Terrain Solutions, Inc.

Environmental Site Assessments • Land Resources Evaluation
Hydrogeology • Environmental Geology • Engineering Geology

PHASE I & III GEOLOGIC FAULT INVESTIGATION
FOR
WATER LINE REPLACEMENT IN THE SHEPHERD FOREST II AREA

A CITY OF HOUSTON PROJECT
(COH WBS NO. S-000035-0192-4 & ATL NO. G13-196)

GENERALLY LOCATED BETWEEN LOOP 610 NORTH AND WEST 34TH STREET AND CENTERED ON SHEPHERD DRIVE IN HOUSTON, HARRIS COUNTY, TEXAS

KEY MAP 452 (Panels P, Q & R)

PREPARED FOR
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PROJECT NO: 1401LN-06

APRIL 28, 2014

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April 28, 2014

Peng Sia Tang, P.E.
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3143 Yellowstone Blvd.
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Subject: Phase I & III Geologic Fault Investigation
City of Houston Water Line Replacement in Ashford Forest Area
(COH WBS No. S-000035-0192-4 & ATL No. G13-196)
Generally located between Loop 610 North and West 34th Street and centered on Shepherd Drive in Houston, Harris County, Texas

Terrain Solutions, Inc. Project No. 1401LN-06

Dear Mr. Tang:

Terrain Solutions, Inc. (TSI) is pleased to submit this report of the Phase I & Phase III Geologic Fault Investigation that was conducted on the above referenced site. This study was performed in general accordance with Terrain Solution's proposal letter (P1312-148) of December 21, 2013 that was accepted via your signature of January 16, 2014.

TSI appreciates the opportunity to be of service to you. Should you have any questions or comments, please do not hesitate to call me.

STATE OF TEXAS
RICHARD G. HOWE
GEOLOGY
27
LICENSED
PROFESSIONAL GEOSCIENTIST

Sincerely,

Richard G. Howe

Richard G. Howe, P.G., C.P.G.
Project Geologist

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EXECUTIVE SUMMARY

Terrain Solutions, Inc. (TSI) has completed a Phase I and Phase III Geologic Fault Investigation for the City of Houston's Water Line Replacement in the Shepherd Forest II Area. The project area, which is mostly within the Shepherd Forest neighborhood, is generally bounded by Ansbury Drive to the west, West 34th Street to the north, Yale Street to the east, and Loop 610 N to the south. The portion of the project alignments that extends outside of the described boundary is along Alba Road between West 34th Street and 35th Street. The project is in an area that is primarily residential with commercial development along major thoroughfares.

TSI's services included a review of available published and unpublished information on faulting in the area, a field reconnaissance, and field mapping of the Eureka Heights fault within the project area. The investigation had two stages: 1) the Phase III investigation which located and mapped the Eureka Heights fault with respect to the project alignments and which gathered data to determine the nature of ground deformation and movement for the fault; and 2) the Phase I investigation which examined the remainder of the project area to identify other surface faults that could be present and have a potential to impact the project.

During the course of this study, TSI looked at historical topographic maps, proprietary subsurface geologic structure maps, historical aerial photographs, and LIDAR imagery. Field mapping incorporated the use of a Total Station and other field equipment to locate the Eureka Heights fault and determine its ground deformation characteristics and past movement rates.

TSI's findings and conclusions – which were derived from review of available geologic information, the field reconnaissance, and field mapping – are summarized below:

- The Eureka Heights Fault crosses through the project area.
- The Eureka Heights fault intersects the project alignments at 1) the intersection of Alba Road and West 30th Street near alignment station no. 1+82 on Alba and near alignment station 16+25 on West 30th Street; 2) in the 1000 block of Stonecrest Drive near alignment station no. 22+76; 3) and at the intersection of West 31st Street and Dunsmere Road near alignment station no. 30+75 along West 31st and near alignment station 6+21 on Dunsmere Road.
- The vertical elevation offset in the streets intersected by the Eureka Heights fault appears to range from 1-1/2 ft. to 2-1/2 ft. The ground deformation zone associated with the Eureka Heights fault appears to vary between 40 and 60 feet.
- Relative elevation measurements of nearby benchmarks across the Eureka Heights fault on Shepherd Drive near West 34th Street have been made by Dr. Carl Norman, Professor Emeritus with the University of Houston, and these show an average movement rate of 0.04 inches per year from 1985 through 2007. The fastest movement observed during this interval was 0.1 inch per year between 1985 and 1987.

- Neither the review of available geologic information nor the field reconnaissance found obvious evidence of other faults in the project area that could impact the project alignment.

Based upon the findings and conclusions of this investigation, Terrain Solutions, Inc. believes that water lines and other linear utilities crossing into the defined fault hazard zones can be impacted by ground movement associated with the Eureka Heights fault. Consequently, TSI recommends that engineering design for the project consider both vertical and horizontal components of ground movement within the identifed fault hazard zones. Such consideration would incorporate the historical, fastest observed vertical movement rate of 0.1 inches per year into the expected life of the water lines that cross through the fault hazard zones. Additionally, estimating the maximum strain rate that could be experienced by the water lines should consider the fastest average vertical movement rates seen in the Houston area: 1 to 1.5 inches per year as historically observed along the Long Point fault which is about 2.3 miles from the Eureka Heights fault at its closest approach.

Considering a typical 74° dip for surface faults, horizontal displacements and movement rates are likely to be about 1/3 that of the vertical. Additionally, it should be remembered that water lines intersecting the fault zone at a right angle or near right angle will experience a more abrupt displacement than those that intersect at a more acute angle. For the latter type of intersection, the longer expanse of water line that will be affected by fault-related ground movement will have the displacement spread over a longer length of line.

Terrain Solutions, Inc. believes the likelihood that other surface faults impact the remainder of the project area is low, and thus does not believe fault-related ground movement is a factor for water line design outside the defined fault hazard zones.

This executive summary does not fully summarize Terrain Solutions, Inc.'s findings, conclusions, and recommendations. Those findings, conclusions, and recommendations are conveyed through the entirety of this report.

INTRODUCTION

PROJECT BACKGROUND & OBJECTIVE

Terrain Solutions, Inc. (TSI) was authorized by Mr. Peng Sia Tang, P.E. of Associated Testing Laboratories, Inc.. to perform a Phase I Geologic Fault Investigation for the City of Houston's Water Line Replacement in the Shepherd Forest II area (COH WBS No. S-000035-0192-4 & ATL No. G13-196).

The project area, which is mostly within the Shepherd Forest neighborhood, has an irregular configuration configuration and is generally bounded by Ansbury Drive to the west, West 34th Street to the north, Yale Street to the east, and Loop 610 N to the south. The portion of the project alignments that extends outside of the described boundary is along Alba Road between West 34th Street and 35th Street.

The objective of this study was two-fold: 1) locate the Eureka Heights fault with respect to the project alignment and determine where and how it likely impacts the project; and 2) identify other faults that may exist in or near the project area.

PROJECT SCOPE

During the course of this investigation, the following tasks were performed:

A search was conducted of available geologic information, including both published and unpublished literature on geologic faulting for the area. Literature reviewed included publications of the U.S. Geological Survey and the Texas Bureau of Economic Geology.

A review of vertical aerial photographs, LiDAR imagery, and U.S.G.S. topographic maps was made to identify surface features that may indicate the presence of surface faults. Harris County LiDAR contour maps for the study area were also viewed.

A field reconnaissance of the subject site and the surrounding area was performed to identify and locate surface features that indicate the presence of surface faults.

The Eureka Heights fault was mapped where it intersected the proposed water lines in the project area, and field data was collected and analyzed for the nature of ground movement rates and surface deformation associated with these faults.

A fault map delineating the Eureka Heights fault and its fault hazard zone was developed for each location where the fault intersected the project alignment.

This report was prepared summarizing Terrain Solutions, Inc.'s findings, conclusions, opinions, and recommendations.

BASIS OF REPORT

This study was performed in general accordance with guidelines established by the Houston Geological Society for Phase I Geologic Fault Investigations.

Although this study has been a reasonably thorough attempt to identify faults in the study area, there is a possibility that existing faults may have escaped detection due to the inherent limitations of a Phase I Fault Investigation or the inaccuracy of published and unpublished data. If faults are present, the surface evidence for them may not be well developed or may be obscured by erosion, soil and vegetation cover, and/or new construction. In comparison, a Phase II Fault Investigation – which consists of the collection of subsurface geologic data via the drilling and geophysical logging of boreholes – adds information not included in a Phase I Fault Investigation and consequently, has a higher certainty for its conclusions.

Terrain Solutions, Inc.'s professional services have been performed using that degree of care and skill ordinarily exercised, under similar conditions, by geological consultants practicing in this or similar localities.

Terrain Solutions, Inc. reserves the right to alter its conclusions and recommendations based on our review of any information obtained after the date of this report. The data obtained during the course of this investigation and this report is for the sole and exclusive use of the Client (Associated Testing Laboratories, Inc. and the City of Houston). Unless permission is granted for other uses by the Client, Terrain Solutions, Inc. will hold all data, papers, correspondences, and reports pertaining to this study confidential to the extent allowed by law.

PROFESSIONAL QUALIFICATIONS

This fault investigation was performed by Richard G. Howe, P.G., C.P.G. Mr. Howe has 38 years of professional experience in geological and environmental applications which include environmental site assessments, UST investigations, engineering geology/hydrogeology studies, and geologic surface fault investigations. He has conducted surface fault investigations for both public and private sector projects. Mr. Howe holds a B.S. in Geology from Lamar University, Beaumont, Texas, and a Master of Geoscience from Texas A&M University, College Station, Texas. His graduate work concentrated in areas relating to engineering geology, hydrogeology, and environmental geology. He is a Licensed Professional Geologist (P.G. #27) in the State of Texas and is a Certified Professional Geologist (CPG #5191) with the American Institute of Professional Geologists.

GEOLOGIC BACKGROUND

GEOLOGIC SETTING

The study area is located in the Upper Texas Gulf Coast, an area underlain by a wedge of sediments that approaches 50,000 feet in thickness along the Texas coastline. These sediments are primarily comprised of gravel, sand, silt, and clay and were deposited in fluvial (river-related), deltaic, coastal, and shallow marine environments. These sedimentary deposits – which dip gently toward the Gulf of Mexico – are broken by normal faults and salt domes.

A review of the Bureau of Economic Geology 1982 Geologic Atlas of Texas Houston Sheet indicates the geologic formation underlying the study area is the Beaumont Formation. The Beaumont Formation was deposited during the Pleistocene Epoch, a geologic time period that began about 2.0 million years ago and ended about 10 to 15 thousand years ago with the retreat of the last continental glaciers in North America. The Beaumont Formation, which consists of interbedded layers of clay, sand, and silt, was primarily deposited in a fluvial and deltaic setting.

The Houston Metropolitan Area lies within the Houston Salt Dome Embayment, a geologic province that contains a large number of salt domes. Salt domes are massive plugs of salt that push upward from great depths through overlying geologic strata. The depths at which they can be found range from just below the surface to several thousand feet. As the salt plug moves upward, it often causes faulting in the overlying sediments. Sometimes these faults reach the surface. In particular, the project area lies in an interdomal area and is thus not impacted by faults associated with salt domes.

NATURE OF SURFACE FAULTING IN THE TEXAS GULF COAST

Geologic faults exist beneath the surface throughout the Gulf Coast region of Texas. Many of these faults extend upward to the surface. These surface faults are found in a swath that extends along the Gulf Coast and ranges from several hundred miles offshore to at least 90 miles inland. In the Houston Metropolitan Area, over 350 surface faults are known or suspected to be present. Surface faults can range in length from hundreds of yards to several miles.

Faulting in the Gulf Coast region consists of two basic types: normal faults that are generally oriented parallel to the coast and normal faults that are associated with salt domes. The parallel-to-coast faults, often called regional faults because of their individual lengths and association with fault systems that can run for tens of miles, generally have greater throws (vertical displacement) and movement rates than those of salt domes. Faults related to salt domes do not follow a consistent orientation, that is, their strikes (orientations) are random. Salt dome-related faults usually have a shorter length than the parallel-to-coast variety.

One hazard presented by surface faults is the ground movement that accompanies them. This displacement of the land can cause damage to buildings, underground utilities, roads, pipelines, and other structures that are nearby or directly over a fault. Fault-related ground movement can cause foundations to break, floors to tilt, windows and doorways to distort, interior and exterior walls to crack, and roofs to leak. Ultimately, this can lead to the loss of structural integrity. Additionally, the vertical displacement across a fault can impact local drainage and result in collection of water on the downthrown side of the fault.

Movement rates of faults are slow, usually less than one inch per year. In general, fault movement rates may be variable and episodic for a specific fault, and some time may pass between movement occurrences. Fault reactivation and variation in fault movement rates can be a result of tectonic (crustal deformation) stresses and may be influenced by subsurface fluid withdrawal via groundwater pumping and oil and gas production or by fluid injection. Fault movement rates can be estimated where older structures or roadways display damage.

A fault scarp – a linear surface feature that displays an abrupt change in ground elevation across it – results from ground movement along a surface fault. The slope of the ground adjacent to the high side of the fault scarp is usually the same as that on its lower side. The fault scarp itself has a steeper slope relative to the slopes on either side of it. Fault scarps can produce linear surface features (lineaments) on aerial photographs and topographic maps. Linear patterns of vegetation can develop along faults primarily as a result of the accumulation of moisture or water on the downthrown side of the fault. Evidence of faulting in undeveloped areas may be obscured due to dense vegetation cover such as woods and underbrush. In urbanized areas, land development often masks the presence of faulting, especially in the case of inactive and slowly moving faults.

INDICATORS OF SURFACE FAULTING

The presence of a surface fault can be indicated from lineaments observed on aerial photographs and other remote images, linear features and drainage patterns depicted on topographic maps, observed damage to buildings and other structures, subsurface geologic information, and/or the existence of an escarpment or certain other geomorphic structures. Any of these indicators by itself may not be sufficient to determine with a high degree of certainty whether or not a surface fault exists. When two or more of these indicators depict coinciding features that are suggestive of a fault, the likelihood that a fault exists increases.

Subsurface exploration can yield geologic information that conclusively determines the presence of a fault. Such procedure entails the drilling and geophysical logging of boreholes and the analysis of the obtained data. Subsurface exploration, a costly endeavor, becomes especially important when the other information sources do not clearly establish the presence or absence of faulting.

Evidence of faulting at the surface is not always readily identifiable and can also be erroneously inferred. Topographic features such as escarpments associated with stream terraces may resemble a fault scarp. However, in many cases these features cannot be traced laterally for any substantial distance or the trend of a particular escarpment might change significantly which would indicate the feature is not related to a fault. Other surface lineaments that can erroneously suggest faulting include pipelines, roads, fence lines, stratigraphic contacts, soil contacts, drainage patterns, and clearings made for seismic surveys during oil & gas exploration. In most cases, observed natural linear surface features on aerial photographs are related to changes in vegetation and moisture, while on topographic maps they are related to changes in slope and/or drainage patterns. Whereas damage to structures can indicate faulting, normal deterioration and deformational effects resulting from expansive clays can produce damage that is similar to that associated with faults.

Though the existence of stream terraces and other linear natural topographic features does not necessarily indicate the presence of a fault, there are times wherein fault scarps are coincident with and are the progenitors of these features. Additionally, there are instances where the fault may be offset from such a topographic feature yet is the cause of its existence and the control on its orientation.

In undeveloped terrain that is covered by dense forest and/or brushy vegetation, the visual, onsite identification of fault scarps can be difficult to impossible. Lineaments that could be associated with faulting are likely to be masked by the heavy overgrowth. In such environments, several lines of boreholes across the study area may be needed to supplement the aerial photograph/topographic map analysis and field reconnaissance. Electric log (geophysical) data obtained from these boreholes can provide an idea of subsurface conditions and the likelihood of fault existence.

GEOLOGIC DATA REVIEW

GEOLOGIC LITERATURE & INFORMATION

TSI reviewed proprietary and published geologic literature and maps regarding faults in the study area. The Houston Sheet of the Geologic Atlas of Texas (1982) shows a fault that corresponds to the Eureka Heights fault passing through the vicinity of the project area.

The Verbeek, Ratzlaff, & Clanton fault map for the North-Central and Western Houston Metropolitan area shows the Eureka Heights fault passing through the project area.

A proprietary, geologic, subsurface structure map shows a down-to-the-coast fault at a depth of approximately 7,500 feet BGS that – if projected to the surface – would likely correspond to the Eureka Heights fault.

REMOTE IMAGERY: AERIAL PHOTOGRAPHS & LIDAR IMAGERY

Aerial Photos

In viewing aerial photographs, features that may indicate the presence of a fault include tonal variations in vegetation, areas of standing water, certain patterns in rice field levees and contour plowing, and certain drainage patterns. Such surface features may have a curvilinear character or may manifest themselves in alignments that form linear expressions. These linear features by themselves do not necessarily prove that a fault is present, but allow for more effective topographic map review and field reconnaissance.

Aerial photographs can assist in determining the age of roads, streets, and other structures in the study area. Such age determination can provide some insight as to fault movement rates should a fault be present in the area. When road and street surfaces as well as other structures are several decades old and do not display evidence of faulting, it reduces – but does not eliminate – the probability that a fault may be present.

Electronic files of historic, vertical, aerial photographs were obtained and reviewed for this study. These aerial photos were originally taken by agencies such as the Houston-Galveston Area Council (HGAC), Texas Department of Transportation (TxDOT), Texas Orthoimagery Program (TOP), National Agriculture Imagery Program (NAIP), Wallace-Zingery, the U.S. Geological Survey (USGS), and the Agricultural Stabilization and Conservation Service (ASCS).

TSI reviewed the following sets of vertical aerial photographs:

Date	Type	Source Photo No.
04-03-44	Black & White	ASCS BQY-4C-24 BQY-4C-25 BQY-4C-62 BQY-4C-63
04-26-53	Black & White	ASCS BQY-12M-204 BQY-12M-205
05-06-53	Black & White	ASCS BQY-16M-26 BQY-16M-27 BQY-16M-28
10-23-62	Black & White	USGS 1-224 1-225 1-226
02-21-69	Black & White	Wallace-Zingery 101
01-22-73	Black & White	??? 173-175
02-23-76	Black & White	USGS 2-390 2-391 2-392
03-25-79	Black & White	TxDOT 1-13-271 1-14-301

Date	Type	Source Photo No.
04-23-86	Black & White	TxDOT 2-11-411 2-12-449 2-12-450
10-10-89	Black & White	TxDOT 2-13-351 2-13-352 3-14-382
02-26-92	Black & White	TxDOT 3-15-825 3-15-827
1996	False Color (Infrared)	TOP 2995_13_2
2000	Color	HGAC 5259, 5260, 5359, 5360
2002	Color	HGAC 5259, 5260, 5359, 5360
2004	Color	HGAC 5259, 5260, 5359, 5360
2005	Color	NAIP 2995_15_3_09072005
2008	Color	HGAC 5259, 5260, 5359, 5360
2012	Color	NAIP 2995_13_2_20120601

Review of the aerial photographs shows the study area to have been an area of transition in 1944 wherein urban development was expanding into a rural setting. In 1944, the Shepherd Forest neighborhood has street and residential development east of the present day Attridge Road whereas the area to the west is undeveloped. In the 1962 aerial photograph, the area is entirely urbanized and the Shepherd Forest neighborhood has been developed in its entirety.

Most of the photos from 1973 through 2008 display some type of road re-surfacing or patching along Loop 610 and/or its service roads. The location of the patches corresponds with the general location of the Eureka Heights fault. Re-surfacing or patching at the location of the Eureka Heights fault on Stonecrest Drive may be present in some of the aerial photos that are later than 1973; however, the discernibleness of these patches or repaving on Stonecrest is not high. The 2012 aerial does show a re-surfaced section along Stonecrest at the known location of the Eureka Heights fault.

No obvious evidence of other faulting in the project area was observed in the aerial photographs.

LiDAR Imagery

LiDAR imagery – digital elevation models (DEMs) developed by Harris County Flood Control District through its 2001 Tropical Storm Allison Project (TSARP) and by the Houston Galveston Area Council 2008 LiDAR survey – show a lineament which corresponds to the Eureka Heights fault crossing the study area. The lineament crosses the project alignments at the intersection of Alba Road and West 30th Street, in the 1000 block of Stonecrest, and near the intersection of West 31st Street and Dunsmere Road.

No obvious linear features indicative of other faulting were observed in the LiDAR imagery for the project area.

TOPOGRAPHIC MAPS

In addition to depicting the configuration of the land surface, topographic maps often show other physiographic features. Consequently, the presence of faults can sometimes be indicated on topographic maps by the shapes of and spacings between contour lines and by certain fault-induced characteristics of streams, ponds, and other landforms.

TSI reviewed the 1915, 1982, and 2013 U.S.G.S. topographic maps for the Houston Heights, Texas 7.5-minute Quadrangle. Additionally, the topographic contour lines derived from the 2008 HGAC LiDAR-survey were examined for the study area.

U.S.G.S 7.5-minute quadrangle topographic maps for Harris and Galveston Counties that were created from around 1915 through the early 1920s have one-foot contour intervals. One-foot contour intervals give expression to subtle variations in topography, and in the relatively flat terrain of the Texas Gulf Coast, such contour intervals can be especially useful in identifying and locating surface faults. The 1915 topographic map for the Houston Heights, Texas 7.5-minute Quadrangle has a one-foot contour interval.

Topographic maps published after the 1920s usually employed a five-foot contour interval. For the relatively flat terrain of the Texas Gulf Coast, this interval size tends to mask slight variations in topography and mainly reflects the general topography of an area. Surface faults with substantial surface expression may be evidenced on topographic maps using five-foot contour intervals; however, surface faults with smaller topographic relief are usually not visible on these maps. The 1982 and 2013 U.S.G.S. topographic maps for the Houston Heights, Texas Quadrangle have a five-foot contour interval.

The LiDAR topographic contour lines were developed from LiDAR (Light Detection And Ranging) elevation measurements acquired through HGAC's 2008 LiDAR survey of the Houston Metropolitan Area. These maps have a one-foot contour interval and, like the historical USGS topographic maps with one-foot intervals, more accurately depict the terrain when compared to five-foot interval maps. Furthermore, since the LiDAR topographic maps result from aerial scan data having an elevation accuracy of $\pm$ 0.5 feet and were developed on a 15-foot grid spacing, the contour lines may show more topographic detail as compared to the historical one-foot interval maps.

The 1915 Houston Heights map displays several fairly linear and relatively parallel contour lines that run from the southwest to the northeast in the general vicinity of the Eureka Heights Fault. The 1982 topographic map shows the 75-foot elevation contour generally along and near the alignment of the Eureka Heights fault north of West 31st Street. In the 2013 map, the 70-foot contour line appears to be largely co-incident with the fault's scarp from Stonecrest Drive northeastward beyond West 31st Street.

The elevation contour lines from the 2008 LiDAR survey have a contour pattern that generally delineates the location of the Eureka Heights fault scarp from Loop 610 N northeastward beyond West 31st Street.

No other evidence of faulting within or near the project area was observed in any of the topographic maps.

FIELD RECONNAISANCE & FIELD MAPPING

OBJECTIVE & APPROACH

The field reconnaissance was conducted by automobile and on foot on March 07 and from March 17 through 21, 2014 to observe the project area and surrounding study area for physical evidence of surface faulting. Any anomalous areas identified on aerial photographs, topographic maps, and available fault maps that could represent a fault are inspected during the field reconnaissance.

During the course of the field reconnaissance, all of the streets within the study area were examined for road surface flexures and/or cracks that would be indicative of faulting. Additionally, the field investigation looked for other evidence of faulting such as escarpments across open areas, various other geomorphic features associated with faults, and damage to buildings, houses, and parking surfaces arising from fault movement.

When circumstances warrant, mapping of faults that are found to be present in the project area is often performed concurrently with the field reconnaissance rather than as a separate effort. For this investigation, segments of the Eureka Heights fault were mapped at its intersections with the project alignment.

RECONNAISSANCE OF THE PROJECT AREA

The study area was driven with select areas being examined on foot. The areas that were walked are along the Eureka Heights fault, at locations along the project alignment where the Eureka Heights fault intersects the project alignment, and at other locations where some type of surface anomaly or irregularity was encountered. Flexures in road and ground surfaces were noted as to location, orientation, and topographic relief.

Whereas flexures in road and ground surfaces as well as other surface features indicative of faulting were looked for, no obvious evidence of surface faults – other than features associated with the Eureka Heights fault – was observed within the study area. Observed irregularities in road surfaces or across open areas that were not associated with the Eureka Heights fault appear to be a result of human activity or non-fault related, natural geomorphic phenomena.

Eureka Heights Fault

During the field reconnaissance, the Eureka Heights fault was found to cross the project area and to be in proximity to the USGS' delineation of it as well as the LiDAR DEM lineaments and the linear contour lines derived from LiDAR. The field evidence for the Eureka Heights fault consists of abrupt elevation differences in street surfaces which are accompanied by visible fault scarps in adjacent residential yards. At times, as on West 31st Street and Dunsmere Road, the elevation change in the street is accompanied by cracks in the pavement and street curbs as well as an abrupt change in slope. The immediate elevation drop across the fault typically ranges from about 1-1/2 feet to 2-1/2 feet and is always down-to-the-southeast. Some of the houses sitting atop the fault or extending partway into its deformation zone show signs of past ground motion such as cracked and patched masonry.

In the Shepherd Forest neighborhood, the Eureka Heights fault strikes (trends) to the northeast with a variable direction which is compounded by the fault's sinuosity. The Eureka Heights fault crosses the proposed water line alignments in the intersection of Alba Road and West 30th Street, in the 1000 block of Stonecrest Drive, and just south and east of the intersection of West 31st Street and Dunsmere Road. At West 31st Street the fault appears to begin taking a more easterly course.

MAPPING THE EUREKA HEIGHTS FAULT

Because of property accessibility issues as well as liability concerns, TSI did not develop a continuous map of the Eureka Heights fault across the project area. Instead, mapping of the Eureka Heights fault was limited to those locations where the fault intersected the project's proposed water line.

Field Measurements

Field mapping was accomplished using a variety of field equipment that included a Trimble Geo 7 handheld GPS device, a Sokkia Total Station, a 300-foot engineer's tape, a roller tape, and a Brunton pocket transit.

Measurements of points on the fault scarp, where discernible on adjacent properties, were made with respect to surveyed benchmarks in the street, and elevation profiles along or near the street's centerline were shot across street elevation changes associated with the fault. The mapped points along with the elevation profiles were used to locate and delineate the fault and provide an estimate of the width of its ground deformation zone.

Elevation Profiles

Elevation profiles are developed from field measurements of relative elevations across a fault scarp. The purpose of elevation profiles is to help define various characteristics of the fault which include: scarp height, the location of the fault trace, movement rates, and ground deformation zone width. Ideally, the profile lines are oriented as perpendicular to the fault as practicable and are generally centered on the fault. Measurements along each profile line are usually started from the upthrown end and, consequently, are referenced to it. The horizontal distance axis on the elevation profiles shows the distance of each elevation point from the upthrown end point of the profile (0 ft.).

Five elevation profiles were developed for the project area, and they were placed at the Eureka Heights fault's intersection with Alba Road, West 30th Street, Stonecrest Drive, Dunsmere Road, and West 31st Street (Plates II, III & IV). Relative elevations along each profile were measured along the center line of the street with the Total Station. The map locations of the profiles were determined by tying them to survey markers located in the street.

Because the fault's angle of intersection with the street centerlines is acute, the length of each elevation profile was corrected to provide an idea of the rate of elevation change and the amount of ground deformation that is normal to the strike of the fault. The correction was made by multiplying the horizontal distance of each elevation point by the sine of the angle of intersection. It should be noted that elevation profiles shot along paved streets may not reflect actual scarp height and deformation zone width since they can be masked by the brittle behavior of steel-reinforced concrete. Nevertheless, such elevation profiles can be useful in providing an estimate of the fault's ground deformation.

Field observations along with the elevation profiles indicate the deformation zone of the Eureka Heights fault ranges from about 40 to 60 feet in width and the scarp height ranges between 1-1/2 to 2-1/2 feet. The actual scarp height at some points could be greater than measured since the height may have been reduced by development and street re-construction. Also, the actual width of the deformation zone could be less than the amount indicated by the profiles since street construction could alter the actual scarp width.

The elevation profiles are in the Appendix of this report.

FAULT MAP DEVELOPMENT

Data collected in the field was interpreted, plotted, and analyzed on a base map that was provided by ATL. The fault maps for this report (Plates II, III, & IV) were developed from this base map.

MAP CONSTRUCTION

A fault map was made for each location in the project area where the project alignment is intersected by the Eureka Heights fault. Information used to construct the fault maps consists of mapped points along the fault scarp on properties adjacent intersected streets, observed deformation zone widths, mapped cracks in the street pavement and curbs, and elevation changes observed in the elevation profiles. The fault maps show the approximate location and strike of the fault trace, the approximate angle of intersection between the fault and the project alignment, and the fault hazard zone.

The fault hazard zone is designed to contain the ground movement that runs along the fault. To ensure that it does, the width of the hazard zone incorporates the following factors: 1) the estimated and/or measured width of the fault's ground deformation zone; 2) the uncertainty of the actual position of the fault at locations where it is not clearly discernible; 3) the sinuosity of the fault; and 4) the variability in the width of the ground deformation zone along the fault. To facilitate engineering design, the width between and the orientation of the upthrown and downthrown limits of the hazard zone may be adjusted so that they are perpendicular to the project alignment and street ROW boundaries.

FAULT HAZARD ZONE LOCATIONS

The following table lists the approximate locations where the Eureka Heights fault intersects the project alignments and gives the angle of intersection and the length of the fault hazard zone at that location:

Street	Fault Intersection Station No.	Approx. Angle of Fault Intersection with the Project Alignment	Hazard Zone Extent Station Nos.
Alba Road at West 30th Street	1+82	42°	0+80 to 2+57
West 30th Street at Alba Road	16+25	48°	15+62 to 17+13
1000 Block of Stonecrest Drive	22+76	32°	21+57 to 23+82
West 31st Street at Dunsmere Road	30+75	32°	29+77 to 32+25
Dunsmere Road at West 31st Street	6+21	58°	5+53 to 6+98 (@ north ROW boundary along W. 31st Street)

DISCUSSION OF FAULT MOVEMENT

Understanding the nature of fault-related ground movement is critical to successful design of a linear structure that crosses a surface fault. The characteristics of ground movement that must be considered are the sense of movement and the rate of movement.

The amount of ground movement and the rate at which it moves varies along the strike of the fault. The greatest amount of fault movement and the fastest movement rates are usually found near the center of the fault. As the ends of the fault are approached, the ground displacement and its rate of movement diminish until they reach zero at the fault's termini.

The zone of ground deformation that runs along the fault is part of its make-up. Within the ground deformation zone, displacements and movement rates vary. Those points closest to the trace of the fault have the greatest amount of movement and movement rates. As you move away from the fault, the amount of movement and the movement rate diminish to zero. The edge of the ground deformation zone is defined by the points where ground movement is zero.

Ground Movement Rate

Evidence that the Eureka Heights fault may still be moving is indicated by cracks in the road surface where the fault crosses Dunsmere Road and West 31st Street. The cracks in of themselves do not provide a rate of movement, however.

The most recent measured movement rates along the Eureka Heights fault were made by Dr. Carl Norman, Professor Emeritus of the University of Houston's Geosciences Department. According to Dr. Norman, the average vertical, annual movement rate from 1985 through 2007 was 0.04 inches/year at benchmarks set across the Eureka Heights fault along Shepherd Drive near West 34th Street. During this time period, the fastest rate of vertical movement occurred between 1985 and 1987 and was approximately 0.1 inch per year.

In comparison, the fastest historical, vertical movement rates reported for a fault in the west and northwest Houston area was along the Long Point fault which had an average annual movement rate between 1 and 1.5 inches/year. At its nearest approach to the Eureka Heights fault, the Long Point fault is about 2.3 miles away.

Sense of Fault Movement

In addition to the potential movement rate for the faults, another aspect of ground movement should be incorporated into the project design – the sense of ground motion that may be encountered by the project alignment. Ground movement can be divided into vertical and horizontal movement. Both of these movement components derive from the dip slip that occurs along the fault plane. Dip slip is the movement that occurs along one side of a fault relative to the other, and its direction is perpendicular to the strike (orientation) of the fault and is along the fault plane.

For surface faults on the Texas gulf coast, the typical dip of a fault plane at the surface is about 74°. The motion along the fault plane has two components of movement – horizontal and vertical. The horizontal and vertical components along a fault plane dipping 74° can be calculated as follows:

Horizontal component:

$$x = d \cos\phi \quad \text{or} \quad x = y/\tan\phi$$

Vertical component:

$$y = d \sin\phi \quad \text{or} \quad y = x \tan\phi$$

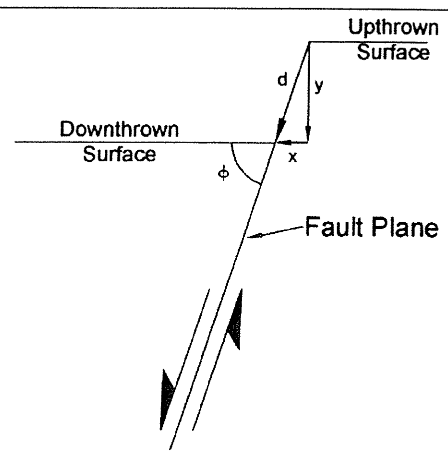
where d is the dip slip movement,

x is the horizontal component of movement,

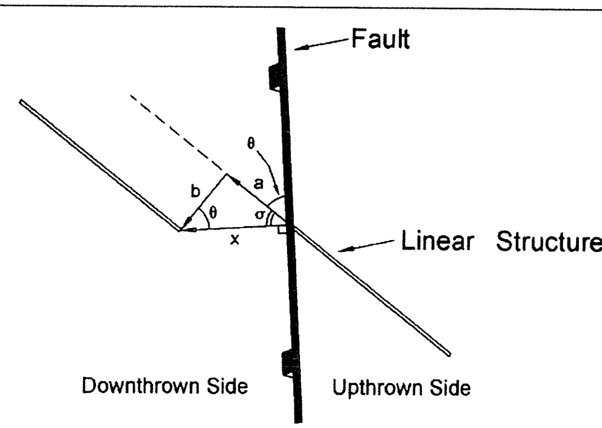
y is the vertical component of movement

ϕ is the dip angle.

For a dip of 74° and a dip displacement of 1 ft., the horizontal component is 0.28 ft. and the vertical component is 0.96 ft., and this yields a vertical to horizontal movement ratio of approximately 3 to 1 for the typical fault dip. The following diagram on the left illustrates dip slip movement along a normal fault:



CROSS SECTION PERPENDICULAR TO A FAULT SHOWING COMPONENTS OF DIP SLIP MOVEMENT



MAP VIEW SHOWING HORIZONTAL COMPONENTS OF FAULT-RELATED OFFSET FOR A LINEAR STRUCTURE INTERSECTING A FAULT

When a linear structure intersects a fault perpendicularly, the anticipated movement on the structure can be calculated using the components of dip slip, i.e., for every foot of vertical displacement the horizontal displacement is 1/3 ft.

However, when a linear structure intersects a fault at an acute angle, the horizontal movement undergone by the linear structure is more complex as illustrated by the above diagram on the right. In the diagram, line "a" represents the extensional component of offset and line "b" is the lateral component of offset. Knowing "x" (the horizontal component of dip slip movement) and knowing θ (the angle of intersection – aka intercept angle – between the linear structure and the fault), the offset components can be calculated:

$$a = x \sin\theta$$

$$b = x \cos\theta$$

FINDINGS, CONCLUSIONS, OPINIONS, & RECOMMENDATIONS

Based upon the field reconnaissance, field mapping, and review of available information obtained for this project, TSI's findings, conclusions, opinions, and recommendations are listed below.

FINDINGS & CONCLUSIONS

The Eureka Heights Fault crosses through the project area.

The Eureka Heights fault intersects the project alignments at 1) the intersection of Alba Road and West 30th Street near alignment station no. 1+82 on Alba and near alignment station 16+25 on West 30th Street; 2) in the 1000 block of Stonecrest Drive near alignment station no. 22+76; 3) and at the intersection of West 31st Street and Dunsmere Road near alignment station no. 30+75 along West 31st and near alignment station 6+21 on Dunsmere Road.

The vertical elevation offset in the streets intersected by the Eureka Heights fault appears to range from 1-1/2 ft. to 2-1/2 ft. The ground deformation zone associated with the Eureka Heights fault appears to be vary between 40 and 60 feet.

Relative elevation measurements of nearby benchmarks across the Eureka Heights fault on Shepherd Drive near West 34th Street have been made by Dr. Carl Norman, Professor Emeritus with the University of Houston, and these show an average movement rate of 0.04 inches per year from 1985 through 2007. The fastest movement observed during this interval was 0.1 inch per year between 1985 and 1987.

Neither the review of available geologic information nor the field reconnaissance found obvious evidence of other faults in the project area that could impact the project alignment.

OPINIONS & RECOMMENDATIONS

Based upon the findings and conclusions of this investigation, Terrain Solutions, Inc. believes that water lines and other linear utilities crossing into the defined fault hazard zones can be impacted by ground movement associated with the Eureka Heights fault. Consequently, TSI recommends that engineering design for the project consider both vertical and horizontal components of ground movement within the identified fault hazard zones. Such consideration would incorporate the historical, fastest observed vertical movement rate of 0.1 inches per year into the expected life of the water lines that cross through the fault hazard zones. Additionally, estimating the maximum strain rate that could be experienced by the water lines should consider the fastest average vertical movement rates seen in the Houston area: 1 to 1.5 inches per year as historically observed along the Long Point fault which is about 2.3 miles from the Eureka Heights fault at its closest approach.

Considering a typical 74° dip for surface faults, horizontal displacements and movement rates are likely to be about 1/3 that of the vertical. Additionally, it should be remembered that water lines intersecting the fault zone at a right angle or near right angle will experience a more abrupt displacement than those that intersect at a shallower or more acute angle. For the latter type of intersection, the longer expanse of water line that will be affected by fault movement will have the displacement spread over a longer length of line.

Terrain Solutions, Inc. believes the likelihood that other surface faults impact the remainder of the project area is low, and thus does not believe fault-related ground movement is a factor for water line design outside the defined fault hazard zones.

LIMITATIONS

This report is an instrument of service of Terrain Solutions, Inc. The report was prepared for and is intended for the exclusive use of the Client (Associated Testing Laboratories, Inc. and the City of Houston). The report's contents may not be relied upon by any other party without the express written permission of Terrain Solutions, Inc. and the Client.

The conditions and recommendations contained in this report are based on Terrain Solutions, Inc.'s review of available documents and geologic field investigation techniques. Terrain Solutions, Inc.'s findings and conclusions must be considered probabilities based on professional judgment applied to the limited data Terrain Solutions, Inc. was able to gather during the course of this fault study.

The report's findings are based on conditions that existed on the date of Terrain Solutions, Inc. site visits and should not be relied upon to precisely represent conditions at any other time. All conclusions are qualified by the fact that no excavations or borings were made and no geophysical surveys or loggings were conducted. Additionally, shallow soil conditions, cultural activities, vegetative cover, new construction & development, slow fault movement rates, and repair of previously existing fault damage are circumstances that may obscure fault-related features.

The accuracy of Terrain Solutions, Inc.'s depiction of the fault zones on the investigation's Fault Zone Maps is largely dependent on the reliability of the base map provided by Associated Testing Laboratories, Inc..

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Geologic Atlas of Texas, Houston Sheet, Bureau of Economic Geology, Univ. of Texas at Austin, Revised 1982.

Houston Heights, Texas 7.5 Minute Topographic Quadrangle Map, U.S. Geological Survey, 1915.

Houston Heights, Texas 7.5 Minute Topographic Quadrangle Map, U.S. Geological Survey, 1982.

Houston Heights, Texas 7.5 Minute Topographic Quadrangle Map, U.S. Geological Survey, 2013.

"Investigation of 'Surface' Faults in Texas Gulf Coast Region – Recommended Standards of Practice for Investigating Geologic Faults in the Texas Gulf Coast Region," Houston Geological Society Bulletin, Van Siclen, De Witt, et al, March 1985.

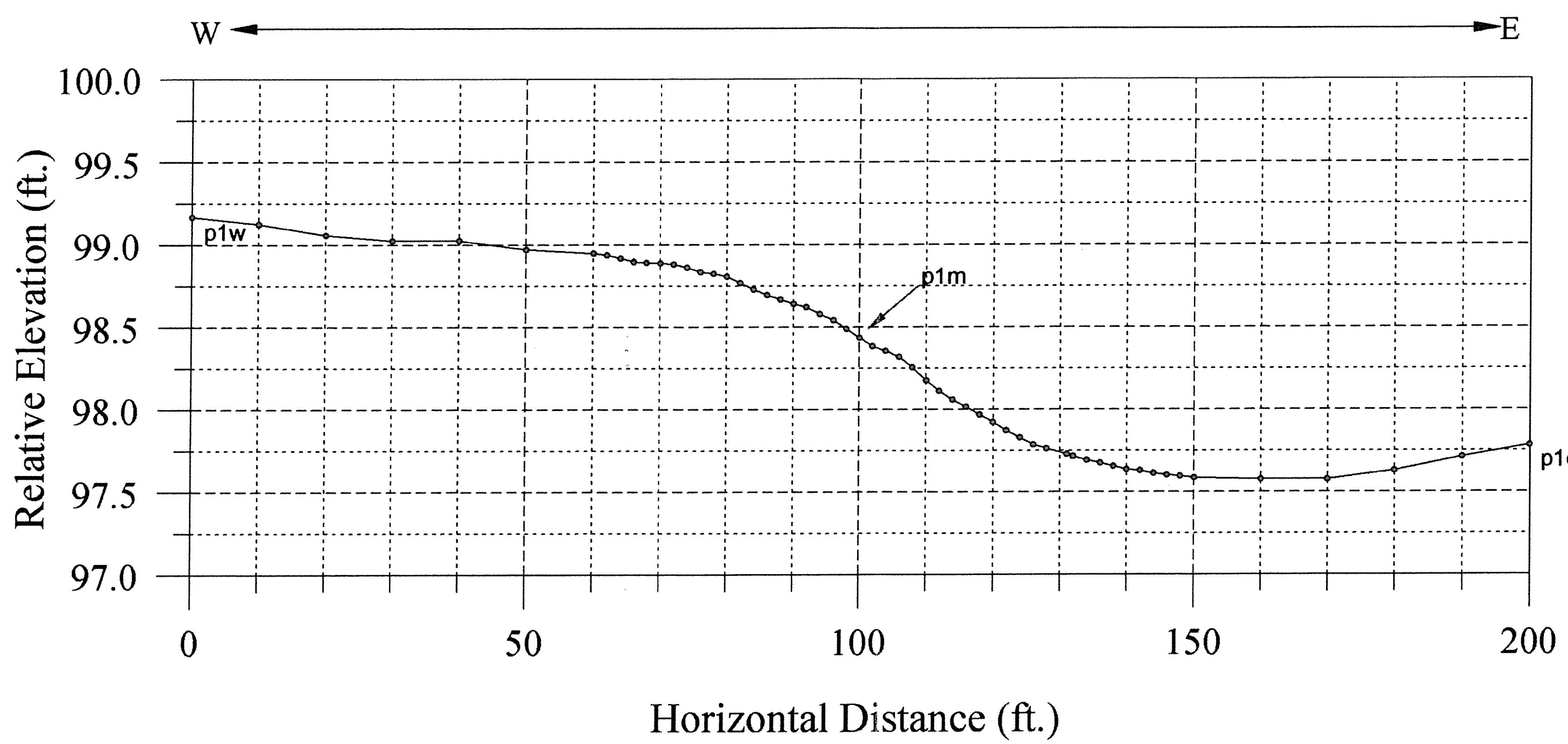
Norman, Carl, PhD., Consulting Geologist, personal communications, March 2014.

Verbeek, E.R., Ratzlaff, K.W., and Clanton, U.S., Map MF-1136: Faults, Houston Metropolitan Area, Texas, U.S. Geological Survey, 1979.

ELEVATION PROFILES

Elevation Profile 1
Eureka Heights Fault
TSI Project No. 1401LN-06

West 30th Street @ Alba Road

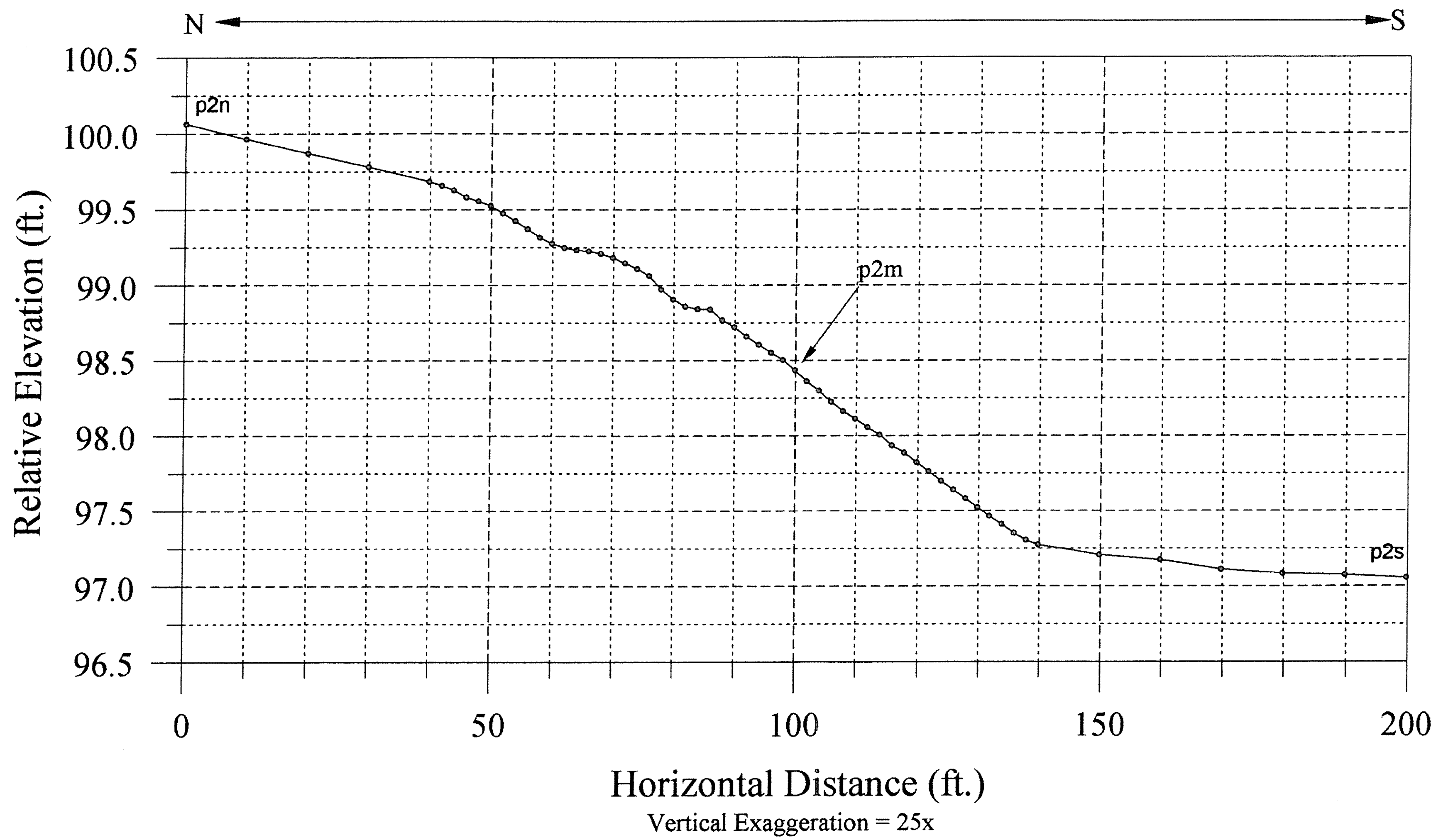


Vertical Exaggeration = 25x

Elevation Profile 2
Eureka Heights Fault

TSI Project No. 1401LN-06

Alba Road at West 30th Street

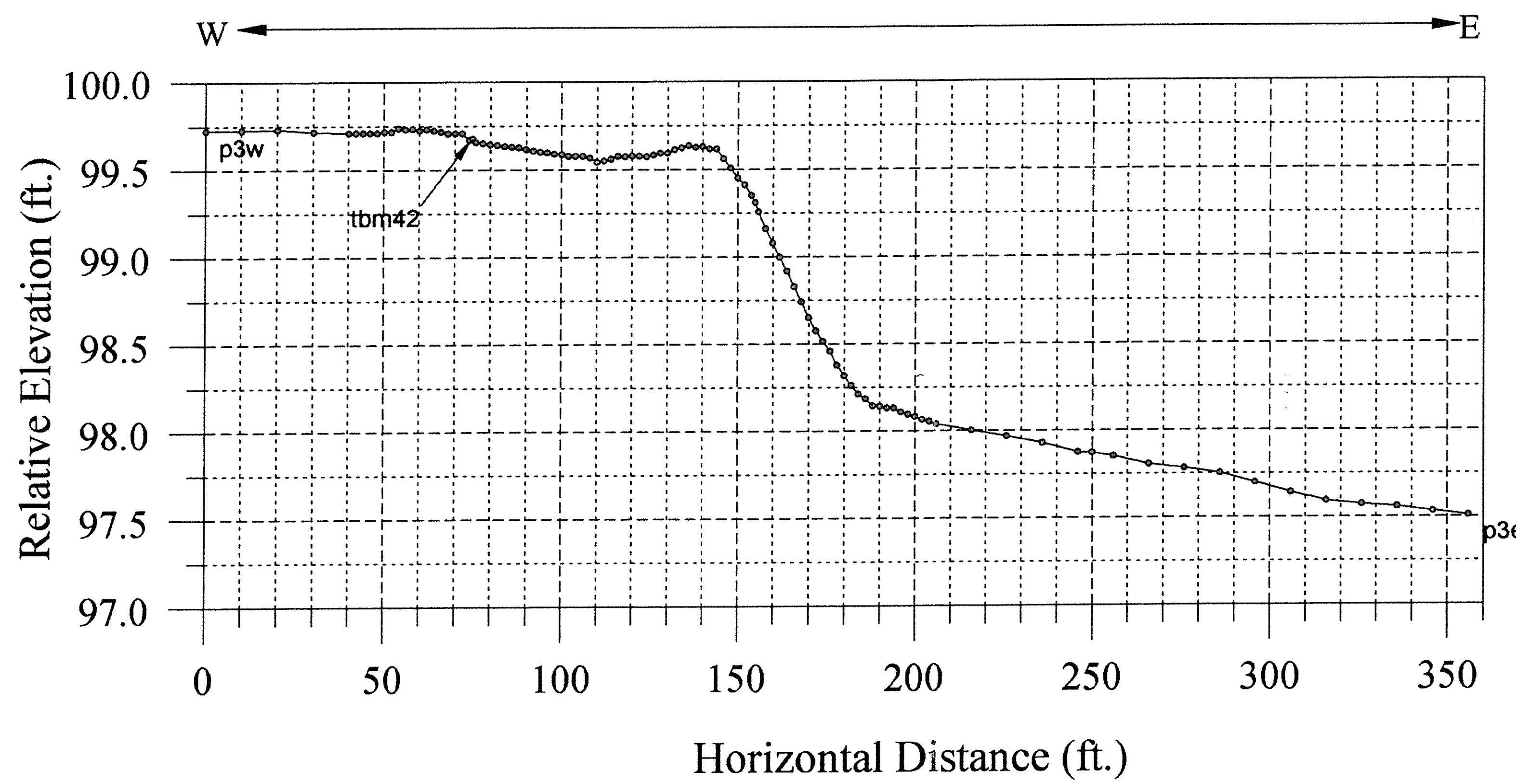


Elevation Profile 3

Eureka Heights Fault

TSI Project No. 1401LN-06

West 31th Street @ Dunsmere Road

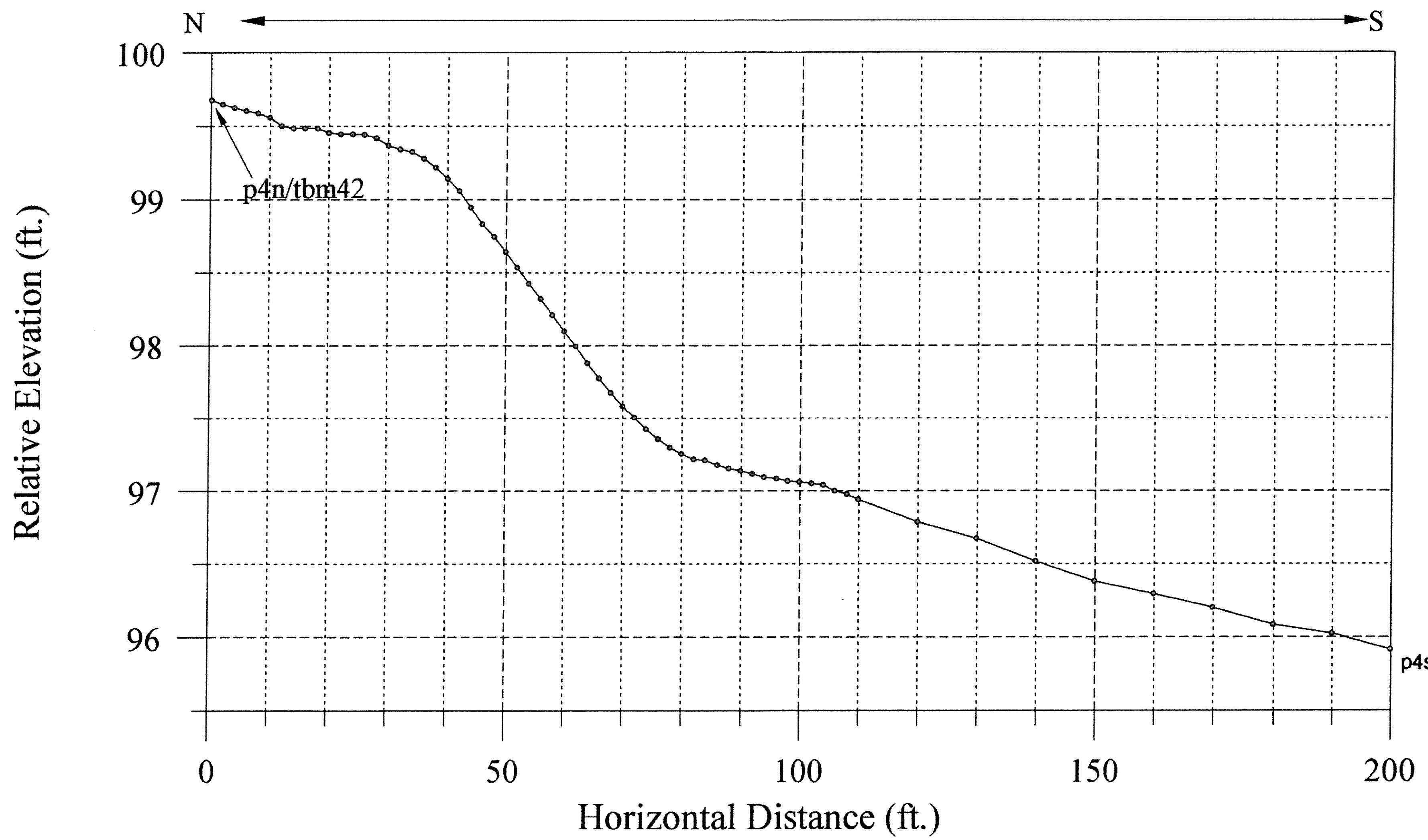


Vertical Exaggeration = 50x

Elevation Profile 4
Eureka Heights Fault

TSI Project No. 1401LN-06

Dunsmere Road at West 31st Street



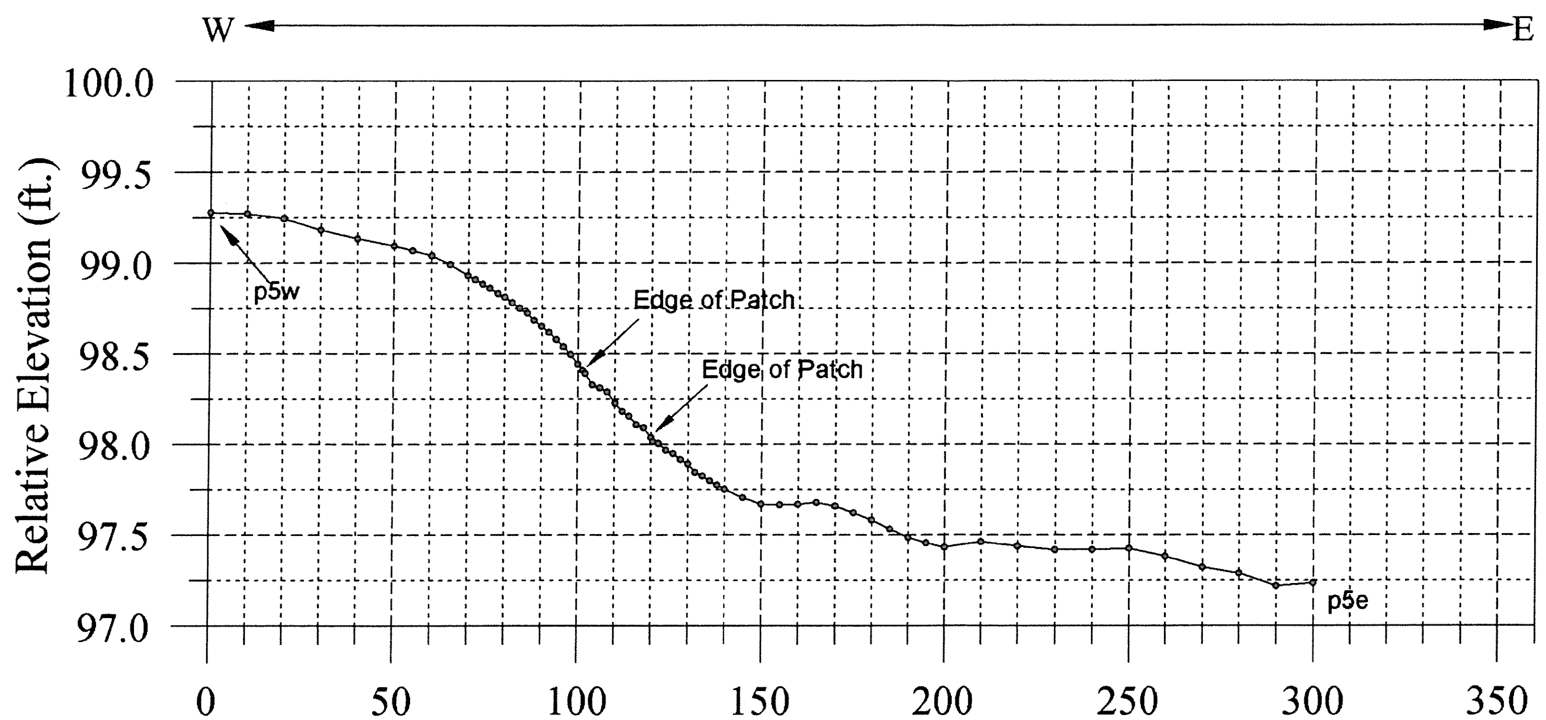
Vertical Exaggeration = 25x

Elevation Profile 5
Eureka Heights Fault

March 2014

TSI Project No. 1401LN-06

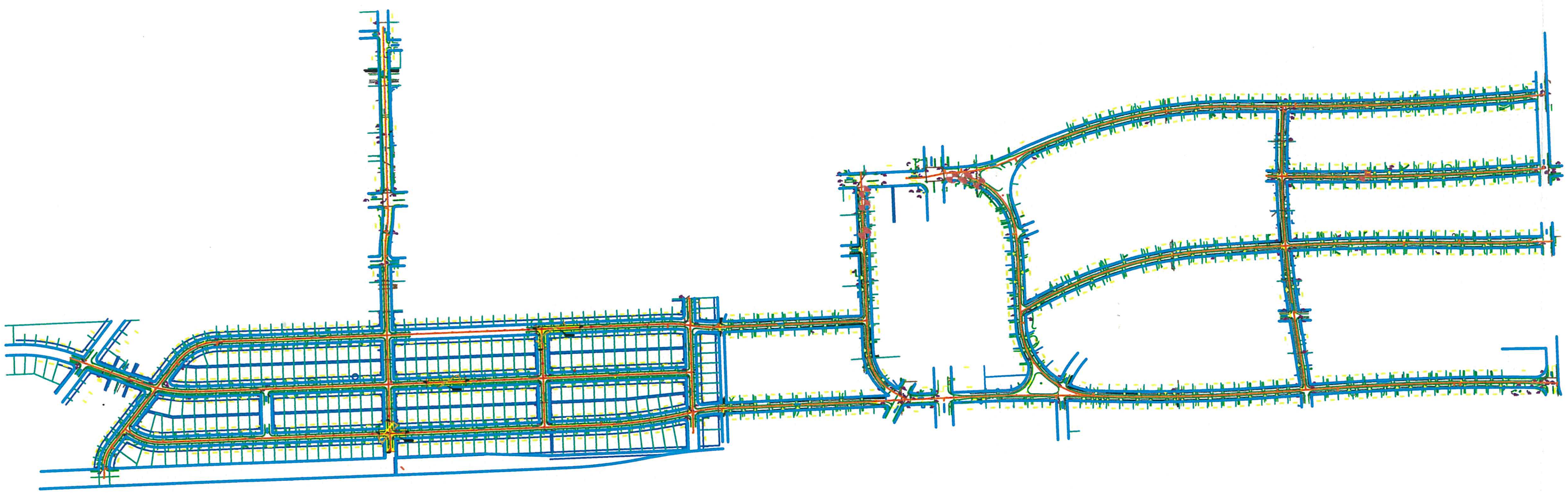
1000 Block of Stonecrest Drive

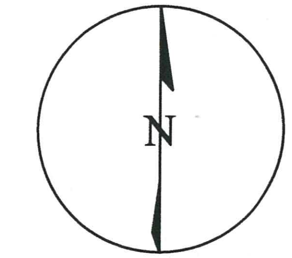


Horizontal Distance (ft.)

Vertical Exaggeration = 50x

PLATES





APPROX. SCALE: 1 in. = 700 ft.

0 ft. 700 ft. 1400 ft.

PLATE I

TERRAIN SOLUTIONS INC.

SITE MAP

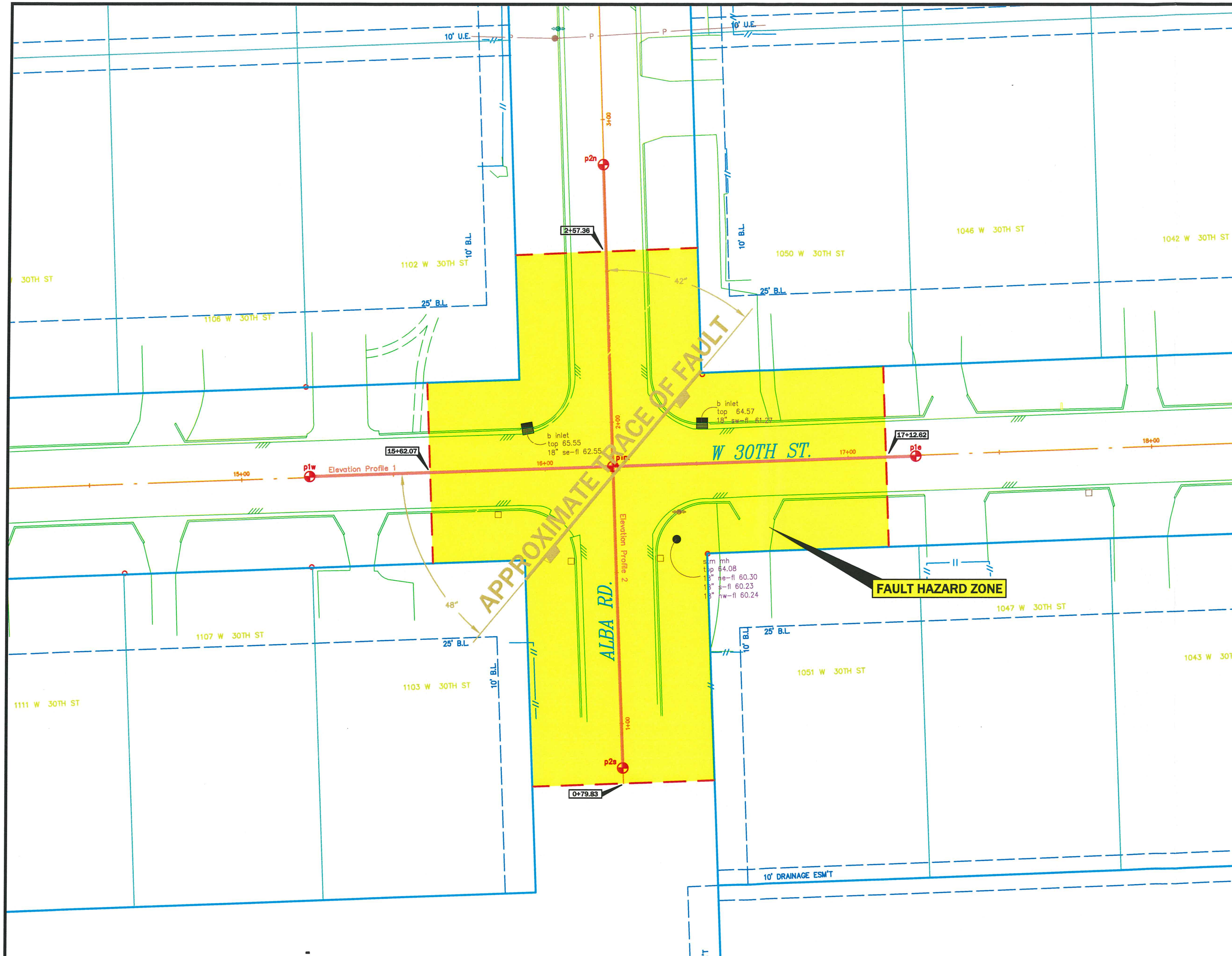
SHEPHERD FOREST II
WATER LINE REPLACEMENT
City of Houston
WBS No. S-000035-0192-4
ATLI Project No. G13-196

STATE OF TEXAS
RICHARD G. HOWE
GEOLOGY
27
LICENSED
PROFESSIONAL GEOSCIENTIST

Richard G. Howe
DATE: 04/28/2014

RICHARD. G. HOWE
LICENSED PROFESSIONAL GEOSCIENTIST NO. 27

NOTE:
Base Map provided by Associated Testing Laboratories, Inc.



N

APPROX. SCALE: 1 in. = 30 ft.

0 ft. 30 ft. 60 ft.

LEGEND

ELEVATION PROFILE END POINT

FAULT HAZARD ZONE

PLATE II

TERRAIN SOLUTIONS INC.

FAULT ZONE MAP 1

SHEPHERD FOREST II
WATER LINE REPLACEMENT
City of Houston
WBS No. S-000035-0192-4
ATLI Project No. G13-196

STATE OF TEXAS
RICHARD G. HOWE
GEOLOGY
27
LICENSED
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Richard G. Howe

DATE: 04/28/2014

RICHARD. G. HOWE
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NOTE:
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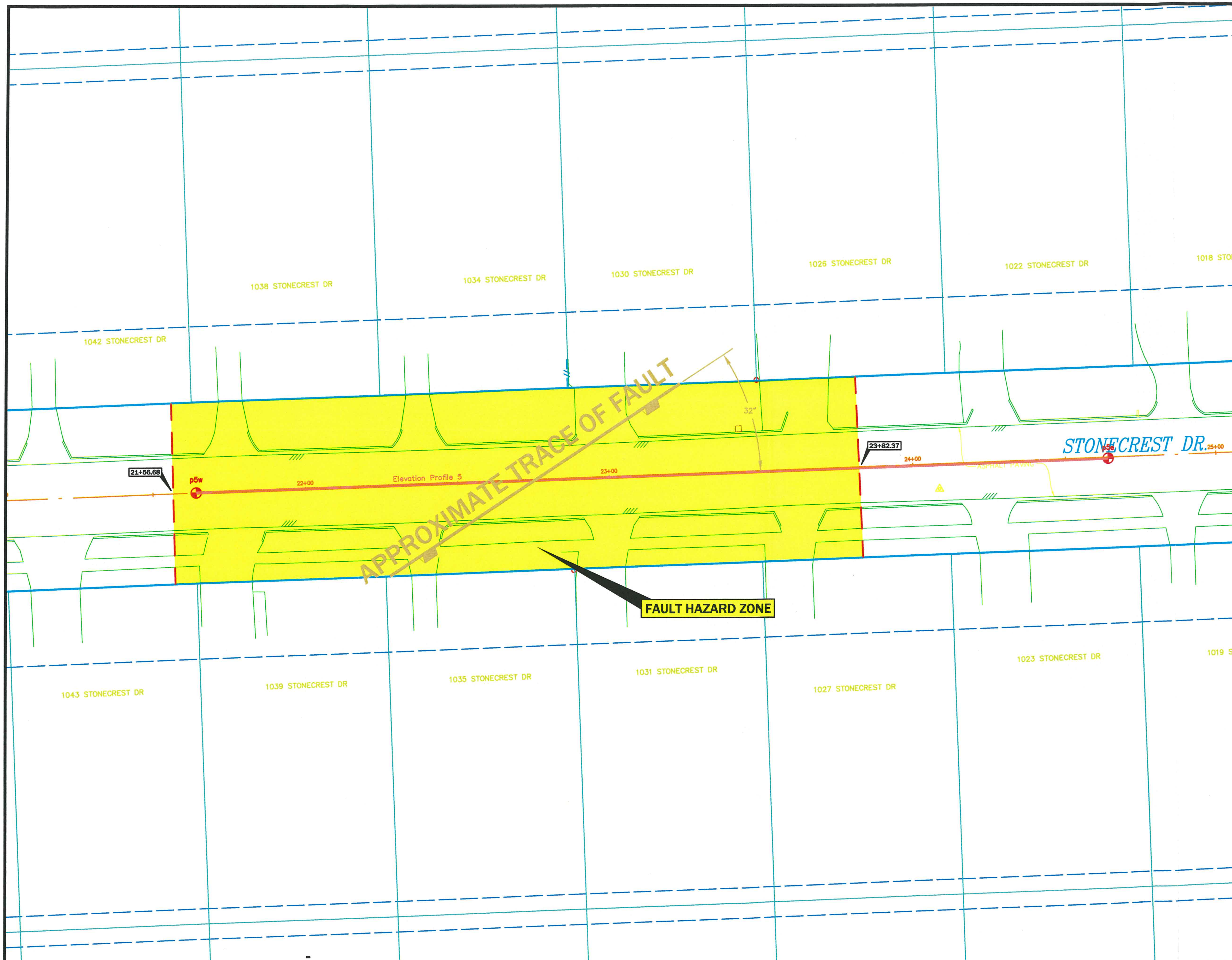

N

APPROX. SCALE: 1 in. = 30 ft.

0 ft. 30 ft. 60 ft.

LEGEND

- ELEVATION PROFILE END POINT
- FAULT HAZARD ZONE

PLATE III

TERRAIN SOLUTIONS INC.

FAULT ZONE MAP 2

SHEPHERD FOREST II
WATER LINE REPLACEMENT
City of Houston
WBS No. S-000035-0192-4
ATLI Project No. G13-196

STATE OF TEXAS
RICHARD G. HOWE
GEOLOGY
27
LICENSED
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Richard G. Howe DATE: 04/28/2014

RICHARD. G. HOWE
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NOTE:
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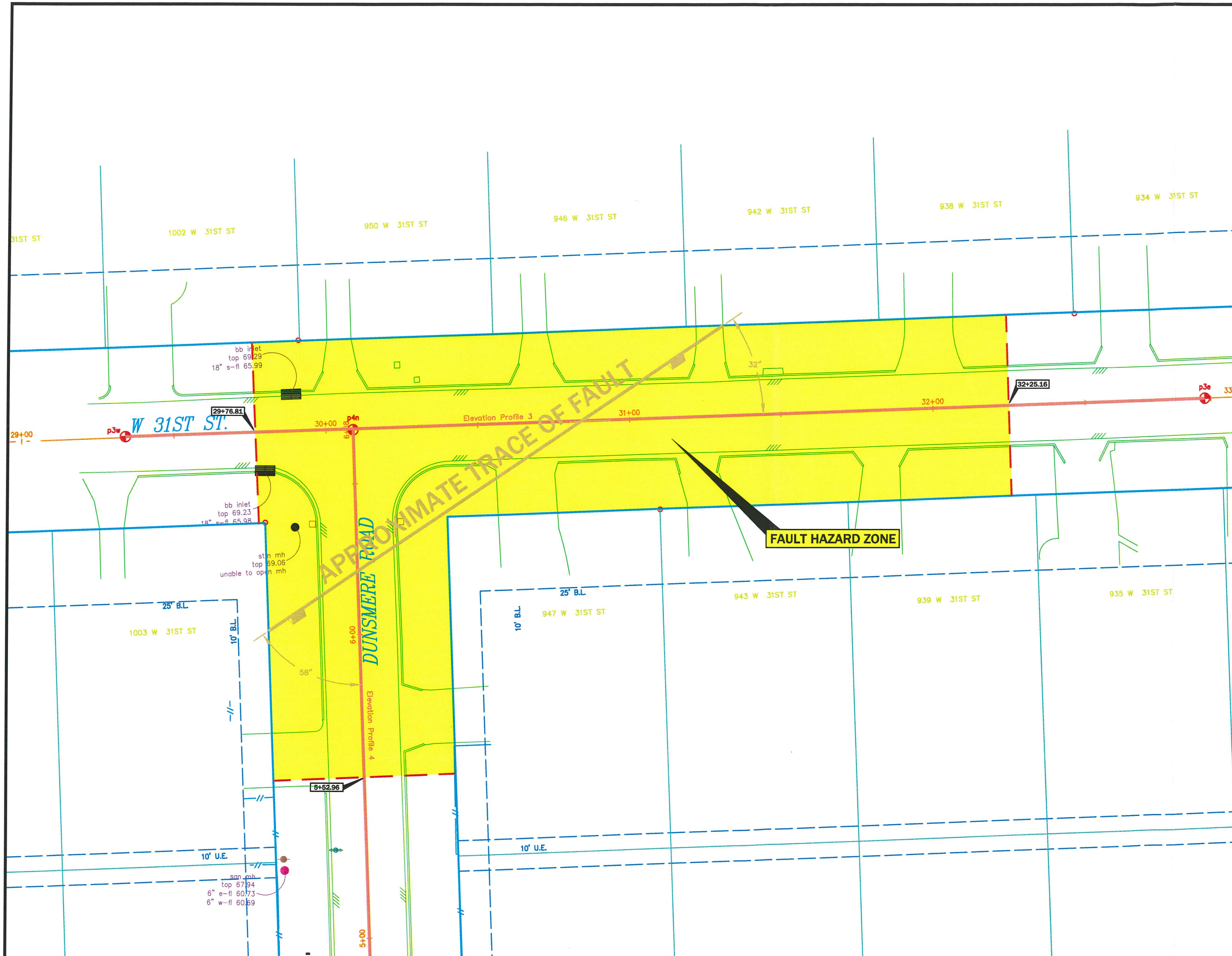

N

APPROX. SCALE: 1 in. = 30 ft.

0 ft. 30 ft. 60 ft.

LEGEND

- ELEVATION PROFILE END POINT
- FAULT HAZARD ZONE

PLATE IV

TERRAIN SOLUTIONS INC.

FAULT ZONE MAP 3

SHEPHERD FOREST II
WATER LINE REPLACEMENT
City of Houston
WBS No. S-000035-0192-4
ATLI Project No. G13-196

STATE OF TEXAS
RICHARD G. HOWE
GEOLOGY
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Richard G. Howe

DATE: 04/28/2014

RICHARD. G. HOWE
LICENSED PROFESSIONAL GEOSCIENTIST NO. 27

NOTE:
Base Map provided by Associated Testing Laboratories, Inc.

PHOTOGRAPHS

Photo 1 – View to the north across the Eureka Heights fault on Alba Road at West30th Street.

Photo 2 – View to the north across the Eureka Heights fault on Dunsmere Road at West31th Street.

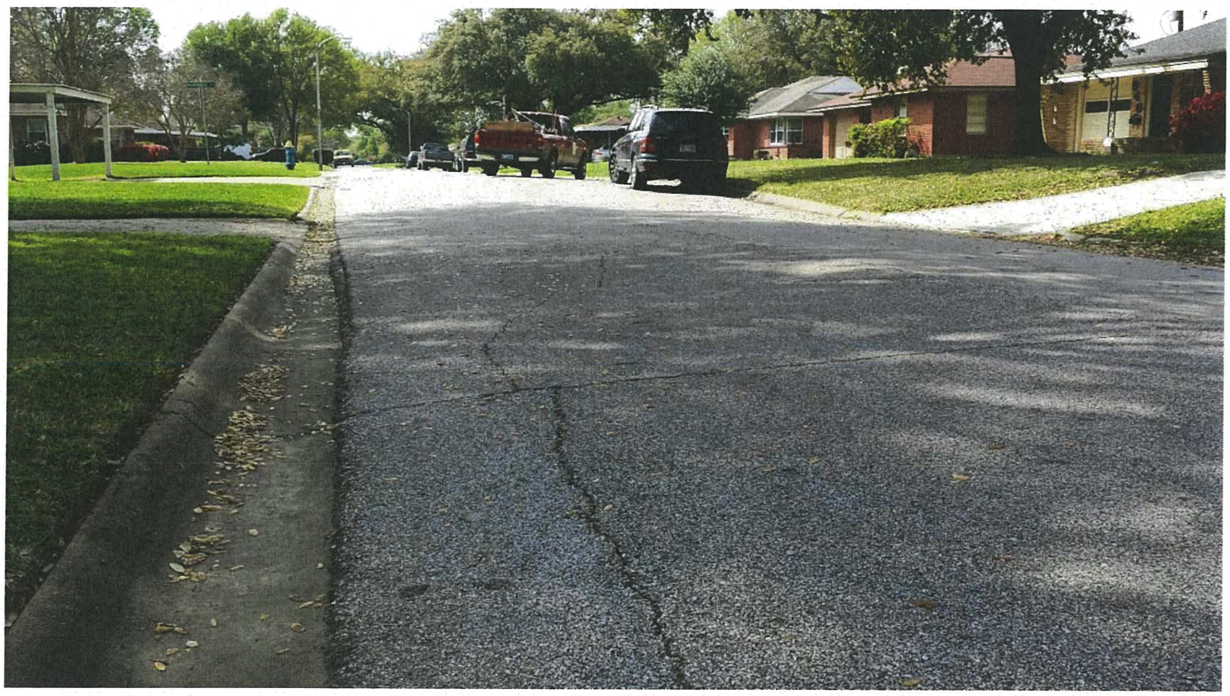

Photo 3 – View to the west across the Eureka Heights fault on West 31st Street at Dunsmere Road.