The influence of faults in basin-fill deposits on land subsidence, Las Vegas Valley, Nevada, USA

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Abstract The role of horizontal deformation caused by pumping of confined-aquifer systems is recognized as contributing to the development of earth fissures in semiarid regions, including Las Vegas Valley, Nevada. In spite of stabilizing water levels, new earth fissures continue to develop while existing ones continue to lengthen and widen near basin-fill faults. A three-dimensional granular displacement model based on Biot's consolidation theory (Biot, MA, 1941, General theory of three-dimensional consolidation. Jour. Applied Physics 12: 155–164) has been used to evaluate the nature of displacement in the vicinity of two vertical faults. The fault was simulated as (1) a low-permeability barrier to horizontal flow, (2) a gap or structural break in the medium, but where groundwater flow is not obstructed, and (3) a combination of conditions (1) and (2). Results indicate that the low-permeability barrier greatly enhances horizontal displacement. The fault plane also represents a location of significant differential vertical subsidence. Large computed strains in the vicinity of the fault may suggest high potential for failure and the development of earth fissures when the fault is assumed to have low permeability. Results using a combination of the two boundaries suggest that potential fissure development may be great at or near the fault plane and that horizontal deformation is likely to play a key role in this development.

Résumé On considère que la déformation horizontale provoquée par un pompage dans un aquifère captif joue un rôle dans le développement des fissures du sol en régions semi-arides, comme la vallée de Las Vegas (Nevada). Malgré des niveaux d'eau stabilisés, de nouvelles fissures du sol continuent de se développer en longueur et en largeur au voisinage de failles dans les bassins sédimentaires. Un modèle de déplacement granulaire tri-dimensionnel, basé sur la théorie de la consolidation de Biot (Biot, M A, 1941, General theory of three-dimensional consolidation. Jour. Applied Physics 12:155–164), a été utilisé pour évaluer la nature du déplacement au voisinage de deux failles verticales. La faille a été simulée comme 1) une barrière de faible perméabilité pour l'écoulement horizontal, 2) une rupture structurale dans le milieu, mais sans obstruction de l'écoulement, et 3) une combinaison des deux précédentes conditions. Les résultats indiquent que la barrière de faible perméabilité favorise fortement le déplacement horizontal. Le plan de faille constitue aussi un lieu de subsidence différentielle verticale significative. Les fortes contraintes calculées au voisinage de la faille laissent penser qu'il existe un fort potentiel de rupture et le développement de fissures du sol quand on suppose que la faille possède une faible perméabilité. Les résultats utilisant une combinaison des deux conditions suggèrent que le développement potentiel de fissures peut être grand sur ou à proximité du plan de faille et que la déformation horizontale joue vraisemblablement un rôle clé dans ce développement.

Resumen Se conoce la contribución que la deformación horizontal causada por el bombeo de sistemas acuíferos confinados tienen en el desarrollo de fisuras en regiones semiáridas, como es el caso del Valle de Las Vegas (Nevada, Estados Unidos de América). A pesar de la estabilización de los niveles, se continúa desarrollando nuevas fisuras, mientras las ya existentes se alargan y ensanchan cerca de las fallas de relleno de cuenca. Se ha utilizado un modelo tridimensional de desplazamiento granular basado en la teoría de consolidación de Biot (Biot, M.A., 1941. General theory of three-dimensional consolidation. J. Applied Physics, 12: 155-164) para evaluar la naturaleza del desplazamiento junto a dos fallas verticales. Se ha simulado cada falla como (1) una barrera de baja permeabilidad al flujo horizontal, (2) un hueco o ruptura estructural en el medio pero sin obstrucción al flujo de aguas subterráneas, y (3) una combinación de las dos condiciones anteriores. Los resultados indican que la barrera de baja permeabilidad incrementa enormemente el desplazamiento horizontal. El plano de falla también representa una situación de subsidencia diferencial vertical significativa. Los valores

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elevados que se han calculado para la deformación en la proximidad de la falla pueden sugerir que existe un alto potencial de fallo y desarrollo de fisuras cuando se supone que la falla posee una baja permeabilidad. Si se combinan los dos contornos, los resultados sugieren que el desarrollo potencial de fisuras puede ser mayor en o cerca de el plano de falla, y que es probable que la deformación horizontal desempeñe un papel clave en él.

Keywords Aquifer deformation · Earth fissures · Faults · Flow modeling · Subsidence

Introduction

The quantification of land subsidence because of groundwater withdrawal has typically been accomplished by (1) periodic land-surface leveling to calculate temporal changes in elevation by GPS (Global Positioning System) or InSAR (Interferometric Synthetic Aperture Radar) techniques or by more classical leveling methods (for example, Ikehara and Phillips 1994), (2) installation of extensometers, which allow direct and accurate site measurements of subsidence to whatever depth the extensometer pipe or cable extends (Riley 1969), and (3) the use of subsidence models that calculate vertical compaction of fine-grained deposits resulting from a reduction in porewater pressures (Helm 1975, 1976; Hanson 1989; Williamson et al. 1989; Leake and Prudic 1991; Morgan and Dettinger 1996; are examples). The latter method, namely modeling, requires data from the first two approaches. However, when coupled with groundwater flow models, modeling can provide areal distributions of simulated vertical compaction at the basin scale.

Land subsidence because of groundwater withdrawal generally is not a serious problem if an entire region subsides in a broad bowl-shaped depression, except near the sea coast, flood-prone river stretches, or where aqueducts and other elevation-sensitive structures reside. The major concern and problems related to subsidence are the potentially destructive results caused by differential vertical subsidence (Bell 1981; Holzer and Pampeyan 1981), horizontal displacement (Allen 1971), and earth fissures (Bell and Price 1991). At Long Beach, California, although 9 m of subsidence occurred in an urban area along the sea coast, the most costly damage (buckled pipelines, twisting railroad tracks, etc.) was caused by horizontal displacement (Poland and Davis 1969).

The mechanism responsible for vertical differential subsidence has been largely attributed to variations in the thickness of compressible deposits across a vertical fault or other subsurface structure that abruptly limits the potential for compaction in one area relative to an adjacent area. This type of differential subsidence is believed to be quite common in Las Vegas Valley across basin-fill faults (Holzer 1978; Bell 1981; Bell and Price 1991; Helm 1994a).

Although earth fissures are destructive, the mechanisms leading to their formation and propagation are not completely understood. Consequently, understanding the mechanisms leading to the formation of earth fissures is currently a major focus in land-subsidence research (Helm 1994a; Sheng and Helm 1995; Burbey 1996). This paper deals with the role that basin-fill faults may have in the development and quantitative understanding of earth fissures. A three-dimensional perspective of subsidence is required to make such an evaluation.

Several theories have been proposed with regard to the origin and location of earth fissures. Classical theories of extensional strain caused entirely by bending at the land surface, as described above, require that a fissure begins at the land surface and migrates downwards for the duration of extensional bending. Some hydrologists have theorized that horizontal seepage forces (Lofgren 1968) or desiccation (Narasimhan and Holzer 1978) may contribute to the development of earth fissures. Carpenter (1993) suggests that differential subsidence and possibly tectonically weakened brittle-zone deposits may account for fissure development near Eloy Arizona. Helm (1994a) argues that failure likely occurs somewhere within the lower part of the unsaturated zone where cohesive strength is not great enough to resist failure when horizontal tension within the underlying active zone of deformation or the saturated zone is large. Earth-fissure propagation is then upward through the brittle unsaturated zone to the land surface. One weakness of the bending-beam theory (as the sole mechanism) is that it can not account for the occurrence of numerous fissures located far from the zone of active subsidence and drawdown (Anderson 1989; Bell and Price 1991). Some earth fissures in Las Vegas Valley occur near basin-fill faults, but others are located where little active subsidence and water-level drawdown exist, often near the periphery of the basin. Similarly in the Picacho Basin in Arizona, fissures occur near valley perimeters where aquifers at depth have negligible drawdown, but are truncated by basement rock (Carpenter 1993). Hydraulic-head distributions in the vicinity of these fissures and the resulting strain regime suggest that the fissures were not likely to be initiated by differential vertical subsidence alone. Explanation for these earth fissures can, however, be explained by horizontal movement within the skeletal aquifer framework because of groundwater pumping (Helm 1987, 1994a; Burbey 1993, 2001; Sheng and Helm 1995; Burbey and Helm 1999).

The formation of earth fissures associated with groundwater withdrawal is generally associated with the following conditions or criteria:

1. An arid to semiarid climate in which a relatively thick, brittle unsaturated zone overlies and rides passively on a deforming aquifer system (Helm 1994a) that is under stress because of pumping.
2. Long-term overdraft of the principal aquifer system. When an aquifer is pumped for long periods – typically on the order of decades, and where discharge is significantly greater than natural recharge, the aquifer generally experiences greatly increased effective stress and subsequent strain and deformation.

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3. Unconsolidated basin-fill deposits with fairly high coefficients of compressibility. Under a Hookian (elastic) stress–strain constitutive relation, the degree to which a porous material compresses under a given stress depends on the coefficient of compressibility of the material. Subsequent displacements (and their relative magnitude between hydrogeologic units) in both the vertical and horizontal directions, therefore, are a function of aquifer compressibility (Helm 1984, 1987, 1994b; Burbey 1999; Burbey and Helm 1999). The volume compressibility can be defined in terms of the shear modulus and Poisson's ratio in three-dimensional settings. As horizontal movement occurs within the deforming aquifer system, the brittle overburden may experience increased strain, which is translated from the deforming aquifer system below (Sheng and Helm 1995). The brittle unsaturated zone has little cohesive strength to resist failure because of its limited moisture content.
4. An abrupt discontinuity in horizontal hydraulic conductivity or transmissivity related to lithology or structure. Any zone of weakness, such as a fault or heterogeneity in either the aquifer or overlying unsaturated zone, may result in failure within the unsaturated zone if tensional stresses in the vicinity of the weakness are significant. Such failure may result in the initiation of a fissure at the land surface.
5. Differential vertical compaction (Feth 1951; Bouwer 1977; Jachens and Holzer 1979, Holzer and Pampeyan 1981; Jachens and Holzer 1982). Differential subsidence often results from heterogeneous thicknesses of compressible sediments in the subsurface. This differential movement at the land surface can cause extension of the surface deposits as bending (horizontal strain) occurs in the near-surface brittle deposits. Helm (1994a) suggests that differential compaction at depth causes rotation of the overlying surface deposits toward the side with greater compaction. This mechanism contributes to the formation of earth fissures, but Helm contends that it is not a requirement for their occurrence.

Although differential compaction contributes to the formation of earth fissures, this study explores the extent to which horizontal aquifer deformation contributes to initiating fissures at land surface. Quantification of potential hazards associated with earth fissures requires an evaluation of horizontal aquifer deformation as a contributing mechanism. It will be shown that differential vertical subsidence can occur across a vertical fault plane without differences in thickness of compressible deposits across the fault plane.

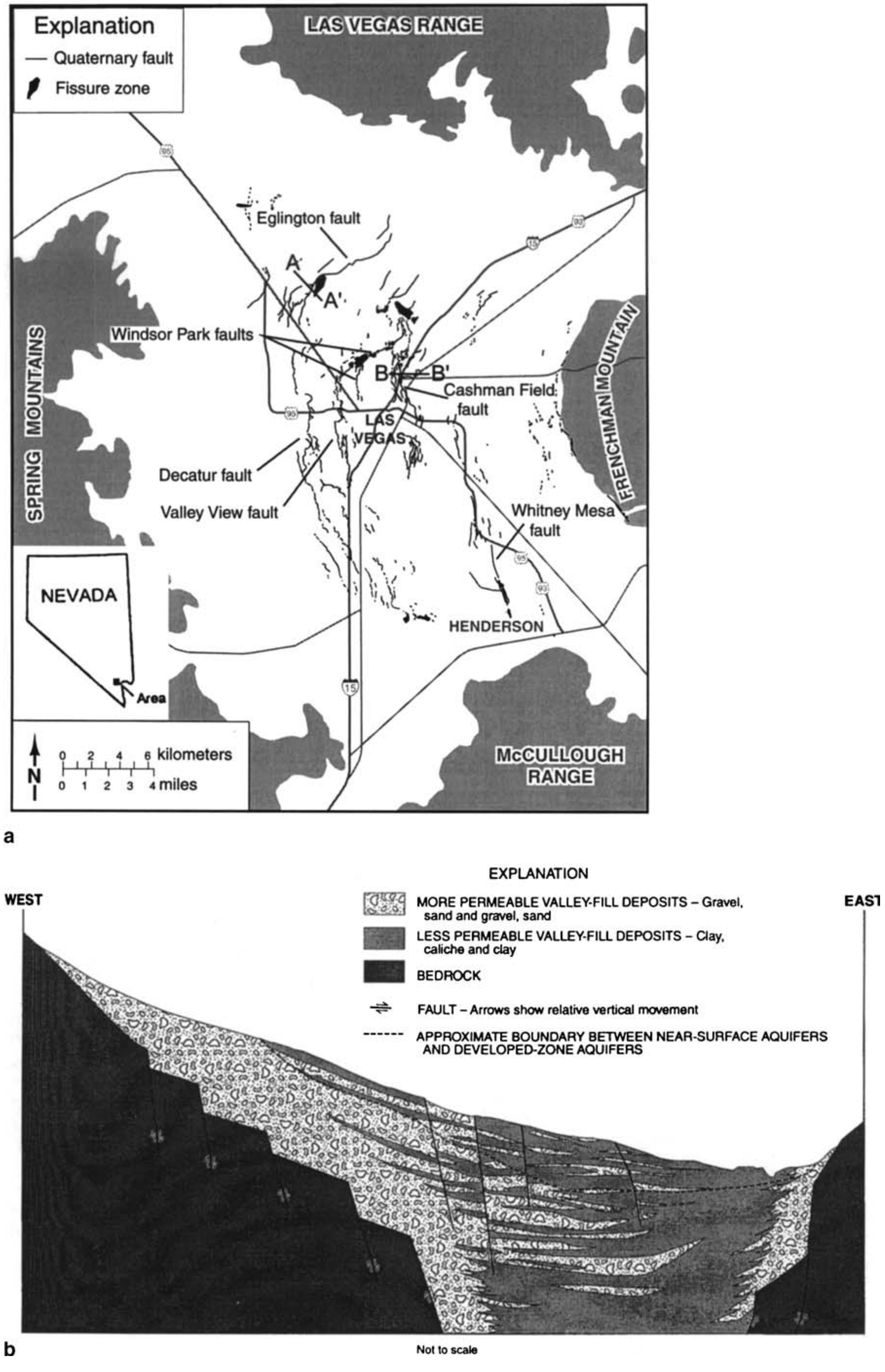
Vertical and Horizontal Aquifer Deformation

Aquifer deformation occurs in both the vertical and horizontal directions in response to fluid withdrawal from confined aquifer systems (Helm 1987; Burbey 2001). The following discussion refers to the active zone of deformation, or saturated-zone movement. The overlying unsaturated zone is believed to move passively over the active aquifer system, deforming in response to the underlying saturated zone (Helm 1994a). Mechanisms for vertical deformation of aquifers caused by pumping are well documented (Poland and Davis 1969; Poland et al. 1972; Helm 1975, 1976) and will not be reiterated here.

Horizontal strain and deformation caused by fluid withdrawal are usually overlooked or ignored as being negligible compared with vertical strain and deformation, largely because the horizontal compressibility of the coarse-grained aquifer materials tend to be much lower than the compressibility of the fine-grained confining units that affect vertical deformation. The tradition of assuming no horizontal skeletal strain within an aquifer dates back to Theis (1935) and Jacob (1940) who derived the transient groundwater flow equation from first principles in physics (such as mass conservation). For computational convenience, these authors assumed that horizontal strain was negligibly small. They justified this mathematical assumption by surmising that aquifer movement might be found to be horizontally constrained. This surmise has only recently been tested empirically and numerically for the first time. Neither field data (Yerkes and Castle 1969; Wolff 1970; Carpenter 1993; Burbey 1996) nor numerical models (Burbey 1999, 2001) have corroborated Theis' and Jacob's assumption. Measured field data suggest that horizontal deformations are typically within an order of magnitude of measured vertical deformations. If horizontal stresses associated with prolonged aquifer pumping are large, then the resulting horizontal strains and displacements at specific regions in the aquifer system could also be large. Aquifer systems tend not to be laterally homogeneous. Therefore, understanding how the migrating horizontal strain and deformation fields resulting from continuous pumping may be affected by the presence of aquifer heterogeneities is of great importance in evaluating the mechanical and hydrological effects of such features.

Aquifer Heterogeneities and Their Relation to Earth Fissures

In the arid southwestern United States, earth fissures have become an interesting problematic, and costly hydrologic phenomenon. Earth fissures have resulted in millions of dollars worth of damage to structures (Bell 1981; Bell and Price 1991) as well as countless millions of dollars worth of unresolved litigation (Shlemon et al. 1995). Two types of heterogeneities are most responsible for earth fissure development because of pumping in this part of the country: (1) basin-fill faults that extend vertically through the aquifer system creating an abrupt horizontal change in the hydrogeologic conditions (Bell 1981; Bell and Price 1991; Helm 1994a; Burbey 1996), and (2) an abrupt change in aquifer thickness (or aquifer


Explanation
Quaternary fault
Fissure zone
LAS VEGAS RANGE
95
Eglington fault
93
15
A
A'
SPRING MOUNTAINS
Windsor Park faults
B
B'
Cashman Field fault
FRENCHMAN MOUNTAIN
95
LAS VEGAS
Decatur fault
Valley View fault
Whitney Mesa fault
95
93
NEVADA
Area
HENDERSON
15
N
0 2 4 6 kilometers
0 1 2 3 4 miles
McCULLOUGH RANGE
a
EXPLANATION
WEST
EAST
MORE PERMEABLE VALLEY-FILL DEPOSITS – Gravel, sand and gravel, sand
LESS PERMEABLE VALLEY-FILL DEPOSITS – Clay, caliche and clay
BEDROCK
FAULT – Arrows show relative vertical movement
APPROXIMATE BOUNDARY BETWEEN NEAR-SURFACE AQUIFERS AND DEVELOPED-ZONE AQUIFERS
b
Not to scale

transmissivity) usually associated with a low permeable bedrock knob protruding into the aquifer system from below, which greatly limits the thickness over which compression can occur (Lofgren 1978; Jachens and Holzer 1979, 1982; Anderson 1989; Carpenter 1993;). This paper will focus only on item (1) above, the association of earth fissures with basin-fill faults.

The effect of faults on hydrogeologic systems is highly complex and varies widely from setting to setting. In this analysis, Las Vegas Valley is used as the field prototype basin for the numerical modeling investigation. Las Vegas Valley (Fig. 1a), is a structural basin filled with unconsolidated to semi-consolidated deposits ranging in texture from gravels to clays (Fig. 1b). The percentage of clay increases toward the center of the basin. Two basin-fill faults are examined (A–A′ and B–B′ in Fig. 1a). According to J.W. Bell (Nevada Bureau of Mines and Geology, written communication 2002) there are minor differences in stratigraphy, lithology, and hydraulic head across these faults, yet subsidence differences are substantial (Fig. 2). InSAR-derived displacement maps (Amelung et al. 1999; Hoffman and Zebker 2001) indicate that the Eglington fault (A–A′) represents the eastern boundary of a steep-sided subsidence bowl to the northwest (Bell and Price 1991). Only a few wells exist within 2 km of this fault and, according to the hydraulic-head data measured at these sites, it is unlikely that there is more than 2 m of head change occurs locally across the fault, yet over 1.4 m of subsidence has been measured across the fault since 1963 (Bell 1981; Fig. 2a). This local head change across the Eglington fault is insignificant compared with the large head changes that have occurred throughout the basin (Fig. 3).

Obviously, these results suggest the importance of the faults to land subsidence, yet their hydraulic and mechanical characteristics are not well understood. Numerous investigations have been undertaken to ascertain the nature of near-vertical faults in poorly lithified sediments as are those described here. Rawling and others (2001) suggest that this type of fault does not tend to act as a vertical flow conduit and horizontal flow across the fault can be greatly impeded largely because of the lack of associated fractures. Others have suggested that preferential paleo-fluid flow along these faults has resulted in the precipitation of calcium cements that now tend to impede fluid flow (Mozley and Goodwin 1995). Haneberg (1995) indicates that head differences will only be large if the fault has a significantly smaller transmissivity than the adjacent aquifer. If the fault has a similar or larger transmissivity, head changes may be minimal across the fault plane. Although these papers address the hydraulic nature of faults, they do not address the mechanical nature of the faults or the relationship of the faults and associated earth fissures, a major emphasis of this investigation.

◀ **Fig. 1** **a** Location map of Las Vegas Valley, Nevada, with mapped basin-fill faults and earth-fissure zones. Modified from Bell et al. (2001). Sections *A–A′* and *B–B′* are shown in Fig. 2. Fig. 1. **b** Conceptualization of hydrogeologic units through Las Vegas Valley showing several basin-fill faults. Modified from Maxey and Jameson (1948)

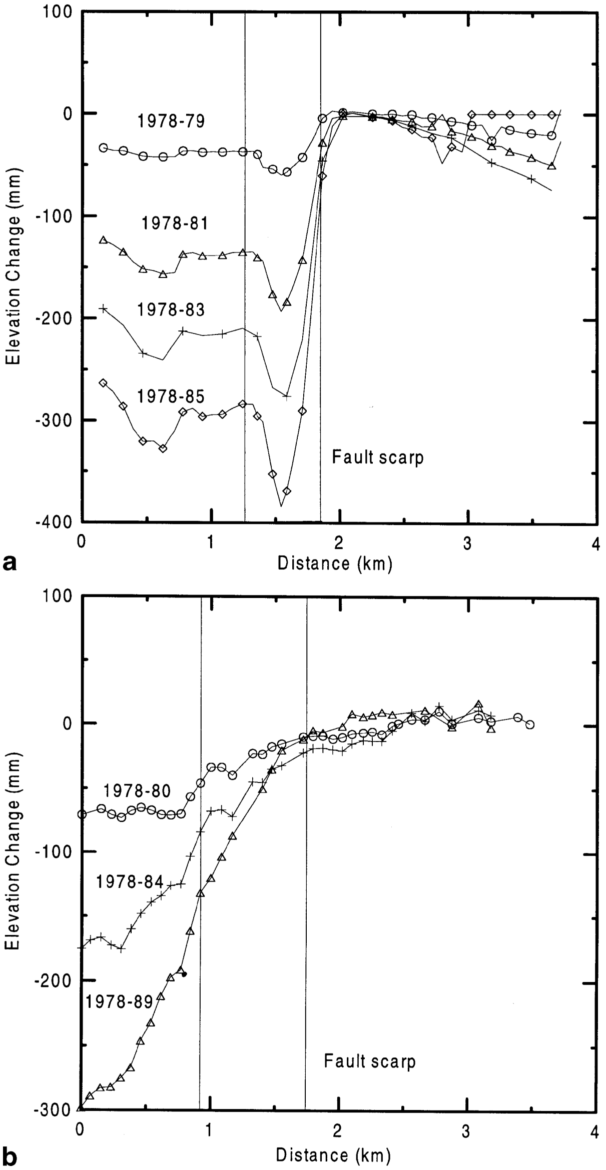
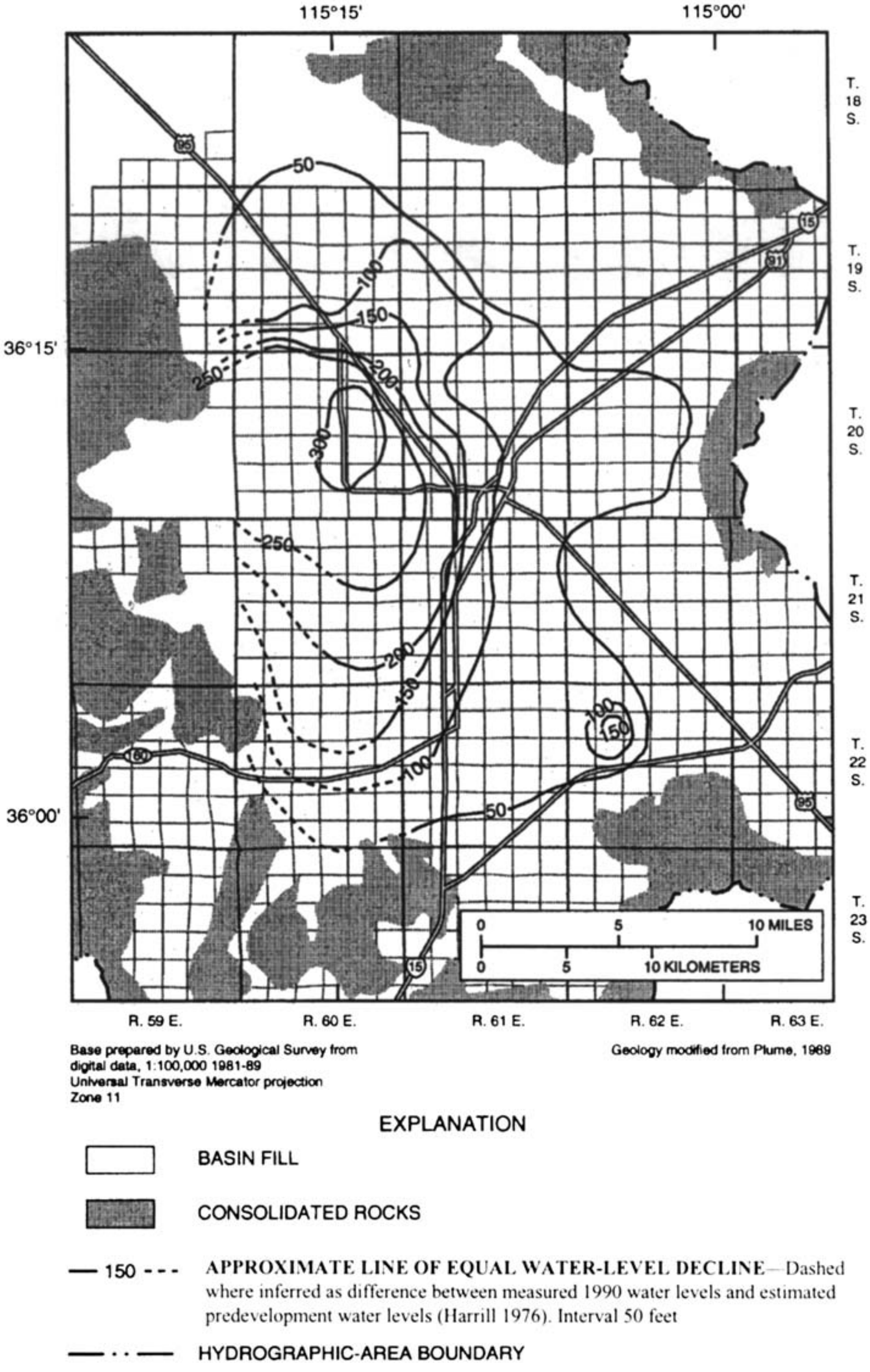


Fig. 2 Measured subsidence across **a** section *A–A′*, and **b** section *B–B′* shown in Fig. 1 (from Bell and Helm 1998) and calculated relative to a fixed benchmark. Actual subsidence may be greater than shown. The *vertical lines* represent the extent of the fault scarp according to land-surface elevations. In both cases, the scarp is down to the right (east). The fault trace itself is located somewhat to the right (east) of the current scarp, which is eroding westward

Earth fissures tend to occur as systems of cracks that form in a semiparallel fashion to the adjacent fault (Bell 1981; Bell and Helm 1998). Earth fissures associated with the Eglington fault occur where the scarp and steep subsidence gradient are juxtaposed. Fissures have not formed along other stretches of the subsidence bowl

Fig. 3 Net water-level declines of the principal aquifer from predevelopment to 1990 (from Burbey 1995)



where the gradient is large. Clearly, a connection exists between the fault and the earth fissures; however earth fissures do not form along all faults where subsidence gradients are large. The subsidence associated with the Cashman Field fault in Fig. 2b (B–B′ in Fig. 1a) does not have any fissures associated with the large subsidence gradient across the fault plane; however, significant fissure systems have been mapped north, south, and northwest of this line of section.

It is unclear what type of boundary these faults (Fig. 2) are imposing on the hydrogeologic conditions at depth. Conwell (1965) documents groundwater impedance across at least one fault scarp in Las Vegas Valley; however, as already addressed, little evidence for abrupt head changes exist across these faults. Furthermore, it is unclear from available field data whether horizontal aquifer deformation is also influenced by the presence of the vertical faults.

Without the availability of detailed water-level and horizontal-deformation data in the vicinity of the faults, it is difficult to predict where fissures may form in relation to the fault systems throughout the valley. Consequently, the Las Vegas Valley Water District has designated a buffer zone of up to 2,000 ft around the faults shown in Fig. 1 (Bell and Price 1991) as being potentially susceptible to fissure development. Without more precise understanding of the mechanisms responsible for the development of earth fissures, and the role that faults and groundwater pumpage play in their genesis, over protection around fault zones is a legitimate but costly alternative; legitimate because of potential litigation if new fissures are to form in their vicinity; costly because large areas of prime real estate are rendered potentially unsafe for building. A better methodology is needed to quantify subsidence processes in the vicinity of basin-fill faults.

The specific purpose of this study is to evaluate the potential influence of basin-fill faults on the development of earth fissures. In other words, do these faults influence the location and magnitude of aquifer strain and deformation? Secondly, does the behavior of the faults as barriers or conduits to both groundwater flow and effective stress influence potential fissure development? These questions are addressed through the use of a coupled fluid flow and three-dimensional solid-displacement model.

Modeling Approach for Flow and Deformation

A granular displacement model based on Biot's theory of three-dimensional consolidation (Biot 1941; Burbey and Helm 1999) is used to evaluate strain components in three dimensions. This model couples granular displacement with groundwater flow in an elastic porous medium. The form of Biot's coupled equations (Burbey 1999) used here can be expressed as

$$(G+\lambda)\nabla(\nabla \bullet \mathrm{u}) + G\nabla^2\mathrm{u} = \rho_w g \nabla h \text{ and} \quad (1a)$$

$$K\nabla^2 h = \frac{\partial}{\partial t}(\nabla \bullet \mathrm{u}), \quad (1b)$$

where G is the shear modulus, K is the hydraulic conductivity, **u** is a vector representing the displacement field of solids, λ is one of Lame's constants expressed in terms of the shear modulus, G, and Poisson's ratio, ν, in the equation, $\lambda=2\nu G/(1–2\nu)$.

Equation (1) has been implemented into MODFLOW (McDonald and Harbaugh 1988; Burbey and Helm 1999) as a separate module where the displacement field of solids is calculated with the most recently calculated hydraulic-head values determined from MODFLOW. Iteration is employed at each time-step to allow both displacements and heads to be updated until convergence is achieved. Coupling between Eqs. (1a) and (1b) is weak and has been shown to be stable and to produce accurate results for flow-induced displacement (Burbey and Helm 1999). This model is referred to here as the granular displacement model (GDM).

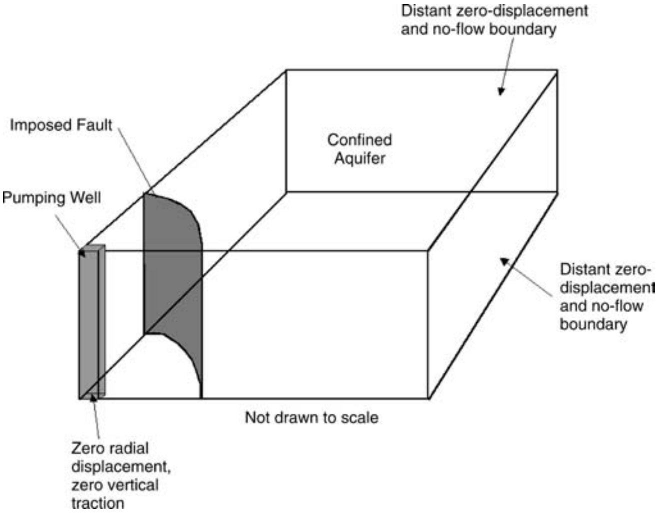


Fig. 4 Conceptual model used for numerical simulations showing boundary conditions. Fault is located 94 m from the pumping well. One-fourth of the aquifer is simulated for convenience

Table 1 Aquifer properties and initial conditions used for simulation results shown in Figs. 5, 6, and 7

Property or condition	Value
Pumping rate, Q	6.3×10^{-3} m^3/s
Hydraulic conductivity, K	1×10^{-4} m/s
Poisson's ratio, ν	0.25
Shear modulus, G	6.5333×10^{6} N/m^2
Specific weight of water, $\rho_w g$	9.8×10^{3} N/m^3
Lame's constant, λ	6.5333×10^{6} N/m^2
Specific storage, S_s	9×10^{-4}/m
Aquifer thickness, b	100 m

Hydraulic and mechanical boundary conditions are specified at each boundary. The hydraulic boundaries are those already programmed and used within MODFLOW and implemented as changes from an initial state. These include specified head and specified flux conditions. Mechanical boundaries are specified as either changes in traction (stress) from an initial state or as zero-displacement conditions. The program has been tested and compared with a two-dimensional axisymmetric finite-element Biot program (HDM) written by Smith and Griffiths (1988) and modified by Hsieh (1996), and the results of the GDM model compare favorably with the HDM model (Burbey and Helm 1999).

The conceptual model used to evaluate the hydraulic and mechanical nature of basin faults in Las Vegas Valley involves a three-layered system with thicknesses, beginning from the top, of 5, 45, and 50 m, respectively. For the simulations described herein, a pumping well occurs at the corner of a horizontally extensive aquifer (Fig. 4). One-fourth of a Cartesian coordinate system is simulated with the well located at x=0 and y=0. The grid size increases geometrically as one moves radially away from the pumping well. At the well, the horizontal grid spacing is 0.05 m. At the outside perimeter of the model, the grid size is 3,750 m. This design was implemented to reduce perimeter boundary effects that may influence the simulation results during the pumping event. At the perimeter boundary, no-flow and zero-displacement conditions were assigned normal to the boundary, and zero change in traction condition was assigned to the perimeter boundary in the shear direction. That is to say, no friction is simulated in the vertical direction along the perimeter boundaries so that subsidence can occur at the well bore as well as along the outer boundaries without inhibition from the boundary wall. In effect, the aquifer can be assumed to be horizontally infinite. At the well bore, horizontal granular movement is constrained to be zero at the well screen for all time (no grains are pumped from the aquifer). The aquifer is assumed to be confined and pumping occurs from all three layers at rates that depend on the model-layer thickness (equal flux from each layer). From a numerical point of view, the aquifer system is homogeneous. Realistically, however, the system involves a thick aquifer with numerous compressible interbeds (Fig. 1b). Numerical simulation involves the implementation of the thickness of compressible beds contained within the aquifer system by using an average specific-storage value that accounts for the thickness of compressible lenses within the principal aquifer. Changes in total load associated with water-level declines because of pumping are not considered to be great enough to severely impact the results, and the upper boundary is considered to be traction-free (no applied stress but free to deform). Table 1 lists the aquifer parameter values for the properties and initial conditions used in the model simulations.

Imposed Fault Boundaries

Internal fault boundaries require additional hydraulic and mechanical conditions to simulate a vertical fault plane within the pumped aquifer. Three types of conditions are simulated for a vertical fault. The first fault condition (FC1) is where the fault behaves as a horizontal flow barrier, but remains a continuum for the skeletal matrix – that is, no mechanical boundary is induced for granular deformation in the horizontal direction. The hydraulic boundary conditions are imposed using the program written for MODFLOW by Hsieh and Freckleton (1993) to simulate horizontal-flow barriers. This program allows specification of thin low-permeability units between existing horizontal cells within the finite-difference grid network. In addition, an assumption is made that the width of the simulated low-permeability feature is negligibly small in comparison with the horizontal dimensions of the cells in the grid, and no storage exists within the low-permeability zone being simulated.

The second type of simulated fault condition (FC2) involves implementing an open vertical fracture within the skeletal aquifer matrix. That is, the skeletal matrix is discontinuous across the vertical fault plane. Specified traction-boundary conditions are implemented along each face of the fault plane. These boundary conditions take on the form

$$\delta t_x = \delta\sigma'_{xx} = -(2G+\lambda)\frac{\partial u_x}{\partial x} - \lambda\left(\frac{u_x}{x} + \frac{\partial u_z}{\partial_z}\right) = 0 \qquad (2a)$$

$$\delta t_y = \delta\sigma'_{xy} = -G\left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}\right) = 0 \qquad (2b)$$

$$\delta t_z = \delta\sigma'_{xz} = -G\left(\frac{\delta u_x}{\delta z} + \frac{\delta u_z}{\delta x}\right) = 0 \qquad (2c)$$

where δt_x, δt_y, and δt_z represent the incremental changes in total traction in the x, y, and z directions, respectively; $\delta\sigma'_{xx}$, $\delta\sigma'_{xy}$, and $\delta\sigma'_{xz}$ are the incremental effective stress changes in the x, y, and z directions occurring along a cell face (or plane) perpendicular to the positive x direction. Equation (2) is valid along the plane y=0 where the stress on the vertical face of the fault in the x direction is assumed to be zero. This is reasonable because the two sides of the fault plane are assumed to be disconnected mechanically; that is, they do not touch one another physically. Changes in strain result from changes in fluid pressure. Grain-to-grain stress change along the vertical boundary walls is assumed to be zero in the horizontal direction. Likewise, changes in shear stress are set to be zero. That is, no shear strength exists in the directions normal to x. Stated another way, there is no resistance to shear movement along the vertical fault plane. Boundary conditions analogous to Eq. (2) are also incorporated for the y direction (along the plane x=0), but are not written out here.

In conjunction with the imposed traction boundary for FC2, fluid flow is not inhibited. That is, there is no imposed fluid barrier resulting from the fault. The fluid is assumed to move freely across the fault plane, normal to the fault, as though the aquifer were completely homogeneous. Simulating the fault as a high-conductivity zone would have little if any affect on the flow pattern because the fault is thin relative to the aquifer as a whole (Haneberg 1995). In the third fault boundary condition (FC3), it is assumed that the fault behaves as both a fluid-flow barrier across the fault and that there is no resistance to aquifer movement vertically along the fault. In FC3, both the zero-traction boundary conditions for the granular matrix and the fluid-flow barrier across the fault are implemented.

These three conditions cover three possible manifestations that a fault may impose on the aquifer system during pumping. Hydraulic or mechanical conditions parallel to the fault plane are not simulated.

The imposed fault is implemented 94 m from the idealized pumped well (Fig. 4). The well in Fig. 4 is square in cross section, but its shape is irrelevant because its radius can be considered infinitesimal relative to the distance to the fault boundary. Because of the conceptual design representing one-fourth of an infinitely extensive radial aquifer, the fault effectively surrounds the well bore as opposed to being represented as a linear feature located a fixed distance along a plane on one side of the pumped well. In this conceptual approach, the impact of pumping will create a "worst-case" scenario with respect to the magnitude of this type of aquifer deformation and head change for the pumping rate imposed. In Las Vegas Valley, the main subsidence bowl (west of Eglington fault, Fig. 1a) is largely constrained by faults to the east and south, and by the transition from basin-fill deposits to consolidated rock to the west. Hence, the imposed simulation boundaries are not too different from the field conditions.

It is assumed that the thickness of compressible deposits is uniform within the aquifer; thus, any vertical differential movement is associated with boundary effects because of the fault and not to factors associated with differential thickness of compressible deposits across the fault plane. Although many of the fault scarps in Las Vegas Valley are associated with significant vertical offset, generally downward toward the east, little evidence exists from lithologic logs to suggest that there is an abrupt change in the thickness of compressible deposits across these faults within the principal aquifer system in the vicinity of the lines of section described earlier. Hence, these types of heterogeneities were not simulated here.

Simulation Results

The simulated vertical basin-fill fault was first evaluated as a horizontal flow barrier where the fault has a horizontal conductance that is two orders of magnitude less than the surrounding aquifer. In effect, the fault can be viewed as being 1 m wide and having a horizontal hydraulic conductivity two orders of magnitude less than the aquifer. No mechanical boundary condition is implemented for the fault. Figure 5 shows the simulation results for scenario one for times of 0.7, 6.5, and 58 days of pumping. Greatly increased drawdowns (by a factor of about three) occur on the side of the fault with pumping (Fig. 5a). Additionally, greatly increased vertical displacement (subsidence) occurs on the side of the fault with the pumped well (a factor of three greater than the condition without the fault hydraulic boundary condition; Fig. 5b). Differential subsidence is significant, but an almost constant strain condition (slope of displacement curve) exists across the fault, similar to Fig. 2b observed in the field. Figure 5c represents the simulated horizontal aquifer deformation. The fault tends to cause the peak of maximum displacement to remain over the fault through the duration of the simulation, even though both analytic and numerical models indicate that maximum horizontal deformation migrates outward from the pumped well with respect to time in the case with no fault (Helm 1994b; Burbey and Helm 1999) and is generally of much lower magnitude than simulated here. The horizontal-displacement curve suggests that compressional strain occurs on the side of the fault nearest the pumped well; whereas, extensional strain occurs on the side of the fault opposite the pumped well for the entire duration of pumping. A zero radial-strain condition remains fixed at the vicinity of the fault.

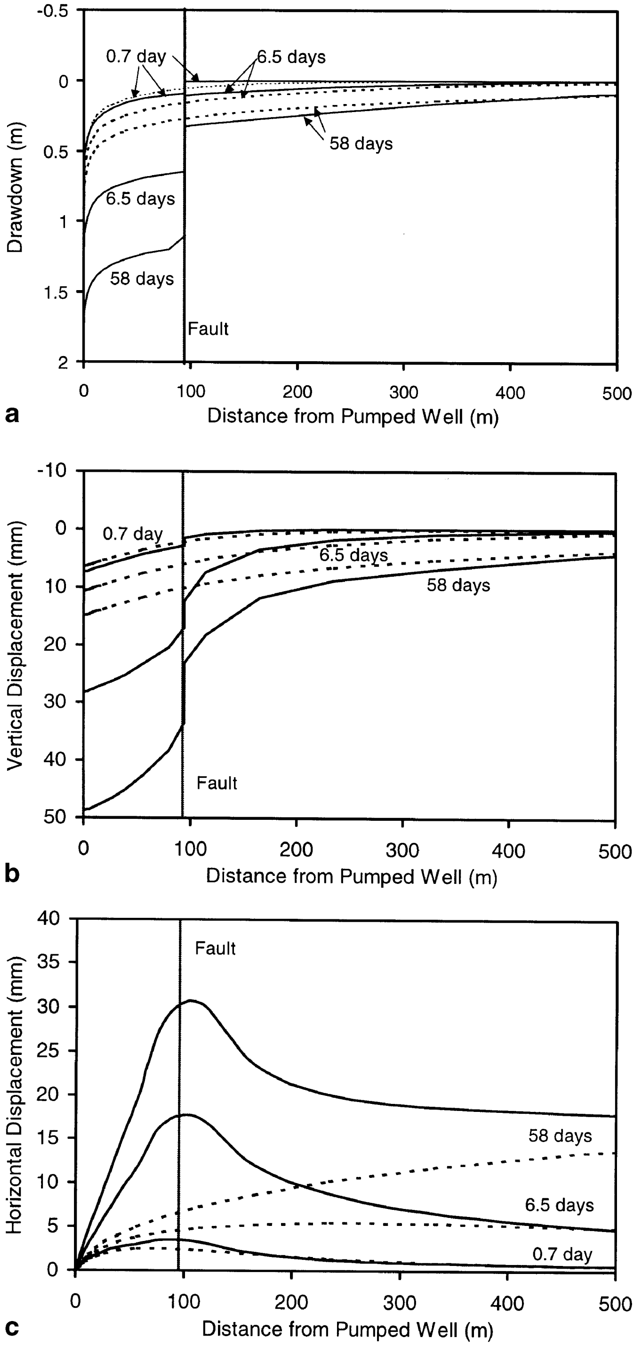


Fig. 5 Simulated **a** drawdown, **b** vertical displacement, and **c** horizontal displacement for the case where the fault represents a barrier to horizontal flow (*solid lines*) and the case where no boundary is simulated (*dashed lines*)

In the second simulation scenario, the vertical fault is considered as a mechanical boundary only. That is, groundwater moves freely across the fault without inhi-

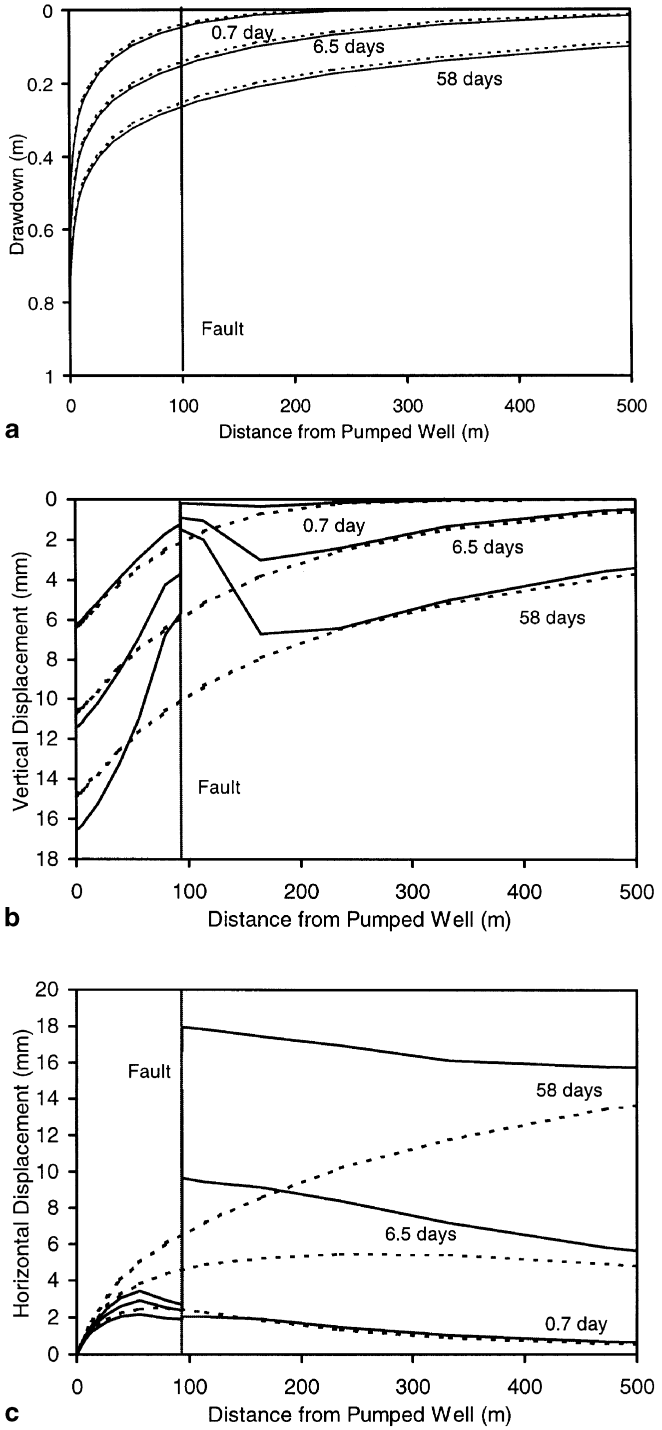


Fig. 6 Simulated **a** drawdown, **b** vertical displacement, and **c** horizontal displacement for the case where the fault represents a mechanical boundary only (*solid lines*) and the case where no boundary is simulated (*dashed lines*)

bition. Hence, a physical break or discontinuity exists within the aquifer, but the discontinuity is assumed to be free of flow-inhibiting cementation, gouge, or other fine-grained granular material. Figure 6 shows the simulation results for the second simulation. Little change in drawdown occurs as a result of the mechanical barrier (Fig. 6a). Simulated vertical displacement is only slightly increased at the well bore, but is vastly changed in the vicinity of the fault as a greatly reduced amount of subsidence is simulated. This is likely to be the result of greatly reduced mechanical stress conditions within and adjacent to the fault plane (Fig. 6b). In effect, the fault has its own zone of influence. At distances greater than about 200 m from the pumped well, the simulated vertical displacement curves closely match those of the homogeneous condition, indicating that subsidence is a result of drawdown alone at distances greater than about 200 m from the fault. Horizontal displacement (Fig. 6c) undergoes a very rapid change in magnitude along the fault plane or, more appropriately, from one side of the fault plane to the other. This phenomenon can be readily explained by the presence of the assumed discontinuity between the walls of the fault plane. On the side of the fault toward the well, horizontal deformation is constrained by the well bore boundary condition (zero horizontal skeletal movement). Hence, for the case here where the pumped well is located in fairly close proximity to the fault, only a small amount of horizontal movement is simulated even though groundwater moves freely across the fault to the pumped well. Although the fault boundary is free to move toward the pumped well, the fault constrains movement such that a "mini" peak and trough occurs on the side of the fault toward the pumped well. On the side of the fault away from the pumped well, no constraint is placed on skeletal movement in the horizontal direction toward the well bore because of the stress-free condition along the wall of the fault plane. The fault boundary away from the pumped well would move much more rapidly toward the well than the side of the fault toward the pumped well. Therefore, under this scenario, the fault would tend to close or heal itself over time. The overall magnitude and shape of the horizontal displacement curve on the side of the fault nearest the pumped well is largely dependent on the proximity of the fault from the pumped well. Had the fault been located a greater distance than 94 m, as simulated here, the magnitude of horizontal displacement would similarly increase.

In the third simulation, the imposed fault is represented as both a flow and mechanical boundary. Under the imposed fault-boundary conditions, drawdown is increased on the side toward the well much like the condition with a flow boundary only (Fig. 7a). Figure 7b illustrates that the simulated vertical deformation is different from either of the previously applied fault-boundary conditions, with regard to shape and magnitude of displacement. Vertical deformation is greatly increased on the side of the fault toward the pumped well and the shape of the deformation is concave upward. In a direction radially outward from the pumped well, vertical displacement decreases rapidly in the vicinity of the fault boundary. A "hinge point" exists near the fault where little or no subsidence is simulated, then subsidence again increases radially outward for a distance of about 100 m before dissipating steadily beyond about 250 m. This

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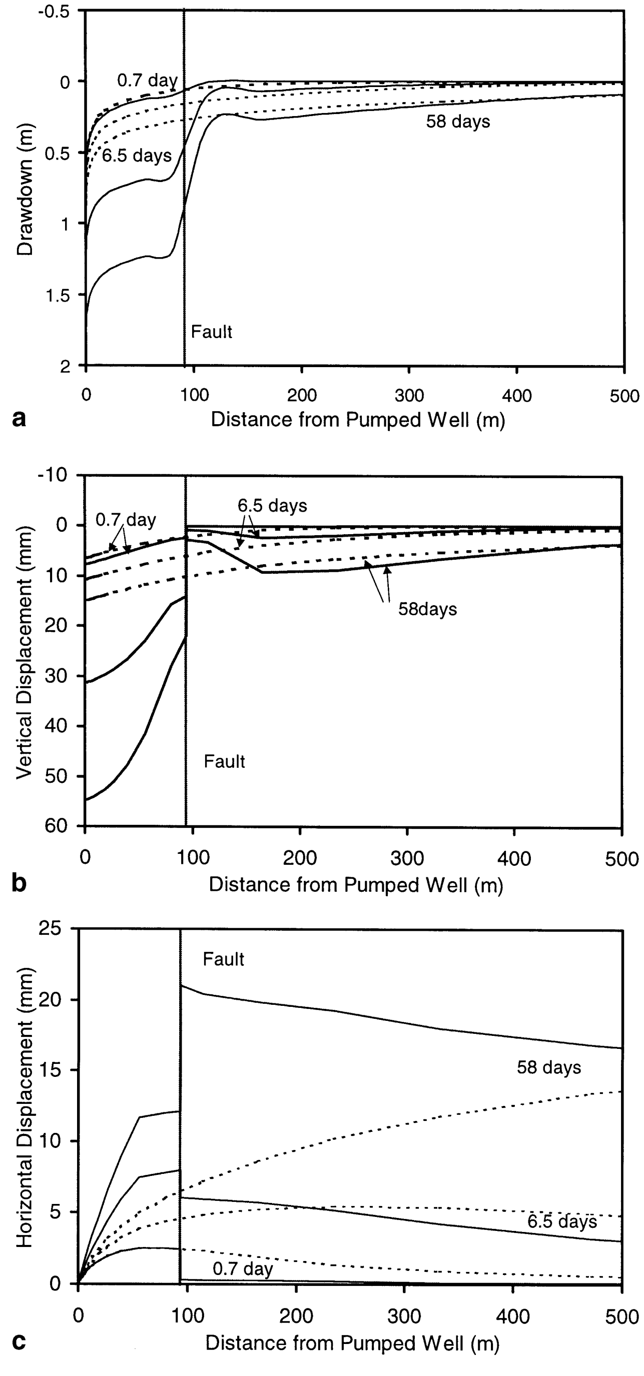

Fig. 7 Simulated **a** drawdown, **b** vertical displacement, and **c** horizontal displacement for the case where the fault represents both a mechanical and flow boundary (*solid lines*) and where no boundary is simulated (*dashed lines*)

condition is very similar to the observed subsidence pattern shown in Fig. 2a. Simulated horizontal deformation is greatest in the vicinity of the fault and nearly four times as large as that simulated in the homogeneous aquifer on the side of the fault away from the well. However, unlike the results for the purely mechanical boundary condition, significantly greater horizontal deformation occurs on the side of the fault toward the pumped well. Horizontal radial strain is near zero on either side of the fault, but a discontinuity exists within the fault resulting in the greatly increased displacement on the side away from the pumped well. It appears that the zone of maximum horizontal deformation will remain fixed over the fault plane through time with the side of the fault nearest the well always having the lesser total magnitude of displacement. It is uncertain whether the differences in magnitude across the fault will lead to healing or possibly rotation of the fault plane, which could increase the potential for fissure development. It is clear, however, that the fault is responsible for the large magnitude of displacement as well as the location of maximum horizontal movement.

Discussion

Because only vertical-deformation information, measured at the land surface, is available in the vicinity of basin-fill faults in Las Vegas Valley, and at only a few sites, it is difficult to determine the nature of the faults and their influence on flow and skeletal aquifer physical conditions at depth. Had detailed water-level data been available across the fault systems, a better understanding of the behavior of the fault zone could be inferred. However, even with only vertical-deformation data having been measured, certain generalizations can be made concerning both the nature of basin-fill faults in this region, and the role that aquifer deformation in a horizontal direction may play in the development of earth fissures. Except for Helm (1994a), no author has implied that horizontal aquifer deformation has any influence in earth-fissure development caused by pumping. As stated earlier, this is because horizontal movement in the aquifer has been largely overlooked as an influential mechanism in the subsidence processes, and this type of field data has not been available or successfully measured.

The three types of boundaries imposed for the vertical basin-fill fault produced very different simulation results suggesting that faults are complex, heterogeneous features that can not be characterized without careful field investigation and sufficient data. Vertical-deformation data alone are not sufficient to adequately characterize the role of faults in the development of earth fissures. Both horizontal-deformation and water-level data are needed to adequately characterize the role these faults may have on groundwater flow and skeletal deformation. However, even with the simplified simulations presented in this study, some broad generalizations can be made with regard to the contribution of horizontal deformation in the genesis of fissure development.

The strain conditions resulting from differential vertical subsidence alone (Fig. 5b) may not be sufficient to induce failure of the overlying unconsolidated deposits for the case where the fault behaves as a flow boundary. Field data indicate that no fissures occur along the line of section described by Fig. 2b where differential subsidence is obvious across the fault scarp. Furthermore, along the northeastern side of the largest subsidence bowl in Las Vegas Valley, where large differential movement has been measured at the Eglington fault (Fig. 1a), fissures have been observed only at the intersection of where the greatest subsidence gradient crosses this obliquely bisecting fault. Although simulated horizontal deformation is always greatest at the location of the fault under the condition that is a flow barrier (Fig. 5c), it appears that a structural weakness in the skeletal framework of the overlying brittle unsaturated zone is necessary for failure to occur. If a weakness develops, horizontal deformation will likely contribute to the initiation of a fissure because of the magnitude of simulated horizontal movement along the fault and the simulated strain conditions occurring on either side of the fault.

On the basis of simulation results for the purely mechanical fault boundary case, fissure development would likely be caused by bending associated with differential vertical subsidence and not horizontal deformation. Results indicate that vertical deformation and strain are significantly increased in the vicinity of the fault. With regard to horizontal deformation, simulation results suggest that the closer the pumping center is to the fault boundary, the greater the likelihood that the fault would heal itself over time as compressional strain migrates outward (Fig. 7c).The large measured differential subsidence of the fault shown in Fig. 2a, appears to most closely fit the characteristic condition of a mixed boundary where the fault behaves as both a hydraulic and mechanical boundary as shown in Fig. 7b. The combination of greatly increased horizontal deformation, large differential subsidence, and a change from compressional to extensional horizontal strain in the vicinity of the fault plane implies that fissures may form in the presence of such a fault boundary condition. The simulated vertical subsidence profile in Fig. 7b closely matches that of the measured subsidence profile in Fig. 2b, suggesting that the measured portion of this particular fault may represent a combination of both a hydraulic and a mechanical boundary to some degree.

Fissures have also been observed in the far southern part of Las Vegas Valley where little subsidence and drawdown have occurred. These fissures are located in the vicinity of basin-fill faults like most other fissure zones observed in the valley. However, unlike the other fissures, differential vertical subsidence probably does not contribute to the development of these features. It is unlikely that these features are the result of seismic activity or desiccation. Burbey and Helm (1999), Sheng and Helm (1994), and Helm (1994b) have indicated that a large amount of cumulative horizontal movement can occur well beyond where active subsidence or drawdown are present. In the presence of a zone of structural weakness, it is possible that such fissures are solely the result of horizontal deformation in the aquifer resulting from pumping many miles north of this location. Because of the large distance between the pumping location and the fissures, a large amount of horizontal movement may occur adjacent to and on the side of the fault nearest the pumped well. However, additional field data are needed to verify the numerical results.

Conclusions

Little is known about the influence of faults on the skeletal aquifer movement. Yet, in order to adequately quantify the relation of these faults to associated earth fissures, a better understanding of the mechanisms responsible for fissure development is needed. Numerical simulations involving both flow and skeletal granular movement are needed to understand the mechanisms that may influence the formation of earth fissures in the vicinity of vertical faults in basin-fill deposits.

Evidence from measured subsidence across several fault scarps in Las Vegas Valley suggests that horizontal aquifer deformation is at least partly responsible for the current widespread fissure development in many parts of the basin. Current water-management practices have greatly mitigated vertical deformation or subsidence, yet field data indicate that horizontal deformation can be locally quite large with the seasonal rate of horizontal movement exceeding that of the vertical rate of subsidence. The magnitude of horizontal deformation is a function of the distance from the center of pumping, the pumping rate, the time since the initiation of pumping, the hydraulic diffusivity of the aquifer, and the presence of heterogeneous barriers or boundaries that may impede flow and/or displacement.

The purpose of this study was to quantitatively illustrate subsidence near basin-fill faults by evaluating the role that faults may play in the genesis of earth-fissure development within a heavily pumped aquifer system. Limited data consisting of level lines across the Eglington and Cashman Field faults over a 10-year period indicate that differential subsidence occurs across fault scarps, but that the magnitude of differential movement can vary significantly from fault to fault. The shape of the subsidence profile across a fault may be more indicative of the mechanism leading to earth-fissure development. Without detailed hydraulic-head data in the vicinity of the faults, it is difficult to make generalizations about the possible mechanisms responsible for local fissure development. Hence, efforts should be made to quantify heads across faults where earth fissures continue to form and create hazards. Numerical simulations suggest that horizontal deformation in aquifers contributes to earth-fissure development. It appears that the degree to which horizontal movement may influence such development depends on the nature of the fault. Based on this preliminary study, fissures in the vicinity of faults that behave as either flow barriers, or a combination of flow and mechanical barriers, appear to be conducive to being significantly influenced by horizontal deformation in aquifers. Fissures in the vicinity of faults that do not behave as horizontal barriers to flow are probably more inclined to be caused by differential vertical subsidence.

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Some faults are probably not susceptible to fissuring because (1) they do not represent a significant barrier of any kind, (2) there are no weaknesses in the overlying brittle unsaturated zone from which tensile strain may induce failure, or (3) they are not sufficiently stressed from pumping to become potential threats to fissure development in the near future.

Modeling of this type can help to better quantify the effects of individual faults and their potential for fissure development. For isotropic homogeneous material, vertical subsidence profiles to a large extent reflect drawdown profiles. In contrast, cumulative horizontal displacement extends to distances where drawdowns are small or negligible (Burbey and Helm 1999). Hence, the calculation and measurement of horizontal movement in aquifers can be ignored only at the peril of those citizens, businesses, and corporations who reside in Basin and Range type valley settings and the government officials who are responsible for their well-being and for the environment.

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