerous residential developments are present in the region and the area immediately west of the planned basin is currently being developed.

The Project consists of the construction of a channel along Reems Road and a basin located a quarter mile north of Olive Avenue, which will convey stormwater drainage for the 100-year event to the Falcon Dunes golf course/detention basin on the northeast corner of Reems Road and Northern Avenue. The Falcon Dunes golf course/detention basin drains into the Dysart Drain, which ultimately drains into the Agua Fria River. The earthen Reems Road channel will connect with an existing channel at Peoria Avenue and then convey flows southward along the west side of Reems Road for a mile and a half, where it will connect with the Falcon Dunes detention basin. The Reems Road basin will be located on the west side of Reems Road between Peoria Ave. and Olive Ave. The primary objective of this study is to evaluate the potential impact of earth fissuring and subsidence upon the future design and operation of the Project components.

3.0 INVESTIGATIVE APPROACH

The following discussion summarizes the investigative methods and data sets compiled for this evaluation. The approach includes four basic components: 1) compilation and review of existing data; 2) acquisition and analysis of synthetic aperture radar interferometry; 3) analysis of project-specific high resolution aerial digital imagery; and 4) ground reconnaissance of the project site.

3.1 Review of Existing Data

Existing data was compiled from a variety of sources, including published technical literature, regulatory agency databases, District files, and Maricopa County Department of Transportation (MCDOT) files. The published resources include regional geological and geohydrological studies from the U.S. Geological Survey, the Arizona Geological Survey, and the U.S. Bureau of Reclamation. The use of regulatory agency databases was restricted to Arizona Department of Water Resources (ADWR) well information, including both well construction reports for ADWR registered wells and historical water level data from the Groundwater Site Inventory (GWSI) data base. The District's library of reports was utilized to search for historical subsidence information concerning the local area, specifically the Dysart Drain project. Survey data for 1990 was extracted from the White Tanks/Agua Fria Area Drainage Master Study (WLB Group, 1992). Recent survey data, from 2003 for the project area, was obtained from the GDACS USPLSS Cadastral Corners spreadsheet available on the MCDOT Land Survey Section's website. The public records database at the MCDOT offices was searched for historical as-built drawings for roads near the project site, in order to obtain additional historical elevation information for the area.

To a large extent, the information described above has been compiled, digitized and presented in tabular form or in plan and profile. Relevant data is summarized in the following figures:

- Figure 3 – Surficial Geology
- Figure 4 – Gravity Data, Depth to Bedrock, and Depth to the Luke Salt Deposit
- Figure 5 – ADWR Well Locations
- Figure 6 – Water Level Data Trends
- Figures 7 through 11 – Subsidence Data for Reems Rd., Peoria Ave., Olive Ave., and Northern Ave.
- Appendix A – ADWR Well Report

3.2 Synthetic Aperture Radar Interferometry (InSAR)

The application of repeat-pass synthetic aperture radar interferometry (InSAR) to characterize the distribution and rate of ground subsidence in the study area is of profound significance in managing the risks associated with ground subsidence and earth fissuring. Interferometry has the capacity to detect and quantify minute changes in terrain elevation by comparing phase variances of satellite-based, side-looking radar data between orbits of a similar trajectory.

ADWR is currently applying InSAR as part of a long-range study of basin subsidence in Arizona. Recent interferograms developed by ADWR on the basis of 2000-2006 SAR data were compiled and analyzed for the project area. In addition, InSAR images previously provided by ADWR were also utilized. Five InSAR images, spanning the time from December 1996 to August 2006, are presented in Appendix B. InSAR data from 1996 to 2000 originated from the ERS-1 or ERS-2 satellites, and three interferograms are presented from this time period. An additional two interferograms from 2004 to 2006 are presented, with data from the RADARSAT or ENVISAT satellites.

InSAR is a highly processed product and represents an interpretive analysis of raw satellite data from no less than two individual data sets. It suffers from both atmospheric and terrain influences that affect the quality of the image. Procedures used in the processing of the data by ADWR reduce the impact of these atmospheric and terrain influences. The remaining constraint is decorrelation due to rapid changes in the ground surface. This phenomenon can be caused by plowing and crop changes in agricultural areas, or urban development. One complete color cycle (e.g., red to red or blue to blue) on the interferograms represents about 2.8 centimeters of elevation change between the two orbital observations. The initial pixel size is 30 meters, though processing can reduce this to 10 meters.

3.3 High Resolution Aerial Photography

High resolution color aerial photography of the entire project area was provided by the District. Aerial coverage was obtained on October 28, 2006, at a resolution of 0.32 feet. The imagery provided to AMEC had been exported as a high image quality portable document format (.PDF) file, and therefore the exact resolution of the analyzed imagery is unknown. The imagery was evaluated for the purpose of identifying features indicative of the presence of earth fissures. These features include elongated fissure gullies, alignments of potholes and other small depressions, lineations in the vegetative cover, and subtle linear ground features caused by shading. However, nearly all of the native features of the ground surface have been altered and obscured by agricultural use or residential construction. The analysis of the aerial photography yielded no features indicative of earth fissures.

3.4 Ground Reconnaissance

A ground reconnaissance site visit was performed to inspect the project alignment for subsidence or earth fissure-related features that would affect the integrity of the planned channel and basin. The farmland and graded dirt roads along the fields revealed no features indicative of earth fissures. There were no noticeable changes in grade along Reems Road, between Peoria Avenue and Northern Avenue. No earth fissures or features indicative of possible earth fissures were found at the project site.

4.0 GEOLOGICAL SETTING

4.1 Geologic Overview

The Reems Road Channel and Basin project site lies within the western portion of the Salt River Valley atop a broad, flat alluvial basin called the Luke Basin. As depicted on Figure 1, the region is bounded by the Agua Fria River to the east and the flanks of the White Tank Mountains to the west. The Western Salt River Valley (WSRV) is a typical component of the Sonoran region of the Basin and Range physiographic province. The Sonoran region contains many broad, deeply founded, alluvium-filled basins, separated by structural highlands composed of competent bedrock. The White Tank Mountains are one of these uplifted highlands, composed of both metamorphic and granitoid bedrock (Reynolds and others, 2002). The Luke sub-basin contains basin fill deposits of the Salt River Valley that can be subdivided into three units: Lower Alluvial Unit (LAU), Middle Fine-Grained Unit (MFGU) and Upper Alluvial Unit (UAU) (Prokopovich, 1983; BurRec, 1976).

As indicated by the depth to bedrock contours presented by Richard and others (2007), the Luke basin is deepest approximately 3 miles east-southeast of the south end of the Reems Road Channel. The prominent negative gravity feature shown by the Bouguer gravity data by Sweeney and Hill (2001) is in part an expression of a large salt body, containing some 15 cubic miles of halite (Eaton and others, 1972). The contours on Figure 3 showing the lateral extent and depth to the top of the Luke Salt Deposit (Rauzi, 2002) indicate that the salt body pinches out to zero near the project site. The salt body was likely formed in a non-marine environment in the center of a closed clastic sedimentary basin that was bounded by the active White Tank detachment fault along its west side (Spencer and Rauzi, 2005). The geophysical data developed by Peterson (1968) indicates that the salt may extend to a depth from 6,900 to 9,000 feet.

4.2 Regional Alluvial Stratigraphy

The Luke salt body is surrounded by unconsolidated and slightly indurated sediments composed of laterally discontinuous beds of clay, silt, sand, and gravel, with subordinate deposits of calcrete and evaporites (Stulik and Twenter, 1964). Stulik and Twenter (1964) further describe the WSRV basin fill as being of unknown maximum thickness, with 2,784 feet of sediments penetrated without reaching bedrock at a location some three miles south of the project site near Litchfield Park.

The characteristics of the WSRV basin fill and the distribution of fine-grained sediments with the basin were first evaluated by Stulik and Twenter (1964), based on well driller's logs of irrigation wells. This study revealed the presence of a predominantly fine-grained profile in several wells located near the project site, down to a datum of about 700 feet above MSL, or a depth of about 400 feet in the referenced area. Additional well logs across the Luke Basin are graphically depicted in U.S. Bureau of Reclamation (BurRec) studies for the Central Arizona Project (BurRec, 1976). These logs display the presence of fine-grained fill to depths up to 2000 feet.

As discussed by Prokopovich (1983) and the BurRec (1976), the basin fill deposits of the Salt River Valley are comprised of unconsolidated to weakly indurated sediments deposited on an irregular bedrock surface. From a geotechnical perspective, the upper basin sediments likely classify as stiff soils to soft rock, with the deep Tertiary deposits in the realm of soft to moderately indurated rock. The basin deposits are quite variable, ranging from fine-grained clay and silt deposits of lacustrine or playa origins, to coarse clastics derived from the adjacent upland. The BurRec (1976) appears to be the first to define the basin fill into three lithologic units, all of which are likely present in the alluvial profile of the regional study area. The following describes the characteristics of the three alluvial units, from oldest to youngest, largely as described by Laney and Hahn (1986) and the BurRec (1976):

- **Lower Alluvial Unit (LAU)** – These Middle to Late Tertiary deposits are in fault and erosional contact with the competent bedrock floor and buried flank of the basin, and are comprised of what is often referred to as conglomerate. The conglomerates are often interbedded with anhydrite, gypsiferous mudstone and basalt. The coarser fraction is often poorly sorted with faint bedding, consisting of sand- to cobble-sized particles in a silty to clayey matrix. Significant calcium carbonate content is common in the matrix, to the extent that the porosity of the unit is affected. The LAU may be absent where the bedrock is less than 400 feet from the surface. However, these units are not defined as time-stratigraphic divisions, and investigators commonly include the shallow, clastic deposits near the basin margins as part of the LAU. At the edges of the Luke basin, the BurRec (1976) indicates well intercepts of the LAU at depths of about 1,100 to 1,200 feet, but wells up to 2000 feet in the center of the basin did not reach the LAU.

- **Middle Fine-Grained Unit (MFGU)** – This unit is often restricted to the center of the alluvial basin of Central Arizona. Regionally, this lithology of the unit is described as intercalated playa, alluvial fan and fluvial deposits of silt, soft siltstone, and silty sand and gravel. Compared to the LAU, the MFGU likely contains a higher fraction of clay and silt, with a comparable concentration of calcium carbonate. Prokopovich (1983) notes that the MFGU contains clay and silt beds deposited in internally drained basins, resulting from damming due to tectonic movement and volcanism. The BurRec (1976) depicts a considerable thickness of the MFGU in the Luke basin, in the range of about 450 to more than 800 feet, with the top of the unit from about 700 feet deep to 1200 feet deep in the basin center.
- **Upper Alluvial Unit (UAU)** – The UAU is comprised of Late Tertiary and Quaternary clastic material, derived locally from the surrounding bedrock terrain and deposited as a mantle over the older basin fill deposits. In contrast to the MFGU, the UAU was deposited by an externally drained stream system. BurRec (1976) graphical logs of wells located in the Luke basin depict a thickness of UAU from 700 feet to 1200 feet deep in the basin center.

4.3 Surficial Geology

The local surficial geologic units (Figure 3) in the study area, as broadly described by Reynolds and Grubensky (1993), Reynolds and Skotnicki (1993), Field and Pearthree (1991) and Demsey (1988) are comprised of an assemblage of unconsolidated Quaternary alluvial fan deposits and stream deposits associated with the Agua Fria River system. Blissenback (1954) and Harvey (1992) describe alluvial fans as being composed of a complex assemblage of stream channel deposits, sheet flow deposits from larger floods (which cause avulsion of the small watercourses across the fan surface), and thick debris flow and/or mudflow deposits from large infrequent floods. The fans likely include a minor component of aeolian deposits. Alluvial terrace deposits associated with the Agua Fria River are found along the eastern margin of the study area. General descriptions of the surficial units found in the Project area are presented below and are taken from Field and Pearthree (1991), Reynolds and Grubensky (1993), and Eaton and others (1972):

- **Young Alluvium in Modern Stream Channels (Qyc)** – Deposits are dominated by clastic sediments of sand and gravel, with some cobbles and rare boulders. The age of unit Qyc is less than 3,000 years before present (ybp). Within the study area, this unit is limited to the active channels associated with the Agua Fria River drainage system.

- **Young Alluvium (Qy)** – Outside the active braided channels, this unit is locally comprised of a limited thickness of silty to clayey sand and sandy silt, overlain by a thin mantle of aeolian silty sand. Little soil development is present and Stage I carbonate cementation development is common in the lower sands, with the upper loess largely uncemented. Moderate to strong rubification (reddening) is common in this unit. Within the ephemeral channels, the upper aeolian deposits are absent, with larger amounts of gravel and cobbles present. Nearer the mountain front, the unit contains coarser sediments, including silt, sand and gravel mixtures. The age of unit Qy ranges from about 10,000 to >3,000 ybp. This unit is widespread throughout the project area.

- **Younger Middle Alluvium (Qm2)** – This unit is locally comprised of moderately cemented (Stage I to II) clayey to silty sands, occasionally interbedded with silty to sandy gravels. These deposits usually display poor soil development and some rubification. The age of unit Qm2 ranges from 10,000 to 150,000 ybp. Qm2 deposits are widespread throughout the study area, with the greatest concentrations occurring in the northwestern corner of the area.

- **Older Middle Alluvium (Qm1)** – This unit consists of a poorly sorted, angular to sub-angular mixture of silt, sand and gravel deposits. The surfaces are moderately dissected on the upper piedmont with 3 to 20 feet of relief above the active channels. Interfluvial areas are generally flat and expansive with poorly preserved bar and swale topography. Desert pavement is moderately to well developed and is found over 50 to 75 percent of the surface. Underlying soils are characterized by weakly developed argillic horizons with Stage II to III calcification. The age of unit Qm1 ranges from 300,000 to 1,000,000 ybp. Qm1 deposits are widespread throughout the study area, with the greatest concentrations occurring in the northwestern corner of the area.

- **Older Alluvium (Qo)** – Unit Qo is composed of early Pleistocene to late Pliocene alluvial fan deposits greater than 1,000,000 years in age. The unit generally consists of poorly sorted subangular gravels containing minor amounts of finer material, ranging in thickness from a thin veneer over bedrock pediments to tens of feet thick. The surfaces of unit Qo are deeply dissected up to 50 feet within interfluvial areas and have well-rounded ridges with intervening swales or ravines. Soils are generally eroded away, exposing remnants of Stage IV to VI petrocalcic horizons. Unit Qo is found as terrace deposits associated with the Agua Fria River.

- **Tertiary Alluvium (Tsy)** – This unit consists of Pliocene chiefly fluvial deposits. This unit is locally comprised of moderately cemented silt, sands, and gravels. A few low hills of Tsy deposits are located to the southeast of Luke Air Force Base, where the Luke Salt Deposit is the shallowest. These Tertiary age deposits are thought to be the result of doming of the salt body, which exhumes the older alluvial deposits.

5.0 HYDROGEOLOGICAL CONDITIONS

Groundwater in the basin fill deposits of the WSRV is a significant and highly exploited resource used for domestic, municipal, industrial, and agricultural purposes. As depicted in Figure 5, over 30 wells registered with the ADWR are present within the area directly adjacent to the Project. Within the regional study area, there are an additional 30 wells with historical water level data from the Groundwater Site Inventory (GWSI) data base. These wells range from small domestic installations of limited yield, to large irrigation wells capable of discharging several thousand gallons per minute.

Groundwater withdrawn from the basin deposits near the Project area largely originates from the UAU, with its thickness estimated by the BurRec (1976) to be locally about 800 to 1200 feet, and current groundwater levels at depths from approximately 400 to 500 feet. Figure 6 shows hydrographs for GWSI wells in the vicinity of the Project. Groundwater in the study area has declined significantly due to well withdrawals far exceeding recharge. This decline commenced in the 1940s as agricultural development began in earnest in the west valley. By the early 1980s groundwater levels had declined up to 350 feet in the region. Since the 1980s, local groundwater has recharged, and levels have increased about 50 to 150 feet.

6.0 GROUND SUBSIDENCE AND EARTH FISSURING DUE TO GROUNDWATER WITHDRAWAL

6.1 Overview of Subsidence Process

Ground subsidence due to groundwater withdrawal in alluvial basins in the Southwest is a process of differential compaction of deep sediments. Through geologic time, groundwater levels in the alluvial basin material were at or near the ground surface, or at elevations controlled by the rivers and drainage systems traversing the basins. Activities of man have changed and are continuing to affect groundwater levels in many of these basins. Damming of rivers in mountainous reaches of the upland watersheds has reduced available recharge. Groundwater pumping, primarily for agricultural, industrial and municipal use, has significantly impacted stored groundwater in many areas. In modern times, groundwater level declines of 100 feet to several hundred feet due to pumping have occurred in many basins in Arizona and throughout the Southwest.

Lowering the groundwater elevation in a column of alluvial basin material increases the effective stress. This change in effective stress is an increase in loading on the material column. If that column consists of granular materials, typically sands and gravels, compression of the material below the initial water level takes place rapidly. Until granular particle contact points are changed by compression, at least some of the compression can be recovered elastically if water levels rise and effective stress decreases. Compression that results from particle slipping or crushing will tend to have much less elastic rebound. If the material column contains a significant fraction of fine-grained materials, typically clays, consolidation of the material below the initial water level takes place slowly. The time frame of the consolidation is a function of the permeability of the material, where lower permeability increases consolidation time. Consolidation is further a function of the distance to higher permeability zones which can relieve the excess pore pressure by draining water from clay-rich materials. Greater distances to such permeable drainage zones increase consolidation time. Although consolidation increases can be modeled as an elastic phenomenon, rebound of the consolidation is typically not recoverable with a decrease in loading.

Soils are much less compressible when reloaded up to the preconsolidation pressure than when loaded above the preconsolidation pressure (Lambe and Whitman, 1969). In many basins, the ground surface has been higher (relative to the underlying bedrock) than at the present time due to erosion. The eroded alluvium preconsolidated the basin profile. Increases in effective stress less than the preconsolidation stress represented by the now eroded alluvium would result in minor subsidence. Once increases in effective stress due to a declining groundwater table exceed the preconsolidation stress, further subsidence will occur at a much greater rate, representing normal consolidation of the alluvial basin materials.

Where differential rates and magnitudes of subsidence occur over relatively short distances, horizontal strains can become sufficient to cause earth fissuring. Jachens and Holzer (1979, 1982) evaluated the threshold tensile strains for fissuring based on studies of the Eloy-Casa Grande area of central Arizona. These studies included precise leveling and geophysical surveys, and comparisons with other cases of fissuring due to groundwater withdrawal. Jachens and Holzer (1982) concluded that most fissuring occurred at horizontal tensile strains in the range of 0.02 to 0.06 percent. This compares with the threshold strains for cracking of compacted clays zones in dam embankments (or compacted clay liners) of about 0.1 to 0.3 percent (Leonards and Narain, 1963; Covarrubais, 1969).

6.2 Overview of Earth Fissure Development

The first recorded observance of earth fissuring in Arizona was in 1927 near the town of Picacho, well southeast of the study area (Leonard, 1929). Since that time, eleven subsiding Central Arizona regions within the Basin and Range province have been identified, all with suspected or verified earth fissures (Fellows, 1999; Poland 1981; Holzer and Davis, 1981). Subsequent benchmark studies were undertaken to evaluate the distribution and mechanisms of fissuring (Holzer, 1978 and 1980; Jachens and Holzer, 1979; Laney, Raymond and Winikkar, 1978; Larson and Péwé, 1986).

Earth fissures in areas of large groundwater decline in alluvial aquifers are likely associated with a process termed generalized differential compaction by Carpenter (1994). Three mechanisms are likely at play to ultimately form fissures, including bending of a plate above a horizontal discontinuity in compressibility (Lee and Shen, 1969), dislocation theory representing a tensile crack (Carpenter, 1994), and vertical propagation of tensile strain caused by draping of the alluvium over a horizontal discontinuity in compressibility (Haneberg, 1992). Due to these probable mechanisms, fissures commonly develop along the perimeter of subsiding basins, often in apparent association with buried or protruding bedrock highs, suspected mountain-front faults, or distinct facies changes in the alluvial section.

Fissures often first manifest at the surface as subtle hairline cracks, or as alignments of small potholes, modified by burrowing animals. Overland flow is then intercepted, and the surface manifestation of the fissure grows as piping and caving occur during runoff events.

6.3 Subsidence and Earth Fissuring History of Study Area

The Project area has undergone significant subsidence due to groundwater withdrawal since significant groundwater mining commenced in the West Salt River Valley. Figures 7 through 10 show a series of profiles showing known subsidence from 1957 to 2003. Figure 11 shows groundwater trends and subsidence at the corner of Reems Road and Peoria Avenue and the corner of Reems Road and Olive Avenue.

'Earth cracks' mapped to the southeast of Luke Air Force Base and east of Dysart Road above Glendale Avenue by Stulik and Twenter (1964) provided early documentation of earth fissuring in the project vicinity (Figure 3). By 1973, the US Army Corps of Engineers had documented an earth fissure in the vicinity of Cottonwood Lane and Olive Avenue that trended generally to the northeast (SHB, 1982) that was also documented by Schumann (1992). Vertical displacement in this fissure zone can be observed on the Olive Avenue road surface and in a lined irrigation canal on the south side of Olive Avenue just east of the interim Loop 303 highway (AMEC, 2007). Further to the west, the Fenne Knoll Fissure system near the south end of McMicken Dam was reported by SHB (1982). Earth fissures east of Dysart Road and north of Glendale Avenue continue to show measurable movement (AMEC, 2007).

In addition to earth fissures, early indications of subsidence in the area included collapsed well casings as reported in Eaton and others (1972). Existing ground line profiles for roadway improvements to Reems Road from Northern to Peoria Avenues in 1965 had elevation discrepancies from 1957 USGS topographic quadrangle map elevations of about 2 feet at Northern Ave to about 4 feet at Peoria Avenue (MCHD, 1965). By 1990, during survey work for the White Tanks/Agua Fria Area Drainage Master Study (WLB Group, 1992), subsidence in the project area had reached about 17 to 18 feet compared to the 1957 USGS elevations (Figures 7 through 11). Furthermore, the local area encompassing the project was identified to be at the center and maximum elevation drop of a major subsidence depression. The overall depression extends from the vicinity of the White Tank Mountains to the west, to the Luke Salt Body to the southeast, and to Surprise to the north.

The reversal of flow in the Dysart Drain, which caused flooding around Luke Air Force Base in 1992 (Schumann, 1992), was further confirmation of this subsidence depression, and earth fissures in the area mark regions of maximum horizontal strain along the depression margins. Earth fissures are not expected in the center of the subsidence depression where ground strains would tend to be in compression and not tensile in nature. Given the 2003 data from the MCDOT Land Survey Section, recent continued but much reduced subsidence has been documented through the subsidence depression region. Between about 1990 and 2003, only about 0.8 to 0.9 feet of additional subsidence has been documented across the project area. InSAR results to the southeast of the Project indicate a maximum subsidence rate of about 0.3 feet over a 3 year period from 1997 to 2000 (Appendix B).

The groundwater level and limited subsidence history around the project area is summarized in Figure 11. Between the 1940's to the 1980's, groundwater levels dropped about 250 feet, and a maximum of 17 to 18 feet of subsidence occurred between about 1957 and 1990. Since the late 1980's, the groundwater level has recovered about 50 to 70 feet while another 0.8 to 0.9 feet of subsidence has occurred. Apparent differential elevation changes quantified by InSAR interferometry results for 1997 to 2000 in the vicinity are consistent with this recent subsidence trend.

BurRec (1972) data for the basin includes an electric resistivity log for a deep well (B-03-01 32dda) in the project vicinity. Electrical resistivities measured in the well below a depth of about 400 feet were less than 10 ohm-meters. Low resistivities continue through the 2,000-foot depth of the well, and became very low in the middle alluvial unit interpreted to begin at a depth of about 1,200 feet. Both the low resistivities and the apparent time-delayed consolidation of basin materials, as indicated by repeat survey and InSAR interferometry, resulting in continued but reduced subsidence are consistent with clay-rich basin materials underlying the project site.

In contrast, the considerably reduced subsidence at the western edge of the basin is consistent with a much shallower low resistivity profile at a deep well near Glendale Avenue and Cotton Lane (B-03-02 34bbb). There the lower alluvial unit, logged as conglomerate, begins at a depth of about 1,100 feet, the initial pre-development groundwater level was deeper, and the historic water level decline was less than at the project site. Similarly, older, much less compressible alluvium to the southeast of the project site was probably uplifted by the action of doming in the Luke Salt Body, so that groundwater declines in that area have not resulted in significant subsidence.

7.0 DISCUSSION

Available subsidence data indicates that the Reems Road Channel and Basin are located in an area that has seen significant subsidence due to groundwater withdrawal. No known earth fissures are present along the alignment of the proposed channel or basin and the closest documented earth fissure is located approximately 1 mile to the northeast and east. No new earth fissures were documented as part of this investigation. The proposed channel and basin are located in an area where subsidence has likely created compressional stresses in the ground, therefore, the formation of earth fissures in the past or future is unlikely.

The potential for future differential subsidence to affect future grades of the proposed channel does exist and may pose a risk for the proposed structures. Subsidence profiles (Figures 7 through 10) indicate that past subsidence north of the proposed basin declines to the north. If future subsidence were to occur, it is anticipated that this trend would continue, indicating that grades along this portion of the proposed channel would likely be steepened by future subsidence.

Subsidence profiles (Figures 7 through 10) to the south of the proposed basin show that past subsidence declines to the south of Olive Avenue. If future subsidence were to occur, it is anticipated that this trend would also continue, indicating that grades along this portion of the proposed channel would likely be lessened by future subsidence. The planned basin drains to the south along this segment of the channel. If future subsidence were to occur, it could impact the ability of the basin to drain as designed. It is unlikely that future subsidence would impact the capacity of the basin itself; however increased grade in an unlined channel above could increase the sediment load reaching the basin.

The occurrence of subsidence is intimately connected to groundwater withdrawal. The groundwater history of the study area (Figures 6 and 11) indicates that in the past 30 years, groundwater levels have increased by 50 to 150 feet. As this has occurred, subsidence rates have significantly decreased from their maximum rates of at least 0.5 ft/yr between 1957 and 1992 to about 0.03 ft/yr from 1992 to 2007. Since 1992, about 0.5 feet of subsidence has been observed. If current groundwater trends extend into the future, in is anticipated that subsidence rates will continue to decline. If groundwater trends reverse and groundwater levels begin to fall in the future, it is anticipated that subsidence rates would increase, possibly significantly if groundwater withdrawal is equally significant.

InSAR results in the study area were variable due to significant decorrelation from agricultural activity. Useful data in the vicinity of Luke Air Force Base was utilized for general subsidence trends. As agricultural land in the study area is converted to residential or other municipal uses, decorrelation is decreasing with time. The most recent scene dated from July 2005 to August 2006 provides some useful date near the north end of Project and it is anticipated that future development will reduce decorrelation.

8.0 RECOMMENDATIONS

It is recommended that the District monitor groundwater trends of key wells in the area of the proposed Reems Road Basin and Channel for a radius extending five miles from the proposed basin location. The groundwater monitoring can be achieved through the use of on-line resources provided by ADWR. Well B-03-01 29BCC (Figure 5) is located in the vicinity of the planned basin and the District should develop and evaluate groundwater trends annually for the life of the project as well as other wells within the 5-mile radius.

In addition to monitoring groundwater elevations, it is recommended that the District directly monitor subsidence trends through the use of periodic surveys of the channel and basin profiles, and the use of InSAR. As discussed in Section 7.0, it is anticipated that as development in the study area continues decorrelation issues with the InSAR data will be reduced.

Subsidence monitoring through surveying techniques can be achieved through the use of dedicated Global Positioning System (GPS) monuments installed at half-mile centers along the profile of the channel and basin. The GPS monuments should be designed to be permanent and vandal-resistant. Initially, a baseline for the data should be established by monitoring annually for three years. After the initial baseline is established the frequency of monitoring can be adjusted to best match the data trends.

Consideration of ability of the planned channel to accommodate future subsidence should be given. Generally, earthen channels are more easily adjusted in the event that the channel grade changes due to subsidence, though drop structures could be added as needed for a lined channel. If channel grade is increased, the resulting increase in flow velocity may indicate that a lined channel will function better. In areas where channel grade could decrease, consideration of additional freeboard should be given to accommodate any reduction in capacity of the channel and the ability of the basin to drain.

9.0 REFERENCES

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FIGURES

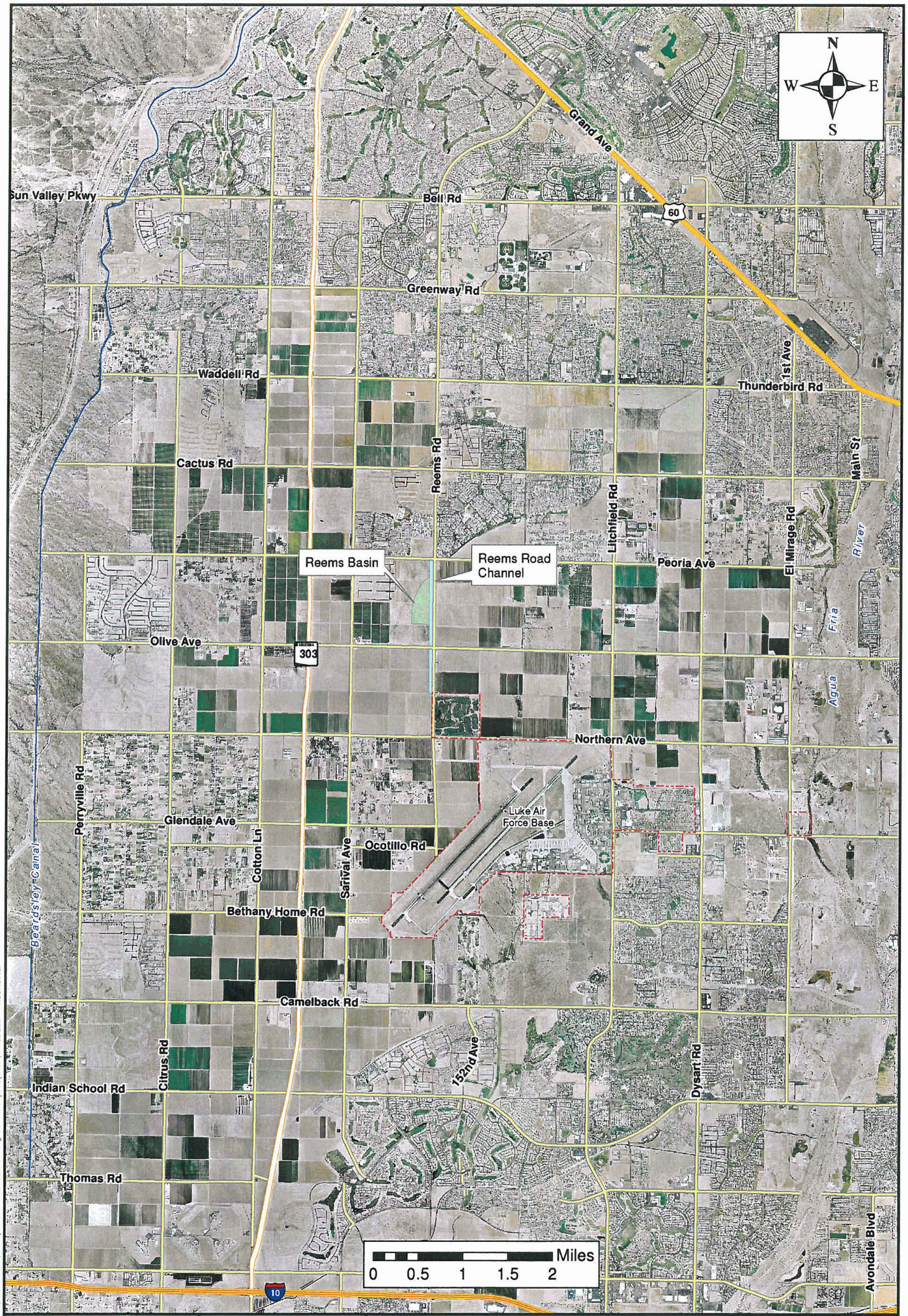

Image source: Air Photo USA June, 2006	JOB NO.: 7-117-001074 DESIGN: KED DRAWN: PWB DATE: 10/9/2007 SCALE: 1" = 1 mile	**Preliminary Ground Subsidence and Earth Fissure Evaluation** **Flood Control District of Maricopa County** **Reems Road Channel and Basin** **Contract FCD 2006C020, Work Assignment No. 2** VICINITY MAP FIGURE 1	amec

Map Document: (X:\Projects\7-117-001074\MXD\Figure 2 Project Location_Map.mxd) 10/9/2007 -- 3:50:26 PM

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Preliminary Ground Subsidence and Earth Fissure Evaluation
Flood Control District of Maricopa County
Reems Road Channel and Basin
Contract FCD 2006C020, Work Assignment No. 2

Project
Location

FIGURE
2

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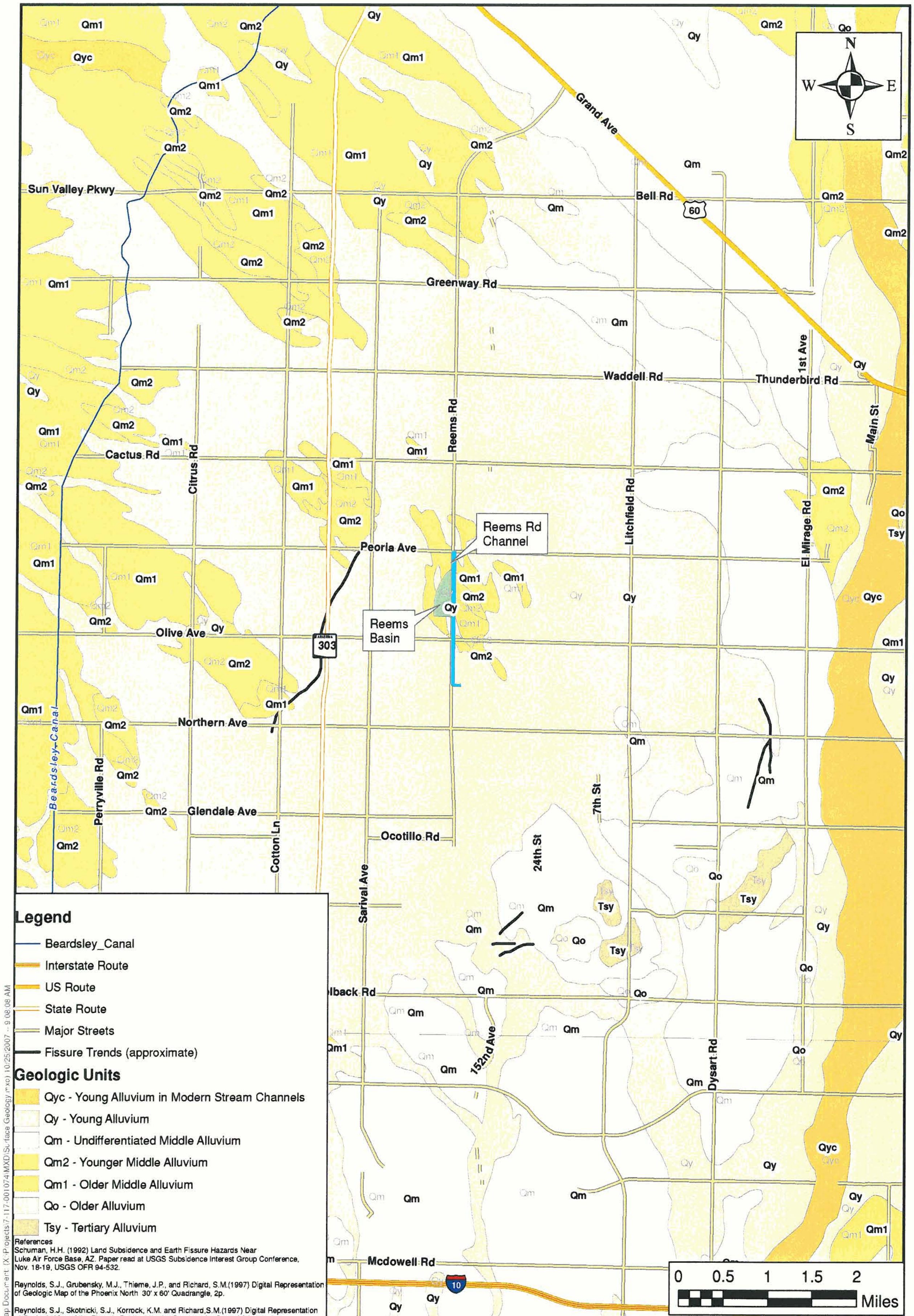

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Preliminary Ground Subsidence and Earth Fissure Evaluation
Flood Control District of Maricopa County
Reems Road Channel and Basin
Contract FCD 2006C020, Work Assignment No. 2

SURFICIAL GEOLOGY

FIGURE 3

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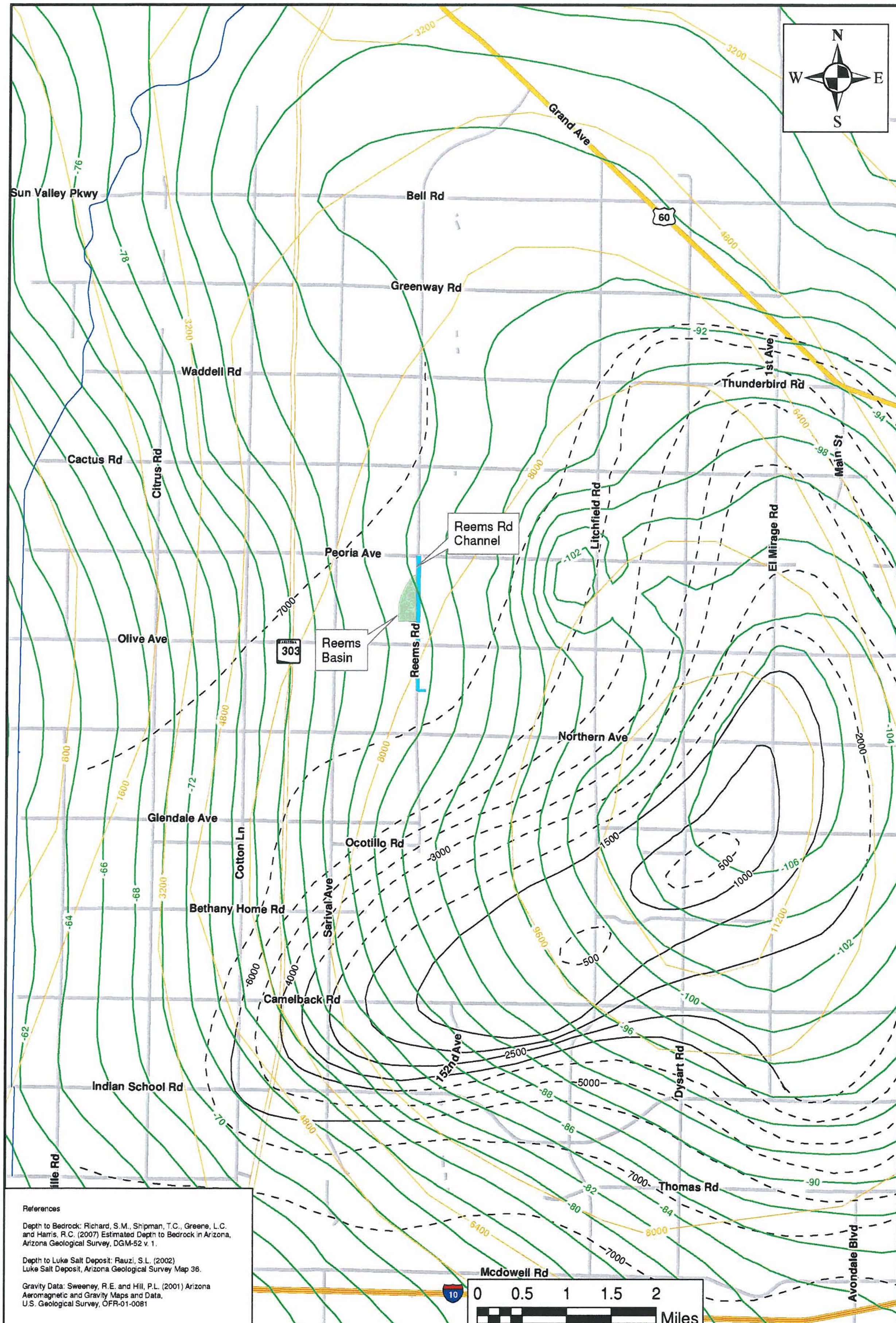

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Depth to Luke Salt Deposit: Rauzi, S.L. (2002) Luke Salt Deposit, Arizona Geological Survey Map 36.

Gravity Data: Sweeney, R.E. and Hill, P.L. (2001) Arizona Aeromagnetic and Gravity Maps and Data, U.S. Geological Survey, OFR-01-0081

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Legend

- Beardsley_Canal
- Depth to Bedrock (feet)
- Bouguer Gravity Contours (milligals)

Depth to Luke Salt Deposit (feet)

- Approximate
- Actual

JOB NO.:	7-117-001074
DESIGN:	KED
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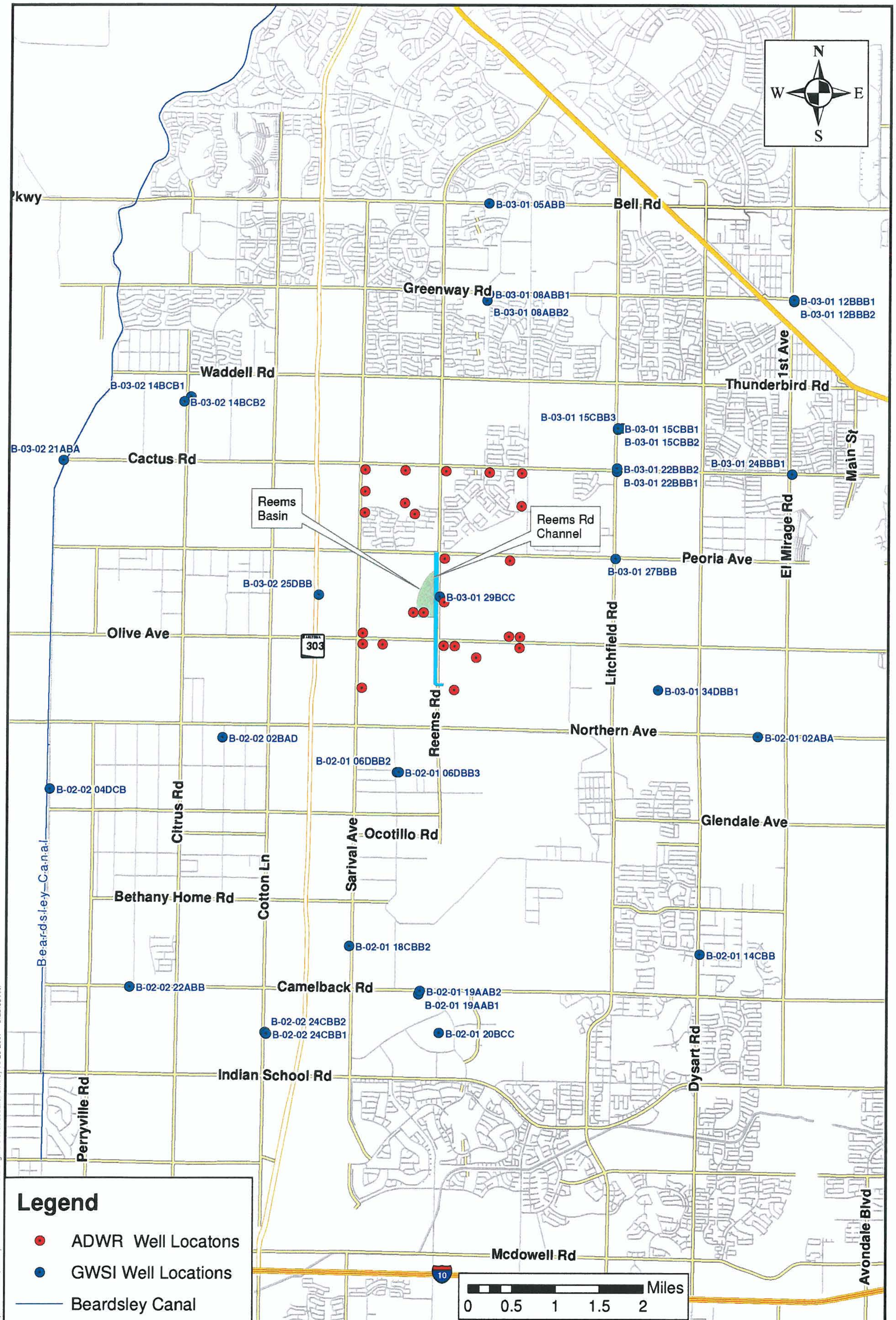
DATE:	10/19/2007
SCALE:	1" = 1 mile

Preliminary Ground Subsidence and Earth Fissure Evaluation
Flood Control District of Maricopa County
Reems Road Channel and Basin
Contract FCD 2006C020, Work Assignment No. 2

Gravity Data, Depth to Bedrock, and Depth to Luke Salt Deposit

FIGURE 4

amec



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Preliminary Ground Subsidence and Earth Fissure Evaluation
Flood Control District of Maricopa County
Reems Road Channel and Basin
Contract FCD 2006C020, Work Assignment No. 2

ADWR Well Locations

FIGURE 5

amec

APPENDIX A

ADWR WELL REPORT

ADWR Well Report

ID #	PROG.	COUNTY	LOCATION	160	40	10	WELLTYPE	WELLUSE	WATERUSE	INSTALLED	WELL DEPTH	WATER LEVEL	OWNER
086408	55	MARICOPA	T 3 N R 1 W S 20	NW	NW	NW	NON-EXEMPT	WATER PRODUCTION	IRRIGATION	3/17/1981	1,239	0	CHARLES INVESTMENT LLC JESSIE INVESTMENT LLC GILBERT AZ 85234
200469	55	MARICOPA	T 3 N R 1 W S 19	SE	NW	NE	GEOTECHNICAL	GEOTECHNICAL	TEST		0	0	LENNAR COMMUNITIES DEVELO 2702 N 44TH ST STE 100A PHOENIX AZ 85008
201563	55	MARICOPA	T 3 N R 1 W S 29	SE	SE	SE	CATHODIC	CATHODIC	TEST		450	0	AMERIGAS 14702 W OLIVE WADDELL AZ 85355
211805	55	MARICOPA	T 3 N R 1 W S 31	NW	NE	NW	WITHDRAWAL PERMIT	WATER PRODUCTION	TEST		0	0	WOOLF FARMS, LLC 426 NORTH 44TH STREET, SUITE PHOENIX AZ 85008
212491	55	MARICOPA	T 3 N R 1 W S 19	NW	SW	NW	WITHDRAWAL PERMIT	WATER PRODUCTION	TEST		0	0	COURTLAND HOMES, INC. 5333 N 7TH STREET STE 305 PHOENIX AZ 85014
400419	55	MARICOPA	T 3 N R 1 W S 20	NE	NE	NE	EXEMPT				0	0	R G 2223, INC 6730 N SCOTTSDALE RD #230 SCOTTSDALE AZ 85253
400495	55	MARICOPA	T 3 N R 1 W S 20	NW	NW	NW	EXEMPT	ABANDONED	DOMESTIC		0	0	R.G. 2223 INC 6730 N SCOTTSDALE RD #230 SCOTTSDALE AZ 85253
481755	55	MARICOPA	T 3 N R 1 W S 19	NE	SW	SW	EXEMPT	ABANDONED	DOMESTIC		0	0	LENNAR COMMUNITIES DEVELO 1150 W GROVE PARKWAY #209 TEMPE AZ 85283
481950	55	MARICOPA	T 3 N R 1 W S 19	NE	SW	SW	NON-EXEMPT	ABANDONED	IRRIGATION		0	0	LENNAR COMMUNITIES 1150 W GROVE PARKWAY STE 1 TEMPE AZ 85283
584309	55	MARICOPA	T 3 N R 1 W S 30	SE	NE	SW	GEOTECHNICAL	GEOTECHNICAL	NONE	12/6/2000	1,500	475	THE LONDON GROUP 4343 E CAMELBACK PHOENIX AZ 85018
589039	55	MARICOPA	T 3 N R 1 W S 30	SE	NW	SE	NON-SERVICE	WATER PRODUCTION	DOMESTIC		0	0	ROSE GARDEN ESTATES, LLC 4343 E. CAMELBACK PHOENIX AZ 85018
593638	55	MARICOPA	T 3 N R 1 W S 20	NE	SE	SE	NON-SERVICE	WATER PRODUCTION	MUNICIPAL	12/31/2002	1,517	0	CITY OF SURPRISE WATER SE 12425 W BELL ROAD STE D100 SURPRISE AZ 85374
601885	55	MARICOPA	T 3 N R 1 W S 19	NE	NW	NW	NON-EXEMPT	ABANDONED	IRRIGATION	1/24/1978	1,595	500	COURTLAND HOMES, INC. 5333 N 7TH STREET STE 305 PHOENIX AZ 85014

ADWR Well Report

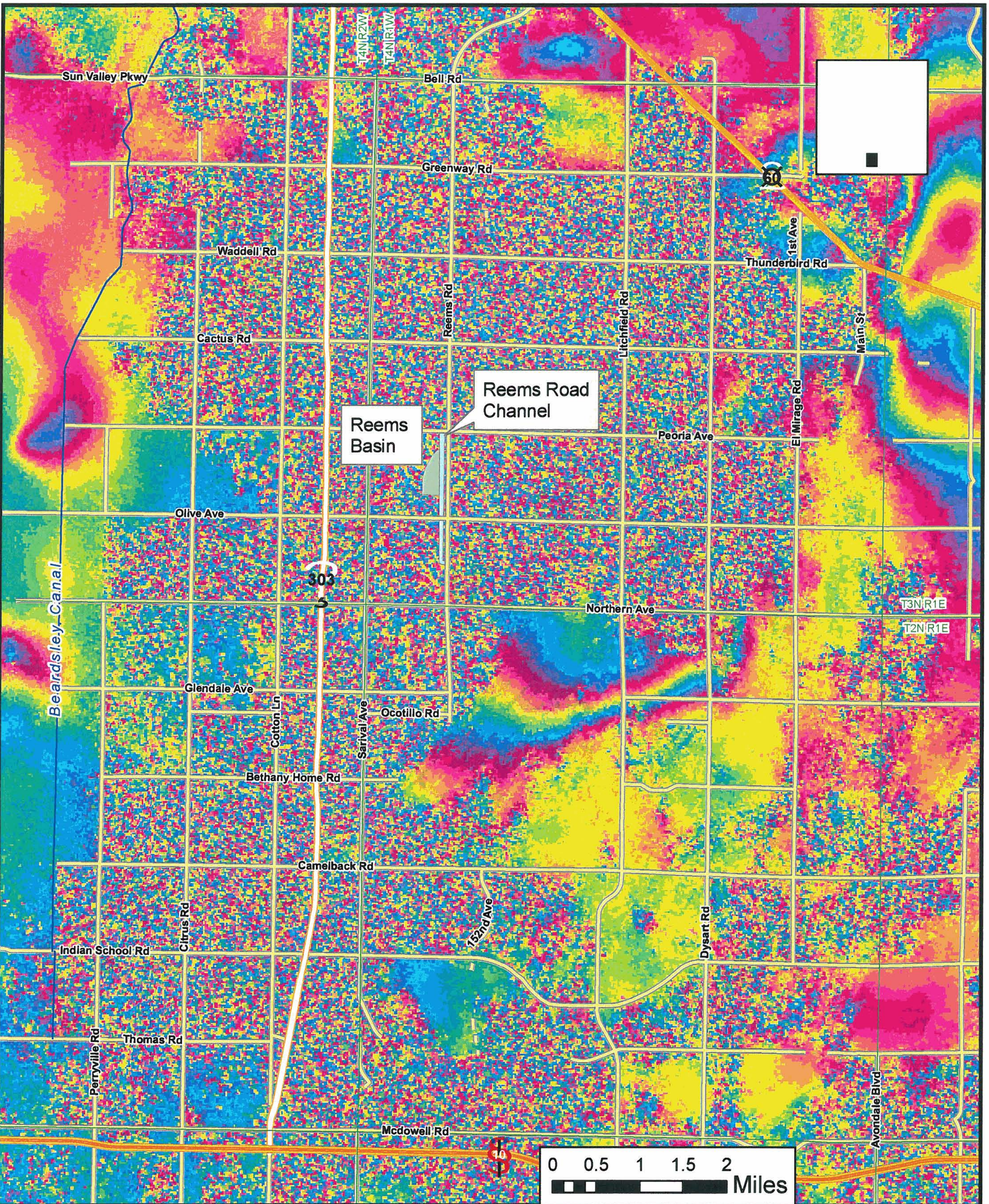
ID #	PROG.	COUNTY	LOCATION	160	40	10	WELLTYPE	WELLUSE	WATERUSE	INSTALLED	WELL DEPTH	WATER LEVEL	OWNER
601886	55	MARICOPA	T 3 N R 1 W S 19	NE	NW	NW	NON-EXEMPT	WATER PRODUCTION	IRRIGATION	1/1/1946	943	475	ARANDA PROPERTIES INC 7201 EAST CAMELBACK RD STE SCOTTSDALE AZ 85251
601887	55	MARICOPA	T 3 N R 1 W S 19	SW	NW	NW	NON-EXEMPT	ABANDONED	IRRIGATION	8/14/1977	1,100	550	LENNAR COMMUNITIES DEVELO 1150 W GROVE PARKWAY #209 TEMPE AZ 85283
601888	55	MARICOPA	T 3 N R 1 W S 19	NW	NW	NW	NON-EXEMPT	WATER PRODUCTION	IRRIGATION	1/14/1946	592	520	COURTLAND HOMES, INC. 5333 N 7TH STREET STE 305 PHOENIX AZ 85014
601889	55	MARICOPA	T 3 N R 1 W S 32	SW	NW	NE	NON-EXEMPT	WATER PRODUCTION	IRRIGATION	7/8/1977	1,100	475	FLOOD CONTROL DISTRICT OF 2801 W DURANGO AVE PHOENIX AZ 85009
606610	55	MARICOPA	T 3 N R 1 W S 30	SW	SW	SW	NON-EXEMPT	WATER PRODUCTION	DOMESTIC	4/1/1950	705	450	PROPERTY RESERVE ARIZONA 50 E NORTH TEMPLE SALT LAKE CITY UT 84150
607537	55	MARICOPA	T 3 N R 1 W S 20	NE	NW	NW	NON-EXEMPT	ABANDONED	IRRIGATION	1/1/1938	1,200	535	R G 2223, INC 6730 N SCOTTSDALE RD #230 SCOTTSDALE AZ 85253
608545	55	MARICOPA	T 3 N R 1 W S 32	NW	NE	SE	NON-EXEMPT	WATER PRODUCTION	IRRIGATION	5/3/1980	1,210	450	WOOLF,L 401 E BIRD LANE LITCHFIELD PARK AZ 85340
608546	55	MARICOPA	T 3 N R 1 W S 32	NW	NW	NE	EXEMPT	WATER PRODUCTION	DOMESTIC		1,050	500	WOOLF,L 401 E BIRD LANE LITCHFIELD PARK AZ 85340
608547	55	MARICOPA	T 3 N R 1 W S 20	NW	NW	NW	EXEMPT	ABANDONED	DOMESTIC	1/1/1963	2,051	485	R.G. 2223 INC 6730 N SCOTTSDALE RD #230 SCOTTSDALE AZ 85253
610102	55	MARICOPA	T 3 N R 1 W S 29	SW	NW	NW	NON-EXEMPT	WATER PRODUCTION	IRRIGATION	1/1/1961	1,400	430	WOOLF BROTHERS, 301 E FOREST HILLS PHOENIX AZ 85022
610103	55	MARICOPA	T 3 N R 1 W S 29	NW	NW	NW	NON-EXEMPT	WATER PRODUCTION	IRRIGATION	1/1/1944	1,200	430	WOOLF BROTHERS, 301 E FOREST HILLS PHOENIX AZ 85022
610104	55	MARICOPA	T 3 N R 1 W S 29	SE	SE	SW	NON-EXEMPT	WATER PRODUCTION	IRRIGATION	4/1/1974	1,350	430	WOOLF BROTHERS, 301 E FOREST HILLS PHOENIX AZ 85022
610105	55	MARICOPA	T 3 N R 1 W S 32	NE	NE	NE	NON-EXEMPT	WATER PRODUCTION	IRRIGATION	5/1/1978	1,320	430	WOOLF,L 401 E BIRD LN LITCHFIELD PARK AZ 85340

ADWR Well Report

ID #	PROG.	COUNTY	LOCATION	160	40	10	WELLTYPE	WELLUSE	WATERUSE	INSTALLED	WELL DEPTH	WATER LEVEL	OWNER
610106	55	MARICOPA	T 3 N R 1 W S 32	NW	NE	SE	NON-EXEMPT	WATER PRODUCTION	IRRIGATION	5/1/1979	1,400	435	WOOLF,L 401 E BIRD LANE LITCHFIELD PARK AZ 85340
610107	55	MARICOPA	T 3 N R 1 W S 32	NW	NW	NW	NON-EXEMPT	WATER PRODUCTION	IRRIGATION	1/1/1963	1,200	440	WOOLF,L 401 E BIRD LN LITCHFIELD AZ 85340
610108	55	MARICOPA	T 3 N R 1 W S 31	NW	NW	NW	NON-EXEMPT	WATER PRODUCTION	IRRIGATION	1/1/1963	1,500	440	WOOLF LIVING TR, THE, 8805 N REEMS RD WADDELL AZ 85355
610109	55	MARICOPA	T 3 N R 1 W S 31	SW	NW	NW	NON-EXEMPT	WATER PRODUCTION	IRRIGATION	4/1/1975	1,400	435	WOOLF LIVING TR, THE, 8805 N REEMS RD WADDELL AZ 85335
626943	55	MARICOPA	T 3 N R 1 W S 29	NE	NE	NW	NON-EXEMPT	WATER PRODUCTION	IRRIGATION	3/1/1948	927	545	JUSTICE BROTHERS, RT 1 BOX 662 PEORIA AZ 85345
801047	55	MARICOPA	T 3 N R 1 W S 29	SE	SE	SE	NON-EXEMPT	WATER PRODUCTION	INDUSTRIAL	5/17/1976	780	519	WOOLF BROTHERS, 401 E BIRD LANE LIRCHFIELD PARK AZ 85340

APPENDIX B

InSAR



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Data Source:
Repeat-Pass Synthetic Aperture Radar Interferogram
December 30, 1996 to December 20, 1999.
One color cycle represents ~ 2.8 cm of vertical elevation change.

Produced by:
Arizona Department of Water Resources

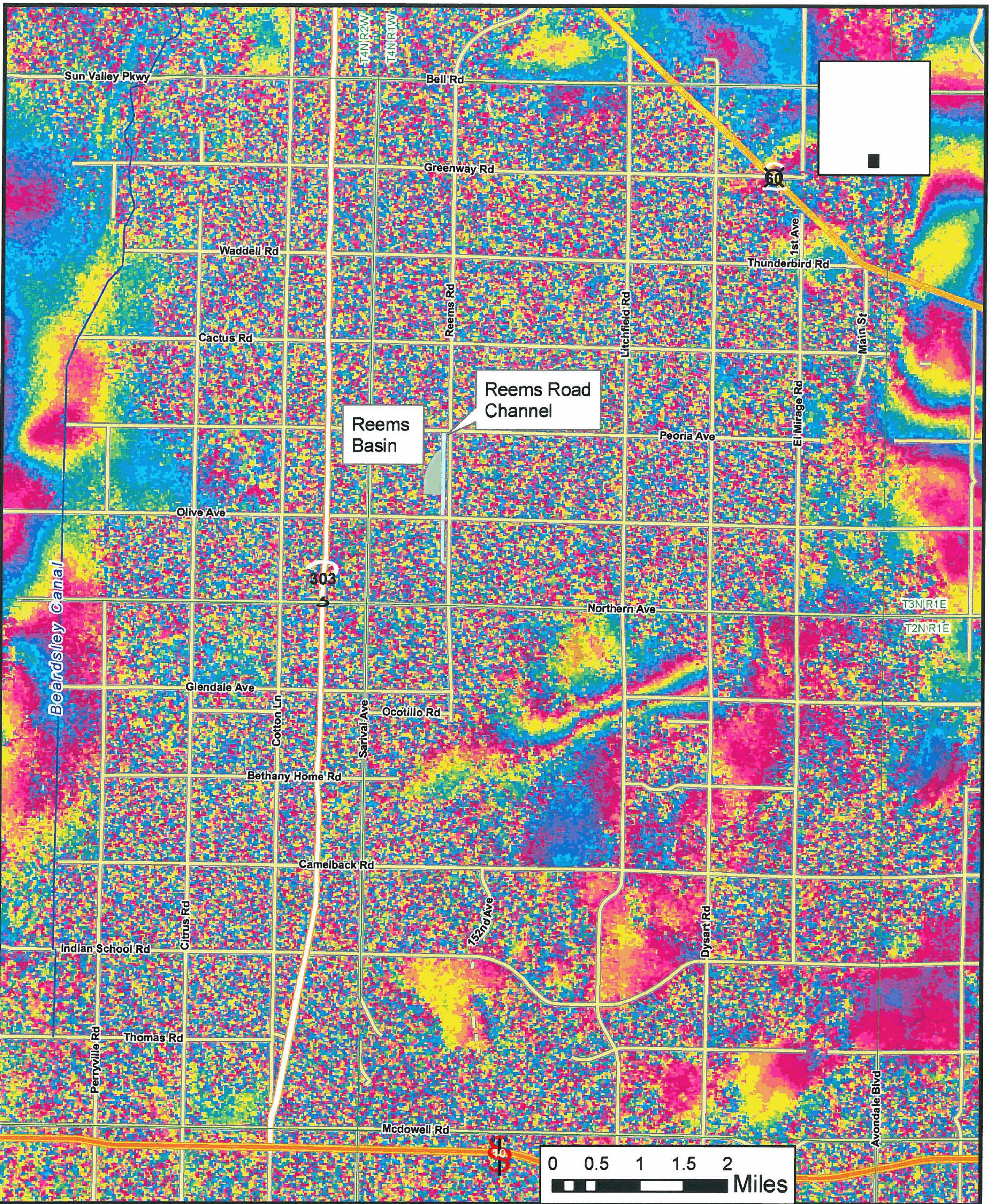
JOB NO.:	7-117-001074
DESIGN:	KED
DRAWN:	PWB
DATE:	10/15/07
SCALE:	1" = 1.5 mile

Preliminary Ground Subsidence and Earth Fissure Evaluation
Flood Control District of Maricopa County
Reems Road Channel and Basin
Contract FCD 2006C020, Work Assignment No. 1

InSAR Dec. 1996 to Dec. 1999

FIGURE
B-1

amec



Data Source:
Repeat-Pass Synthetic Aperture Radar Interferogram
March 10, 1997 to October 30, 2000.
One color cycle represents ~ 2.8 cm of vertical elevation change.

Produced by:
Arizona Department of Water Resources

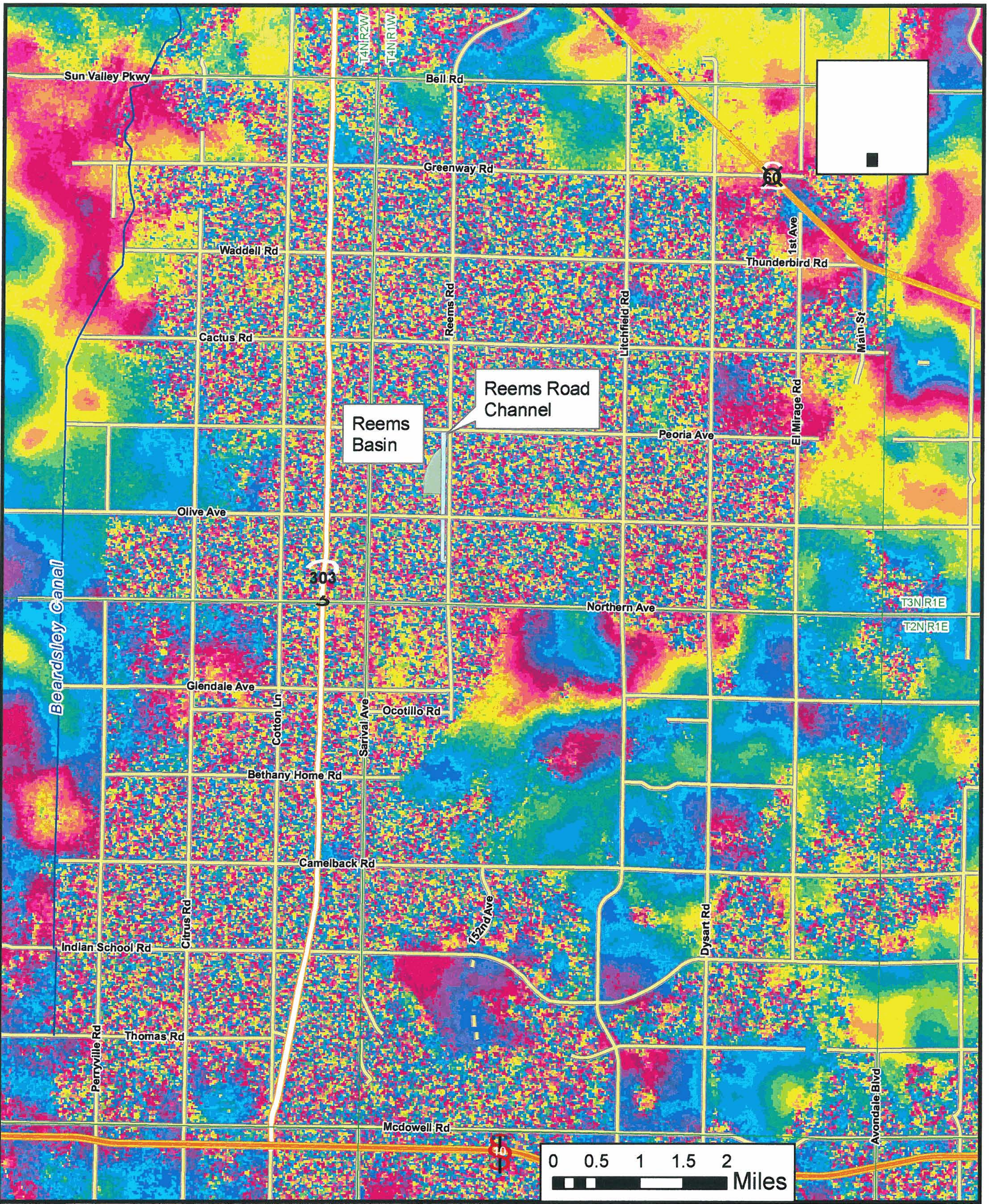
JOB NO.:	7-117-001074
DESIGN:	KED
DRAWN:	PWB
DATE:	10/15/07
SCALE:	1" = 1.5 mile

Preliminary Ground Subsidence and Earth Fissure Evaluation
Flood Control District of Maricopa County
Reems Road Channel and Basin
Contract FCD 2006C020, Work Assignment No. 1

InSAR March 1997 to October 2000

FIGURE
B-2

amec



Map Document: (X:\Projects\7-117-001074\MXD\Figure B-1_InSAR96-99.mxd) 10/19/2007 -- 8:18:51 AM

Data Source:
Repeat-Pass Synthetic Aperture Radar Interferogram
June 8, 1998 to May 8, 2000.
One color cycle represents ~ 2.8 cm of vertical elevation change.

Produced by:
Arizona Department of Water Resources

JOB NO.:	7-117-001074
DESIGN:	KED
DRAWN:	PWB
DATE:	10/15/07
SCALE:	1" = 1.5 mile

Preliminary Ground Subsidence and Earth Fissure Evaluation
Flood Control District of Maricopa County
Reems Road Channel and Basin
Contract FCD 2006C020, Work Assignment No. 1

InSAR June 1998 to May 2000

FIGURE
B-3

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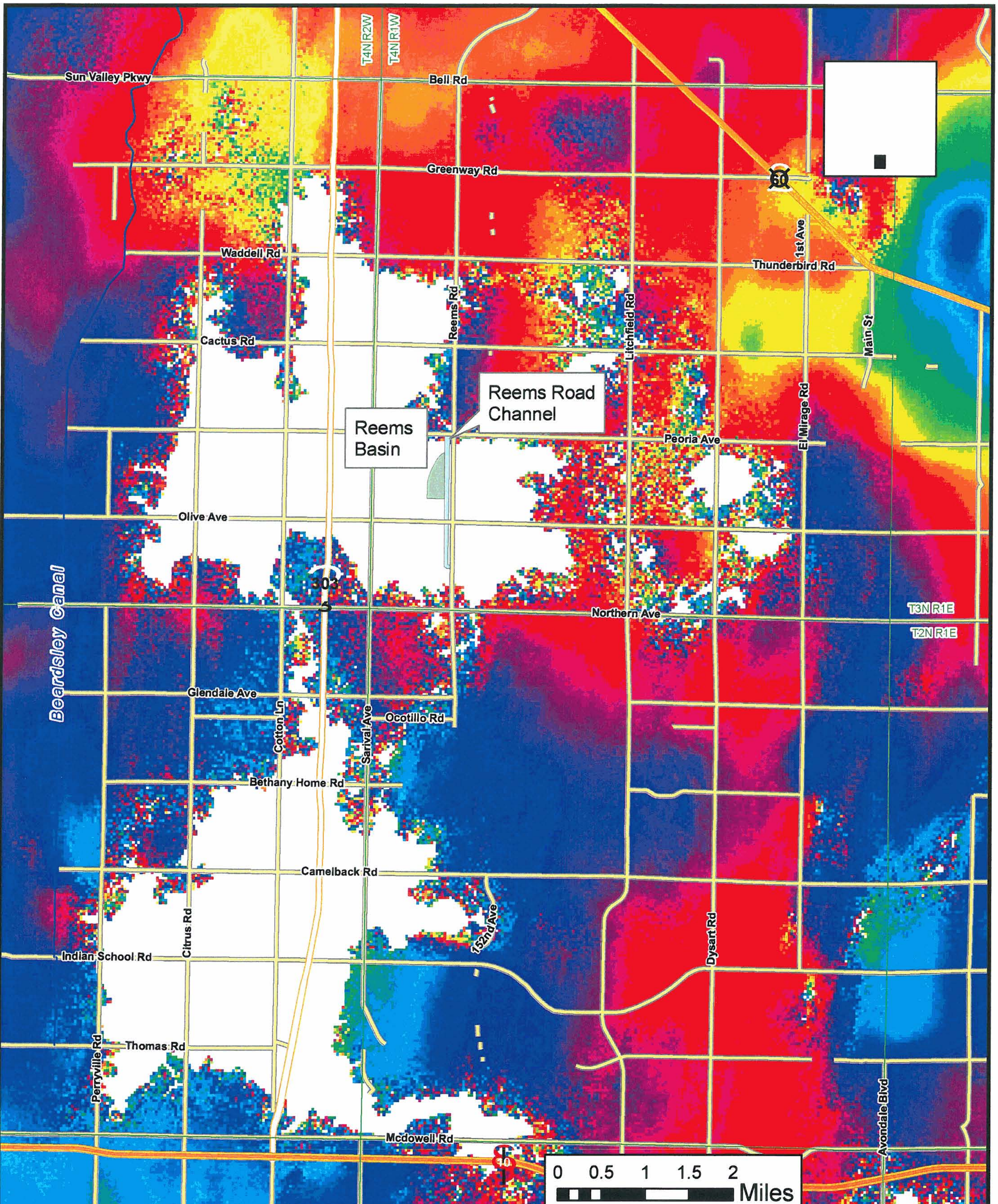

Map Document: (X:\Projects\7-117-001074\MXD\Figure B-1 InSAR96-99.mxd) 10/19/2007 -- 8:18:51 AM

Data Source:
Repeat-Pass Synthetic Aperture Radar Interferogram
September 24, 2004 to September 19, 2005.
One color cycle represents ~ 2.8 cm of vertical elevation change.

Produced by:
Arizona Department of Water Resources

JOB NO.:	7-117-001074
DESIGN:	KED
DRAWN:	PWB
DATE:	10/15/07
SCALE:	1" = 1.5 mile

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Flood Control District of Maricopa County
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InSAR September 2004 to September 2005

FIGURE **B-4**

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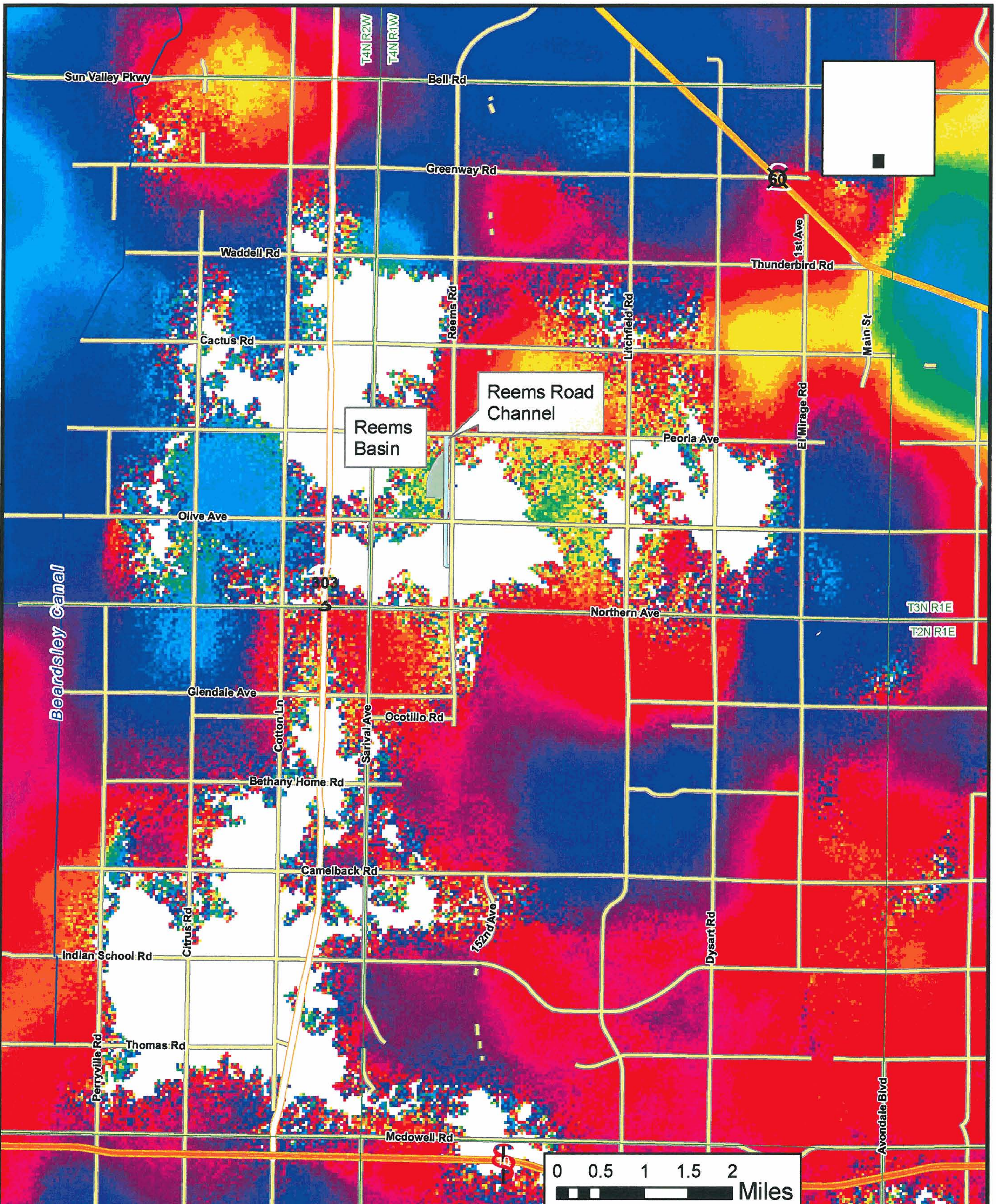

Data Source:
Repeat-Pass Synthetic Aperture Radar Interferogram
July 9, 2005 to August 21, 2006.
One color cycle represents ~ 2.8 cm of vertical elevation change.

Produced by:
Arizona Department of Water Resources

JOB NO.:	7-117-001074
DESIGN:	KED
DRAWN:	PWB
DATE:	10/15/07
SCALE:	1" = 1.5 mile

Preliminary Ground Subsidence and Earth Fissure Evaluation
Flood Control District of Maricopa County
Reems Road Channel and Basin
Contract FCD 2006C020, Work Assignment No. 1

InSAR July 2005 to August 2006

FIGURE
B-5

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