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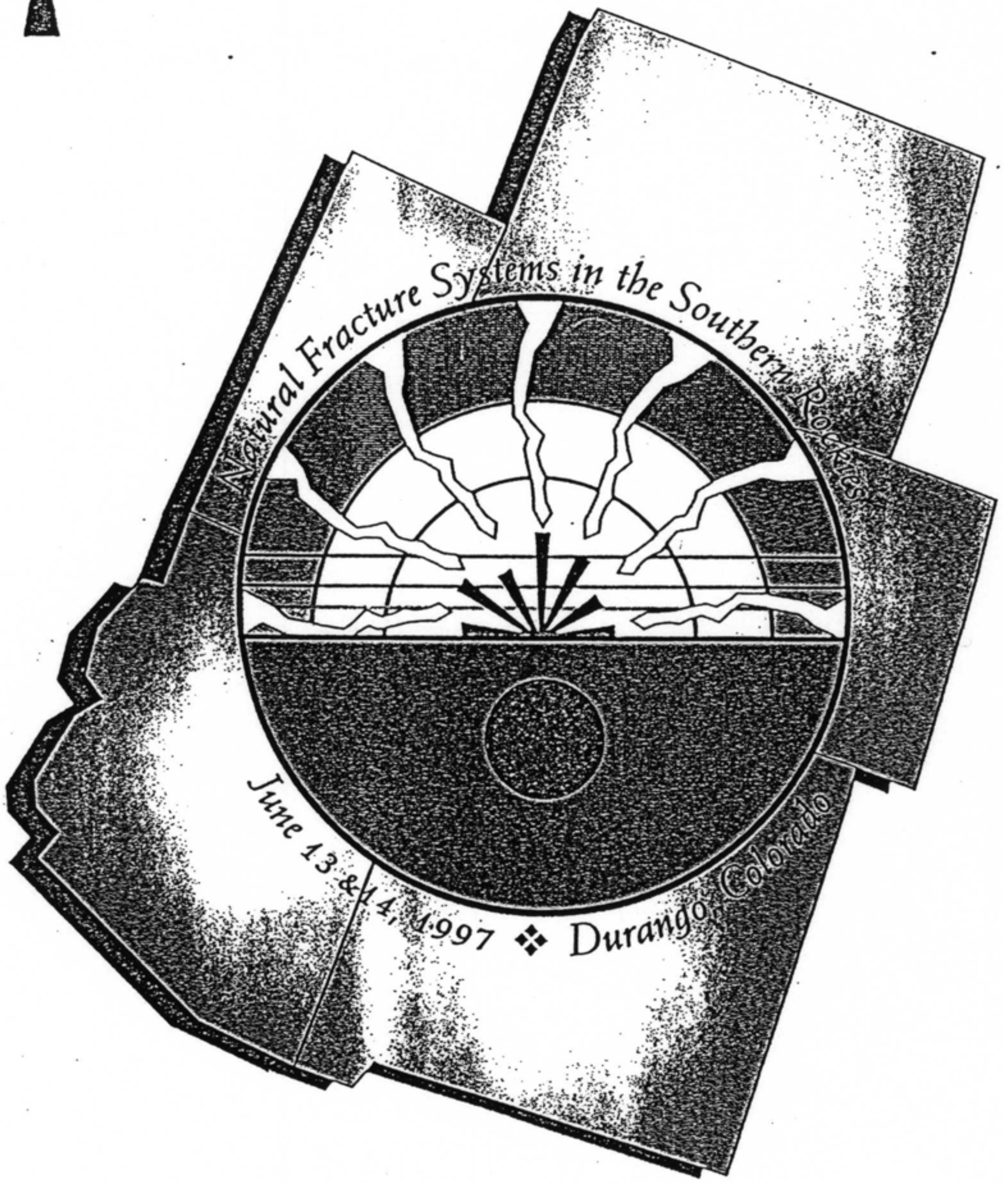

NATURAL FRACTURE SYSTEMS IN THE SOUTHERN ROCKIES

EDITORS

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Hydrocarbon Contamination and Transport in Fractured Bedrock Aquifers Along the Zuzax Fault, Tijeras Canyon, New Mexico

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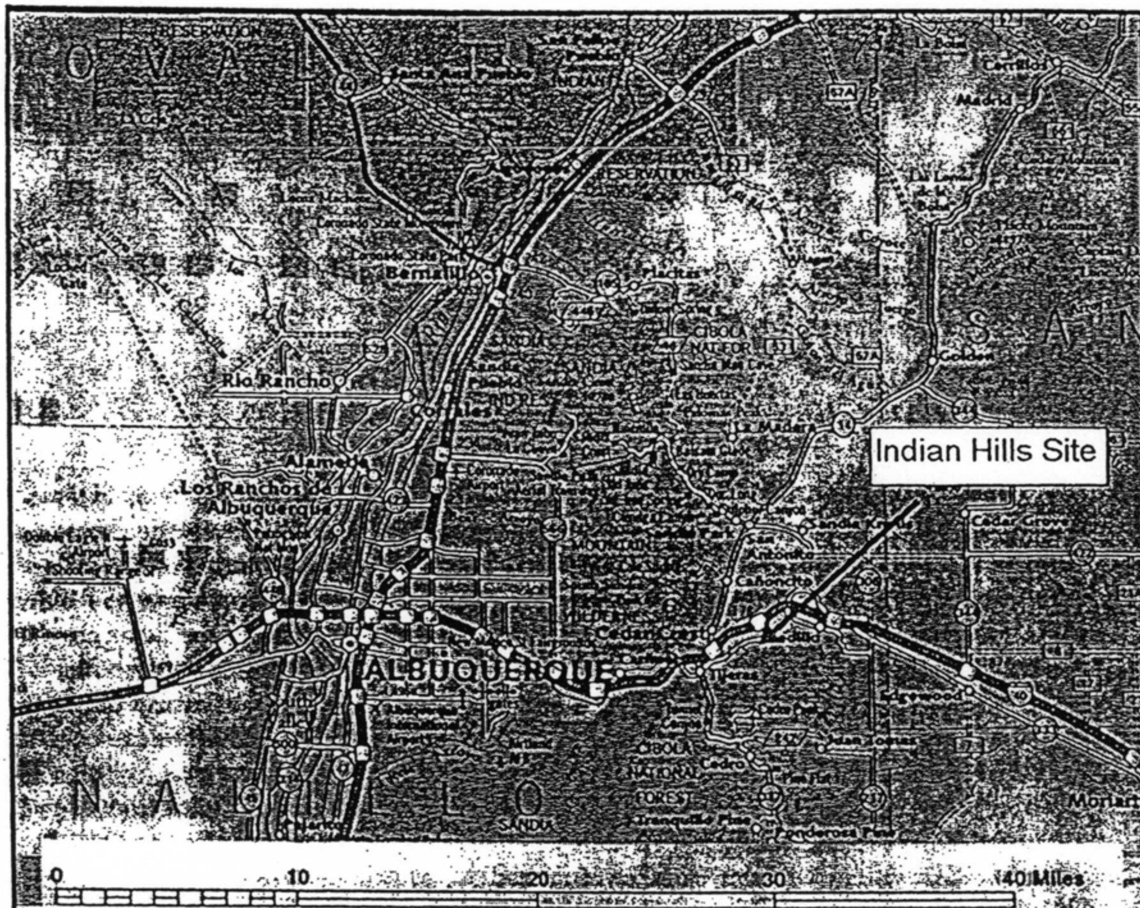
ABSTRACT

Two separate hydrocarbon plumes located along the Zuzax fault near Tijeras, New Mexico have migrated into both unconfined and semiconfined aquifers in the Paleozoic Abo and Madera Formations and have contaminated several domestic and commercial wells in the area. Groundwater flow beneath the site occurs in fractured sandstone and limestone beds which are separated by mudstone and shale aquitards. An extensive benzene, toluene, ethylbenzene, xylenes (BTEX) and methyl-tert-butyl ether (MTBE) plume and a smaller BTEX/EDC (dichloroethane) plume originate from separate locations. In both source areas, phase separated hydrocarbons (PSH) are present in perched water zones within fractured siltstone or sandstone beds. In the BTEX/MTBE source area, the perched water zone leaks into a deeper aquifer utilized by domestic and commercial water users in the area. Under the influence of down gradient pumping stresses, hydrocarbon contamination of the aquifer located below the BTEX/MTBE contaminant source at a depth of 60 to 80 feet has migrated vertically along a splay of the Zuzax fault into a semiconfined aquifer located at a depth of 110 to 190 feet below ground surface. The BTEX/MTBE contaminant plume has subsequently migrated approximately one-half mile down gradient along the northeast trending Juniper Ridge half-graben which parallels the Zuzax fault. Pumping test data and contaminant plume geometry indicate that graben bounding faults are low-permeability barriers to horizontal ground water flow and contaminant migration, but likely act as pathways for vertical ground water flow and contaminant migration. Pumping tests conducted on wells completed into each aquifer show strong boundary effects from graben bounding faults, exhibit dual porosity characteristics, and demonstrate communication between the upper two aquifers. Hydraulic conductivity (k) values for the upper two aquifers range from fracture k values of 110 ft/day and matrix k of 12 ft/day for upper Aquifer A to a fracture k of 40 ft/day and a matrix k of 1 ft/day for underlying Aquifer B. Fracture k of lowermost Aquifer C is 15 ft/day; matrix k could not be determined from the Aquifer C pumping test. The aquifer test data demonstrate a decrease in fracture and matrix k with depth. Estimated solute transport rates are 3 ft/day for Aquifer A and 1.2 ft/day for Aquifer B.

INTRODUCTION

A hydrogeological investigation into hydrocarbon contamination of fractured bedrock aquifers in the lower Abo and upper Madera Formation in Tijeras Canyon between Tijeras and Zuzax, New Mexico (Figure 1) has been conducted by the authors and Glorieta Geoscience, Inc. (GGI) for the New Mexico Environment Department (NMED). The site is located approximately 15 miles east of Albuquerque along the Tijeras fault zone, a series of northeast-striking, subvertical faults extending



Scale
Source: New Mexico Road and Recreation Atlas, 1995

Figure 1. Site location map.

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over a distance of more than 50 miles from southwest of Albuquerque to the Cañoncito area south of Santa Fe (Abbott and Goodwin, 1995). The investigation was initiated after a local resident reported tasting gasoline in water pumped from her domestic supply well. Subsequent sampling and water quality testing confirmed the presence of hydrocarbon constituents in several domestic and commercial supply wells in the area. Initial sampling indicated that contaminated domestic wells 120 to 160 feet deep were located adjacent to relatively shallow (85-feet deep) domestic wells which exhibited little or no hydrocarbon contamination (Drake et al., 1992). Two separate hydrocarbon plumes and sources were identified during the course of the site investigation; 1) a large benzene, toluene, ethylbenzene, xylenes (BTEX) and methyl-tert-butyl ether (MTBE) plume originating from the Canyon Auto source area; and, 2) a smaller EDC/BTEX plume originating from the Turner Branch (TB) source area (see Figure 5).

In conjunction with NMED, GGI conducted an investigation utilizing: 1) geologic mapping, 2) measurement of fracture orientations, 3) installation and sampling of monitoring wells, and 4) aquifer testing. The authors supervised a drilling program wherein wells were completed into three separate aquifers and localized overlying perched water zones between 30 and 240 feet below grade. The selection of screened intervals and surface

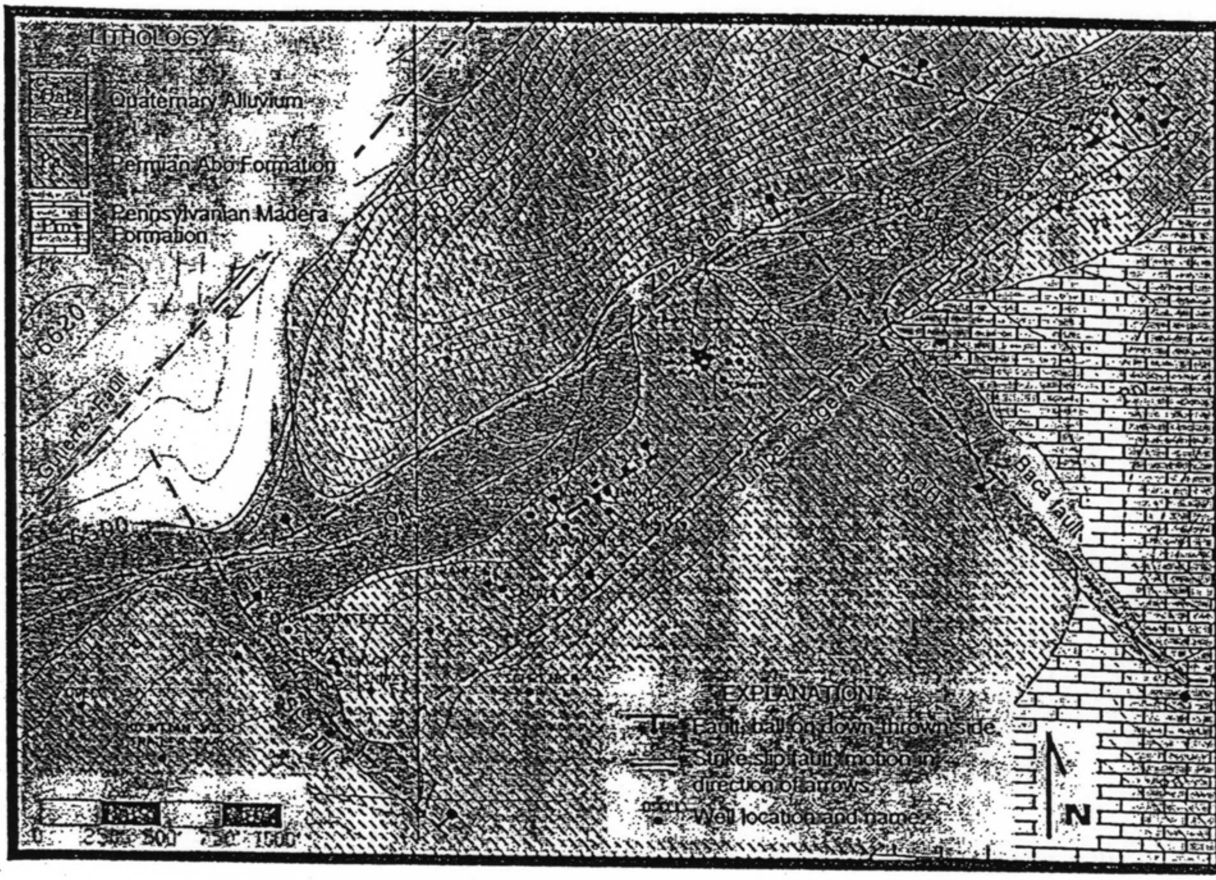

Figure 2. Geologic Map of the Indian Hills site, Tijeras, New Mexico.

casing depths were based on lithologies and fracture zones observed in continuously cored samples. Pumping tests ranging in length from one to seven days were then conducted on the three aquifers underlying the site. Water levels were also monitored on a regular basis during pilot scale remediation tests one day to three weeks in length.

HYDROGEOLOGIC SETTING

The Indian Hills Site lies along the northeast trending Zuzax and Juniper Ridge faults and is underlain by upper Paleozoic sedimentary rocks overlain unconformably by Quaternary alluvium (Figure 2). Ground water flow beneath the site occurs in fractured sandstone and limestone beds which are separated by leaky aquitards composed of mudstone and shale. Due to the interfingering nature of the Abo/Madera Formation contact, facies changes and pinching out of channel sandstone beds within each formation, correlating between individual boreholes, and correlating between boreholes and outcrops, are problematic. An analysis of slickensides in core samples and in outcrops indicate a predominance of normal and right lateral movement, although examples of left lateral and reverse movement can also be found. Ground water flow in the site vicinity is strongly structurally controlled.

Stratigraphy

The study area is underlain by the Pennsylvanian Madera Formation, Permian Abo Formation, and Quaternary valley fill deposits (Figure 2). The Abo Formation consists of reddish-brown mudstone and shale with interbedded lenticular sandstone and arkose beds. Some terrestrial limestone

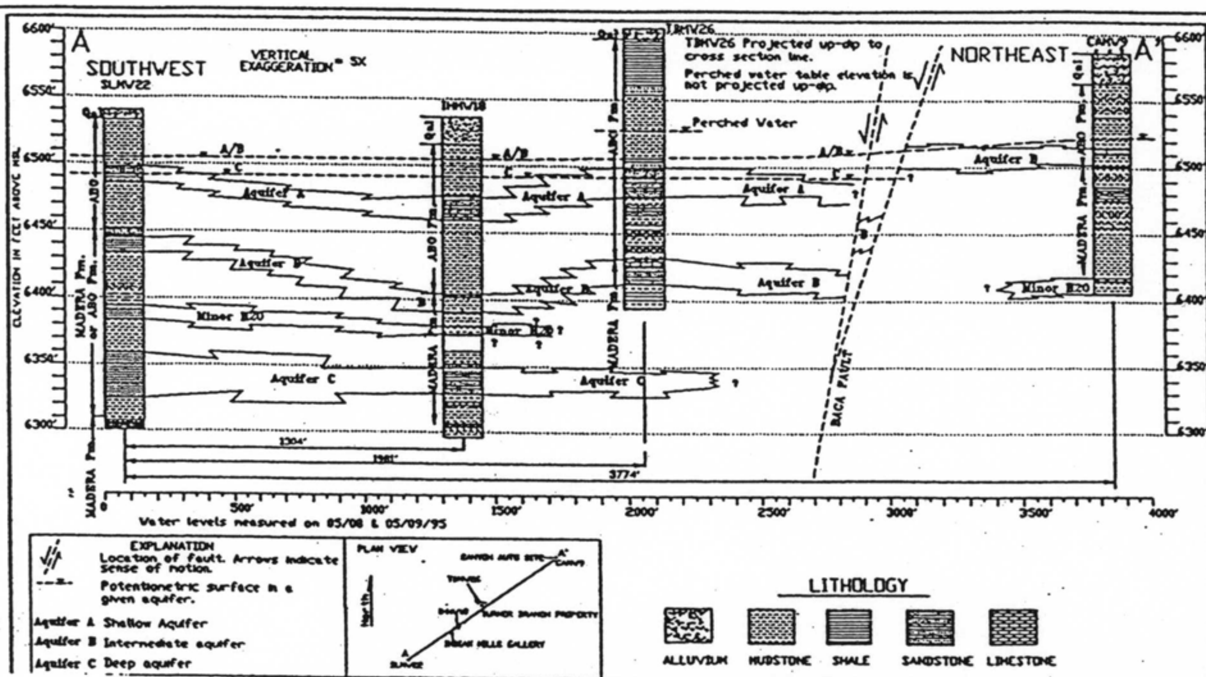

Figure 3. Hydrogeologic cross section of the Indian Hills site.

beds are present near the base of the Abo Formation (Kelly and Northrop, 1975). The upper Madera Formation consists of interbedded grey limestone, sandstone, and variegated mudstone, with massive marine beds predominating in the lower Madera Formation. The top of the Madera Formation in the Sandia Mountains and the site vicinity is mapped at the top of the highest marine fossil-bearing beds in the Madera-Abo sequence (Kelley and Northrop, 1975). The overlying Permian Yeso Formation, San Andres Limestone and Glorieta Sandstone are exposed northwest of the study area and are in fault contact with the Cretaceous Mancos Shale along the Gutierrez fault.

Structure

The predominant structural geological feature in the site vicinity is the northeast-trending Tijeras fault zone. The Tijeras fault zone transcects the Sandia and Manzano mountains and extends at least 55 miles from the Rio Grande Rift to the Cañoncito fault zone in the southern Sangre de Cristo Mountains and likely extends to the Picuris-Pecos fault zone, forming a fault system with a length of approximately 110 miles (Lisenbee et al., 1979). The Tijeras-Cañoncito fault system in large part follows the northeast strike of foliation and schistosity of Precambrian rocks; this crustal anisotropy has been the locus of movement during succeeding episodes of deformation (Lisenbee et al., 1979). Although some authors have suggested that the Tijeras-Cañoncito fault system was active as early as Precambrian time (e.g. Lisenbee et al., 1979) more recent research indicates that the oldest documented activity on the Tijeras-Cañoncito fault system occurred during the Laramide orogeny, during which time the predominant movement was right-lateral slip (Abbott, 1995).

The Tijeras-Cañoncito fault system was reactivated during the late Cenozoic in response to regional extension across the Rio Grande Rift, during which time dip slip was the dominant component of movement, with subordinant left slip motion (Lisenbee et al., 1979). In contrast, Abbott (1995) states that Neogene deformation along the Tijeras fault was characterized by left-lateral slip related to extension associated with formation of the Rio Grande Rift. Abbott (1995) also notes that the Tijeras fault has been active during the Quaternary.

The Indian Hills site lies along the northeast trending Zuzax fault, a splay of the Gutierrez fault located within the Tijeras fault zone. Predominant fracture orientations are primarily oblique (north-northwest) and secondarily parallel to the Zuzax and Gutierrez faults (Drake and Lazarus, 1991). Several high angle normal faults are oriented parallel to the dominant north-northwest fracture orientation and oblique to the Zuzax fault in the site vicinity (Figure 2).

Within the site, the Juniper Ridge fault parallels the Zuzax fault. The Juniper Ridge fault is inferred based on the presence of the Juniper Ridge escarpment, a change in water levels across the fault, and the presence of slickensides both in core from the Indian Hills Gallery well nest and in outcrop near Canyon Auto Chevron. Although slickensides observed in outcrop near Canyon Auto Chevron indicate right lateral motion for the Juniper Ridge fault, the predominant sense of motion (strike slip vs. dip slip) is unknown. Assuming movement on the Juniper Ridge fault is down to the northwest (based on the topographic expression of the Juniper Ridge escarpment), the Juniper Ridge and Zuzax faults bound a northwest-tilted graben.

Although predominant structural elements trend from southwest to northeast, the north-northwest trending cross-cutting faults also play an important role in controlling groundwater flow and contaminant migration (both vertical and horizontal) through the site. The cross-cutting faults are generally truncated by the Zuzax fault, and may also be truncated by the Juniper Ridge fault. This indicates that more recent movement has occurred on the Zuzax, and possibly the Juniper Ridge fault, or that movement along cross-cutting faults is in response to movement along the primary structures which parallel the trend of the Tijeras fault zone. The Baca fault is an important cross-cutting structure which offsets the aquifer system by approximately 100 feet (Figure 3).

Aquifer System

Three aquifers and two separate shallow discontinuous water-bearing zones (referred to as "perched" ground water in this paper) in the Abo and Madera Formations have been defined based on lithology, aquifer characteristics, and the presence or absence of hydrocarbon constituents. Water bearing intervals within the lower Abo and uppermost Madera Formation generally occur in fractured sandstone and limestone, and are separated by aquitards composed of mudstone and shale. In order from uppermost (nearest to ground surface) to lowermost, the aquifers are referred to as Aquifers A, B, and C. Discontinuous perched water zones occur in interbedded siltstone, mudstone, and thin sandstone beds located above Aquifer A or B.

Stratigraphically, Aquifer A occurs in a fractured sandstone layer within the Abo Formation, Aquifer B occurs in fractured sandstone and limestone at the Abo/Madera Formation contact or in fractured sandstone within the Abo Formation, and Aquifer C occurs in fractured, finely bedded sandstone within the Madera Formation (Figure 3). The aquifer system is tilted approximately 15% to the northwest, and is offset across several faults which transect the site. In the area between Canyon Auto and the Baca Fault, Aquifer A is absent; Aquifer B is the upper aquifer and is unconfined, and Aquifer C is semiconfined or confined. Aquifers B and C are downdropped to the southwest across the Baca Fault (Figure 3); within this area Aquifer B changes from unconfined to leaky-confined. Aquifer A is present southwest of the Baca Fault. Aquifer A is apparently recharged from Juniper Ridge and receives a small amount of water and MTBE via upward leakage from Aquifer B. Aquifer C is present throughout the site and, based on available hydrologic data (Drakos and Lazarus, 1994) and the absence of any hydrocarbon constituents, is isolated hydrologically from Aquifer B. Aquifer B contains BTEX constituents within the area of the contaminant plume. The perched water zone contains phase separated hydrocarbons (PSH) in the source areas of the site.

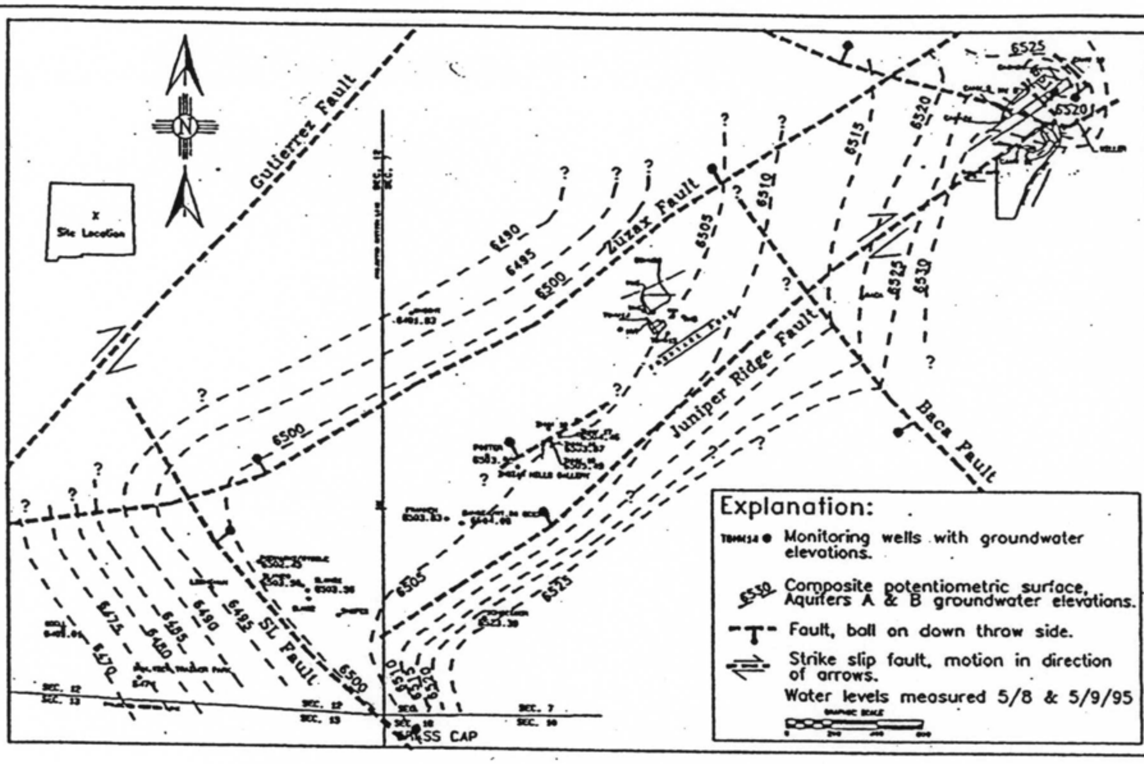

Figure 4. Potentiometric Surface Map for Aquifers A and B.

Ground Water Flow Direction

Ground water flow in the Indian Hills GWPA site vicinity is strongly structurally controlled. Due to leakage between Aquifers A and B, the two aquifers have a similar head and a composite Aquifer A and B potentiometric surface map can drawn (Figure 4). The groundwater gradient in the site vicinity is from northeast to southwest, parallel to Tijeras Canyon, and from southeast to northwest, from Juniper Ridge across the Zuzax Fault (Figure 4). The potentiometric surface is relatively flat within Juniper Ridge Graben, between the northwest trending cross-cutting SL and Baca faults (Figure 4). Recharge occurs along the Baca and SL faults, along the Juniper Ridge fault, and from the up gradient (northeast) end of Tijeras canyon.

EXTENT OF HYDROCARBON PLUME

A network of ground water monitoring wells has been installed to delineate the horizontal and vertical extent of the hydrocarbon plume beneath the site (Figure 5). The geometry of the contaminant plume indicates that contaminant migration is strongly influenced by pumping stresses and by structural geologic controls on ground water flow. Two separate hydrocarbon contamination sources have been identified at the Indian Hills site: a BTEX/MTBE plume in the perched water zone and in Aquifer B in the vicinity of the Canyon Auto property and a BTEX/EDC plume localized in the vicinity of the TB property in the perched water zone. The BTEX/MTBE plume extends approximately 3/4 of a mile down gradient from the Canyon Auto source area within the Juniper Ridge graben (Figure 5) and has contaminated leaky-confined Aquifer B at a depth of 110 to 160 feet below the surface. Phase separated hydrocarbons are present adjacent to the Canyon Auto source area.

Leaky-confined aquifer B has been contaminated as a result of downward leakage from the perched zone in the Canyon Auto source area and

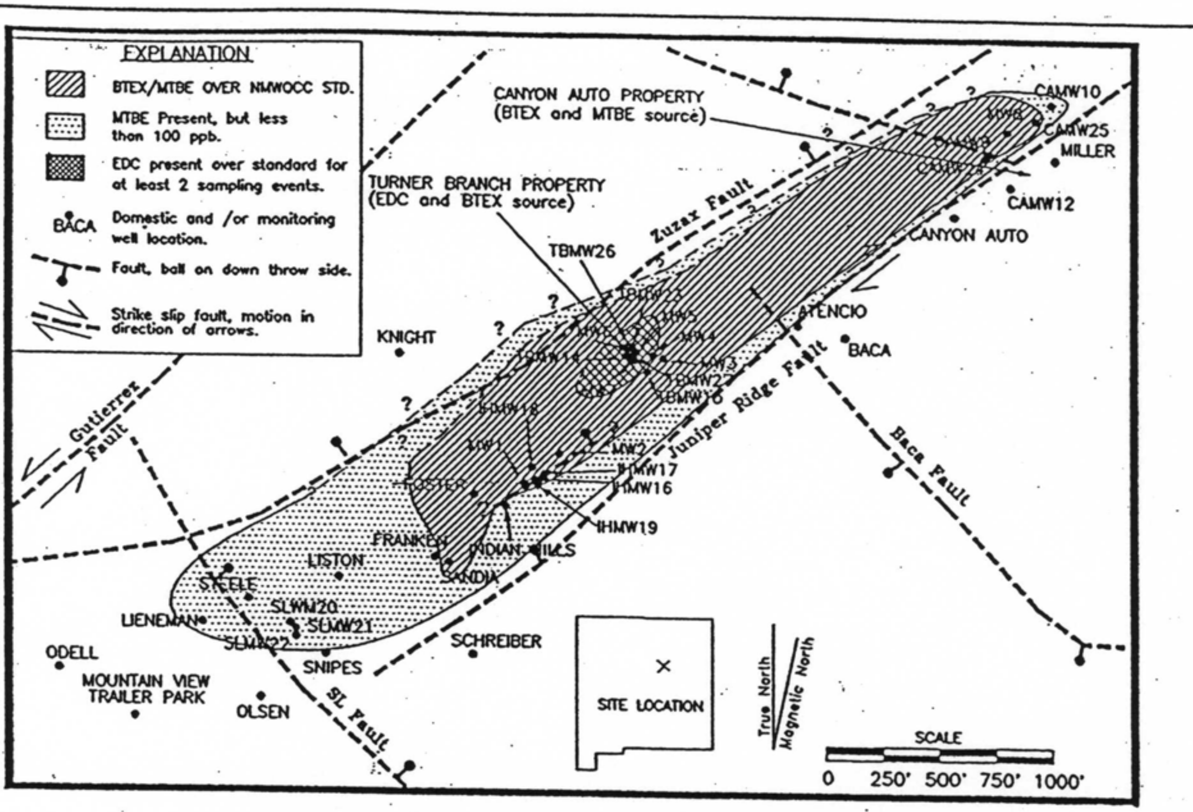

Figure 5. Hydrocarbon Plumes, Indian Hills site, Tijeras, New Mexico.

as a result of downward ground water flow along the Baca Fault. It is likely that downward ground water flow and contaminant migration along the Baca Fault was induced by pumping of several domestic wells (Indian Hills Gallery well, Sandia Well Drilling/Sandia Furniture well, Roman Franken well, and several other domestic wells in the area) located down gradient from but within the same structural block as the Canyon Auto source area (Figure 5). Aquifer testing data presented below demonstrate that pumping effects from discharge rates of 5 to 10 gallons per minute (gpm) are observed at distances of one-half mile or more. These rates are often equaled or exceeded during typical domestic well use.

Hydrocarbon contamination of ground water has not been observed on the southeast side of the Juniper Ridge fault, indicating that the fault acts as a barrier to horizontal ground water flow and contaminant migration. The presence of low MTBE concentrations in the Lieneman domestic well suggests that the SL fault is not a strictly impermeable boundary; however, MTBE or BTEX constituents have not been observed down gradient from the Lieneman well (Figure 5). The steepening in the ground water gradient and the absence of hydrocarbon constituents in wells down gradient of the Lieneman well indicate that down gradient contaminant migration is inhibited by the SL fault. Due to the absence of monitoring wells or deep domestic wells on the northwest side of the Zuzax fault, data for evaluating the effect of the Zuzax fault on contaminant migration in the site vicinity are lacking. Sandstone beds within the Abo Formation dip 10° to 15° to the northwest on the south side of the Zuzax fault and dip 25° to 35° to the northwest on the north side of the Zuzax fault. It is likely that low-permeability mudstone or shale beds are juxtaposed against higher-permeability sandstone beds across the fault and that the Zuzax fault acts as an impermeable

Well	Dist. from pumping well (feet)	Aquifer	Total Draw-down (feet)
IHMW17	0	B	43.83
IHMW19	49	B	40.46
TBMW26	683	B	36.62
SLMW21	1310	B	2.72
IHMW16	44	A	3.32
TBMW23	700	A	2.92
CAMW24	2420	P/B	1.75
IHMW18	61	C	0.01

Table 1. Drawdown at end of seven-day pumping test in Aquifer B; time (t) = 10,060 min., Q = 18.3 gpm.

boundary.

AQUIFER TESTING RESULTS

A seven-day pumping test was conducted from November 30 to December 7, 1995 using pumping well IHMW17, completed into Aquifer B. Observation wells completed into Aquifers A, B, C, and one perched water zone were monitored during the test. The test was run at an average discharge (Q) of 18.3 gpm. Drawdown was observed in wells completed into Aquifer A and possibly the perched water zone in addition to wells completed into Aquifer B (Table 1). These data demonstrate that leakage occurs between aquifers A and B, and likely from the perched water zones into the underlying aquifers.

Although analysis of drawdown data are complicated by recharge derived by leakage from Aquifer A and by impermeable boundary effects caused by the Juniper Ridge and Zuzax faults, fracture and matrix aquifer characteristics may be calculated. Early-time drawdown data are used to calculate relatively high transmissivity (T) values of 400 to 850 ft^2/day, whereas late-time drawdown yield relatively low T values of 13 to 16 ft^2/day (Table 2). The early-time T values are representative of the highly transmissive fractures, whereas the low T values are representative of the non-fractured sandstone and limestone matrix. The low T values are similar to a matrix T of 16 ft^2/day calculated from a pumping test in the Permian Sangre de Cristo Formation sandstone/shale sequence (correlative to the Abo Formation) near Pecos, New Mexico (Drakos, 1997). Using an average aquifer thickness of 15 feet for Aquifer B, hydraulic conductivity (k) ranges from an average of 40 ft/day for the fractures to 1 ft/day for the matrix.

A separate 24-hour pumping test was conducted at an average Q of 30 gpm using pumping well IHMW16 completed into Aquifer A in April, 1994. Analysis of aquifer test data indicate relatively higher T values of 2700 ft^2/day (k = 110 ft/day) for fracture characteristics and 310 ft^2/day (k = 12 ft/day) for matrix characteristics (Table 3). While the order of magnitude difference in early-time vs. late time T values shows that Aquifer A is a dual porosity system, the matrix T is an unusually high value for an Abo or Sangre de Cristo Formation aquifer. It is likely that at the shallow depth of Aquifer A (40 to 70 feet), micro fractures extend throughout the entire sandstone aquifer, greatly increasing effective porosity. The relatively lower T values observed for Aquifer B, encountered at a depth of 110 to 178 feet below surface throughout the site, is an indication of decrease in fracture aperture and/or connectedness with depth.

The decrease in T with depth is further substantiated by data from a 24-hour pumping test using well IHMW18, completed into Aquifer C. The pumping test was conducted in April, 1994 at an average Q of 15 gpm. Aquifer C was encountered in IHMW18 from 189 to 215 feet below ground surface. Observation wells were not available for this test. A transmissivity of 310 ft^2/day (k = 12 ft/day), interpreted to represent fracture characteristics, was calculated from this test. Due

Well Name	Radial Distance (feet)	Early Time Data (fracture characteristics)		Late Time Data (matrix characteristics)	
		Transmissivity (ft^2/day)	Storage	Transmissivity (ft^2/day)	Storage
TBMW26	680	400	$1.5x10^{-4}$	13	$9x10^{-5}$
IHMW19	49	540	$3.1x10^{-4}$	14	$1.4x10^{-2}$
IHMW17	--	850	--	16	--
Average		600	$2.3x10^{-4}$	14	

Table 2. Summary of aquifer test analysis, December, 1995 seven-day pumping test, Indian Hills site. All wells completed into Aquifer B.

Well Name	Radial Distance (feet)	Early Time Data (fracture characteristics)		Late Time Data (matrix characteristics)	
		Transmissivity (ft^2/day)	Storage	Transmissivity (ft^2/day)	Storage
TBMW15	705	2500	0.0008	390	0.0005
IHMW2	139	2100	0.003	350	0.004
IHMW1	39	3200	0.009	240	0.05
IHMW16	--	3000	--	260	--
Average		2700		310	

Table 3. Summary of aquifer test analysis, April, 1994 24-hour pumping test, Indian Hills site. All wells completed into Aquifer A.

to the relatively short test duration and low discharge rate, Aquifer C matrix characteristics could not be calculated.

It is likely that fracture T and porosity controls the solute transport rate through the site whereas matrix T and storage coefficient (S) control long-term water availability at the site. Using an estimated effective porosity of the fracture zone of 20%, an average ground water gradient of 0.006 ft/ft between the Canyon Auto source area and the SL fault, and the Aquifer B fracture zone k of 40 ft/day, the solute transport rate in Aquifer B is:

(40 ft/day)x(0.006 ft/ft)/(0.2) = 1.2 ft/day.

Similarly, the the fracture zone solute transport rate in Aquifer A is:

(110 ft/day)x(0.006 ft/ft)/(0.2) = 3 ft/day.

CONTAMINANT TRANSPORT INDUCED BY PUMPING STRESSES

Movement of contaminants through the aquifer system in the site vicinity is strongly influenced by pumping stresses. The seven-day pumping test resulted in significant dewatering of wells completed into Aquifer B in addition to several feet of drawdown in Aquifer A wells located within the Juniper Ridge half-graben between the Baca and SL faults (Table 1; Figure 2). The drawdown observed in CAMW24, completed into the leaky perched water zone above Aquifer B in the Canyon Auto source area, indicates that vertical ground water flow and contaminant migration can be induced in the source area by pumping in Aquifer B from IHMW17, located 2400 feet away in the down gradient direction. Vertical ground water flow along the Baca Fault is likely induced by pumping from leaky-confined Aquifer B in the area down gradient from the fault. The initial vertical migration of hydrocarbon contamination from the perched water zone into Aquifer B and subsequently downward along the Baca fault was likely a result of pumping from the domestic wells located in the vicinity of IHMW17.

Pumping IHMW17 as a containment well at a lower discharge (9.6 gpm) over a longer time period (21 days) confirmed that the entire Aquifer A and B system in the Juniper Ridge graben between the Baca and SL faults can be dewatered by pumping continuously from Aquifer B. As a result of strong boundary effects and preferential drawdown within the Juniper Ridge graben, 45 feet of drawdown was observed at a distance of 683 feet from the containment well after 21 days of continuous pumping. Over 3 feet of drawdown was observed at a distance of 2704 feet, the furthest monitoring point available in the aquifer being pumped.

CONCLUSIONS

Aquifer test data and contaminant plume geometry demonstrate that contaminant migration through aquifers along the Zuzax fault, Tijeras, New Mexico is structurally controlled. Aquifer test data are indicative of a dual porosity aquifer system, wherein fracture transmissivity is an order of magnitude or more greater than aquifer matrix transmissivity. Fracture transmissivity and porosity control the solute transport rate through the site whereas matrix T and storage coefficient (S) control long-term water availability at the site. The aquifer test data demonstrate a decrease in fracture and matrix k with depth. Pumping test data also demonstrate that leakage occurs between aquifers A and B, and likely from the perched water zones into the underlying aquifers. Estimated solute transport rates are 3 ft/day for Aquifer A and 1.2 ft/day for Aquifer B.

Movement of contaminants through the aquifer system in the site vicinity is strongly influenced by pumping stresses. The initial vertical migration of hydrocarbon contamination from the perched water zone into Aquifer B and subsequently downward along the Baca fault was likely a result of pumping from the domestic wells located in the vicinity of IHMW17. The entire Aquifer A and B system in the Juniper Ridge graben between the Baca and SL faults can be dewatered by pumping continuously from Aquifer B at discharge rates of 10 gpm or less.

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