CHARACTERIZATION OF A FRACTURED AQUIFER USING THE COLLOIDAL BORESCOPE

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Quantifying and characterizing groundwater flow in fracture flow systems is a difficult task due to the complexity of these systems. The recently developed colloidal borescope is a useful instrument that can provide direct measurements of flow velocity and direction from wells completed in fractures. The colloidal borescope was recently used in the Sandia Mountains near Albuquerque, New Mexico to supplement an ongoing investigation at a leaking underground storage tank site. Results from the field investigation using the colloidal borescope showed that groundwater flow directions in the unfractured zones agreed with the regional groundwater flow directions. In fractured zones, groundwater flow directions were in a direction corresponding to fracture trends that were different than the inferred potentiometric surface. Groundwater velocities in the fractures were an order of magnitude higher than velocities observed in the unfractured flow zones. The resultant flow direction of the unfractured and fractured flow zones agreed with the observed flow direction of a groundwater hydrocarbon plume.

Key words: groundwater flow direction, velocity, colloidal borescope, measurement, fractured aquifer

INTRODUCTION

The complexity of groundwater flow and subsequent contaminant migration in fractured porous hydrogeologic systems has been recognized for years. Traditional methods of installing monitoring wells and measuring the potentiometric surface to determine groundwater flow directions in these fractured systems has not always proved to be a reliable approach. Gernand and Heidtman (1997) used a 24-well, 21-day pumping test to analyze a low-yielding fractured aquifer. But as Moore (1997) points out, the hydraulic conductivity values calculated from most aquifer tests in fractured rocks are meaningless. Gupta *et al*. (1994) used tracer tests to show that groundwater flow directions in fractured porous media could be diagonal to the hydraulic gradient as determined by water levels in monitoring wells. Groundwater flow and contaminant transport in fractured porous aquifers is further complicated by flow in the porous blocks. Flow in sandstone or siltstone blocks may be in the direction of the hydraulic gradient while groundwater in the fractures will migrate in a direction parallel to the fractures. It is a

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combination of these characteristic flows that ultimately determines the actual direction of contaminant migration in fractured porous systems.

Accurately measuring the rate and direction of groundwater flow in a fractured porous system requires additional analyses beyond the traditional potentiometric surface analysis. As previously noted, tracer tests are one available option. Tracer tests, however, can be difficult, time intensive, and expensive to perform.

An alternative to tracer tests for directly measuring groundwater flow rates and directions is the colloidal borescope. Jointly developed by Oak Ridge National Laboratory and R. J. Electronics Inc., the colloidal borescope is inserted into a monitoring well and directly observes groundwater flow velocity. The colloidal borescope is capable of measuring flow at selected depths within a well and thus has the ability to measure flow from individual fractures. The result is an aerial and vertical distribution of groundwater flow velocities that is useful for the interpretation of contaminant migration in complex flow systems.

This paper describes the design and operation of the colloidal borescope, and the interpretation of field data collected at a site near Albuquerque, New Mexico. The work presented in this paper was conducted as part of the Bernalillo County Environmental Health Department and the Department of Energy Technology Deployment Initiative, in cooperation with MDM Service Corporation of Albuquerque.

INSTRUMENT DESCRIPTION AND OPERATION

The colloidal borescope consists of a CCD (charged-couple device) camera, a flux-gate compass, an optical magnification lens, an illumination source, and a stainless steel housing (Figure 1). The device

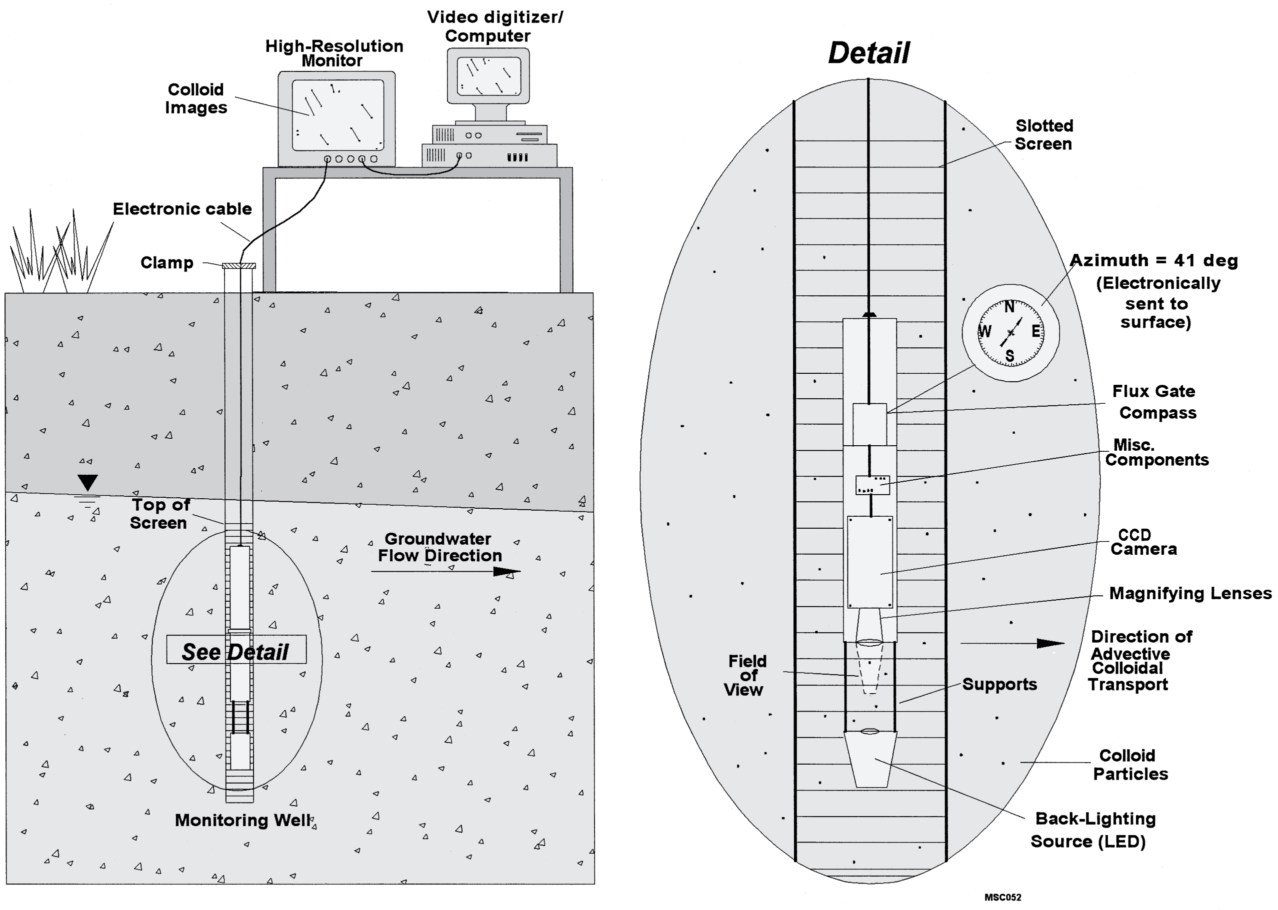

Figure 1. Conceptual diagram of the colloidal borescope.

is approximately 89 cm long and has a diameter of 44 mm, thus facilitating insertion into a 5-cm-diameter monitoring well. Upon insertion into a well, an electronic image magnified 140X is transmitted to the surface, where it is viewed and analyzed. The flux-gate compass is used to align the borescope in the well. As particles in the groundwater pass beneath the lens, the back lighting source illuminates the particles in a manner similar to a conventional microscope with a lighted stage. A video frame grabber digitizes individual video frames at intervals selected by the operator.

A software package developed by Oak Ridge National Laboratory compares the two digitized video frames, matches particles from the two images, and assigns pixel addresses to the particles. Using this information, the software program computes and records the average particle size, number of particles, speed, and direction. A 25 MHZ 486 PC compatible computer is capable of analyzing flow measurements every four seconds resulting in a large data base after only a few minutes of observations. Since standard VHS video uses 30 frames per second, a particle that moves 1 mm across the field of view could be captured in subsequent frames 1/30 of a second apart. This would result in an upper measurement velocity range of 3 cm/s. For low flow conditions, the delay between frames can be set for large time periods resulting in a lower velocity range for stagnant flow conditions.

Flow velocities measured by the colloidal borescope were verified using a laminar flow chamber developed at the Desert Research Institute in Boulder City, Nevada. At a flow velocity in the laminar flow chamber of 0.10 cm/s, and verified by a tracer test, the colloidal borescope measured a comparable velocity value of 0.11 cm/s (Kearl, 1997).

Only zones that display consistent horizontal laminar flow in a steady direction over a substantial time period (greater than 2 h) should be considered. Swirling flow zones may be the result of adjacent low-permeable sediments, positive skin effects, vertical flow gradients, or nearby preferential flow zones that dominate flow in the observed zone. Measurements in swirling flow zones should be disregarded. However, if steady directional flow is observed, typical of a preferential flow zone, then reliable measurements are possible.

For the colloidal borescope to be an effective tool in characterizing groundwater flow velocity, it is necessary to differentiate and quantify the influence of aquifer heterogeneity, filter packs, and well skins on flow in a well bore. This is a difficult task because the hydraulic conductivity of the filter pack and surrounding formation may be unknown and/or the skin effects not easily quantified. However, following some basic assumptions and general guidelines, it is possible to select reliable data and estimate a range of groundwater velocities.

At field sites, observed well bore flow velocities exceed predicted velocities, even for values that are adjusted based on a conversion factor for predicting seepage velocity from well bore velocity values. If theoretical work and laboratory results indicate that the borescope provides reliable flow measurements within a specified range, then this evidence would suggest that velocities in the well bore represent the maximum flow velocities in an aquifer. It would further suggest that the maximum velocity and not the average linear velocity over the entire screen length dominate flow in the well bore under ambient flow conditions. In no instances have velocity measurements using the colloidal borescope been less than values predicted by independent hydraulic information. Swirling, nondirectional flow zones may be representative of lower-permeable material within the permeable section of the aquifer or positive skin affects due to poor well construction practices, with the flow velocity being magnified by the transfer of momentum from adjacent, higher-flow zones.

Based on the work presented by Kearl (1997), colloidal borescope measurements in the field should be reduced by a factor of 1 to 4 to calculate seepage velocity in the adjacent porous medium. This factor is based on the impact of a borehole on the surrounding flow field and is discussed in detail by Kearl (1997). For comparison, borescope measurements presented in this paper represent the flow velocities in the preferential flow zones compared with average flow velocity measurement obtained by conventional methods. Consequently, the velocity values given in these figures should be reduced by a maximum factor of 4 to obtain the seepage velocity in the adjacent porous medium. It should be re-emphasized that the colloidal borescope is measuring the maximum velocity values in preferential flow zones in a heterogeneous aquifer and not the average linear velocity.

The colloidal borescope has been used to develop the micropurge sampling methodology (Kearl *et al.*, 1994) and to characterize flow in heterogeneous aquifers (Kearl and Roemer, 1998). In addition, the instrument has been used at numerous sites across the United States to evaluate groundwater flow conditions and the effectiveness of remediation treatment systems.

SITE DESCRIPTION

Field measurements using the colloidal borescope were conducted at the East Mountain Site east of Albuquerque in the Sandia Mountains. The site is adjacent to Interstate 40 near the Zuzax exit. A service station and several individual residences that rely on groundwater supply wells as a source of water are located in the area. Leaking underground storage tanks at the service station resulted in a large groundwater plume that has migrated down the valley in a southwesterly direction (Figure 2). This plume has contaminated several domestic wells and resulted in the placement of several groups of monitoring wells to characterize the size and extent of the groundwater plume.

The East Mountain Site hydrology is characterized by the Madera Limestone that dips to the northwest, a regional potentiometric surface that parallels the dip, and a fracture subset from the major faults that trends roughly north-south (Figure 3). The Madera Limestone consists of a lower gray limestone member and an upper arkosic limestone member. For more than half of the east slope residence in the Sandia Mountains, the Madera Limestone is the principal aquifer (Titus, 1980). Mainly solution-enlarged channels in the limestone beds that tend to be localized along fractures and bedding planes provide permeability and porosity. The average yield from wells completed in the Madera Limestone is 12 gallons per minute (gpm).

Monitoring wells tested in this area were com-

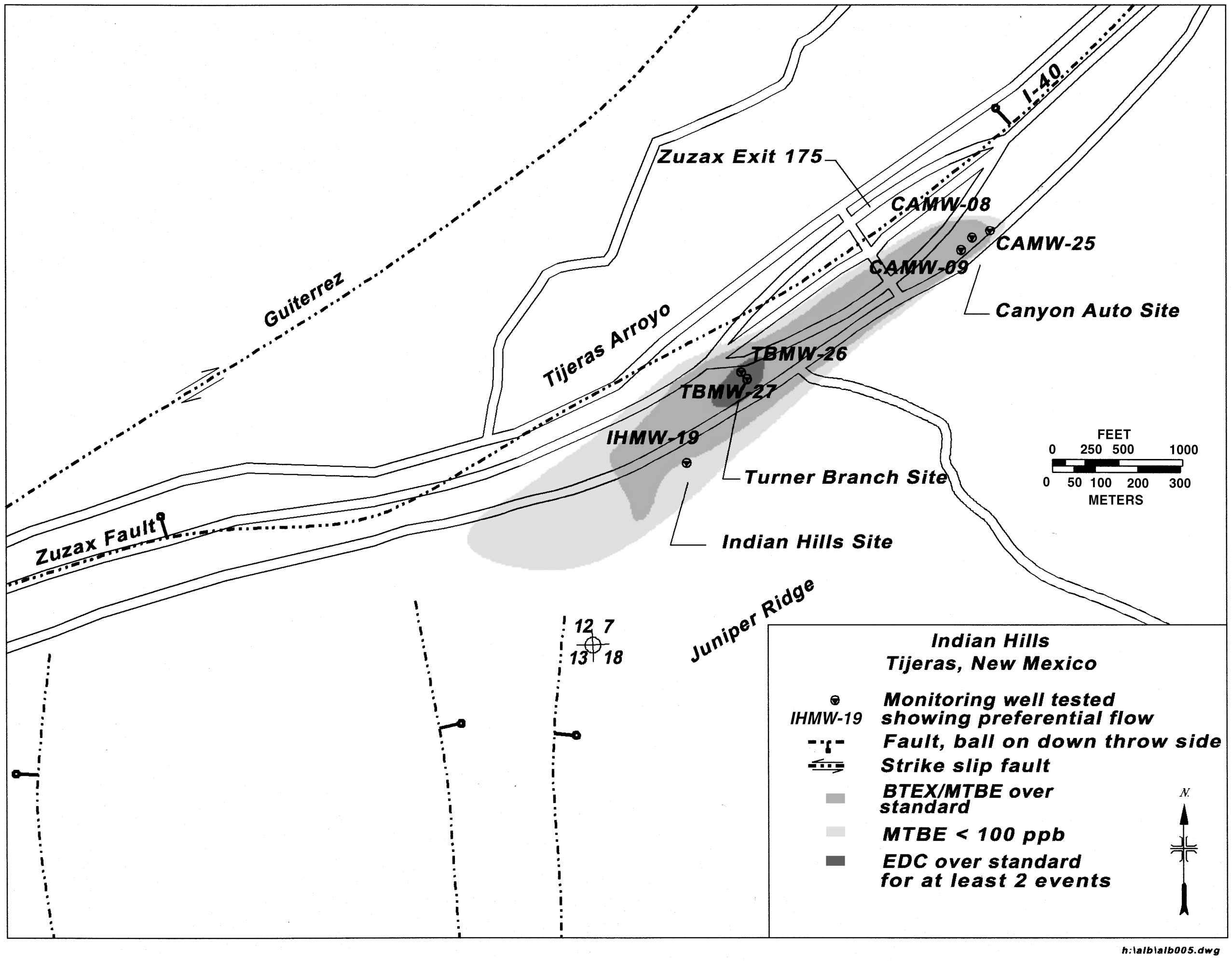

Figure 2. Site Location and extent of groundwater contaminant plume.

pleted in fractured bedrock consisting of the Madera Limestone and other sedimentary units. The other principal sedimentary unit at the study site is the Permian age Abo Formation. It consists of dark-red to reddish-brown shale with interbedded sandstone beds. Water is yielded principally from fractured sandstone beds with wells in the area capable of producing from 4 to 40 gpm.

As illustrated in Figure 3, there are numerous faults that have been mapped in the study area. The valley is bound by the Guiterrez and Los Pinos faults (not pictured in figure) that trend in a northeast to southwest direction. A series of conjugate faults, believed to be associated with these major faults, trend in a north-south direction. Although only three of these conjugate faults are shown in Figure 3, it is believe that they extend through the valley but are hidden by alluvium. The boring logs for the area show numerous fracture zones that support this belief. Determining the relationship of these faults to the groundwater flow system was an objective of the colloidal borescope field investigation.

FIELD MEASUREMENT RESULTS

Two distinct flow regimes were identified based on colloidal borescope measurements. Slow flow that trends in a dominant northwest direction was observed in most of the wells tested. However, in wells CAMW-08 and TBMW-26 (Figure 3), a southern flow near suspected fault zones yielded velocities an order of magnitude higher than those in

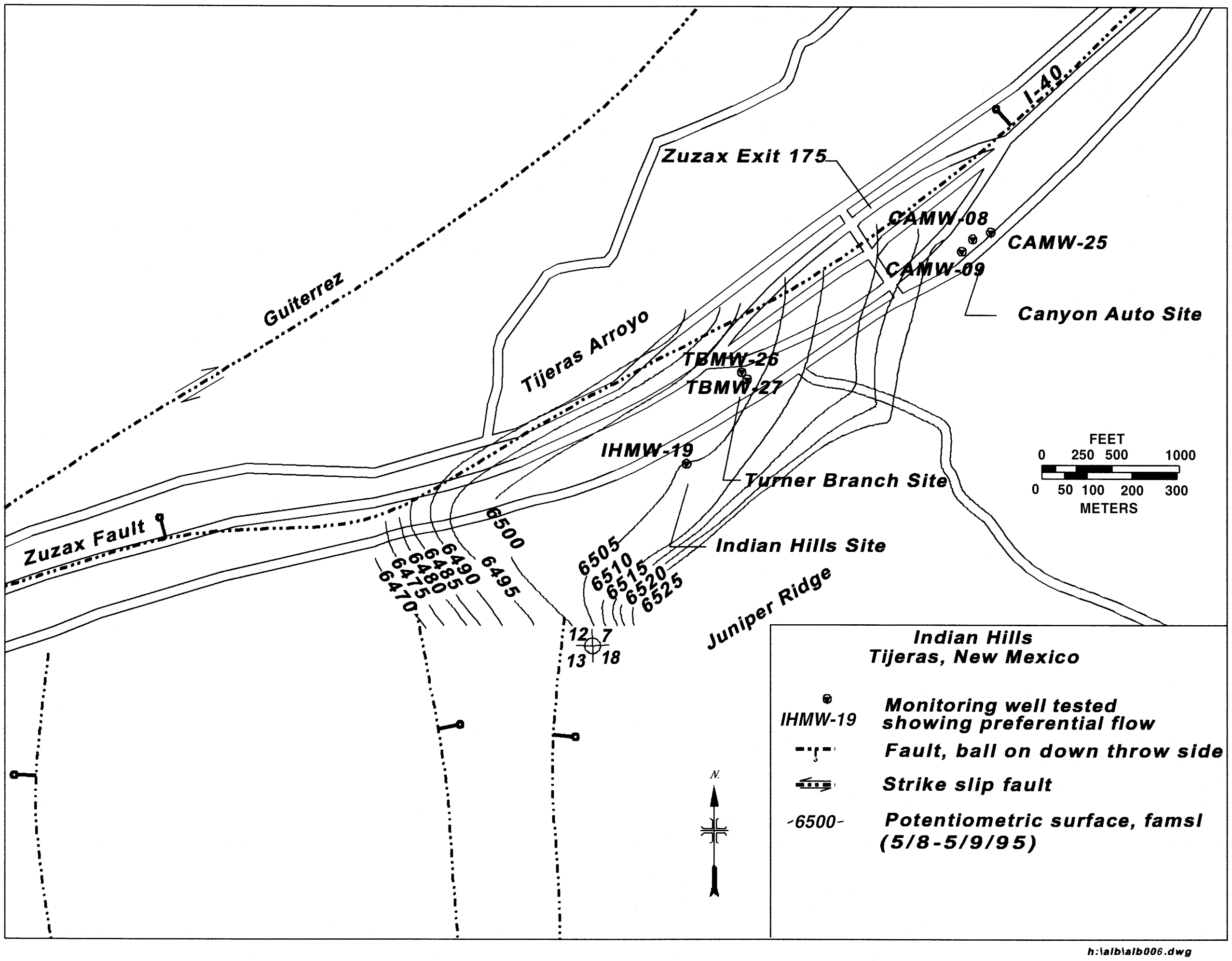

Figure 3. Regional potentiometric surface and location of major faults as mapped by Kelly and Northrop (1975).

wells showing a northwest direction. This southerly flow component is consistent with the mapped faults in the area as noted by Kelly and Northrop (1975).

Figures 4 and 5 illustrate groundwater flow direction and velocity data from zones completed in an unfractured portion of the aquifer, and a zone believed to intersect a fracture, respectively. These results are typical for the wells measured during the study. For wells in the unfractured portion of the aquifer, groundwater exhibits a northwest flow direction consistent with the regional potentiometric map. Conversely, for wells believed to intersect frac-

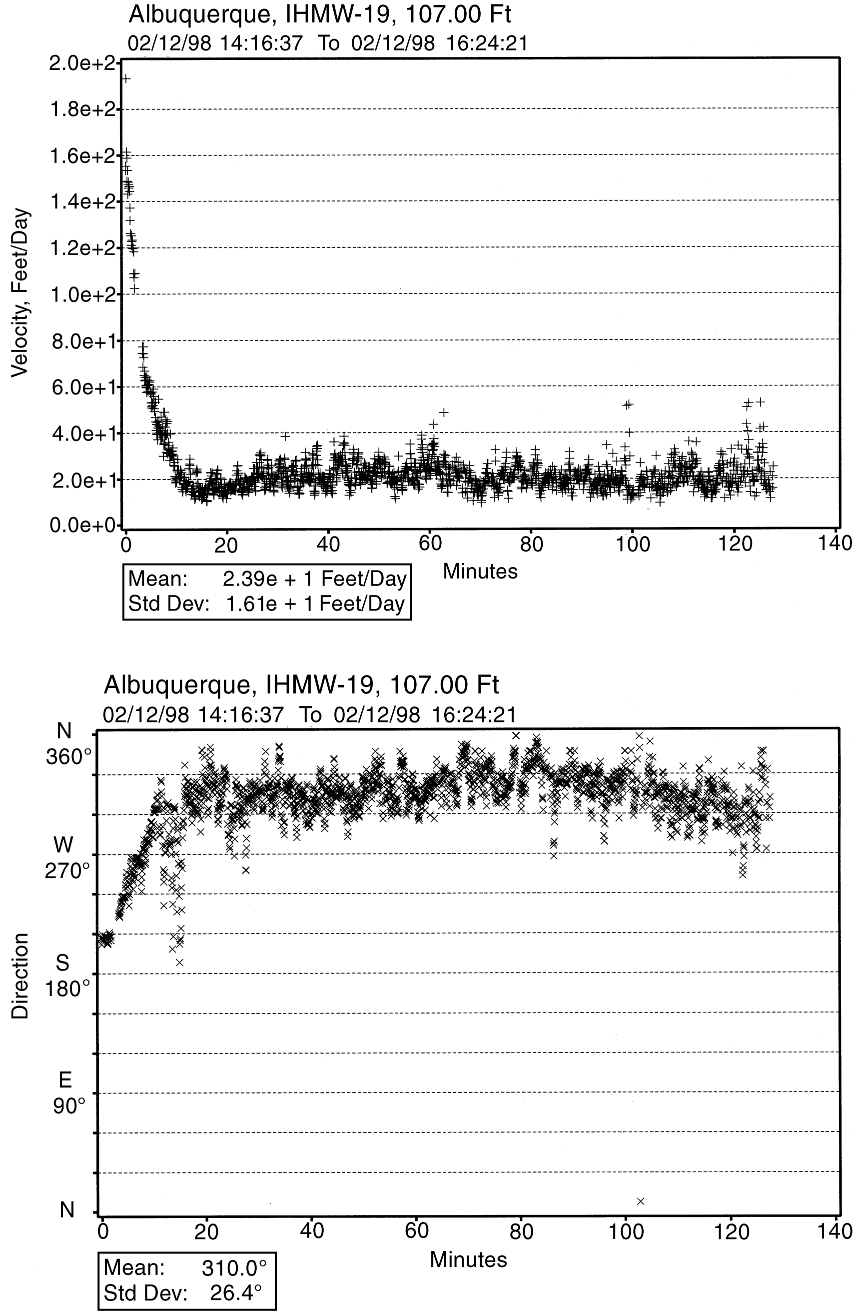

Figure 4. Groundwater flow rate and direction for an unfractured zone based on colloidal borescope measurements.

tures, the groundwater flow is in a southern direction parallel to the conjugate fractures. Groundwater velocities in these fracture zones are approximately one order of magnitude higher than those in the unfractured zones. This evidence suggests that the faults are acting as preferential flow zones, which dominate the groundwater flow component and redirect the hydrocarbon contamination from the northwesterly regional flow direction to a southern direction parallel to the fault trend.

Listed below are descriptions of flow direction and velocity measurements from the individual test

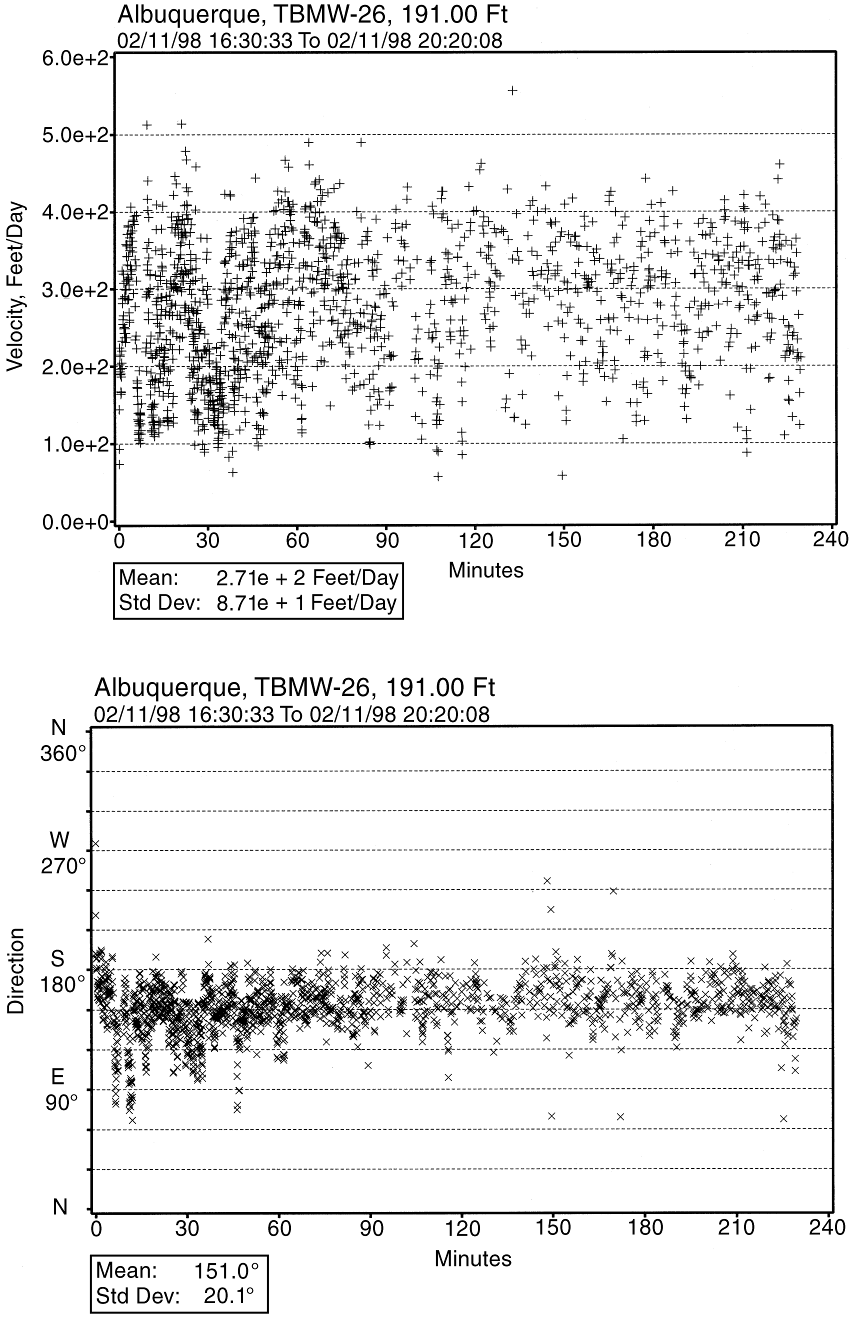

Figure 5. Groundwater flow rate and direction for a fractured zone based on colloidal borescope measurements.

wells as illustrated by rose diagrams in Figure 6.

Well CAMW-08 Depth: 62.5 ft
Oscillating flow with relatively high velocities (15 ft/d adjusted for well bore effects). Appears to be associated with a set of fractures. Southern flow direction.

Well CAMW-09 Depth: 172.0 ft
Large variation in the flow, generally in a northwest direction at 8 ft per day (adjusted). Flow direction parallels the dip and potentiometric surface.

Well CAMW—25 Depth: 96.0 ft
Very few particles in this well but a west-northwest flow direction at 7 ft/d adjusted flow velocity.

Well TBMW-26 Depth: 191.0 ft
Steady flow in a south-southeast direction at a high adjusted velocity of 68 ft/d. This test zone is believed to be associated with a fault or fracture zone.

Well TBMW-27 Depth: 44.0 ft
Steady northwest flow consistent with the regional groundwater gradient. Flow velocity is approximately 6 ft/d, similar to other zones not believed to be associated with fracture zones.

Well IHMW-19 Depth 107.0 ft
Steady northwest flow consistent with the regional groundwater gradient. Flow velocity is approximately 6 ft/d, once again similar to other zones not believed to be associated with fracture zones.

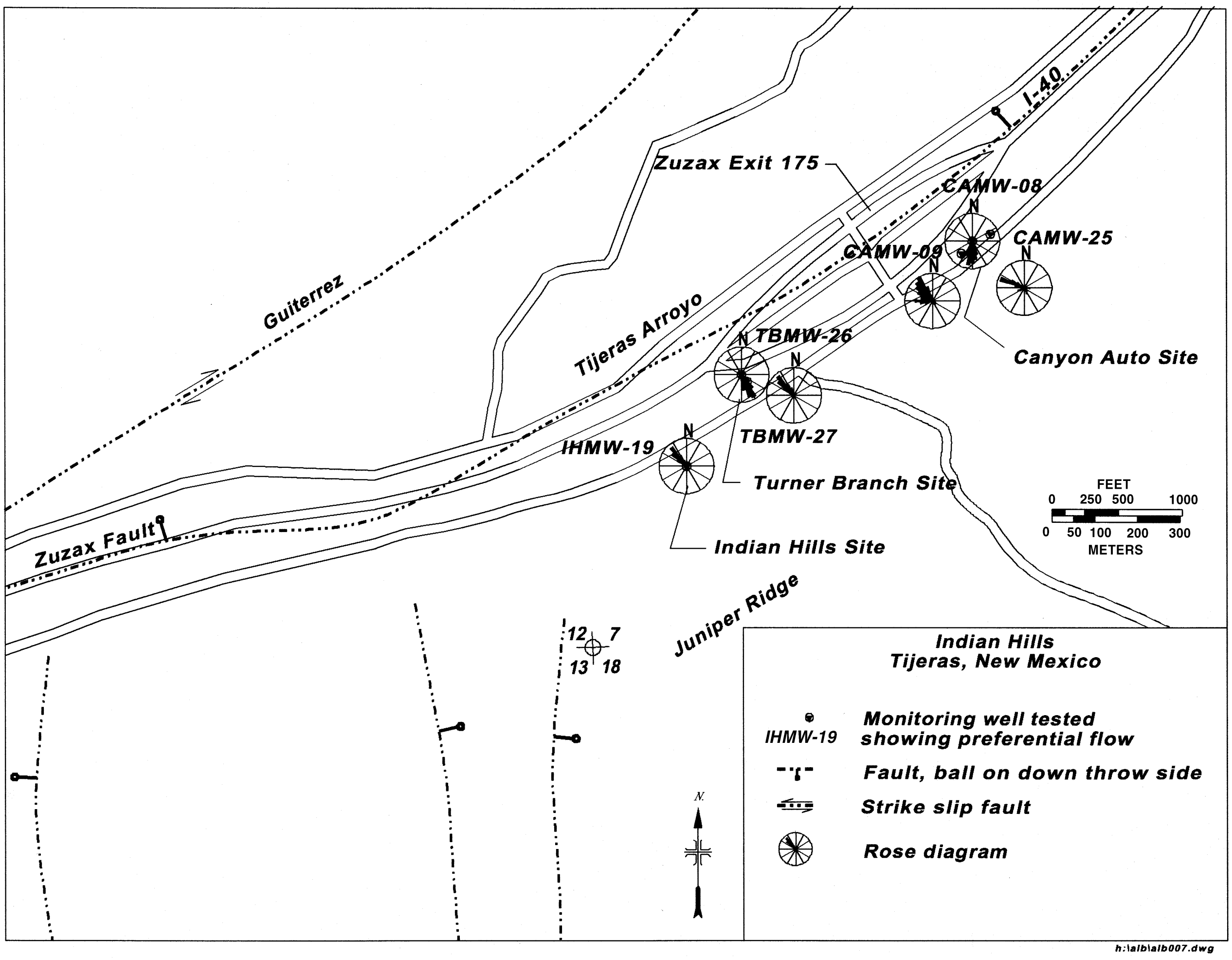

Figure 6. Groundwater flow directions based on colloidal borescope measurements.

DISCUSSION AND CONCLUSIONS

Test results from the colloidal borescope survey at the East Mountain site show a northwest flow direction in the unfractured flow zones that is consistent with the regional groundwater flow direction. In fractured zones, however, flow is parallel to the direction of fracture trends. Groundwater flow velocities in these fractured zones are approximately one order of magnitude higher than velocities in the surrounding unfractured portions of the aquifer.

The high velocity preferential flows associated with these fault zones help explain the location of the contaminant plume relative to the regional potentiometric map. Although the regional groundwater flow is northwest, preferential flow associated with the faults at high velocities in the southern direction results in a combined flow component that trends southwest as indicated by the location of the contaminant plume. Tracer tests have documented groundwater flow direction diagonal to potentiometric surfaces; however, to our knowledge this is the first direct measurement supporting that observation.

Results from the field investigation at the East Mountain Site have shown that the colloidal borescope is an effective tool for providing groundwater flow information in complex fractured aquifers. The colloidal borescope provides direct measurements at specific locations and, when combined with other site information, provides a comprehensive understanding of groundwater flow and contaminant migration.

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