GEOLOGIC FEATURES AND THEIR POTENTIAL EFFECTS ON CONTAMINANT MIGRATION, SANTA SUSANA FIELD LABORATORY

BY

Howard G. Wilshire, Ph.D.

October 5, 2006

Disclaimer: This study was prepared for the Santa Susana Field Laboratory Advisory Panel, a project of the Tides Center. The work of the Panel was conducted under a contract with the California Environmental Protection Agency pursuant to funds provided by the California Legislature. The statements and conclusions in this report are those of the contractor and not necessarily those of the California Environmental Protection Agency. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.

October 5, 2006

Geologic Features and their Potential Effects on Contaminant Migration, Santa Susana Field Laboratory

Howard G. Wilshire, Ph.D.

ABSTRACT

The Santa Susana Field Laboratory (SSFL) site is located on the upper part of a small mountain range, and flanked by populated areas at lower elevations. The SSFL's operations have led to widespread, heavy contamination of soils, rock, and groundwater at the site. Central questions are whether the contamination has been, or can be, contained on-site, and the possibility of polluting local water supplies for surrounding communities. This report focuses on the geologic evidence for on-site containment of pollutants, and is based largely on reports commissioned by Rocketdyne and publications in the open literature based on those studies.[1] Many of these reports contend that natural geologic barriers prevent off-site migration of contaminants in groundwater. The geologic features proposed to constitute aquitards--barriers that greatly retard the movement of groundwater--include faults, and fine-grained sedimentary rocks that are interleaved with more porous and permeable sandstones.

My review of the Rocketdyne consultant's reports reveals that the preponderance of evidence in those reports contradicts the conclusion that most of the faults and fine-grained units are aquitards. A big weakness in the Rocketdyne consultants' hypothesis is the inferior quality and quantity of field-derived information about the physical character of these features. Both the fault zones and fine-grained rocks are more susceptible to erosion than the coarser-grained sandstones that crop out prominently on the SSFL, and so are not as well exposed. But the descriptions of existing outcrops and other exposures, as well as the data in numerous well logs, directly contradict claims that the faults and fine-grained units are barriers to groundwater migration.

All of the reports I reviewed suppose that rainwater moves to the water table mainly through fractures in hard rock lying beneath surficial sediments. Movement of groundwater below the water table also takes place in fractures rather than through the body of the rock, as would be

expected for layers of very porous and permeable unfractured aquifer rocks. All rock types at the site are fractured, including fine-grained layers. Most of the faults comprise zones of open fractures along with some occasionally occupied by finely-ground rock gouge, which could locally impede groundwater movement. Fractures in fault zones and those cutting fine-grained units show evidence of circulation of meteoric water, that is water of recent atmospheric origin. Thus, the evidence strongly favors transmission of water, with or without contaminants, preferentially through many fractures rather than by percolation through the body of the rock. The fractures associated with faults and in fine-grained units are just as capable of transmitting water as fractured sandstone.

I conclude that Rocketdyne's model of compartmentalized groundwater units bounded by faults and fine-grained units, which are supposed to prevent contaminated groundwater from moving to surrounding areas, is not supported by the preponderance of evidence and cannot be considered viable. The presence of faults and fine-grained rock units on the SSFL site does not eliminate the possibility for off-site subsurface contaminant migration.

INTRODUCTION

This report is based primarily on review of a large literature on the Santa Susana Field Laboratory (SSFL), Ventura County, California and surrounding regions, prepared mainly by technical consultants to the Boeing Corporation and its predecessor operators of the site, relevant to the storage and movement of contaminants in surficial and deep aquifers beneath the SSFL and surrounding regions. Principal site-specific reports reviewed date from the 1980s to the present, and show progressive refinements in understanding of the site geology, but also provide valuable information on temporal changes in concepts and information. Unfortunately, even the modern reports contain many internal inconsistencies and different reports lack comparability with regard to such items as locations of major structural features and locations of wells with respect to those and other geologic features. There are many conflicting comments about the character of stratigraphic units and a general lack of measurements that would allow critical evaluation of geohydrologic models. Inadequate testing of models of behavior based on very local findings does not engender confidence in the general conclusions reached.

Geologic features at the SSFL and surrounding regions that may affect migration of contaminants are fractures, which constitute the dominant avenues connecting surface and groundwater and are the avenues through which groundwater migrates; surface drainage channels, which drain rainwater to surrounding lower areas; variations in types of rock, which may enhance or retard movement of groundwater; the presence or absence of cementing agents in otherwise porous lithologies of the aquifer(s) and of dense sandstones with reduced porosity and permeability (a measure of the ease with which water moves through a rock), which may influence movement of groundwater; the presence or absence of rock ground to fine paste (gouge) in fault zones, which may impede water flow; fracture filling by deposition of minerals (calcium carbonate and iron oxides) from circulating waters derived from rainfall; fracture opening or reopening by young earth movements; and minerals in sedimentary rocks that may react or bond with contaminants carried by groundwater, which may slow or stop contaminant migration.

In addition to geologic features, human activities also may play significant roles in the distribution and redistribution of contaminants: the SSFL is punctured by so many holes drilled for multiple purposes, that the wells themselves may provided conduits for distributing contaminants. There is no guarantee that abandoned wells have been properly closed and sealed from the surrounding environment. Indeed, in 1987 it was found that "No information is available concerning methods for historic well abandonment, on-site or off-site."[2] Disturbance and artificial redistribution of contaminated sediments at the surface, along with natural erosion, enhances migration of contaminants both into the groundwater and to surface runoff neither of which is confined to the site.

GEOLOGIC ASPECTS OF THE CHATSWORTH FORMATION

Sedimentary rocks comprising the major part of the SSFL and immediate surroundings are dominantly interleaved layers of sandstone and finer grained rocks such as siltstones and shales. These stratified rocks are characterized by rapid lateral and vertical change, reflecting their complex depositional environment.[3] This has made understanding the fine points of site stratigraphy (the sequence of bedded rocks), which is critical to predicting contaminant migration, difficult. Compounding the difficulty of thorough site characterization is poor exposure of important stratigraphic units, in particular those broadly called "fine grained units." While "packages" of beds can be traced laterally for large distances, the details of how they may affect groundwater movement are largely obscure. Important features of the sedimentary rocks that probably formed more or less contemporaneously with their deposition include widespread occurrence of dense and cemented sandstones; these properties may significantly affect movement and storage of groundwater, but the distribution of such variants is not known. More information is available on particular hydrologic characteristics of representative rock types, but what they reveal is extreme variation—ranging over orders of magnitude variation in matrix (body of the rock exclusive of fractures) hydraulic conductivity for example.[4] Another difficulty is the absence of distinctive marker beds in the stratigraphic section that would aid identification of stratigraphic units intersected by wells and beds offset by faults—sandstones and fine-grained units look much the same wherever they occur in the section.[5]

Description of Sandstones

In general, site-specific descriptions of sedimentary rocks exposed in the SSFL and intersected by wells are cursory, and measured sections are lacking. Field description of sandstones, the dominant rock type (lithology) in the SSFL, is very inadequate, and mostly is couched in terms of fine-grained units used to subdivide the sandstones.[6] Generally, the only information given on sandstones is that they range from fine- to coarse-grained. Mineralogical characteristics of the rocks, particularly diagenetic alteration products (alteration products caused by reactions between trapped seawater and sediment particles), including clay minerals, in sandstones have not been characterized, and the distribution of solid organic carbon phases is poorly known. The type(s) of clay minerals and the presence of organic carbon have an important bearing on whether contaminants can be locked in the sediments or not. Non site-specific description of sandstone characteristics[7] indicates the presence of substantial quantities of clay alteration products of detrital (fragmental) plagioclase and potassium feldspars, and biotite as well as of those minerals in small rock fragments. Generally the clay minerals are not characterized, but some are labeled "illite" or "chlorite," without adequate documentation. Carbonate cement and alteration products of detrital minerals and components of lithic fragments are generally described as calcite, but staining revealed the presence of ferroan-carbonate.[7] Thus, even the best available descriptions of primary and secondary mineral components of the sandstones are quite indadequate to assess their role in contaminant migration.

Well logs commonly cite the presence of hard or very dense sandstones and calcarous cementation of sandstones, and commonly also describe hard to very hard fine-grained rocks, some of which are cemented, but most are not so-described. "Hard sandstone" is recognized as an important lithologic type, and was interpreted as resulting from carbonate cementation.[8] However, well logs (for example RD-65)[9] record the presence of both cemented and non-cemented hard sandstones as well as many calcareous to very calcareous sandstones not described as hard. Other logs (for example, RD-5C and 61)[9] record both well-cemented and only slightly cemented hard sandstones. It should also be noted that well logs also report cementation of fine-grained lithologies, not just sandstones.[10] The cause(s) of the hardness is not clear, but it may nevertheless affect groundwater flow and storage. Virtually no information was found on the composition of widespread carbonate cements, or of the nature of clay minerals, commonly logged as constituents of sandstones.[11] Clay filling of fractures in sandstones is commonly logged in well samples,[12] but no information is provided on the types of clay minerals present, their proportions, or where they came from. Such features may have an important bearing on interaction of contaminant-bearing water and aquifer rocks. Also, well-cemented sandstones are considered by MWH to be aquitards,[13] but as such are not factored into the designation of Groundwater Units (volumes of rock bounded by faults and fine-grained units, which are considered to be hydrologic units independent of adjacent units—discussed below) or into any local assessment of water levels and contaminant distributions.

Thin gravel beds and rock fragments in coarse-grained sandstones occur randomly in the Upper Chatsworth Formation. No adequate description of the rock types occurring as clasts in these sediments was found in technical reports, other than the non site-specific descriptions given by Carey. Carey describes lithic (rock fragment) components of the sandstones as comprising metamorphic phyllite, micaceous quartzite, and slate/argillite, granitic fragments, and volcanic rocks.[14] The absence of any detailed information on the primary and secondary mineralogy of lithic fragments in sandstones and in gravel beds within the sandstones, introduces additional unknowns into assessing contaminant interaction with Chatsworth Formation rocks.

Although the presence in sandstones of partial to complete fracture fillings by carbonate or other minerals is frequently described by field investigations and in well logs,[15] little information is provided on the composition of the fillings, and no assessment is made of the role of such fillings in changing patterns of groundwater flow. Fracture fillings and staining of fracture surfaces provide direct evidence of circulation of meteoric waters (waters of recent atmospheric origin), and thus allow assessment of the efficacy of supposed aquitards. An accurate characterization of these features is also important in any computer modeling and simulation of local groundwater reservoirs concerning contaminant movement.

Description of Fine-Grained Units

Site-specific field descriptions of fine-grained units are as lacking as those of sandstones, although somewhat more effort has gone into mapping their outcrop distribution in the eastern part of the SSFL.[16] Fine-grained units, commonly referred to in sum as "shale" are composed of sandstone (very fine- to medium-grained), siltstone, and shale. In places they are mapped as separate from interbedded sandstones "typical" of Upper Chatsworth Formation sandstones (for example, Shale 2, Shale 3, and Lower Chatsworth Formation beds), and in other places such sandstones are lumped with the fine-grained units (for example, the Woolsey Member). In outcrop, Shale 2 comprises three "fine-grained" units within the SSFL, which join as one or two units north of the SSFL.[17] The stratigraphic separation of two of these units is as much as 275 feet (assuming a 30 degree dip), yet Shale 2 is described in one report[18] as consisting of thin interbeds of siltstone and shale and fine to medium sandstone beds locally reaching a maximum thickness of nearly 15 feet, and in another report[19] as consisting mainly of shale and siltstone beds, typically less than 1 foot thick and interbedded with fine-grained sandstone. Still another report[20] describes Shale 2 as consisting of at least two individual shale beds separated by sandstone, the total being never less than 50 to 100 feet thick. The Woolsey Member is variously described by these same reports as 200 feet thick and consisting of interbedded shales, siltstones, and sandstones, with a laterally extensive sandstone (of unspecified thickness) near the middle, or as poorly exposed interbedded shale, siltstone, and sandstone.

Other fine-grained units appear not to be lumped with thick sandstones, but are nevertheless very poorly described. These include the Upper and Lower Line Beds, Happy Valley Member, and Upper and Lower Bowl Beds. The ELV and Lot Beds in the western part of the SSFL may play a role in pump tests (described below), but no field descriptions were found. Generalizations about the lithologic makeup of fine-grained units reflects the paucity of measured sections: for example, one report characterizes fine-grained units as composed of more than 80 percent clay shale and siltstone,[21] whereas in other places those rock types are given as 50 percent.[22] No descriptions are provided of lateral variability, except for an occasional comment that individual beds may pinch out along strike. Mineralogical and textural information on siltstones, shales, and claystones is notably missing. In particular, identification of clay minerals and their proportions is critical to understanding contaminant sorption characteristics. The nature and distribution of solid organic carbon materials, also important regarding contaminant sorption, are poorly characterized. Although a number of well logs note cementation of fine-grained strata, no description is otherwise provided.

The very limited usefulness of the field descriptions of fine-grained units is in part due to generally poor exposure, but this could have been usefully rectified by trenching. Indeed, even the location of some of these units is not known with any precision, especially in respect to well locations. In addition, the issue of the role of fine-grained units in movement of groundwater, critical to the Rocketdyne hypothesis that they are important barriers to groundwater movement, is clouded by inconsistent definitions of the units and the absence of site-specific measured sections. Use of the existing data set on fine-grained units makes identification of units offset by faults suspect (discussed below). Movement of groundwater in and through these units is complicated by pinch-outs of individual beds and cut-and-fill structures (during deposition, fine-grained units commonly were cut by erosion channels that were subsequntly filled with coarser sediment, forming what are called cut-and-fill structures),[23] which could facilitate movement of groundwater through fine-grained units. Common soft-sediment deformation (complex fault and fold structures formed by slumping before the sediment was completely hardened by lithification) and cross-bedding may retard preferred water migration along bedding features, and erratic cementation also may affect water and contaminant migration. None of these is considered by groundwater flow models, nor applied to interpreting pump and other tests of hydraulic connectivity, and as a consequence the models are simplistic, and a great deal of room is created to misinterpret pump and other tests.

Fine-grained units commonly are cited as being aquitards on the basis of very low hydraulic conductivities. This property is, however, measured only on unfractured samples. That fractures in fine-grained units are avenues for circulation of groundwater is shown by iron and manganese staining of fracture surfaces, commonly reported in drill logs; such fractures also track meteoric water movement, and show that pathways through fine-grained rocks are as common as those in sandstones.[24] Studies elsewhere indicate that the presence of hydraulically active open fractures in fine-grained deposits are extremely difficulty to spot during field assessments.[25] Aquifers below clayey confining layers commonly are contaminated, indicating preferential movement of water through the aquitards in fractures, root holes, and stratigraphic windows such as cut-and-fill structures and pinchouts of aquitards.[26] Lab experiments with large (1.6 foot diameter) naturally fractured clay samples demonstrated entry and rapid flow of trichloroethylene (TCE) dense non-aqueous phase fluid (TCE; the most widespread contaminant at the SSFL) in fractures with apertures of 17 μm or larger (for scale, a typical human hair is 20 μm in diameter); this study notes that dense non-aqueous phase liquids (DNAPL) are a problem in the subsurface because they do not dissolve in water. They migrate as nonwetting liquids and commonly pool on top of clayey strata where fractures allow easy entry and provide pathways for downward DNAPL flow. Migration of contaminants in fractures is controlled by the fracture aperture, fracture network geometry, and fluid conditions.[27] Numerical simulations indicate that fractures with apertures as small as 10 μm can greatly accelerate transport of dissolved contaminants through clayey aquitards into underlying aquifers.[28] The presence of fractures in fine-grained deposits at the SSFL, and direct evidence that they have provided avenues for fluid movement, are clearly inconsistent with the Rocketdyne model of groundwater barriers, yet they receive no critical analysis in the reports, nor were they the subjects of comprehensive site characterization.

Description of Fractures

Sedimentary rocks of the SSFL and surrounding regions are intensely fractured. Joints and bedding plane fractures formed in all stratigraphic units as a consequence of unloading as the rocks were brought to the surface. Sedimentary rocks of the Cretaceous Chatsworth Formation, which makes up most of the SSFL, are gently folded—the SSFL is located on the south limb of a west-plunging syncline. This results in the strata dipping between about 20 and 30 degrees to the NW. Thus, bedding plane fractures also share those inclinations. Joints normal to bedding planes, may remain vertical or depart from vertical as the beds in which they occur are tilted, depending on the orientation of the axis of rotation within the bedding plane.[29] Because the structure of the Chatsworth Formation is relatively simple, it is possible to distinguish joints and bedding plane fractures in core samples. Interestingly, for six coreholes widely spread across the SSFL, 51% to 73% of fractures are oriented in directions inappropriate for joints or bedding planes, and fractures in another three coreholes showed no prevailing fracture orientation, thus including an unquantified fraction that are neither joints nor bedding plane fractures.[30] With the extreme range of fracture orientations recorded in the rock cores, it seems unreasonable to suppose that the preferred paths for water and contaminant migration are known—that is, vertical and horizontal.[31] This greatly complicates understanding movement of contaminated water in both the unsaturated and saturated zones, and makes the conclusion that TCE contaminants migrate directly downward from the points of their release simplistic. There is no *a priori* reason to suppose that fractures with any of a variety of orientations may not provide preferred pathways for contaminant migration and thus alter the destination of contaminants from that presently conceived.

Evidence of faulting is common in 5 of 7 coreholes that are not located in the immediate vicinity of mapped faults,[32] and is logged in many other non-cored wells also not in the immediate vicinity of mapped faults. Mapped faults of two major orientations—approximately E-W and NE-SW—occur within and adjacent to the SSFL. Principal NE-trending faults in and near the SSFL are the Shear Zone, Box Canyon, Skyline, and Santa Susana Pass.[33] Owing to poor exposure (the faults commonly occupy depressed areas concealed by surficial sediments), descriptions of the faults are poor and lacking in critical information. Indeed the locations of the faults and extent of related fracture zones is commonly not known with any precision—for example, identification of a stratigraphic unit by electric log was needed to decide which side of the Shear Zone the RD-45 well cluster is on,[34] a matter of substantial importance in assessing the hydrologic role of the Shear Zone (discussed below). Uncertainty about the exact location of the Shear Zone (and other faults) is also shown by big differences in map locations of some faults.[35]

The Shear Zone is described as a 25-50 foot wide zone of intense fracturing, with fractures spaced <1 inch apart and about parallel to the strike of the fault. "Relatively" fine-grained gouge is said to be present in many of the outcrops, but no information is given about how many fractures contain gouge and how many are free of it. Tabular bodies of gouge to >1 foot thickness, vertical and parallel to strike of the Shear Zone, are described, but their extent is not mentioned, and no description, not even grain size, is provided. In the Black Canyon exposure, the fault zone is said to consist of sandy siltstone with abundant caliche (calcium carbonate deposited from meteoric water), and "fractured rock" at least five feet wide; how much of this, if any, is gouge and what kind of rock other than siltstone is involved is not mentioned. The mode of occurrence of caliche, of importance in considering the role of faults in groundwater movement, is not mentioned. It is further stated that the fracture characteristics vary, but how is not revealed.[36] Another description indicates that caliche is common along fracture surfaces, locally 1-2 feet thick near the surface, and that gouge is present along <u>some</u> fractures. More widely spaced fractures (1-3 feet) nearly parallel to the fault trace "typically" show iron staining.[37] Other descriptions do not differ substantively, and offer no additional useful information. Missing from these accounts is description of gouge commesurate with the importance attached to it in controlling groundwater movement; indeed there appears to be no tests at all of physical and chemical properties of gouge. Whether carbonate mineralization occurs in gouge is not clear from these descriptions, but this and iron staining could be of great importance in tracking movement of water in the fault zones. Two core samples from holes not drilled in or adjacent to faults (C-7 and C-8) are described in one case as "calcite gouge" and the other, as platy with apparent calcite interlaminations,"[38] suggesting that meteoric waters have penetrated even gouge within faults. In three other coreholes, "dolomitic gouge" is logged, again suggesting penetration of gouge by groundwater.[39] Also missing is information on the extent within the fault and adjacent fracture zones of unfilled fractures. If joints provide preferred avenues for migration of water, it seems not unreasonable to expect the same of fault-related fractures.

Very limited descriptions of the Box Canyon Fault are provided in two reports.[40] A single road cut exposure indicates that the fault zone is at least 12 feet wide, consisting of closely spaced fractures and two sandy siltstone gouge zones; one is one foot thick, the other three feet thick. No other characteristics are described, and elsewhere the precise location of the fault is not known.

The Santa Susana Pass Fault Zone is identified east of the pass by displacement of Shale 2, but its location to the west, which is more relevant to issues of SSFL hydrology, is much less certain.[41] The fault zone consists of multiple subparallel fault traces (identified by polished, striated surfaces, which in places are associated with closely spaced fractures (presumably lacking polished and striated surfaces). In places fault traces are occupied by gouge to several inches thick, and caliche is found on several fault traces. Caliche typically occurs in tabular zones <4 inches thick, approximately parallel to fault traces. At several locations, caliche shows anastomozing polished surfaces, suggesting small-scale fault movement continuing after caliche mineralization of fault traces. This is further indicated by brecciation of some diabase dikes (tabular igneous rocks) after they were intruded into the fault zones. The western-most exposure of this fault zone is a 30-40 foot wide zone of multiple polished and striated surfaces, closely spaced fractures, and thin caliche zones that are parallel to the fault zone. It would be useful to know if fractures as well as fault traces are occupied by caliche or stained as a result of passage of groundwater. Farther west, in the area most relevant to the SSFL, there are no exposures of the fault zone.

A single cursory description of the Skyline Fault is provided.[42] The dip of the fault is 52-76 degrees southeast; apparent left-lateral displacement of a shale bed plus down-dip striae suggest displacement is down to the west (in which case, the fault is a thrust fault). No description of gouge or caliche, if any, is provided. The Skyline Fault as represented in 1997 extends much farther to the north than shown on more recently published maps.

East-west (E-W) faults include the Burro Flats, Coca, Tank, North, Hidden Valley, IEL, and Woolsey Canyon faults, and smaller unnamed faults. The longest of these faults in the SSFL are

Burro Flats, Coca, and North faults.[43] No site-specific description of the Burro Flats Fault, which is not artificially exposed in the SSFL, is provided. The Coca Fault, in contrast to the Shear Zone, consists of a single failure surface "associated with" 3-4 inches of gouge. A zone about 30 feet wide of fractures spaced 5-10 feet apart is approximately parallel to the fault trace; these fractures are healed and commonly strongly mineralized with iron oxide, indicating prior circulation of meteoric waters through these fractures. Locally fractures < 3 inches apart occur within 2-4 feet of the fault trace. The south-most branch of the fault (in the vicinity of Skyline Fault) lacks gouge and significant fractures. North Fault consists of several branches in a zone at least 200 feet wide. There is either no gouge or <1/4 inch of gouge on exposed failure surfaces. Map representations of this fault differ substantially.[44]

The Tank Fault is exposed by artificial cuts near its junction with Skyline Fault. It consists of 6-8 discontinuous failure surfaces in a zone about 10 feet wide. More attention has been accorded E-W faults east of the Shear Zone.[45] Two faults—the Woolsey Canyon and IEL Faults—were recognized and mapped years after a number of hydrologic studies had been reported for the area in question, and representation of the Happy Valley Fault changed substantially over time (discussed below). Unfortunately, field descriptions of the faults are not much improved over time and precise locations are mostly obscure owing to poor exposure. Most of the descriptions are based on artificial exposures (road cuts), which are necessarily limited, so full characterization of the faults within the SSFL is lacking.

The Woolsey Canyon Fault Zone is described as about 400 feet wide and consisting of fault traces with <1 inch to about 20 feet displacements. Thin gouge, consisting of anastomozing stringers <0.1 inch thick of sandy siltstone is said to be "typically" present, and fractures are "typically" not associated with the small-offset faults. The fault about 4,000 feet east of RD-53 is marked by a single trace with 3-5 inches of clay gouge, and a zone of close-spaced fractures extending at least 10 feet north of the trace. Here the gouge contains nodules and veins of caliche,[46] indicating penetration of the gouge by meteoric waters.

The IEL Fault is based on a linear drainage between wells RD-31 and the RD-43 cluster and offset of the Happy Valley Member. The only, inadequate, descriptions of the fault zone are obtained from cores of corehole C-1 because it is otherwise poorly exposed. A possible fault near RD-72 is suggested by a linear drainage and possible offset of the Happy Valley Member, is not shown on maps.[47] This, along with the IEL Fault, should be trenched to determine the presence of the RD-72 fault and the characteristics of both. The characteristics of these faults have an important bearing on Groundwater Unit designations and interpretations of the distribution of contaminants (discussed below).

The Happy Valley Fault, represented on early maps as a single trace, is now represented as a wide zone of small-displacement faults surrounding at least two fault traces with significant displacements.[48] A roadcut exposure on one of the larger fault traces shows a 3 inch to 1.5 feet wide zone with sandy silt gouge, and lacking adjacent fracturing.

SSFL SITE FEATURES AFFECTING MOVEMENT OF GROUNDWATER

General

The complex conditions of formation of the Chatsworth Formation created a highly variable section of bedded sedimentary rocks. In addition, events that modified the physical and chemical properties of the sediments accompanying and following their lithification, structural deformation during emplacement of the Chatsworth rocks in their present positions, and modifications resulting from circulation of meteoric waters through the sediments all have conspired to create a complex geohydologic system. This makes the task of understanding the behavior of contaminants released in this system daunting. The difficulty of this task is further compounded by an apparently erratic distribution of contaminants in the areas of their release, which likely affects their redistribution by infiltration, surface runoff, and in the atmosphere.

Matrix properties of the sedimentary rock types considered important in the conceptual site model for distribution of TCE are extremely variable. Hydraulic conductivities for all types range over at least 3 orders of magnitude and as much as 5 orders of magnitude.[49] Values for matrix porosity, permeability, carbonate content, and organic carbon all show wide ranges of variability.

Matrix properties of all the common rock types are restrictive of groundwater movement, and it is well-recognized that groundwater moves most efficiently at the SSFL through fractures. Bulk hydraulic conductivity that accounts for fractures is shown by packer tests to vary over 3 orders of magnitude within single wells over short stratigraphic intervals.[50] On a larger scale, many tests of hydraulic conductivity have been made on wells with large open intervals to assess the effects of fractures—resultant vertically averaged hydraulic conductivities representative of the SSFL range over 4 orders of magnitude.[51] Values of bulk permeability, also including the effects of fractures, range over 5 orders of magnitude.[52] Bulk hydraulic conductivity of close-spaced wells in well clusters vary by as much as 3 orders of magnitude.[53] This variability is not tied uniquely to any geologic feature that can be mapped or extrapolated in three dimensions with any certainty, which makes prediction of groundwater and contaminant behavior speculative at best.

Large gaps in information were noted in the descriptive sections, and substantial amounts of information are underutilized. Some unexpected responses of the system, such as very erratic and sporadic appearance of contaminants in wells, the presence of high levels of contaminants in one well and not in an adjacent well, responses to pump tests,[54] and many others may result from complex distributions of lithologies such as hard and cemented strata and variable mineralogy, that can never be known with any certainty. Considering the importance placed on fault gouge as a groundwater flow retardant, it is surprising that not a single measurement of the physical properties of this lithology is reported in the literature I reviewed. Indicators of past groundwater flow, such as caliche, iron oxide, and clay fracture filling and fracture staining have not been analyzed to show what, if any, fracture groups (joints, bedding planes, or the more abundant stress fractures other than faults) have been preferentially used by flowing water, or how they may affect current and future groundwater movement and contaminant distribution. This has a direct bearing on the current model of TCE DNAPL distribution.

Role of Fractures (unassociated with faults)

Fractures, including joints, bedding plane fractures, and stress fractures not corresponding in orientation to either of the other categories (recognized in core samples), are well-recognized to represent the principal conduits for movement of groundwater in the Chatsworth Formation, based on very low matrix permeabilities, porosities, and hydraulic conductivities of all principal rock types, and by direct observations during well drilling. It is also well-established by field examination that most joints are discontinuous, and thus provide complex pathways for movement of groundwater.[55]

Characterizing the SSFL on the basis of joint patterns measured in the field,[56] however, has limited usefulness because simplifying assumptions required by models of groundwater and contaminant behavior cannot rigorously be made. One study, by the U.S. Geological Survey, concluded that there is little correlation between observed fracture systems and highly permeable zones; that major fractures may vary greatly in effective hydraulic aperture over very short distances; the orientation of highly permeable zones may be quite different from the observed strike and dip of the individual fracture segments composing a fracture zone; and irregular fracture systems cannot be approximated by assuming planar fractures of uniform aperture.[57]

Role of Faults

Faults and Associated Fractures

The current assertion by the site operator that faults in the SSFL and nearby areas are aquitards is surprising in view of the also widely held belief by Rocketdyne consultants that fractures are the principal conduits for groundwater flow in the Chatsworth Formation. This is based on the belief (not supported by any measurements) that fault gouge impedes groundwater flow and that gouge is everywhere present in fault zones (not supported by descriptions of the faults). Yet, every major fault in and near the SSFL is described as a zone comprising not only fault traces but many fractures. The fault zones are described as only sporadically gouge-filled and none of the accompanying fractures is occupied by gouge. Moreover, as mentioned above, some gouges are themselves occupied by caliche stringers or carbonate cement or nodules, which indicate transmission of meteoric waters through the gouge. Furthermore, most fault zones are described as having tabular bodies of caliche parallel to fault traces, again showing migration of meteoric waters in the fault zones—these are not merely surficial, but are described in well samples to hundreds of feet depth. There can be little doubt that the various lithologic variants, including gouge, in fault zones make water flow in the zones complex, like that in all fractures of the Chatsworth Formation, but that does not make them universal aquitards.

Faults and Water Supply

It has been noted that historic well test data indicate that the most transmissive fracture zones are the east-west zones along which wells WS-4A, WS-12, and WS-13 (North Fault) are located, and the northeast-southwest zone along which well WS-5 is located (Shear Zone).[58] However, in summarizing the hydrogeology of the SSFL, a more recently published report states that wells along major structural features did not show a preferential response to shutdown and restart of the pumping wells: "In fact the only wells in which a response was obvious were those located at distance from any known structural feature or observed linear feature."[59] As shown in Table 1, this statement significantly distorts the facts reported in Table 4 of the 1997 Hydraulic Communications Report. Of the 17 wells (excluding pumped wells) that responded rapidly to cessation and/or restart of the pumped wells, 9 (53%) are on or in close proximity to major faults, and 8 (47%) are distant from mapped faults (of these 8 wells, half are in close proximity to the pumped well RD-63). More damning is that of 94 wells that did not respond rapidly to either cessation or restart of pumping, 34 (36%) are on or in close proximity to major faults, and 60 (64%) are distant from mapped faults. This assessment is based on Fig. 2-9, Near-Surface Groundwater Study, which shows faults not recognized in the 2000 report, and extensions of the North Fault, which includes two additional clusters that would not be counted as in close proximity to faults if the 2000 maps were used.

Features of Specific Faults

Shear Zone

Evidence used to support the Shear Zone as an aquitard includes offset of water levels across the fault zone, variously described as "more than 200 feet" to 300 to 400 feet for the same set of wells.[60] A big problem with this interpretation is the very limited data available from wells on the west side of the Shear Zone, and the offset relies on a selected, but not fully representative, data set on water levels in wells on the east side of the Shear Zone—a more representative set of wells shows offsets ranging from -92 feet (two wells on the east side of the Shear Zone have water levels lower than those on the west side) to 230 feet (2 wells selected by MWH for comparison) (Table 2).[61] The large degrees of freedom allowed by limited data are illustrated in Exhibit 1, which represents an estimate of historic water level changes in the central part of the SSFL. The large water level depression is due to pumping water supply wells, which reduced water levels by as much as 500 feet in the 1950s. Pumping ceased for about 20 years from 1963 to 1984,[62] so Exhibit 1 represents aggregate water level changes through 1997. The drawdown contours loop around WS-8 in the west, extend eastward across the Shear Zone to loop around WS-5 and RD-2,[63] then northward to loop around WS-14 and WS-4A on North Fault, looping westward to encompass WS-12 and WS-13, then back to WS-8. There are no wells to constrain the contours from crossing the Shear Zone south of WS-5, nor is there any requirement that the 100 to 200 foot contours be so closely controlled by well WS-4a. An alternative representation would be northward extension of all contours on the west side of the Shear Zone north of WS-5, which might at least partially explain the water level drop across the Shear Zone near WS-14 and RD-37. Representation of the water level drop as vertical across the Shear Zone (e.g. Conceptual Site Model, Fig. 4.6) is an assumption, not a fact.

It is further argued that maintenance of the water level offset of over 200 feet across the Shear Zone would require a significant reduction in hydraulic conductivity in the Shear Zone. Hydraulic conductivities in wells on opposite sides of the Shear Zone, are in the 10^{-4} to 10^{-5} cm/sec range, requiring a hydraulic conductivity on the order of 10^{-7} cm/sec in the Shear Zone. The hydraulic conductivity of the Shear Zone has not been estimated, but that of WS-5, which is very close to the Shear Zone or on it is estimated to be 3.1 X 10^{-4} cm/sec.[64] It is noteworthy that estimates of hydraulic conductivities for wells on or immediately adjacent to other faults also may be relatively high (RD-53, Woolsey Canyon Fault, 6.6 X 10^{-4} cm/sec; RD-1, Happy Valley Fault, 1.0-1.2 X 10^{-4} cm/sec; RD-31, IEL Fault, 5.5 X 10^{-4} cm/sec; and adjacent wells in clusters on faults may show wide variation: RD-5 cluster on the Burro Flats Fault, A, 2.0-2.5 X 10^{-4}, B, 1.1 X 10^{-5} to 7.9 X 10^{-6}, and C, 1.3-1.7 X 10^{-5} cm/sec.[64]

The RD-45 well cluster, now considered to be on the west side of the Shear Zone, shows an interesting response between 1994 and 2001 to shutdown and startup of pumping of well WS-5, on the east side of the Shear Zone. RD-45A is interpreted to be open from the Middle Sage Member across the Lower Line Bed into the Lower Sage Member, RD-45B is interpreted to be open only in the Lower Sage Member, and RD-45C is interpreted to be open within and below the Woolsey Member(?).[65] It should be noted that lithologic logs of these wells indicate that the Lower Line Bed is allowable in 45A and C, but not in B, and that identification of the Woolsey Member(?) is not allowable by the lithologic log of 45C, that is, the material logged at the appropriate depth in 45C does not resemble descriptions of the Woolsey Member. Other reports[66] identify this level of 45C as the Happy Valley Member, which also does not resemble the well log. Exhibit 2 shows the long-term hydrographs for wells WS-5 and the RD-45 cluster. RD-45C practically duplicates the water level pattern of WS-5, whereas RD-45A and B do not respond to shutdown or pumping of WS-5. It is noteworthy that shutdown of WS-5 in October

2000 resulted in a makeup of the 80 foot difference in water levels between RD-45A, B and RD-45C. Table 4 of the 1997 Hydraulic Communications report shows all three wells of the RD-45 cluster responding rapidly to well shutdown and restart, but hydrographs show that RD-45A and B are responding to well WS-6, whereas RD-45C is responding to well WS-5. This behavior is perplexing, but it is difficult to see how, at least at the screen level of RD-45C, the Shear Zone can be acting as an aquitard.

The lack of response of WS-14 to a 90-day pump test of RD-73, located on opposite sides of the Shear Zone is further taken as evidence that the Shear Zone is an aquitard.[67] This may well be the case, but until WS-14 is precisely located with respect to the full extent of the Shear Zone and RD-73 is precisely located with respect to the IEL Fault, this will remain uncertain. That conditions in the vicinity of WS-14 are complex is shown by the RD-38 cluster, which is closer to WS-14 than is RD-73. RD-38A did not respond to a pump test of the adjacent RD-38B (see Exhibit 3). This unexpected result is explained by the presence of a hypothetical gouge zone, which was not observed on video logs, between the two wells.[68] To compound the uncertainties, the log of RD-53, located <u>in</u> the Woolsey Canyon Fault Zone that separates RD-73 and the RD-38 cluster, does not mention any fault-related features.[69]

Contours representing drawdown from the RD-73 pump test are shown in Exhibit 4. The contours are interpreted to indicate an apparent rise in hydraulic conductivity about parallel to strike of the Chatsworth Formation, and that "drawdown appears to truncate at the shear zone to the west, and at the Happy Valley Fault to the south."[70] This is based solely on the behavior of WS-14 (discussed in the previous paragraph) because no other wells west of the Shear Zone were monitored, and there is no control for designating the relationship of drawdown to the Happy Valley Fault. Representation of the contours as crossing the subsequently recognized IEL and Woolsey Canyon Faults without deflection does not prove that they are not aquitards, but rather there is no control for the location of the contours—that has not changed since the contours were drawn or the faults were mapped. A possible E-W fault passes very close to RD-72 and RD-32 between the Woolsey Canyon and IEL faults.[71] The presence of a fault in this area is supported by the video log of RD-32,[72] which logs a number of broken zones; a log of RD-72 is not yet available.

Coca Fault

Evidence adduced to support the conclusion that the Coca Fault is an aquitard is extremely limited. It is stated that "Drawdown resulting from pumping in the central portion of SSFL appears to terminate at the Coca Fault..."[73] There is no basis for this as there are no data near the Coca Fault, certainly on the north side of the fault where the drawdown depression exists (see Exhibit 1--the Coca Fault could not be represented on this map because of its poor quality, but the zero contour of the drawdown depression would cross the west end of the fault), and it appears that most or all of the few data points on the south side of the fault are on the fault and are so-listed in the endnote reference 62, Table 2.9). The hydraulic conductivity of the Coca Fault, or its immediate environs, could not be determined because the wells located in or immediately adjacent to the fault did not yield sufficient water for testing. Accordingly, the fault's hydraulic conductivity is noted as $<1.0 \times 10^{-6}$ cm/sec. Well WS-10, cited in Table 2.9 of reference 62 as being on the Coca Fault, is not shown on any map to which I have had access. A number of other wells in both Sandstone 1 (RD-36A, 36C, just east of the Shear Zone, RD-40, adjacent to the Skyline Fault, and RD-55B, south of the Coca Fault west of its termination) and Sandstone 2 (RD-19, 21, 22, 23, 33A, 51B, 54A, 54B, and 60, all distant from mapped faults except 51B, which is possibly on North Fault) also failed to yield sufficient water for hydraulic conductivity testing and are arbitrarily assigned the same low conductivity value notwithstanding much higher conductivities in nearby wells.[74] It is possible that wells located on the Coca Fault are poor water producers because the fault, unlike the Shear Zone and other faults, is not associated with intensively fractured rocks (see Description of Faults, above). This holds also for the Skyline and Tank Faults, for which there is no supporting evidence that they are aquitards.

North Fault

There are very limited data available for assessing North Fault as an aquitard, and the precise locations of the main strand and subsidiary strands appears to be unknown. It is noted, however, that wells WS-12 and WS-4A, located on North Fault, respond to pumpage of WS-13, which is close to the map representation of North Fault. Well WS-9B, located south of North Fault, but closer to WS-13 than is WS-12, does not respond to pumping of WS-13. WS-4A is less responsive than WS-12, but the effect of WS-13 pumping may be dampened by the very prompt response of WS-4A to precipitation.[75] This behavior suggests that North Fault is a conduit for transmission of water, but potential effects of pumping wells on the fault on wells located distant from the fault is not clear. Rates of response through the different kinds of fracture systems (clusters of steep fractures in the fault zone) and discontinuous, complex joint and stress fracture systems may cloud pump testing results. This is consistent with the behavior of wells WS-4A, WS-12, and WS-14 in the 1996 hydraulic communications study.[76] These wells did not respond immediately to shutdown of WS-6, but water levels in those wells (see Exhibit 3 for well locations) began to rise five to seven days later. This was true also of WS-13, but it could have been responding to RD-9 as well as WS-6. The drawdown pattern shown in Exhibit 1 also supports North Fault as a groundwater conduit.

Woolsey Canyon Fault Zone

There is very limited information available to support the assertion that the Woolsey Canyon Fault Zone is an aquitard.[77] A pump test run on RD-38B recorded no response in adjacent RD-38A,[78] both located a short distance downslope from the outcrop of the Woolsey Canyon Member and a short distance north of the Woolsey Canyon Fault Zone.[79] This is interpreted to mean that there is "...a significant aquitard between...225...and 235 feet that is believed to likely be associated with fine-grained gouge produced by the Woolsey Canyon Fault." However, there is no support for this in the video log although such features are observed in video logs of other wells. It is also stated that "Moreover, RD-38A is slightly closer to the mapped Woolsey Canyon Fault than is RD-38B."[79] This discussion suggests that the precise location of the Woolsey Canyon Fault is not known, as might be questioned from the fact that the RD-53 well log does not mention the presence of fault indicators even though the well is located within the mapped fault zone. It is further stated[79] that "The fact that faults are reported in parts of the borehole [RD-38B] in which groundwater elevations show no evidence for the presence of an aquitard is probably the result of the variability of fine-grained gouge characteristics associated with faults at the SSFL." This is to say that faults are aquitards in some places and not others, which is likely the case, but to invoke fault features where they are not observed as an explanation for pump test results is another matter.

The only evidence adduced to support the claim that the Woolsey Canyon Fault Zone is an aquitard is a large difference in TCE concentration in well RD-72 (6,500 ppb 11/00), south of the Woolsey Canyon Fault Zone and RD-53 (140 ppb 8/00), mapped as within the fault zone. Other wells north of the fault zone (RD-36B, C) also have lower TCE concentrations (11/00) than RD-

72. Among the problems with this interpretation is the lack of information of where RD-72 may be located with respect to a possible fault in close proximity to RD-72 (see Exhibit 4). In addition, RD-72 has a history of sporadic TCE detects, at times showing no contamination.[80] As shown in Exhibit 4, drawdown contours for a pump test of RD-73, and in Exhibit 5, water level contours for Groundwater Unit 1a as recognized in 2000, the contours pay no attention to faults, including the Woolsey Canyon Fault Zone, the IEL Fault, and the possible fault near RE-72, not recognized at that time. However, no new data that would discredit the interpretations represented by the contours have been made available subsequently. Thus, the role of the Woolsey Canyon Fault Zone as an aquitard is putative.

IEL Fault

Certain wells on the south side of the IEL Fault (HAR-16 and RD-73) show no significant differences in water levels from those on the north side of the fault (RD-35A, RD-35B, and RD-72). Nonetheless, the IEL Fault is considered to be an aquitard because all the wells are screened in the same stratigraphic unit (Canyon Member), the topography between the IEL and Woolsey Canyon Faults is relatively flat, and the area is outside the influence of groundwater extraction wells. It is not altogether clear why this qualifies the IEL Fault as an aquitard. If the direction of groundwater flow is controlled by bedding of the stratigraphic units, their orientation in this immediate area is such that flow should be intercepted by the IEL Fault, and water levels should vary if the fault is an aquitard.[81] The location of RD-73 with respect to the IEL Fault needs to be clarified, as does the location of RD-72 with respect to a possible unmapped fault before a clear case is made for the role of the IEL Fault. Moreover, water levels in HAR-1, 24, and 25, all south of the IEL fault and east of the Shear Zone, need to be factored into this argument because all have similar lithologic logs and reach approximately the same depths as HAR-16.[82]

Representations of drawdown contours from a pump test of RD-73 (Exhibit 4) and of water levels in Groundwater Unit 1a (Exhibit 5) do not show any effect of the then-unrecognized IEL Fault, but no new data have been provided to show the contours to be wrong.

The presence of perchlorate (measured February 2000) in the wells south of the IEL Fault (including HAR-1, 16, 24, 25, and RD-73) but not in RD-35A north of the fault is taken as suggestive evidence that the fault is an aquitard, but the possibility of slow migration such that perchlorate has not yet reached RD-35A is considered, probably because TCE concentrations in wells on both sides of the fault are similar.[83]

The behavior of TCE in corehole C1, at south edge of the IEL Fault, and in well RD-35B north of the Fault suggests significant problems for the IEL Fault as an aquitard.[84] Although C1 is shown as slightly south of the IEL Fault, it is believed to intersect the fault at a shallow depth and to remain in the fault zone to its total depth (TD) of 600 feet, which the core log supports. RD-35B is considered to be farther from the TCE release area because, in contrast to C1, there is no TCE mass in the unsaturated zone sampled by RD-35B. However, the maximum concentrations of TCE in C1 are only slightly higher than those in RD-35B, leading to the conclusion that "Migration of TCE from the infiltration location (near C1) to RD-35B likely occurred through the fracture network," that is, across the IEL Fault. "RD-35B is located down-dip of C1 such that the interbedded unit found 145 feet bgs in C1 that contains the maximum TCE concentrations for this hole correlates with the interbedded zone at 295 feet bgs in RD-35B when the apparent angle of bedding is accounted for. However, TCE concentrations in this bed at RD-35B were non-detect, suggesting that lateral TCE migration could not have been controlled by bedding planes alone, and that TCE migration readily occurs across beds." Inasmuch as "interbedded" is defined (p. 18) as thinly bedded siltstone with minor interbeds of sandstone and shale, this means that TCE migration is not impeded by fine-grained units. Special propensities of TCE DNAPL are called upon to explain the deep penetration of TCE in all of the coreholes: "The deep vertical penetration of TCE at both RD-35B and C1 as well as the other coreholes at the site shows a strong propensity for TCE DNAPL to migrate vertically across and through beds, even though there are strong contrasts in rock matrix properties and fracture properties between the different lithologies." Since core samples represent lateral conditions for only a few inches, this conclusion seems somewhat far-reaching. Because the dominant fractures logged in the coreholes dip less than 70 degrees, substantial lateral flow likely occurs, and mass balances are simply speculation based on very incomplete sampling and poor records of contaminant inputs. It is noted, however, that despite the postulated "drillhole-like" migration of TCE DNAPL, "this does not exclude migration of high TCE concentrations by groundwater flow from C1 to RD-35B over the past 50 years." Which means that the IEL Fault is not an aquitard.

Happy Valley Fault

Description of the Happy Valley Fault reveals that the precise location of the fault zone is not known, and that the area around the mapped fault zone is more broken by faulting than represented by the map,[85] making it difficult, along with the paucity of nearby wells, to judge the claim that the Happy Valley Fault Zone is an aquitard. Water levels in wells north of the Happy Valley Fault Zone (HAR-1, 16, 24, and 25) are approximately 140 feet higher than wells south of the fault (RD-1, 10).[86] Both RD-1 and RD-10, which occupy the same positions at the south edge of the mapped Happy Valley Fault Zone as WS-5, are affected by pumping of WS-5. In the 1996 site-wide pump test, RD-1 and WS-5 were both pumped, and both affected RD-10. For this test, HAR-16 also was pumped, and hydrographs of the other wells used for water level comparisons across the Happy Valley Fault Zone can be read as responding to pumping of either HAR-16 or WS-5 or both.[87] Pumping of RD-1 was stopped in October 2000 with the result that water levels in RD-10 rose, but those in HAR-1 did not.[88] Whether this is a meaningful comparison is open to question because HAR-1 is located very close to, and possibly within, the Shear Zone, and its lithologic log is quite different from those of RD-1 and RD-10. The water level comparisons are complicated by the role, if any, of the fine-grained Happy Valley Member because the wells north of the fault zone are screened in the Canyon Member and those to the south are screened in the Bowl Member. It should be noted that the lithologic logs of WS-5, RD-1, and RD-10 are all notably deficient.

Water Flow in Faults

As mentioned above, the close association of faults (demonstrable movement) with fractures along which movement is not demonstrable, and along which gouge is not present, the non-universal distribution of gouge in fault fractures, and abundant evidence of water flow in fault zones, and even in gouge, represented by caliche and fracture-wall staining clearly show that fault zones transmit water. Yet, reports by company contractors on the SSFL widely hold the view that "Available data indicate that the faults are not preferential flow paths and do not provide a mechanism for rapid and/or distant solute transport. The presence of fine-grained gouge created within the fault is believed to be responsible for their reduced permeability."[89] "The available site data do not support the existence of through-going structural features that could act as preferred groundwater flow pathways."[90] "Accordingly, the major faults at SSFL are not likely to be preferred, through-going groundwater flow pathways."[91] This belief is surprising considering the equally widely held view that the principal flow paths of groundwater at the SSFL are fractures.

A number of statements based on the assumption that faults are aquitards seem open to obvious alternative interpretation, for example: "Groundwater often emerges as springs or seeps within the faults and at locations where fine-grained units intersect faults;"[92] "The presence of a spring along the Shear Zone Outcrop 2 suggests that, as within the SSFL, the structure also acts as an aquitard in offsite areas."[93] The most straight-forward interpretation of these observations is that the faults are conduits for groundwater flow, a widely held view for many faults in other parts of the arid and semi-arid western U.S. The faults are, after all, fracture zones penetrating rocks that have very low matrix permeability and would be expected to act as preferential flow paths. Fault zones as preferential groundwater flow paths (competing with other fractures which also are preferential flow pathways) that extend for some distance might interfere with lateral groundwater flow controlled by bedding or bedding plane fractures simply by intercepting such flow and moving it along steeper pathways. The fault zones, however, provide pathways for contaminant migration off site as do other fracture systems at the SSFL. It is not as though these conduits are open pipes, however. Actual pathways in the fault zones may be complex, with flow diverted from fracture to fracture by caliche plugging, sporadic presence of gouge, and younger tectonic movements.

Role of Fine-Grained Units

The near-universal claim by Rocketdyne contractors that fine-grained units act as aquitards is poorly supported by deficiencies in description of fine-grained units, as outlined above, which indicates a high level of uncertainty about their properties at any specific location; lack of information on the distribution of facies included within mapped units, such as sandstone, siltstone, and claystone, that might have highly variable hydrologic properties; and the near complete absence of field-based data on such features as fracture staining and caliche fracture fill. Since the fine-grained rocks also are fractured, a broad-brush assignment of such units as aquitards is no more appropriate than assignment of all sandstones as aquitards based on their low matrix hydraulic conductivities.

As described below, principal lines of support for fine-grained units acting as aquitards include significant changes in water level across such units (Shale-2, Upper and Lower Line Beds, the Woolsey Member, the Happy Valley Member and Upper and Lower Bowl Beds), significant differences in hydraulic responses to pump tests across fine-grained units (Shale 2, Upper Line Bed), control of spring outlets (Shale-2), differences in VOC (volatile organic compound) concentrations across such units (Lower Line Bed, Woolsey Member, Happy Valley Member and Lower Bowl Bed).[94] It should be noted that these tests relate mostly to specific well locations and thus test the effect of fine-grained units only in localized areas, not throughout their extent. It should also be noted that the quality of these lines of evidence ranges from good to poor.

Features of Specific Stratigraphic Units

Shale-2

Exhibit 6 illustrates the case that Shale-2 acts as an aquitard between Sandstones-1 and -2 (old designations), as seen in water levels in wells RD-4, WS-9, HAR-19, and HAR-20 screened in Sandstone-1, and HAR-21, HAR-6, HAR-5, and RD-15 screened in Sandstone-2. Wells RD-4 and WS-9 are pumped wells with water levels governed by long-term extraction. Wells screened in Sandstone-2 are about 200 to 300 feet higher than those screened in Sandstone-1. It should be noted that the section in Exhibit 6 is viewed toward the south, contrary to normal practice.[95] The section does not position HAR-20 and HAR-21 consistently with the rather complex representation of Shale-2 in Fig. 2-9 of the Near-Surface Groundwater study. In addition, the well distribution is a shotgun pattern, but no information is given on how the wells were projected to the section line. It also is not clear why other wells in the area were not used to assess the water level differences—wells not used that might represent Sandstone-1 conditions include RD-49A, RD-49B, RD-49C, and C-5, and those that might represent Sandstone-2 conditions, but which were not used, include HAR-22, HAR-23, and RD-16.

An unassessed alternative to the interpretation that Shale-2 in this particular area is acting as an aquitard is shown by the dashed line drawn in on the section line of Exhibit 6. This is meant to indicate the possibility that the water levels in HAR-19 and HAR-20 are on the side of a drawdown cone produced by pumping of RD-4 and WS-9. The drawdown cone could intersect the ground surface east of the wells screened in Sandstone-2 and thus not have affected their water levels.

An additional test of Shale-2 as an aquitard is based on the site-wide pump test in 1996. It is stated "In the central part of the SSFL, extraction wells are all screened in Sandstone-1. After groundwater extraction was stopped, groundwater levels in most of the wells screened in Sandstone-1 increased. In contrast, groundwater levels in most of the wells screened above Shale-2 within Sandstone-2 continued their seasonal decline after extraction stopped."[96] In fact, Table 4 of the Hydraulic Communication study shows that of 32 wells in the central (Sandstone-1) and western (Sandstone-2) areas, 14 Sandstone-1 wells (44%) and 18 Sandstone-2 wells (56%) showed continued water level decline with no response to either shutdown or startup; of 4 wells in these areas, 1 Sandstone-1 well (25%) and 3 Sandstone-2 wells (75%) showed no apparent trends and no response to shutdown or startup.[97] This does not support the claim made for Shale-2 as an area-wide aquitard.

A sound case for at least local aquitard behavior of Shale-2 is emergence of a spring about 120 feet downstream from a contact between Sandstone-2 over Shale-2, with a 35-40 degree dip.[98] It would be useful to have at least a minimal description of the lithology of Shale-2 at that particular locality, as well as the precise location with respect to the Shear Zone.

Lot Bed, ELV Member

A 47-day pump test of well RD-63 with monitoring of 8 surrounding wells from April 25 to June 11, 1996[99] may have provided information on the then-unrecognized fine-grained Lot Bed and ELV Member within Sandstone-2 stratigraphically above Shale-2. The test was done as a distance-drawdown test, but, depending on screened intervals, Wells RD-17, RD-18, RD-19, and RD-27 might have been affected by the presence of the fine-grained units, and perhaps dampen the great apparent variability in hydraulic conductivities of Sandstone-2.

Upper Line Bed

Support for the Upper Line Bed being an aquitard is found in the 150 foot difference in hydraulic head of RD-39A and RD-39B. RD-39A is screened solely in the Upper Sage Member and RD-39B solely in the Middle Sage Member. The Upper and Middle Sage Members are separated by the Upper Line Bed. A pump test of RD-39B did not affect the water level in RD-

39A, lending further support to the Upper Line Bed being an aquitard.[100] Since RD-39A is the only well screened solely in the Upper Sage, this provides only a very skimpy basis for assessing the broader role of the Upper Line Bed; moreover, there are only two wells, one periodically dry, screened solely in the Middle Sage (RD-39B and RD-36A). Because of the proximity of RD-39A and B to the Shear Zone, more confirmatory evidence is needed to assess the role of the Upper Line Bed. The pump test may or may not be significant, considering the similar behavior of RD-38A and RD-38B and the lack of tangible evidence of separation by an aquitard (described in connection with the Woolsey Canyon Fault Zone above), and the behavior of the Lower Line Bed described below.

Lower Line Bed

Evidence adduced to support the Lower Line Bed as an aquitard includes comparison of water levels in RD-36A and RD-39B, open solely in the Middle Sage Member above the Lower Line Bed with that in RD-36C, which is screened solely in the Lower Sage Member.[101] It is stated that " "...groundwater levels in the Middle Sage Member (at RD-39B) are approximately 45 feet lower than the groundwater levels in wells screened beneath the Lower Line Bed within the Lower Sage Member (at RD-36C)." In addition, the water level in the Middle Sage Member at RD-39B, which is open in and slightly below the Lower Line Bed is 113 feet lower than that in RD-36B. If the Lower Line Bed serves as an aquitard, the reverse relations in water levels would be expected. This also indicates at least a 70 foot head difference within the Lower Sage Member between close-spaced wells.

It is further pointed out that TCE concentrations in wells screened in the Middle Sage Member are very low to non-detect, whereas those screened in the Lower Sage Member north of the Woolsey Canyon Fault Zone have consistently been in 10s of μg/L at RD-36B and OS-24 or 100s of μg/L at RD-36C.[102] Since OS-24 is open through the Lower Line Bed, it is not clear how the TCE distribution bears on the Lower Line Bed being an aquitard. Considering the conclusions reached on TCE behavior in C1 and well RD-35B (see discussion under role of the IEL Fault), little confidence can be placed in variations of TCE across fine-grained units or faults.

Woolsey Canyon Member

Two wells (RD-66 and RD-71) are open in the Woolsey Canyon Member and the underlying Canyon Member. Water levels in these wells are 160 to 230 feet lower than those in wells (RD-36B, open in the Lower Line Bed and Lower Sage Member, which overlies the Woolsey Canyon Member, and RD-38A, open solely in the Lower Sage Member), which is interpreted to show that the Woolsey Canyon Member is an aquitard (see Exhibit 7 for diagrammatic representation of well open intervals with respect to stratigraphy). Water levels identical to those in RD-66 and RD-71 are found in wells open solely to the Woolsey Canyon Member (RD-36D) and open to the Lower Sage and Woolsey Canyon Members (RD-38B).[103] Problems that arise with this interpretation include the potential influence of the Woolsey Canyon Fault Zone on which at least one of the wells (RD-66) is located. If the Woolsey Canyon Member is an aquitard, it is difficult to understand why the water level in RD-38B, open to the Lower Sage Member and the upper part of the Woolsey Canyon Member, is the same as water levels in RD-66 and RD-71, open to the Woolsey Canyon Member and the underlying Canyon Member. Water levels interpreted to represent the Lower Sage Member indicate hydraulic head differences of 70 to 230 feet over short distances.

West of the Shear Zone, wells C3, RD-45A, and RD-45B are located within the Lower Sage Member, stratigraphically above the Woolsey Canyon Member. A section between 585 and 655 feet depth in RD-45C is tentatively interpreted to represent the Woolsey Canyon Member (note that this earlier was interpreted to represent the Happy Valley Member, but the log of RD-45C for that interval does not resemble descriptions of either the Woolsey Canyon or Happy Valley Members; identification of the Lower Sage Member in C3, RD-45A, and 45B also has difficulties because of uncertain location of the Lower Line Bed—see discussion of Shear Zone). The water level in RD-45C, thought to be open below the top of the Woolsey Canyon Member was at the time of the measurements about 80 feet lower than that of wells C3, RD-45A, and RD-45B.[104] As previously discussed, this difference was made up with the shutdown of WS-5 in 2000 (Exhibit 2).

Happy Valley Member, Upper and Lower Bowl Beds

There are essentially no data suitable to assess the possible roles of these fine-grained units as aquitards. The wells cited (RD-43 cluster and RD-32) for assessing the role of the Happy Valley Member differ in surface elevation by an amount comparable to differences in water levels. Moreover, the RD-43 cluster is likely on the IEL Fault, and RD-32 is located on a possible, unmapped fault that also passes through RD-72. There are no data to assess the role of the Bowl Beds. It is stated[105] that "Based on the characteristics of other fine-grained units and the limited data presented above, it is expected that both the Happy Valley Member and the Upper and Lower Bowl Beds significantly influence groundwater flow and subsequently [sic], solute transport." Considering the paucity of descriptive information on these units, and the tenuous evidence to support such a general conclusion, it is better to say that the role of these units in site hydrology and the distribution of contaminants is not known.

DISTRIBUTION OF PERCHLORATE

To clarify issues with the distribution and redistribution of perchlorate at and near the SSFL, tabulated data[106] on measured concentrations of perchlorate in various media are recast to show the variability of perchlorate in surface media and temporally in the principal areas of release (Building 359 and Happy Valley) and in surface water redistribution. Perchlorate concentrations in surface water within and runoff from the principal areas of perchlorate release are tabulated to show variability both in area and in time within the areas of release (Table 3), and in runoff outside the area of release (Table 4). Perchlorate in soils (Tables 5-6) and soil leachates (Tables 7-8) are recast to show lateral variability (same depth or small depth range, different times of measurement) and vertical variability (same date of measurement, different depths) for the Building 359 RFI (Tables 5, 7), and the Happy Valley RFI (Tables 6, 8). Note that same-date vertical sampling is weak.

Perchlorate in surface water in the Building 359 area (Table 3) varies over approximately two orders of magnitude, and includes 24 percent non-detects. Perchlorate in surface water in the Happy Valley area (Table 3) varies over approximately two orders of magnitude, and includes 23 percent non-detects. Thus, surface waters in the two principal areas of release that may infiltrate to groundwater, run off the release areas, or evaporate, have highly variable concentrations of perchlorate. Perchlorate in runoff outside of the areas of release at the Happy Valley outfall HV-1 (Table 4) varies over approximately one order of magnitude, and includes 27 percent non-detects, reflecting the temporal and spatial variability in the source area.

Perchlorate in soil samples from the Building 359 area (Table 5) show a lateral variability over a small depth interval of approximately three orders of magnitude with 48 percent non-detects, and a vertical variability over about 15 to 24 feet of approximately two orders of magnitude with zero to 71 percent non-detects for small samples. Perchlorate variability in soils from the Happy Valley area (Table 6) show lateral variability over approximately two orders of magnitude with 61 percent non-detects, and vertical variability over about 0.2 feet of approximately one order of magnitude with 25 percent non-detects. This variability may reflect spatial and temporal variations in input, the efficacy of local infiltration pathways, or losses to surface water.

Perchlorate in soil leachate samples from the Building 359 area (Table 7) show a lateral variability of about three orders of magnitude with 6 percent non-detects, and a vertical variability of about one to two orders of magnitude with 25 to 70 percent non-detects. Perchlorate variability in soil leachates from the Happy Valley area (Table 8) show lateral variability over approximately two orders of magnitude with 43 percent non-detects, and vertical variability over approximately two orders of magnitude with 21 percent non-detects. This variability may reflect spatial and temporal variations in input, the efficacy of local infiltration pathways, or losses to surface water.

Although sampling frequency is commonly poor, perchlorate in near-surface groundwater[107] also is erratic and individual measuring stations report concentrations ranging over one to three orders of magnitude, with varying percentages of non-detects. Better sampling frequency is available for Chatsworth groundwater monitoring. Six wells (HAR-25, RD-01, RD-10, RD-21, RD-47, and RD-54A, with 5 to 15 measurements), show erratic results with values ranging from a factor of two to as much as two orders of magnitude. Other wells (e.g., HAR-01, HAR-16, HAR-24 with 5 to 11 measurements) consistently showed positive values ranging at most by a factor of 3.[108] The somewhat lower variability of perchlorate in well samples may reflect sampling of larger intervals.

Samples from 35 offsite wells[109] report only a single positive perchlorate value for Chatsworth Formation groundwater (in RD-59A). The sampling frequency generally is large—an average of 5 samples, ranging from 1 to 10, over 1 to 5 years. Five wells (OS-9, OS-17, and the RD-59 cluster) were sampled more frequently (as many as 52 samples from OS-9 over two months) mainly because of putative results. The first sample taken from RD-59A (8/98) reported a small positive value for perchlorate, but 21 following samples through 8/03 were below detection, as were 12 samples from RD-59B, and 11 from RD-59C.

In May 2003, the DTSC reported two samples from OS-9 with high perchlorate values (140 and 150 μg/L), and followed this in June with four additional samples, two of which were below detection, and the remaining two reported 36 and 39 μg/L perchlorate. This precipitated a study reporting results of 171 samples collected from 79 locations over a distance of about 3 miles starting in northern SSFL and following the drainage along which OS-9 is located. No detectable perchlorate was found, with the possible exception of one onsite sample, from 140 sediment leachate samples, 14 surface water samples, 15 spring/seep samples and 2 rock chip samples. MWH concludes from these findings that no perchlorate has been transported offsite via the surface water pathway within or groundwater pathway to the Northern Drainage.[110] The question of the positive values reported by DTSC, however, remains unresolved. Considering that even in the areas of principal perchlorate use, leachate non-detections range from 25 to 70 percent and this is likely to increase with distance of transport, these conclusions appear over-stated. Furthermore, considering that perchlorate use took place dominantly in the 1950s and 1960s and perchlorate compounds are highly soluble, locations distant from the source and along active drainages would appear to be the most susceptible to flushing of the contaminants. The groundwater samples likely provide more reliable measures, but the samples obtained are essentially spot samples in time and subject to a high probability for non-detection.

Reports of perchlorate in shallow groundwater in Simi Valley are discounted by Rocketdyne as having been derived from the SSFL[111] on the grounds that perchlorate is detected sporadically at low concentrations at several locations "throughout" Simi Valley. Surface and subsurface pathways to the SSFL are said to be "incomplete," which apparently means there are no detections of perchlorate between Simi Valley and the SSFL (with the exception of OS-9). On these bases, it is suggested by Rocketdyne that the Simi Valley values are either false readings or are low-level sporadic detects from past activities that have nothing to do with the SSFL—for example, use of Chilean nitrate fertilizers that contain small amounts of natural perchlorate or incompletely burned flares left on roadways. However, Chilean fertilizers with trace levels of perchlorate represent only 0.1% of fertilizer use in the U.S., according to the EPA, with 99.9% of fertilizers containing no perchlorate,[112] and if individual road flares were the cause, then perchlorate contamination would be found in essentially all groundwaters, as road flares are ubiquitous. Solid rocket fuel is the main source of perchlorate contamination found in groundwater, acording to the California Department of Toxic Substances Control.[113] Roughly a quarter of monitoring wells in Simi Valley have reported perchlorate contamination, generally at levels above the state's Public Health Goals. Additional perchlorate has now been identified between SSFL and Simi, at the site of the proposed Runkle Ranch development. As no convincing alternative sources of perchlorate have been substantiated, and, considering that "sporadic detection" applies even to the SSFL areas in which perchlorate use was concentrated, Rocketdyne's claim about fertilizer or road flares being the cause of the contamination in Simi is not a compelling argument.

CONCLUSIONS

There is seemingly a huge amount of data on the geology and hydrology of the SSFL. The gaping holes that remain, however, are mainly due to the fact that most available information is from well cuttings and a few coreholes, and field samples not known to be representative. Well data are very valuable to be sure, but it must be borne in mind that they represent lateral variations of only a few inches in a highly variable system. There are important variables affecting the migration of contaminants at and beyond the SSFL that can never be fully known, such as the distribution of cemented and hard sandstones, the distribution of sandstones, siltstones, and shales that comprise "fine-grained" units, the presence of faults with obscure surface expressions, the distribution of fault-related fracture systems, and the distribution of stress fractures not fitting the orientations of joints or bedding. This makes modeling of contaminant migration an exercise in over-simplification.

Important roles are ascribed by Rocketdyne to fine-grained units and faults as aquitards in the SSFL, but this is based on the slenderest of evidence. "Fine-grained units" are themselves composed of highly variable assemblages of strata with differing lithologic and hydrologic properties, yet practically nothing is known of their lateral variations because of poor exposure. They include sedimentary structures such as cut-and-fill structures and bed pinchouts that provide pathways for contaminant movement across the fine-grained units considered to be aquitards. The fine-grained beds are known to be fractured, both at the surface and at depth, supplying the same kinds of water flow pathways as are provided through the coarser sandstones—yet, in citing their role as aquitards, reference is almost always made to the low hydraulic conductivity of a few measured, unfractured samples. Substantial evidence of contamination of aquifers below similar aquitards elsewhere is interpreted as preferential groundwater flow through fractures. Experimental evidence likewise shows the efficacy of water and contaminant flow through even tiny fractures in clay aquitards.

Assertions about the apparent behavior of fine-grained units as aquitards, such as water level changes across their boundaries, are based on very localized use of wells that were not drilled to test this role, and appear to be subject to alternative interpretation not invoking an aquitard role. A good argument for a fine-grained stratum acting as an aquitard is found in a single case of spring emergence, but not even a minimal description is given of the lithology of that stratum. In some other cases, water level data may support at least local aquitard behavior of some fine-grained units, but uncertainties about stratigraphic identifications in wells drilled for other purposes than to test the aquitard nature of the units, and inconsistent results from closely spaced fine-grained beds, such as the Upper and Lower Line Beds, do not give compelling support. To argue, as is done for the Upper and Lower Bowl Beds, that they are aquitards because they are fine-grained like other aquitards is not acceptable.

Fault zones also are poorly exposed, but are considered without question to represent aquitards, with the presence of fine-grained gouge (rock flour produced by grinding of rock as movement takes place along the faults) considered to be the active ingredient in retarding water flow. The exposures that do occur, however, show clearly that gouge is not everywhere present along fault fractures, and that wide zones of intensely fractured rock lacking any gouge typically accompany the faults. Good evidence in the form of caliche (calcium carbonate deposited from circulating groundwater) fracture-filling and staining of fracture surfaces in fault zones indicate that the fault zones are conduits for flow of groundwater. Because the fault zones and their component fractures are generally inclined steeper than about 50 degrees, they may impede lateral flow of groundwater if there are not crossing fractures (no description that I am aware of mentions crossing fractures, but they should be sought). Emergence of springs where faults intersect the ground surface is stronger evidence that the faults are conduits than that they are aquitards as is invoked. As with fine-grained units, changes in water levels across faults are based on very localized circumstances, some subject to alternative interpretation. These findings also are based on wells that were not drilled to test the aquitard role of faults. Other information, such as the distribution of TCE east of the Shear Zone, provides compelling evidence that some faults at least are not aquitards.

With no better information than has been provided on the behavior of fine-grained units and faults as aquitards, there appears no compelling basis for distinction of Groundwater Units, which supposedly compartmentalize groundwater in independent volumes bounded by faults and fine-grained units. This notion is cited as support for the belief that contaminants are contained on the SSFL but is based on little credible evidence. This situation could be substantially improved with a drilling program specifically designed to test the roles of these important features of the SSFL. It should be borne in mind, however, that critical gaps in information bearing on migration of contaminants at the SSFL—such as the distribution of cemented and hard sandstones and fine-grained beds, locations of gaps in fine-grained units provided by cut-and-fill structures and stratigraphic pinchouts, and other lithologic characteristics that may affect contaminant distribution--are likely never to be known in sufficient detail to predict future contaminant migration with any certainty. The best option, then, is a comprehensive remediation program to remove or appropriately treat known contamination and to establish a long-term comprehensive monitoring system to identify contamination that has escaped detection.

REFERENCES AND NOTES

1. The Rocketdyne reports reviewed for this report were all provided by the California Department of Toxic Substances Control. They include all principal reports related to the geology and geohydrology of the site and nearby areas. Access to the reports was open and copying freely allowed. Since reviewing the documents had to be done in the DTSC office and time was limited, the following reports or large plates and figures were not thoroughly reviewed and copying them was not practical: Hargis & Associates, Phase I Investigation of Hydrogeologic Conditions, SSFL 1985; Figs. 4, 8 of 1986 Phase II Groundwater Investigation; Lithologic log, TD, screened interval(s), and water level(s) in WS-14 [p. 4-1, Geol. Characterization 2002][p. 20, Appx. B, Conceptual Site Model]; Plates, figures, tables for Groundwater Resources Consultants Hydrogeologic Assessment Report 11/30/87, plus appendices F-K. Desired access was not obtained to the Boeing pump test, C-1 2003 [Near-surface Grndwater report, p. 2-3]; and Pump test

of RD-35B, begun 12/01, cited p. 5-10 Geol. Characterization 2002] because they were not available at the time of my last visit to the DTSC office.

2. Groundwater Resources Consultants, Hydrogeologic Assessment Report, Santa Susana Field Laboratory (November 30, 1987), p. 22.

3. M.H. Link, R.L. Squires, and I.P. Colburn (editors), Simi Hills Cretaceous Turbidites, Southern California, Society of Economic Paleontologists and Mineralogists, Pacific Section (1981), 134 p.; J.C. Hurley, B.L. Parker, and J.A. Cherry, Source Zone Characterization at the Santa Susana Field Laboratory—Rock Core VOC Results for Core Holes C1 through C7 (December 22, 2003), p. 18.

4. Hurley et al., Source Zone Characterization, p. 8.

5. J.R. Wagner, Technical Memorandum, Geology and Hydrogeology of the Eastern Simi Hills Study Area (September 2003), p. 2-3.

6. Site-specific descriptions, such as they are, of sandstone units are given by MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory (February 2002); Montgomery Watson, Technical Memorandum, Conceptual Site Model, Movement of TCE in the Chatsworth Formation (April 2000); Montgomery Watson, Appendix A (of Conceptual Site Model), Geologic Characterization, Santa Susana Field Laboratory (April 2000); and Wagner, Technical Memorandum, Geology and Hydrogeology of the Eastern Simi Hills Study Area.

7. S. McD. Carey, Sandstone Petrography of the Upper Cretaceous Chatsworth Formation, Simi Hills, California, in Simi Hills Cretaceous Turbidites, Southern California, eds. M.H. Link, R.L. Squires, and I.P. Colburn, Society of Economic Paleontologists and Mineralogists, Pacific Section (1981): 89-97.

8. Hurley et al., Source Zone Characterization, p. 21-22.

9. Groundwater Resources Consultants, Well Compendium (September 20, 1995).

10. For example, Cores C-1, C-2, C-7, and possibly C-6 report carbonate cement in fine-grained lithologies (MWH, Technical Memorandum, Corehole Drilling Operations (C-1 through C-7) (September 2002). Note also that silica (?) is also reported as a possible cementing agent of sandstone (MWH, Technical Memorandum, Corehole Drilling Operations, Former Sodium Disposal Facility (September 2002).

11. For example, clay minerals are logged as constituents of sandstones in wells RD-35, 36B, 36C, 44, 51B, 57, 58C, 61(Groundwater Resources Consultants, Well Compendium. The only information on composition of carbonates other than designation as calcite or caliche, is mention of "dolomitic" gouge or fracture filling in sandstones and some fine-grained rocks (Cores C-1, C-3, C-4, C-5, C-6, C-7; MWH, Technical Memorandum, Corehole Drilling Operations (C-1 through C-7); the term "dolomite" apparently is used to designate carbonates that do not effervesce vigorously in HCL. Whatever the composition of the carbonate, its presence in gouge suggests that gouges may not be as effective as aquitards as represented.

12. Partial and complete filling of fractures in sandstones and siltstones is logged in corehole samples CH-1, CH-2, CH-3 (Groundwater Resources Consultants, Results of Collection and Analyses of Rock Cores, (May 4, 1992), and in cores C-1, C-2, and C-4 (MWH, Technical Memorandum, Corehole Drilling Operations (C-1 through C-7). In some cores, the clay fracture linings are referred to as "alteration products." Such fracture fillings occur in fine-grained rocks as well as sandstones.

13. MWH, Perchlorate Source Evaluation and Technical Report, v. 1, Report on Perchlorate Use and Occurrence in Environmental Media at SSFL (February 2003), p. 5-8.

14. S. McD. Carey, Sandstone Petrography of the Upper Cretaceous Chatsworth Formation, Simi Hills, California, in Simi Hills Cretaceous Turbidites, Southern California, eds. M.H. Link, R.L. Squires, and I.P. Colburn, Society of Economic Paleontologists and Mineralogists, Pacific Section (1981): 90-92.

15. Carbonate fracture filling is widely reported both in sandstones and fine-grained rocks, for example in Cores C-1, C-3, C-7 (MWH, Technical Memorandum, Corehole Drilling Operations (C-1 through C-7), C-8 (MWH, Technical Memorandum, Corehole Drilling

Operations, Former Sodium Disposal Facility (FSDF) (September 2002), CH-1, CH-2, CH-3 (Groundwater Resources Consultants, Results of Collection and Analyses of Rock Cores), RD-32, RD-38, RD-41C, RD-43C, RD-44, RD-45C, RD-52C, RD-55B, RD-58C, and OS-24 (Groundwater Resources Consultants, Well Compendium).

16. Descriptions of fine-grained units are provided by MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory; Montgomery Watson, Technical Memorandum, Conceptual Site Model; Montgomery Watson, Appendix A (of Conceptual Site Model); and Wagner, Technical Memorandum, Geology and Hydrogeology of the Eastern Simi Hills.

17. As represented in Fig. 2-9 of MWH, Near-Surface Groundwater Characterization Report, Santa Susana Field Laboratory (November 2003).

18. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory (February 2002), p. 3-9.

19. Montgomery Watson, Technical Memorandum, Conceptual Site Model (April 2000), p. 3-3.

20. Montgomery Watson, Appendix A (of Conceptual Site Model), p. 5.

21. Montgomery Watson, Appendix A (of Conceptual Site Model), p. 4.

22. Wagner, Technical Memorandum, Geology and Hydrogeology of the Eastern Simi Hills, p. 3.

23. Deposition of the Chatsworth Formation took place on submarine alluvial fans, characterized by rapidly changing conditions of sedimentation. Channels feeding sediment to the fans periodically became choked with debris causing the channel to be abandoned and new ones formed. Where the channels cut through older fine-grained sediments and become filled with coarser debris, the resulting structures are called cut-and-fill structures. After lithification of the sediments and elevation to their present positions, the cut-and-fill structures may serve as groundwater pathways across fine-grained units.

24. Iron and/or manganese staining of fracture surfaces and adjacent rock is reported for Cores C-1, C-2, C-3, C-4, C-5, C-7 (MWH, Technical Memorandum, Corehole Drilling Operations (C-1 through C-7), C-8 (MWH, Technical Memorandum, Corehole Drilling Operations, Former Sodium Disposal Facility), CH-1, CH-2, CH-3 (Groundwater Resources Consultants, Results of Collection and Analyses of Rock Cores), and RD-58C (Groundwater Resources Consultants, Well Compendium).

25. J.A. Cherry, Hydrogeologic Contaminant Behaviour in Fractured and Unfractured Clayey Deposits in Canada, in eds. H.E. Kobus and W. Kinzelbach, *Proceedings of the International Symposium on Contaminant Transport in Groundwater* (Rotterdam, A.A. Balkema 1989), v. 3, 11-20.

26. B.L. Parker, J.A. Cherry, and S.W. Chapman, Field Study of TCE Diffusion Profiles Below DNAPL to Assess Aquitard Integrity, *Journal of Contaminant Hydrology* 74 (2004): 197-230.

27. S.K. O'Hara, B.L. Parker, P.R. Jorgensen, and J.A. Cherry, Trichloroethene DNAPL Flow and Mass Distribution in Naturally Fractured Clay: Evidence of Aperture Variability, *Water Resources Research* 36 (2000): 135-147.

28. B. Harrison, E.A. Sudicky, and J.A. Cherry, Numerical Analysis of Solute Migration Through Fractured Clayey Deposits Into Underlying Aquifers, *Water Resources Research* 28 (1992): 515-526.

29. Maximum departure from an originally vertical joint orientation occurs when the axis of rotation is parallel to the strike of bedding, and minimum departure occurs when the axis of rotation is parallel to the dip of bedding. It is not known when the joints formed with respect to folding of the beds, so there is no *a priori* of identifying joint fractures in cores. A simplifying assumption that the joints, other than bedding plane joints, formed vertically, so that present angles of dip of less than 60-70 degrees (corresponding to bedding dips of 30-20 degrees) would not qualify as joints. In addition, much scatter might occur as a result of differing physical properties of the different lithologies, including hard and cemented zones and their relations to surrounding lithologies.

30. Hurley et al., Source Zone Characterization, Table 16. In this tabulation, horizontal fractures were noted as "horizontal" in field notes. The percentages of non-joint orientations given here add horizontal fractures to the "other" category, which represents fractures not qualifying as joints or bedding plane fractures, because horizontal orientation does not fit either joint or bedding plane orientations. The figures are: corehole C-1: 70%, C-2: 64%, C-3: 64%, C-4: 51%, C-5: 64%, C-6: 73%, C-7: 60%. No data are available for corehole C-8 (MWH, Technical Memorandum, Corehole Drilling Operations, Former Sodium Disposal Facility. Fracture orientations in three coreholes drilled in 1992 (Groundwater Resources Consultants, Results of Collection and Analyses of Rock Cores, May 4, 1992) show that no strike or dip direction of fractures prevailed at the three coreholes. Fracture densities are 40 per 100 feet at CH-1, 10 at CH-2, and 30 at CH-3.

31. Rectilinear fracture patterns such as shown in Fig.l 2.1 and elsewhere in the Conceptual Site Model apparently do not represent underground conditions at the SSFL, and underscore the remark "The geometry of the fracture system at the SSFL has the greatest uncertainty, and can most significantly affect the initial conceptual model" (Montgomery Watson, Technical Memorandum, Conceptual Site Model, p. 2-1).

32. Hurley et al., Source Zone Characterization at the Santa Susana Field Laboratory, p. 18; Groundwater Resources Consultants, Well Compendium.

33. Descriptions of faults are found in MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, Montgomery Watson, Appendix A (of Conceptual Site Model), and Wagner, Technical Memorandum, Geology and Hydrogeology of the Eastern Simi Hills Study Area.

34. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 3-9.

35. Substantial differences in location of the Shear Zone can be seen by comparing Fig. 14 (Groundwater Resources Consultants, Hydraulic Communication Study (June 3, 1997) with Fig. 2-9 (MWH, Near-Surface Groundwater Characterization Report, Santa Susana Field Laboratory). Even in the case of wells in close proximity to exposures of the Shear

Zone, descriptions provided do not (and perhaps cannot) indicate whether the well is within or outside of the fault zone. A good example is WS-14 just west of an exposure of the Shear Zone (Montgomery Watson, Technical Memorandum, Conceptual Site Model, p. 28); water levels in WS-14 and its behavior in pump tests are important elements of some hydrologic interpretations, so its exact location with respect to the Shear Zone should be determined.

36. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 4-1 to 4-2.

37. Montgomery Watson, Appendix A (of Conceptual Site Model), p. 6-7.

38. Core C-7 at 265 feet depth is logged as "calcite gouge" on fracture surface, striated. It is not clear if the gouge is striated or the fracture surface; Core C-8 at 310 feet depth is logged as fault gouge, platy, silty, apparent calcite interlaminations (MWH, Technical Memorandum, Corehole Drilling Operations (C-1 through C-7).

39. "Dolomitic gouge," apparently referring to mineralized gouge rather than gouge composed of dolomite fragments, is logged in Corehole C-1 at 340 feet; in C-3 at 233 feet (?), 274 feet, 280 feet, and 319 feet (?); in C-5 at 269 feet; in C-6 at 258 feet; and in C-7 at 265 feet, 287 feet, 289 feet, and 378 feet (MWH, Technical Memorandum, Corehole Drilling Operations (C-1 through C-7). It would be extremely useful to thin-section these samples and determine the textural relations of the carbonate to the broken gouge minerals.

40. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 4-2; Wagner, Technical Memorandum, Geology and Hydrogeology of the Eastern Simi Hills Study Area, p. 9.

41. Wagner, Technical Memorandum, Geology and Hydrogeology of the Eastern Simi Hills, p. 5-6.

42. Montgomery Watson, Appendix A (of Conceptual Site Model), p. 8.

43. Montgomery Watson, Appendix A (of Conceptual Site Model), p. 6-11.

44. The length of Skyline Fault is very differently represented on 1997 maps (Groundwater Resources Consultants, Hydraulic Communication Study, Fig. 2) than on 2003 maps (MWH, Near-Surface Groundwater Characterization Report, Santa Susana Field Laboratory, Fig. 2-9). Montgomery Watson, Appendix A (of Conceptual Model), p. 9, ends the North Fault near WS-12, whereas Fig. 2-9 of the Near-Surface Groundwater report extends it, with queries, well westward to the RD-56 well cluster.

45. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 4-2 to 4-4.

46. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 4-3.

47. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 4-3 to 4-4.

48. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 4-3.

49. The rock-type categories recognized are Fine to Coarse sandstone, Hard sandstone, Banded sandstone (comprising alternating layers of coarser and finer sandstone), Breccia, and Siltstone (commonly with thin interbeds of sandstone and shale). (Hurley et al., Source Zone Characterization at the Santa Susana Field Laboratory, p. 21-22). No separate measurements are made for shale, claystone, or conglomerate, and, as lithologic types present, none for fault gouge or joint fillings. "Hard sandstone" is interpreted to be hard because of carbonate cement (p. 22), but as mentioned in the description of sandstones, there are sandstones described in well logs as hard, but not cemented, and many described as cemented, but not hard. In addition some fine-grained rocks are described as hard, with or without cement. Thus, the list of rock types focused on in this study is far from complete. Moreover, it should be born in mind that core samples and cuttings from wells provide only a very narrow (3-6 inches) view of the materials present, and commentary on and interpretations of lateral extent of any particular property are mostly speculative.

50. L. P. Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, Santa Susana Field Laboratory, Hydrogeology Summary Report (April 2000), p. 28-29.

51. Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, Table 4.1.

52. Groundwater Resources Consultants, Phase II Groundwater Investigation, v. 1 (October 29, 1986), p. 12.

53. Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, Table 2.11. Well clusters examined are RD-5A-C; RD-33B-C; RD-34A-C; RD-48B-C; RD-49A,C; RD-52A,C; and RD-55A-B. These clusters represent site-wide conditions, RD-5 (Lower Chatsworth, on Burro Flats Fault), RD-33, 34 (Sandstone 2); RD-48 (Lower Chatsworth); RD-49 (Sandstone 1); RD-52 (Sandstone 2, Shale 2, on North Fault), and RD-55 (Sandstone 1, near Coca Fault).

54. Groundwater Resources Consultants, Hydraulic Communication Study, p. 8-9, 14.

55. Montgomery Watson, Appendix A (of Conceptual Site Model), p. 13-14.

56. Montgomery Watson, Appendix A (of Conceptual Site Model).

57. F.L. Paillet, A.E. Hess, C.H. Cheng, and E. Hardin, Characterization of Fracture Permeability With High-Resolution Vertical Flow Measurements During Borehole Pumping, *Groundwater* 25 (1987): 28-40.

58. Groundwater Resources Consultants, Hydrogeologic Assessment Report, p. 43. This report also includes well WS-6 as constructed along a NE-trending fracture zone, a fracture zone not appearing on any of the maps used for this report. Also, well WS-9A is said to be located on a NW-trending fracture zone, apparently referring to a segment of the Burro Flats Fault, but the well is somewhat removed from the mapped fault (Fig. 2-9, Near-Surface Groundwater Study.

59. Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, p. 31.

60. 400 feet is cited by Wagner, Technical Memorandum, Geology and Hydrogeology of the Eastern Simi Hills Study Area, p. 7, the 200 feet figure from Smith (Haley & Aldrich),

Appendix B, Conceptual Site Model, p. 32. Montgomery Watson, Technical Memorandum, Conceptual Site Model, p. 4-4 indicate "nearly 300" feet of water level offset. The 200 and 300 feet figures are cited in reports published in April 2000, the 400 feet citation is dated September 2003.

61. Only two west-of-Shear Zone wells are available for this use—WS-14 and RD-37. The east-side wells selected for water level comparison are RD-35A, B, 53, 72, and 73 (MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 5-2). As stated on p. 5-2, the contrast in water elevations across the Shear Zone "...was most evident" when comparing these wells. It is less evident when other east-side wells are compared with the two west-side wells (Table 2).

62. Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, Fig. 1.2.

63. This does not accord with the statement "Drawdown resulting from pumping in the central portion of SSFL appears to terminate at the...Shear zone." (Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, p. 33). Page 33 of this report also observes that water level decline is "noted to the west of the Shear Zone near WS-5, but may result from the long-term pumping of RD-1 and RD-2." But, both RD-1 and 2 are also east of the Shear Zone, so such an effect would have to cross the Shear Zone.

64. Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, p. 32, Tables 2.2, 2.5. WS-5 is listed as on the Shear Zone in Table 2.9. A problem with generalizations about hydraulic conductivities of rocks on opposite sides of the Shear Zone is that the only measurements of bulk hydraulic conductivity on the west side of the Shear Zone are a long way from the Shear Zone or are on faults (see Table 2.2).

65. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 5-13.

66. Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, p. 30, Fig. 2.17.

67. Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, p. 18-20.

68. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 5-9.

69. Groundwater Resources Consultants, Well Compendium.

70. Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, p. 20.

71. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 4-4.

72. Groundwater Resources Consultants, Well Compendium.

73. Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, p. 33.

74. Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, Tables 2.2, 2.3, listed as non-productive wells at the bottom of the tables, p. 36.

75. Groundwater Resources Consultants, Phase II Groundwater Investigation, v. 1 (October 29, 1986), p. 14.

76. Groundwater Resources Consultants, Hydraulic Communication Study, p. 30-31.

77. It is asserted that the faults identified during the 2001 field program (i.e., Woolsey Canyon, IEL, and Happy Valley Faults) show that they behave as aquitards (MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 7-1).

78. MWH, Near-Surface Groundwater Characterization Report, Santa Susana Field Laboratory, Fig. 2-9.

79. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 5-9.

80. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 5-8.

81. More direct evidence of the role of the IEL Fault may have been obtained by a pump test of corehole C1 that was in process in 2003 (reported by MWH, Near-Surface Groundwater Characterization Report, Santa Susana Field Laboratory, p. 2-3).

82. HAR-16, chosen as representative of wells south of the IEL Fault, has a total depth of 120 feet in sandstone; HAR-1, HAR-24, and HAR-25, not used in this comparison, have total depths of, respectively, 110, 110, and 90 feet. Like HAR-16, HAR-1 and HAR-25 are solely in sandstone; HAR-24 shows about 20 feet of siltstone at the top of the well, then sandstone in the remainder.

83. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 5-9 to 5-10.

84. Hurley et al., Source Zone Characterization, p. 19, p. 30-32.

85. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 4-3 to 4-4.

86. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 5-10 to 5-11.

87. Groundwater Resources Consultants, Hydraulic Communication Study.

88. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 6-3.

89. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 7-1.

90. Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, p. 36.

91. Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, p. 24.

92. MWH, Perchlorate Source Evaluation and Technical Report, v. 1 (February 2003), p. 59.

93. Wagner, Technical Memorandum, Geology and Hydrogeology of the Eastern Simi Hills Study Area, p. 8.

94. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 5-1.

95. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 5-1. This is similar to the diagram produced in Fig. 4.4, Montgomery Watson, Technical Memorandum, Conceptual Site Model, which views the section line from the south.

96. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 5-2.

97. Wells in Sandstone 1 that continued decline and did not respond to pump shutdown or startup include: RD-5B, RD-5C, RD-41A, RD-42, RD-53, RD-55A, RD-55B, RD-58A, RD-58B, RD-58C, HAR-8, WS-7, WS-11. Wells in Sandstone 2 that continued decline and did not respond to pump shutdown or startup include: RD-13, RD-15, RD-16, RD-17, RD-19, RD-20, RD-21, RD-26, RD-27, RD-29, RD-50, HAR-5, HAR-6, HAR-20, HAR-21, HAR-22, HAR-23, WS-9B. Wells that showed no trend and did not respond to pump shutdown or startup include: RD-11 (Sandstone 1), RD-7, RD-33A, RD-33C (Sandstone 2).

98. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 5-6.

99. Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, p. 21-22.

100. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 5-3 to 5-4.

101. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 5-4 to 5-5.

102. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 5-5.

103. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 5-5 to 5-6.

104. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 5-12 to 5-13.

105. MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory, p. 5-6 to 5-7.

106. MWH, Perchlorate Source Evaluation and Technical Report Update (November 2003).

107. MWH, Perchlorate Source Evaluation and Technical Report Update (November 2003), Table 2-1Q.

108. MWH, Perchlorate Source Evaluation and Technical Report Update (November 2003), Table 2-1S.

109. MWH, Perchlorate Source Evaluation and Technical Report Update (November 2003), Table 2-1T1.

110. MWH, Northern Drainage Perchlorate Sampling Results Technical Memorandum (November 2003).

111. MWH, Perchlorate Source Evaluation and Technical Report, v. 1 (February 2003), p. 86-101; MWH, Perchlorate Source Evaluation and Technical Report Update (November 2003), p. 1-9.

112. E.T. Urbansky, T.W. Collett, W.P. Robargo, W.L. Hall, J.M. Skillen, and P.F. Kane, Survey of Fertilizers and Related Materials for Perchlorate (ClO_4-), *U.S. Environmental Protection Agency*, Final Report, EPA/600/R-01/1ba (2001), 26 p.

113. California Department of Toxic Substances Control, Fact Sheet November 2002, Perchlorate Identified in Simi Valley Groundwater.

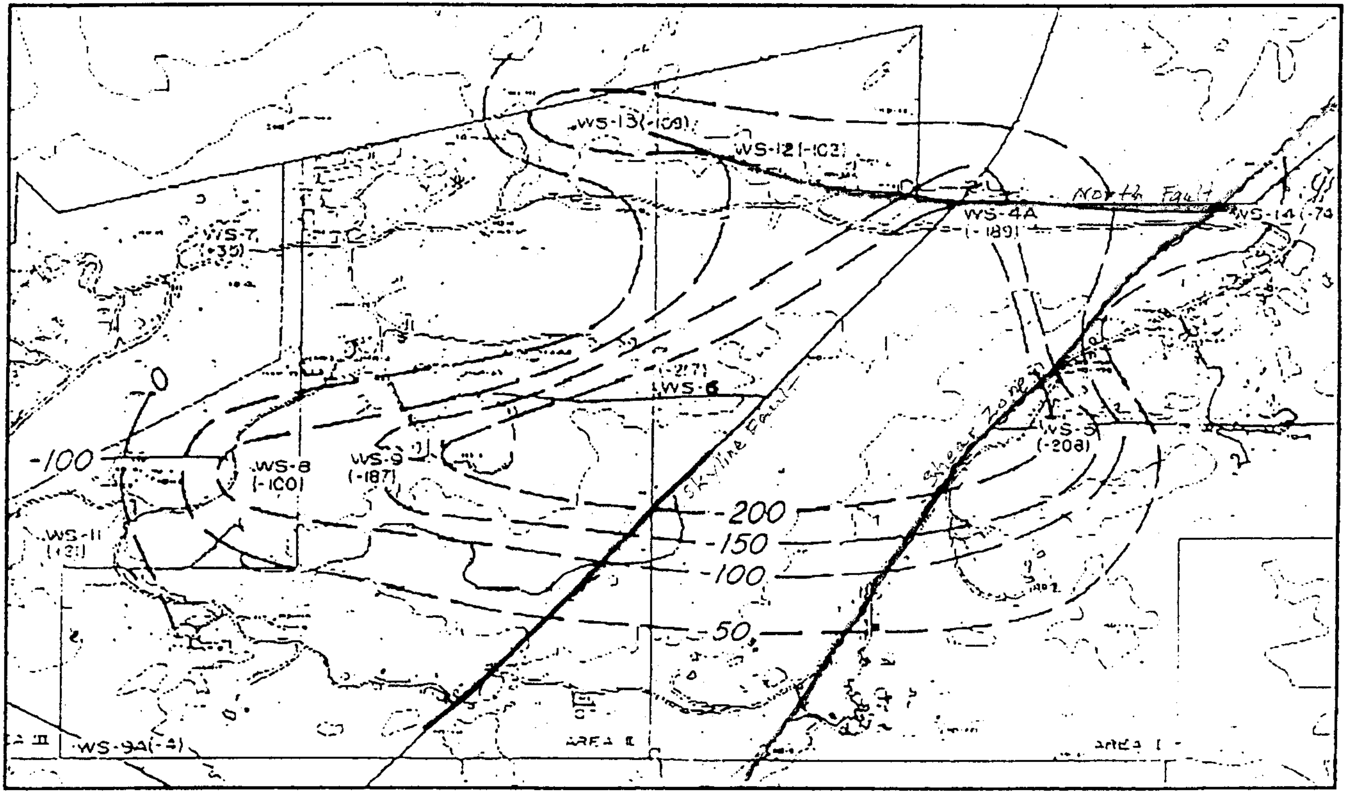
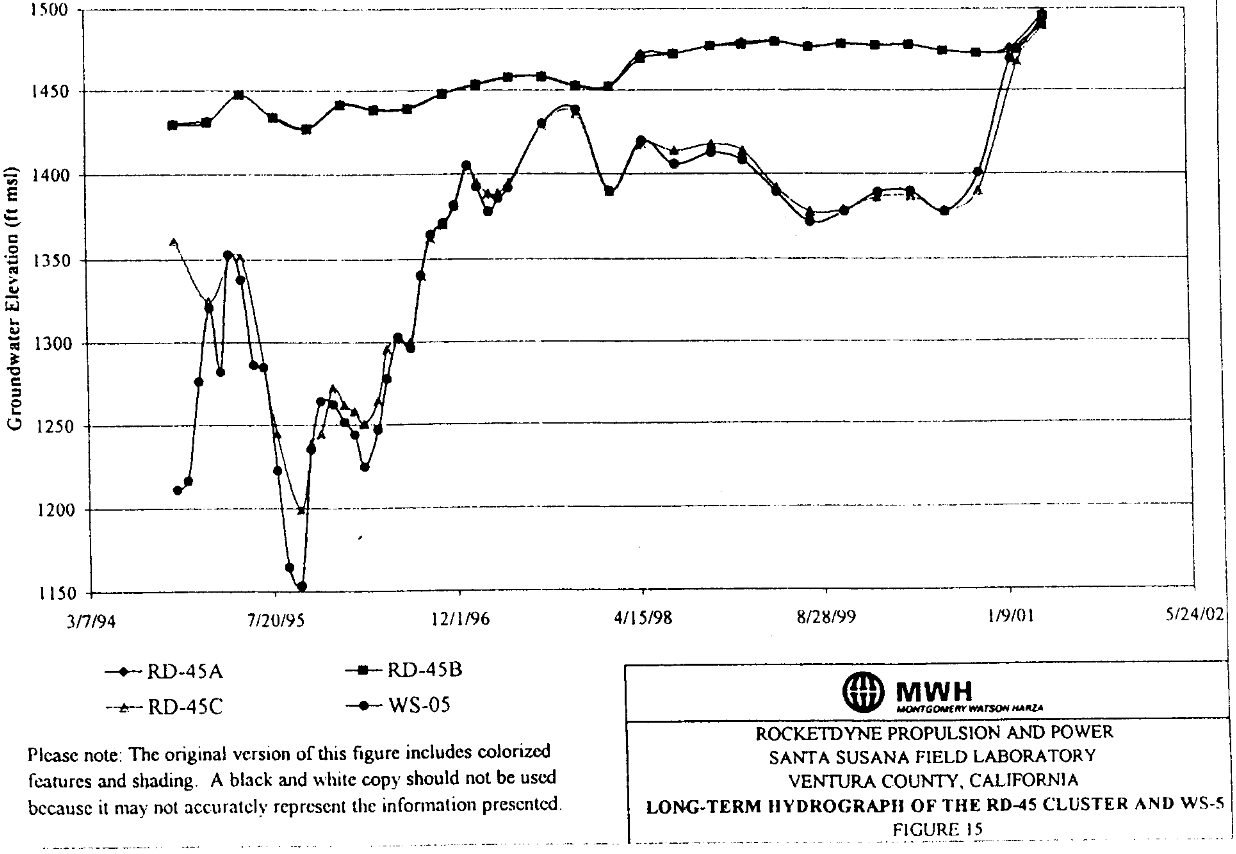


Exhibit 1. Drawdown contours (in feet) from water extraction, 1954-1997 in the northeastern part of theSSFL. From L. P. Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, Santa Susana Field Laboratory, Hydrogeology Summary Report (April 2000), Figure 1.9.



Please note: The original version of this figure includes colorized features and shading. A black and white copy should not be used because it may not accurately represent the information presented.

MWH
MONTGOMERY WATSON HARZA

ROCKETDYNE PROPULSION AND POWER
SANTA SUSANA FIELD LABORATORY
VENTURA COUNTY, CALIFORNIA
LONG-TERM HYDROGRAPH OF THE RD-45 CLUSTER AND WS-5
FIGURE 15

Exhibit 2. Hydrographs, 1994-2001, for wells WS-5, RD-45A, RD-45B, and RD-45C. From MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory (February 2002), Figure 15. Note faults differ from current representations.

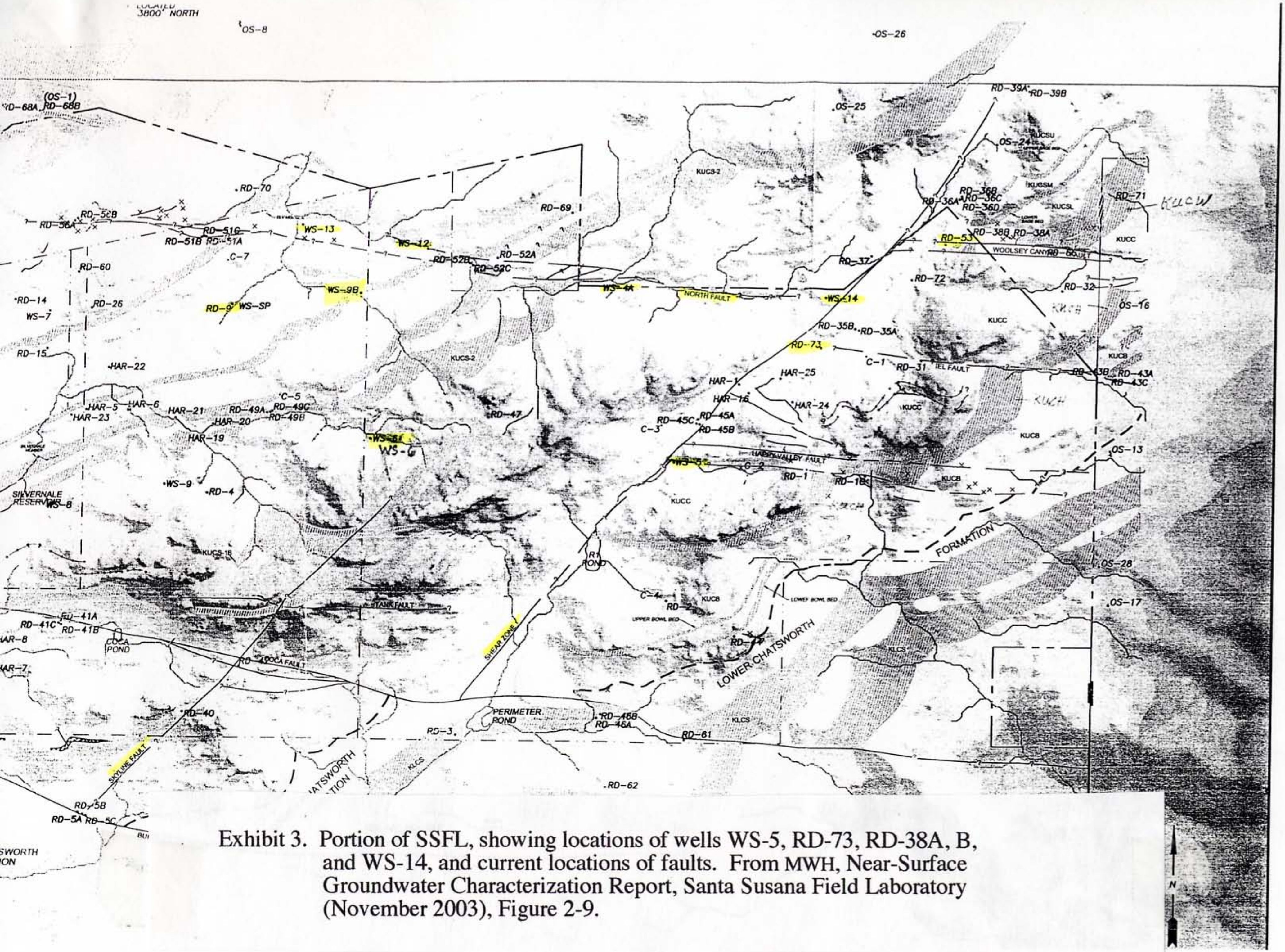
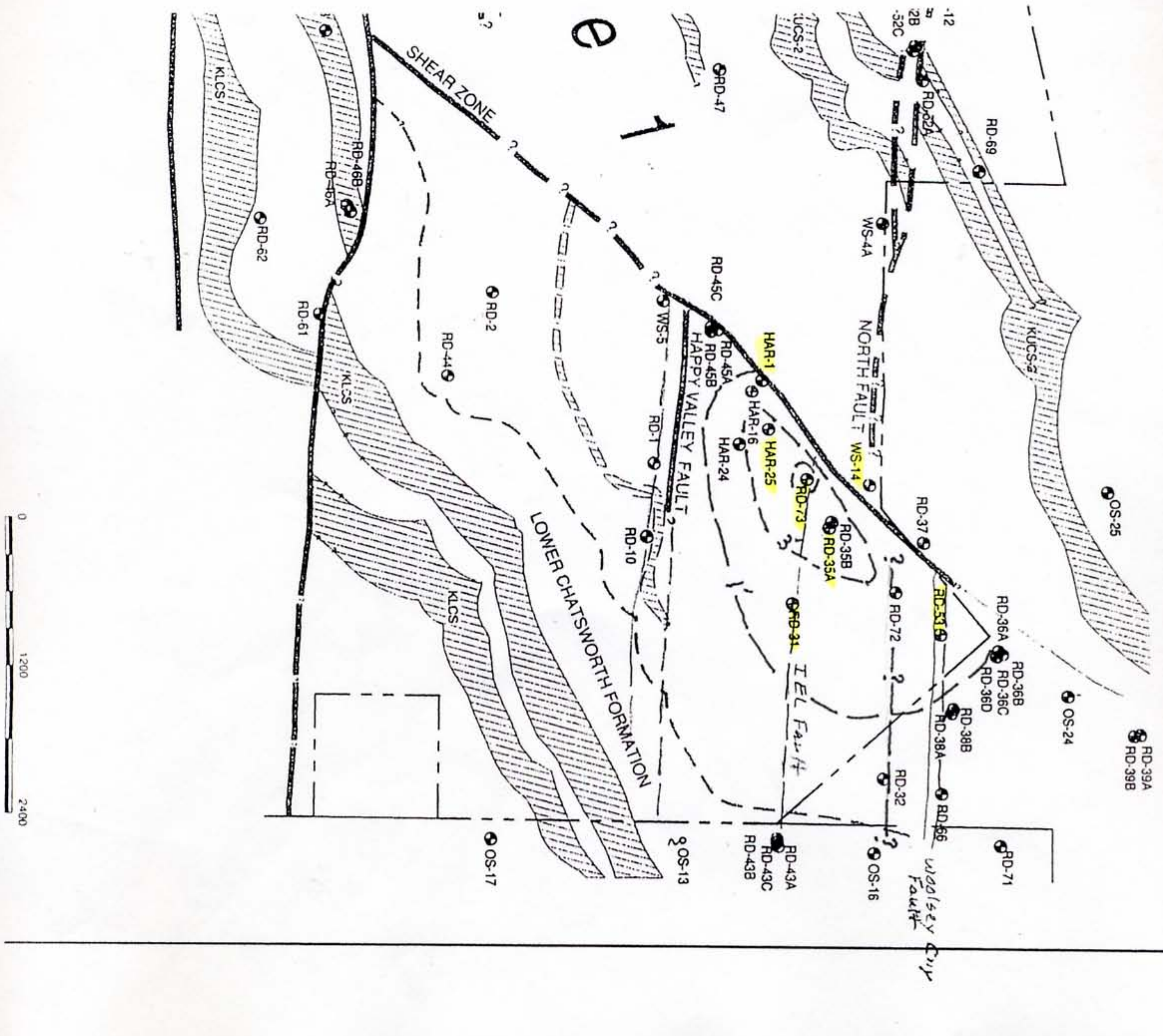


Exhibit 3. Portion of SSFL, showing locations of wells WS-5, RD-73, RD-38A, B, and WS-14, and current locations of faults. From MWH, Near-Surface Groundwater Characterization Report, Santa Susana Field Laboratory (November 2003), Figure 2-9.

Exhibit 4. Portion of SSFL, showing drawdown contours for 90-day (May to August 1997) pump test of RD-73 (from L. P. Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, Santa Susana Field Laboratory, Hydrogeology Summary Report (April 2000), Figure 2.9), and locations of subsequently mapped Woolsey Canyon and IEL Faults and enlarged Happy Valley Fault Zone (from MWH, Near-Surface Groundwater Characterization Report, Santa Susana Field Laboratory (November 2003), Figure 2-9). A possible E-W fault passes very close to RD-72 and RD-32 (MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory (February 2002), p. 4-4). The video log of RD-32 logs fault indicators (Groundwater Resources Consultants, Well Compendium (September 20, 1995); no logs available for RD-72.



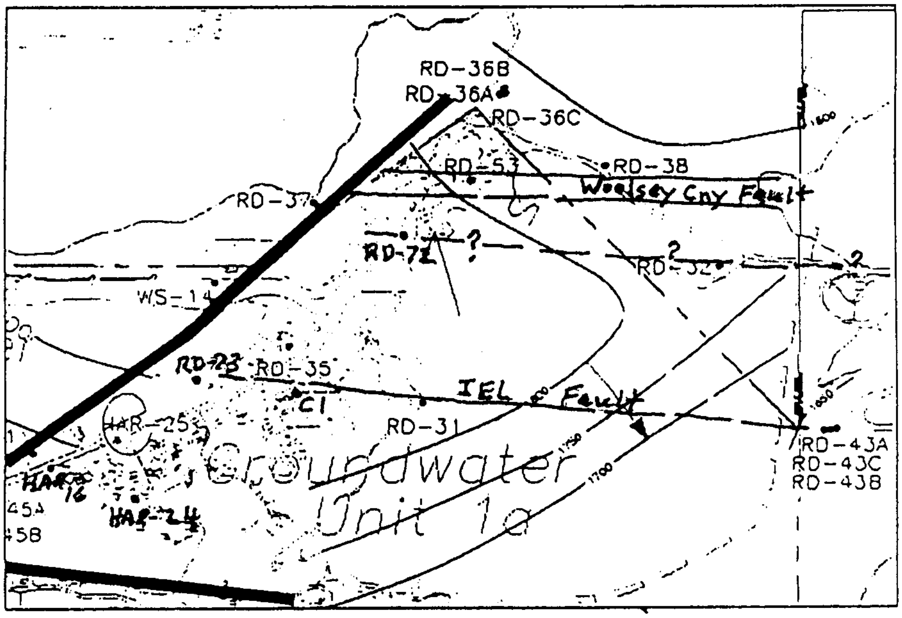


Exhibit 5. Portion of SSFL, showing water level contours for Groundwater Unit 1a as recognized in 2000 (from L. P. Smith (Haley & Aldrich), Appendix B, Conceptual Site Model, Santa Susana Field Laboratory, Hydrogeology Summary Report (April 2000), Figure 3.2), and locations of subsequently mapped Woolsey Canyon and IEL Faults and enlarged Happy Valley Fault Zone (from MWH, Near-Surface Groundwater Characterization Report, Santa Susana Field Laboratory (November 2003), Figure 2-9). A possible E-W fault passes very close to RD-72 and RD-32 (MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory (February 2002), p. 4-4).

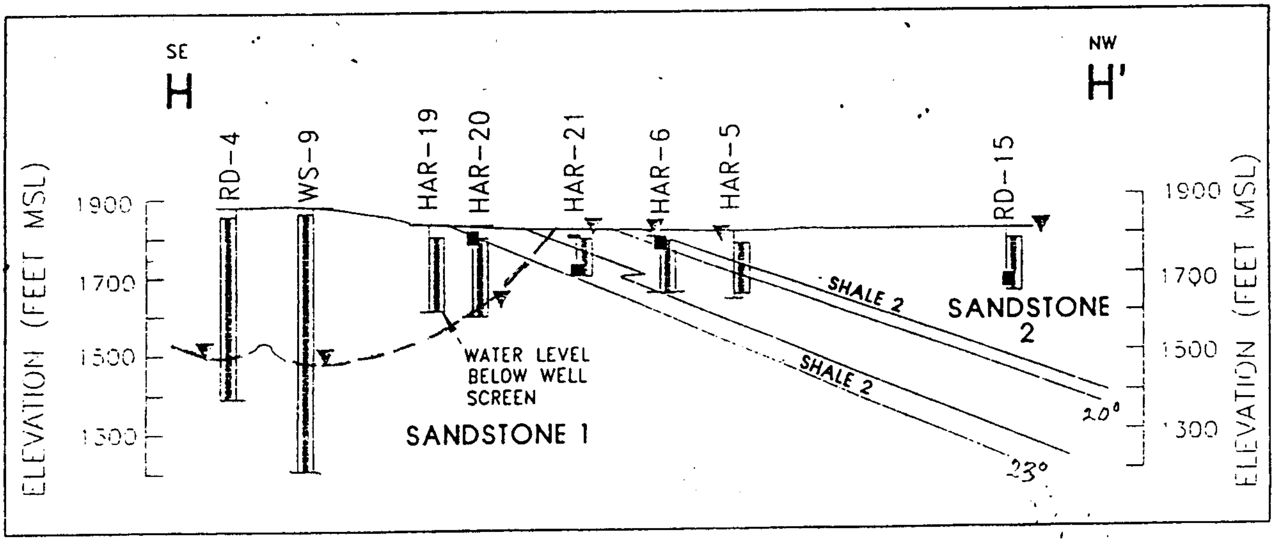


Exhibit 6. Section illustrating 200-300 feet difference in water elevations in wells screened on opposite sides of Shale 2 (from MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory (February 2002), p. 5-1). Note section line is viewed toward the south, contrary to normal practice.

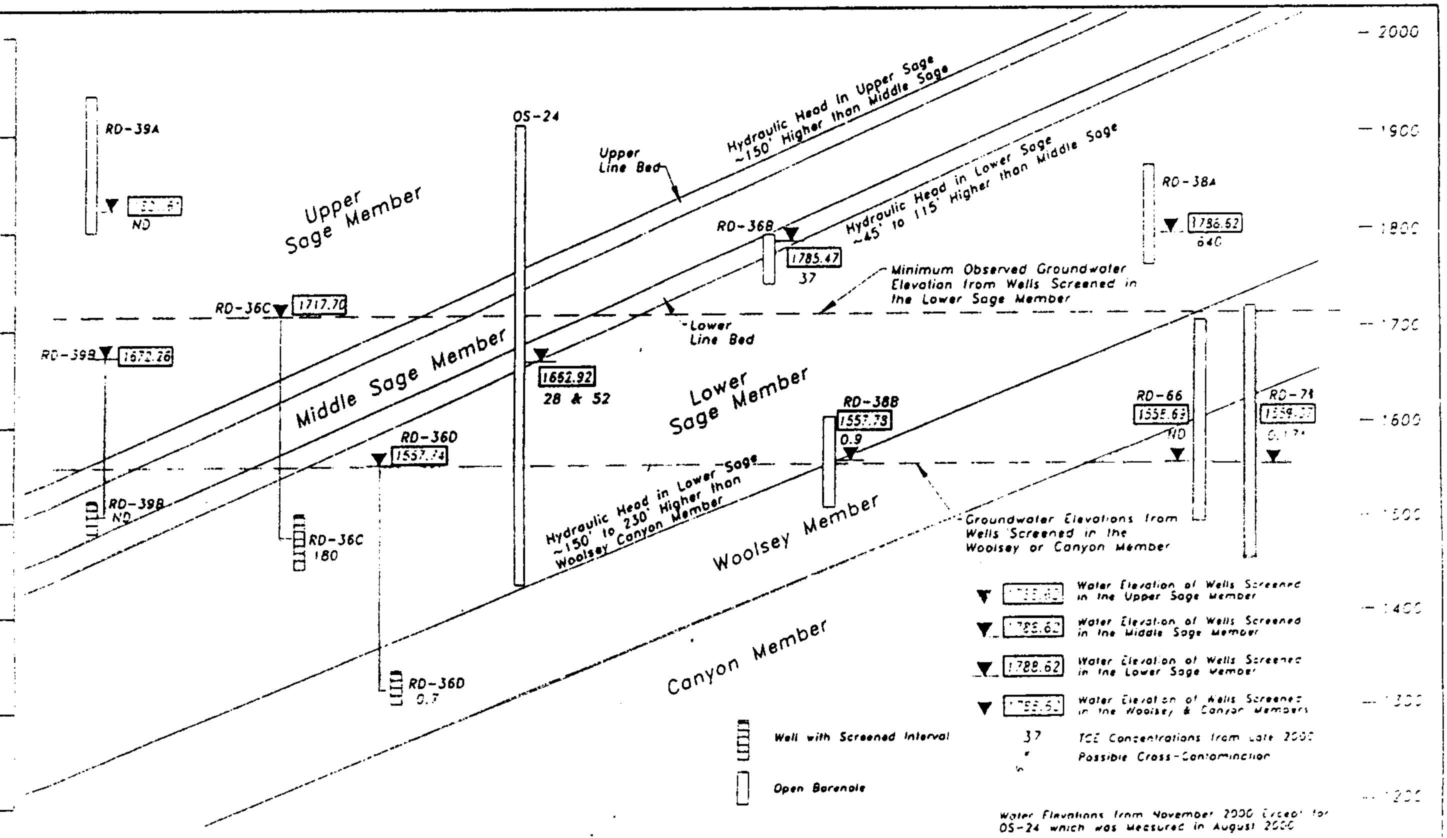


Exhibit 7. Diagrammatic representation of the stratigraphic positions of open intervals for wells RD-39A, RD-39B, RD-36C, RD-36D, OS-24, RD-36B, RD-38B, RD-38A, RD-66, and RD-71 (from MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory (February 2002), p. 5-6).

Table 1. Locations With Respect to Major Structures of Wells that Responded to Cessation and/or Pumping, 1996 Hydraulic Communications Study[1]

	Wells Located on or in Close Proximity to Major Faults that Responded to Pumping[2]	Wells Located Away From Major Faults that Responded to Pumping[2]
	RD-5A; RD-10; RD-40; RD-41B; RD-41C; RD-43A; RD-45A; RD-45B; RD-45C	RD-30; RD-33B; RD-34A; RD-34B; RD-34C; RD-47; RD-54A; WS-SP[3]
TOTAL (%)	9 (53)	8 (47)
	Wells Located on or in Immediate Proximity to Major Faults that Did Not Respond to Pumping	Wells Located Away From Major Faults that Did Not Respond to Pumping
	RD-5B; RD-5C; RD-31; RD-36A; RD-36B; RD-36C; RD-37; RD-38; RD-39; RD-41A; RD-42; RD-43B; RD-43C; RD-46; RD-48A; RD-48B; RD-48C; RD-50; RD-51A; RD-51B; RD-51C; RD-52A; RD-52B; RD-52C; RD-53; RD-58A; RD-58B; RD-58C; RD-61; HAR-1; HAR-17; WS-4A; WS-12; WS-14	RD-3; RD-6; RD-7; RD-8; RD-11; RD-12; RD-13; RD-14; RD-15; RD-16; RD-17; RD-18; RD-19; RD-20; RD-21; RD-22; RD-23; RD-24; RD-25; RD-26; RD-27; RD-28; RD-29; RD-32; RD-33A; RD-33C; RD-35; RD-44; RD-49A; RD-49B; RD-49C; RD-54B; RD-54C; RD-55A; RD-55B; RD-56; RD-57; RD-59A; RD-59B; RD-59C; RD-60; RD-62; HAR-5; HAR-6; HAR-8; HAR-20; HAR-21; HAR-22; HAR-23; HAR-24; HAR-25; HAR-26; WS-7; WS-8; WS-9B; WS-11; WS-13; OS-1; OS-24; OS-25
TOTAL (%)	34 (36)	60 (64)

[1] Groundwater Resources Consultants, Hydraulic Communication Study, Santa Susana Field Laboratory, Boeing North American, Ventura County, California (June 3, 1997); proximity to structures assessed using MWH, Near-Surface Groundwater Characterization Report, v. 1 (November 2003), Fig. 2-9.

[2] Excludes pumped wells

[3] Note Wells RD-30, RD-34A, RD-34B, RD-34C, and WS-SP are in immediate proximity to a pumped well

Table 2. Comparison of Water Levels in Wells Straddling the Shear Zone[1]

Well Number	Water Elevation	Offset Compared to RD-37 and WS-14, in feet	Stratigraphic Unit in Which Screened[2]
West of Shear Zone Wells			
RD-37	~1650		Not known
WS-14[3]			Not screened, units intersected not known
East of Shear Zone Wells, Wells Selected by MWH for Comparison			
RD-35A	~1880	~230	Upper Chatsworth Formation
RD-35B	~1880	~230	Upper Chatsworth Formation
RD-53[3]			Located in Woolsey Canyon Fault Zone
RD-72[3]			
RD-73[3]			
East of Shear Zone Wells, Wells Not Selected by MWH for Comparison			
OS-24	1662.92	13	Not screened, begins in Lower Sage
RD-36A	1820.28	170	Middle Sage
RD-36B	1785.47	135	Lower Sage + Lower Line Bed
RD-36C	1717.70	68	Lower Sage
RD-36D	1557.74	-92	Woolsey Member
RD-38A	1786.62	137	Lower Sage
RD-38B	1557.78	-92	Lower Sage + Woolsey Member
C-1[3]			
RD-31[3]			Lower Canyon
HAR-24[3]			Lower Canyon
HAR-25[3]			Lower Canyon
RD-39A	1821.61	172	Upper Sage
RD-39B	1672.26	22	Middle Sage

[1] Water levels measured in November 2000 except OS-24, measured in August 2000 (MWH, Technical Memorandum, Geologic Characterization of the Eastern Portion of the Santa Susana Field Laboratory (February 2002), p. 5-6, Fig. 8).

[2] Although some wells are open through several stratigraphic units and others are screened in different units, the offset comparisons made in the MWH report cited above and other reports cite only offsets of wells in the Upper Chatsworth Formation, not individual members of that formation. This is at least partly due to the fact that the unit in which RD-37 is located is not known and the units penetrated by the open well, WS-14 are not known. With such limitations, it is only reasonable to compare all of the relevant east-side wells with RD-37 and WS-14.

[3] Data not available.

Table 3. Perchlorate in Surface Water Samples, Building 359 Area I AOC (left column), Happy Valley Area I AOC (remaining columns)[1] Values in Bold are Below the Detection Limit

Date	mg/L Perchlorate	Date	mg/L Perchlorate	Date	mg/L Perchlorate	Date	mg/L Perchlorate	Date	mg/L Perchlorate
1/19/2001	**0.005**	3/5/2000	**0.004**	2/14/2003	**0.004**	2/25/2003	0.072	2/25/2003	0.084
3/15/2003	0.17	3/5/2000	**0.008**	2/14/2003	**0.004**	2/25/2003	0.059	2/25/2003	0.091
3/15/2003	0.086	3/5/2000	0.044	2/25/2003	0.017	2/25/2003	0.058	2/25/2003	0.0069
3/15/2003	0.054	3/8/2000	0.008	2/25/2003	0.012	2/25/2003	0.06	2/25/2003	0.008
3/15/2003	0.019	3/8/2000	0.500	2/25/2003	0.012	2/25/2003	0.062	2/25/2003	0.0071
3/15/2003	0.0064	3/8/2000	0.500	2/25/2003	0.016	2/25/2003	0.065	2/25/2003	0.013
3/15/2003	0.052	4/18/2000	**0.004**	2/25/2003	**0.004**	2/25/2003	0.067	2/25/2003	0.011
3/15/2003	0.0022	4/18/2000	0.0062	2/25/2003	**0.004**	2/25/2003	0.062	2/25/2003	0.0097
3/15/2003	**0.004**	4/18/2000	0.021	2/25/2003	0.015	2/25/2003	0.069	2/26/2003	**0.004**
3/15/2003	**0.004**	4/18/2000	0.010	2/25/2003	0.013	2/25/2003	0.074	2/26/2003	**0.004**
3/15/2003	**0.004**	4/18/2000	**0.004**	2/25/2003	0.012	2/25/2003	0.027	2/27/2003	0.017
3/15/2003	0/12	4/18/2000	0.010	2/25/2003	0.0014	2/25/2003	0.029	2/27/2003	0.27
4/14/2003	0.075	4/18/2000	0.012	2/25/2003	**0.004**	2/25/2003	0.029	2/27/2003	0.63
4/14/2003	0.051	4/18/2000	0.013	2/25/2003	**0.004**	2/25/2003	0.034	2/27/2003	0.094
4/14/2003	0.0083	4/18/2000	**0.004**	2/25/2003	**0.004**	2/25/2003	0.039	2/27/2003	0.072
4/14/2003	0.0085	1/12/2001	0.058	2/25/2003	**0.004**	2/25/2003	0.04	2/27/2003	0.051
4/15/2003	0.57	2/13/2001	0.040	2/25/2003	**0.004**	2/25/2003	0.024	2/27/2003	0.053
		2/13/2001	0.013	2/25/2003	**0.004**	2/25/2003	0.03	2/27/2003	0.059
		2/13/2001	0.0042	2/25/2003	0.19	2/25/2003	0.025	2/27/2003	0.057
		2/13/2001	**0.004**	2/25/2003	0.22	2/25/2003	0.016	2/27/2003	0.018
		2/13/2001	**0.004**	2/25/2003	0.18	2/25/2003	0.015	2/27/2003	0.019
		2/13/2001	0.0095	2/25/2003	0.29	2/25/2003	0.021	2/27/2003	0.018
		2/13/2001	**0.004**	2/25/2003	0.31	2/25/2003	0.021	2/27/2003	0.023
		2/13/2001	0.014	2/25/2003	0.32	2/25/2003	0.022	2/27/2003	0.024
		2/27/2001	0.025	2/25/2003	0.055	2/25/2003	0.026	2/27/2003	0.017
		2/14/2003	0.038	2/25/2003	0.065	2/25/2003	0.018	2/27/2003	**0.004**
		2/14/2003	0.037	2/25/2003	0.065	2/25/2003	0.019	3/15/2003	0.0061
		2/14/2003	0.013	2/25/2003	0.062	2/25/2003	0.019	3/15/2003	**0.004**
		2/14/2003	0.01	2/25/2003	0.071	2/25/2003	0.076	3/15/2003	**0.004**
		2/14/2003	0.0075	2/25/2003	0.065	2/25/2003	0.091	3/15/2003	0.0019
		2/14/2003	**0.004**	2/25/2003	0.063	2/25/2003	0.097	3/15/2003	0.011
		2/14/2003	**0.004**	2/25/2003	0.071	2/25/2003	0.075	3/15/2003	**0.004**

---

[1] From MWH, Perchlorate Source Evaluation and Technical Report Update (November 2003), Table 2-1 M 1. Recast to show variability of perchlorate concentrations over time and on same date of measurement

Table 4. Perchlorate Data in Surface Water at Happy Valley Outfalls HV-1 and HV-2 (mg/L), Illustrating Sporadic Occurrence of Perchlorate[1]

Date	HV-1	HV-2
1998		
3/25/98	0.020	
5/5	0.0351	
5/5	0.022	
5/14	0.0283	
5/14	0.00824	
2000		
2/21/00	**<0.020**	
2/23	0.016	
3/5	0.013	
3/6/3/8/3/9	**<0.004**	
3/10	**<0.004**	
3/11	0.017	
4/18	**<0.008**	
2001		
1/12/01	0.008	
2/13	0.0055	
2/26	0.0042	
2/27	**<0.004**	
3/5	0.0053	
3/6	**<0.004**	
3/7	0.0049	
3/8	0.0052	
3/9	0.0048	
3/12	**<0.004**	
2003		
2/12/03	0.0047	**<0.004**
2/25	0.012	**<0.004**
3/15	0.0053	**<0.004**
5/3	**<0.004**	0.0046
5/3		0.0066

[1] MWH, Happy Valley Interim Measures Work Plan Addendum & Amendment (June 2003).

There are a few discrepancies between this listing and that in MWH, Perchlorate Source Evaluation and Technical Report Update (November 2003), Table 2-1N, but they do not change the substance of the data.

Table 5. Perchlorate in Soil Samples, Left Columns Show Variation at the Same Depth, Right Columns Show Variation at Different Depths, Sampled at the Same Date, Building 359 Area I AOC[1] Values in Bold Are Below the Detection Limit

Lateral Variation Between 1 and 2 Feet Depth			Vertical Variation, Same Date of Sampling		
Date	Depth (feet)	mg/kg Perchlorate	Date	Depth (feet)	mg/kg Perchlorate
12/19/1997	1	2.9	12/19/1997	1	2.9
4/10/1998	1	**0.04**		13.5	0.07
12/1/1997	1	**0.01**		20.0	0.08
12/4/1997	2	**0.01**		24.5	0.12
1/23/1998	2	0.95	12/1/1997	0.5	0.03
1/23/1998	2	**0.01**		0.5	**0.01**
1/15/2001	2	**0.05**		0.5	**0.01**
1/15/2001	2	0.19		1	**0.01**
1/15/2001	2	2.43		5	**0.01**
1/16/2001	2	0.06		10	0.06
1/16/2001	2	**0.05**		15	**0.01**
1/1/2001	1.5	71.29	1/15/2001	2	**0.05**
1/17/2001	2	0.287		2	0.19
4/30/2001	1	0.022		2	2.43
4/30/2001	1	4.66		6	0.12
4/30/2001	1	0.128		6	**0.05**
5/25/2001	1	**0.05**		6	0.11
5/25/2001	1	**0.05**		10	0.06
5/25/2001	1	1.21		10	0.22
1/22/2001	2	**0.05**		14	0.09
1/22/2001	2	**0.05**		14	0.16
				17	**0.05**
				17	0.28

[1] From MWH, Perchlorate Source Evaluation and Technical Report Update (November 2003), Table 2-1A.

Table 6. Perchlorate in Soil Samples, Left Columns Show Variation at the Same Depth, Right Columns Show Variations at Different Depths, Sampled on the Same Date, Happy Valley Area I AOC[1] Values in Bold Are Below the Detection Limit

Lateral Variation Between 0 and 0.5 Feet Depth			Vertical Variation, Same Date of Sampling		
Date	Depth (feet)	mg/kg Perchlorate	Date	Depth (feet)	mg/kg Perchlorate
11/19/1997	0.5	**0.01**	8/18/2003	0.2	**0.042**
11/19/1997	0.5	**0.01**		0.2	0.078
12/9/1997	0	**0.01**		0.2	0.56
12/9/1997	0.5	**0.01**		0.2	**0.04**
12/9/1997	0.5	**0.01**		0.2	**0.041**
1/23/1998	0.5	**0.01**		0.2	**0.041**
10/24/2000	0.5	**0.05**		0.2	**0.041**
10/24/2000	0.5	**0.05**		0.2	**0.042**
10/25/2000	0.5	**0.05**		0.2	**0.041**
10/25/2000	0.5	**0.05**		0.2	**0.041**
10/25/2000	0.5	**0.05**		0.37	**0.041**
10/25/2000	0.5	**0.05**		0.37	0.14
10/25/2000	0.5	**0.05**			
10/30/2000	0.5	**0.05**			
10/30/2000	0.5	**0.05**			
11/7/2000	0	0.03			
11/17/2000	0.5	**0.05**			
7/7/2003	0.04	4.1			
7/7/2003	0.04	0.043			
7/7/2003	0.04	**0.041**			
7/7/2003	0.04	**0.044**			
7/7/2003	0.04	**0.042**			
7/7/2003	0.04	0.037			
7/7/2003	0.04	0.17			
7/7/2003	0.04	0.075			
7/7/2003	0.04	0.049			
7/7/2003	0.04	0.024			
7/7/2003	0.04	0.12			
7/7/2003	0.04	1.6			
7/7/2003	0.04	**0.04**			
7/7/2003	0.04	0.12			
7/7/2003	0.04	0.018			
7/7/2003	0.04	0.52			
8/18/2003	0.2	0.078			
8/18/2003	0.37	0.041			
8/18/2003	0.2	0.56			
8/18/2003	0.37	0.14			
8/18/2003	0.2	**0.04**			
8/18/2003	0.2	**0.041**			
8/18/2003	0.2	**0.041**			
8/18/2003	0.2	**0.041**			
8/18/2003	0.2	**0.042**			
8/18/2003	0.2	**0.041**			
8/18/2003	0.2	**0.041**			

[1] From MWH, Perchlorate Source Evaluation and Technical Report Update (November 2003), Table 2-1A.

Table 7. Perchlorate in Soil Leachate Samples, Left Columns Show Variation at the Same Depth, Right Columns Show Variation at Different Depths,Sampled on the Same Date, Building 359 Area I AOC.[1] Values in Bold are Below the Detection Limit

Lateral Variation at 0.5 Feet Depth			Vertical Variation, Same Date of Sampline		
Date	Depth (feet)	mg/L Perchlorate	Date	Depth (feet)	mg/L Perchlorate
1/11/2001	0.5	0.100	1/15/2001	2	0.025
3/5/2003		0.057		2	0.156
3/5/2003		0.0062		2	2.403
6/30/2003		**0.004**		6	0.015
7/15/2003		**0.004**		6	0.057
7/28/2003		**0.004**		6	0.080
8/11/2003		0.21		10	**0.005**
8/11/2003		0.0718		10	0.049
8/11/2003		4.19		10	0.030
8/11/2003		1.4		14	**0.005**
8/11/2003		0.0111		14	0.040
8/11/2003		2.87		14	0.073
8/11/2003		0.0481		17	0.023
8/11/2003		0.313		17	0.125
8/11/2003		0.463		18	**0.005**
8/11/2003		0.5		21	**0.005**
8/11/2003		0.799	1/16/2001	2	0.007
8/11/2003		0.217		2	**0.005**
8/11/2003		0.03		2	0.019
8/11/2003		0.2		6	0.011
8/11/2003		0.242		6	**0.005**
8/12/2003		0.37		6	0.005
8/12/2003		0.051		9.5	0.007
8/12/2003		0.46		10	**0.005**
8/12/2003		0.12		10	**0.005**
8/12/2003		0.12		13	**0.005**
8/12/2003		0.17		14	0.005
8/12/2003		0.03		18	**0.005**
8/12/2003		1.9		22	**0.005**
8/12/2003		0.12		26	**0.005**
8/12/2003		0.15	6/30/2003	0.04	**0.004**
8/12/2003		0.025		0.04	**0.004**
8/12/2003		0.053		0.04	**0.004**
8/14/2003		0.029		0.04	0.033
8/14/2003		0.016		0.04	**0.004**
8/14/2003		0.047		0.33	0.025
8/14/2003		0.013		0.33	**0.004**
8/14/2003		0.0045		0.33	0.0069
8/14/2003		0.11		0.33	**0.004**
8/14/2003		0.045		0.5	**0.004**
8/14/2003		2.9			
8/14/2003		0.023			
8/20/2003		0.14			
8/20/2003		0.0066			
8/20/2003		0.013			
8/20/2003		0.51			
9/25/2003		0.058			

[1] From MWH, Perchlorate Source Evaluation and Technical Report Update (November 2003), Table 2-1 B1.

Table 8. Perchlorate in Soil Leachate Samples, Left Columns Show Variation at the Same Depth, Right Columns Show Variation at Different Depths,Sampled on the Same Date, Happy Valley Area I AOC.[1] Values in Bold are Below the Detection Limit

Lateral Variation at 0.5 Feet Depth			Vertical Variation, Same Date of Sampling		
Date	Depth (feet)	mg/L Perchlorate	Date	Depth (feet)	mg/L Perchlorate
10/23/2000	0.5	0.082	7/1/2003	0.04	0.0075
10/23/2000		0.005		0.04	0.23
10/27/2000		**0.005**		0.04	0.0013
3/4/2003		**0.004**		0.04	0.0041
3/4/2003		**0.004**		0.04	0.32
7/1/2003		**0.004**		0.04	0.0011
7/2/2003		**0.004**		0.04	0.0044
7/7/2003		**0.003**		0.04	0.0068
7/7/2003		0.0028		0.04	0.005
7/7/2003		**0.003**		0.33	0.0033
7/7/2003		**0.003**		0.33	0.0047
7/7/2003		**0.003**		0.33	0.0051
7/7/2003		**0.003**		0.33	0.1
7/7/2003		0.0043		0.33	0.0012
7/7/2003		0.0126		0.5	**0.004**
7/7/2003		0.0084		1	**0.004**
7/7/2003		0.0095		2.5	**0.004**
7/7/2003		0.0369		3	0.0029
7/7/2003		0.012		3.5	**0.004**
7/7/2003		0.0021			
7/7/2003		0.001			
7/7/2003		0.0015			
7/7/2003		0.0022			
7/7/2003		0.0145			
7/7/2003		0.009			
7/7/2003		0.0375			
7/7/2003		0.0045			
7/15/2003		0.032			
7/15/2003		0.032			
7/16/2003		0.0036			
7/28/2003		**0.004**			
8/7/2003		**0.004**			
8/7/2003		**0.004**			
8/12/2003		**0.004**			
8/12/2003		**0.004**			
8/12/2003		0.53			
8/12/2003		0.042			
9/22/2003		**0.02**			
9/25/2003		**0.008**			
9/25/2003		0.022			

[1] From MWH, Perchlorate Source Evaluation and Technical Report Update (November 2003), Table 2-1 B1.