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CHARACTERIZATION OF HYDROSTRATIGRAPHY AND GROUNDWATER FLOW ON THE SOUTHWESTERN SAN ANDRES MOUNTAINS PEDIMENT, NASA-JSC WHITE SANDS TEST FACILITY

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Abstract—National Aeronautics and Space Administration environmental investigations at White Sands Test Facility require the detailed characterization of groundwater flow through fractured bedrock. East-to-west groundwater flow from San Andres Mountain-front recharge areas across the pediment slope is complex as a result of variable hydrostratigraphy and fracturing within the bedrock aquifer. Previous investigations have indicated that flow across the pediment is enhanced by a saturated alluvial paleochannel eroded in the bedrock and infilled with post-Laramide detritus derived from the Bear Canyon fold and thrust belt. The paleochannel contains Santa Fe Group alluvial-fan deposits, and is locally intercepted by the groundwater table to create a saturated alluvial hydrostratigraphic unit. Elevated hydraulic conductivities within this proposed unit have been used to conceptualize groundwater flow within a three-dimensional site-wide bedrock groundwater model. A 1997 field study evaluated a narrow midsection of the paleochannel formed as a result of confining hydrogeologic conditions. A pumping well (IS-1), 1000 ft Westbay® multiport monitoring well (BLM-33), and several existing conventional wells were utilized for an aquifer test to delineate hydrostratigraphic units and groundwater flow. A stratified sequence of five hydrostratigraphic units (HUs) were correlated across the study area within Oligocene volcanic bedrock between the groundwater table at 300 ft and 1020 ft. These units were designated: Santa Fe Group alluvium, <30 ft thick (HU-1); trachyte, 50–60 ft thick (HU-2); rhyolitic ash-flow tuff, 120–250 ft thick (HU-3); interbedded rhyodacites/quartz rhyodacites, 250–320 ft thick (HU-4); and dacite, >150 ft thick (HU-5). Study results indicate a minimal thickness of saturated alluvium and no enhancement of groundwater flow. Pervasive carbonate cementation of the saturated alluvial matrix drastically reduces the porosity of the alluvium to that of fractured bedrock (<5%). A step drawdown test and continuous rate-pumping test were performed at well IS-1 within the relatively productive HU-4. Groundwater depths were monitored using an automated data-logging system that allowed the simultaneous measurement of formation fluid pressures at several locations within Westbay® multiport and adjacent aquifer test wells. Pump test data calculations yielded hydraulic parameters for HU-4 of: $K = 2.1 \times 10^{-6}$ to 1.4×10^{-5} ft/sec; $T = 58.6$ to 386.5 ft^2/day; and $S = 1.5 \times 10^{-5}$ to 1.4×10^{-4}. Groundwater is hosted within a leaking, semi-confined, fractured-bedrock aquifer that was dewatered during the pre-test development and post-test recovery phases. The hydrostratigraphic data generated for this study warrant revision of the existing groundwater model. Groundwater heads must be recalibrated to simulate the semi-confined nature of bedrock-hosted groundwater, as opposed to unconfined saturated alluvium. Further definition of HU-1 and HU-2 hydraulic parameters within the upper 120 ft of the aquifer are required to conceptualize the previously undefined hydrostratigraphic and groundwater flow data.

INTRODUCTION

Study area description

The National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) White Sands Test Facility (WSTF) is located 18 mi northeast of Las Cruces, New Mexico (Fig. 1). The facility covers 60,500 acres on the western flank of the southern San Andres Mountains. A paved road that intersects US-70 1 mi west of Organ, New Mexico, provides access to the facility. Primary WSTF activities include the testing of spacecraft propulsion systems and ground support equipment, and hazard and failure analyses performance testing for space-shuttle materials and components.

This paper summarizes the results of a NASA WSTF study on the interplay between hydrostratigraphy and groundwater flow within a hydrogeologically significant area of the southwestern San Andres Mountains pediment slope. The study area incorporates the narrow midsection or pinch-point of a previously reported paleochannel inferred to enhance east-to-west groundwater flow across the WSTF pediment slope. Enhanced flow within the paleochannel is important relative to the potential movement of low-concentration groundwater contaminants derived from historical WSTF operations. The study area has dimensions of 2000 by 4000 ft (Fig. 2), and is located primarily within the SE¼ sec. 33, T20S, R3E. Figure 2 delineates the position of the proposed saturated alluvial paleochannel that continues to the WSTF pediment slope margin 5000 ft to the west. The inferred channel terminates within the Western Boundary Fault Zone (WBFZ), a northwest-trending series of subparallel normal faults that step down to the west. The WBFZ increases the depth to bedrock from 400 ft to >2000 ft, based on drilling data. The Jornada del Muerto Basin located west of the WBFZ has an estimated alluvial thickness of 2600 ft, based on seismic interpretations (Maciejewski, 1996), and hosts an unconfined alluvial aquifer.

Hydrogeological review

Following Laramide uplift, erosion of the saturated alluvial paleochannel was caused by detritus derived from the uplifted San Andres Mountain front east of WSTF within the Bear Peak fold and thrust belt. The groundwater table within the study area is confined to the fractured bedrock with the exception of the paleochannel, which hosts a confined area of saturated Tertiary–Quaternary Santa Fe Group coalescent alluvial-fan deposits. The paleochannel was proposed to be constricted between a low-conductivity, non-transmissive flow-banded rhyolite

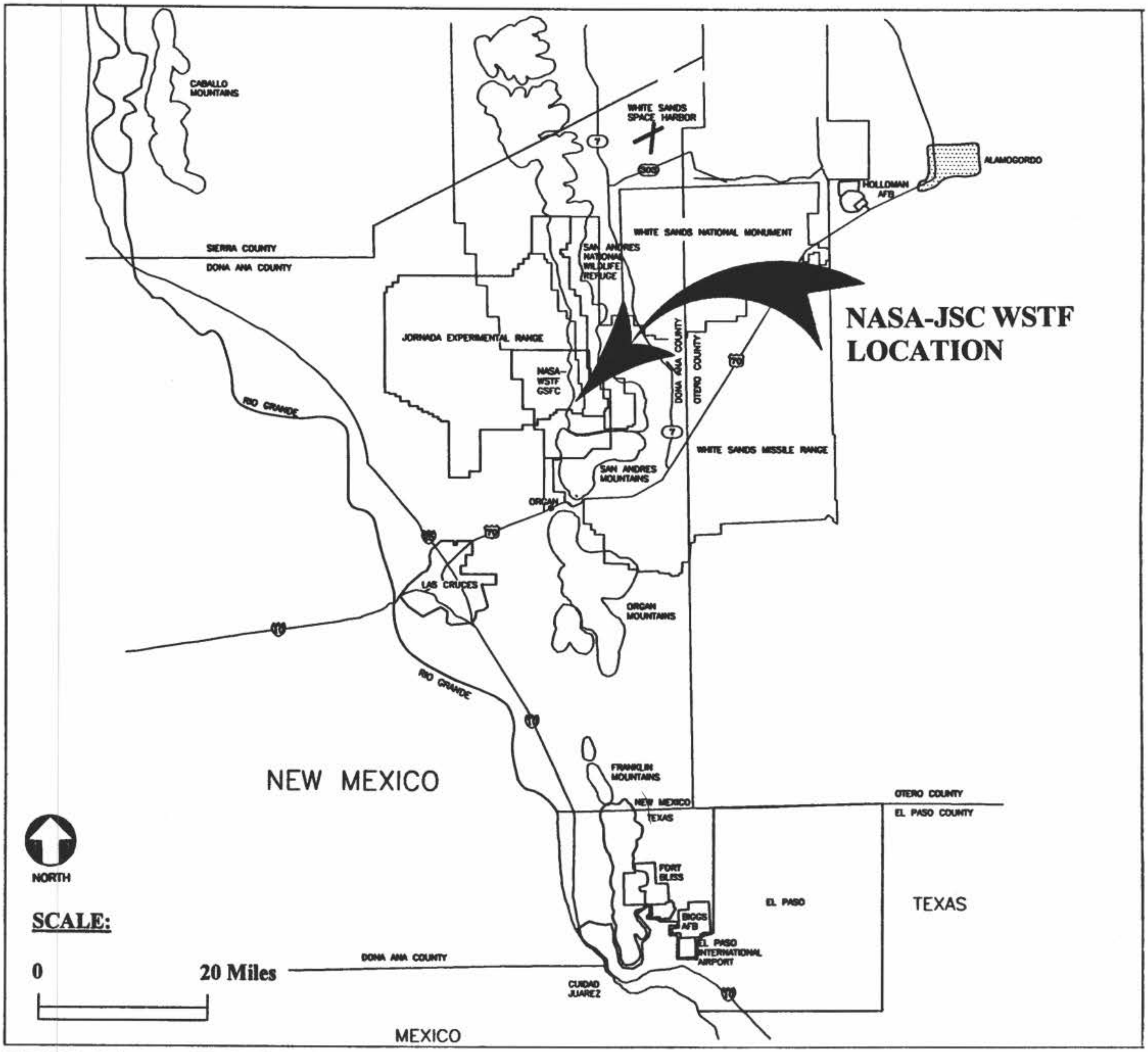

FIGURE 1. Index map of NASA-JSC White Sands Test Facility located 18 mi northeast of Las Cruces, New Mexico.

(FBR) to the north, and an area of low conductivity bedrock to the south (Fig. 2). While the detailed distribution of the FBR remains undefined, reduced potentiometric surface levels 150 ft lower than adjacent wells, minimal fracturing of the unit and low hydraulic conductivities support confinement of the paleochannel. Several dry boreholes and conventional wells define the confining area of low-conductivity bedrock to the south.

Groundwater modeling investigations at WSTF are performed using a three-dimensional site-wide bedrock (3DSWB) model. The 3DSWB model utilizes the U.S. Geological Survey's three-dimensional finite difference code MODFLOW to simulate groundwater movement and allow predictive flow simulations. The predictive simulations accommodate evolving boundary conditions resulting from increased groundwater withdrawals in the Jornada del Muerto Basin 10 mi southwest of WSTF near US-70. Groundwater flow scenarios within the study area have been previously set up to evaluate the potential to intercept flow as a result of low-concentration groundwater contamination below WSTF. Reduced flow to the west is achieved through groundwater extraction wells placed in the narrow paleochannel midsection adjacent and south of the FBR unit; although the effectiveness of the system is under evaluation. Groundwater interception can also be achieved by aquifer dewatering.

SUPPLEMENTAL BOREHOLE/WELL FIELD INSTALLATION

The study utilizes data from three pre-existing conventional groundwater monitoring wells (BLM-9-419, BLM-21-400 and BLM-22-570), and four supplemental boreholes (IS-1, Pilot-1, Pilot-2, and Pilot-3) installed to delineate the local hydrostratigraphy and groundwater flow, and support aquifer testing. Borehole IS-1 was converted to a pumping well (IS-1) and borehole Pilot-2 converted to a 1000-foot multiport monitoring well/observation well (BLM-33). The boreholes were located near the paleochannel axis, where >100 ft of saturated alluvium was anticipated. Information from the supplemental boreholes indicated that the dimensions and significance of the paleochannel had been greatly over estimated.

Borehole IS-1 was located 322 ft southwest of well BLM-21-400, downgradient along the paleochannel axis (Fig. 2). The borehole was drilled to 867 ft below ground surface (bgs) with bedrock and groundwater coincident at 310 ft bgs. Recovery testing during drilling yielded a low groundwater production of 1.5–3.0 gallons per minute (gpm) at 550 ft, and increased groundwater production of 19.4 gpm at 700 ft. Borehole conditions between 550 and 700 ft were poor, with abundant sloughing. Groundwater production did not increase below 755 ft, where the borehole walls were competent with no visible fractures. A 4-in.-diameter flush-joint stainless-steel pumping well was installed within the IS-1 borehole for anticipated aquifer testing flow rates of 20–30 gpm. The well was screened between 595 ft and 855 ft bgs.

Borehole Pilot-1 was installed 3000 ft downgradient of the study area at the inferred paleochannel mouth prior to its intersection with the WBFZ (Fig. 2). The location was selected to enhance saturated alluvial groundwater production by increasing the source area upgradient of the borehole. The borehole was drilled to 580 ft bgs with no saturated alluvium encountered. Bedrock was intercepted at 400 ft bgs and static groundwater at 412 ft bgs. A recovery test at 580 ft bgs indicated limited groundwater production of 1.5–2.1 gpm.

Borehole Pilot-2 was installed 267 ft northwest of well IS-1 (Fig. 2). The borehole was advanced to 1020 ft with bedrock and static groundwater intercepted at 340 ft. Recovery tests indicated production of 1.4 gpm at 400 ft bgs and 7.4 gpm at 680 ft bgs. Unconsolidated bedrock was encountered between 700 and 800 ft bgs, and groundwater production increased to 20 gpm. The borehole below 800 ft bgs was highly competent, non-fractured, and yielded no additional groundwater. A 1.5-in. diameter Westbay® multiport well was installed to 1000 ft using retrofit techniques through a retractable 3.5-in. steel sleeve due to unstable borehole conditions. The well was constructed with six monitoring zones between 330 and 985 ft.

Borehole Pilot-3 was installed 648 ft northwest of well BLM-33 to complete a cross section across the paleochannel (Fig. 2). No saturated alluvium was identified. Volcanic bedrock was intercepted at 350 ft bgs and groundwater at 498 ft bgs. Borehole recovery testing yielded negligible groundwater at 400 ft, 5 gpm at 600 ft and 11 gpm at 911 ft bgs.

GEOLOGY

Stratigraphy

Cross section A–A' (Fig. 3) extends along the axis of the inferred paleochannel between the NASA 300 Area and monitor well JP-2-447 west of the WBFZ. A bedrock transition exists across the Hardscrabble Hill fault (mapped in outcrop by Seager, 1981) from Pennsylvanian–Permian sedimentary rocks in the east (Lead Camp Limestone, Panther Seep and Abo Formations) to Oligocene volcanic rocks related to the Organ Mountains intrusive complex in the west. The study-area bedrock is Oligocene (30–33 Ma) volcanics, locally classified as ash-flow tuffs (Tvt). The bedrock is unconformably overlain by a veneer of late Pliocene–Quaternary (<7 Ma) Santa Fe Group alluvium (QTa2 - coarse-grained proximal to mid-fan) that is between 300 and 350 ft in thickness. The alluvium is bimodal, with the boundary between sedimentary-rich and

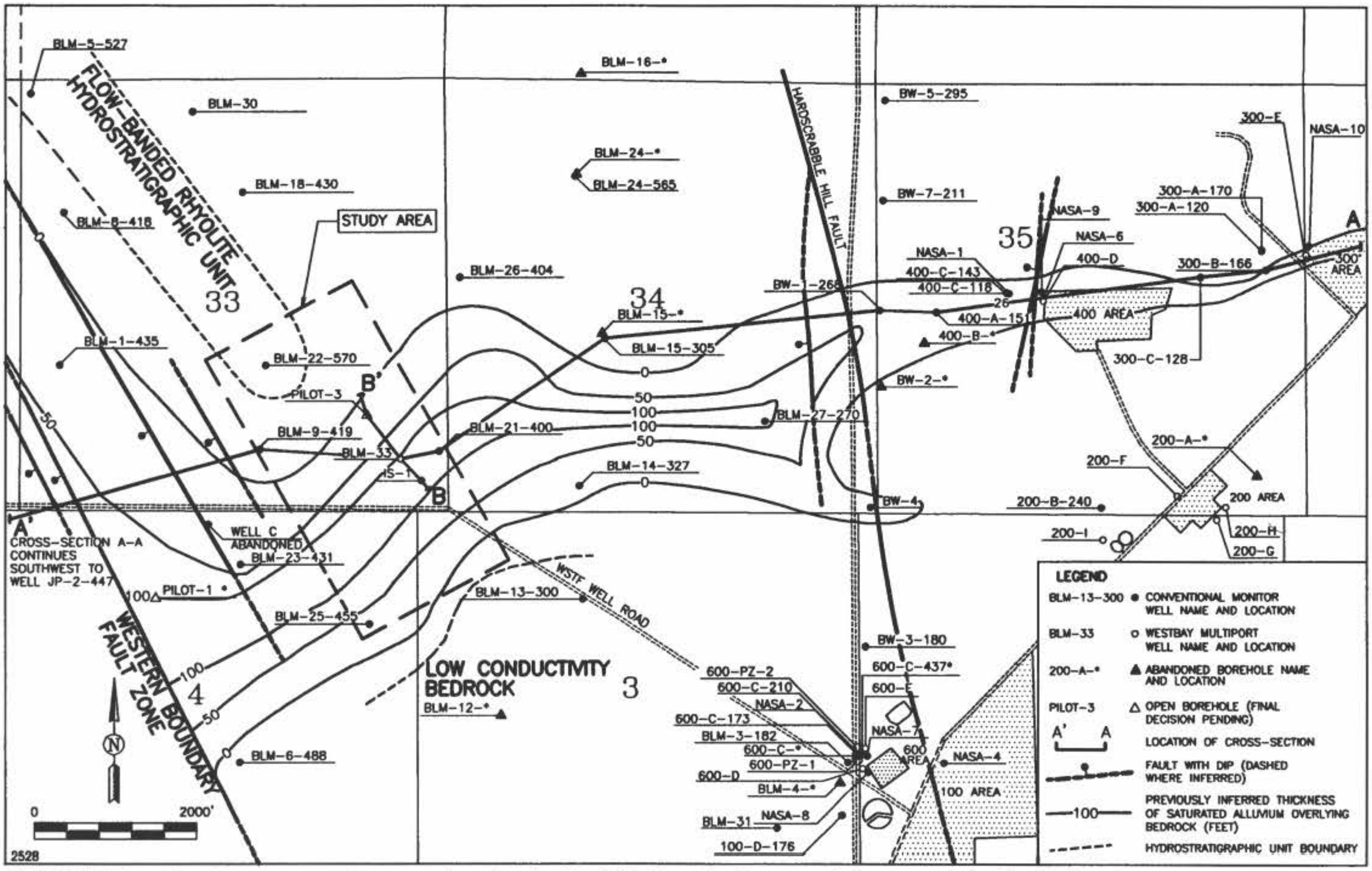

FIGURE 2. Location of study area and cross sections showing local Rio Grande rift structural features and the distribution of a previously inferred, saturated, alluvial paleochannel.

volcanic-rich alluvium at approximately 120 ft bgs. Surficial soils in the area of the Doña Ana-Regan Association (SCS, 1980) are composed of deep, well-drained soils formed on fans and piedmonts.

The Oligocene ash-flow tuffs extend to the depth of drilling at 1020 ft, and comprise stratified rhyolitic ash-flow tuff, rhyodacite, dacite, quartz latite and latite with a composite thickness of at least 670 ft (as evidenced in the BLM-33 borehole). The tuffaceous volcanics are related to the Organ Mountains intrusive complex (Seager, 1981), and were derived as a result of explosive volcanism that followed the Laramide Orogeny from the Late Eocene through Miocene epochs. Microporphyritic vitric-lithic-crystal ash-flow tuffs predominate. The study area hydrogeology, based on lithology, geophysics and recovery testing, is presented on cross section B–B' (Fig. 4).

Structure

Two significant structures at WSTF, previously interpreted as post-Laramide saturated alluvial paleochannels, converge east of well BLM-21-400, to form a single channel that extends west-southwest into the WBFZ. Although saturated alluvium within the paleochannel has been inferred to provide preferential drainage across the pediment, current data do not support this hypothesis.

Rio Grande rift deformation of the WSTF pediment slope commenced at 30 Ma (late Oligocene) as a result of east–west-directed extensional forces that formed a series of northwest-trending structural depressions and adjacent fault-bounded mountains. Regional soil-survey data within the area (Gile et al., 1981) indicate that numerous faults in the area displace the Quaternary alluvium, and that faulting has continued to present. The Jornada del Muerto Basin began forming as a result of extension and rifting in the Rio Grande valley. The basin was subsequently infilled with the Santa Fe Group alluvial sediments derived from erosion of the basin-bounding mountain fronts.

The bedrock surface below the western part of WSTF gently dips at between 2 and 4° to the west. The pediment is broken by northwest-southeast normal faults with dips of 60–90° and displacements of up to 100 ft. Downward movement along the faults is generally to the west toward the basin axis. The regional-scale WBFZ defined through drilling has >1600 ft of stepped offset along a subparallel series of north-northwest trending normal faults. The study area is relatively unaffected by faulting, with the only identified structure (Maciejewski, 1996) being a northwest-trending normal fault downgradient of well BLM-21-400, with 20 ft of downthrow to the west (Figs. 2 and 3).

HYDROGEOLOGY

Conservative estimates of mountain-front recharge at WSTF vary between 70 and 100 acre-ft/yr/mi. Recharge to water-bearing

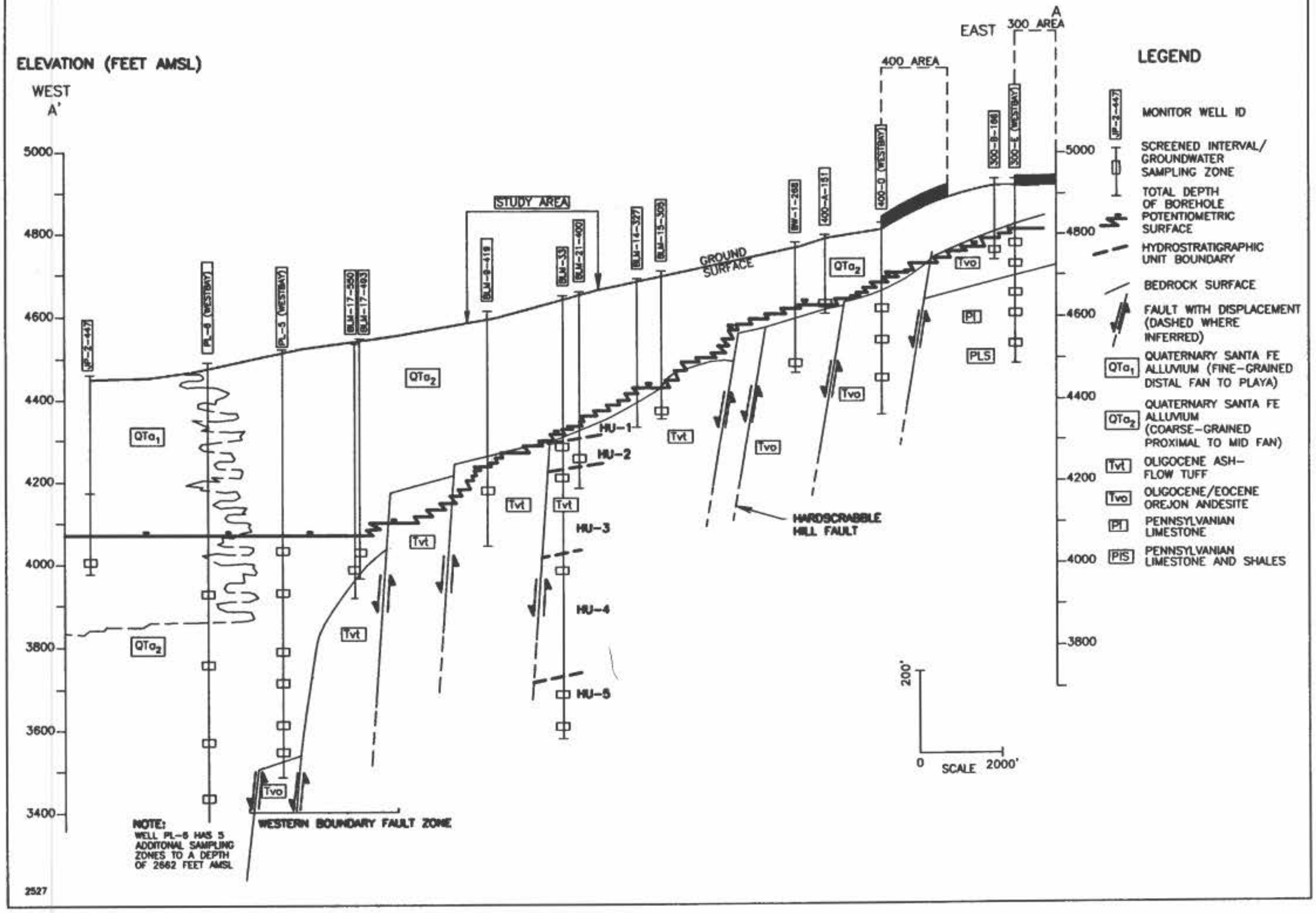

FIGURE 3. East–west cross section A–A' across WSTF showing geology, structure and hydrogeological features.

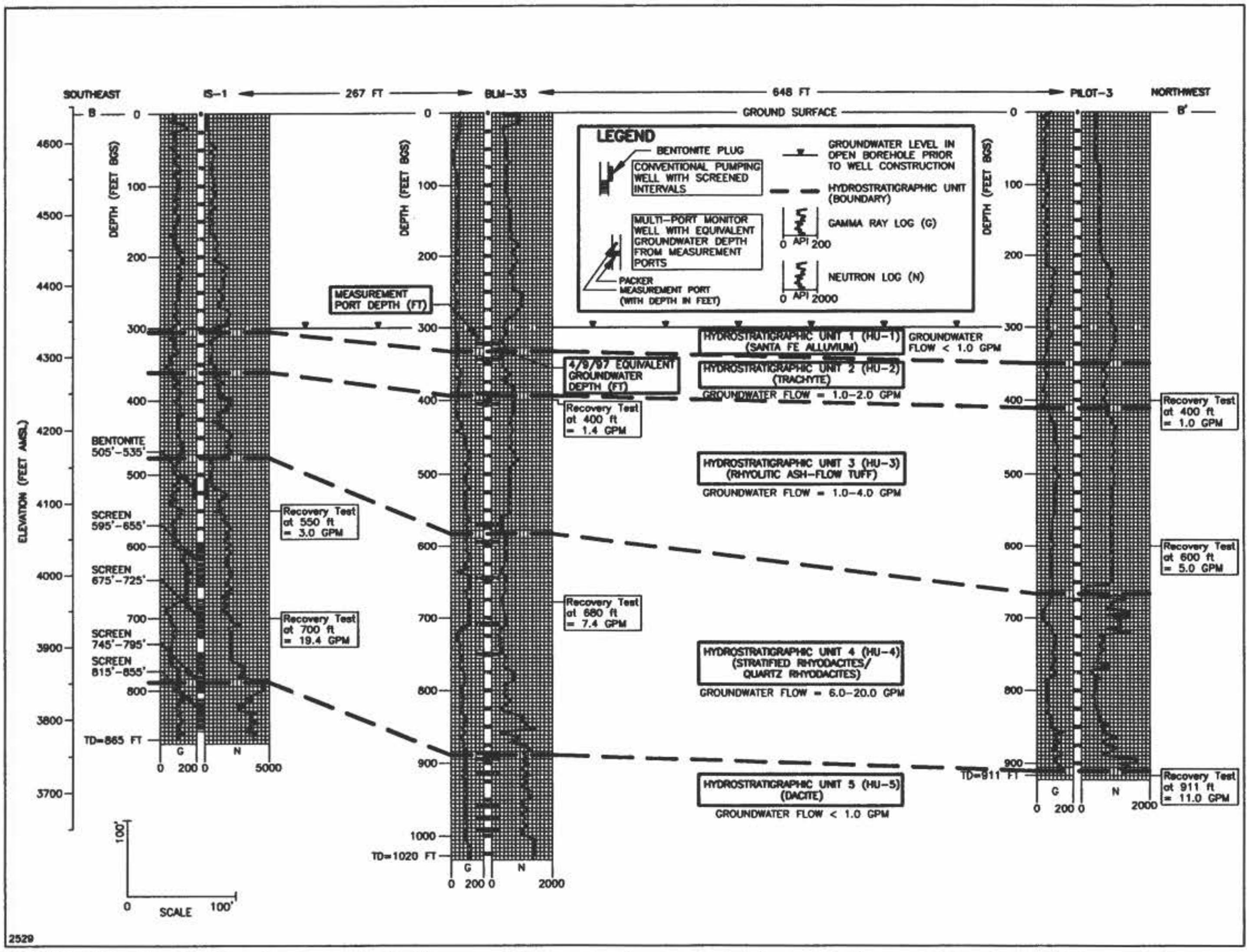

FIGURE 4. Southeast-northwest cross section B–B' across study area showing geophysical log correlations and the position of hydrostratigraphic unit boundaries.

lithologies occurs across fractured bedrock between the San Andres Mountains to the east and Jornada del Muerto Basin to the west. The amount of recharge to the WSTF pediment is increased in the vicinity of the Bear Canyon catchment area, upgradient of the proposed paleochannel. A large arroyo, coincident with the proposed paleochannel at depth, drains the NASA 300 and 400 Test Areas and was eroded as a result of drainage from Bear Canyon. The discharge of water from the 300 and 400 Test Areas represents the primary man-made recharge to the aquifer with a total of 90 acre-ft/yr estimated. Recharge takes place over a length of 7000 ft along the arroyo floor downgradient of the 300 and 400 Areas. The infiltration of water to bedrock occurs upgradient of the study area, except under flash flood conditions. Given an arroyo floor width of 10 ft, this translates to an infiltration rate of 0.15 ft/day, which is well within the range of sandy to gravelly sediments.

Aquifer conditions on the pediment slope are typical of a semiconfined fractured bedrock aquifer. Previous interpretations indicate enhanced groundwater flow within a saturated alluvial paleochannel, where increased permeability was proposed to create a preferential pathway for groundwater. The dimensions of the saturated alluvial paleochannel and the porosities of the alluvial sediments have both been significantly reduced as a result of this study. Aquifer conditions within the Jornada del Muerto Basin are unconfined to leaky confined where impermeable cemented horizons act as upper confining horizons.

Hydraulic parameters

Groundwater within the WSTF fractured bedrock flows west with an average hydraulic gradient of 0.05 ft/ft. This gradient becomes negligible west of the WBFZ within the Jornada del Muerto Basin alluvial aquifer. Hydraulic parameters significant to the development of the 3DSWB groundwater model include hydraulic gradients, aquifer thickness, horizontal hydraulic conductivity (K), and storage coefficient (S). Hydraulic parameters and water yields from bedrock units in the pediment area are significantly lower than from the Jornada del Muerto Basin.

Hydraulic properties of the WSTF bedrock aquifer have been determined through slug testing and pump testing. K values within the tuff units of the study area range from 0.07 to 0.1 ft/day. K values for the thick alluvium in the Jornada del Muerto Basin range from 10 to 40 ft/day, several orders of magnitude greater than the WSTF bedrock lithologies. Relative to the deep basin alluvium, paleochannel alluvium in the pediment area shows low K values. A pump test in the paleochannel alluvium performed at well NASA

6 (immediately downgradient of the 400 Test Area and upgradient of the study area) yielded a K value of approximately 10 ft/day. Hydraulic conductivity values within the paleochannel decrease by one to two orders of magnitude to the west. Core samples from wells completed in the ash-flow units, including the FBR unit (well BLM-5-527), display no visual matrix porosity, with fracture porosity (typically less than 1%) being considered the predominant hydraulic pathway.

Hydraulic conditions in the ash-flow units are variably confined to unconfined. Permeable fractures encountered in FBR wells BLM-5-527 and BLM-22-570 showed hydraulic pressures which caused rises of 46–65 ft within the unit following penetration of the aquifer. Leaky confined aquifer conditions occur within the Jornada del Muerto Basin. These conditions were determined through drilling observations and pump tests, where hydrostatic pressures caused water levels in boreholes to rise when water-producing intervals were penetrated.

HYDROSTRATIGRAPHIC UNITS

A hydrostratigraphic unit may represent an entire stratigraphic unit, a portion of a stratigraphic unit, or a combination of adjacent stratigraphic units with consistent hydraulic properties. Hydrostratigraphic unit boundaries and their correlations across the study area are integrally related to the groundwater-flow distribution at WSTF. Although lithologic and geophysical data sources may be sufficient for the location of a hydrostratigraphic unit boundary, the position is often refined based on supplemental data such as equivalent groundwater elevations from Westbay® multiport fluid pressures. Fracture connections near the hydrostratigraphic unit boundaries may extend the hydraulic conditions characteristic of one unit inside the boundary of an adjacent unit. The boundary can be modified accordingly to incorporate the fracture connection. Additional data such as groundwater chemistry can then be used to confirm the integrity of the boundary position.

Determination of hydrostratigraphic unit boundary locations

Borehole lithology and stratigraphy

Santa Fe Group alluvium in the study area extends to depths of between 300 and 350 ft bgs (Fig. 3). Bedrock is composed of a sequence of Oligocene rhyolitic ash-flow tuffs and trachytic to dacitic lava flows, which can be correlated with the Cueva Tuff (Dunham, 1935) and Tuff of Cox Ranch (Seager, 1981). The lowermost 30 ft of the alluvium is saturated to form HU-1, although water yields are minimal.

The uppermost bedrock volcanic unit (HU-2) is a trachyte flow between 50 and 60 ft thick. The trachyte is grayish orange-pink in color with a porphyritic texture. Subhedral phenocrysts vary in size up to 0.1 in., and are predominantly plagioclase feldspar (70%) and quartz (20%) with minor biotite. The aphanitic matrix is composed predominantly of potassium feldspar. Alteration of the feldspars is pervasive, with 50% degraded to clay. Underlying the trachyte is a rhyolite ash-flow tuff between 120 and 250 ft thick (HU-3). The rhyolite is light gray in color and variably equigranular to microporphyritic. Subhedral and anhedral phenocrysts to 0.1 in. in size comprise 70% plagioclase and 20% quartz with accessory biotite and pyroxene. Alteration of the feldspars to clay is low at less than 10%, and the rock is highly indurated.

The rhyolite is underlain by a variable sequence of stratified rhyodacites and quartz rhyodacites between 250 and 320 ft in thickness (HU-4). The units are variably colored light red, light gray, and light greenish-gray. Textures are generally porphyritic with subhedral phenocrysts of plagioclase (80%) and quartz (20%) to 0.1 in. in size. The alteration of the rock to clays is pervasive at 60%. The base of the section is characterized by a dacite of at least 150 ft in thickness (HU-5). The dacite is pink in color with a strongly porphyritic texture. Phenocrysts to 0.15 in. in size comprise euhedral tabular plagioclase and quartz. The aphanitic matrix includes abundant K-feldspar and quartz. Biotite and pyroxene mafics comprise 10% of the rock and are finely disseminated in the matrix. The alteration of feldspar to clay is minimal at less than 5%.

Borehole geophysics

Geophysical logs were used to supplement lithologic observations for hydrostratigraphic interpretations, and identify the relative porosity of the vertical section below the groundwater table. Gamma ray logs and hydrostratigraphic unit delineations for boreholes IS-1, BLM-33 and Pilot-3 along cross section B–B' are presented in Figure 4. Gamma ray summaries for HU-1 (Santa Fe alluvium) show relatively low values of 35–45 American Petroleum Institute units (API), indicative of limited quantities of radioactive minerals within the sedimentary clasts. Values increase to between 60 and 80 API within HU-2 (trachyte), indicative of the alluvium/volcanic bedrock contact. Unit HU-3 (rhyolitic ash-flow tuff) shows consistently high values for gamma of 120 API, which can be used as a marker horizon in adjacent wells/boreholes (Fig. 4). HU-4 (interbedded rhyodacites and quartz rhyodacites) shows highly irregular API values of between 70 and 180, representative of variable compositions within a stratified volcanic sequence. The gamma logs in HU-5 (dacite) reflect consistently high values of 120 API, which extend to the depth of drilling.

Neutron logs are used as total porosity indicators under saturated conditions, and are generated by recording neutron impacts on a detector mounted adjacent to a constant neutron source. Energy is lost in impacts with hydrogen, the principal component of water. A summary of neutron logs and the delineation of hydrostratigraphic units in boreholes/wells IS-1, BLM-33 and Pilot-3 are provided in Figure 4. Neutron logs were used to support selective placement of groundwater sampling zones in well BLM-33. Marked declines from 1000 to 300 API at the top of HU-1 identified the position of the static groundwater table. HU-2 was characterized by relatively low and variable neutron values between 200 and 350 API, which indicated an increase in porosity. HU-4 at depth showed highly irregular values of between 200 and 1500 API, with numerous relatively favorable zones with respect to porosity. In contrast, HU-3 (650–850 API) and in particular HU-5 (1000–1500 API) showed elevated neutron responses and minimal porosity.

Electric logs measure the current loss (resistance) between two electrodes. Variations are caused by differences in the character of the volcanics and the mineral content of the groundwater. Dry formations are poor electrical conductors and show very high resistivities. HU-1 shows a significant resistivity decrease from 225 to 75 ohm-m, marking the position of the groundwater table. The logs show significantly lower resistivities between 10 and 20 ohm-m for HU-2 and HU-4 than the other units, corresponding to increased porosity. Both HU-3 and in particular HU-5 show resistivities between 100 and 220 ohm-m, indicating relatively dry units. Spontaneous potential logs were run in conjunction with resistivity logs and represent naturally occurring electric voltages that result from chemical and physical changes at formation boundaries. A slight negative response in the SP for HU-4 supports the HU-3/HU-4 hydrostratigraphic boundary position.

Caliper logs were used to establish fracturing, caving, borehole quality for Westbay® packer locations, and support lithological observations. The upper borehole in the vicinity of HU-1 through HU-3 was of moderate quality with minimal diameter variation. Isolated caves marking fracture intersections over 2–3-ft intervals occurred within HU-2 and HU-3. Significant deterioration of the boreholes occurred within HU-4, where walls were detected only 70 ft into the 250–320-ft thick unit. Caving in the central unit yields unstable borehole walls with no feasibility of open-hole logging. In significant contrast, the HU-5 borehole was highly competent, with no visible caves, fractures, or irregularities.

Westbay® multiport monitoring system well BLM-33

Westbay® multiport well BLM-33, installed within the Pilot-2 borehole, was utilized to support the delineation of hydrostratigraphic units. Sampling zones were placed strategically to provide information from each hydrostratigraphic unit. The positions of the packers were modified based on caliper results to conform to intervals of high borehole integrity. The positions of six-well BLM-33 monitoring zones between 330 and 985 ft, measurement ports and the pressure profile results (equivalent groundwater levels from fluid pressures) for September 9, 1997 are presented on Figure 5. The pressure profile data show compatible equivalent heads within each of the hydrostratigraphic units, which contrast values within adjacent units. The results supported the placement of hydrostratigraphic unit boundaries established on the basis of lithology and geophysical logs. The relatively productive HU-1, HU-2 and HU-4 show equivalent groundwater depths between 300 and 340 ft bgs, which approximate regional groundwater table values. HU-3 and HU-5 showed reduced equivalent groundwater depths between 400 and 510 ft bgs, which support minimal yields during field recovery testing and low porosities in geophysical logs.

Hydraulic gradients, flow directions and flow rates

Three-point calculations performed utilizing wells BLM-21-400, BLM-9-419, and BLM-25-455 confirmed an average horizontal hydraulic gradient of 0.05 ft/ft for the study area. The horizontal flow direction generated from three-point calculations was west at 268°. Available vertical hydraulic gradients within the study area generated from the equivalent groundwater depth data are provided on Figure 5. The vertical flow net shows that the overall vertical hydraulic gradient across the volcanic section is moderately downward at approximately 0.33 ft/ft, which is comparable to other wells installed within volcanic bedrock.

Equivalent groundwater depths from fluid pressures near the top of the aquifer within HU-1 and HU-2 at between 322 and 300 ft bgs respectively show an upward vertical gradient of 1.0 ft/ft indicating confined conditions across the boundary. HU-3, considered an aquitard based on geophysical and multiport well data, shows equivalent groundwater levels of 400–478 ft bgs, which creates an apparent strong downward vertical gradient of 2.1 ft/ft across the HU-2/HU-3 boundary. HU-4, characterized by relatively abundant water, shows elevated equivalent groundwater levels of between 315 and 389 ft bgs, which promote a strong apparent gradient of 1.6

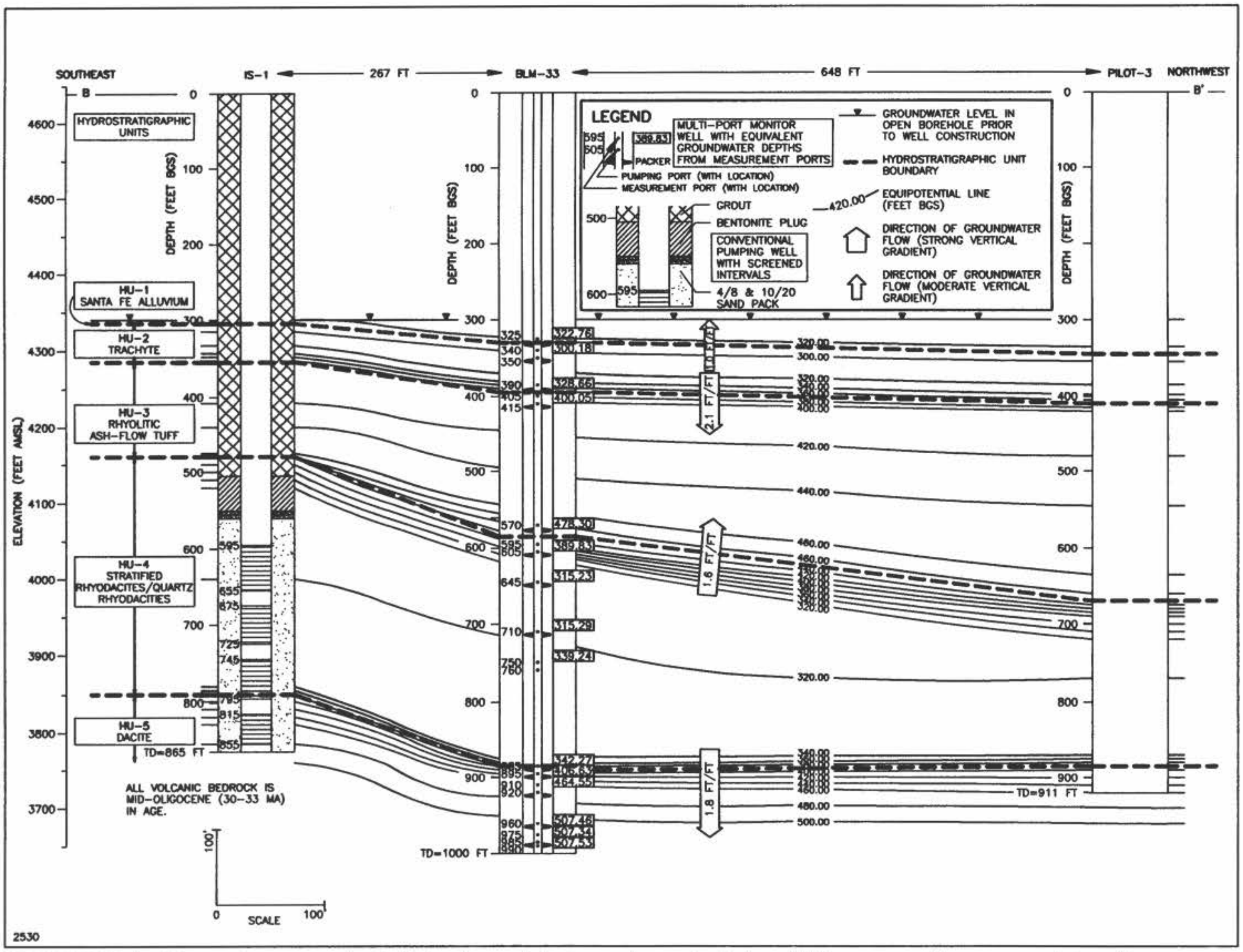

FIGURE 5. Vertical flow net for cross section B–B' showing equivalent groundwater depths from fluid pressures and apparent vertical gradients.

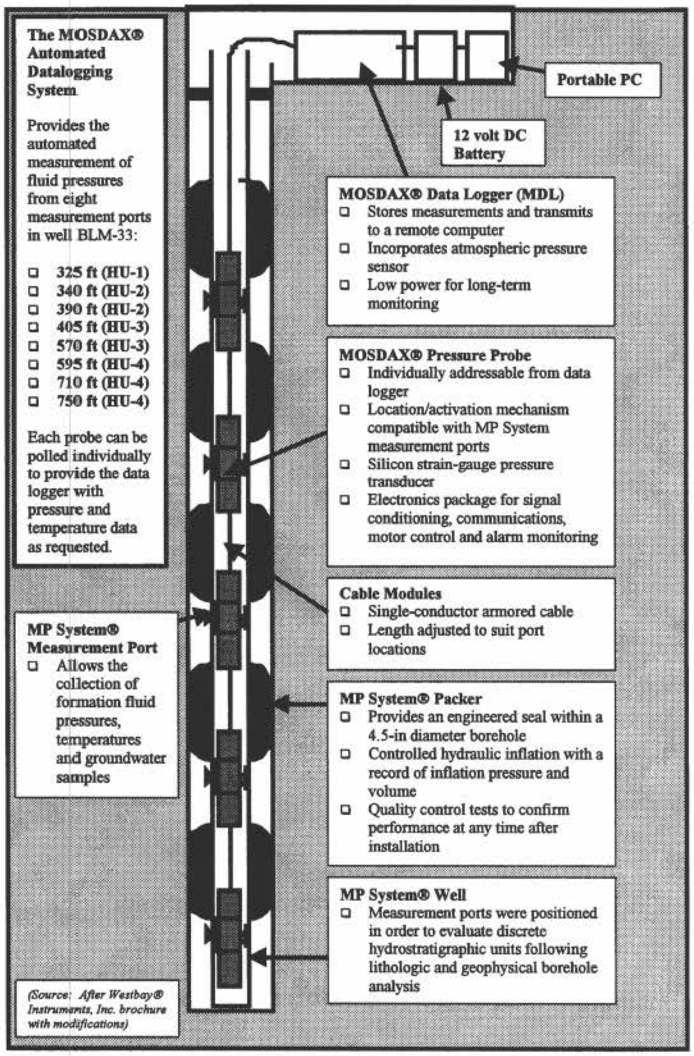

FIGURE 6. Generalization of the Mosdax® automated data-logging system utilized in multiport-well BLM-33 for aquifer testing.

ft/ft across the HU-3/HU-4 boundary. HU-5, which is also considered an aquitard shows reduced equivalent groundwater levels of between 464 and 507 ft bgs, creating a strong apparent downward gradient at the HU-4/HU-5 boundary of 1.8 ft/ft. Figure 5 provides a flow net with groundwater apparently flowing outward from the relatively productive HU-2 and HU-4.

IS-1 AQUIFER TEST

Aquifer test instrumentation

Aquifer testing was performed using a 10-hp, 40 gpm Grundfos submersible pump suspended at 849 ft bgs in pumping well IS-1. A MOSDAX® pressure transducer was secured to a 1.5-in.-diameter drop pipe 20 ft above the pump at 829 ft. Observation wells BLM-21-400 and BLM-33 were also equipped with pressure transducers. All fluid pressures were monitored using the MOSDAX® automated data-logging system (Fig. 6).

The MOSDAX® Data Logger (MDL) provides the simultaneous measurement of multiple fluid pressures within Westbay® multiport or conventional monitoring wells. Stacked MOSDAX® pressure probes equipped with silicon strain-gauge pressure transducers allow access to multiple measurement ports within a single multiport well. The equipment operator inputs data collection frequencies for the aquifer test to the MDL. The frequency of data collection was modified over designated aquifer test intervals during instrumentation setup. Pressure and temperature data from individual probes were accessed during testing through interaction between the MDL and a portable computer.

The MDL was linked with single-pressure probes within pumping well IS-1 at a depth of 829 ft bgs, and observation well BLM-21-400 at a depth of 357 ft bgs. Eight pressure probes were installed within multiport well BLM-33. The individual probe locations, measurement port depths, and the corresponding zones and HUs monitored are provided in Table 1. Immediately prior to MOSDAX® pressure-probe installation, the integrity of well BLM-33 was compromised at depth due to unstable bedrock. As a result, the deepest pressure probe installed within well BLM-33 (Probe #4) was at 750 ft bgs.

Aquifer test design

Two aquifer tests were performed at Well IS-1: a 400-minute step-drawdown test (SDT); and a 36-hr constant-rate test (CRT). The 400-min SDT was performed utilizing 100-min step-flow rates of 10, 15, 20, and 25 gpm. Following the SDT, recovery was monitored for 116.5 hr (6990 min) prior to the start of the CRT. Following aquifer recovery, the CRT was performed at 24 gpm for 36 hr (2160 min). Because well IS-1 is screened in a confined aquifer, this time period was regarded as sufficient to observe any effects the pumping may have on the monitored zones in the adjacent observation wells. Once the pump was shut off, groundwater recovery was monitored for 128.3 hr (7700 min).

During pump testing, wells BLM-9-419, BLM-21-400, BLM-22-570, and BLM-33 all located within a 2300-ft radius of well IS-1 (Fig. 2), were used as observation wells. Well IS-1 was screened within HU-4 and into the top of HU-5 between 595 and 855 ft. Groundwater production was predominantly from HU-4, which generally yielded in excess of 60% of groundwater flow within the volcanic section based on lithologic, geophysical and multiport pressure profile data. The thickness of HU-4 used in pump test calculations was 320 ft.

During pre-testing development, the water level in well IS-1 did not recover to previous levels after each episode of pumping. This indicated a strong potential for dewatering of the aquifer within HU-4. Observation well BLM-33 registered significant responses during SDT and CRT pumping, and observation well BLM-21-400 exhibited minor response several hours after the initiation of

Probe ID	Port depth (ft below ground surface)	Zone or well monitored (ft below ground surface)	Hydrostratigraphic unit (HU) monitored	Hydraulic parameters (method and results) K in ft/sec, T in ft^2/day, S (dimensionless)
0	0	Atmospheric	None	—
4	750	Well BLM-33 715–885	HU-4	Birsoy-Summers: K = 2.5 x 10^{-6}, T = 70.4, S = 4.6 x 10^{-5} Theim: K = 2.1 to 2.3 x 10^{-6}, T = 58.6 to 65.5 Cooper-Jacob: K = 2.3 x 10^{-6}, T = 65.0, S = 1.5 x 10^{-5} Theis Recovery: K = 7.6 x 10^{-6}, T = 211.2 Theis Curve Match: K = 1.4 x 10^{-5}, T = 386.5, = 1.4 x 10^{-4}
5	710	Well BLM-33 650–710	HU-4	
6	595	Well BLM-33 575–605	HU-4	
7	570	Well BLM-33 420–570	HU-3	—
8	405	Well BLM-33 395–415	HU-3	—
9	390	Well BLM-33 355–390	HU-2	—
10	340	Well BLM-33 330–350	HU-2	—
11	325	Well BLM-33 0–325	HU-1	—
12	829	Well IS-1	HU-4	Refer to ports 4 through 6 in well BLM-33 for parameters
14	357	Well BLM-21-400	HU-2	—

TABLE 1. Well IS-1 aquifer test MOSDAX® probe locations, monitoring zones, hydrostratigraphic units, and aquifer parameters.

pumping. Individual pressure-probe results within the same hydrostratigraphic unit in well BLM-33 indicated compatible response times, which were significantly different to adjacent units. SDT and CRT data for probes in well BLM-33 indicate the following response times for an equivalent groundwater level drop of 0.1 ft: HU-1: no response; HU-2: 60–120 min; HU-3: 600–2160 min; and HU-4: 7–15 min.

Aquifer characteristics

Aquifer test analyses were performed using the Birsoy-Summers (Kruseman and de Ridder, 1992), Cooper-Jacob (Anderson, 1993), and Theis Recovery and Curve Match (Kruseman and de Ridder, 1992; Driscoll, 1986) Methods. The curve generated from a drawdown versus time plot for the CRT (Theis Recovery Method), coupled with information collected during drilling and multiport well installation, indicate that well IS-1 is producing from a leaking (semi-confined), fractured, bedrock aquifer.

The confining HU-3 which overlies HU-4 is leaky, in that probes within both HU-3 and HU-2 responded during pumping. Data from the Theis Curve Match Method indicate that a combination of fracture drainage and leakage from upper units causes the drawdown curve to attain a reduced slope after about 100 min of pumping. A summary of HU-4 aquifer parameters calculated from SDT and CRT data is included in Table 1.

GROUNDWATER MODELING

Impact of data on the WSTF 3DSWB model

New hydrostratigraphic and groundwater-flow data from the study area reduce the dimensions and significance of a previously inferred, saturated, alluvial paleochannel believed to enhance groundwater flow on the WSTF pediment. These data warrant significant revision of existing conceptualizations within the 3DSWB model. Groundwater heads within the MODFLOW code will be reviewed and recalibrated to simulate the semi-confined, bedrock-hosted groundwater as opposed to unconfined saturated alluvium.

Aquifer properties from the results of the aquifer tests in HU-4 appear to be consistent with a stratified porous-media aquifer. This indicates that the equivalent porous media approach applied during the 3DSWB modeling is appropriate within the study area. Significantly, groundwater in units HU-3, HU-4, and HU-5 is under confined conditions, and the transition to confined conditions with depth appears to occur near the interface between HU-2 and HU-3. These data also indicate a degree of uncertainty in modeling HU-3 as an aquitard. Because HU-3 is located between the zone of pumping (HU-4) and the shallow non-productive portion of the aquifer is within HU-1 and HU-2, the nature of flow across the zone remains unclear.

NASA is presently developing a local three-dimensional groundwater-flow model for the study area to accommodate the new hydrogeological data. Further definition of basic input parameters (hydraulic gradient, aquifer thickness, hydraulic conductivity, and the aquifer-storage coefficient) are required for HU-1 and HU-2 within the upper 120 ft of the aquifer. The localized groundwater model will be utilized to support the vertical distribution of hydrostratigraphic units and groundwater flow on the WSTF pediment slope, and will be subsequently integrated into the site-wide 3DSWB model.

CONCLUSIONS

Five hydrostratigraphic units were defined within and immediately above Oligocene volcanic bedrock between depths of 300 and 1020 ft within a hydrogeologically significant area on the southwest San Andres pediment slope. Data from this study reduce the dimensions and significance of the paleochannel hydrostratigraphic unit as a preferential groundwater-flow conduit and enhance the contribution of bedrock-hosted flow. The five units were designated: Santa Fe Group alluvium, <30 ft thick, <1 gpm groundwater yield (HU-1); trachyte, 50–60 ft thick, 1–5 gpm yield (HU-2); rhyolitic ash-flow tuff, 120–250 ft thick, 1–4 gpm yield (HU-3); interbedded rhyodacites/quartz rhyodacites, 250–320 ft thick, 6–20 gpm yield (HU-4); and, dacite, >150 ft thick, <1 gpm yield (HU-5).

Pervasive carbonate cementation of the saturated alluvial matrix drastically reduces the porosity of HU-1 to <5%, which is characteristic of fractured bedrock. The cemented alluvium forms a confining unit to the underlying fractured bedrock aquifer. Relatively high groundwater yields in HU-2 and HU-4 are supported by equivalent groundwater depths from fluid pressure measurements of 300 and 340 ft bgs, which approximate the regional groundwater table. Negligible groundwater yields within aquitards HU-3 and HU-5 correspond to reduced equivalent groundwater depths of 400–510 ft bgs.

Aquifer testing within HU-4, which yields in excess of 60% of groundwater within boreholes, indicates hydraulic parameters of: K = 2.1×10^{-6} to 1.4×10^{-5} ft/sec; T = 58.6 to 386.5 ft^2/day; and S = 1.5×10^{-5} to 1.4×10^{-4}. Groundwater is hosted within a leaking, semi-confined, fractured bedrock aquifer, which was dewatered within HU-4 during the pre-test development and post-test recovery phases.

The study data warrant revision of existing conceptualizations within the WSTF 3DSWB groundwater model. Further definition of HU-1 and HU-2 hydraulic parameters within the upper 120 ft of the aquifer are required to construct a study area-specific model, which will be utilized to conceptualize the previously undefined hydrostratigraphic and groundwater flow data.

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