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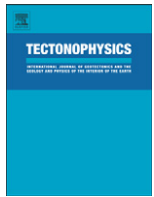
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Surface deformation in Houston, Texas using GPS

Richard Engelkemeir^a, Shuhab D. Khan^{b,*}, Kevin Burke^b^a Schlumberger Information Solutions, Houston, TX 77056, United States^b Department of Earth and Atmospheric Sciences, University of Houston, Houston, TX 77204, United States

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ABSTRACT

Surface deformation in the Houston area has been quantified by using a variety of methods including LIDAR, InSAR, extensometers, drilling (to approximately 100 m), and Ground Penetrating Radar. In this paper we report on GPS data acquired during the period between 1995 and 2005 that found evidence of ongoing subsidence (up to -56 mm/year) in northwestern Houston and of possible horizontal surface movement towards the Gulf of Mexico (up to 6 mm/year). We describe the methods of data-processing used in the study and speculate on the possibility that the active elevation of salt domes, mainly at the south and east of the city, may indirectly influence other surface movements including fault movements and subsidence over areas >1 km². Making use of our observations and analysis could help in natural hazard mitigation in the Houston area and possibly also indicate approaches to surface subsidence study that might be used in other urban areas.

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1. Introduction

The city of Houston lies within the wide coastal shelf margin of the Gulf of Mexico small ocean basin in a region in which extension over the future site of the Gulf began with Triassic rifting (approximately 230 Ma to 200 Ma, Salvador, 1991) and reached a peak in a brief episode of sea-floor spreading during the Middle to Late Jurassic (between approximately 160 Ma and 145 Ma, Bird et al., 2005). Subsequent sediment deposition on the northwestern Gulf Coast has resulted in the progradation of a continental margin sedimentary wedge into the Gulf of Mexico basin throughout the Latest Jurassic, Cretaceous, and Cenozoic (since approximately 150 Ma, Winker, 1982). Paleogene (approximately 65 Ma to 22 Ma) deposition on the margin was predominantly in South Texas, but Neogene deposition (since approximately 22 Ma) has been concentrated in East Texas and Southern Louisiana. Regions of most active growth faulting around the Gulf of Mexico typically occur near the currently prograding shelf margins. The area in which Houston is located lay near the then prograding shelf margin during the Oligocene (approximately 34 to 22 Ma) but active fault movement occurs in Houston today. In this paper we address this anomalous behavior and phenomena related to it. GPS observations in other areas have been used successfully to measure and monitor displacement/subsidence (e.g., Teatini et al., 2005, Tosi et al., 2009).

Repeat-pass Interferometric Synthetic Aperture Radar (InSAR) provides for detailed mapping of the vertical component of deforma-

tion, but does not address the horizontal (Williams, 2001). InSAR measurements yield phase differences, which, after unwrapping, provide a measure of vertical deformation. Using InSAR Buckley et al., 2003 have shown strong linear interference fringes along the Long Point Fault. These fringes result from interactions between the fault and the Jersey Village subsidence depression (Buckley et al., 2003). Buckley et al (2003) also observed a similar linear phase signature associated with faults of the Addicks Fault System. However, there do not appear to be clear interferogram signals associated with the other faults.

2. Active geological structures of the Houston area

2.1. Houston faults

Houston faults are part of a population of hundreds of faults that cut Pleistocene and Holocene sediments on the Texas coastal plain between Beaumont and Victoria (Verbeek, 1979) (Fig. 1 inset). Paine (1993) considered that regional subsidence has been active along the Texas coast at least since the Pleistocene and Verbeek (1979) estimated that more than 10% of the faults between Beaumont and Victoria were active during the 20th century. Active surface faults in the Houston area have been mapped by many workers (Clanton and Amsbury, 1975; Verbeek, 1979; O'Neill and Van Siclen, 1984; Shaw and Lanning-Rush, 2005; Engelkemeir and Khan, 2008). Fig. 1 shows active surface faults that have been mapped using LIDAR data (as red lines, Engelkemeir and Khan, 2008). Because there are no recorded earthquake epicenters in the Houston area, fault motion is considered to occur by aseismic creep. Faults in the metropolitan Houston area have exhibited both spatial and temporal variabilities in movement

* Corresponding author. Tel.: +1 713 743 3411.

E-mail address: sdkhan@uh.edu (S.D. Khan).

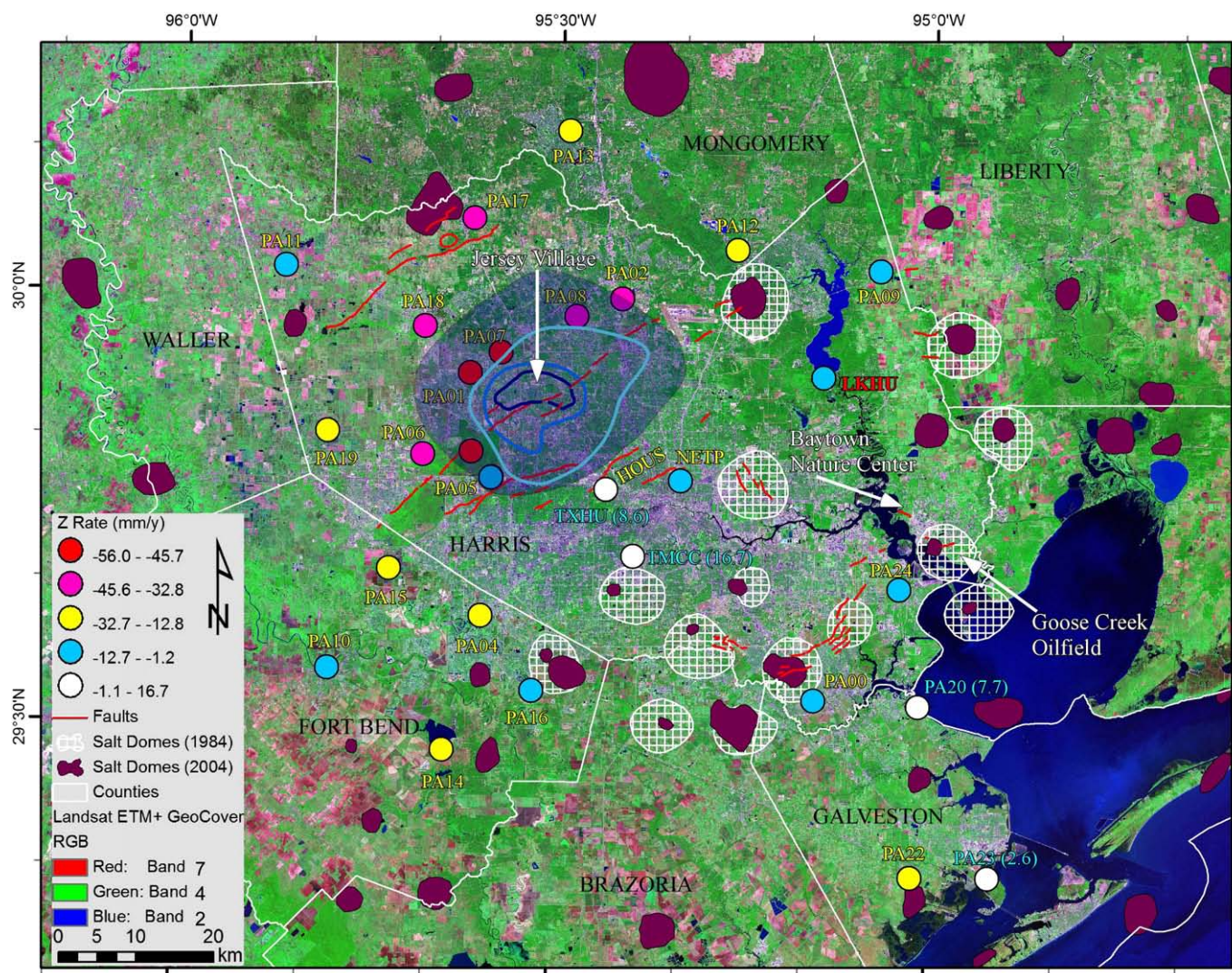


Fig. 1. Rates of vertical motion observed in this study. The Lake Houston site (LKHU), shown in bold red, is the base station for processing. Sites with high error rates (Table 1) are not shown here. Faults are from Engelkemeir and Khan (2008) and are for Harris County only. There are two versions of the salt domes, illustrating the ambiguity of their extent. The older salt dome data are from O'Neill and Van Siclen (1984), while the recent salt dome data are from Huffman et al. (2004). Contours for the Jersey Village subsidence depression for the period 1978 thru 1995 are also shown. PA07 is located in Jersey Village. The contour interval is 30 cm, with the outer contour corresponding to subsidence of 0 cm. This study covers 1995 to 2005 and indicates the (50 km × 20 km) depression 30 km northwest of downtown Houston is expanding to the northwest.

(Mastroianni, 1991). Movement on active faults has caused damage to structures including buildings, pipelines, and roads. Fault locations have, in some cases, remained unknown until accumulated slip has resulted in significant damage, but ongoing maintenance has in other cases minimized damage to structures from active faults. Rates of movement on individual faults have been reported to have been as high as 3 cm/year (Buckley et al., 2003; Norman, 2005).

Many of Houston's surface faults have been linked to the abundant subsurface faults well known in petroleum exploration (Van Siclen, 1967), which show evidence of increasing throw with depth. Faults that show evidence of increasing throw with depth are called "growth faults" because they are interpreted to have moved, continuously or episodically, while deposition was in progress. Movements during deposition result in a greater thickness of sediment on the down-thrown side of the fault (Hardin and Hardin, 1961). "Down to the basin" faults, generating extension toward the Gulf of Mexico basin, dominate in the Houston area (Sheets, 1971). Accommodation of extension in the hanging walls of those faults is expressed in either or both of antithetic faults and rollover anticlines (Ellis and McClay, 1988; Xiao and Suppe, 1992). Antithetic surface faults in Houston have been reported from opposite the most active sections of the

primary faults (Norman, 2005), and at least 11 of those faults are currently active. Similar faults have been studied in Louisiana (Gagliano et al., 2003). Dokka (2006) mapped active boundaries of a rapidly moving block approximately ~60,000 km² in area in and offshore Louisiana. Active blocks of this extent have been inferred to have existed in the Houston area when it was closer to the continental margin (see for example Fig. 1 in Rosenfeld and Pindell, 2003) but such large scale active blocks are not considered now to exist in the Houston area today, which is presently much further from its active continental margin.

2.2. Subsidence

Surface subsidence in Houston may be related to a variety of causes including fluid withdrawal, sediment compaction, and surface faulting. Houston area surface fault activity has been attributed to subsidence resulting from fluid (usually water, but in some cases oil and gas) withdrawal. One of the recognized associations of faulting with fluid withdrawal was in the vicinity of the Goose Creek Oil Field (Pratt and Johnson, 1926). The interaction between Houston surface faults and subsidence is complex and not well understood, although

Holzer and Gabyrsh (1987) found a temporal correlation over a 5-year period between ground water withdrawal and the amount of fault slip, and Kreitler (1976) argued that the faults compartmentalize subsidence. Subsidence depressions of up to several square kilometers in area have been identified in the Houston region, which are not associated with known active faults (O'Neill and Van Siclen, 1984). Paine (1993) attributed current subsidence throughout the Texas coastal region to oil and gas withdrawal in areas in which there is no ground water extraction, but Dokka (2006) attributed subsidence in coastal Louisiana to tectonic factors.

2.3. Salt tectonics

Most (80%) of the faults in the Houston area occur over or close to salt domes (Norman, 2005). Many are radial faults (Verbeek and Clanton, 1978) that are typically short and commonly bound grabens. Salt domes are widely distributed in the region (Fig. 1) but the number, size, and shape of salt domes vary from map to map. A recent publication (Huffman et al., 2004) shows between 20 and 30 salt domes in a broad belt parallel to the coast. In some cases the local fault pattern has been attributed to interactions among the salt dome faults and regional faults (Cloos, 1968).

Worldwide, fault motion has been shown to trigger reactive salt diapirism as in the Canyonlands of Utah (Walsh and Schultz-Ela, 2003), and withdrawal of salt has been considered to have induced faulting as in the southern Dead Sea basin (Larsen et al., 2002). In other places workers have found a typically basinward progression in which listric normal faults dipping toward the basin occupy a region of gravity gliding (Fort et al., 2004). In this environment salt domes have been found down-dip of the extending region.

Rowan (1995) distinguished reactive, active, and passive salt diapirs. Reactive diapirs typically arise from thinning of the overlying section. Active diapirs involve uplift and or piercement of the overlying sediments while passive diapirs grow along with the deposition of the sediments. Most of the salt diapirs in the northwestern Gulf of Mexico appear to be passive (Rowan, 1995), but some may have originated in reactive diapirism and others may

have subsequently become active (Rowan, 1995). Families of faults in which salt plays a key role have been analyzed by Jackson et al. (2003). The families range from planar normal faults near the up-dip limits of a basin to toe thrusts at the basinward limits of the salt, in which folding and thrust faulting accompany the emplacement of allochthonous salt (Hossack, 1995; Peel et al., 1995). A great variety of faults is found between these limits. The partial withdrawal of salt leads to a system of listric normal faults that dip toward the basin. These are known as roller faults. They commonly detach remnant salt bodies that are termed “rollers” (Fig. 2). Salt “welds” occur where beds that were initially separated by salt are now in contact as a result of salt withdrawal.

3. Data and methods

GPS data were obtained from the Houston-Galveston Coastal Subsidence District (HGCSD). The data cover a 10-year span, from 1995 through 2005, and consist of daily RINEX (Receiver Independent Exchange, Hofmann-Wellenhof et al. (2001) format observations. Two types of sites were involved. Some sites were continuously operating reference stations (CORS), while the others were mobile stations occupied in rotation for a week at a time (Zilkoski et al., 2003). This procedure is known as a PAM (Port-A Measure). The antennae at PAM sites are elevated 2.5 m above the ground at the monument, which consists of a cemented pipe reaching to a depth of up to 6 m to minimize the effects of climatically induced soil movements. Movements of this kind are prevalent in the Houston area because of the presence of swelling clays. The three CORS in the studied area are affixed to extensometers that extend to a depth of at least 550 m to ensure stability. An extensometer consists of a borehole with an inner pipe that rests on a concrete plug at the bottom. The motion of the ground surface relative to the top of the inner pipe provides a measure of subsidence.

The depth of the borehole is chosen to pass through shallow aquifers (Zilkoski et al., 2003). The GPS sites are not close to either faults or salt domes. They have been chosen to avoid such local structures in order to better monitor regional subsidence

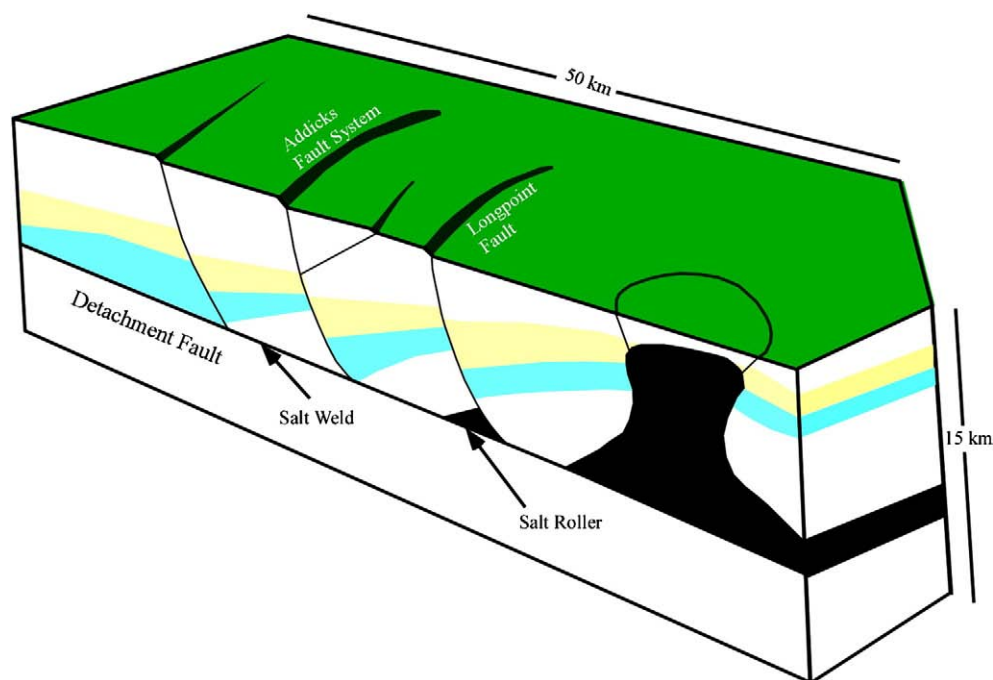


Fig. 2. Sketch showing a suggested association between active faults and rising salt domes. The faults are considered to reactivate on growth faults that sole out in a detachment surface. A salt roller and salt welds (Jackson et al., 2003) help to accommodate movement that culminates in the rise of a salt dome. Geodetic monitoring of several kinds could be used to test this hypothesis.

(C. Middleton, 2008, personal communication). Additional data used in the analysis were downloaded from the NGS Web site (NGS, 2007). These data consisted of both broadcast and precise ephemerides for the GPS satellites and RINEX files from the Texas Department of Transportation (TxDOT) for the Houston CORS site.

Dates were selected to provide as broad coverage as possible for all of the PAM sites. In 1995 there were only four PAM sites, but the number of PAMs had grown to 28 in 2005. In some cases no data were available for all possible input sites for a selected interval. Houston is driest in December and January and for that reason observation dates were chosen at the beginning and end of the year to minimize contributions to measured distances related to a moist atmosphere and also the effects of swelling clays. All receivers are dual frequency and measure full-cycle carrier phase data in L1 and L2. Both CORS and PAM sites record data at a 30 s interval and records are nominally for a 24 h period.

Data were processed using the NGS PAGES software (Blackwell and Hilla, 2000; NGS, 2007). A recent version (pnt6-h) was used. Utility processing was performed using Unavco's TEQC (TEQC, 2007). The Lake Houston CORS (LKHU) was used as the reference site for GPS processing. It was chosen because it has been an NGS CORS throughout the time of the study (Addicks and the Northeast Treatment Plant were initially cooperative CORS and not archived by the NGS). If the Lake Houston record was missing or appeared to have problems, the corresponding day was not processed. Data were processed using WGS84 (G873) as the coordinate system. WGS84 (G873) is a revised version of the standard WGS84 coordinate system and takes into account recent geodetic measurements employing Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and GPS (Hofmann-Wellenhof et al., 2001). It is essentially equivalent to the 1997 version of the International Terrestrial Reference Frame

(ITRF). This reference system was chosen as it most closely corresponds to the epoch of the data being studied.

A spreadsheet providing data availability was used to select dates for processing so both adequate site coverage and temporal sampling could be provided. Computational resources and data availability precluded processing each day. Data was converted to RINEX format if necessary. Bad records encountered after beginning a PAGES run would necessitate choosing another date. The PAGES processing sequence consists of the following key steps:

- 1) Merge all RINEX files
- 2) Triple difference solution
- 3) Synchronize observations
- 4) Choose Baselines
- 5) Choose Ref PRNs, fix cycle skips
- 6) Final combined baseline solution.

Following successful completion of the PAGES run the SINEX2G program was run which accumulates the results in a set of ASCII files. One of the files lists the positions for each date and site. A custom program was written to read and process this file, building a dynamic time series for each site.

The PAGES software returns geocentric coordinates (X, Y, Z), and latitude, longitude, and GPS ellipsoidal heights in the chosen coordinate system. The latitudes and longitudes were converted to Northings and Eastings in UTM zone 15 using the USGS Proj.4 coordinate transformation utilities (Evenden, 1991). A least-squares fit was done for each component of the time series (ellipsoid elevation, Northings and Eastings) of each site. A file showing the sorted records was examined and records with a significant deviation in the time series were removed to avoid skewing the data with

Table 1
Results of GPS data analysis for sites studied in this study.

Sites	Z vector (mm/year)	Z error (mm/year)	X vector (mm/year)	X error (mm/year)	Y vector (mm/year)	Y error (mm/year)	Number of days during 1995–2005	Number of occupations
PA01	–45.66	3.1	–12.65	2.0	–3.76	1.7	3316	24
PA02	–35.73	2.0	–13.10	1.5	–1.49	1.3	3573	23
PA03	–46.16	2.4	–13.46	1.7	–1.65	1.4	3573	25
PA04	–22.14	3.4	–10.54	2.5	–6.36	2.5	1790	18
PA05	–40.45	4.9	–8.94	1.7	–0.90	1.6	3125	16
PA06	–36.79	2.5	–13.28	2.5	–1.33	1.7	1776	20
PA07	–56.02	2.8	–10.89	2.4	–1.52	1.7	1777	19
PA08	–36.70	3.2	–12.35	2.0	0.93	1.6	1467	13
PA09	–3.02	2.5	–10.50	1.6	1.33	1.7	1870	21
PA10	–6.85	4.5	–5.67	4.7	–2.22	2.7	1897	22
PA11	–5.55	3.9	–10.27	2.1	–1.36	1.6	1870	18
PA12	–22.68	6.3	–10.02	2.8	–0.89	2.0	1674	14
PA13	–24.25	3.0	–9.82	2.0	–2.15	2.0	1741	20
PA14	–12.83	4.5	–14.67	2.4	0.88	2.6	1068	12
PA15	–14.39	7.6	–0.28	4.4	0.23	4.4	1494	17
PA16	–8.91	5.0	–26.34	3.4	6.95	2.8	1067	16
PA17	–35.67	6.9	–10.93	3.0	–3.04	1.9	1048	9
PA18	–32.82	3.1	–9.86	2.2	–0.99	1.5	1733	21
PA19	–20.63	4.0	–13.10	3.1	–1.93	1.9	1068	15
PA20	7.74	6.8	7.74	2.7	–0.77	1.7	337	4
PA21	36.63	42.4	28.51	122.1	–5.02	32.9	735	8
PA22	–17.30	5.6	–12.90	1.7	–1.16	3.1	992	6
PA23	2.65	3.3	–12.25	2.0	–7.62	2.1	961	5
PA24	–6.09	7.1	–7.36	4.0	–2.84	4.2	343	7
PA26	–10.93	33.0	–7.60	8.5	0.92	2.0	736	5
PA27	–45.07	27.4	–15.97	11.0	–5.34	2.8	992	12
PA28	4.97	19.7	–3.89	2.5	–8.82	4.8	340	8
HOUS	–14.69	3.2	–17.83	2.1	–4.42	1.7	2164	52
PA00	–5.37	2.1	–11.85	1.6	–6.28	1.8	2929	14
LKHU	–1.23	1.0	–12.46	1.1	–0.76	1.0	3573	92
ADKS	–5.72	3.2	–13.80	2.0	–2.74	1.7	3193	81
NETP	–5.01	2.6	–11.85	1.5	–3.97	1.4	3573	86
TMCC	16.67	6.5	–13.34	4.5	–7.87	3.2	444	22
TXHU	8.63	4.5	–8.66	4.0	–3.06	2.2	713	23

erroneous results. This allowed for computation of vertical and horizontal displacement vectors. As a check, horizontal displacement vectors for North American plate motion were computed for the ITRF 97 North American pole (3.1 N, 102.27 E, 0.1995°/My: C. DeMets, 2008, personal communication). This pole describes the motion of the North American plate in the no net rotation frame (NUVEL 1A; Argus and Gordon, 1991). Differential displacement vectors were also computed. Since all of the GPS sites are local it is not appropriate to extract plate motion from the GPS data (cf. Calais et al., 2006). Instead, the displacement vector for the Lake Houston site was subtracted from the other sites. The primary output was a point shapefile, with a point for each site and including computed rates and errors. This file was subsequently employed by other programs to generate display graphics such as error ellipses and horizontal displacement vectors.

4. Results and discussion

Data from 34 GPS sites in the Houston area have been analyzed in this study to yield the movement in 3D of the sites with respect to each other (Table 1). In this section, motions of these sites are related to known features of the region: 1) surface faults, 2) salt domes, and 3) subsidence. Fig. 1 shows the observed subsidence rates along with

contours for the Jersey Village (PA07) subsidence depression (Stork and Sneed, 2002). Fig. 1 also shows the locations of salt domes. There are two versions of the salt domes, illustrating uncertainty about their horizontal extent.

Vertical and horizontal vectors and their errors are shown. The remarks column of Table 1 refers to site-specific observations. Note that HOUS and TXHU are the old and new TxDOT CORS and are at the same location. Quoted error values correspond to 1 standard deviation from the mean for each de-trended time series plus a 1 mm/year fixed noise term. Note that PA25 was destroyed shortly after installation (Michel and Kasmarek, 2007) and contributed no data.

The ongoing subsidence in the Jersey Village subsidence depression can be clearly seen in Fig. 1 and Table 1. It corresponds generally with the contours, but shows a shift towards the northwest. The contours are for the 1978–1995 period, while this study covers 1995–2005. The present results indicate that the subsidence depression is expanding towards the northwest, which may reflect the direction in which population is growing. Ground water drawdown has ceased in most of the Houston area but continues in northwestern and western Harris County and northern Fort Bend County. Extensometers are measuring increasing compaction in those areas (Michel and Kasmarek, 2007). An effect attributed to subsidence was the

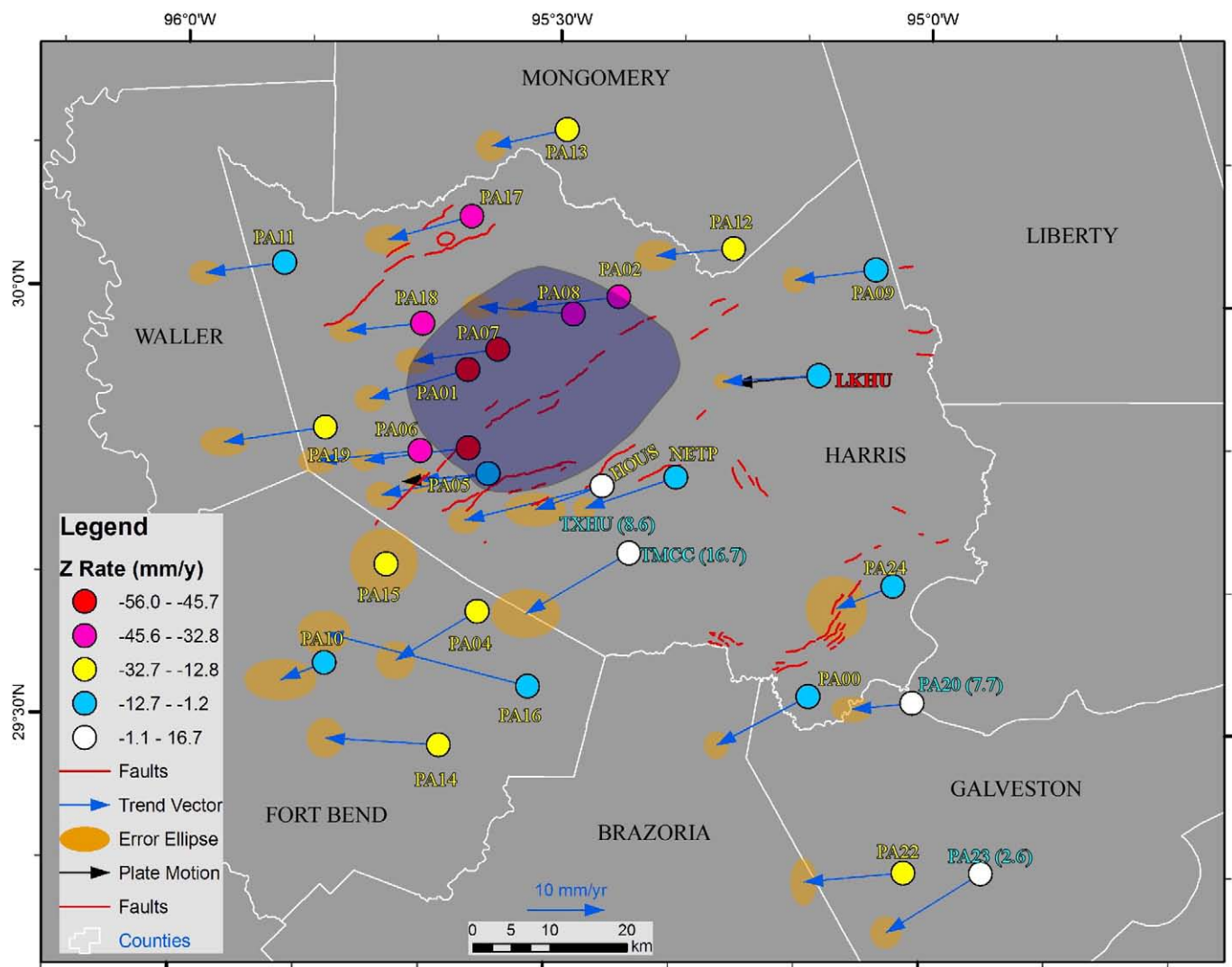


Fig. 3. GPS displacement rate vectors and associated error ellipses. Most sites are moving just south of west. The predominant component is the motion of the North American Plate as measured in WGS 84 (G873) reference frame during the interval. Scale of error ellipses is the same as that of the vectors, where 10 km corresponds to a rate of 10 mm/year. Vectors computed from the North American rotation pole (ITRF 97: 3.1 N, 102.27 E, 0.1995°/My) are shown as black arrows at the LKHU and ADKS sites. Symbols for other features are the same as in Fig. 1, including vertical rates. Sites PA10, PA15 and PA16 differ by more than 50% from the mean and are considered suspect.

abandonment of the Brownwood subdivision (Coplin and Galloway, 1999), which began to be developed in the late 1930s. Elevations were initially around 3 m above sea level, but by the late 1970s subsidence of more than 2.5 m had occurred and the subdivision was subject to frequent flooding. Hurricane Alicia destroyed the subdivision in 1983 and it has since been converted into the Baytown Nature Center. Subsidence in Brownwood was related to ground water withdrawal for petrochemical plants along the Houston Ship Channel and for the city of Baytown. Similar subsidence has also affected the area around the San Jacinto monument. More than 40 ha of the park's 360 ha have been submerged. Recent InSAR measurements (Stork and Sneed, 2002) confirm the abatement of subsidence in the Houston Ship Channel area and ongoing subsidence in the Jersey Village area of west Houston.

In most of the other locations listed in Table 1 there is some subsidence, but a few of the sites are experiencing uplift. Two of those sites are near the coast (PA20 and PA23); another is the TMCC CORS site; while the fourth is the current TxDOT site TXHU. The earlier TxDOT site, HOUS, showed subsidence during the period (1995–2005). The two coastal sites (PA 20 and PA 23) are undergoing uplift, but only have a few observations. The TMCC site has several observations but only covers an interval of a little more than a year. The uplift of the TXHU site is notable because the HOUS site previously

at that location showed subsidence. The last point for the HOUS time series has coordinates (elevation and position) very close to the first point for the TXHU time series. This site lies in the graben formed by the Eureka Heights and Memorial Faults. The Eureka Heights Fault is active, so continued subsidence is expected.

Fig. 3 shows the displacement vectors, for the same area shown in Fig. 1. The vectors show a predominant displacement generally to the south of west. Since the data were all processed with the same coordinate system this represents motion of the North American plate during this interval. Similar vectors were observed for the Houston area by Gan and Prescott (2001). Fig. 3 also shows velocity vectors for the North American pole position and rotation computed and plotted for both LKHU and ADKS. These vectors are in good agreement with the GPS velocities. GPS Error ellipses are also shown. With a few exceptions the displacement vectors show a consistent orientation and length. The bulk of the displacement is due to motion of the North American plate during the interval. A few sites show extremely high or low velocities, which probably indicate error: Site PA16 shows a high displacement rate. It is located near the Blue Ridge salt dome, which has topographic relief of almost 20 m (communication towers are placed on its top). There is almost no displacement at sites PA10 and PA15. Both sites show high x and y errors. Preliminary runs with only some of the data showed that PA15 seemed to be inconsistent

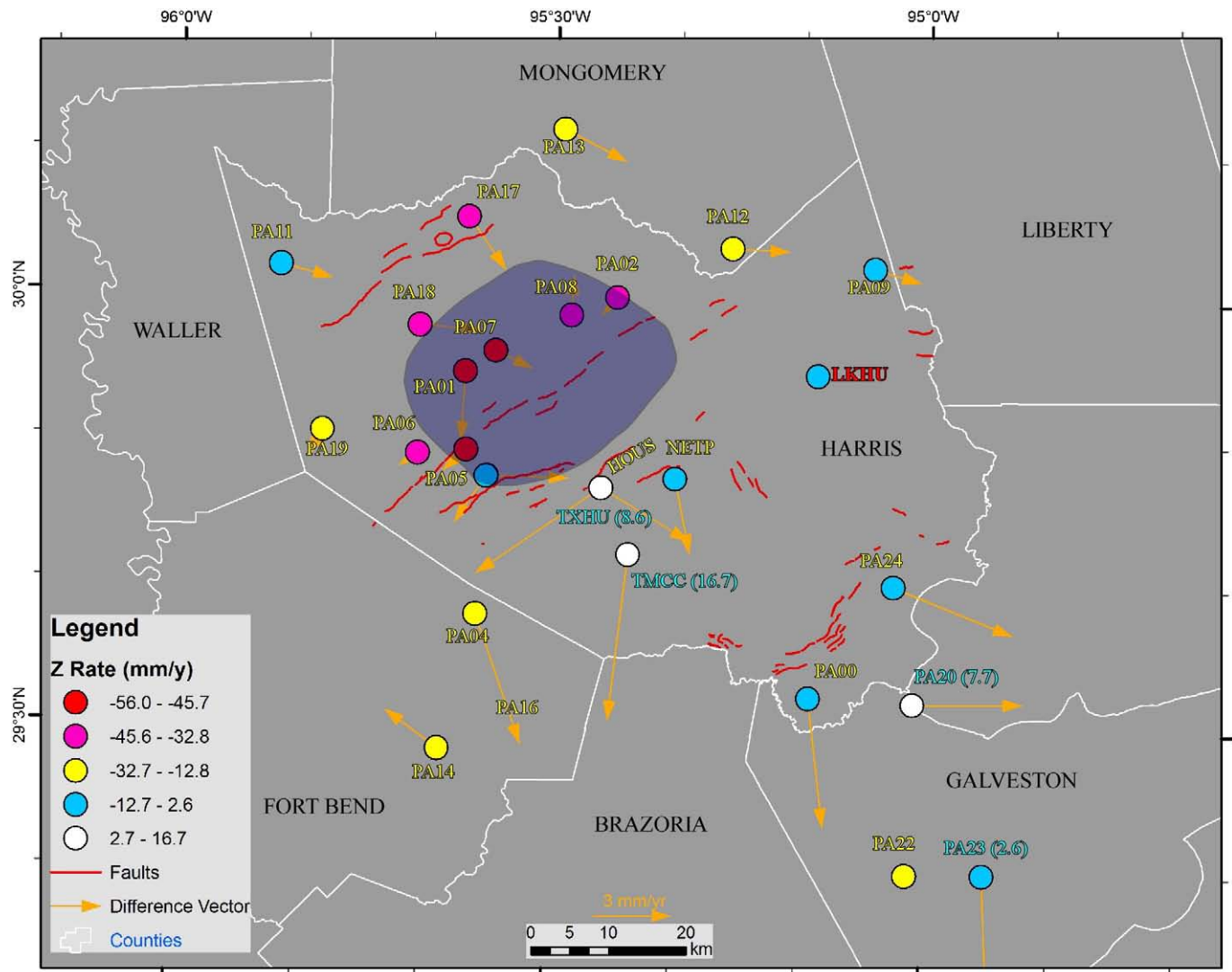


Fig. 4. GPS relative motion vectors, subtracting LKHU displacement. This means LKHU shows no displacement. Sites PA10, PA15 and PA16 are excluded (see Fig. 1). Relative motion vectors are magnified by 3 compared with vectors in Fig. 1. Most vectors show a component of motion to the south. A southeasterly trend would be expected for regional subsidence into the Gulf of Mexico basin. Symbols for other features are the same as in Fig. 1.

between runs. Sites PA10, PA15 and PA16 differ by more than 50% from the mean and have been omitted from further examination.

Fig. 4 shows differential displacement vectors for all the sites (as noted above, sites PA10, PA15, and PA16 showed anomalous velocities and have been omitted from this figure). Vector subtraction is sensitive to slight changes in both length and angle, but there are some discernable patterns to the relative vectors. Most sites have a component of relative motion towards the south. A southeasterly trend would be expected for regional subsidence into the Gulf of Mexico basin. The motion in the northern part of the region is less than that in the southern area. This may be due to contributions from the Jersey Village subsidence depression. Data from a longer period of time and involving more sites (HGCSO has 56 PAMs in 2007) may provide more information.

4.1. A possible integrated mechanism for active faulting, subsidence, and salt dome elevation in the Houston area

Regional normal faults are concentrated northwest of Houston and salt domes to the southeast (Fig. 1). We suggest that there is a possibility that ongoing rise of the salt domes in southeast Houston may be driving the current reactivation of the faults to the northwest and also of the regional faults at depth. If the regional faults at depth include roller faults along which salt is being extruded basinward, and that salt is feeding the salt domes, the continuing rise of the salt domes will produce accommodation space at depth into which downthrown roller fault blocks from farther northwest can move.

5. Conclusions and recommendations

1. GPS is a powerful tool for monitoring surface deformation. The GPS data clearly document significant ongoing subsidence of the Jersey Village subsidence depression, along with lesser subsidence throughout the region. Horizontal displacements were largely due to motion of the North American plate during the study interval. Displacement differences among occupied sites may be indicative of regional motion towards the Gulf of Mexico, possibly related to movement along active faults.
2. With additional resources, GPS profiles across selected fault scarps would provide further monitoring of fault activity. Care would need to be taken to ensure the stability of each monument.
3. Complementary remote sensing measurements of: (i) changes in salt dome surface elevation, (ii) subsidence, and (iii) fault activity over time could be designed that test the possibility that rising salt domes are driving the surface deformation in Houston. A campaign lasting over at least a decade would be desirable, if not essential.
4. A regional study of displacements in the Gulf Coast extending inland at least 500 km may provide additional insights into Gulf Coast deformation. Such a study could use existing CORS and IGS sites and supplement other work on eastern North America (e.g., Gan and Prescott, 2001; Calais et al., 2006).

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