Chapter 2. Initial Hydrogeologic Conceptual Site Model

2.1. Introduction

Figure 2.1-1 presents an aerial view of the Quarry site. The headwaters of the West Branch of Greenlaw Brook lie to the west, and the former Nose Dock Area lies to the east. The Quarry site is located near a topographic divide, with drainage generally to the west toward West Branch of Greenlaw Brook. Surface water drainage in the network of hangars and taxiways of the former Nose Dock Area to east of the Quarry is generally to the south and east (East Branch of Greenlaw Brook Drainage).

Past investigations at the Quarry have focused on the upper and lower tiers (Figure 2.1-2). The lower tier is approximately 0.81 hectare (2 acres) in size and contains water year round, which drains through an excavated ditch into the Greenlaw Brook wetland. The upper tier is approximately 1 hectare (2.5 acres) in size, is crescent-shaped, and is bordered on the north and east by rubble. Sloping bedrock escarpments rise approximately 9 meters (30 feet) to the unexcavated Quarry rim. To the west, the upper tier of the Quarry drops vertically approximately 9 meters (30 feet) to the lower tier.

Between 1983 and 1985, approximately 105 to 110 drums were removed from the upper tier. The contents of these drums were not determined, but their discovery launched a series of field investigations. Several phases of investigation took place starting in the late 1980's, culminating in a Final Remedial Investigation (RI) report in 1997 (ABB-ES, 1997). Development of a Feasibility Study (FS) was complicated by the late discovery of several hundred previously unidentified buried drums. During 1998, supplemental characterization studies were initiated, and a magnetometer survey (i.e., EM-34 and EM-61) identified a large anomaly along the eastern edge of the upper tier. Subsequent test-pitting and removal actions were focused on the wedge-shaped mass of talus, spoils, and soil which extended from the "rim" of the upper tier to the "floor." An additional 348 drums, 155 cubic meters (205 cubic

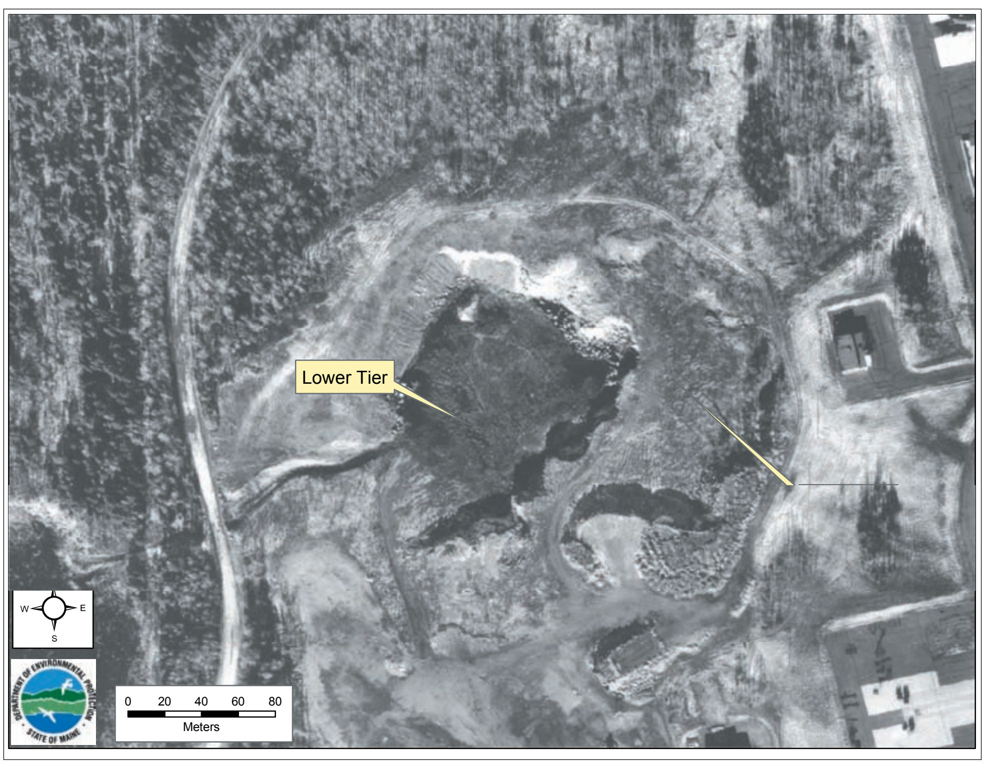

Figure 2.1-1. Aerial view of the Loring Air Force Base Quarry.

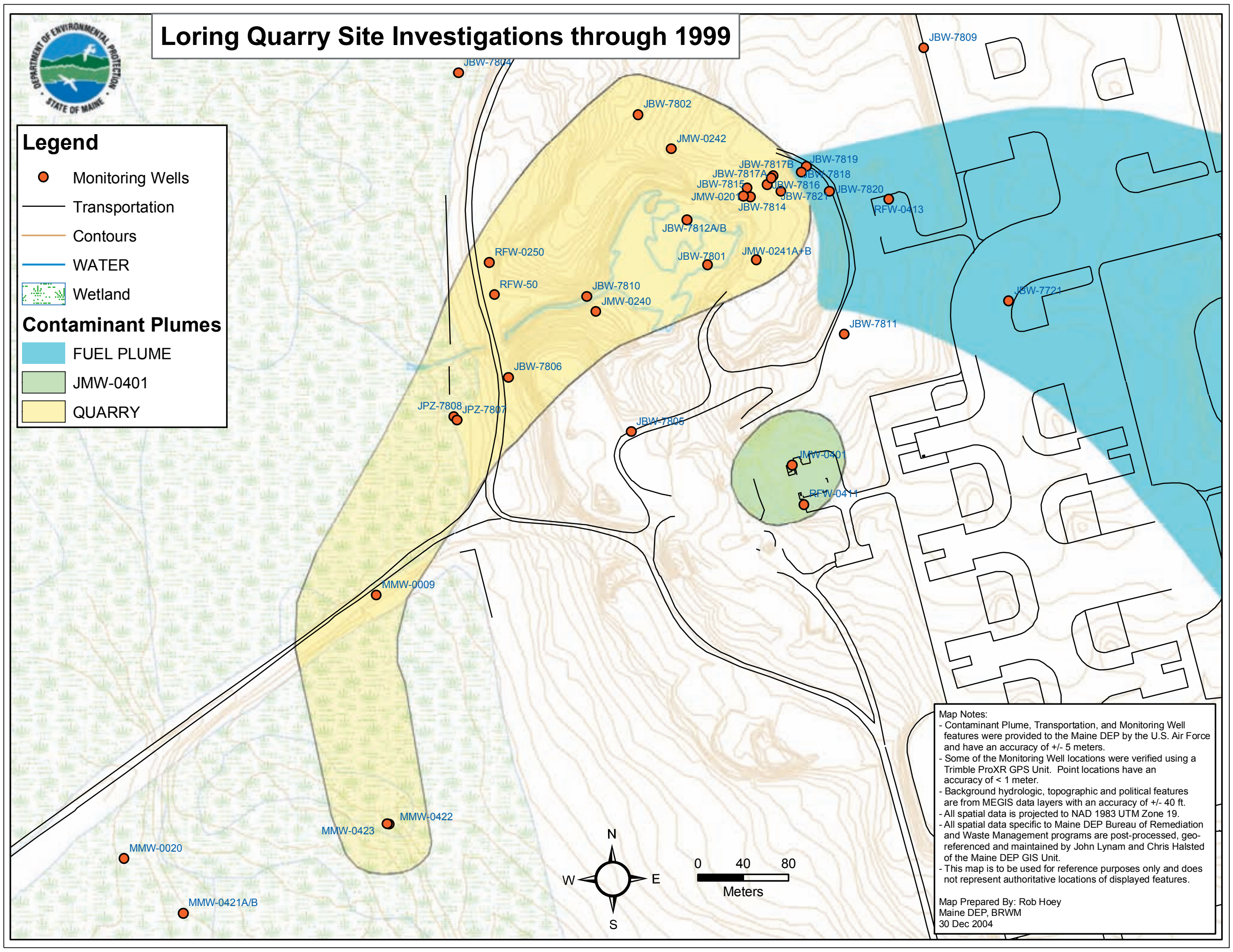

Figure 2.1-2. Results of previous ground water investigations at the Quarry.

yards) of contaminated soil, and approximately 3,800 liters (1,000 gallons) of waste oils, lubricants, and fuels were removed from this area. In 1999 a remedial approach was finalized, and final FS, Proposed Plan, and ROD documents were completed (HLA, 1999a; HLA, 1999b; U.S. EPA, 1999). The final remedy included a Technical Impracticability (TI) waiver for ground water restoration in the Quarry plume, but the TI waiver also included specific expectations regarding testing of remedial technologies at the site, thus setting the stage for the current research project.

The development of a conceptual model to describe fluid flow and contaminant distribution in the fractured limestone at the Quarry was an evolution resulting from a series of hydrogeologic investigations (HLA, 1998; HLA, 1999c) undertaken before the steam system was designed and the process wells drilled. The investigations employed surface geophysical methods including azimuthal resistivity; magnetometer surveys (EM-16, very low frequency (VLF), and EM-34); diamond-core rock drilling; borehole geophysics (caliper, electrical methods, acoustic televiewer (ATV), and borehole image processing system (BIPS)); specific capacity tests; and straddle packer sampling for ground water chemistry. The HLA reports summarize the conceptual model with three components: bedrock structure, hydraulic conductivity distribution, and contaminant distribution.

The initial conceptual model provided guidance on the presumed extent of the NAPL distribution, the distribution of subsurface geological features, and direction of ground water flow, and was the basis of the initial design of the steam injection study. The well locations, spacing, completion depths, and use (injection versus extraction) were chosen based on that model. However, as with most SER projects, the data obtained during the drilling of the steam injection and extraction wells, and the testing and operation of the wells once completed, allow a more accurate conceptual model of the subsurface hydraulic conductivity and contaminant distribution to be developed. Thus, the well pattern selected is not expected to be the optimum design since information obtained during implementation was not available during the design phase.

2.2. Bedrock Structure

Figure 2.2-1 presents bedrock structural geology at the regional scale. The bedrock of northeastern Maine is a sequence of volcanic and marine sedimentary formations of Ordovician-Devonian age. Beginning approximately 40 km (25 miles) west of Loring and traversing to the east, the bedrock formations include the Winterville basalt; sandstones and conglomerates of the Madawaska, Frenchville, and Jemtland Formations; the New Sweden calcareous siltstone; and the Carys Mills limestone. These rocks have been subjected to low-grade metamorphism and deformation associated with several orogenic events. Regional folding parallels the strike of lithologic contacts, which is oriented to the northeast. The folding occurs at several scales with the first-order folds represented by the regional anticlinoria and synclinoria with wavelengths of tens of kilometers. Second–order folds have wavelengths on the kilometer scale. Third-order folds with wavelengths on the order of tens of meters are evident in large outcrops such as the Loring Quarry (Roy, 1987). Mesoscopic folding with wavelengths on the order of centimeters and other manifestations of structural deformation are also commonly observed in outcrop and core samples.

Due to historical use of the site as a rock quarry, the overburden and shallow, weathered bedrock commonly observed across Loring have largely been removed. As a result, the geology in the Quarry consists of a competent, yet fractured, sequence of the Carys Mills Formation. This formation is primarily composed of interlayered argillaceous gray limestones and calcareous siltstones. The bedrock is micritic and thinly laminated with significant calcite infillings occurring along bedding and fracture planes.

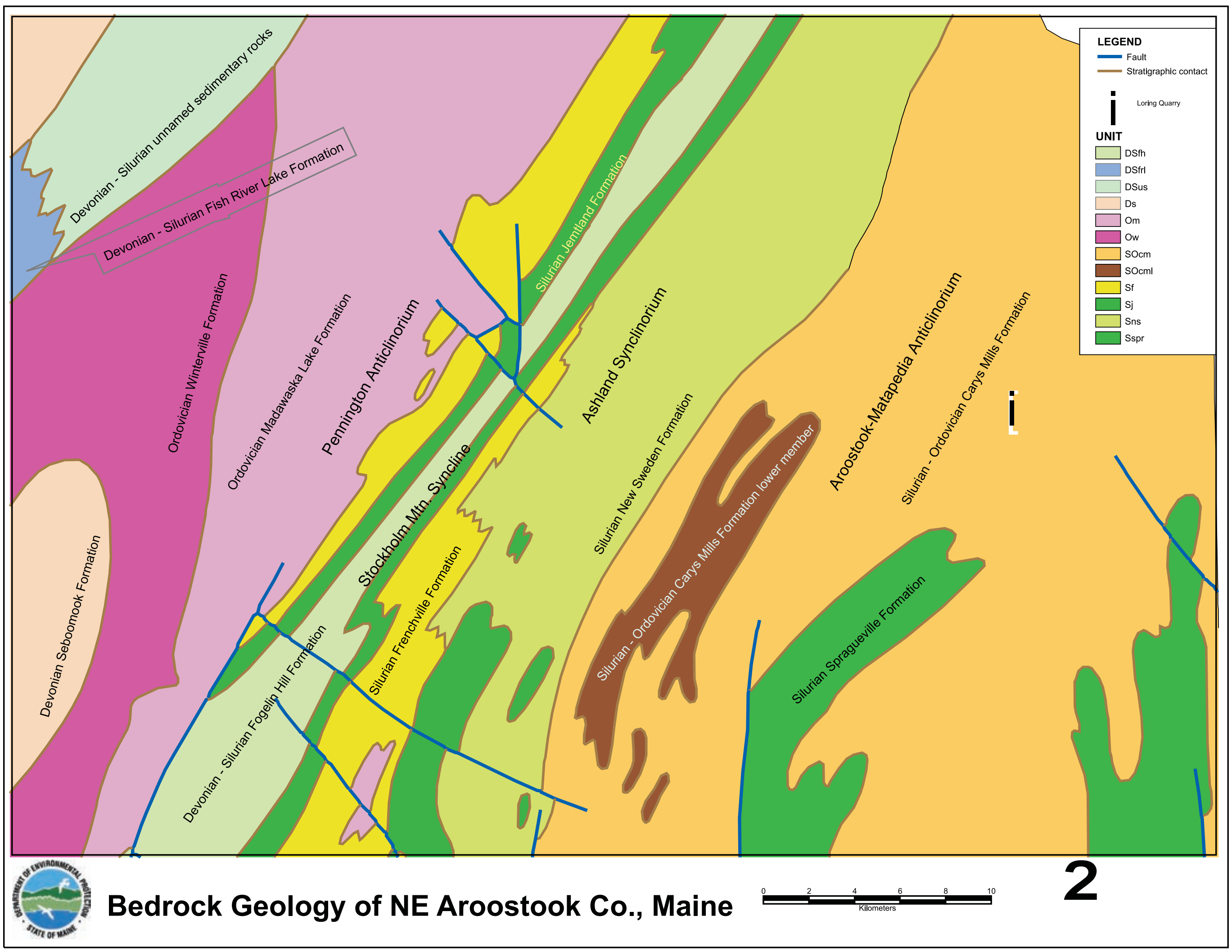

Figure 2.2-1. Bedrock geology of northeastern Aroostook County, Maine.

Figure 2.2-2 presents the primary structural features in the vicinity of the Quarry. Several major structural features are evident from exposures at the Quarry. The first is an anticline plunging N10E. The axial plane strikes north, dips steeply to the east, and bisects the lower tier of the quarry. This feature was interpreted from outcrop and borehole data of bedding orientation. Bedding in the western part of the Quarry dips steeply to the northwest. Bedding in the eastern portion of the lower tier and in the upper

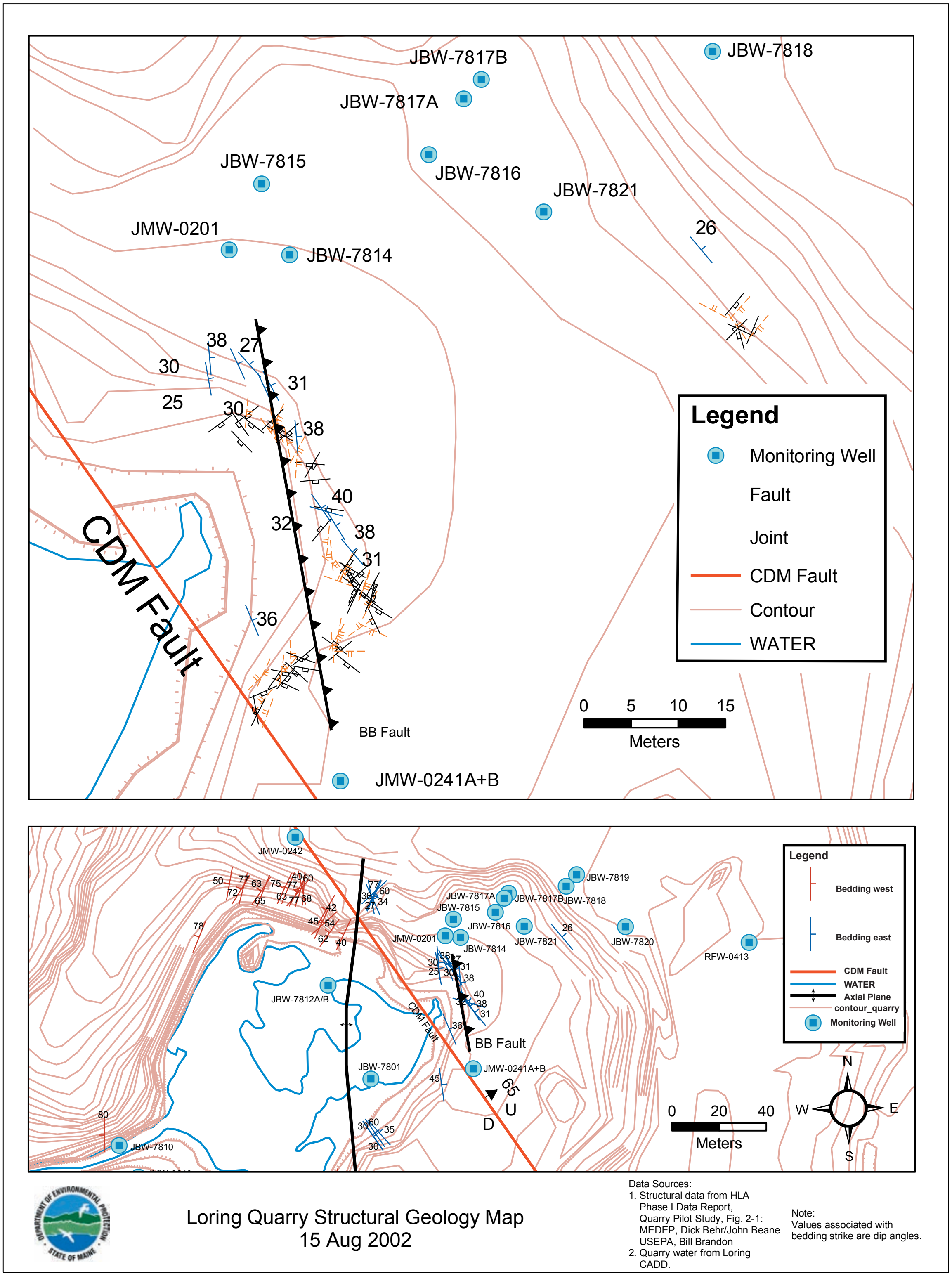

Figure 2.2-2. Primary structural features of the Quarry.

tier generally dips moderately to the northeast. A second major feature is a significant fault named the “CDM Fault,” which strikes north-northwest, dips steeply to the northeast, and more or less coincides with the boundary between the upper and lower tiers. Additionally, a number of low- to moderate angle “thrust” or “reverse” faults, which are generally parallel or sub-parallel to bedding, have been identified beneath the upper tier. Prominent among these features, the “BB fault” outcrops along the steep rock face separating the lower and upper tiers. The bedding-parallel features (BB Fault and related structures) which dip beneath the upper tier appear to be related to a major thrust/reverse fault which outcrops on the south Quarry wall in the lower tier, west of the trace of the CDM fault. The interrelationships between the CDM fault and the series of more gently dipping thrust/reverse faults (BB Fault, etc.) are not clear. However, all features appear to be pene-contemporaneous (i.e., related to the same paleo-stress field), with the last displacement of this type occurring along the CDM fault. A diagrammatic cross-sectional representation of the fracturing at the Quarry, which focuses on the upper tier, is shown on Figure 2.2-3.

In the upper tier, bedding plane fractures are one of three predominant fracture sets. The other two are northwest and northeast striking sets of steeply dipping fractures. The northwest trending fractures (N30W to N30W) cross the axis of the quarry fold at a high angle. The northeast trending fractures strike approximately N40E and thus generally coincide with the regional strike of the lithology and the first-order fold axes, but are oblique to the axis (N10E) of the third-order Quarry fold.

2.3. Hydraulic Conditions

Ground water in the upper tier is encountered at approximately 6 to 9 meters (20 to 30 feet) below ground surface (bgs). Ground water flow in the Quarry area is generally from a piezometric high in the Nose Dock Area (east of the Quarry) to the Greenlaw Brook wetland (approximately 300 meters (1,000 feet) west of the Quarry). The horizontal gradient over this area is 0.03, but it steepens significantly beneath the upper tier of the Quarry. Vertical gradients are downward in the zone beneath the upper tier and upgradient of the Quarry. Water level measurements downgradient of the Quarry indicate upward vertical gradients and discharge to the Greenlaw Brook wetland.

Specific capacity tests were conducted in several boreholes in and near the Quarry to provide a relative indication of the transmissivity distribution. The results of these tests range from 0.12 to 435 lpm/meter (0.01 to 35 gpm/ft). Within the upper tier, the range is 0.12 to 12.4 lpm/meter (0.01 to 1 gpm/ft), which is approximately equal to transmissivities of $1x10^{-6}$ to $1x10^{-4}$ m^2/s (1.1 x 10^{-5} to 1.1 x 10^{-3} ft^2/s). The higher values tended to be within 10 to 15 meters (30 to 50 feet) of the surface.

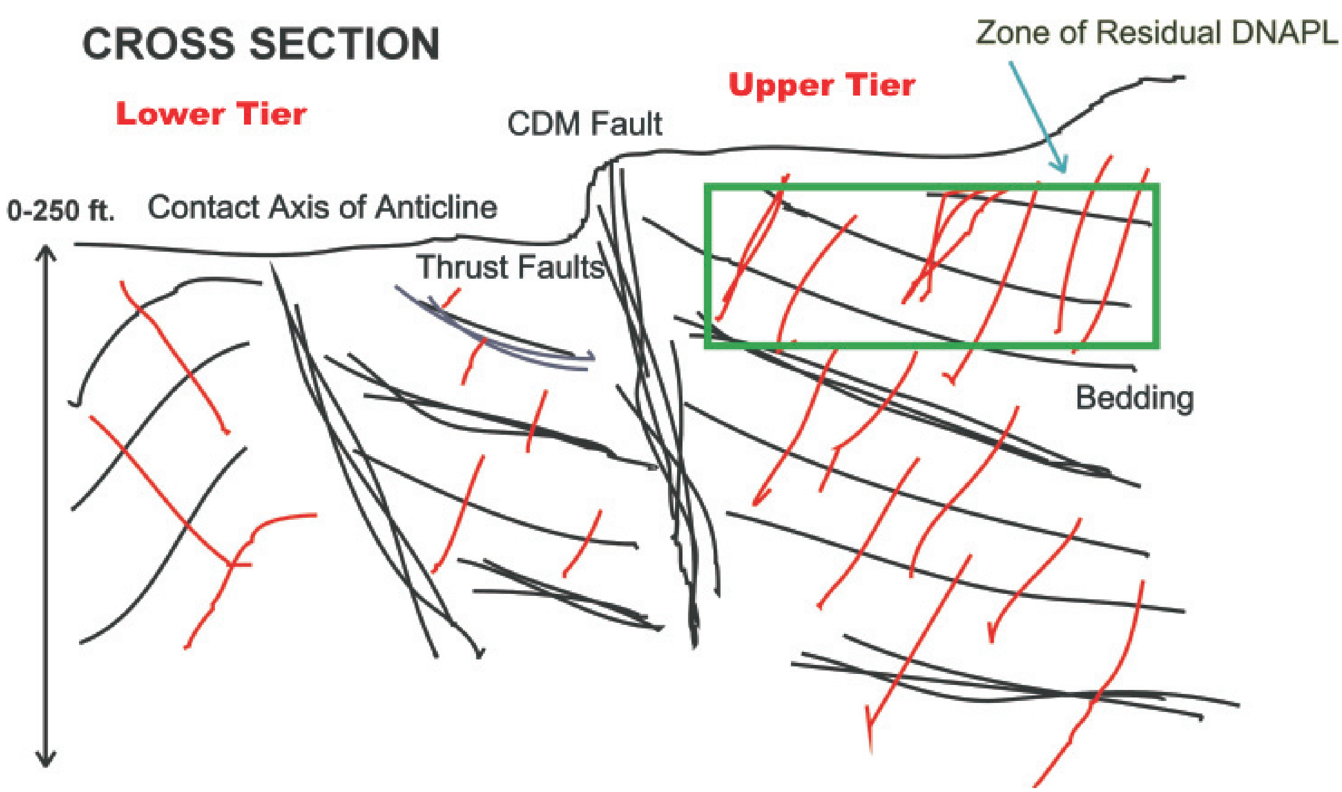

Figure 2.2-3. Diagrammatic cross-sectional representation of the fracturing of the Quarry.

2.4. Contaminant Distribution

Figure 2.4-1 presents a plan view of the Quarry area, showing wells used for characterization prior to the SER research project. Field programs between 1994 to 1998 defined a narrow plume of chlorinated solvents with a limited fuel component that originates in the upper tier and was initially believed to discharge into the Quarry wetland. Dissolved-phase concentrations within the upper tier are suggestive of the presence of DNAPL. PCE was the most-commonly detected chlorinated solvent, and the maximum concentration detected was 38 mg/l at 21 meters (70 feet) bgs in well JMW-0201. JMW-0201 also had the maximum concentrations found for trichloroethylene (TCE) (8.1 mg/l), cis-1,2-dichloroethylene (DCE) (5.5 mg/l), and vinyl chloride (0.076 mg/l). High concentrations of carbon tetrachloride (4.3 mg/l) were found in JBW-7821, while JBW-7817B contained the highest concentrations of benzene (24 mg/l) and toluene (360 mg/l). Other maximum ground water concentrations for the contaminants of concern include 1,2-dichloroethane (DCA), (0.021 mg/l) in JBW-7818 and naphthalene (0.018 mg/l) in JBW-7817A. Concentrations of PCE in the lower tier drop off by more than two orders of magnitude over a distance of approximately 45 meters (150 feet). Wells to the east of the upper tier contained fuel components, including benzene, toluene, ethylbenzene, and xylenes (BTEX), at high concentrations.

Plate 2.4-2 is true-scale cross-sectional representation of the contaminant distribution beneath the upper tier (HLA, 1999c). According to the Phase II Data Report and Interpretation (HLA, 1999c), it was believed that PCE was released in the area around JBW-7816, JBW-7817 and JMW-0201, and migrated vertically through axial plane and regional joint fracture systems to the bedding plane fractures, where a majority of the spent solvent appeared to be stored. The lateral extent of the PCE DNAPL was believed to be limited to the upper tier in this area, although its distribution was not well constrained, particularly to the north. The vertical distribution of CVOCs was generally thought to be limited primarily to the upper 30 meters (100 feet) of bedrock, although the only deeper borehole in the vicinity at that time, JBW-7816, showed concentrations of approximately 0.040 mg/l at depths up to 45 meters (149 feet) bgs. Based on color, relative observed viscosity, and chemical results, it was believed that LNAPL identified in JBW-7817 was an oil lubricant, and the LNAPL in JBW-7819 was a mixture of weathered fuel (presumably gasoline) and possibly

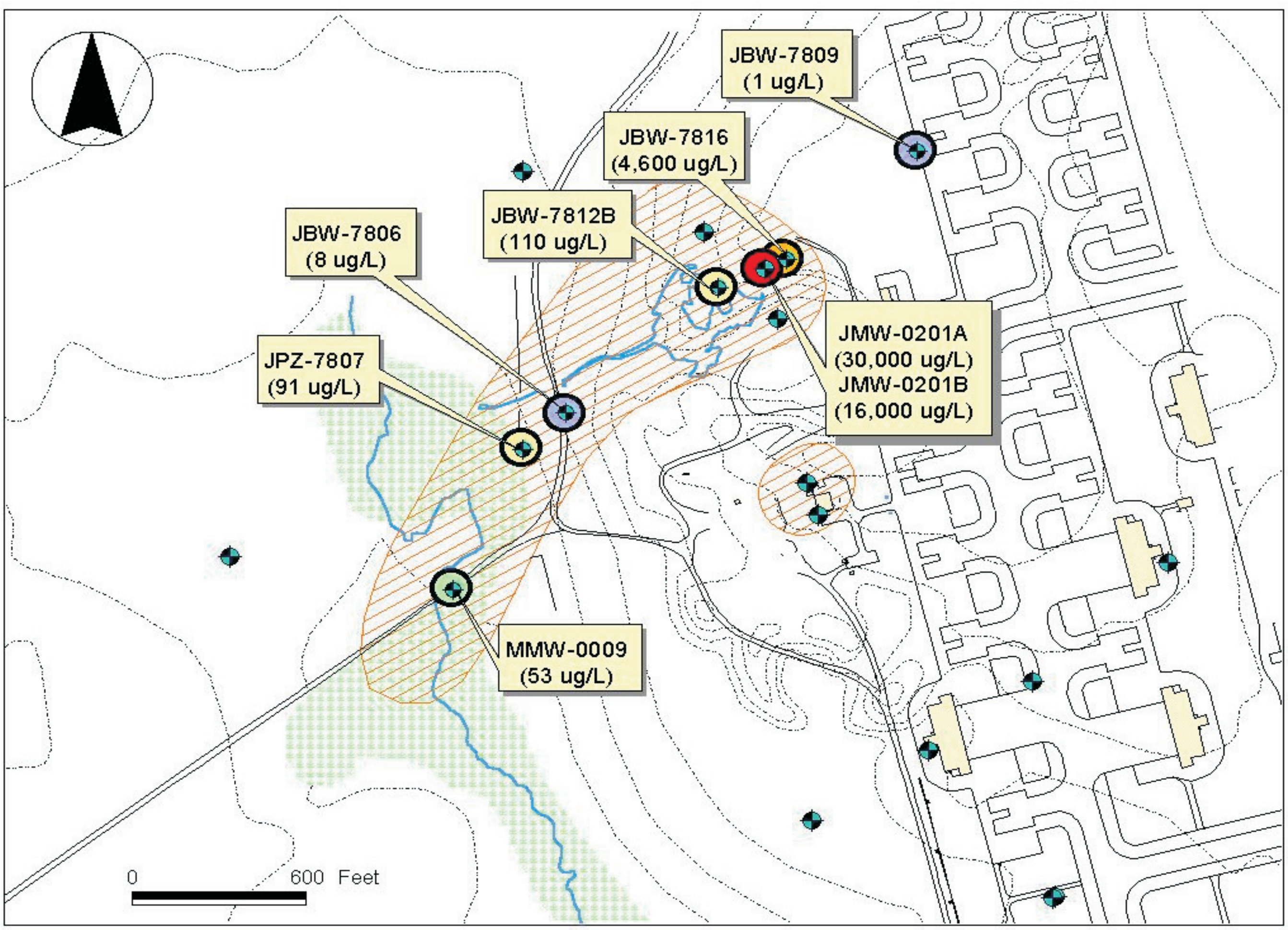

Figure 2.4-1. Loring Quarry PCE plume map.

lubricants. The detection of other chemical species, including carbon tetrachloride, carbon disulfide, and chloroform in wells JBW-7821 and JBW-7818, suggests a hydraulic and source relationship between these two wells that is not directly related to the source of PCE in JMW-0201, JBW-7816, and JBW-7817A.

2.5. Initial Conceptual Site Model

The conceptual site model (CSM) which emerged after the completion of the Phase I and II investigations can be summarized as follows. The upper tier was believed to be comprised of a more or less contiguous block of rock which was bound on the west by the CDM fault, and "floored" by a series of bedding-parallel, NE-dipping, thrust and/or reverse faults. On the basis of outcrop observations, the CDM fault was thought to generally represent a significant geologic boundary. East of the CDM fault, in the upper tier, a complex but somewhat regular series of geologic features were identified, which included the following:

- ***Bedding Plane Fractures***: parallel or subparallel to bedding and bedding-parallel faults, strike NW-SE, moderate dips to the NE;
- ***Axial Plane Fractures*** (i.e., those fractures parallel to the central axis of the regional fold system): strike NE-SW, dip steeply either to the NW or SE, with moderate to steep dips;
- ***Regional Joint Fractures***: strike NW-SE and dip steeply either to the SW or NE at a variety of dip values (mainly steep dips).

Of these features, bedding plane fractures were believed to be the most significant with respect to ground water movement (and contaminant transport) as they accounted for over half of all fractures identified, contained the largest apertures observable from cores, and were believed to account for the majority of the responses measured during hydraulic testing.

Chemical weathering of the rock mass was generally observed to be quite limited, particularly as evidenced from fresh subsurface core samples, and fracturing was generally sparse. The bedrock ground water flow system was, therefore, generally conceptualized as a system dominated by fracture-controlled flow within a low permeability matrix. On a site-wide scale, ground water flow gradients were generally observed to be westward from the upper tier, toward the lower tier, the Quarry Wetlands, and the West Branch of Greenlaw Brook. Vertical gradients in the upper tier were generally downward, and upward gradients were observed in the vicinity of the surface water features to the west. However, this simple model did not consider hydrogeologic controls on ground water flow other than at the gross, site-wide scale. For example, the CDM fault's relationship to ground water flow and contaminant transport was not examined, but the fault's orientation and geologic character suggested that it might act to impede, or at least influence, the more generalized ground water movement from east to west. Bedding and the CDM fault both strike more or less orthogonally to the presumed east-to-west general ground water flow direction; however, the existing wellfield density was not sufficient to resolve the head-field gradients or to identify specific fracture-controlled ground water pathways in greater detail with respect to this feature or within the upper tier generally. Further resolution of ground water flow pathways was beyond the scope of the Phase I and II characterizations.

Contaminant distribution data from the upper tier suggested that it contained more than one source zone. Contaminants were believed to be located mostly in the hydraulically dominant bedding plane fractures. Ground water contaminant concentrations in the upper tier suggested that DNAPL was present (believed to be primarily residual DNAPL); however, it was believed that the residual DNAPL was confined to the upper tier, as concentrations in wells in the lower tier were lower by several orders of magnitude. Beneath the upper tier, the source zone was defined, mainly based on ground water samples, to generally coincide with a region of dissolved CVOC values greater than 1 mg/l. This source region was thought to be generally controlled by bedding parallel fracturing as it indicated a similar geometry to bedding, i.e., moderately dipping to the northeast. The high-concentration zone was identified from roughly 9 to 20 meters (30 to 65 feet) bgs on the western side of the upper tier, and deeper on the eastern side, from roughly 14 to 29 meters (45 to 95 feet) bgs.

While the rather strong influence of bedding dip on contaminant distribution was clear, it was less clear that this alone explained the source zone geometry, or whether these were the primary contaminant migration pathways within and beyond the upper tier. Nevertheless, to a large extent, this CSM, and its inherent limitations, guided the initial decisions with respect to the area to be targeted for remediation, injection and extraction well placement, depth of treatment, and the overall geometry of the subsurface elements of the SER system. Not surprisingly, information collected from the installation of the first series of SER wells dictated changes in the CSM, which are described in subsequent chapters.