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Land Subsidence in Las Vegas, Nevada, 1935–2000: New Geodetic Data Show Evolution, Revised Spatial Patterns, and Reduced Rates

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ABSTRACT

Subsidence in Las Vegas Valley has been geodetically monitored since 1935, and several generations of maps have depicted more than 1.5 m of total subsidence. This study presents new geodetic data that reveal insights into the spatial distribution and magnitude of subsidence through the year 2000. In particular, synthetic aperture radar interferometry (InSAR) and global positioning system (GPS) studies demonstrate that subsidence is localized within four bowls, each bounded by Quaternary faults. Conventional level line surveys across the faults further indicate that these spatial patterns have been present since at least 1978, and based on the new geodetic data a revised map showing subsidence between 1963 and 2000 has been developed. A comparison of the location of the subsidence bowls with the distribution of pumping in the valley indicates that subsidence is offset from the principal zones of pumping. Although the reasons for this offset are not well understood, it is likely the result of heavy pumping up-gradient from compressible deposits in the subsidence zones. A compilation of subsidence rates based on conventional, InSAR, and GPS data indicates that rates have significantly declined since 1991 because of an artificial recharge program. The rates in the northwest part of the valley have declined from more than 5–6 cm/year to about 2.5–3 cm/year, a reduction of 50 percent; in the central and southern parts of the valley, rates have declined from about 2.5 cm/year to only a few millimeters per year, a reduction of more than 80 percent.

INTRODUCTION

Background and Purpose

Las Vegas was the fastest-growing metropolitan area in the United States during the past decade, with a growth rate of 62 percent and a population that increased from 852,000 to more than 1.3 million, according to the 2000 U.S. Census. It is located in a 1,300-km^2 alluvial valley in southern Nevada that receives between 12 and 20 cm/year average annual precipitation. Groundwater has supported development in Las Vegas since 1905, when the first wells were drilled. Beginning in 1972, groundwater resources have been supplemented with as much as 430 hm^3/year[1] of imported water from the Colorado River, which has provided for the continuing population growth in the area. Annual groundwater withdrawals, however, have consistently exceeded estimated natural recharge since the 1960s. These withdrawals have resulted in long-term depressurization of the aquifer system, regional decline of water levels, the development of earth fissures, and more than 1.5 m of land subsidence.

Maps showing subsidence in Las Vegas have historically been based on conventional leveling of first-order accuracy benchmarks established in 1935 and 1963 by the National Geodetic Survey (NGS). In 1935, the Hoover Dam Level Net was created to regionally monitor the geodetic effects of the reservoir loading associated with the creation of Lake Mead, located about 30 km southeast of Las Vegas. Two primary segments of this net extended through the center of Las Vegas Valley

[1]Convert hm^3 to acre-feet by dividing by 0.00123.

and formed the framework for measuring valley-wide movement. The network was re-surveyed at first-order accuracy in 1940–1941, 1949–1950, 1963, and 1980, and the results provided the basis for the previous subsidence maps. The period 1905–1946 represented the early stages of groundwater development in Las Vegas Valley, and the initial effects of land subsidence were first noted by Maxey and Jameson (1948), who reported as much as 7 cm of subsidence in the center of the valley. By the mid-1960s, a 75-cm-deep subsidence bowl covering more than 500 km^2 had formed (Malmberg, 1964; Mindling, 1971); by 1980, the area of subsidence had increased to more than 1,000 km^2, and the amount of movement had increased to more than 1.5 m (Bell, 1981).

The purpose of this article is to show the evolution of subsidence in Las Vegas and to present the results of new geodetic studies conducted in the last decade that highlight the important changes in our understanding of the magnitude and spatial distribution of the movement. In particular, new space-based synthetic aperture radar interferometry (InSAR) studies, combined with conventional and global positioning system (GPS) survey data, now reveal spatial patterns of land subsidence that require that we significantly revise previous subsidence maps. These data provide new insights into the extent that geologic structure influences the distribution and pattern of subsidence in the valley. These new applications also now allow detailed monitoring of mitigation efforts tied to an artificial recharge program initiated in the early 1990s by the Las Vegas Valley Water District (LVVWD).

In this article, we first present the original data upon which the early subsidence studies were based and then illustrate the evolution of subsidence as groundwater resources were developed throughout the valley. We show how the spatially detailed maps provided by InSAR reveal a substantially different pattern compared with the earlier subsidence maps, which were based on conventional geodetic data. We discuss the reasons for the development of deep, localized subsidence bowls in relation to pumping centers, compressible sediments, and faults. Because these bowls do not correlate directly with either water-level declines or differences in sediment compressibility, we speculate on likely causes for this lack of correlation. Lastly, we present results of the artificial recharge efforts that show that the rate of subsidence has decreased throughout most of the valley since 1991.

Geologic and Hydrologic Setting

Las Vegas is located in a structurally controlled alluvial basin containing hundreds of meters of unconsolidated sediment of Pliocene through Holocene in age. Coarse-grained (sand and gravel) alluvial fan deposits derived from the surrounding mountain ranges form broad piedmonts around the periphery of the valley, and predominantly fine-grained (silt and clay) compressible deposits underlie the central part of the valley (Figure 1A). Impermeable caliche horizons within the alluvial fan deposits and poorly permeable clay horizons within the fine-grained basin fill create confined and semi-confined aquifer conditions and artesian flow. A series of north- to northeast-trending, east-dipping Quaternary faults cut the valley floor, creating a succession of prominent scarps as much as 50 m in height. Initially thought by Maxey and Jameson (1948) to be of natural compaction origin because of the abrupt transition between coarse- and fine-grained sediments along some of the faults (Figure 1B), these scarps are now generally attributed to a combination of natural compaction and tectonic movements during the late Quaternary (Slemmons et al., 2001). Recent geophysical studies (Langenheim et al., 2001) also provided new evidence that the faults extend into the bedrock basement.

Maxey and Jameson (1948) originally estimated that between 31 and 43 hm^3/year of precipitation enter the Las Vegas Valley groundwater system as natural recharge, primarily from the Spring Mountains on the west side of the valley. Subsequent groundwater studies (Harrill, 1976; Morgan and Dettinger, 1996) used similar estimates of natural recharge in flow modeling, but a recent study by Donovan and Katzer (2000) employed a new altitude-precipitation relation that suggested the net annual natural recharge may be in the range of 62–70 hm^3/year.

Groundwater Pumping and Water-Level Declines

Nearly all of the groundwater supply in the valley comes from a zone of confined and semi-confined principal aquifers lying at depths of 200–300 m (Maxey and Jameson, 1948; Harrill, 1976; Morgan and Dettinger, 1996). Water has been withdrawn from the principal aquifers through pumping and artesian flow since 1905, with the most intensive pumping beginning in the 1950s. By 1955, withdrawals were estimated to be about 49.3 hm^3/year (Malmberg, 1965), and by 1968 withdrawals had increased to an all-time maximum of 108.6 hm^3/year (Figure 2). Since the peak in 1968, withdrawals have remained between 74 and 93 hm^3/year. Beginning in 1990, the artificial recharge program has injected between 12 and 30 hm^3/year, reaching a peak in 1998 at 34 hm^3/year.

Because of the net annual overdrafting of the groundwater reservoir since the 1960s, regional depressurization of the principal aquifers has occurred, as evidenced by declining water levels. Decreasing pore-water pressures within the aquifer system produce effective stress

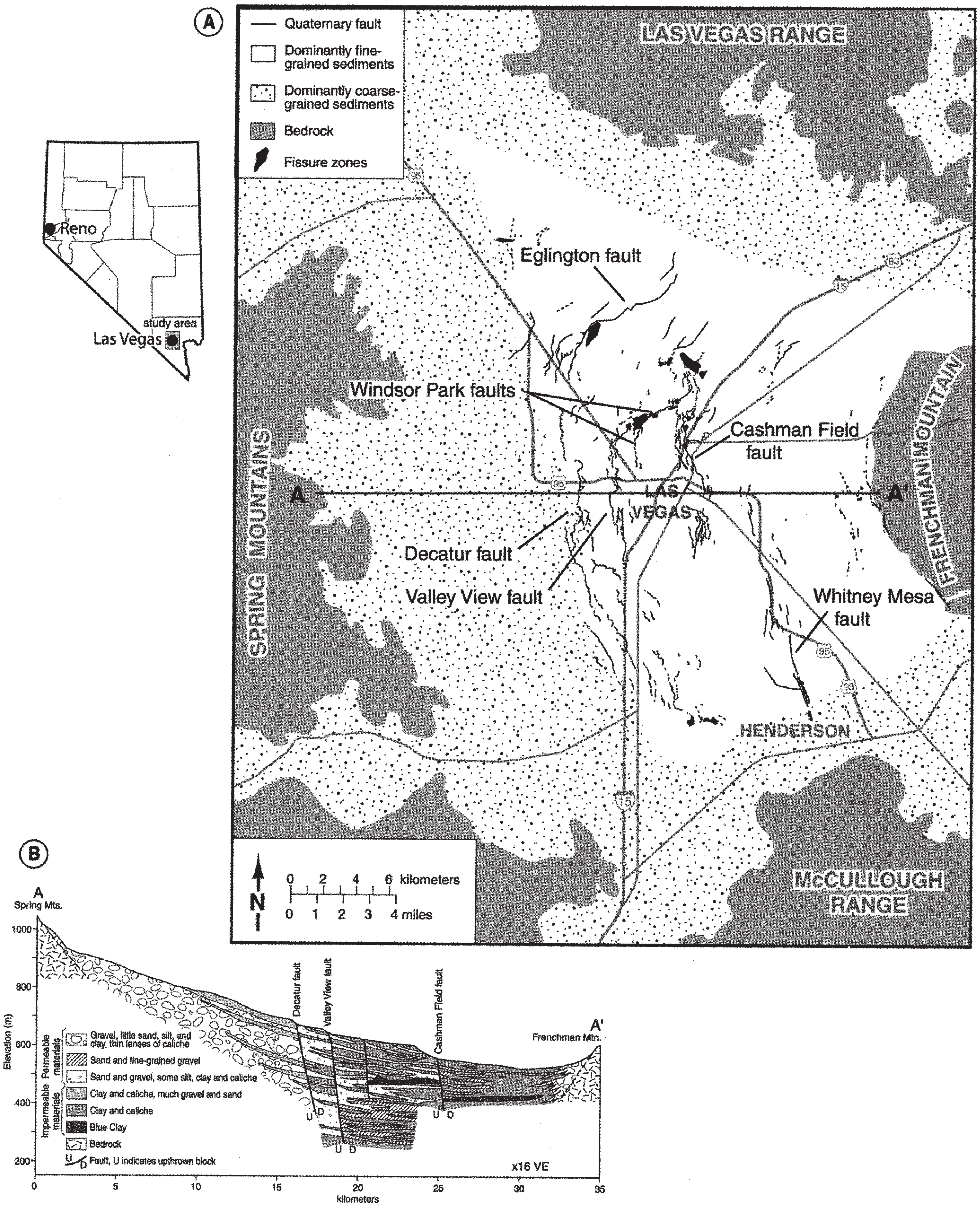


Figure 1. (A) Generalized surficial geologic map of Las Vegas Valley showing distribution of coarse- and fine-grained deposits, principal Quaternary faults, and earth fissure zones. (B) Geologic cross-section (A-A′) is modified from Maxey and Jameson (1948) and schematically illustrates the stratigraphic and fault relations interpreted from well log data.

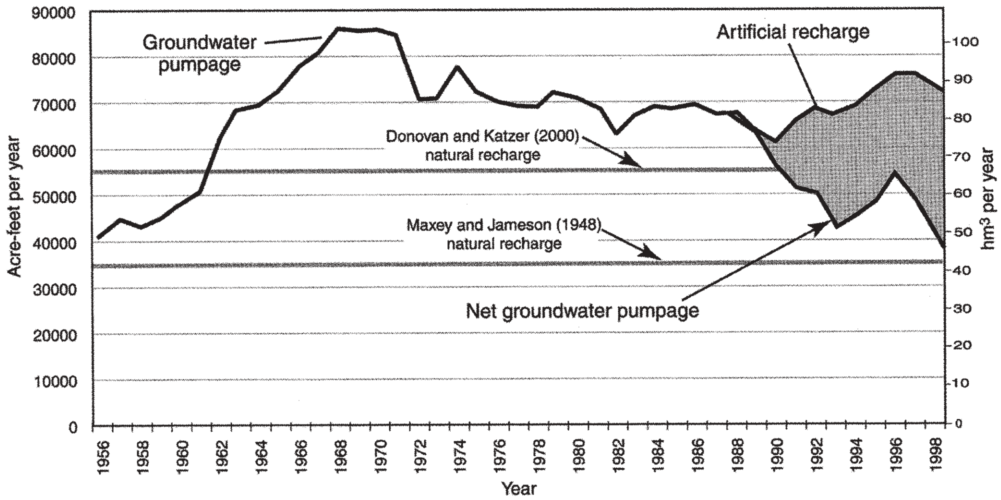


Figure 2. Total groundwater pumpage in Las Vegas Valley from 1955 to 1998 and estimated annual natural recharge rates from the Maxey and Jameson (1948) and Donovan and Katzer (2000) studies. Artificial recharge rates are shown beginning to account for significant volumes in the early 1990s and are included in net groundwater pumpage for those years (Las Vegas Valley Water District, unpublished data).

increases and account for the compaction of the sediments (cf. Terzaghi, 1925). A comparison of 1990 water levels with predevelopment levels shows water-level declines of 15–30 m throughout the valley, with a 90-m maximum decline occurring in the west-northwest part of the valley (Figure 3; Burbey, 1995).

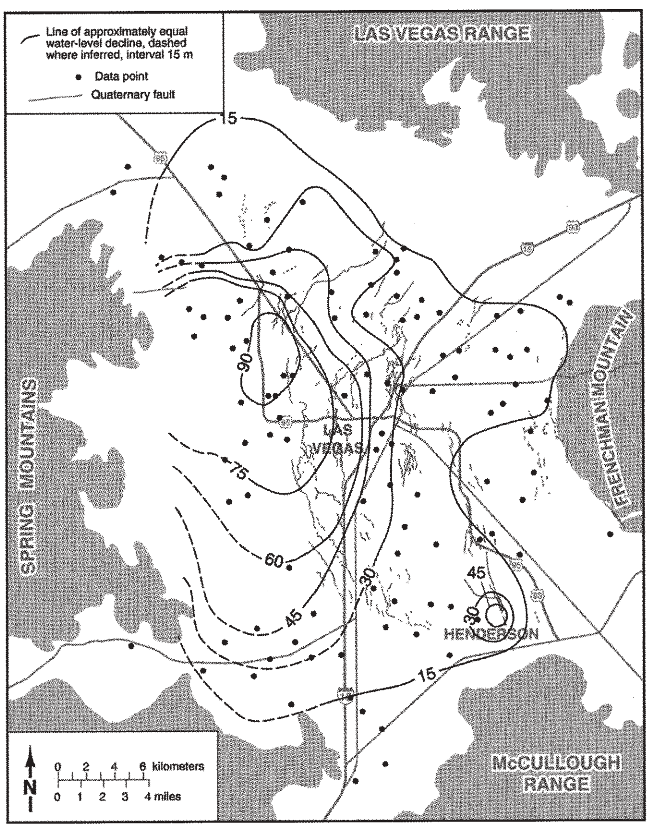


Figure 3. Water-level decline in the principal aquifers from predevelopment to 1990 based on water-level measurements (from Burbey, 1995).

SUBSIDENCE DATA

Early Subsidence Maps

Using the first-order NGS data, early subsidence maps for 1935–1941, 1941–1950, and 1950–1963 were developed by Malmberg (1964) and Mindling (1971); these showed maximum subsidence for these periods of 6 cm, 18 cm, and 67 cm, respectively. A composite 1935–1963 map (Figure 4A) showed that subsidence occurred as a singular bowl located near downtown Las Vegas. Based on re-leveling of some NGS benchmarks by the Nevada Department of Transportation (NDOT) in 1972, Harrill (1976) produced a map of subsidence between 1963 and 1972 that showed for the first time the development of secondary bowls with maximum displacements of 60 cm in some parts of the valley, and he attributed these localized bowls to concentrated heavy groundwater pumping.

1963–1980 Subsidence Map

In 1980, the NGS conducted the last first-order survey of the Las Vegas Valley portion of the net, at which time all lines were surveyed to bedrock benchmark ties. A total of 75 benchmarks surveyed during this campaign provided the basis for the 1963–1980 subsidence map developed by Bell (1981). Combining the results of the 1980 NGS survey with the earlier NDOT results reported by Harrill (1976), the 1963–1980 map showed that subsidence had expanded as a broad

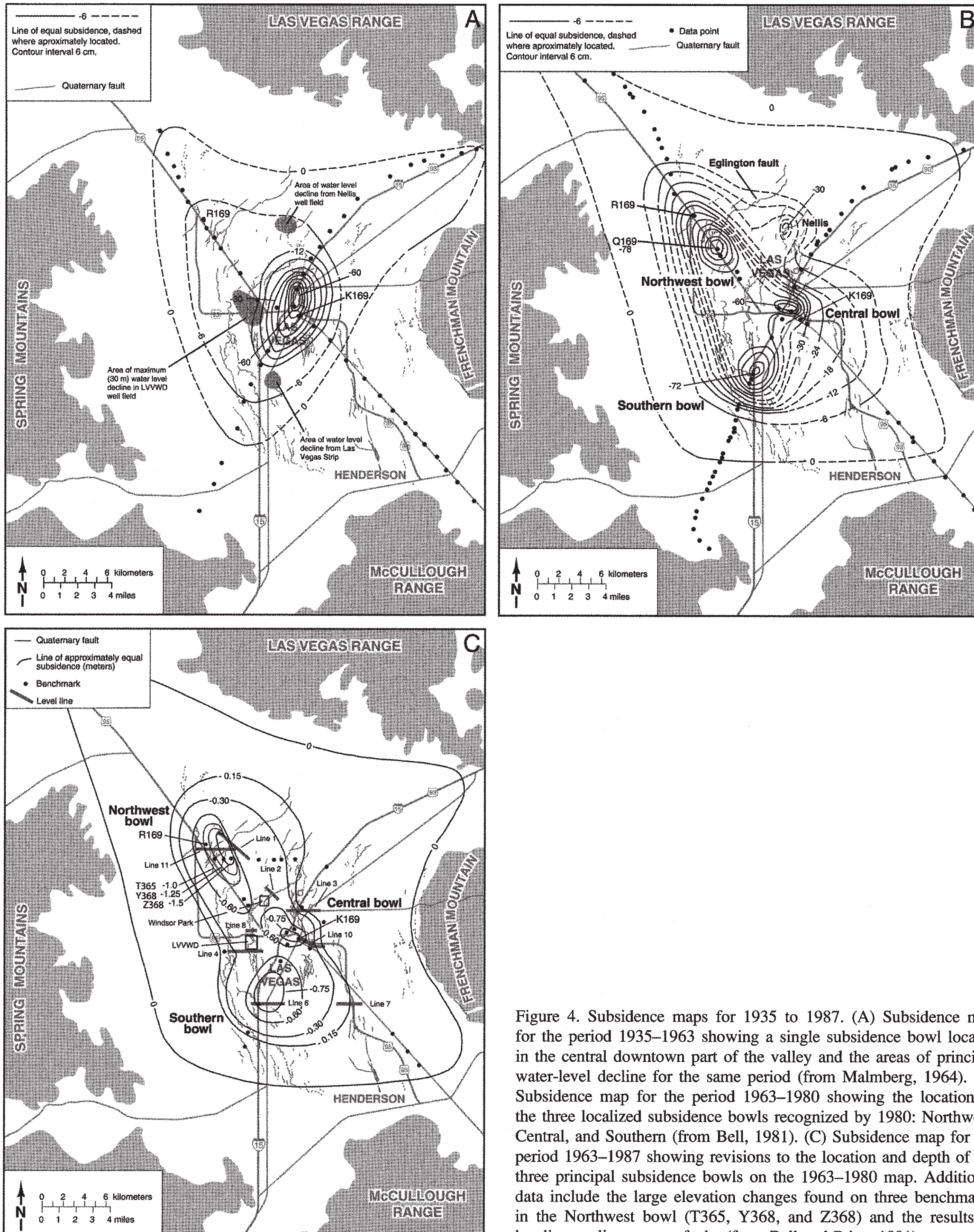


Figure 4. Subsidence maps for 1935 to 1987. (A) Subsidence map for the period 1935–1963 showing a single subsidence bowl located in the central downtown part of the valley and the areas of principal water-level decline for the same period (from Malmberg, 1964). (B) Subsidence map for the period 1963–1980 showing the location of the three localized subsidence bowls recognized by 1980: Northwest, Central, and Southern (from Bell, 1981). (C) Subsidence map for the period 1963–1987 showing revisions to the location and depth of the three principal subsidence bowls on the 1963–1980 map. Additional data include the large elevation changes found on three benchmarks in the Northwest bowl (T365, Y368, and Z368) and the results of leveling on lines across faults (from Bell and Price, 1991).

valley-wide bowl punctuated by several pronounced localized bowls (Figure 4B). The broad valley-wide subsidence bowl was located in the approximate center of the valley and exhibited 48 cm of movement. Three localized subsidence bowls—the Northwest, Central, and Southern bowls—exhibited 78 cm, 60 cm, and 72 cm of movement, respectively. The localization of the subsidence bowls was believed to be related to concentrated heavy pumping in these areas, and movement was inferred to be uniformly distributed about these pumping centers.

1963–1987 Subsidence Map

Using second- and third-order leveling data provided by city and county surveys, Bell and Price (1991) developed a subsidence map for the period 1963–1987 that showed continuing localization of movement (Figure 4C). The three principal localized subsidence bowls were found to be more pronounced and more extensive than had earlier been noted. In particular, the Northwest bowl was found to have subsided more than 1.5 m for the 24-year period, exceeding the total amount occurring since 1935 in the original Central subsidence bowl.

The 1963–1987 map used only 28 of the original 75 benchmarks from the 1980 study because of the loss of benchmarks through urbanization. These benchmarks were sparsely distributed through the valley (Figure 4C), and the elevation changes were assumed to be uniformly distributed around the localized bowls. The 1963–1987 map was produced by conventional interpolation of values between the surveyed benchmarks, similar to the methodology used on previous maps. The pattern of subsidence around the Northwest bowl was adjusted to account for a sharp gradient on the east side of the bowl determined from conventional leveling along level line 1 (Figure 4C). This line and other related conventional lines were established to monitor localized movement across the geologic faults; these are discussed further in the following section.

Level Lines Across Geologic Faults

In 1978 a series of 1.5- to 4.0-km-long, second-order, class I level lines was established across the Quaternary faults that cut the basin floor (Figure 4C) in order to determine whether the faults were potential sites for subsidence-induced fault slip, such as is found on the Picacho fault in central Arizona (Holzer et al., 1979; Carpenter, 1993). The lines were re-surveyed by NDOT annually until 1989; selected line surveys were later conducted in 1991, 1997, and 1999 by the senior author.

The results of leveling between 1978 and 1999 are shown in Figure 5. Line 1 (Figure 5A) extended across the Eglington fault along the east margin of the Northwest subsidence bowl. This line was re-leveled annually until 1985, when it was destroyed by development, at which time the total change was 36 cm, equaling an average annual rate of about 5 cm/year. The maximum differential movement along line 1 occurred on the northwest side of the east-dipping Eglington fault, coincident with the surface trace of the fault scarp. These results provided the basis for delineating the sharp gradient on the east side of the 1963–1987 Northwest subsidence bowl.

Line 2 (Figure 5B) extends across a set of compound faults in the Windsor Park fault zone between the Northwest and Central subsidence bowls (Figures 1A and 4C). For the period 1978–1997, the elevation changes along the line showed a complex but consistent pattern of sharp, relative displacements. The line contains the largest relative displacements between adjacent benchmarks (23 cm between stations 15 and 16) for any of the level surveys, and the line lies just east of the Windsor Park subdivision, an area that exhibited as much as 1.2 m of fissure-related differential movement between 1965 and 1996 (Bell et al., 2001a).

Lines 3 and 10 (Figure 5C and H) are located across the Cashman Field fault on the east side of the Central subsidence bowl. Both lines show similar patterns and magnitudes of displacement across the fault, with as much as 30 cm of movement down to the west into the subsidence bowl since 1978–1980. The west end of line 10 is tied to benchmark K169, one of the few remaining original NGS benchmarks set in 1935.

Lines 4 and 6 (Figure 5D and E) extend across the Decatur and Valley View faults on the west margin of the Central and Southern subsidence bowls. Line 4 was established across the Valley View fault at the main LVVWD well field in 1991, and it exhibited about 6 cm of movement across the fault by 1997. Little differential movement was observed across the Decatur fault during the same period. Established in 1978, line 6 had lost many stations by the last survey in 1997, but the remaining benchmarks indicated 8–10 cm of subsidence at the west and east ends of the line relative to the central part of the line.

Line 7 (Figure 5F) is the only level line that has not shown any significant movement since 1978. The line extended across the Whitney Mesa fault zone in the southeastern part of the valley, an area having little historical subsidence. Total elevation differences of less than 1.5 cm along the line during the entire 1978–1989 period may indicate a small amount of movement, but they can more likely be accounted for by leveling adjustments and uncertainties.

Line 8 (Figure 5G) was established across the Valley View fault in a residential area immediately north of the main LVVWD well field. The line was designed to monitor localized subsidence occurring in the well field, where more than 1 m of movement had been associated with high-yield wells (Bell, 1981). Leveling of the line between 1978 and 1997 showed a maximum cumulative movement of only 8 cm, a lower average annual rate than that measured along line 4 at the southern end of the well field. The results of the 1989 and 1991 surveys were very similar, indicating that movement was arrested, or partially recovered, during this period of early artificial recharge in the well field.

Line 11 (Figure 5I) was established in 1991 to replace line 1 and to monitor continuing movement across the Eglington fault. Between 1991 and 1999, as much as 14 cm of movement occurred across the fault. Although the pattern of relative displacement is not as sharply defined as that on line 1, the leveling data confirm the pattern of movement and show that the northwest side of the fault continued to subside relative to the eastern side.

Fissures

Earth fissures have been recognized in Las Vegas Valley since the 1950s, and they occur in several major zones throughout the valley, according to the most recent compilation in 1998 (Bell et al., 2001a; Figure 1A). They are caused by erosional enlargement of extension cracks produced in the fine-grained basin sediments by subsidence and pumping (Bell, 1981; Helm, 1994). The primary extensional crack may be only a few centimeters or less in width, and it typically does not break the ground surface. However, enlargement of the crack through underground erosion and piping may eventually produce surface fissures several meters in width and broad underground networks of interconnected tunnels and caverns. Fissures remain one of the single most difficult geotechnical problems associated with subsidence in Las Vegas because, once formed, they may remain dormant for many years until activated by heavy surface runoff or new drainage patterns. They also are not easily detected, because they are commonly concealed by soil bridges until the eroded tunnels breach the ground surface. At this point, they may be several meters in width and hundreds of meters in length. Fissure depths are not known, but they may be on the order of tens of meters, possibly extending to the water table. Structures situated above the fissures may experience structural distress because of differential movements associated with collapse of the fissures or continued extensional or vertical movement. Fissures occurring in the Windsor Park subdivision (Figures 4C and 5B) are believed to be responsible for millions of dollars in damage sustained there in the late 1980s (Bell and Price, 1991).

Statistical analysis of the spatial distribution of fissures in the valley shows that they are preferentially located near and along the Quaternary faults (Bell and Price, 1991). Fissure lengths were measured and distances from faults were determined; a total of 18,465 m of fissures was included in the analysis, and a cumulative frequency plot generated by the data (Figure 6) shows that more than 80 percent of the fissures lie within 350 m of a known fault, and 90 percent lie within 600 m.

A mechanism for producing earth fissures has commonly been thought to be related to a 'bending beam' movement of the subsiding ground surface, particularly around the margin of the subsidence bowl, where horizontal extension would be greatest, or to differential settlement over a buried bedrock ridge or stratigraphic discontinuity (Carpenter, 1993). However, Helm (1994) showed that fissures may also be modeled in terms of the horizontal forces associated with compacting sediment or with the horizontal seepage pressures generated by pumping wells. In the first case, differential vertical compaction occurring in a lower, actively compacting aquifer may generate horizontal strain by rotation or torque in the overlying non-compacting sediments. Some of this strain may become localized along preexisting structures such as faults. In the second case, modeling of hydraulic pumping strain can show that differential horizontal forces can be generated at depth by pumping wells that are sufficient to produce horizontal displacement of the aquifer system sediments; the resulting horizontal strains may also be localized along planes of weakness. The high percentage of fissures occurring near faults strongly suggests that either one or both of these models may account for fissure development in Las Vegas.

InSAR Studies

European Space Agency ERS-1 and -2 satellites have been acquiring 56-mm-wavelength synthetic aperture radar (SAR) images of the earth's surface since 1992. Each image shows millimeter-scale radar reflections from the ground surface in about a 80-m^2-pixel format with ground reflection coherence dependent upon vegetation, disturbance, water vapor, and other atmospheric conditions. By precisely co-registering and comparing SAR images flown over the same area, small changes in the position of undisturbed ground surface reflectors, such as buildings, can be detected. Two or more images are precisely compared and analyzed for wave phase changes derived from surface displacements. Phase change maps or SAR interferograms provide spatially detailed information not generally available from conventional geodetic surveys, and they have been used in a variety of crustal movement studies, including earthquakes (Massonnet et al., 1993) and land subsidence (Galloway et al., 1998).

The InSAR study of subsidence occurring in Las Vegas Valley between 1992 and 1997 was first reported

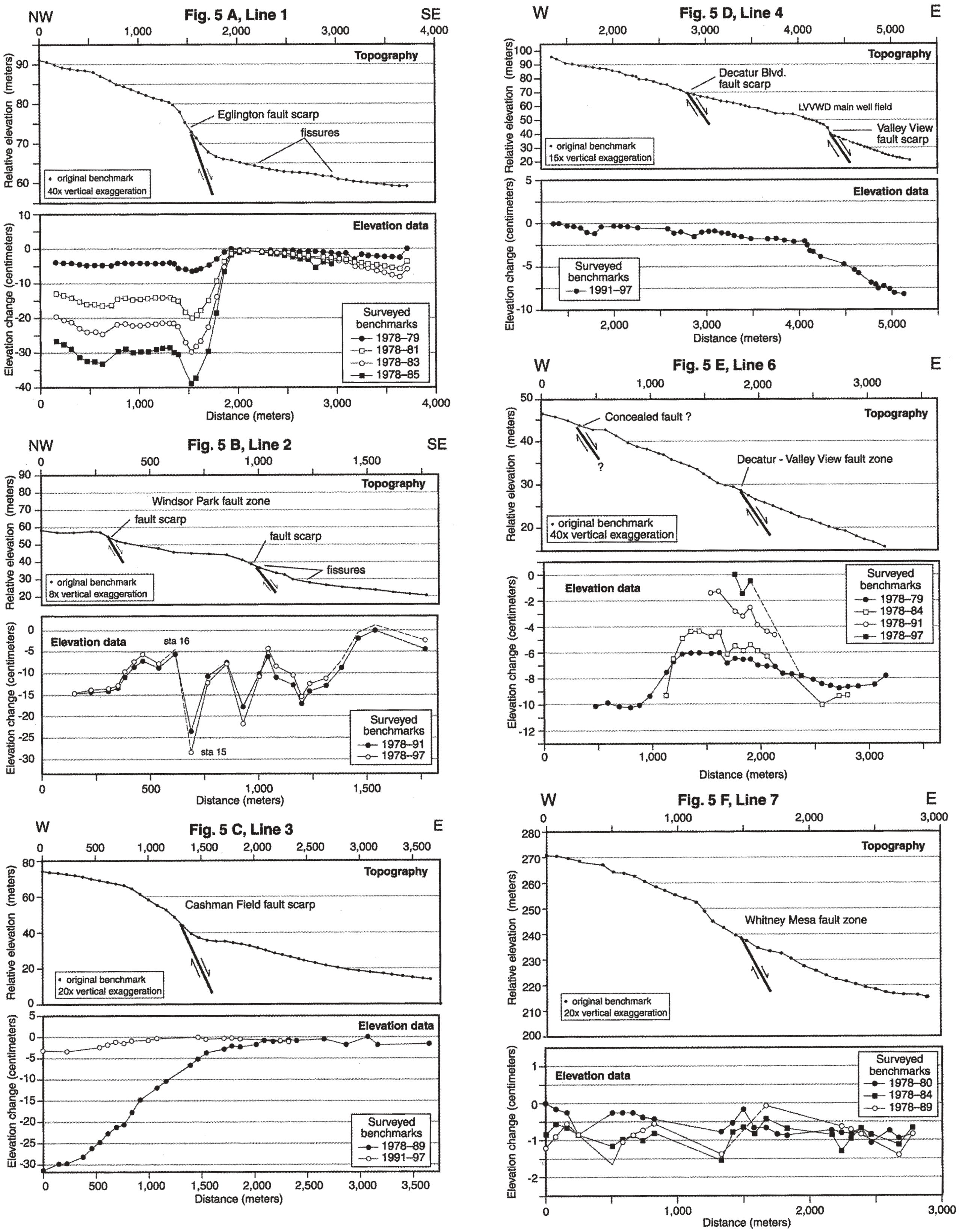


Figure 5. Results of second-order, class I leveling of lines across faults between 1978 and 1999. Location of level lines shown in Figure 4C. The results for each line (Figure 5A through I) show the topographic profile (top) with benchmarks and schematic location of fault traces, and the corresponding elevation changes measured by repeat surveys (bottom).

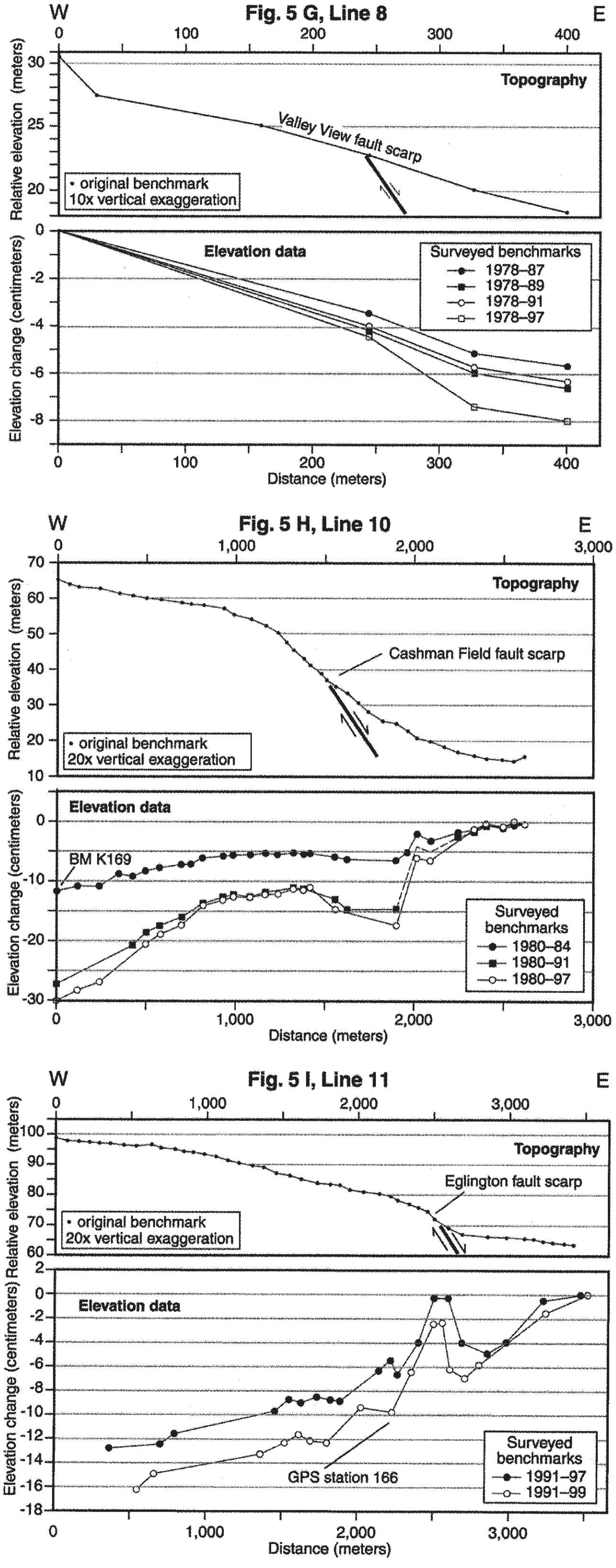


Figure 5 Continued.

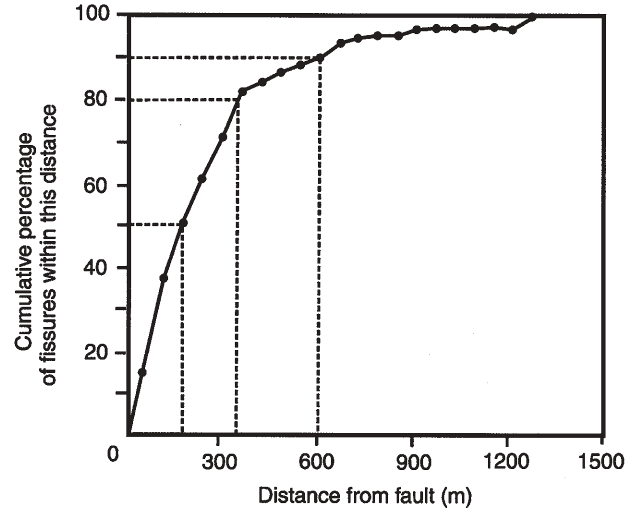
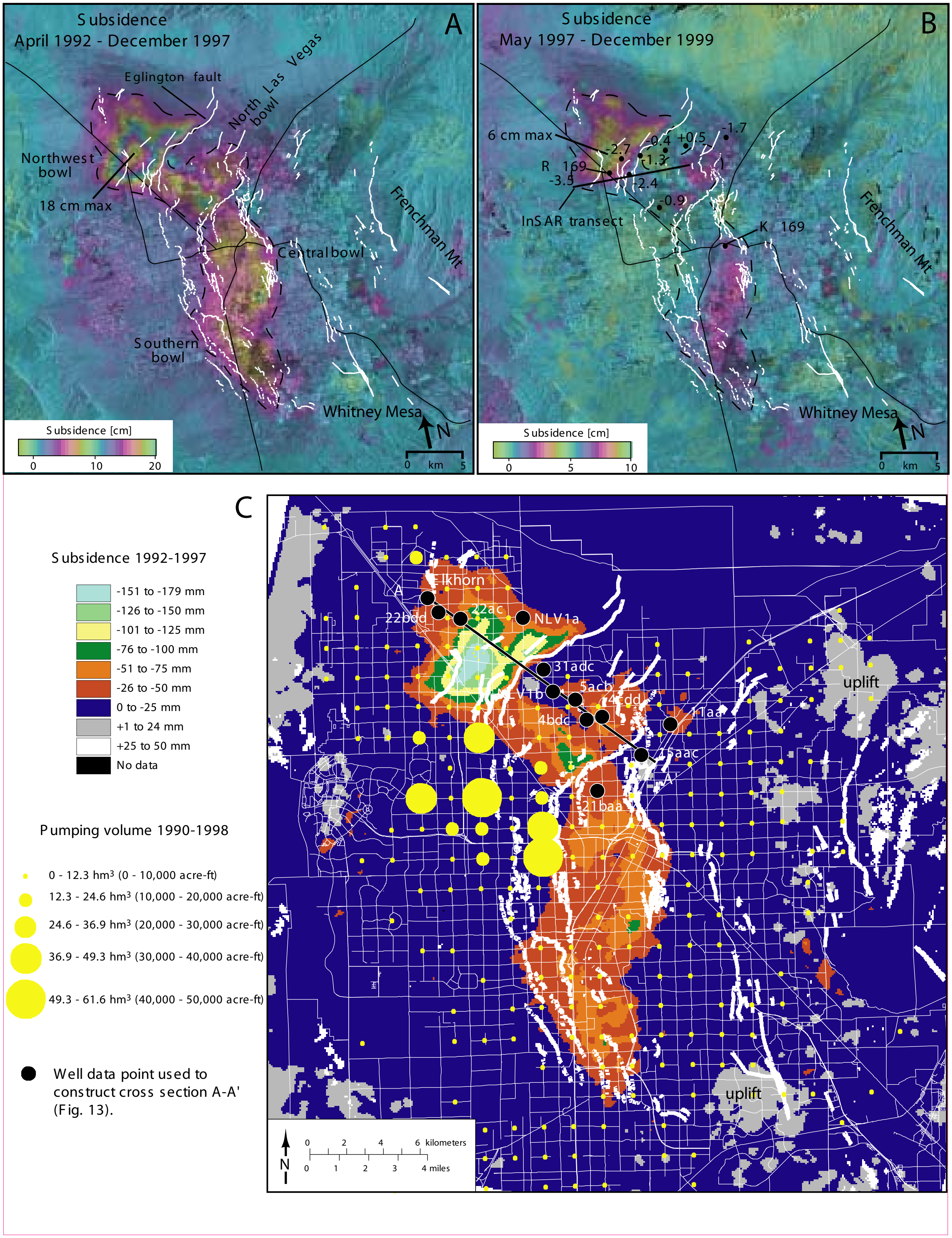


Figure 6. Cumulative frequency plot showing proximal distances between individual fissures and Quaternary faults in Las Vegas Valley. Lengths of fissures were measured and distances to faults were determined from mapped features. A total of 18,465 m of fissures was included in the analysis (from Bell and Price, 1991).

by us in Amelung and others (1999) and is shown in Figure 7A. The interferogram is a composite obtained by summing the results of three differential interferograms for shorter time periods (April 1992–November 1993; November 1993–February 1996; January 1996–December 1997). Subsidence is shown by a color sequence of blue-red-yellow, with one cycle equal to 10 cm. The interferogram shows that subsidence between 1992 and 1997 occurred in a series of elongated bowls that coalesced to form a 5- to 10-km-wide, north-northwest-trending, curvilinear depression along the axis of the valley. The greatest amount of subsidence is concentrated in the Northwest subsidence bowl, where a maximum displacement of 18 cm is indicated by nearly two complete color cycles. The Central subsidence bowl exhibited as much as 10 cm of displacement during this period. Based on the reverse blue-yellow-red color sequence seen in some areas, a few centimeters of uplift can be detected from the interferogram, such as near Whitney Mesa in the southeast part of the valley.

InSAR mapping covering the 1997–1999 period shows similar spatial patterns but smaller elevation changes occurring throughout the valley (Figure 7B). This InSAR map is similarly based on a composite of three shorter-interval interferograms (March 1997–April 1998; April 1998–January 1999; January 1999–December 1999), and it shows that the amount of movement generally declined in most parts of the valley compared with the 1992–1997 period. Here, one complete color cycle represents 5 cm of deformation. As much as 5–6


A
Subsidence
April 1992 - December 1997
Eglington fault
North Las Vegas bowl
Northwest bowl
18 cm max
Central bowl
Frenchman Mt
Southern bowl
Whitney Mesa
Subsidence [cm]
0
10
20
N
0 km 5
B
Subsidence
May 1997 - December 1999
6 cm max
R 169
-3.5
-2.7
-0.4
+0.5
-1.7
-1.3
-2.4
-0.9
InSAR transect
K 169
Frenchman Mt
Whitney Mesa
Subsidence [cm]
0
5
10
N
0 km 5
C
Subsidence 1992-1997
-151 to -179 mm
-126 to -150 mm
-101 to -125 mm
-76 to -100 mm
-51 to -75 mm
-26 to -50 mm
0 to -25 mm
+1 to 24 mm
+25 to 50 mm
No data
Pumping volume 1990-1998
0 - 12.3 hm³ (0 - 10,000 acre-ft)
12.3 - 24.6 hm³ (10,000 - 20,000 acre-ft)
24.6 - 36.9 hm³ (20,000 - 30,000 acre-ft)
36.9 - 49.3 hm³ (30,000 - 40,000 acre-ft)
49.3 - 61.6 hm³ (40,000 - 50,000 acre-ft)
Well data point used to construct cross section A-A' (Fig. 13).
A
Elkhorn
22bdd
22ac
NLV1a
31adc
5acb
4bdc
15aac
21baa
A'
uplift
uplift
N
0 2 4 6 kilometers
0 1 2 3 4 miles

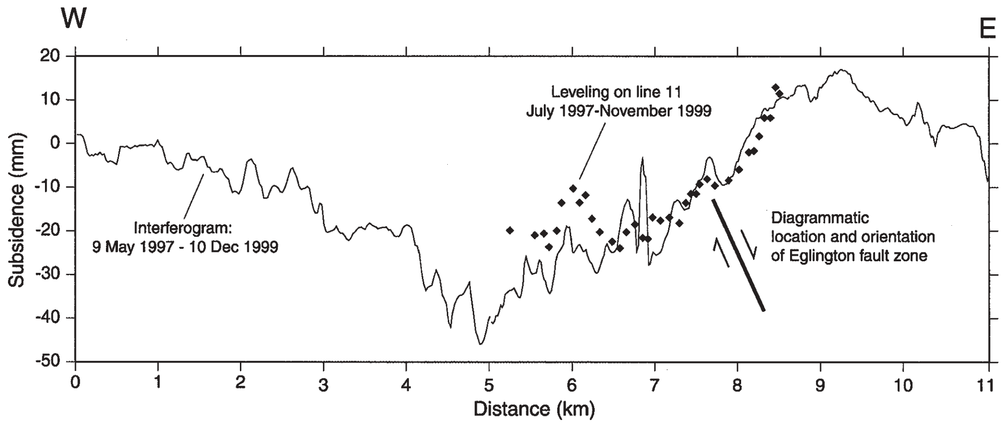


Figure 8. Transect of InSAR data along the same line in part covered by conventional level line 11 (see Figure 7B for location of line). The InSAR data show agreement in value and trend at the millimeter scale, and they indicate that the deepest part of the Northwest subsidence bowl crossed by the transect lies to the west of level line 11. The location of Eglington fault is shown diagrammatically to illustrate the orientation of the fault where it is crossed by the transect.

cm of displacement is visible in the Northwest subsidence bowl, and 2–3 cm of displacement occurred in the central part of the valley. The results of the 1997–1999 InSAR study were ground-truthed using the 1997–1999 conventional leveling data from line 11 (Figure 5I). Figure 8 is a comparison of the line 11 leveling results and the InSAR data extracted from the interferogram along the same transect, and it indicates that the leveling and InSAR results correlate well at the millimeter scale in both magnitude and trend.

GPS Surveys

We have utilized campaign GPS surveys since 1990 to supplement the conventional leveling of benchmarks and to provide additional ground-truth for the InSAR studies. Since 1998, we have used Trimble 4000ssi receivers with geodetic choke ring antennae, which allow high (sub-centimeter) precision in the measurement of benchmark heights. Observations have been conducted using a combination of static and rapid static methodologies, and post-processing has been done using the Trimble software GPSurvey.

In 1995, 1998, and 1999, selected NGS benchmarks were surveyed with GPS in order to measure orthometric height changes relative to the first-order 1963 NGS benchmark survey (Figures 9 and 10). A total of 22 NGS benchmarks were included in the GPS survey, and the network was tied to five stable benchmarks around the margin of the valley. Orthometric heights were calculated from the GPS ellipsoid heights using the GEOID 99 corrections (NGS software). A comparison of the measured 1963–1999 heights showed elevation changes consistent with the subsidence pattern in the valley. In particular, benchmark R169, located in the Northwest bowl, showed a height change of 1.60 m for the period, the maximum change recorded on any benchmark in the valley.

In 1999, a GPS survey was conducted of 11 stations around the Northwest bowl in order to monitor continuing displacement and to provide ground control for the InSAR study. A comparison of the 1998–1999 GPS survey results shows that the measured GPS height changes range from about zero to a maximum of 3.5 cm near the margin of the Northwest bowl (Figure 7B). GPS station 166 was also a common benchmark on the conventional leveling of line 11 (Figure 5I), and the measured GPS displacement of 2.4 cm on this station is

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Figure 7. Synthetic aperture radar interferometry (InSAR) data for Las Vegas Valley for the periods 1992–1997 (A) and 1997–1999 (B). (A) This composite interferogram is based on three separate interferograms and is the basis for identification of four principal subsidence bowls (Northwest, North Las Vegas, Central, and Southern). (B) This composite interferogram was developed from three shorter-period interferograms. The dashed line delineates the 30-mm subsidence contour on the 1992–1997 interferogram. The InSAR transect shows the location of the cross-section of InSAR data extracted from the 1997–1999 interferogram shown in Figure 8. (C) ArcView map showing InSAR and pumping data, and the location of the wells used to construct cross-section A-A′ (see Figure 12). The 1992–1997 InSAR data are in a 25- × 35-m pixel format; subsidence (and uplift) values have been grouped in 25-mm categories. Cumulative pumping for 1990–1998 is shown by yellow circles (Las Vegas Valley Water District, unpublished data). Base map shows street and highway network (white lines) and faults (bold white lines). Areas of uplift (gray) are confirmed by multiple interferograms in the northeast and southeast; other areas may be topographic or atmospheric artifacts.

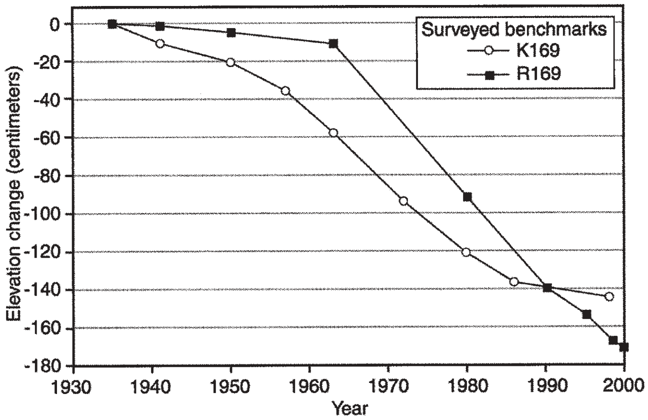

Figure 9. Elevation change for NGS benchmarks K169 and R169. Both benchmarks were established in 1935 and were last re-surveyed by the NGS in 1980; since 1980, K169 has been surveyed by the City of Las Vegas. R169 was surveyed by GPS in 1990 and in 1995 (when it was destroyed); a replacement benchmark was surveyed by GPS in 1998 and 1999.

in good agreement with the conventional 1997–1999 height change of 2.9 cm measured on this point.

DISCUSSION

Evolution of Subsidence Bowls

The pre-1963 subsidence maps delineated generally uniform movement around a singular bowl in the center of the valley, with little movement in the northwest (Figure 4A). Because the bowl was offset from the major pumping center and the area of maximum (30 m) water-level decline, the location of the bowl was generally attributed to the occurrence of more compressible silt and clay deposits and to the more pronounced effects of artesian pressure declines in this part of the valley (Malmberg, 1964; Mindling, 1971). Domenico and others (1966) further suggested that, because the spatial distribution of subsidence was not related simply to the maximum pressure declines, other geologic factors, such as fault-controlled lithology and structure, were influencing the pattern. Engineering properties of the sediments estimated from Atterberg limit values were used to map a central core of highly compressible sediments underlying the Central subsidence bowl. Domenico and others (1966) also proposed that because the bowl was situated along the east edge of the Cashman Field fault, the fault was further facilitating the depression. Later detailed fault mapping (cf. Bell, 1981) showed, however, that the center of the bowl was actually close to benchmark K169, located on the western footwall of the fault.

Between 1963 and 1972, the spatial pattern of subsidence had clearly begun to shift outside of the central

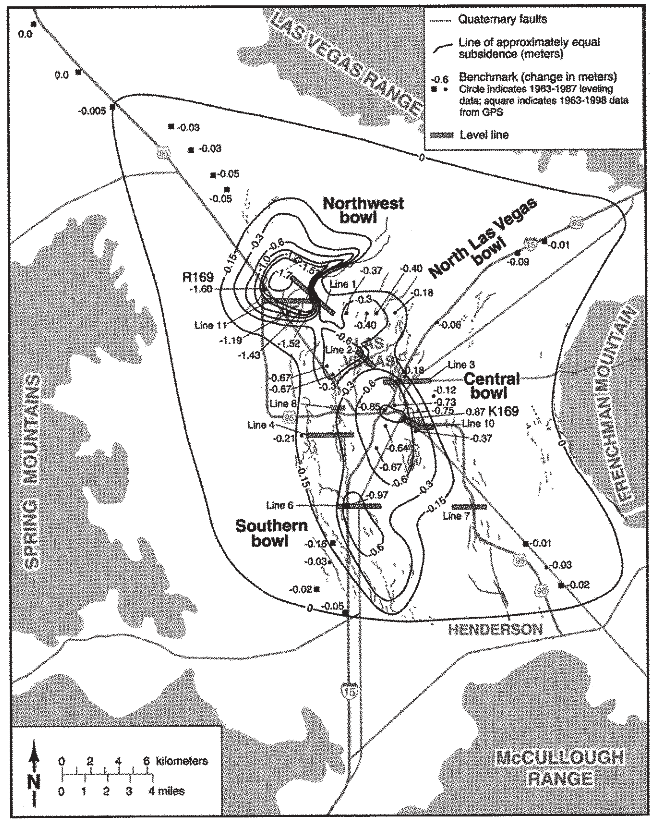

Figure 10. Subsidence map for 1963–2000 based on synthesis of InSAR, GPS, and conventional leveling data. The spatial pattern of subsidence and definition of four localized subsidence bowls are based on the results of the InSAR studies. Conventional geodetic data from 1963–1987 leveling surveys and level line surveys across faults (Figure 5) have been combined with GPS surveys conducted in 1990, 1995, 1998, and 1999 in which GPS elevations were compared with 1963 NGS data. The maximum subsidence measured by these combined methods is 1.7 m in the Northwest bowl.

part of the valley (Harrill, 1976). The single, central subsidence bowl expanded and was partitioned into multiple, localized bowls in the northwest and southern parts of the valley, and a small depression formed in the Nellis well field area (Figure 4A). The Northwest and Southern subsidence bowls exhibited more than 40 cm of subsidence during this period, exceeding that occurring in the Central bowl (30 cm). This was attributed to increased pumping by the LVVWD and the City of North Las Vegas in the west and northwest and by multiple hotel-casino developments pumping along the Las Vegas Strip in the south (cf. Bell, 1981).

By 1980, NGS benchmark elevations showed that the 1972 bowls had become much more pronounced (Figure 4B). The Northwest bowl became the dominant zone of subsidence, exhibiting nearly 80 cm of subsidence for the 1963–1980 period, compared with 60–70 cm in the Central and Southern bowls. The center of the Northwest bowl was placed southeast of the Eglington fault, based on NGS benchmarks surveyed along U.S. Highway 95. A sharply defined Central bowl remained fixed in the center of the valley near benchmark K169, and the Southern bowl remained centered around the north end of the Las Vegas Strip. A recent re-evaluation of the original 1980 NGS data indicated that the 1980 map did not detect the entire spatial extent of the Northwest bowl because of the omission of benchmark R169 in the 1980 compilation. R169 was located several kilometers north of benchmark Q169, which defined the center of the 1980 bowl. A review of the history of the NGS data set indicates that a surveyed elevation on R169 in 1980 was omitted from the original data. The change on R169 between 1963 and 1980 was 81 cm, several centimeters more than Q169, and it showed that the maximum part of the subsidence bowl was actually located farther northwest than shown by the 1980 map.

With the addition of locally derived conventional survey data in 1987, it was evident that the pattern of three smaller subsidence bowls punctuating a broader valley-wide bowl had been persistent since 1963 (Figure 4C). The composite 1963–1987 map incorporated first-order benchmark data together with level line results and modified the size and shape of the 1980 pattern. In particular, additional locally derived benchmark data in the northwest together with the results of leveling along line 1 (Figure 5A) showed that significantly more subsidence had occurred in the Northwest bowl than previously detected, and that the center of the Northwest bowl was located near the Eglington fault. Based on a comparison of elevations of three benchmarks crossing the south end of the Eglington fault (T365, Y368, Z368; Figure 4C), more than 1.5 m of subsidence was found in the center of the bowl for the 1963–1987 period.

New Spatial Patterns Revealed by InSAR

The InSAR maps now reveal several new and significant aspects of the spatial pattern of subsidence not evident on the earlier conventional maps. Most important, the 1992–1997 and 1997–1999 InSAR studies show that the spatial pattern of subsidence is controlled by the Quaternary faults to a much greater degree than had previously been known. The InSAR mapping reveals for the first time that subsidence is occurring in a series of elongated, localized bowls controlled more by the location of the faults that cut the basin floor than by the location of compressible sediment. This contrasts with the spatially uniform patterns delineated on all previous subsidence maps for Las Vegas and with the uniform subsidence patterns commonly inferred in other similar groundwater basins of the western United States (e.g., Schumann and Poland, 1970; Poland et al., 1975). The InSAR pattern also differs from simulated subsidence models for Las Vegas, which relied on water-level and pressure declines and aquifer compressibility parameters to predict movement (Morgan and Dettinger, 1996).

Four subsidence bowls coalesce to form a linear, north-south-trending pattern through the axis of the valley: the Northwest, North Las Vegas, Central, and Southern bowls. The Northwest bowl is now seen to be a triangular depression centered slightly north of benchmark R169 and sharply bounded on the southeast by the Eglington fault. The southern portion of the original Northwest bowl shown on the 1963–1987 map is now seen to be a separate localized bowl, here called the North Las Vegas bowl, which is bounded on its southeast margin by the Windsor Park fault zones. The Central and Southern bowls correspond closely with their original spatial positions but are more linear and continuous, extending farther to the south than had previously been recognized. Both bowls are bounded by the Valley View-Decatur fault zones on the west and by the Cashman Field faults on the east. It is interesting to note that no subsidence is detected along the Whitney Mesa fault zone despite the fact that it is situated within the same thick section of compressible sediments as the subsidence bowls (Figure 1A), an observation consistent with the lack of any significant geodetic movement noted along line 7 (Figure 5F). The InSAR results actually show a slight amount of uplift (2–3 cm) in this area.

Revised 1963–2000 Subsidence Map

We compared the InSAR maps with the results of conventional level lines in order to determine if the new spatial relations depicted by the InSAR were long-term patterns of aquifer system deformation or more recent, temporal features developed during the 1990s. Based on this comparison, we find that the principal features of the subsidence patterns depicted by InSAR are ones that have persisted since at least 1978. Fortuitously, level line 1 was established in the deepest portion of the Northwest subsidence bowl, and the leveling results (Figure 5A) show that the pattern was present as early as 1979. Similar comparisons can be made with lines 2, 3, and 10, which each indicate fault-controlled movement consistent with the InSAR pattern. In retrospect, the significance of the level line data was not fully recognized in earlier studies. Repeat leveling of line 1 and the other lines through 1991 provided intriguing evidence that subsidence was preferentially localized along the faults, but at the time of the last study (Bell and Price, 1991), the degree to which the faults were controlling deformation relative to the basin as a whole was still unknown. The level line data were incorporated in the 1963–1987 map, but contouring of the map was based on conventional interpolation of the benchmark data.

Further evidence of the long-term stability of the InSAR pattern is provided by NGS benchmarks K169 and R169, both established in 1935 (Figure 9). Benchmark K169, located in the Central bowl, began subsiding in the 1940s and by 1963 showed about 60 cm of movement. Benchmark R169 showed little movement until after 1963, when it began to subside at a rate of 5–6 cm/year, eventually surpassing the total amount of movement occurring on K169.

The 1963–1987 subsidence map is here revised to more closely reflect the spatially detailed patterns shown by the InSAR results, while at the same time remaining consistent with the conventional benchmark data. Figure 10 shows subsidence between 1963 and 2000 based on the InSAR pattern, the original 1963–1987 leveling data, and additional conventional leveling data collected by the cities of Las Vegas and North Las Vegas in 1998. In the Northwest bowl, GPS measurements taken in 1990, 1995, 1998, and 1999 (Bell et al., 2001a, 2001b) allow further refinement of total subsidence for the period. The location, shape, and areal extent of the four subsidence bowl contours are derived from the InSAR pattern. The contour values are based on the original 1987 data as modified by subsequent conventional and GPS measurements, and the steepness of the contour gradients is based on leveling data across the faults for 1978–1999.

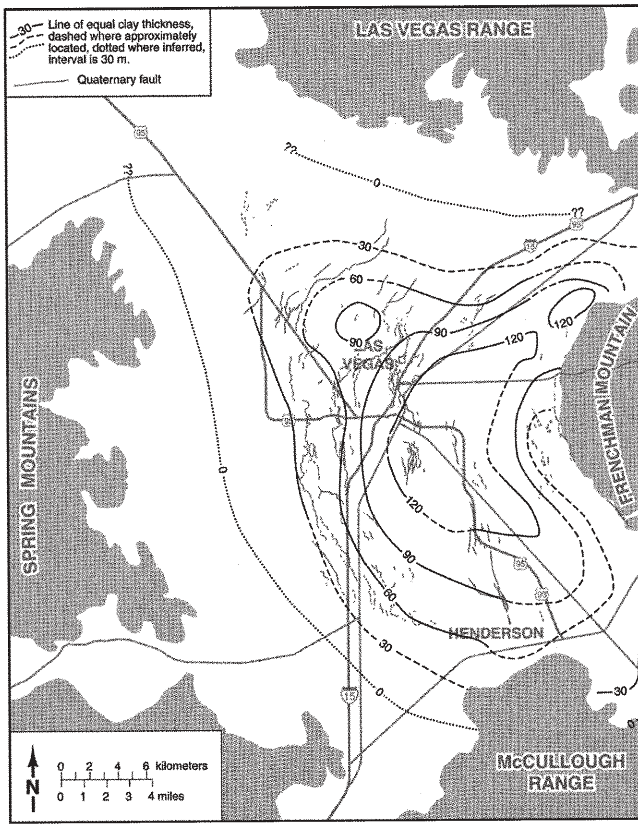

Figure 11. Distribution and thickness of compressible clay deposits in the upper 300 m of sediments in the principal zone of aquifers in Las Vegas Valley (from Morgan and Dettinger, 1996).

Relation of Bowls to Pumping Centers and Water-Level Declines

In contrast to some other subsidence areas in the arid west (cf. Schumann and Poland, 1970), maximum subsidence in Las Vegas is not directly related to the area of maximum water-level decline. Malmberg (1964) and Domenico and others (1966) first noted that subsidence was offset from the main centers of pumping and from the areas exhibiting the greatest water-level and pressure declines. With the development of the additional localized bowls in the northwest and south, similar spatial offsets became evident. Based on the distribution of pumping during the 1963–1990 period of development of the localized bowls, maximum pumping intensity and the area of greatest water-level decline continued to be located west of the subsidence bowls (Figure 3).

A comparison of the spatial distribution of subsidence measured by InSAR between 1992 and 1997 with the distribution of pumping for the 1990–1998 period (Figure 7C) shows that the offset between pumping and movement is a persistent characteristic of subsidence in Las Vegas. The reasons for the offset are not well understood, although, as noted earlier, thickness of the compressible sediments and susceptibility to hydraulic pressure changes have historically been called upon to explain the relation. Although the InSAR mapping shows that the faults are acting as subsidence barriers, no significant differences in hydraulic heads occur across the faults based on water-level studies and modeling (Burbey, 1995; Morgan and Dettinger, 1996), indicating that the faults are not compartmentalizing regional groundwater flow. The Decatur-Valley View faults form the western boundary of the Central subsidence bowl and mark a rapid transition from coarse-grained sediments on the west to compressible, fine-grained sediments on the east (Figure 1B). Although most of the groundwater pumping is occurring in coarse-grained deposits on the footwall side of the fault zone, and subsidence is occurring in the fine-grained sediments on the hanging wall side, a detailed hydrostratigraphic study by Donovan (1996) showed that no measurable differences in hydraulic heads occur across the fault zone. Based on a compilation of water levels from more than 60 wells in the western part of the valley, he showed that the 1993 potentiometric surface was unaffected by either the faults or the subsidence. And, as discussed in the following section on the Eglington fault, there are neither lithologic nor hydraulic head differences that can account for the localized subsidence occurring in the Northwest bowl.

The distribution of compressible sediments in the valley (Figure 11) corresponds in general with the location of the subsidence bowls but does not fully account for the location of maximum movement in these areas. The distribution and compressibilities of the fine-grained deposits were first described by Domenico and others (1966) and Mindling (1971) based on laboratory testing of well drill-hole samples; additional qualitative data were described from well logs by Plume (1984). These studies consistently showed the areas of maximum sediment thickness and compressibilities as lying in the central and northeast parts of the valley. Morgan and Dettinger (1996) used these data to estimate inelastic storage coefficients for the aquifer system and to model subsidence. The simulated subsidence map they developed for the period 1972–1981 reflects only in a general way the pattern measured by geodetic methods, highlighting the complexities of modeling subsidence in the valley. This is particularly evident in the northwest, where the localized bowl is much larger and differently positioned than suggested by their modeling, in part because of the lack of detailed subsurface data available for that part of the valley at the time of their study.

The reasons for the spatial offset between the areas of maximum water-level decline and the subsidence bowls remain uncertain because of a lack of sufficiently detailed analytical data regarding inelastic storage coefficients of the aquifer system and the vertical and horizontal distribution of hydraulic pressure changes. No direct measurements of these values have been made. Studies by Waichler (1991) and Morgan and Dettinger (1996) estimated specific storage coefficients from compaction models calibrated with a few selected subsiding benchmarks (e.g., K169). Because of the intense urbanization of the valley, it is unlikely that any extensive new subsurface data will be developed in the future that could provide the necessary analytical detail on a regional scale. The spatial offset may be best explained only in a qualitative way, as first noted by Malmberg (1964): the offset is simply the result of fine-grained sediments being depressurized by pumping in adjacent areas. The principal areas of pumping (Figure 7C) are located in generally coarse-grained deposits lying high on the potentiometric surface gradient, which slopes approximately from west to east (Harrill, 1976; Donovan, 1996); thus it seems likely that the pumping centers are intercepting groundwater flow that would otherwise sustain the pore-water pressures in the down-gradient portions of the aquifer system containing thicker sequences of compressible aquitards.

Although the up-gradient interception of groundwater flow may explain the development of the North Las Vegas, Central, and Southern subsidence bowls, the Northwest bowl is not as easily related to the areas of heavy pumping. The local potentiometric surface slopes from northwest to southeast in the area of the Northwest bowl (Donovan, 1996), and based on the pumping pattern for 1990–1998 (Figure 7C), the closest area of major pumping lies to the south of the bowl and is thus an unlikely source of the subsidence. It appears most likely that the Northwest subsidence bowl is related to irrigation pumping located north of the bowl and to the collective effect of many small domestic wells within the bowl. Several large irrigation wells located near the Elkhorn well together account for 2.5–3.7 hm^3/year of pumped water and are situated up-gradient from the bowl (Figure 7C). Katzer and others (1998) estimated that more than 300 domestic-supply wells that tap the aquifer in this area can collectively account for about 1.23 hm^3/year of water withdrawal. Many of these wells have been replaced or deepened because of the declining water levels. Although the combined total from domestic and irrigation pumping of 3.7–4.9 hm^3/year in the Northwest bowl is not large compared to the total amount of groundwater pumped throughout the valley (about 90 hm^3 in 1998), many of the wells are less than 150 m in depth and are drilled in fine-grained deposits having low yields and thus a high potential for subsidence.

Subsidence Movement Opposite to Geologic Displacement: The Eglington Fault Example

The level line data together with the InSAR studies confirm that several of the Quaternary fault blocks that cut the basin sediments have been activated by subsidence. Although the movement is controlled by the faults, it is generally distributed across broad zones up to hundreds of meters in width, indicating that movement is not occurring as fault slip *per se,* but rather as fault block deformation. Although initially detected in the level line surveys, the InSAR results further show that some faults are moving opposite, or antithetic, in sense to the original geologic displacements.

The most striking example of this antithetic movement is the Eglington fault. The fault is a subsidence barrier with movement occurring almost exclusively to the north of the scarp in the geologic footwall. To a lesser degree the same pattern of footwall subsidence is evident in the North Las Vegas bowl, where the Windsor Park fault zone forms a similar, but less pronounced, barrier along the southern margin of the bowl. Based on subsurface geophysical data (Plume, 1984; Langenheim et al., 2001) and fault scarp morphology, the Eglington fault is a southeast-dipping normal fault with a surface scarp 30 m in height. The maximum displacement of the Northwest subsidence bowl shown by the InSAR map is located almost entirely within the footwall block of the fault. This relation was noted soon after the first year of repeat surveying of line 1 in 1979 (Bell, 1981).

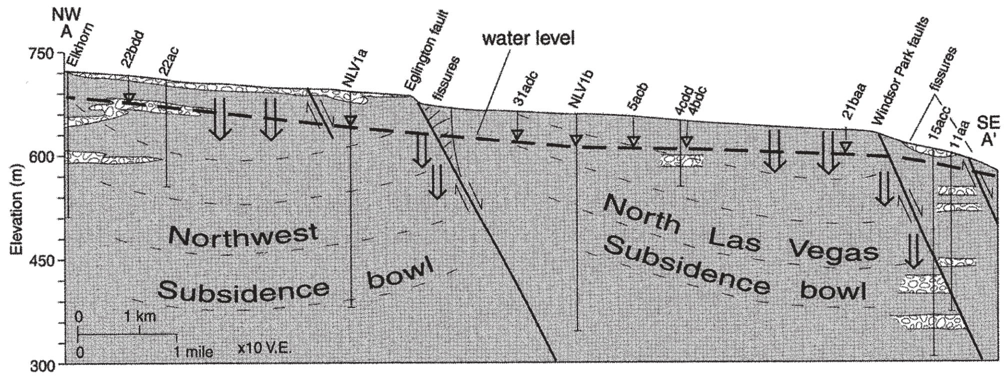

Figure 12. Schematic cross-section across the Eglington fault between the Northwest and North Las Vegas subsidence bowls (see Figure 7C for location). Location and depth of well logs used to determine thickness of compressible fine-grained deposits shown by well designation. Wells NLV1a and NLV1b demonstrate that more than 300 m of fine-grained sediment occurs on both sides of the Eglington fault. Subsidence in the Northwest and North Las Vegas bowls is generating antithetic movement along the fault, shown diagrammatically by the arrows.

The origin of the Eglington subsidence barrier is poorly understood. As noted earlier, some faults in the valley mark sharp lithologic transitions from coarse-grained alluvial fan deposits to fine-grained basin fill sediments; Maxey and Jameson (1948) argued that these transitions demonstrated that these were 'compaction' faults. The Decatur and Valley View faults are examples of such transitions where thick (>300 m) sequences of alluvial fan deposits extending from the Spring Mountains grade abruptly into equally thick fine-grained deposits (Figure 1B).

In contrast, subsurface data across the Eglington fault indicate that no lithologic differences exist across the fault. Hydrostratigraphic mapping of subsurface sediments near the Eglington fault by Donovan (1996) showed that aquifer and aquitard thicknesses are generally uniform across the fault. Based on well log data, a northwest-southeast geologic cross-section constructed tween the Eglington and Windsor Park faults (Figure 12) further shows that the faulted sediments are uniformly fine grained and isotropic; there are no obvious lithologic discontinuities that could account for a hydraulic barrier. In particular, lithologic log data from two wells straddling the Eglington fault (NLV1a and NLV1b) show that both wells contain similar 300-m-thick sections of compressible clay, demonstrating the absence of any lithologic contrast. Water levels in seven of the cross-section wells provide no indication of a regional groundwater effect across the fault, and transmissivities and elastic storage coefficients are similar on both sides of the fault (Donovan, 1996; Morgan and Dettinger, 1996). Some slight differences in recent water levels (Figure 13), however, may indicate localized, short-term effects; during the period of general water-level recovery between 1990 and 1998, the Northwest bowl continued to exhibit water-level declines, with the zero contour lying near the center of the bowl.

Despite the lack of evidence for regional compartmentalization of groundwater flow, the Eglington fault is clearly acting as a subsidence barrier, and it is reasonable to infer that the fault has hydraulic properties that inhibit short-term aquifer flow, aquitard drainage, or both and that produce a subsidence partition. This could be caused by fault gouge or secondary carbonate cementation of the fault zone, common in arid alluvial environments, or by other mineralization occurring along the fault that reduces the transmissivity of the fault zone. Many of the faults in the valley, including the Eglington, have been conduits for groundwater discharge and are sites of paleospring deposits frequently containing secondary calcium carbonate cementation.

One of the most extensive areas of fissures is located along the Eglington fault (Figure 1A), suggesting that the relative subsidence motion across the faults is kinematically related to the development of the fissures. Helm (1994) described four general cases in which vertical differential movements can generate horizontal strain and fissures:

1. Differential compaction in an actively compacting zone at depth causing horizontal displacement in the overlying passive, non-compacting zone
2. Differential compaction between deposits of differing compressibilities in the actively compacting zone
3. Differential compaction caused by the draping effect
4. Differential compaction along faults as the hanging wall sediments compact

As noted earlier, Helm (1994) also showed that horizontal strain originating from pumping-related hydraulic pressure developed in the aquifer may be localized

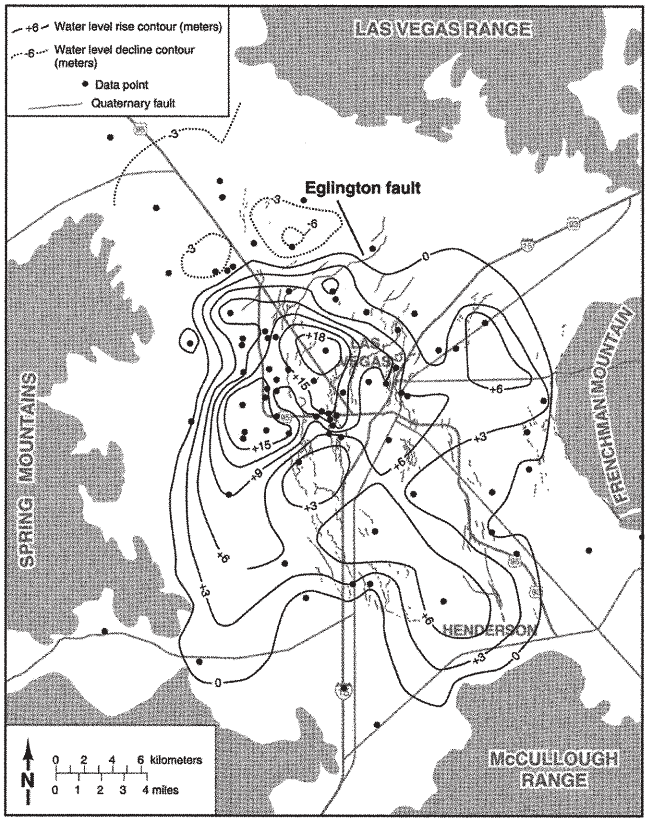

Figure 13. Water-level change for the principal aquifers in Las Vegas Valley between 1990 and 1998 based on measured water levels. Most of the valley exhibited a recovery and rise in water levels, except for the area north of the Eglington fault, where water levels continued to decline (from Las Vegas Valley Water District, unpublished data).

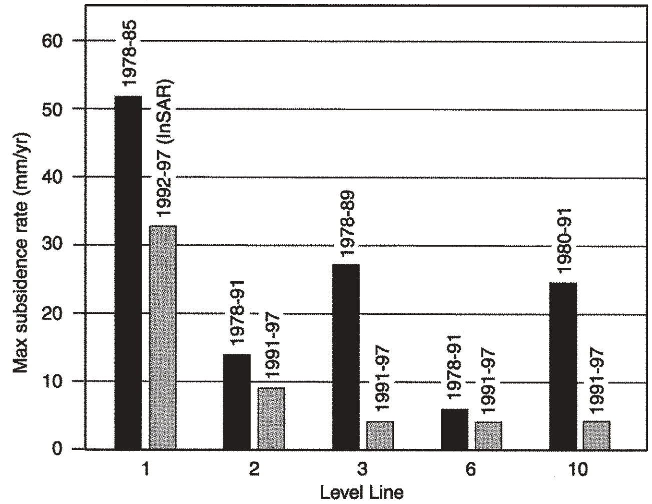

Figure 14. Histogram showing maximum subsidence measured along level lines between 1978 and 1997. Line 1 was destroyed in 1985, and the 1992–1997 data are taken from the InSAR results for the same transect.

along the faults. The location of fissures along the southern end of the Decatur-Valley View fault zone in an area having little historical subsidence supports this model. In the case of the Eglington fissures, Helm (1994) suggested that horizontal hydraulic strain generated by heavy pumping to the west of the fault was possibly responsible for their formation. The pronounced antithetic character of the subsidence movement across the Eglington fault suggests a fifth case for fissure development. In this case, movement of the footwall block away from the hanging wall block may be mechanically generating the tensile strain. Shown diagrammatically in Figure 12, extension near the fault could occur as the footwall subsides away from the fault zone.

Potential for Development of Other Subsidence Bowls

It is important to note that the east-central and northeastern parts of the valley contain some of the thickest sections of compressible fine-grained sediments in the aquifer system (Figure 11). Recent gravity data (Langenheim et al., 2001) also show that the northern and northeastern portions of the valley adjacent to the Las Vegas Range and Frenchman Mountain contain basin fill deposits as much as 3–4 km in thickness. The lack of significant subsidence in these parts of the valley can be attributed to the absence of any significant water-level decline. The northern and northeastern parts of the valley, therefore, should be considered potential sites of future subsidence if increases in net groundwater withdrawals or reductions in hydraulic pressures occur in these areas.

Reduced Rates of Subsidence Since 1991

A comparison of the level line results for the 1978–1991 and 1991–1997 periods indicates that a significant reduction in the rate of subsidence has occurred throughout the valley (Figure 14). Prior to 1991, the rates of subsidence in the Northwest bowl were as much as 5–6 cm/year based on the 1978–1985 leveling of line 1, and rates in the central part of the valley were between 2.5 and 3 cm/year. In the Northwest bowl, conventional and GPS surveys of line 11 (Figure 5I) and benchmark R169 (Figure 9) indicate that the rate is now between 2.5 and 3 cm/year, a reduction of 50 percent. The most dramatic reductions have occurred in the Central bowl, where rates have declined as much as 80 percent. Level lines 3 and 10 both show that the subsidence rates of 2.5–3 cm/year measured between 1978 and 1991 have declined to about 5 mm/year since 1991. The decline of the subsidence rate in the Central bowl is most evident in the long-term record of benchmark K169, located near the center of the bowl in downtown Las Vegas. The benchmark has been surveyed periodically since 1935, and it has shown movement since the first re-surveys were conducted in 1941 (Figure 9). Between 1950 and 1987, the benchmark subsided at a relatively consistent average annual rate of about 3–3.5 cm/year. The benchmark was most recently surveyed in 1998, at which time the height had changed by only 8 cm since 1987, indicating an average rate of less than 1 cm/year during the 1990s.

A reduction in subsidence rates was also noted in the study by Amelung and others (1999), where we observed that InSAR showed the 1992–1997 subsidence rate to be declining, with most of the movement occurring in the 1992–1993 period. During the 1993–1996 period, InSAR data showed that although subsidence continued to occur in the Northwest bowl, the remainder of the valley exhibited little to no subsidence, and several areas of localized uplift developed in response to rising water levels in the central and southern parts of the valley.

In contrast to the central part of the valley, subsidence in the Northwest bowl, although reduced, is continuing at a relatively stable rate of 2–3 cm/year. The 1997–1999 InSAR results show 5–6 cm of subsidence in the Northwest bowl between May 1997 and December 1999, and geodetic data from line 11 and from GPS measurements on benchmark R169 also indicate that the rate has stabilized at 2–3 cm/year.

The reduction in subsidence rates is attributed to the effects of the artificial recharge program initiated by the Las Vegas Water District and the City of North Las Vegas in the early 1990s, which has produced a general recovery of water levels (Figure 13). Although the total volume of groundwater pumped in Las Vegas has remained constant at 73–86 hm^3/year since the late 1970s (Figure 2), more than 185 hm^3 of imported Colorado River water has been recharged during the last decade. Annual recharge reached a peak of 34 hm^3/year in 1998, producing a net (pumping minus recharge) withdrawal of about 52 hm^3 for the year, a volume close to the natural recharge rate recently calculated by Donovan and Katzer (2000).

CONCLUSIONS

New geodetic data developed during the last 10 years have been used in this study to review and revise our understanding of the evolution and spatial patterns of groundwater-related land subsidence in Las Vegas. Based on a comparison of conventional, GPS, and InSAR data, it can be seen that the spatial distribution and magnitude of subsidence in the valley is significantly different than depicted in earlier studies.

The spatial distribution of subsidence in Las Vegas Valley underwent a significant shift after 1963, evolving from a singular bowl located in the central downtown area to several localized bowls, one remaining in the central part of the valley and other large ones developing in the northwest and southern parts of the valley. Prior to 1963, the principal center of pumping was located around the LVVWD main well field about 5 km west of the Central subsidence bowl. The subsequent shift in the spatial pattern was related to a change in pumping distribution, with a significant increase in annual pumpage moving into the west and northwest part of the valley by the 1970s. The new geodetic data, combined with a re-examination of the older leveling data, indicate that the Northwest subsidence bowl became the dominant subsidence area, beginning to move at a rate of 5–6 cm/year at about the same time the shift in groundwater pumping occurred. A re-examination of the 1980 NGS and the 1972 NDOT leveling data show that the Northwest bowl was significantly larger and deeper than was previously known in our earlier studies.

The InSAR studies of subsidence in Las Vegas reveal for the first time that the spatial pattern of movement is very strongly controlled by the faults that cut the valley floor. In contrast to previous maps, which showed uniformly distributed subsidence patterns, the InSAR mapping shows that subsidence is occurring in a series of four principal, elongated, localized bowls bounded by Quaternary faults: the Northwest, North Las Vegas, Central, and Southern bowls. Based on a comparison of the InSAR data with conventional leveling data across the faults dating back to 1978, it can be concluded that the spatial pattern shown by InSAR has been a consistent pattern of movement during the last two decades, allowing a revised subsidence map to be developed for the period 1963–2000. In particular, the pattern shows that the subsidence in the Northwest bowl has been controlled by the Eglington fault, which is acting as a subsidence barrier.

A comparison of the geodetic data with the long-term patterns of pumping indicates that the subsidence bowls are offset from the principal areas of water-level decline, a relation best explained by the general distribution of compressible sediments in the valley and the location of the pumping centers up-slope on the potentiometric gradient from the subsiding areas. A comparison of InSAR data and pumping data for the last decade indicates that this is a persistent pattern that can account for the development of three of the four subsidence bowls. The only exception is the Northwest bowl, where subsidence appears to be related more to irrigation and domestic well pumping occurring within the low-yield, highly compressible fine-grained deposits.

The new geodetic data together with the existing conventional leveling data indicate that subsidence across several of the faults is opposite or antithetic in sense to the original geologic sense of displacement, a relation attributed to the location of the subsidence bowls in the footwall blocks of the faults. The Eglington fault is the most striking example of this antithetic movement, with more than 1.7 m of subsidence of movement occurring in the footwall since 1963. Such movements may provide another case in which extensional strain can develop along faults and produce earth fissures.

A comparison of conventional leveling, GPS, and InSAR data for 1978 through 1999 shows that subsidence rates have declined significantly in most parts of the valley since 1991. The most active Northwest subsidence bowl shows a decline in the subsidence rate from 5–6 cm/year to 2.5–3 cm/year, a reduction of 50 percent. The most dramatic reductions have occurred in the Central bowl, where rates have declined by as much as 80 percent to only a few millimeters per year. These reductions are attributed to an artificial recharge program that has produced a general rise in water levels, arresting subsidence in most parts of the valley except for the Northwest bowl, where movement continues to occur at a stable rate of 2.5–3 cm/year.

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