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PRELIMINARY EARTH FISSURE RISK ZONE INVESTIGATION REPORT HAWK ROCK STUDY AREA MARICOPA AND PINAL COUNTIES, ARIZONA

Submitted to:

Flood Control District of Maricopa County
Phoenix, Arizona

REGISTERED GEOLOGIST
CERTIFICATE NO.
41786
KENNETH C.
FERGASON
Date Signed 9.25.06
ARIZONA, U.S.A.

Submitted by:

AMEC Earth & Environmental, Inc.
Tempe, Arizona

25 September 2006

AMEC Job No. 6-117-001053
Contract FCD 2006C005
Work Assignment 2

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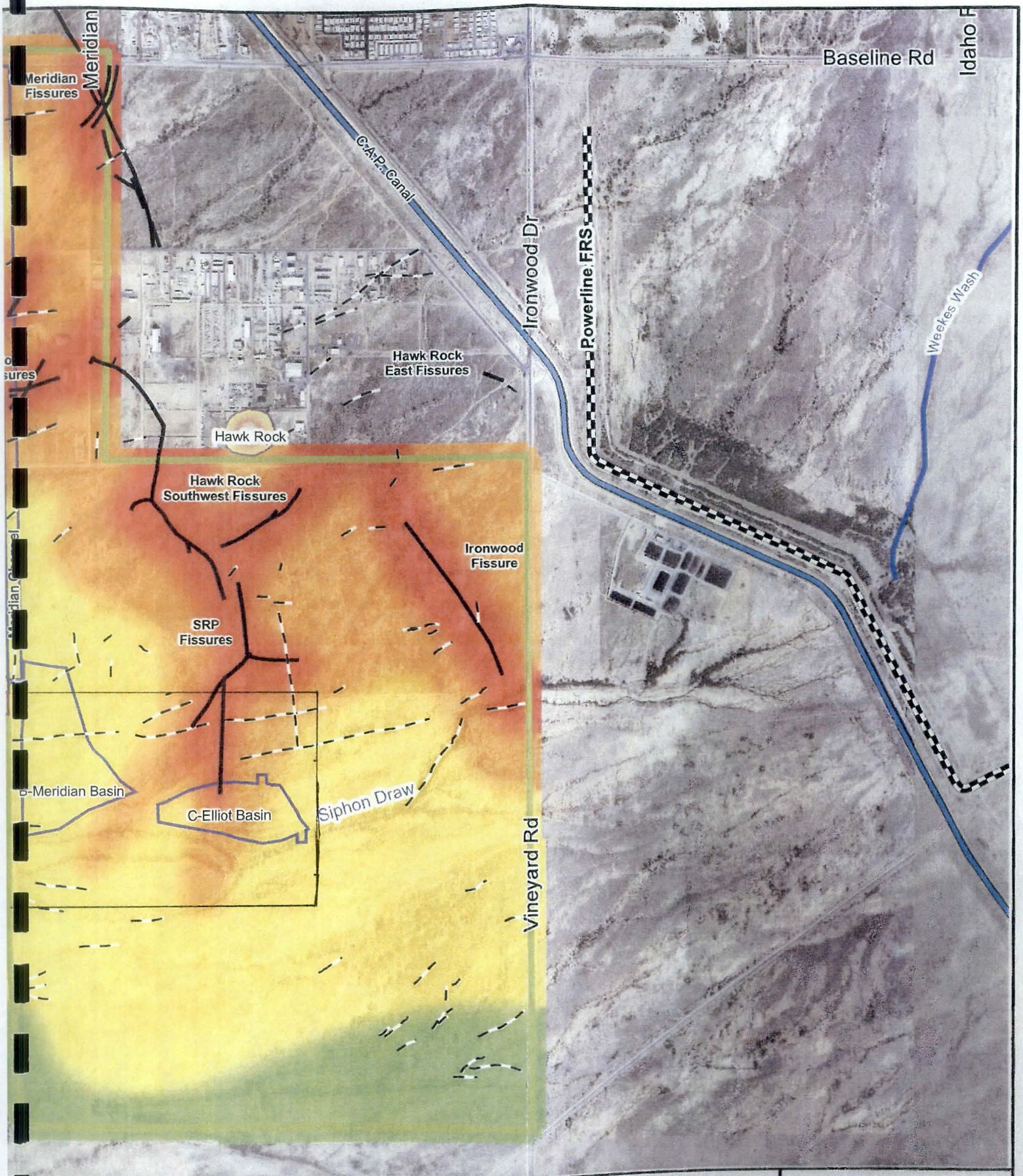

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PRELIMINARY EARTH FISSURE RISK ZONE INVESTIGATION
HAWK ROCK STUDY AREA
MARICOPA AND PINAL COUNTIES, ARIZONA
Contract FCD 2006C005, Work Assignment 2

Earth Fissure Risk Zones

FIGURE 9

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25 September 2006
AMEC Job No. 6-117-001053

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

Attn: Felicia Terry, P.E.

Re: **Preliminary Earth Fissure Risk Zone Investigation Report**
Hawk Rock Study Area
Contract FCD 2006C005
Work Assignment 2
Maricopa and Pinal Counties, Arizona

Transmitted herewith is our final report for the referenced project. This report presents the findings of a preliminary assessment of earth fissure risk of the Hawk Rock study area, a region under consideration by the District for the construction of flood conveyance structures and detention basins.

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

Respectfully submitted,

AMEC Earth & Environmental, Inc.

REGISTERED GEOLOGIST CERTIFICATE NO. 41786 KENNETH C. FERGASON Date Signed 9-25-06 ARIZONA, U.S.A.

Kenneth C. Fergason, P.G.
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Registered Professional Engineer (Civil) CERTIFICATE NO. 13872 LAWRENCE A. HANSEN Date Signed 9/25/06 ARIZONA, U.S.A.

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1.0 INTRODUCTION

The geotechnical investigation detailed herein was necessary to complete a preliminary delineation of earth fissure and ground subsidence risks within an area under consideration by the Flood Control District of Maricopa County (District) for the siting of storm water conveyance and detention facilities, located in the vicinity of Hawk Rock (Sheet 1). A subordinate objective of this evaluation was to provide preliminary design strategies for channels and basins in the identified earth fissure risk zones. These conceptual designs are then supplemented by discussions and recommendations regarding those actions deemed appropriate to detect and reduce the potential consequences of future earth fissure formation and subsidence within regions of elevated risk.

Regarding the regional geohydrological and geological data utilized during this appraisal, this preliminary evaluation largely relied on a recently completed study for the Powerline and Vineyard flood retarding structures, located immediately east of the Hawk Rock study area (AMEC, 2006). The risk assessments performed for this study are qualitative in nature, structured to support the District's selection of appropriate siting alternatives and defensive design options for the facilities under consideration. Geophysical surveys normally performed to search for concealed earth fissures and confirmatory trenching to expose fissures are not part of this preliminary study. Without the employment of these investigative techniques, the degree of uncertainty regarding the distribution of earth fissures is inherently greater than that of the Powerline/Vineyard study area.

This investigation involved office data collection and analyses, followed by a limited field program. Field activities included geological reconnaissance for locating and mapping existing earth fissures. Office work included photogeological interpretations, a review of previously compiled subsidence data, and a qualitative risk analysis regarding the potential for earth fissures and future ground subsidence impacting the facilities under consideration. The investigative tasks are generally described below:

- Completion of a photogeological interpretation of high-resolution aerial photography provided (obtained between January 8 and February 11, 2006) by the District. All observable photo lineaments indicative of earth fissuring were recorded, thereby guiding subsequent field efforts.
- Use of existing synthetic aperture radar interferometric (InSAR) data for the region from 1992 to the present, to evaluate the distribution of past ground deformation.
- Evaluation of ground subsidence data previously compiled for the Powerline/Vineyard FRS study, as it applies to the Hawk Rock study area.
- A zonation of earth fissure hazard and a consideration of ground subsidence risks.
- Development of conceptual design elements to defend against future earth fissure damage to channels and basins.

This study was authorized by the District in July of 2006 under the terms and conditions of Contract FCD 2006C005, with the scope subsequently defined in a geotechnical investigation plan. This work was performed by AMEC for the sole use of the District in managing ground subsidence and earth fissure risks for the Hawk Rock study area. 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 in Sheet 1 presented at the end of this report. This region is located on a gently sloping piedmont southwest of the Goldfield and Superstition Mountains. This erosional surface appears to be comprised of a pediment near the mountain fronts, and coalescing alluvial fan surfaces towards the basin center to the west. The surface is interrupted locally by Hawk Rock, a small outcrop of competent Precambrian granitic rock located in Section 6 of T1S R8E. The terrain slopes to the southwest at a gradient of about 40 feet per mile, ranging in elevation from about 1600 to 1450 feet above MSL. The U.S. Bureau of Reclamation (BurRec) Central Arizona Project (CAP) Salt-Gila Aqueduct, the Powerline FRS and the northern portion of the Vineyard FRS are located northeast and east of the study area. Residential development is present immediately west of the study area, and light industrial properties are located to the northeast in the vicinity of Hawk Rock.

The District is considering the construction of a flood control system, consisting of flood detention capacity in the form of shallow basins, which will receive flow from the Meridian Channel, located on the County line, along the offset, north-south projection of Meridian Road south of Baseline Road. It is understood that improvements to the Meridian Channel will be performed by others, rather than the District, but the flood flows will then be routed to detention basins designed, constructed and maintained by the District. If needed, an east-west conveyance, consisting of a concrete-lined channel, would be constructed by the District north and parallel to the Salt River Project (SRP) powerline corridor.

Four basin sites are under consideration. These are the C-Elliot Basin due south of Hawk Rock, the B-Meridian Basin to the west-northwest, a series of three smaller basins within the SRP Powerline corridor and a residential development north of Elliot Road, and what is termed the New Detention Basins between the SRP Substation and the previously mentioned residences. The underlying primary objective of this study is to aid in the selection of a preferred site for flood detention from this suite of four locations, from the perspective of earth fissure risk.

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) review of existing data and past analyses; 2) acquisition and analysis of synthetic aperture radar interferometry; 3) analysis of project-specific high resolution aerial digital imagery; and 4) ground reconnaissance of photo-lineaments suspected of being earth fissures.

3.1 Review of Existing Data

The review of existing data primarily focused on data included in two previous reports by AMEC (2006 and 2002a). Data compiled in these reports includes: published technical literature, regulatory agency databases, internal District files, and unpublished information in CAP archives. The published resources include regional geological and geohydrological studies, with use of agency databases largely restricted to Arizona Department of Water Resources (ADWR) well information. Gravity data and depth to bedrock are shown on Sheet 1, InSAR data on Figures 1 and 2, and groundwater data on Figure 3.

In addition, Peter Kandaris with the SRP's Geotechnical Department was contacted regarding reports related to the design, construction, and maintenance of their Dinosaur-Kyrene 500 kV transmission line and the Browning Substation. Karen Anglin of AMEC, visited SRP's office and reviewed and copied relevant data.

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.

The Arizona Department of Water Resources (ADWR) is currently applying InSAR as part of a long-range study of basin subsidence in Arizona. Upon request, ADWR provided AMEC with a copy of two interferograms of the East Salt River Valley. Covering the entire study area, the relevant portion of each interferogram is presented as Figures 1 and 2. Figure 1 shows a composite interferogram built from a series of individual interferograms covering a time period from May 1992 to April 2000. Figure 2 shows an individual interferogram covering the time period from October 2002 to April 2004.

Interferometry 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 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.

The InSAR image in Figure 1 is a composite image composed from many individual interferograms. One complete color cycle in Figure 1 represents 9 centimeters (~4 inches) of elevation change over the time period covered.

The InSAR image in Figure 2 is an individual interferogram where one complete color cycle represents 2.8 centimeters (~1 inch) of elevation change between the two orbital observations and the pixel size is 50 meters (~164 feet).

3.3 High Resolution Digital Aerial Photography

In accordance with procedures similar to those outlined by Beckwith and others (1991), high resolution digital aerial photography provided by the District was analyzed. Pixel size is approximately 1 square foot and aerial coverage was obtained between January 8 and February 11, 2006. Coverage areas included the entirety of the study area.

The entire suite of high resolution 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. Results of the photo lineament analysis are presented on Sheet 1. The evaluation was performed using printed hard copies in conjunction with the digital product. Interpretations were completed by Kenneth Fergason, P.G. and reviewed by Ralph Weeks, P.G., both of AMEC.

3.4 Ground Reconnaissance

With the aid of the lineament analyses and interferograms, as discussed above, select photo-lineament features within the study area were visited on the ground, primarily those suspected of being earth fissures. Slight adjustments to the alignment of some features resulted, with other lineaments eliminated due to their obvious cultural origins.

4.0 GEOLOGICAL SETTING

4.1 Geologic Overview

The Hawk Rock study area is located within the Sonoran region of the Basin and Range physiographic province, and is, in part, structurally separated from the central Phoenix valley by the bedrock highs of the Tempe Butte area. The study area lies within the Mesa-Chandler sub-basin, adjacent to the Superstition and Goldfield Mountains that are composed of metamorphic and igneous bedrock. This 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; Lancy and Hahn, 1986; BurRec, 1977).

As implied by gravity data (Oppenheimer and Sumner, 1980; Laney and Hahn, 1986), the valley margins likely contain multiple high-angle normal faults active in Cenozoic time. These faults are now concealed under the basin alluvium, and are often removed from the current mountain-front exposures of competent bedrock.

4.2 Regional Alluvial Stratigraphy

The Lower Alluvial Unit (LAU) is composed of Middle to Late Tertiary conglomerates interbedded with anhydrite, gypsiferous mudstone and basalt. The coarser fraction of this unit is often poorly sorted, contains significant calcium carbonate, is faintly bedded, and consists of sand to cobble-sized particles in a silty to clayey matrix. The LAU is in fault and erosional

contact with the competent bedrock floor and buried flank of the basin. In the western half of the study area, the LAU is approximately 9,200 feet thick, but the top of the unit is typically found within 400 to 500 feet below ground surface (Prokopovich, 1983).

The Middle Fine Grained Unit (MFGU) is usually confined to the center of the basin in central Arizona, but it can be found in contact with basin margins and is approximately 400 feet thick. MFGU contains clay and silt deposited in internally drained basins, resulting from damming caused by tectonic movement and volcanism. Laney and Hahn (1986) show the top of this Mid- to Late Tertiary unit very near the surface, with the basal 100 feet of the unit lacking a high percentage of gravel. Overall, the MFGU has a relatively high sand and gravel content, from 40 to 80 percent within the study area (Laney and Hahn, 1986). Regionally, 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 contains a higher fraction of clay and silt with comparable concentrations of calcium carbonate (Prokopovich, 1983).

The Upper Alluvial Unit (UAU) is Late Tertiary and Holocene clastic material derived from the surrounding bedrock and deposited as a mantle over older basin fill. The unit is a few 10s of feet thick within the study area. The UAU is the resultant depositional product of an externally drained stream system (Prokopovich, 1983).

4.3 Surficial Geology

The study area lies at the distal margin of pediments associated with the Goldfield and Superstition Mountains. The north and central portion of the study area contains Holocene deposits typical of a basin floor, identified as fine-grained distal alluvial fan/alluvial plain and terrace deposits with little soil development (Pearthree and Huckleberry, 1994). These basin floor deposits are incised by younger Holocene piedmont and intermontane deposits identified as channel deposits of ephemeral streams consisting of stratified sand, silt, pebbles, cobbles and boulders with little or no soil development (Pearthree and Huckleberry, 1994).

Huckleberry (1994) mapped the surficial geology of the Apache Junction area, which includes the study area. The following four units are found within the study area and are described below: Holocene Alluvial Channels (map unit Ya2); Holocene Alluvial Surface (Ya1); Undifferentiated Holocene Alluvium (Ya); Holocene to Late Pleistocene Alluvium (Ma2/Ya1); Late Pleistocene Alluvium (Ma2); and Middle to Late Pleistocene Alluvium (Ma1).

- **Holocene Alluvial Channels (Ya2).** This unit is composed of modern ephemeral streams draining the piedmont. Grain sizes typically range from sand to cobbles, and the alluvium is permeable. The alluvium is generally stratified and lacks appreciable soil formation. Drainage patterns are typically dentritic, however, where channels are less contained, they can be distributary. Some of the channels have rectilinear drainage patterns that have formed along two-track roads and earth fissures. Much of the natural drainage is disrupted by the CAP canal and flood retarding control structures (Huckleberry, 1994).

Groundwater in the study area has declined significantly due to well withdrawals, far exceeding recharge (Figure 3). This decline likely commenced in the late 1940s as agricultural development began in earnest in the east valley. Up through the spring of 1964, water levels in the southwestern segment of the study area probably declined about 100 feet (BurRec, 1977). Between the 1960s and the early 1980s groundwater declined and additional 100 to 150 feet. Since the 1980s groundwater decline had lessened or leveled off, with declines less than 50 feet. Total groundwater declines since 1940 in the study area appear to be about 250 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 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).

Helm (1984) presents a simplified computational technique to estimate settlement due to groundwater withdrawal. The method considers the depth of compressible alluvium over bedrock, the amount of groundwater decline and consequent increases in effective stress, and the average Young's modulus (E) of the compressible layers. Both the short-term elastic component of settlement and long-term component due to slow drainage, and the consolidation of the more plastic clays, are represented by E values. Data derived from case histories of subsidence in similar basins is available to assist in estimating E values (Bell, 1981; Holzer, 1981; Helm, 1984).

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 south 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, 1993), 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. Figure 7 summarizes these mechanisms.

As depicted on Figure 8, 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 affects of subsidence in the vicinity of the study area were first identified in the 1970s as part of the investigation for the construction of the CAP canal. As part of AMEC investigations for Powerline FRS and Vineyard FRS (AMEC, 2002a and 2006), subsidence data from multiple sources, including ADOT, CAP, and ADWR, were reviewed, presented, and analyzed.

InSAR coverage from May 1992 to April 2000 (Figure 1) provides an 8-year synopsis of subsidence within the study area. More recent coverage from October 2002 to April 2004 (Figure 2) indicates that these subsidence patterns are continuing to the present. The greatest subsidence is one to two miles north of the study area.

Subsidence continues to occur within the study area, with InSAR data providing the best overview of recent activity (Figures 4 – 6). Recent subsidence values and rates along Profile B-B' are summarized on Figure 5, showing maximum rates of 0.75 inches per year from 2002 to 2004 with typical maximum rates since 1992 in the vicinity of the proposed basins of about 0.65 inches per year. Minimum rates range from 0 to 0.25 inches per year. Subsidence rates along profiles A-A' and C-C' are included in Figures 4 and 6, respectively, and are consistent with those along profile B-B'. This data shows an increase in subsidence rates from 2002 to 2004 compared with rates in the 1990s.

Earth fissures were first identified in the vicinity of Hawk Rock in the late 1970s by Bureau of Reclamation personnel and protective measures for the CAP canal were implemented during construction (AMEC, 2002a). These earth fissures (the Meridian Fissures on Sheet 1) underwent detailed study by BurRec and USGS personnel. Since the 1970s the earth fissure field has continued to actively expand, primarily to the south (the Hawk Rock West, Hawk Rock Southwest Fissures, SRP Fissures, and Ironwood Fissure). SRP has been aware of earth fissures in the vicinity and regularly monitors the growth of the SRP Fissures and the Ironwood Fissure in the vicinity of their east-west powerline (Dinosaur Line) located approximately ½ mile north of Elliot road. These fissures have continued to grow to the south since their monitoring began in the 1990s.

Other lineaments shown on Sheet 1 represent vegetative, tonal, or orientated drainages that could not be ruled out as earth fissures as part of this investigation. These lineaments are most likely human caused or part of streams and washes, but require further investigation to confirm the lack of earth fissures.

7.0 DISCUSSIONS

Based on several lines of evidence, differential ground subsidence, known earth fissures, and the risk of concealed or future fissures have the potential to affect the design and operation of the proposed flood control facilities. The following discussions are presented to further define these potential constraints, and present selected design elements that could be employed to prevent or mitigate the impacts of the ongoing ground deformation upon the functionality and safe operation of both the conveyance and detention components of the proposed system.

7.1 Potential Subsidence Impacts

Little is known about the historical distribution of ground subsidence within the study area, but the occurrence of many fissures flanking and radiating from Hawk Rock is an indication that the amount of local, differential subsidence has been substantial. The InSAR data is clear evidence that subsidence is continuing, and the patterns seen in such data are often indicative of both past and future behavior. Given that assumption, there appear to be selected alternative basin sites, and the Meridian Channel, that could be affected by future differential subsidence.

As can be seen in Profile A-A' (Sheet 1 and Figure 4), the pattern of ground subsidence along the Meridian Channel alignment is such that future subsidence will lessen the invert grade of the conveyance for the first 7500 feet, then increase the grade from 7500 feet to its terminus some 3500 feet to the south. If a concrete-lined channel needs to be constructed to route floodwaters to the west from the terminus of the Meridian Channel to the New Detention Basins, the InSAR pattern indicates that little differential subsidence potential is present. In that plans call for the concrete lining of both the Meridian Channel and the aforementioned east-west lateral, it is anticipated that changes in the erosive characteristics of the flood flow is not of concern. In contrast, a decrease in the capacity of the channel over the long term may be an issue. The C-Elliot Basin site and location of the three small basins within the SRP corridor appear to be in regions of relatively equal subsidence or quiescence. Although the recent InSAR data near the C-Elliot Basin does not display on-going, significant differential subsidence, the existence of a major north/south-trending fissure onsite is an indication that past, local ground deformation has occurred in this locale.

Regarding the basins, the InSAR data indicates that differential subsidence may be occurring at the New Detention Basins site, and the B-Meridian Basin site. In both cases, this differential is very slight, as measured over an 8 year period from the year 1992 until 2000. If such subsidence was to continue at the measured rates or greater, it is plausible to anticipate that basin capacities and reserve freeboard could be compromised. The magnitude of this impact is dependent upon the regional rates of subsidence, and the assumption that the pattern of the subsidence behavior will persist.

Should the District select a basin location that appears to be susceptible to the effects of differential subsidence, it is recommended that yearly monitoring of the crest elevation of any containing embankments around these basins be accomplished, assuming that these basins will

not be constructed fully below the natural grade. It will be prudent to periodically measure the invert profile elevations of the connecting channels to assure that adequate capacity is maintained.

The District should also consider the construction of excess crest width on any basin embankments that may need to be heightened to create additional basin freeboard in the future. Excess freeboard may be an appropriate strategy for conveyance components of the system, such as the upper end of the Meridian Channel. Proceeding with an approach that calls for significant modifications to the geometry of either the basins or the channels should be based upon hydraulic analysis to define capacity, and a further, quantitative appraisal of the anticipated magnitude and distribution of future subsidence.

7.2 Earth Fissure Risk Zones

Before discussing the potential impacts of earth fissures upon the facilities under consideration, it is prudent to delineate the probability of occurrence throughout the study area by mapping fissure risk. As depicted on Figure 9, the following is offered as definitions of four earth fissure risk zones in order of decreasing hazard:

- **Zone 1 (Red) -** Earth fissures are present at this time and will likely continue to develop in the future, as evidenced by multiple investigative methods, including published and un-published mapping, photo lineament analysis, and ground reconnaissance.

- **Zone 2 (Orange) -** Conditions for the past development of earth fissures are present through multiple lines of evidence; however, earth fissures have not been positively identified. A high probability for the future development of fissures exists, and there is a distinct possibility that concealed earth fissures are present. Evidence supporting the possible presence of concealed fissures and the probability for future fissuring includes the proximity to, and trends of known earth fissures, InSAR data and patterns, and the distribution and orientation of photo-lineaments.

- **Zone 3 (Yellow) -** A moderate probability of future earth fissure formation is present, if future differential subsidence occurs, coupled with the current elevated state of horizontal, tensional strain. Evidence supporting this designation includes InSAR data and patterns, and photo-lineament analysis.

- **Zone 4 (Green) -** A low probability of future earth fissure formation exists in Zone 4. Evidence suggests that no significant tensional strain will develop from the occurrence of future subsidence following current patterns.

To every extent, the mapping of earth fissure risk depicted on Figure 9 honors the definitions listed above, with one significant exception. This exception is associated with several northeast-trending lineaments that cross through the New Concrete Lined Channel alignment,

the three small basins within the SRP powerline corridor, and the New Detention Basins site. The region around these lineaments has been designated as falling within Zone 3 due to their presence, even though other lines of evidence, such as the InSAR data, does not indicate a high probability that these lineaments are associated with the presence of fissures. Upon further subsurface investigation of these lineaments, it is likely that the zoning around these features can be adjusted to reflect a Zone 4 condition.

7.3 Earth Fissure Impacts upon Facility Sites under Consideration

The following discussions address earth fissure risk as it applies to each of the alternative sites for detention basins, the Concrete Lined Channel and the Meridian Channel.

- **C-Elliot Basin –** The site of this basin contains a verified earth fissure that trends north-south and crosses the northern boundary of the site. The risk of this fissure extending further to the south is high. Additional, concealed fissures may be present, and the probability that additional fissures will develop is quite high.

- **B-Meridian Basin –** This site contains several lineaments, no verified earth fissures, and slight differential subsidence. Due to these factors the vast majority of the site is designated as having a moderate risk of developing future earth fissures. A moderately high risk designation is assigned to the southeastern corner of the site, due to the presence of a verified fissure to the northeast.

- **Concrete Lined Channel & Three Small Basins –** These sites appear to be in a region of horizontal compression, thereby lessening the risk of earth fissure development. No earth fissures have been detected, but three north-east trending lineaments are present. There is a significant probability that these lineaments are not related to fissuring, and upon verification through subsurface investigation, this area could then be reclassified as a low-risk zone.

- **New Detention Basins –** The fissure risk zonation for this site is influenced by an extended leg of one of the lineaments mentioned above. The site also has experienced slight differential subsidence, as indicated by the InSAR data. Due to these factors, a significant portion of the site is classified as having largely a moderate earth fissure risk.

- **Meridian Channel –** Several verified earth fissures cross the Meridian Channel at the Hawk Rock West Fissure complex (Sheet 1). Additional, concealed fissures may be present, and the probability that additional fissures will develop is quite high. North of the Hawk Rock West Fissures, the Meridian Channel primarily falls within Fissure Hazard Zone 2, with a high probability of future earth fissure development or the presence of concealed fissures. South of the Hawk Rock West Fissures, the Meridian Channel falls into risk Zones 2 and 3.

7.4 Typical Earth Fissure Defensive Alternatives

It is understood that the District and its municipal partners are considering the construction of several types or combinations of typical flood control structural measures. Those components include concrete lined channels, unlined basins, and unlined basins with adjacent embankments. The discussion below includes details of added value components that could be implemented with these typical flood control measures in areas where earth fissures are present or may impact the flood control facility. The intent of the alternatives is to provide a means by which the District and its municipal partners may reduce the risk associated with flood control projects in earth fissure risk zone areas. It is important to note that each of the strategic design elements presented herein is conceptual in nature. Implementation of the concept and its design details must be specific to each site and facility geometry.

The alternatives presented are developed to implement the following defensive actions to defend against two primary failure modes:

- Intercept and control surface runoff to prevent fissure gully formation and loss of foundation support,
- Intercept and control shallow subsurface flow within a fissure to prevent undermining of structures,

It appears that an effective design strategy is to employ "flexible" materials to allow for greater adaptability to defend against fissure gully formation and erosion.

7.4.1 Avoidance

In high fissure risk zones (Zones 1 and 2) it is recommended that avoidance of the location be considered as a primary and most favorable alternative. Detailed geologic hazard assessments should be performed to provide a best-estimate of the areas that would be compromised by earth fissuring. Planning and siting of flood control infrastructure in these areas should be avoided, to the extent feasible. This is the most favorable alternative to reduce the risk associated with construction of flood control projects in a high fissure risk zone.

Placement of the facility components in risk Zone 3 appears prudent, if the District was to consider incorporating defensive elements into the design, and monitor for the occurrence of future fissure formations. Final delineation of the earth fissure risk zones should be based upon more detailed geotechnical studies.

7.4.2 Flood Control Channel

The defense mechanism for a concrete lined flood control channel includes three principal components as depicted in Figure 10. The first component provides a means to intercept the formation of an earth fissure gully as it approaches the channel in a perpendicular or skewed orientation. The component consists of a 4-foot wide excavated trench paralleling the channel

at a maximum distance of 5 feet from the channel edge. The trench should extend a minimum length of 40 feet but no greater than 500 feet in length in accordance with the following matrix:

Table 1
Trench Length Criteria

Distance from Channel to Closest Fissure Surface Expression (*D*)	Minimum Trench Length
0 to 40 feet	40 feet
40 to 100 feet	1 X *D*
100 to 500 feet	2 X *D*
> 500 feet	500 feet

The trench should be backfilled with a permeable backfill material wrapped on all sides, top and bottom, with a 16 oz. non-woven geotextile. A minimum of 2 feet of compacted earthfill shall be provided on top of the trench backfill.

The second component includes incorporation of a double layer of 10 oz. non-woven geotextile beneath the channel concrete lining. Incorporation of the double layer geotextile provides for a disconnection between a potential earth fissure crack and the overlying concrete lined channel. Additionally, the geotextile will preclude free water from entering any underlying fissure crack. The double layer geotextile shall extend from channel bank right to channel bank left and include a keyed toe-down at each bank. The geotextiles should be placed on a minimum of 12 inches of prepared subgrade and overlain with a minimum of 4 inches of bedding sand.

The third component of the alternative includes reinforcement of the concrete channel lining in the area of the other two components. Minimum recommended reinforcement is incorporation of 6x6 – W2.9 x W2.9 welded wire mesh. Use of the reinforcement will provide greater resistance to structural failure should an earth fissure erode beneath the channel lining.

7.4.3 Flood Control Basin

The defense mechanism for a flood control basin includes three principal components as depicted in Figures 11 and 12. The first component utilizes the same intercept trench component as the flood control channel to provided a means to intercept the formation of an earth fissure gully as it approaches the basin in a perpendicular or skewed orientation. Similarly, the component consists of a 4-foot wide excavated trench paralleling the basin at a maximum distance of 5 feet from the basin edge. The trench should extend laterally as detailed in Table 1 and be backfilled as detailed in the previous section.

To intercept the formation of an earth fissure gully as it approaches the basin the second component includes incorporation of a single layer 40-mil High Density Polyethylene (HDPE) liner beneath the basin slope in the area of fissure encroachment. The HDPE liner should

extend from the basin edge to a minimum distance of 10 feet into the basin from the basin slope toe. HDPE liner should be imbedded in a 10-foot deep vertical trench positioned within the basin away from the slope toe. To avoid damage to the liner during periodic basin maintenance, the liner should be covered by a minimum of 2 feet of compacted earthen fill.

To defend against fissure gully formation and erosion within the basin reservoir area, the third component includes incorporation of a single layer of 16 oz. non-woven geotextile within the basin bottom footprint. The single layer of geotextile should cover the entire basin bottom. The geotextile should be placed on a minimum of 12 inches of prepared subgrade and overlain with a minimum of 3 feet of compacted earthen fill.

7.4.4 Flood Control Basin with Embankment

The defense mechanism for a flood control basin with an embankment is similar to the flood control basin alternative, which includes three principal components. The flood control basin alternative is depicted in Figures 11 and 12. The primary difference is associated with the elevation in which the HDPE liner is constructed. The liner should extend into the embankment as shown in Figures 11 and 12.

7.5 Operation and Maintenance

Significant increases in normal flood control project operation and maintenance activities associated with the earth fissure defense alternatives is not anticipated. Normal activities may consist of vegetation control, silt and debris removal, and grading. However, the means and methods by which the activities are performed may require some changes. Since the components are typically buried, greater care during maintenance activities will be required so as not to damage the underlying defensive components. The impacts may be longer time frames to complete maintenance and, potentially, the use of smaller conventional construction equipment. In the event of damage to the underlying components, repair costs would be more significant than in a non-fissure risk zone area.

Increased event visual observation inspections are recommended. Inspection of known fissure locations and the areas between the earth fissure and the flood control project will be required to document and react to any observed surface distress.

Completion of any associated instrumentation and monitoring programs will require additional resources on the part of the District and/or District project partners. Periodic conventional surveys and instrument monitoring will be required to sufficiently document and understand the dynamics of a flood control project with elevated earth fissure risk. Periodic review of monitoring data by a qualified civil engineer or geologist is recommended.

7.6 Earth Fissure Defensive Alternatives Unit Costs

Detailed in Table 2 are estimated unit costs for the earth fissure defense alternative components. Unit costs presented are in addition to those unit costs required for non-fissure flood control alternative construction. Unit costs estimates were developed from recent District flood control project bid tab sheets, verbal discussions with industry suppliers and contractors, and from best available industry recognized construction cost indices (RSMeans, 2005).

Table 2
Estimated Unit Costs

Description	Unit	Unit Price
Earthfill construction	CY	$2.75
Bedding sand construction	CY	$25.00
Deep trenching	CY	$5.25
Permeable backfill construction	TN	$27.50
10 oz non-woven geotextile	SY	$2.00
16 oz non-woven geotextile	SY	$2.25
40 mil HDPE	SY	$6.75
CLSM trench backfill	CY	$100.00
Riprap	CY	$75.00
Gabions with filter fabric	CY	$92.00
Install GPS survey monument	EA	$675.00
Install optical survey monument	EA	$400.00
Install tape extensometer monument	EA	$875.00
Install rod extensometer	EA	$7,250.00
Provide and install TDR cable	LF	$12.00
TDR hardware and software	LS	$5,000.00

7.7 Monitoring and Instrumentation

Recent experiences with risk assessments related to earth fissuring has shown that scheduled surveillance and monitoring reduce risk. Therefore, it is recommended that a monitoring and instrumentation program be implemented in areas of moderate to high fissure risk for the purpose of providing a means in which to reduce risk to flood control facilities. This risk reduction will be realized by quantifying the rate and distribution of ground deformation in the vicinity of the facilities.

Various methods of monitoring include conventional practices both proven and prototype and instrumented in-ground sensing systems. The conventional techniques include the use of horizontal tape extensometers, optical leveling, GPS surveys, geologic ground reconnaissance, and photogeological analysis. Advanced techniques include the processing and interpretation of InSAR imagery, photo-lineament analysis of low sun angle or high-resolution color aerial photography, rod extensometer displacement sensor systems, and time domain reflectometry (TDR) arrays.

The practicality and usefulness of both horizontal rod extensometers and TDR as components of an earth fissure monitoring system is currently under study at the south end of McMicken Dam in a region of active ground deformation. Although prototype versions of these systems have been successfully installed at McMicken Dam, an extended period of application will be necessary to demonstrate their usefulness in quantifying earth fissure activity and detecting the occurrence of new fissures. Use of these technologies in the Hawk Rock study area should not occur until the prototype systems at McMicken prove to be useful and reliable.

Final project designs will be required to specifically develop a monitoring program for the site conditions anticipated. Design considerations will include location, types of monitoring instrumentation, and the procedural components of the monitoring system, including methods of measurement, monitoring frequency, precision minimums and action initiation thresholds.

7.8 Other Considerations

In addition to the alternatives discussed above the following design factors are recommended for design consideration:

- The contributing watershed area up-gradient from fissure risk zones should be hydrologically assessed. Run-off into earth fissures is the principal cause for the development of damaging erosional gullies. Therefore, if run-off into areas prone to fissuring can be reduced or diverted away from the fissure, gully development will be greatly reduced.
- To protect the buried earth fissure defense components, energy dissipation should be included in locations where flood control channels discharge into associated basins. Alternatives to dissipate energy may include riprap, gabions or cast-in-place concrete energy dissipaters.

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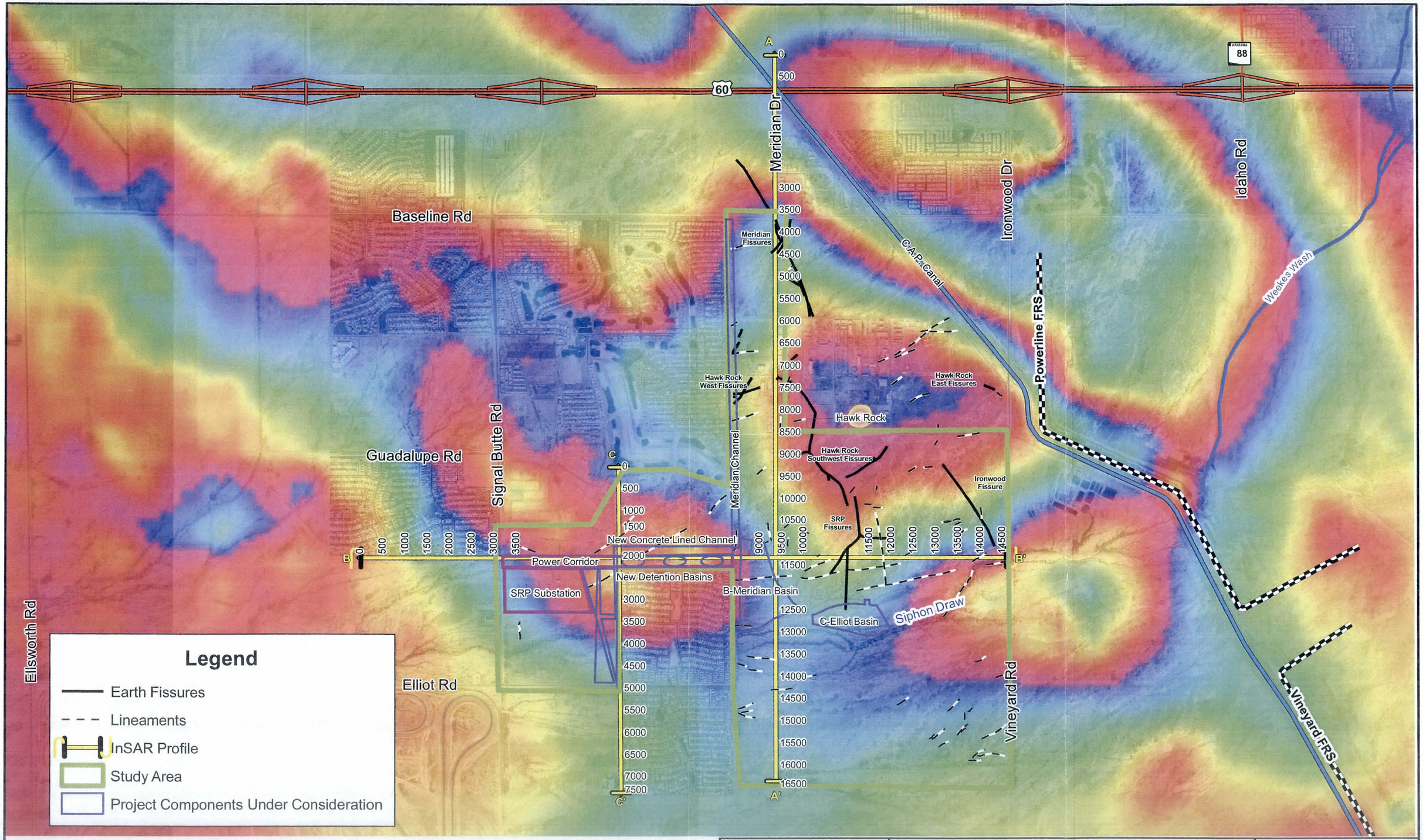
FIGURES



InSAR for the Period from May 1992 to April 2000.
One color cycle represents approximatly 9 cm of elevation change.
InSAR Produced by the Arizona Department of Water Resources.
Refer to Section 3.2 of the report for an explaination of InSAR technology.

0 800 1,600 2,400 Feet

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Color aerial Imagery from FCDMC, taken in January & February, 2006
B&W aerial imagery from USGS DOQQs taken November 14, 1992

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PRELIMINARY EARTH FISSURE RISK ZONE INVESTIGATION
HAWK ROCK STUDY AREA
MARICOPA AND PINAL COUNTIES, ARIZONA
Contract FCD 2006C005, Work Assignment 2

InSAR - 1992 to 2000

FIGURE 1

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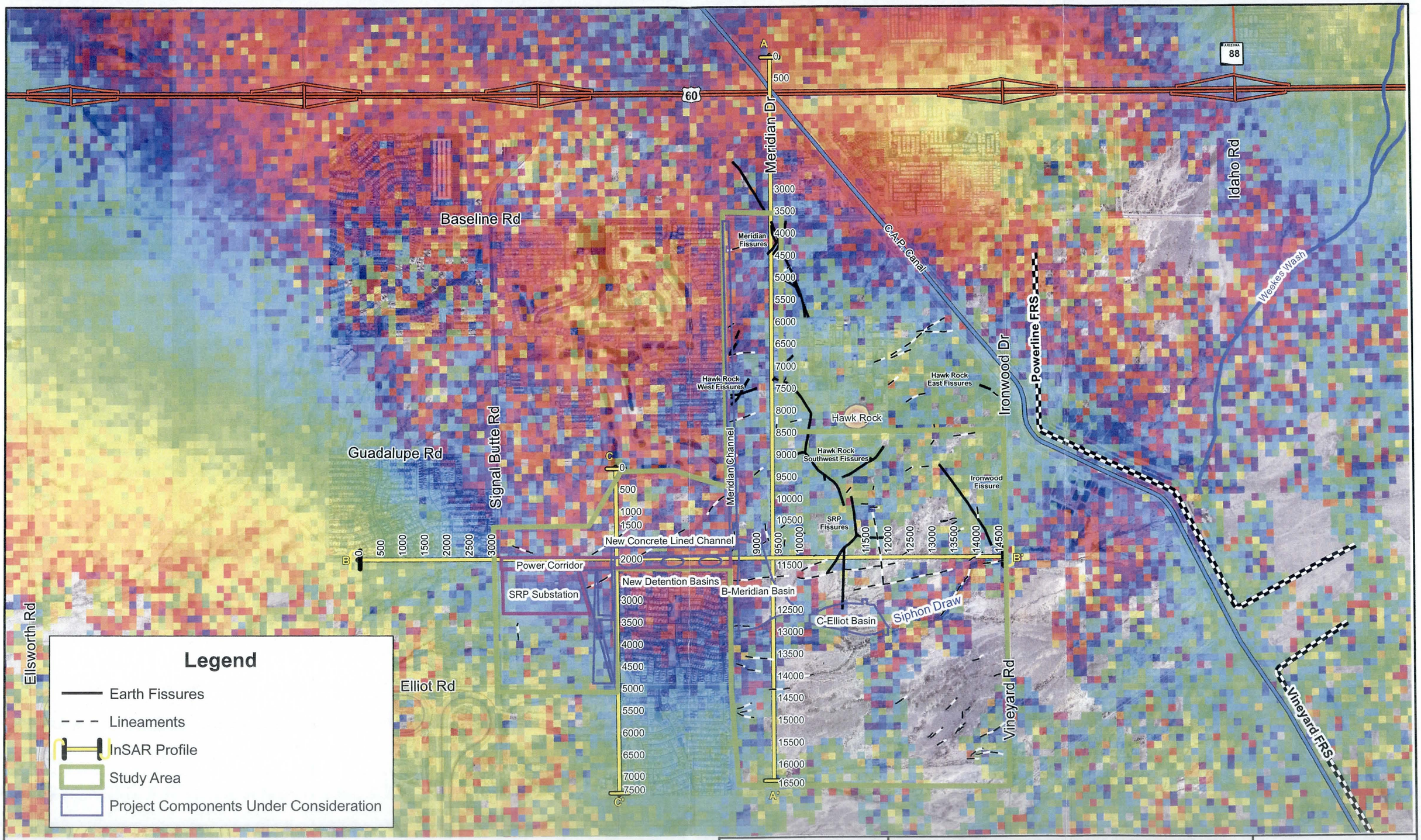

InSAR for the Period from May 1992 to April 2000.
One color cycle represents approximatly 9 cm of elevation change.
InSAR Produced by the Arizona Department of Water Resources.
Refer to Section 3.2 of the report for an explaination of InSAR technology.

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Color aerial Imagery from FCDMC, taken in January & February, 2006
B&W aerial imagery from USGS DOQQs taken November 14, 1992

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PRELIMINARY EARTH FISSURE RISK ZONE INVESTIGATION
HAWK ROCK STUDY AREA
MARICOPA AND PINAL COUNTIES, ARIZONA
Contract FCD 2006C005, Work Assignment 2

InSAR - 2002 to 2004

FIGURE 2

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Figure 3
Groundwater Elevation History

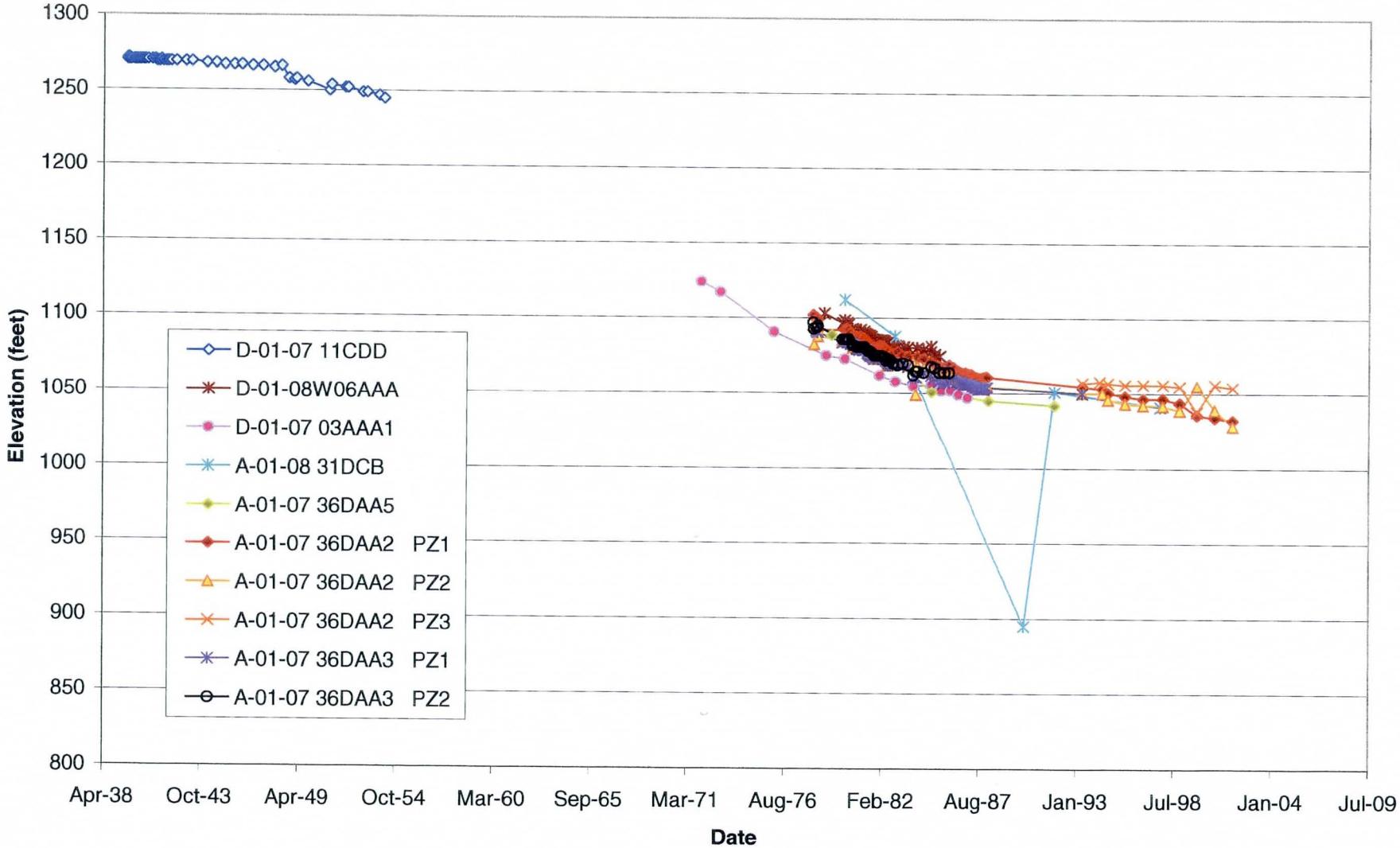


Figure 4
Subsidence Profile A - A'

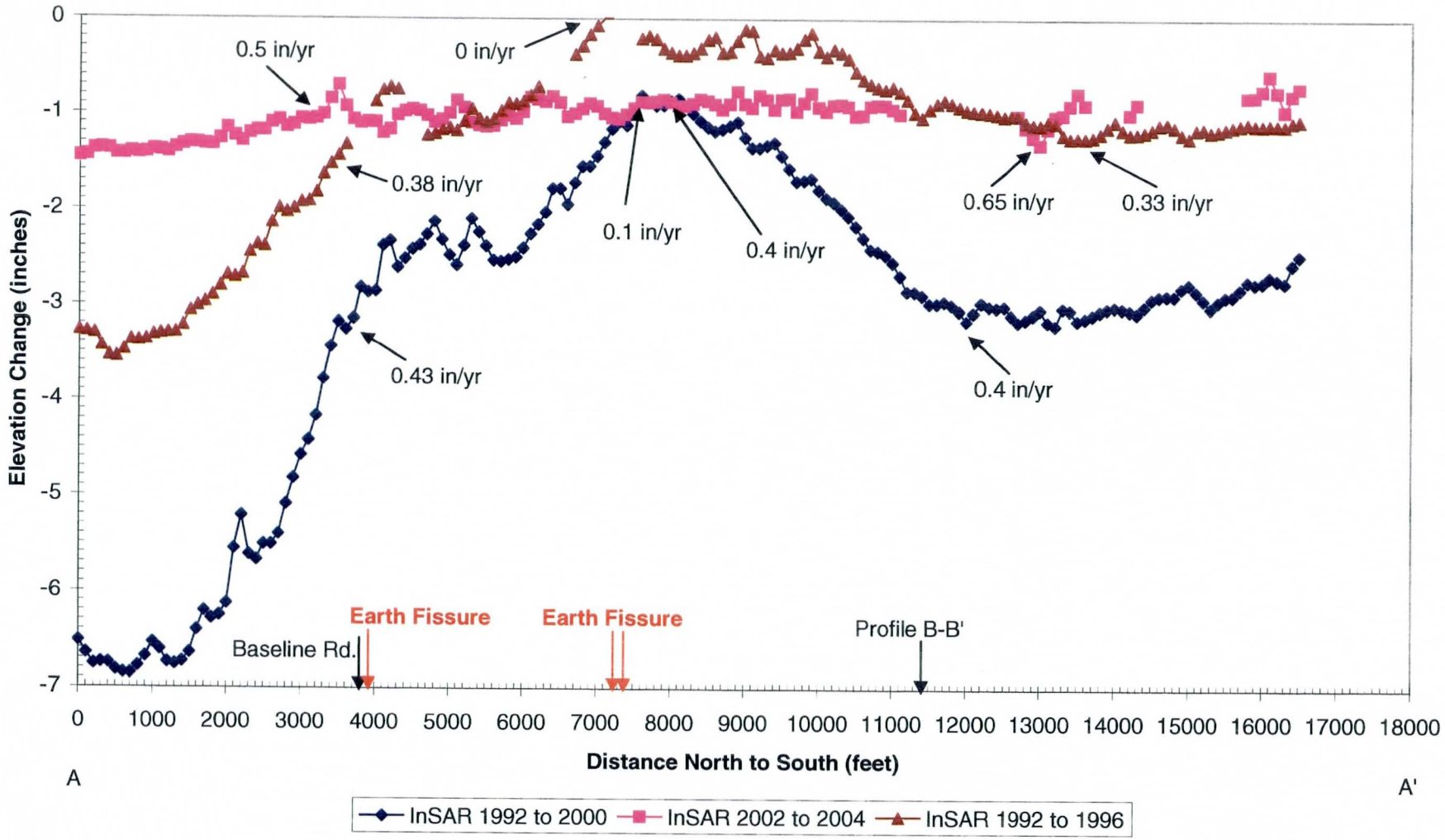


Figure 5
Subsidence Profile B - B'

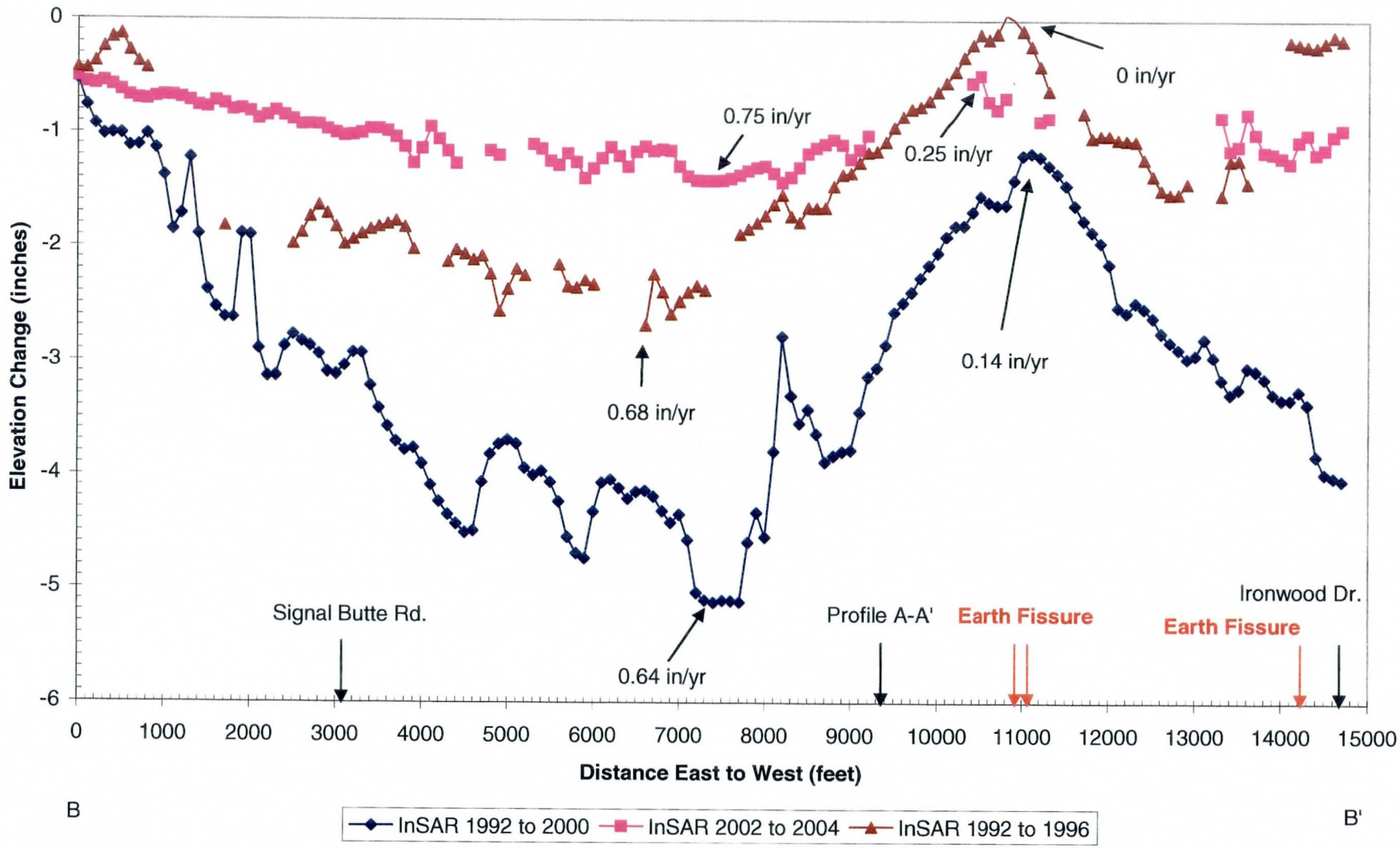
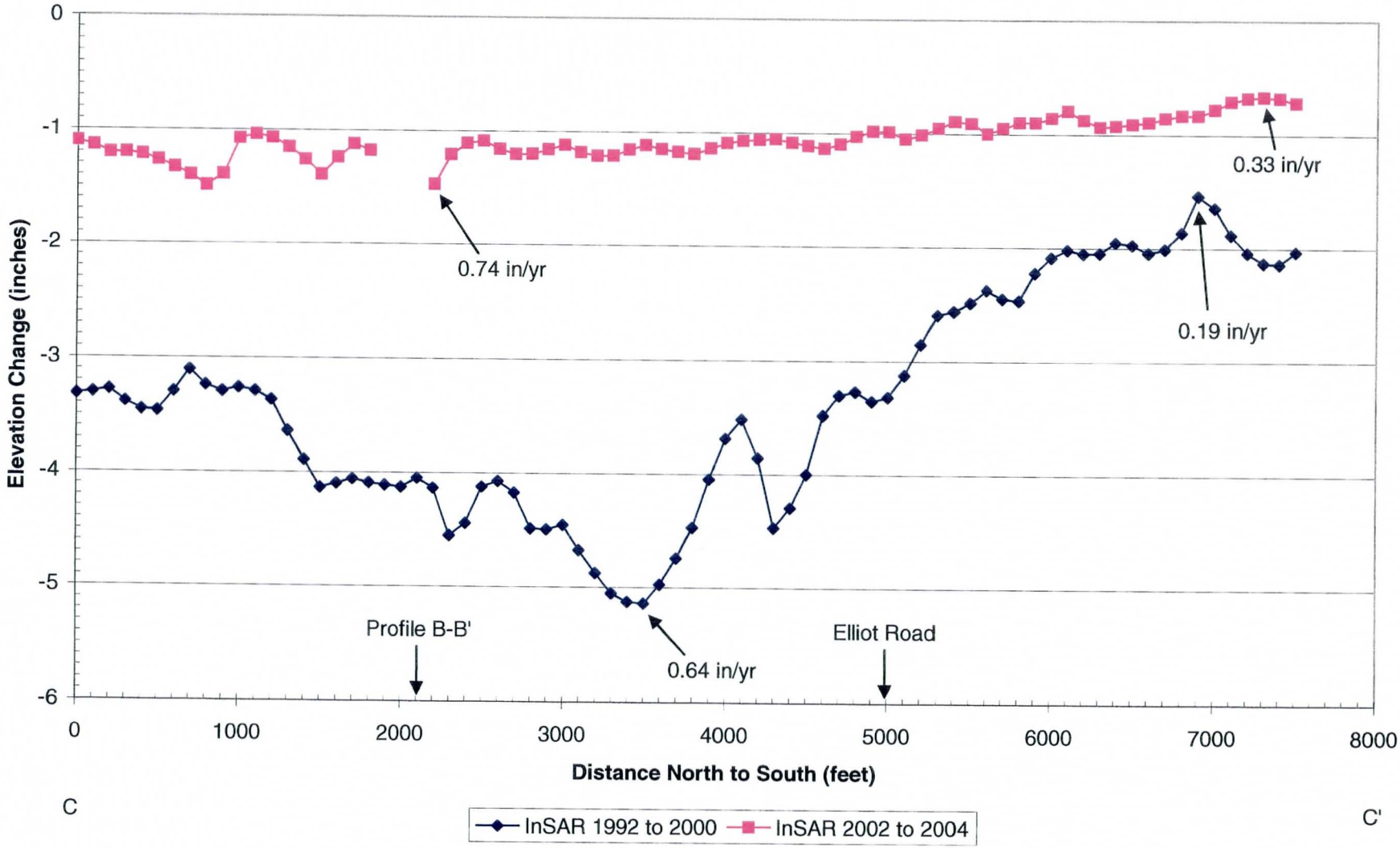
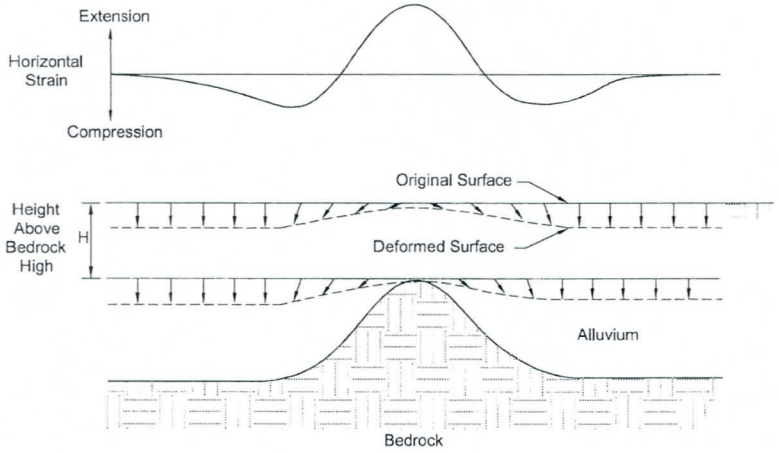
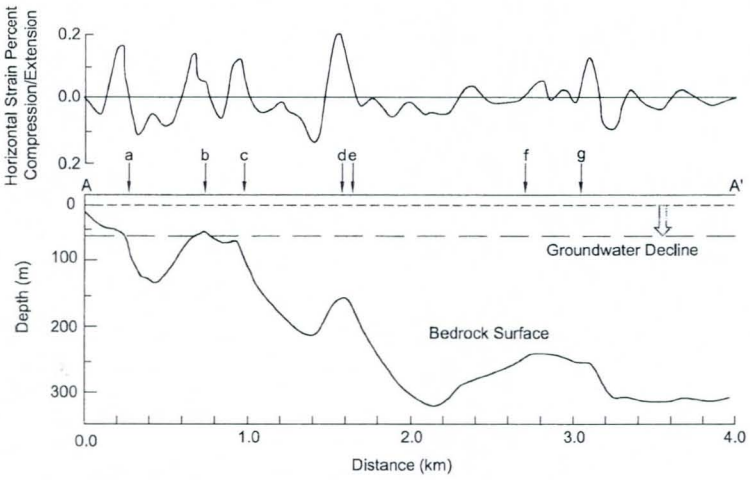


Figure 6
Subsidence Profile C - C'

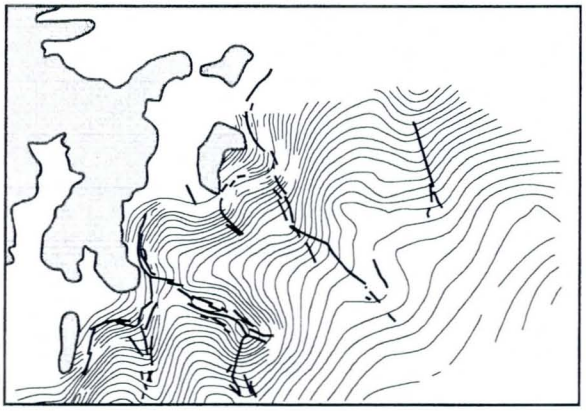




HORIZONTAL STRAIN PROFILE



COMPRESSION/EXTENSION PROFILE



RELATIONSHIP BETWEEN FISSURES AND BURIED BEDROCK SURFACE

After Jachens and Holzer, (1979, 1982)

JOB NO. 6-117-001053	GENERAL FISSURE MECHANISMS		amec
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DRAWN: GWH	PRELIMINARY EARTH FISSURE RISK ZONE INVESTIGATION REPORT HAWK ROCK STUDY AREA FCD 2006C005, WORK ASSIGNMENT NO.2	FIGURE 7	
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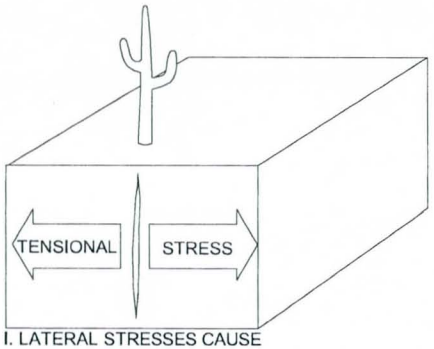
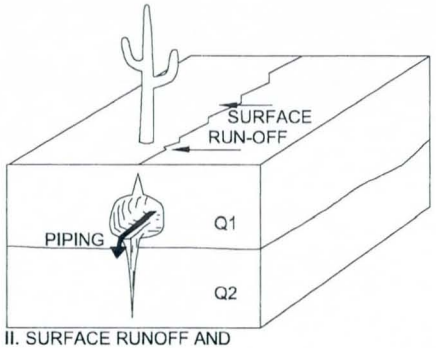
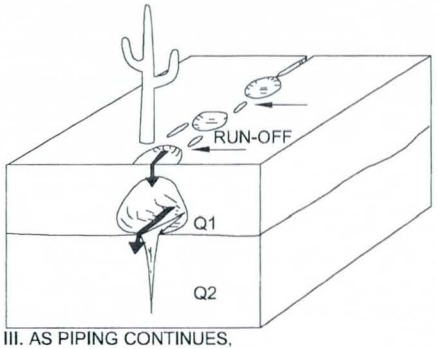


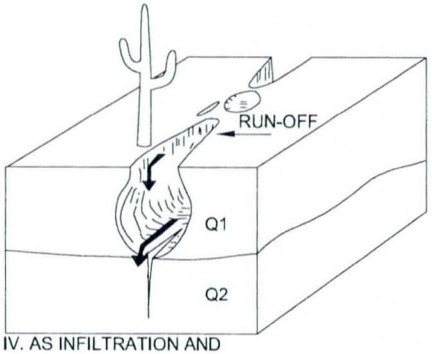
I. LATERAL STRESSES CAUSE TENSION CRACKING



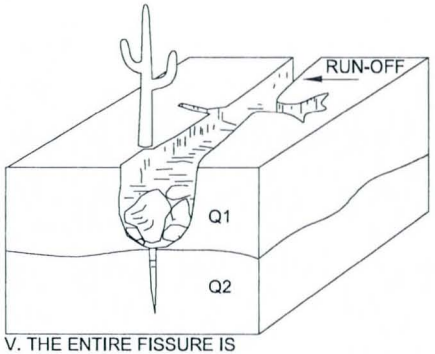
II. SURFACE RUNOFF AND INFILTRATION ENLARGE CRACK THROUGH SUBSURFACE PIPING



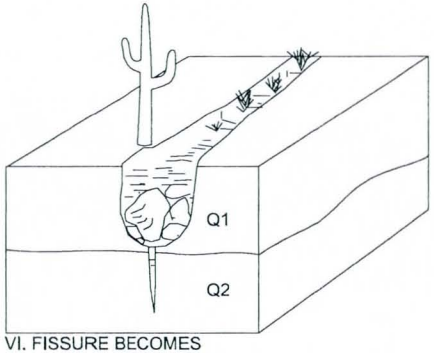
III. AS PIPING CONTINUES, FISSURE BEGINS TO APPEAR AT SURFACE AS SERIES OF POT HOLES AND SMALL CRACKS



IV. AS INFILTRATION AND EROSION CONTINUE, FISSURE ENLARGES AND COMPLETELY OPENS TO SURFACE AS TUNNEL ROOF COLLAPSES



V. THE ENTIRE FISSURE IS OPENED TO THE SURFACE AND ENLARGEMENT CONTINUES AS FISSURED WALLS ARE WIDENED; EXTENSIVE SLUMPING AND SIDE STREAM GULLYING OCCUR



VI. FISSURE BECOMES FILLED WITH SLUMP AND RUN-OFF DEBRIS AND IS MARKED BY VEGETATION LINEAMENT AND SLIGHT SURFACE DEPRESSION; IT MAY BECOME REACTIVATED UPON RENEWAL OF TENSILE STRESS

LEGEND

Q1 - HOLOCENE SOILS WITH STAGE I CEMENTATION
Q2 - PREHOLOCENE SOILS WITH STAGE II CEMENTATION

MODIFIED AFTER BELL, 1981

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DESIGN:	LAH
DRAWN:	GWH
DATE:	8/2006
SCALE:	N.T.S.

STAGES OF FISSURE DEVELOPMENT

PRELIMINARY EARTH FISSURE RISK ZONE INVESTIGATION REPORT
HAWK ROCK STUDY AREA
FCD 2006C005, WORK ASSIGNMENT NO.2

FIGURE 8

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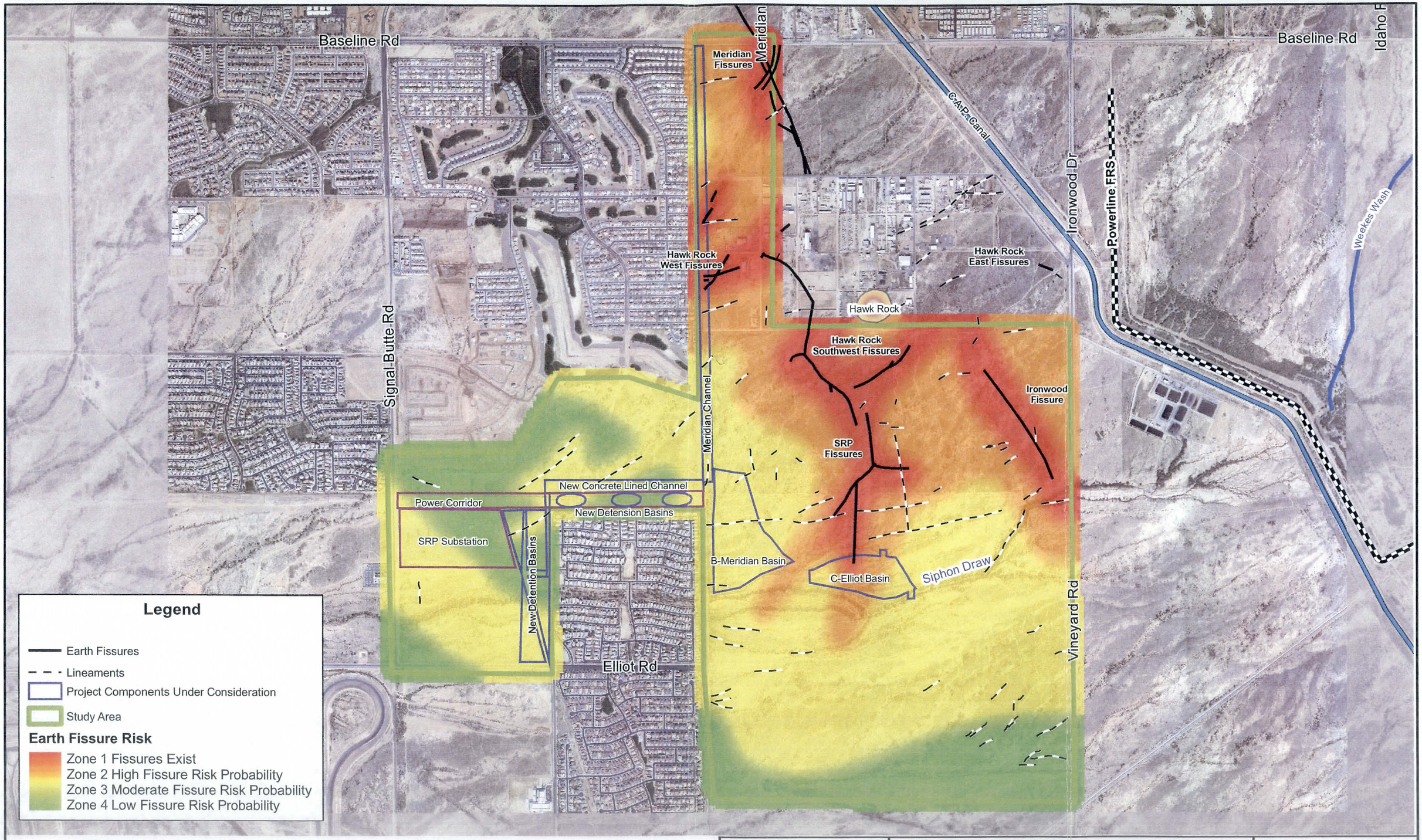

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N

Color aerial Imagery from FCDMC, taken in January & February, 2006
B&W aerial imagery from USGS DOQQs taken November 14, 1992

JOB NO.:	6-117-001053
DESIGN:	KCF
DRAWN:	EMP
DATE:	9/18/2006
SCALE:	1" = 1500'

PRELIMINARY EARTH FISSURE RISK ZONE INVESTIGATION
HAWK ROCK STUDY AREA
MARICOPA AND PINAL COUNTIES, ARIZONA
Contract FCD 2006C005, Work Assignment 2

Earth Fissure Risk Zones

FIGURE 9

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Map Document: (\\Phx1-fs1\gis_share\Projects\6-117-001053\MXD\Risk_Zones.mxd)
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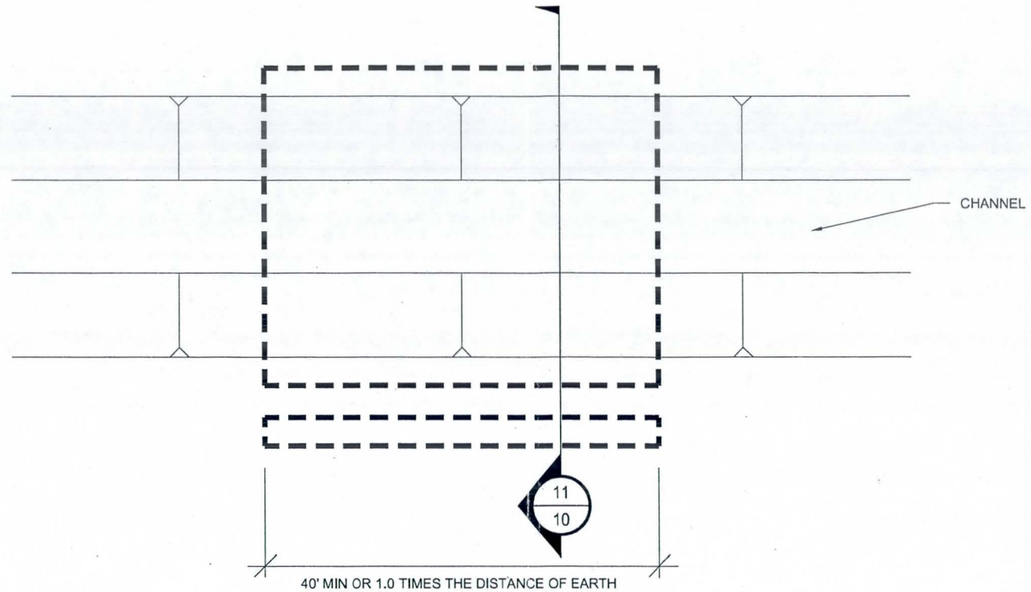
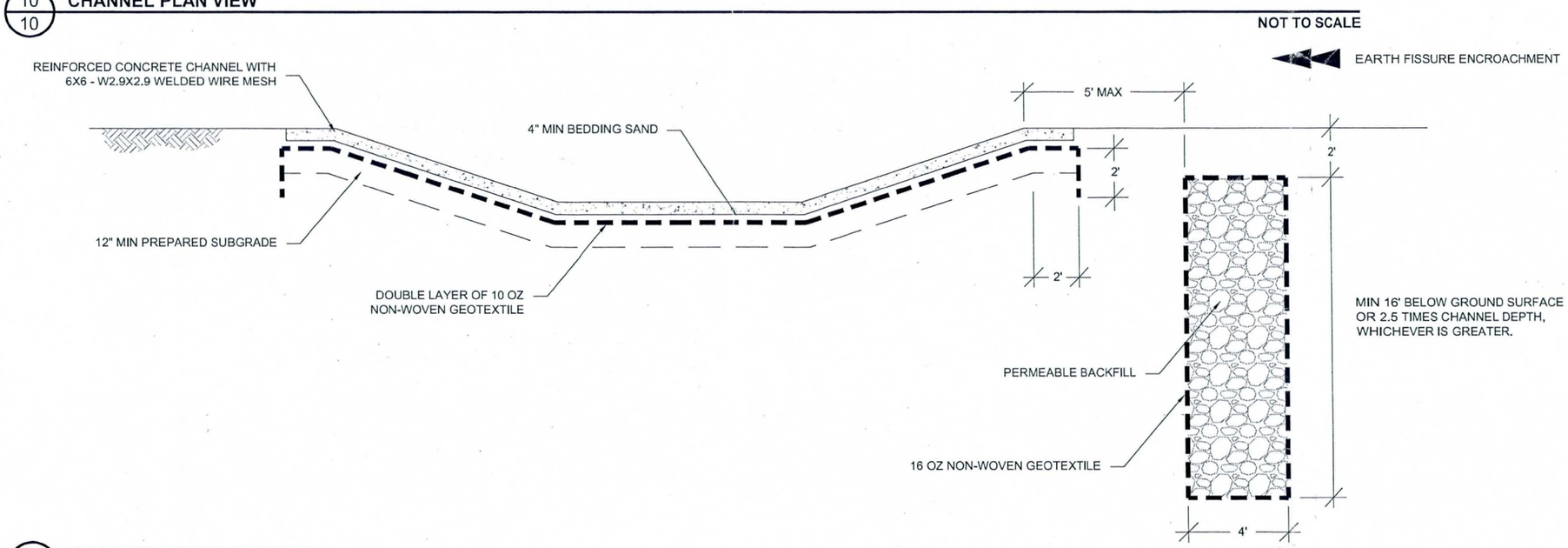


10/10 **CHANNEL PLAN VIEW**

NOT TO SCALE



11/10 **CHANNEL CROSS-SECTION**

NOT TO SCALE

JOB NO.	6-117-001053
DESIGN:	BAH
DRAWN:	GWH
DATE:	8/2006
SCALE:	N.T.S.

CHANNEL ALTERNATIVE
PLAN VIEW AND CROSS - SECTION

PRELIMINARY EARTH FISSURE RISK ZONE INVESTIGATION REPORT
HAWK ROCK STUDY AREA
FCD 2006C005, WORK ASSIGNMENT NO.2

FIGURE 10

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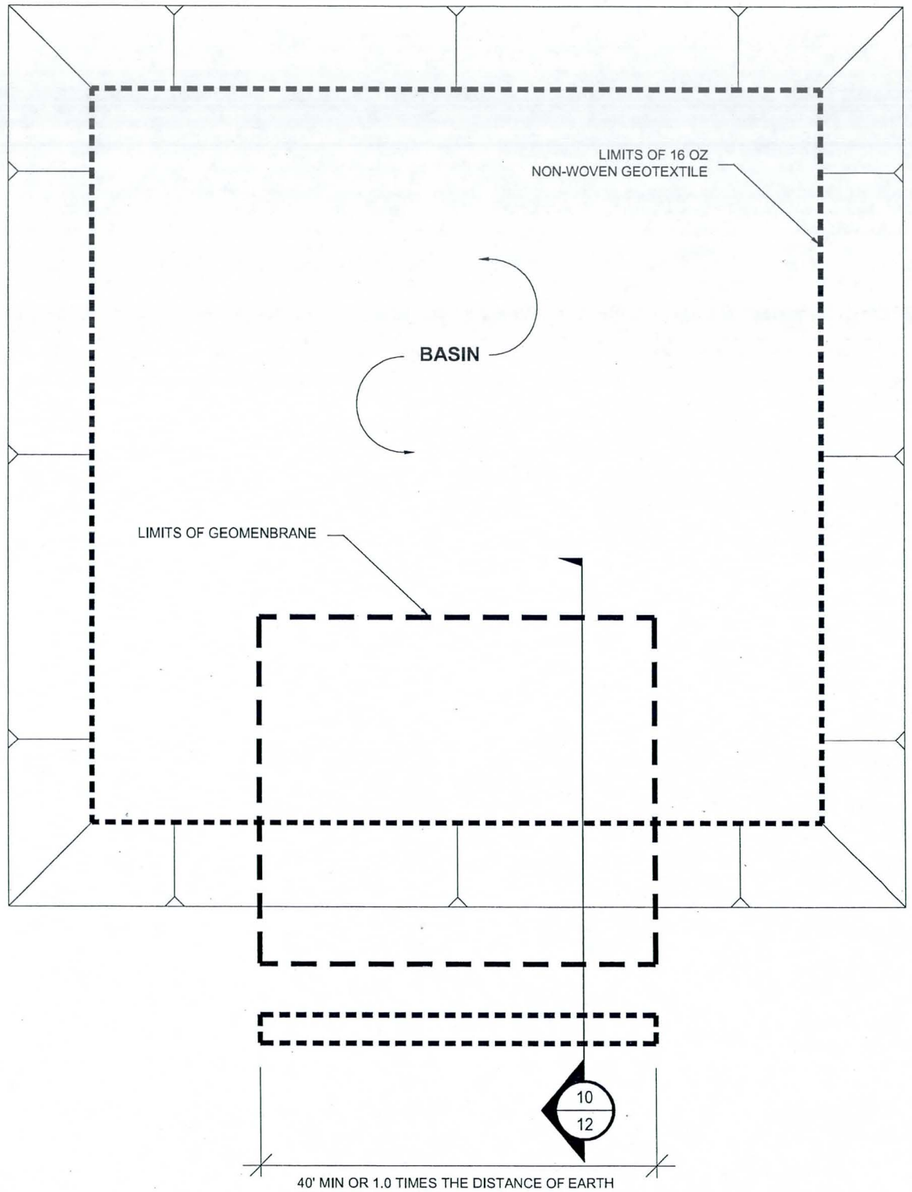
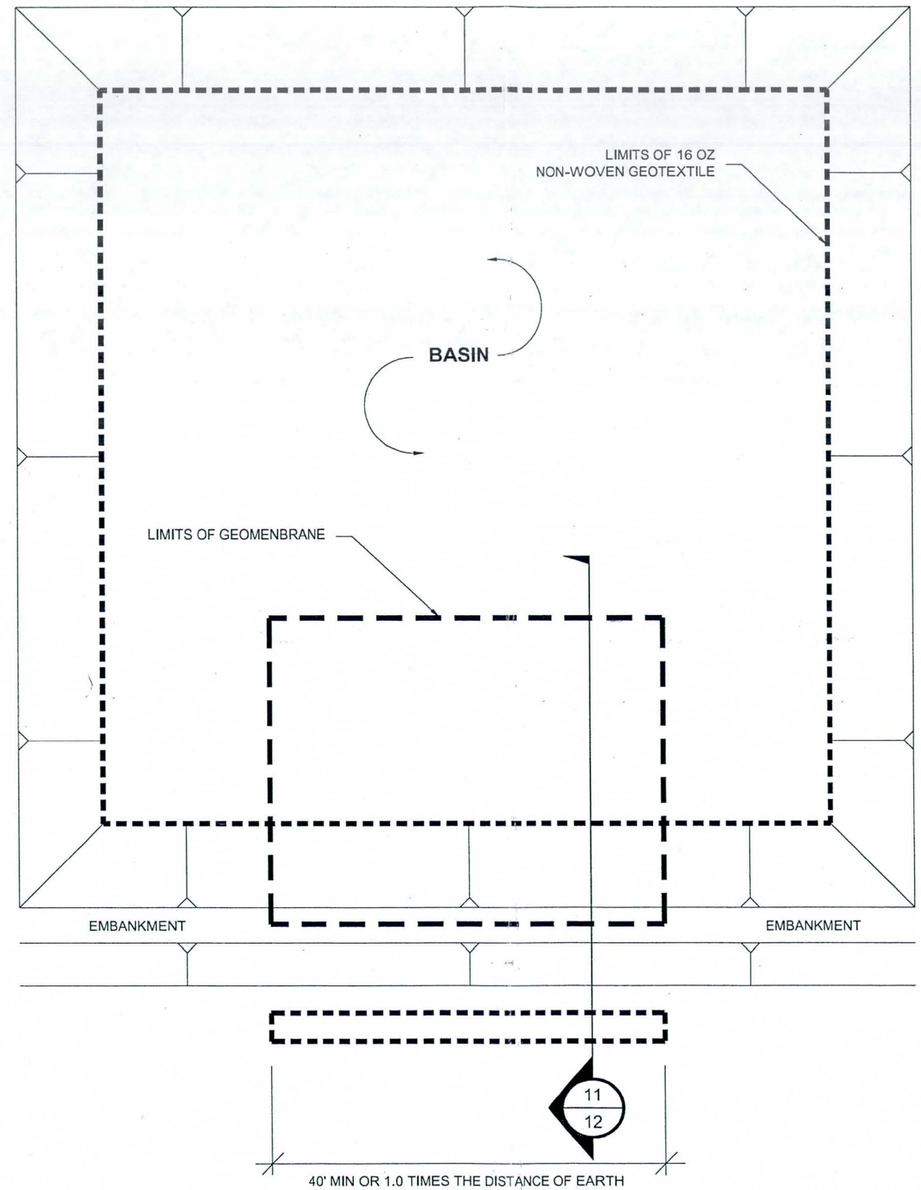


10/11 **BASIN PLAN VIEW**

NOT TO SCALE



11/11 **BASIN WITH EMBANKMENT CROSS-SECTION**

NOT TO SCALE

JOB NO.	6-117-001053
DESIGN:	BAH
DRAWN:	GWH
DATE:	8/2006
SCALE:	N.T.S.

BASIN ALTERNATIVES - PLAN VIEWS

PRELIMINARY EARTH FISSURE RISK ZONE INVESTIGATION REPORT
HAWK ROCK STUDY AREA
FCD 2006C005, WORK ASSIGNMENT NO.2

FIGURE 11

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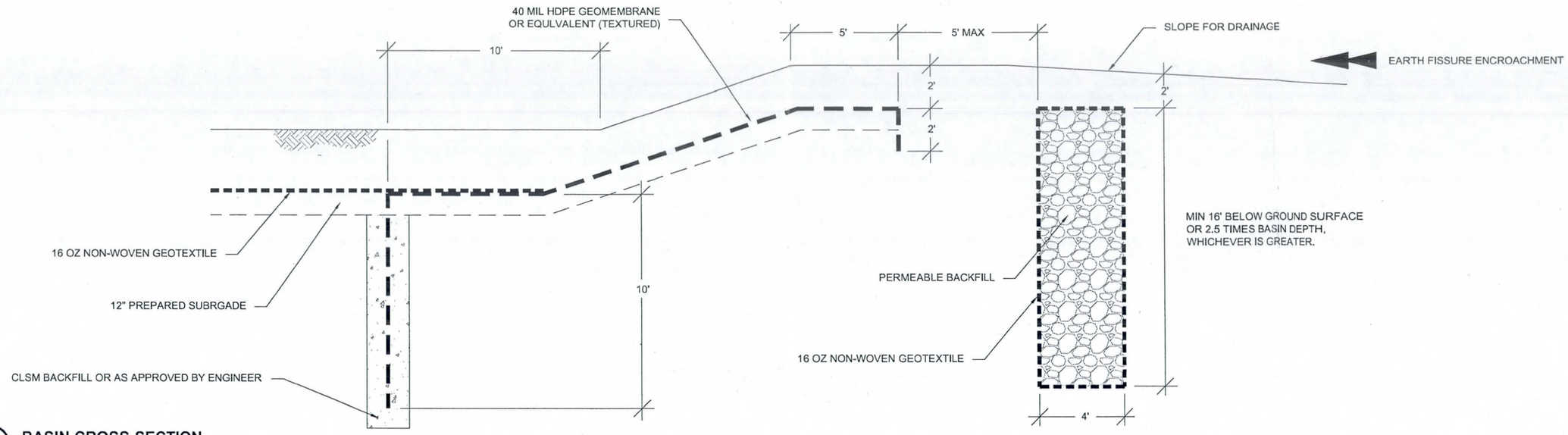
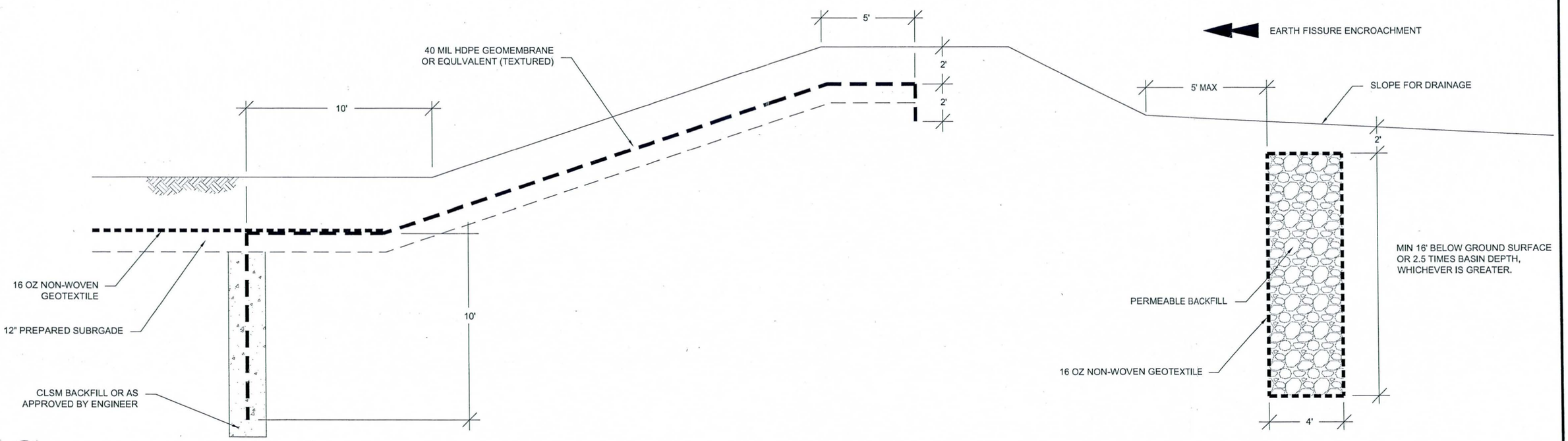


10/12 **BASIN CROSS-SECTION**

NOT TO SCALE



11/12 **BASIN WITH EMBANKMENT PLAN VIEW**

NOT TO SCALE

JOB NO.	6-117-001053
DESIGN:	BAH
DRAWN:	GWH
DATE:	8/2006
SCALE:	N.T.S.

BASIN ALTERNATIVES - CROSS-SECTIONS

PRELIMINARY EARTH FISSURE RISK ZONE INVESTIGATION REPORT
HAWK ROCK STUDY AREA
FCD 2006C005, WORK ASSIGNMENT NO.2

FIGURE 12

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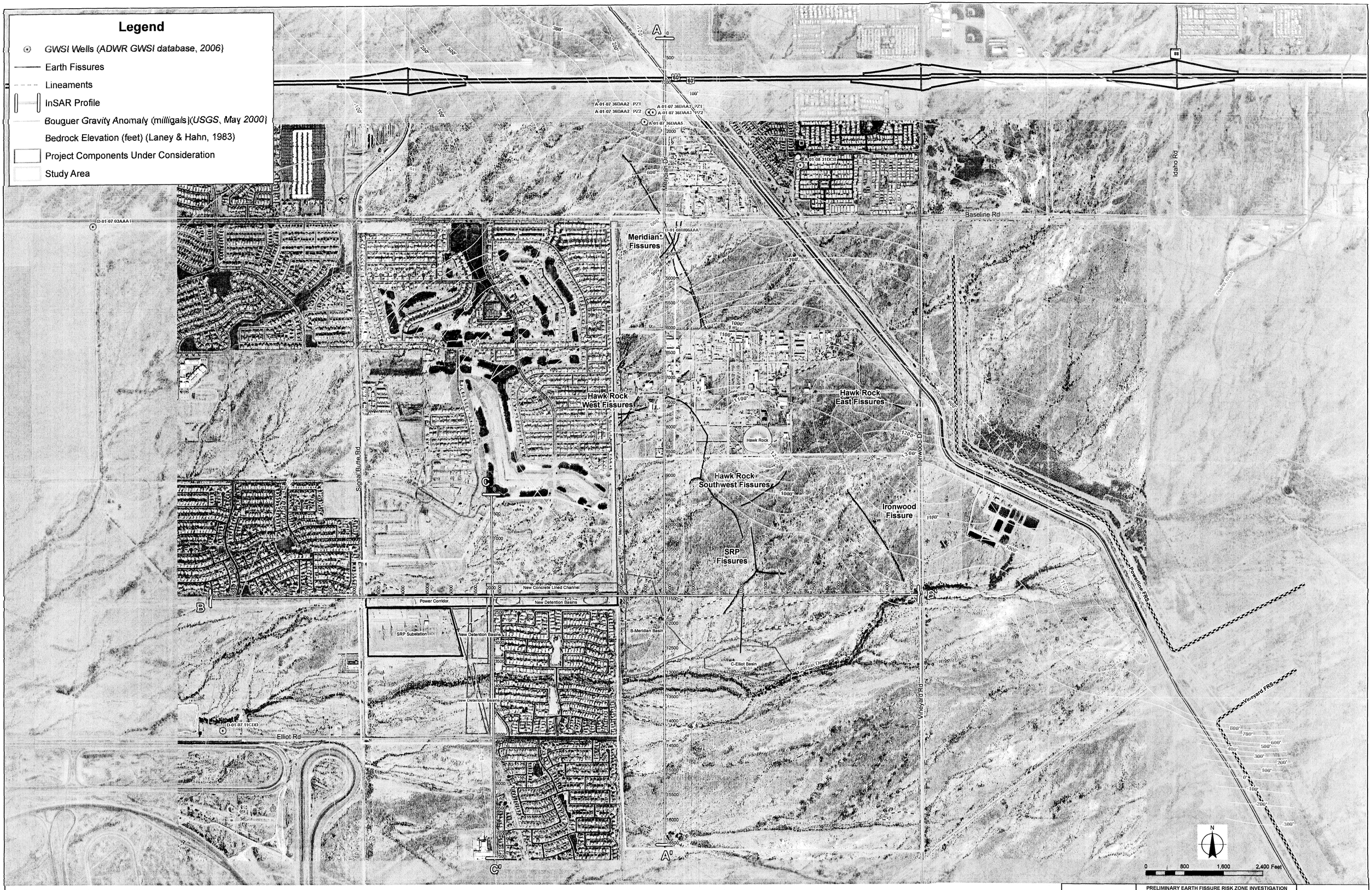
SHEETS



Color aerial imagery from FCDMC, taken in January & February, 2006
B&W aerial imagery from USGS DOQQs taken November 14, 1992

Map Document: (Ipfs1 fs1\gis_share\Projects\6-117-001053\MXD\SHEET 1.mxd)
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JOB NO.:	6-117-001053
DESIGN:	KCF
DRAWN:	EMP
DATE:	09/08/2006
SCALE:	1" = 800'

PRELIMINARY EARTH FISSURE RISK ZONE INVESTIGATION
HAWK ROCK STUDY AREA
MARICOPA AND PINAL COUNTIES, ARIZONA
Contract FCD 2006C005, Work Assignment 2

Site Plan

SHEET 1

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