Characterization of Fractured Rock - A Case Study: Red Devil Mine, Alaska

Characterization and Remediation of Contaminated Groundwater in Fractured Rock

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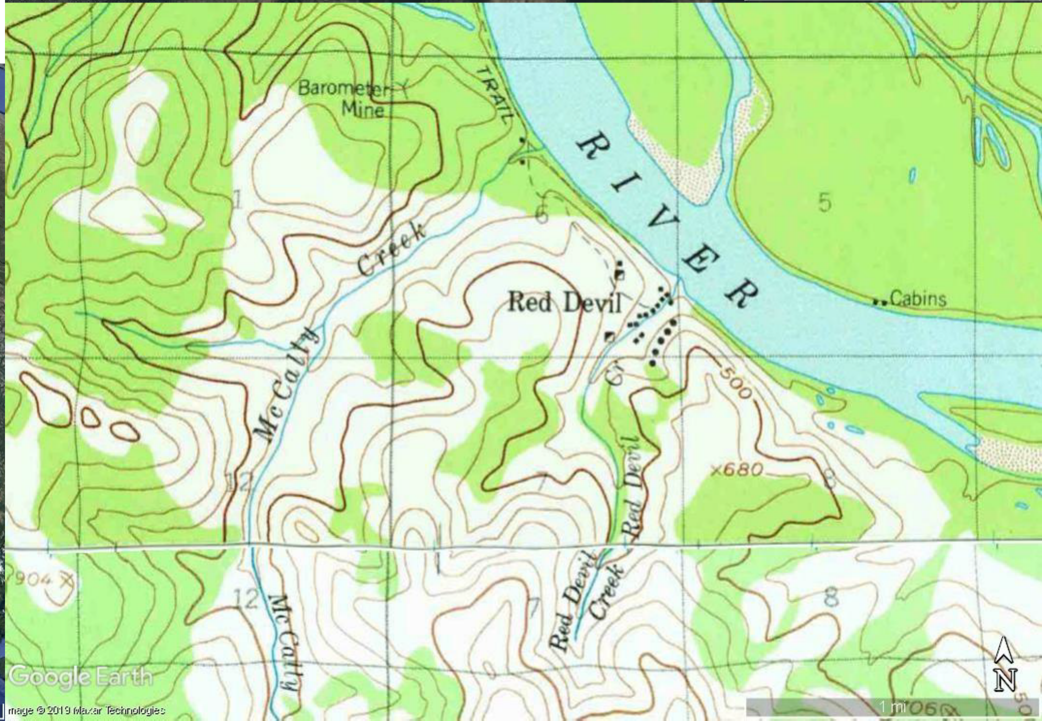
Red Devil Mine

- Abandoned mercury mine and ore processing facility on land managed by BLM in southwest Alaska 250 miles west of Anchorage.
- Southwest bank of Kuskokwim River approximately 1.5 miles from village of Red Devil.
- Historical mining operations left mine waste and other remnants that have affected soil, sediment, groundwater, and surface water.



Studies and Cleanup Activities

1971-2009:

- Various studies by USEPA, ADEC, BLM, USGS
- 1999-2009: Investigations and limited removal and other cleanup activities by BLM

2009: BLM initiated CERCLA Remedial Investigation/Feasibility Study (RI/FS)

- Nature & extent, fate & transport, human health and ecological risk
  - Mine waste, soil, creek and river sediment, groundwater, surface water, biota
- 2012-present: Groundwater and surface water baseline monitoring
- 2014: Non-Time Critical Removal Action
- 2015-2019: RI/FS Supplement for groundwater and Kuskokwim River sediment
- 2017-2019: Additional groundwater and tailings/waste rock characterization

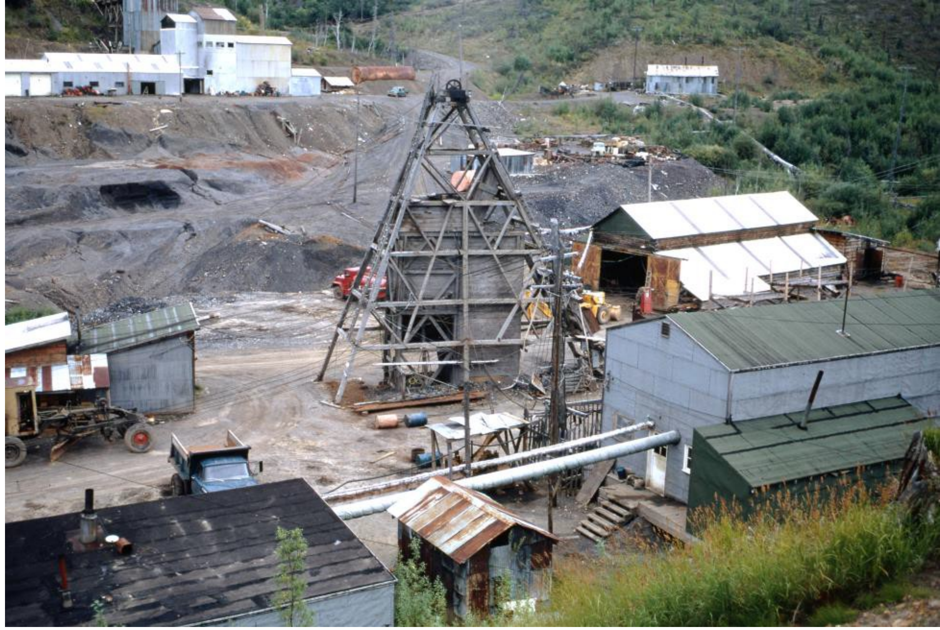
2010: USGS geophysical survey

2010-2017: BLM and USFWS Kuskokwim River investigations

Mineralization

- Primary ore mineral: Cinnabar (HgS).
- Stibnite (Sb_2S_3) also abundant.
- Small amounts of orpiment (As_2S_3) and realgar (As_4S_4) locally.
- Gangue minerals: quartz (SiO_2), white clay, calcite ($CaCO_3$).
- Rare pyrite (FeS_2) locally.
- Other associated mineral: and dickite ($H_4Al_2Si_2O_9$).

Mining Operations



1933 discovered cinnabar float in Red Devil Creek.

1940s:

- Surface exploration (trenching)
- Underground mining via two adits and a shaft
- Not operational 1947 to 1951

1950s:

- 1952 production resumed
- 1954 fire destroyed mine structures and processing facilities on N side of creek
- 1955 new processing equipment and other facilities on S side of creek

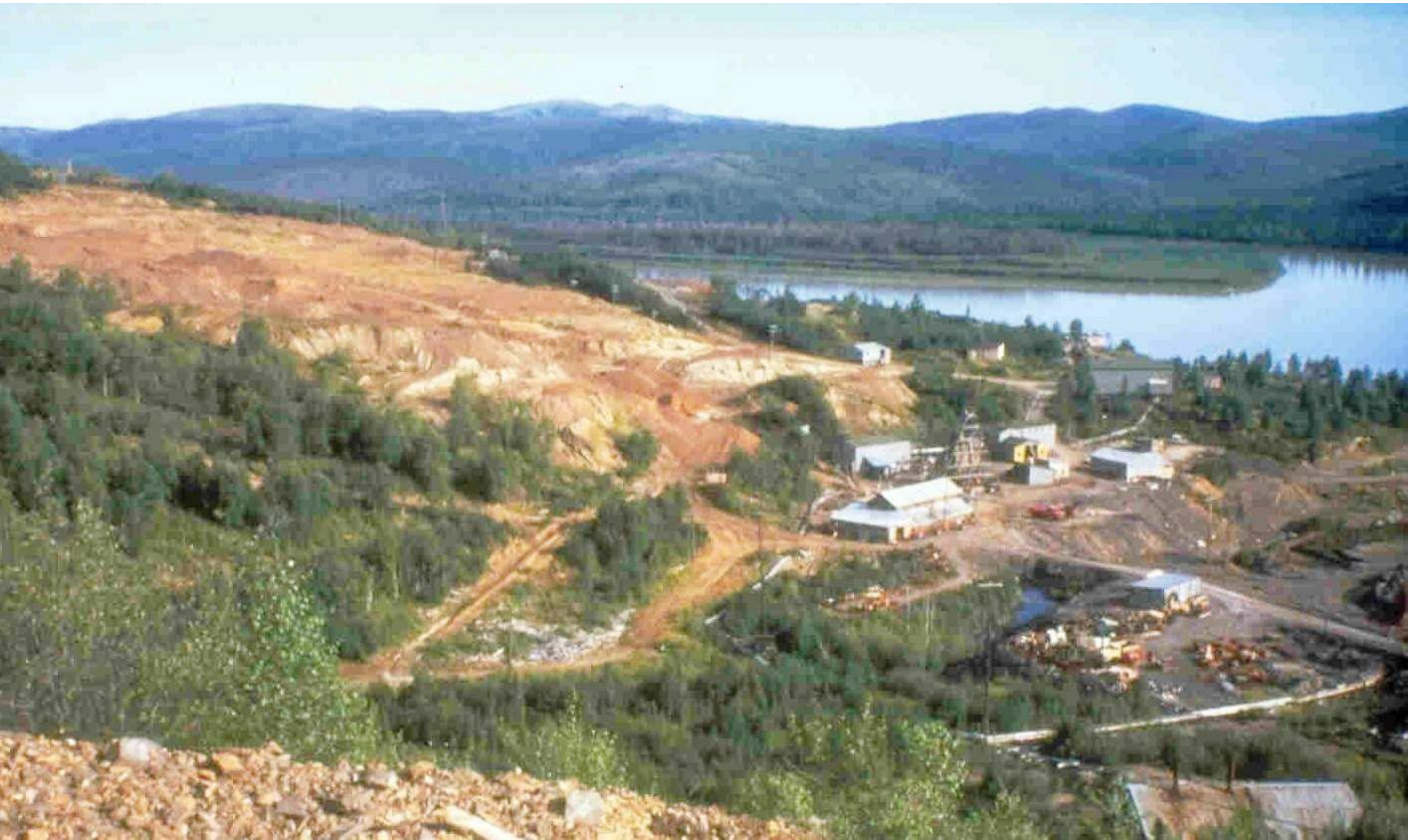
1960s:

- Surface mining and exploration (sluicing of overburden, trenching, pits)
- Underground mining via Main Shaft and other shafts
- In 1963, new adit reportedly driven near Red Devil Creek (location not known)
- Not operational 1964-1969

Mining Operations (cont.)

1969: Resumed underground and surface mining (trenching, bulldozing, pit, and possibly sluicing)

1971: Ceased operations. Dewatering of the underground workings continued until 1982, when mine was closed.



Red Devil Mine in 1971, including the Surface Mined Area on upper left.

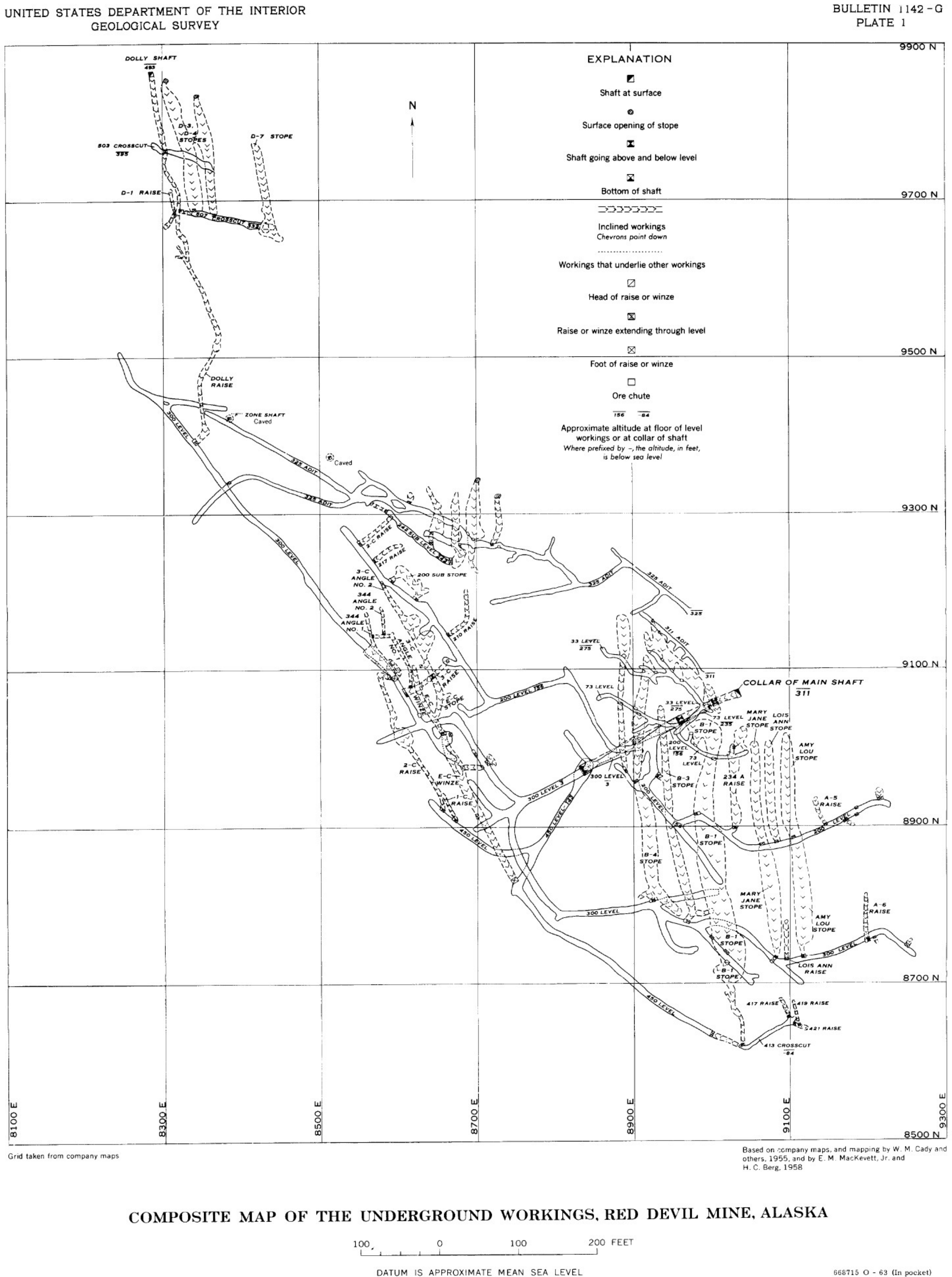
Mine Mapping and Studies

USGS

MacKevett, E.M., and H.C. Berg. 1963. *Geology of the Red Devil Quicksilver Mine, Alaska*. Geological Survey Bulletin 1142-G.

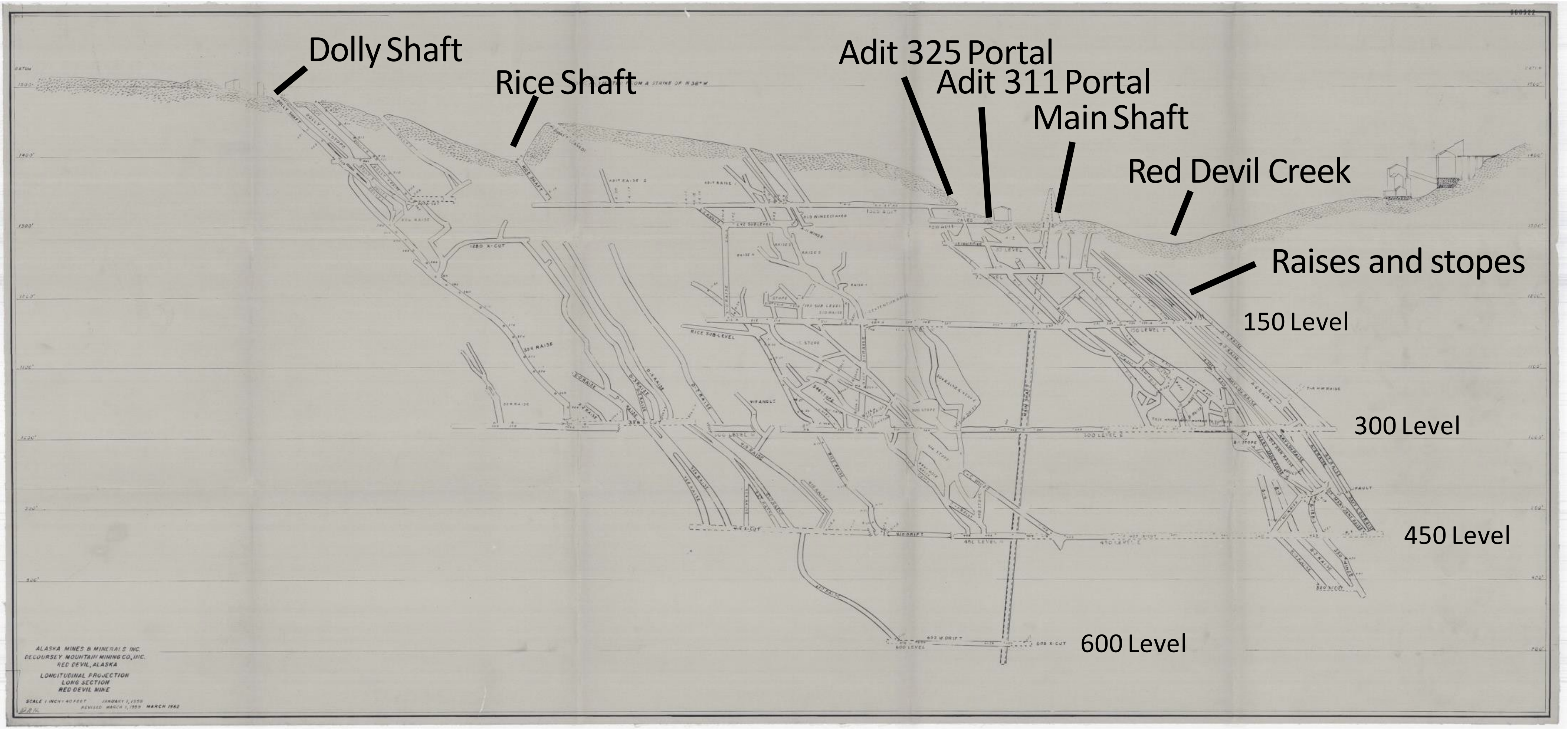
US Bureau of Mines

Malone, K. 1962. *Mercury Occurrences in Alaska*. U.S. Department of the Interior, Bureau of Mines. Information Circular 8131.



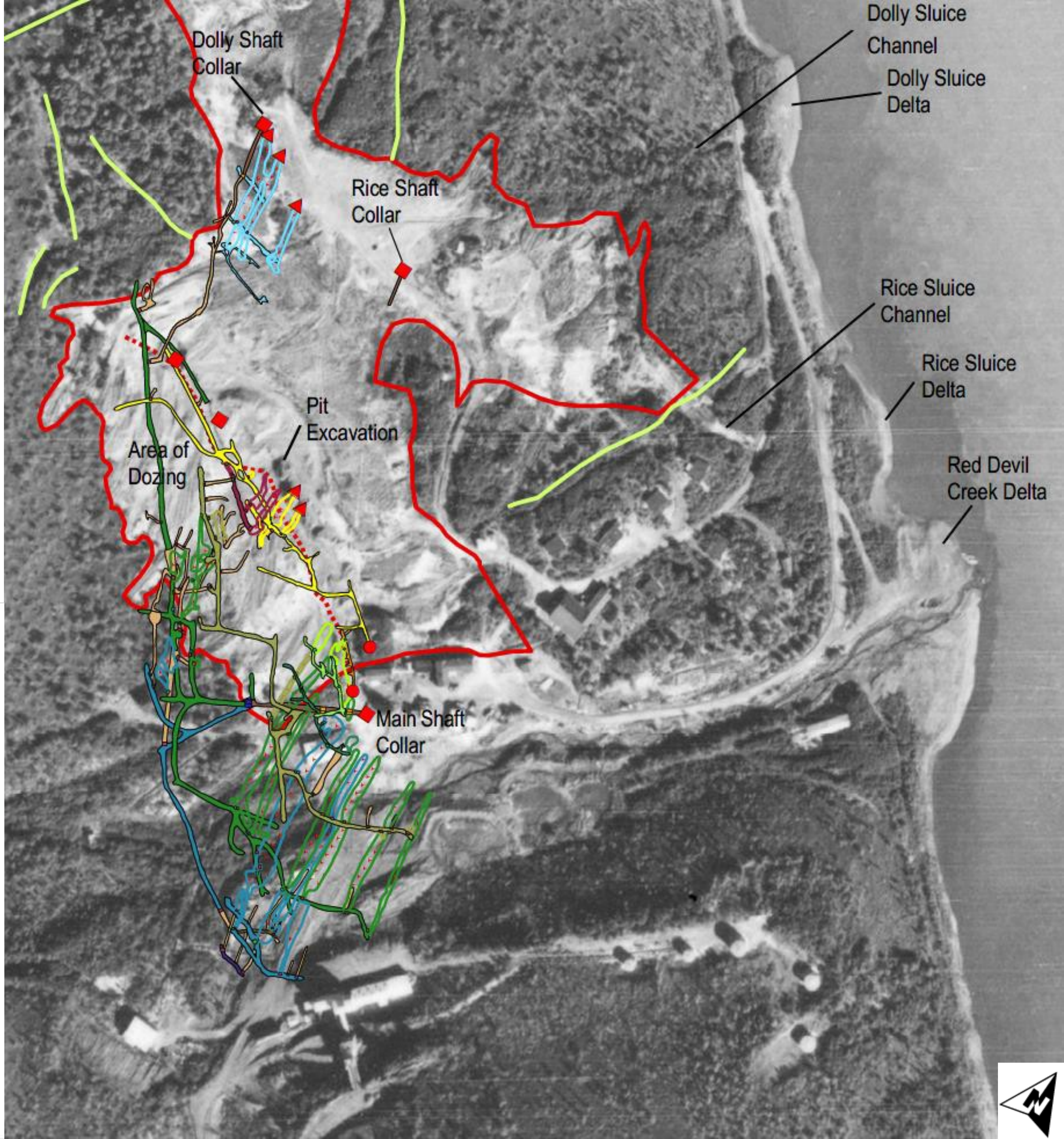
Underground Mine Workings

- As of 1963, 9,600 feet of underground workings (shafts, adits, crosscuts, drifts, raises, and winzes, with workings on five levels). Access via Main Shaft (in Main Processing Area), Dolly Shaft, Rice Shaft, and other small shafts (in surface mined area).



Mine workings cross section as of 1962 (Alaska Mines and Minerals, Inc. and Decoursey Mountain Mining Co., Inc. 1962.)

Surface Mine and Underground Mine (1974 aerial)



Underground Workings

Adits, Levels, and Crosscuts
- Dolly Area Crosscuts
- 325 Adit
- 311 Adit
- 242 Sub-level
- 33 Level
- 73 Level
- 150 Level / 200 Level
- 300 Level
- 450 Level
- 550 Crosscut

Shafts, Raises, and Winzes
- Shaft
- Raise or Winze
- Shaft going above and below level
- Ore shaft
- Stope ("V" points downward)

Other Workings
- Bottom of Shaft
- Foot of raise or winze
- Head of raise or winze

Former Mine Openings
- Adit Portal
- Shaft Collar
- Stope Surface Opening

Sources: Malone 1962 and MacKevett and Berg 1963

Ore Processing

- Waste rock separated from ore at surface in Main Processing Area
- Thermal processing of ore in furnaces and retorts both sides of Red Devil Creek
- Mill and flotation plant operated 1969-1971

Main Processing Area in 1969, showing the flotation mill (left) added to the post-1955 processing building, and the settling ponds.

Mine Waste

Main Processing Area and Red Devil Creek Valley

- Waste rock
- Thermally processed ore (calcines, "tailings")
- Condenser dusts and "slag" including antimony and arsenic oxides
- Flotation tailings (settling ponds)

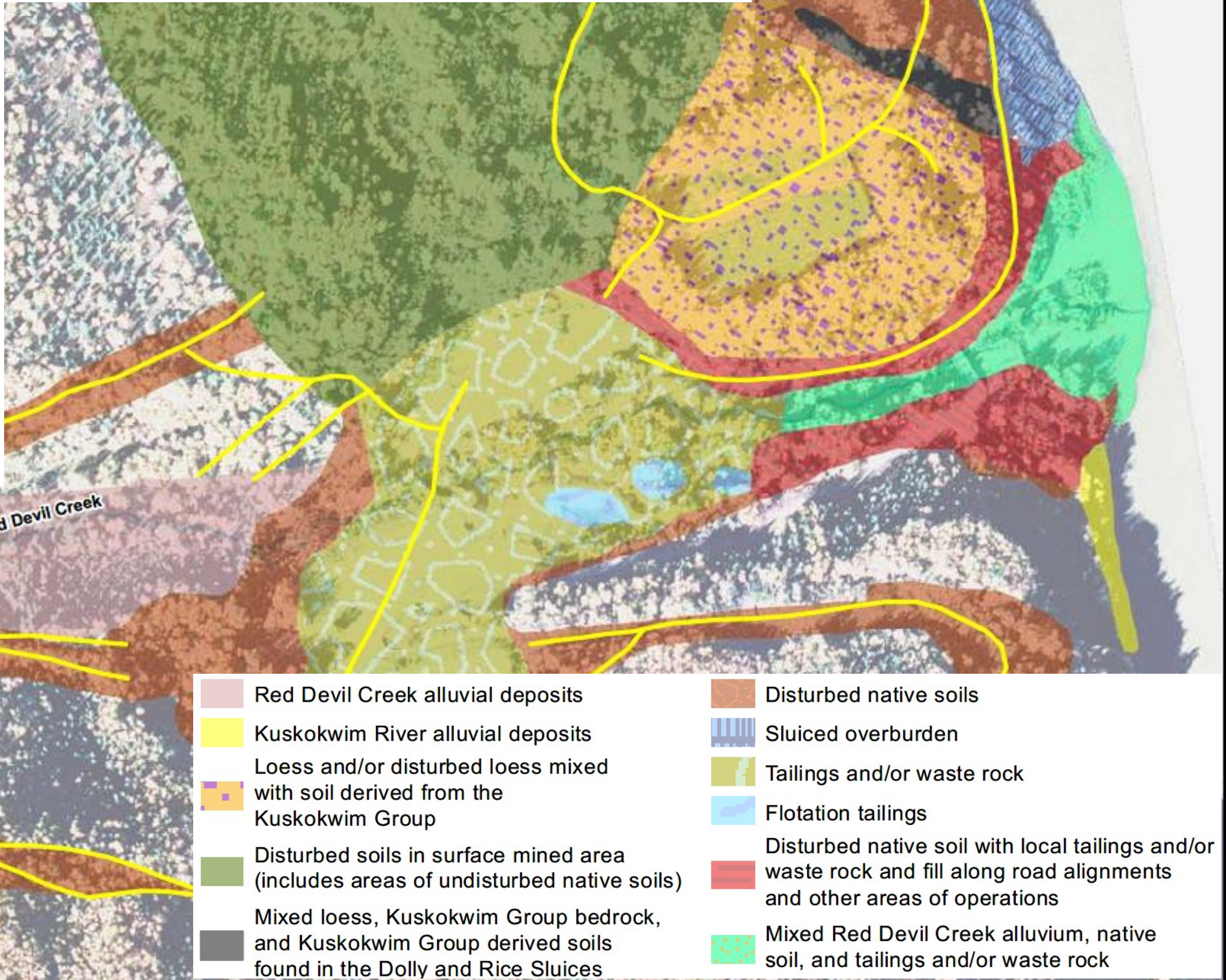
Surface Mined Area and Sluice Deltas

- Dozed and sluiced overburden
- Trench Spoils

Overview of Main Processing Area in 1969 or 1970 from the southeast.

Delineation of Mine Wastes and Native Soils

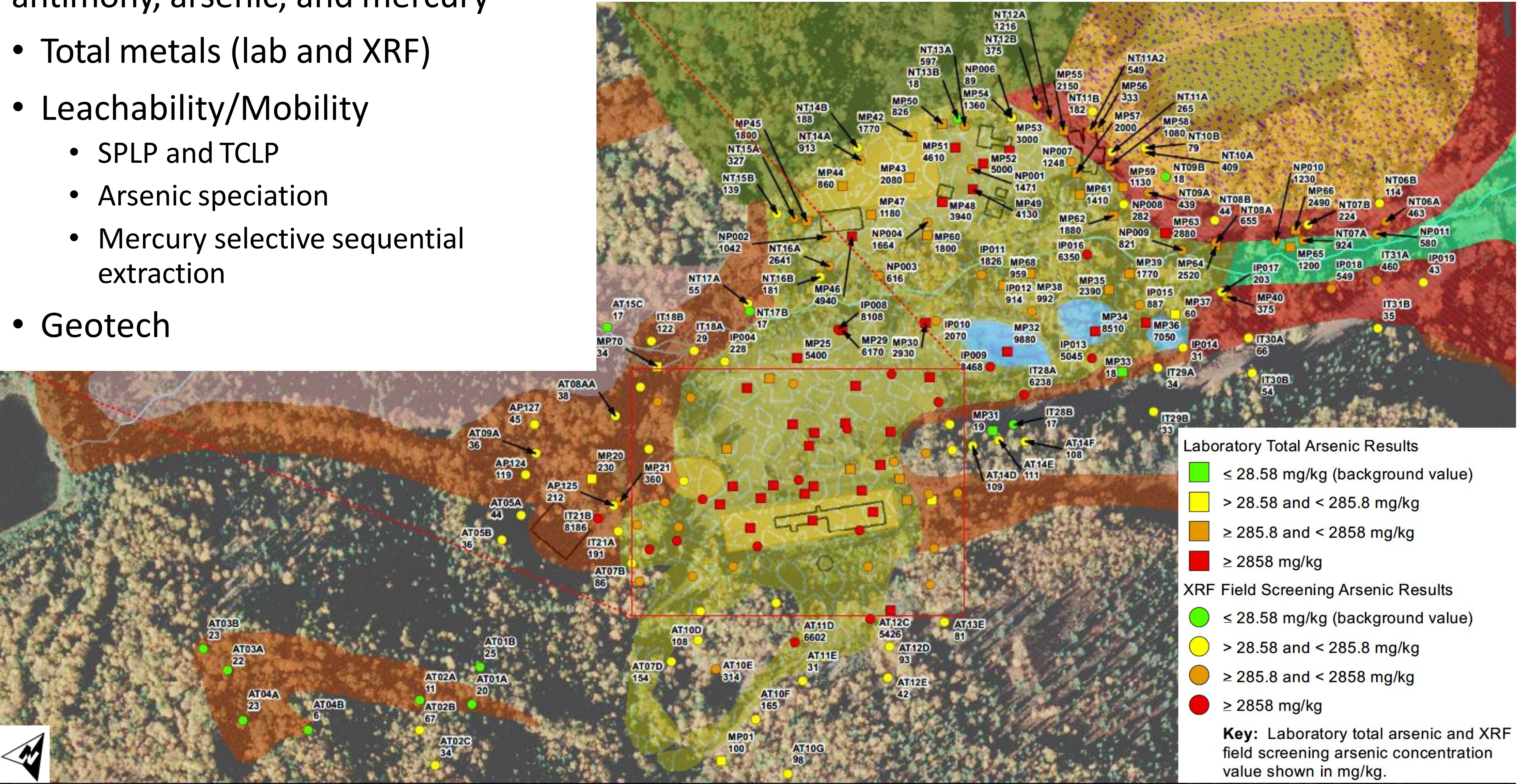
- Historical and recent aerial and land-based photographs, topographic maps, geologic maps, reports of historical mining and ore processing activities.
- Lithology
- Lab and field (XRF) analysis



Primary contaminants of concern: antimony, arsenic, and mercury

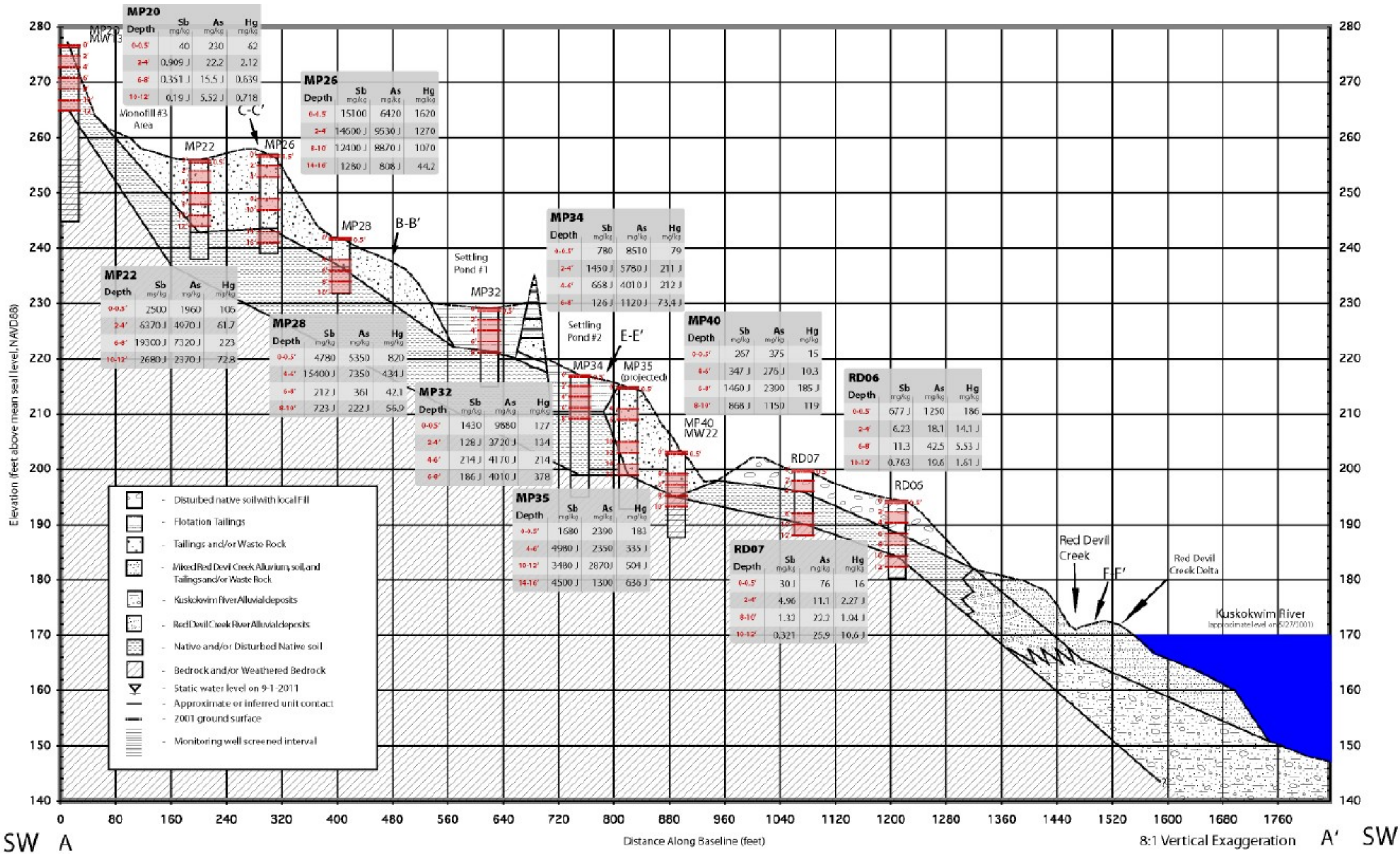
- Total metals (lab and XRF)
- Leachability/Mobility
  - SPLP and TCLP
  - Arsenic speciation
  - Mercury selective sequential extraction
- Geotech

Characterization of Mine Wastes and Soils



Subsurface Identification, Delineation, and Characterization of Mine Wastes and Contaminated Soils

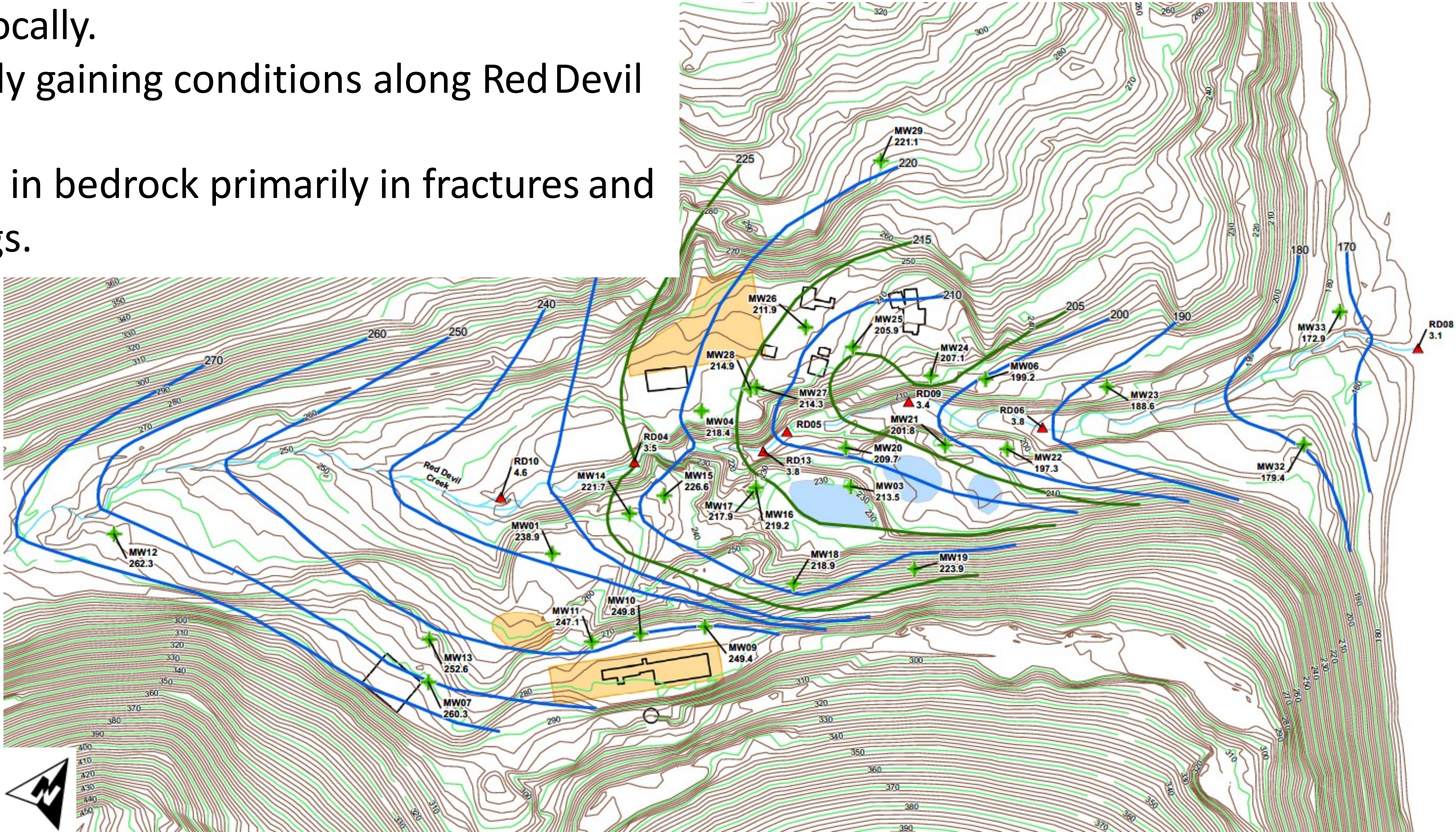
- Mine Waste (waste rock, tailings, flotation tailings)
- Native soil and alluvium
  - Impacted by adsorption of leached contaminants
  - Natural mineralization
- Bedrock



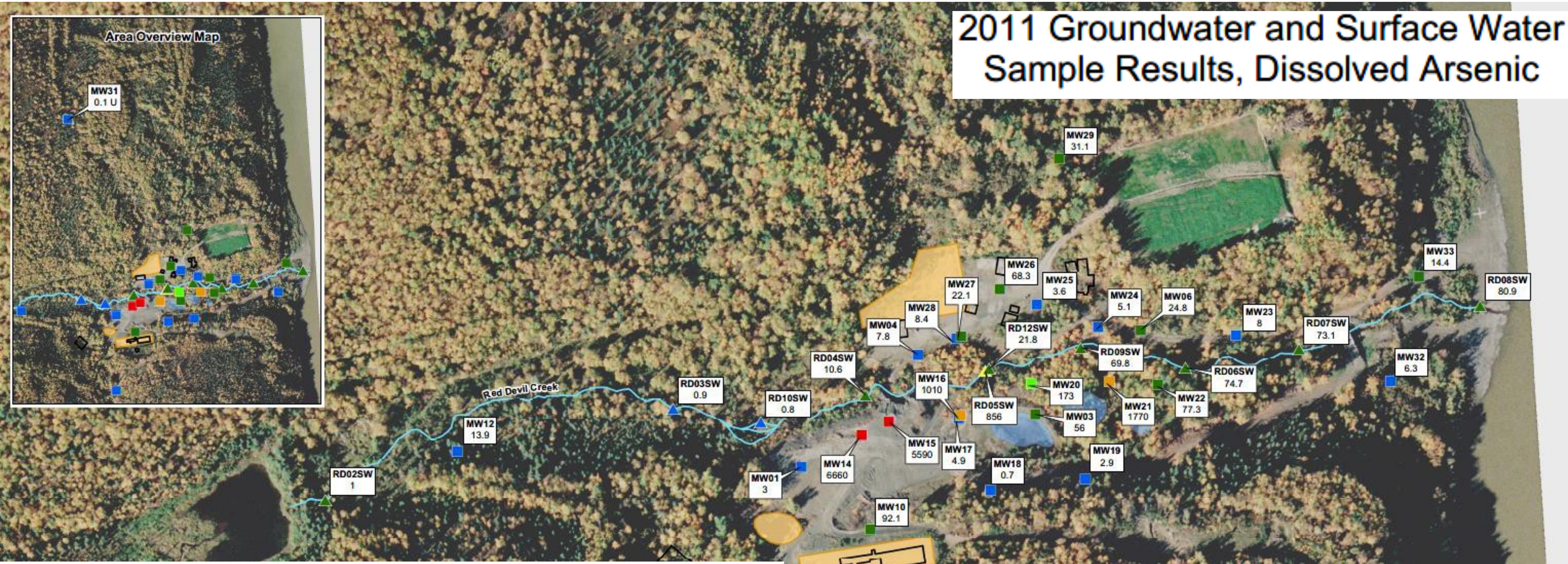
Groundwater and Surface Water Characterization

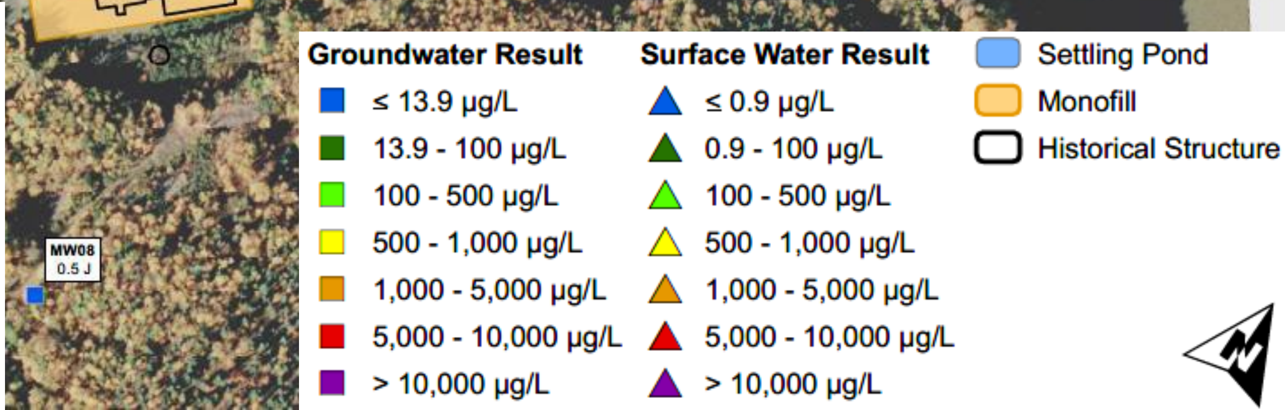
Groundwater

- Groundwater in overburden (mine waste, alluvium, and other native soils) and bedrock in hydraulic communication on scale of site; some segregation locally.
- Predominantly gaining conditions along Red Devil Creek.
- Groundwater in bedrock primarily in fractures and mine workings.



Groundwater

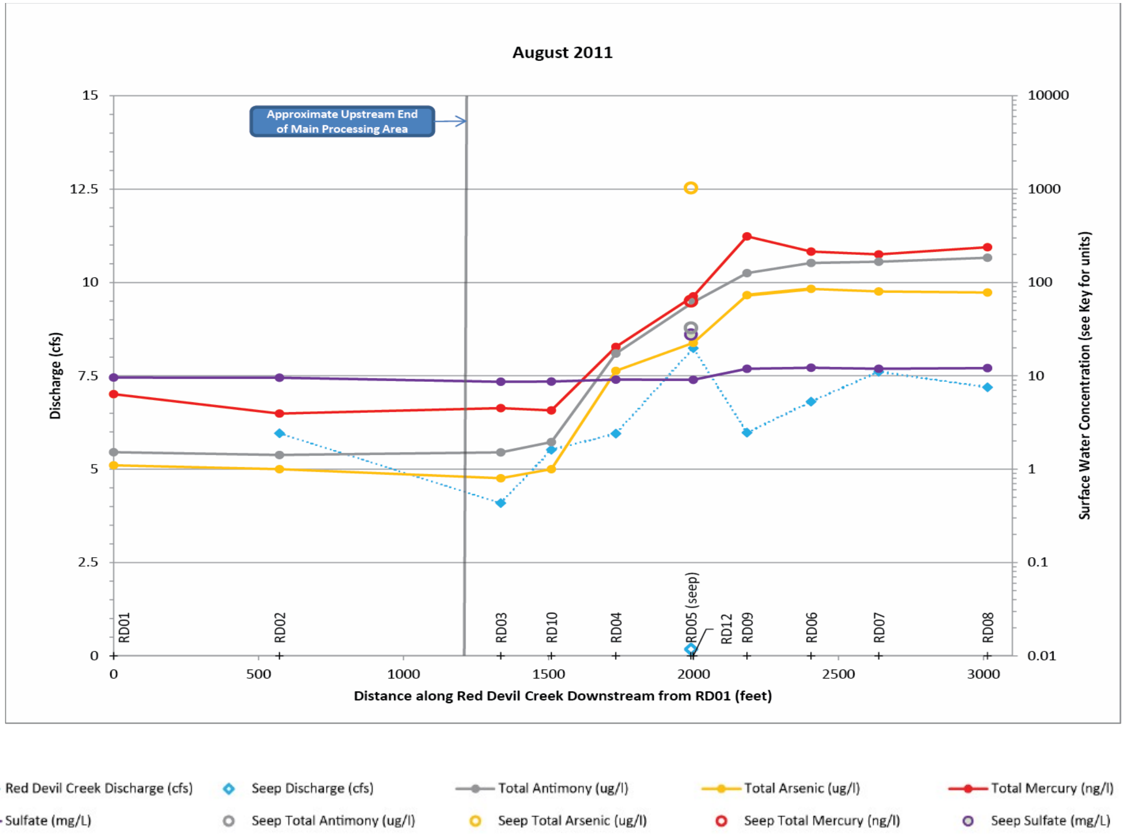


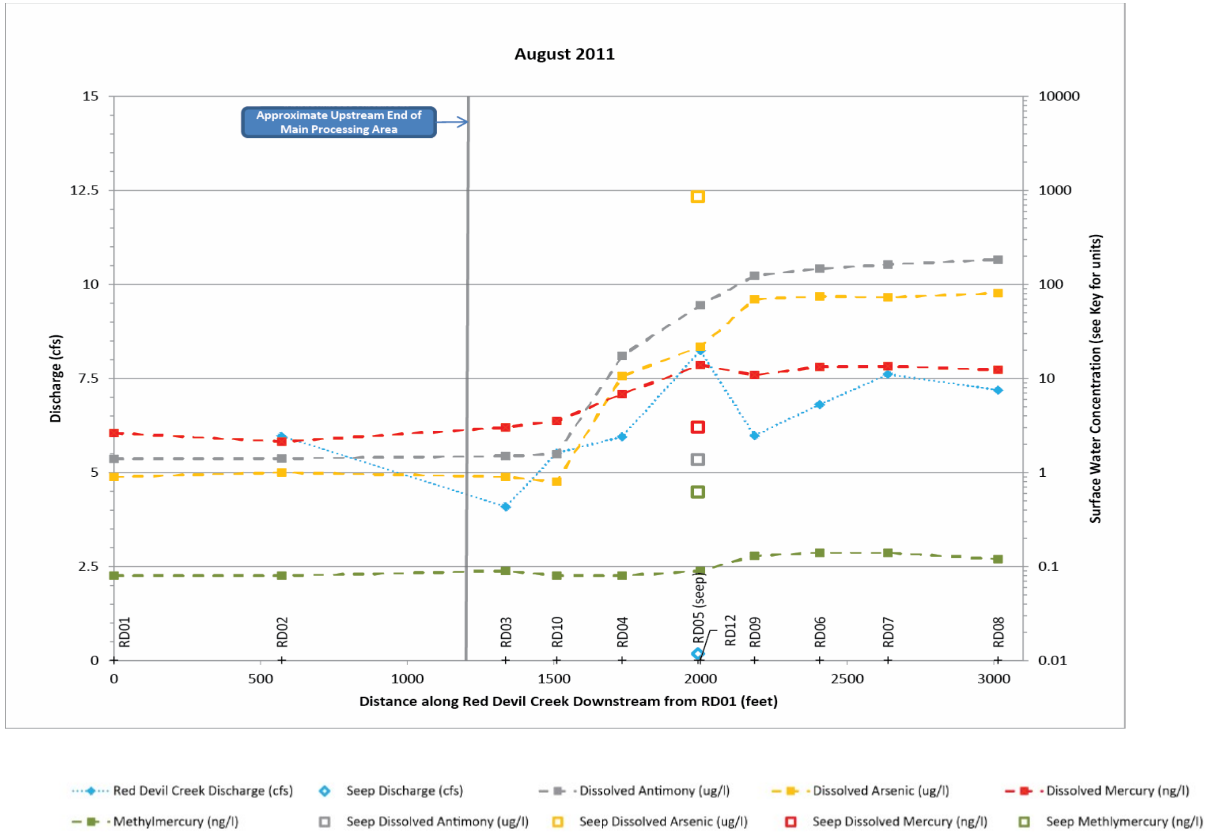


- Groundwater impacted by leaching from mine wastes in vadose and saturated zones.
- Groundwater also influenced by mineralized bedrock and mine workings.
- Seep and nearby baseflow into creek appear related to underground mine workings.

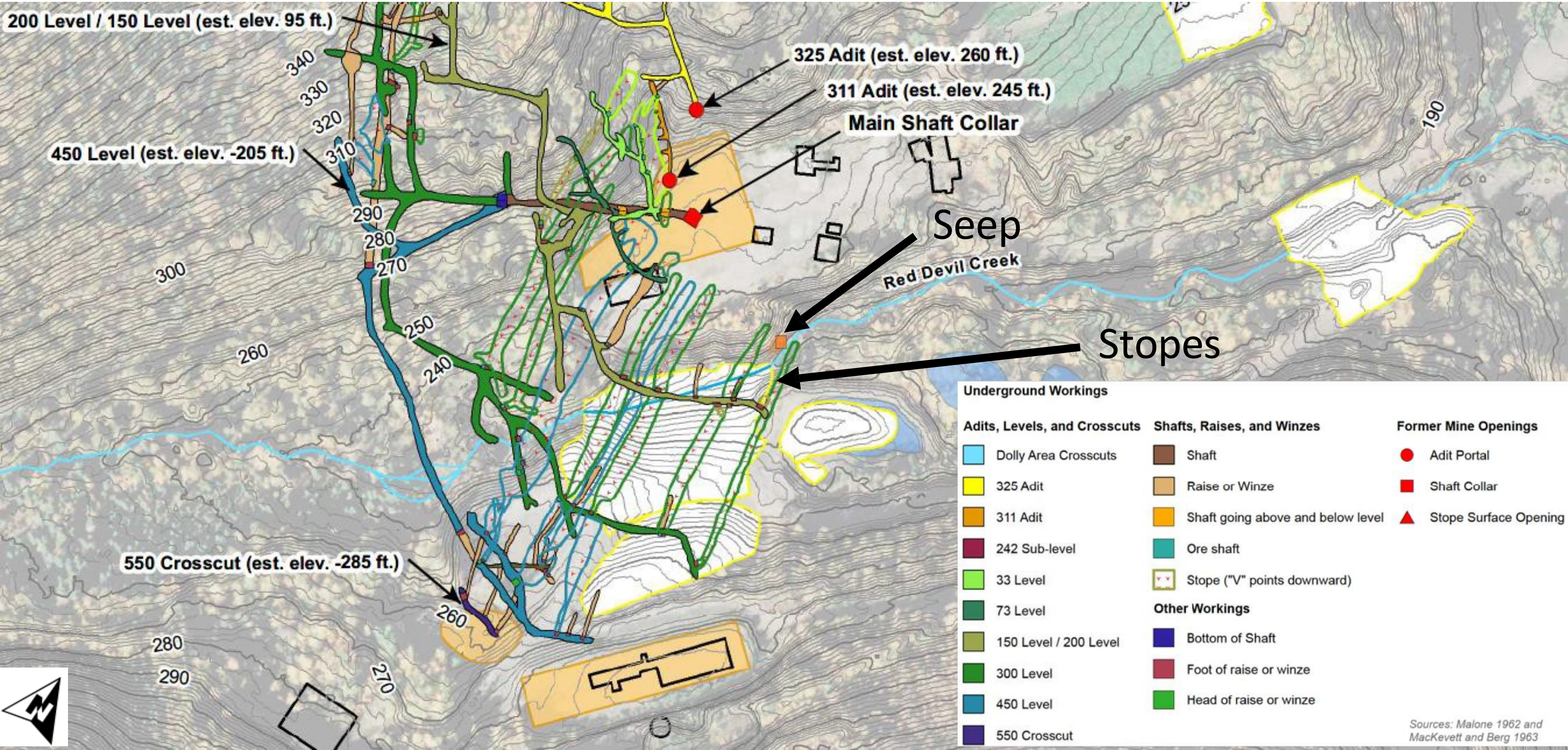
Surface Water

- Red Devil Creek discharge (spring, summer, fall) ranged from <1 to 15 cfs.
- Watershed ~1.08 square miles. Drainage area of mine ~0.16 square mile. Increase in stream discharge generally proportionally to associated drainage area.
- Antimony, arsenic, and mercury increase within and downstream of the Main Processing Area.
- Surface water impacts largely from mine waste in Main Processing Area.
- Some contribution from bedrock and mine workings.





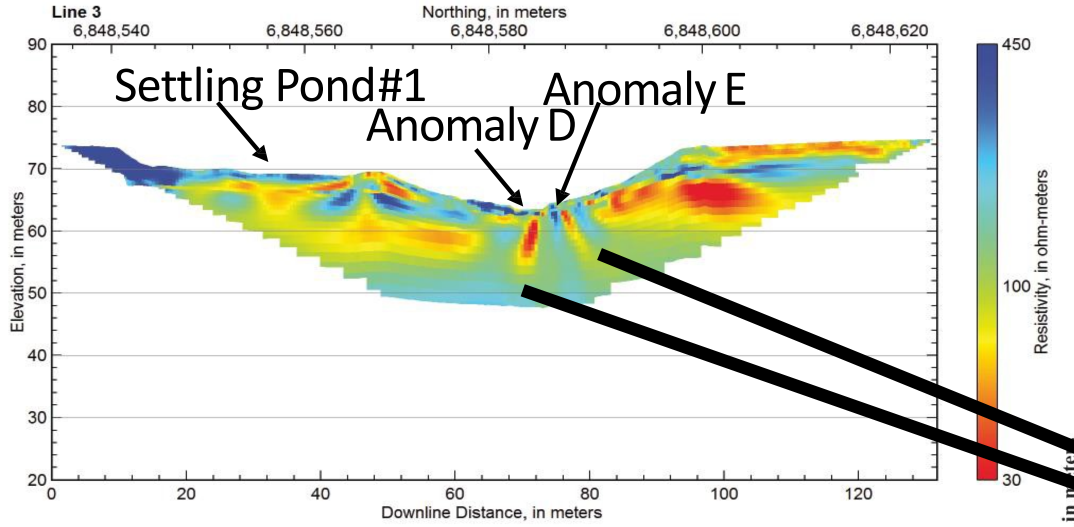
Mine Workings Near Seep in Main Processing Area

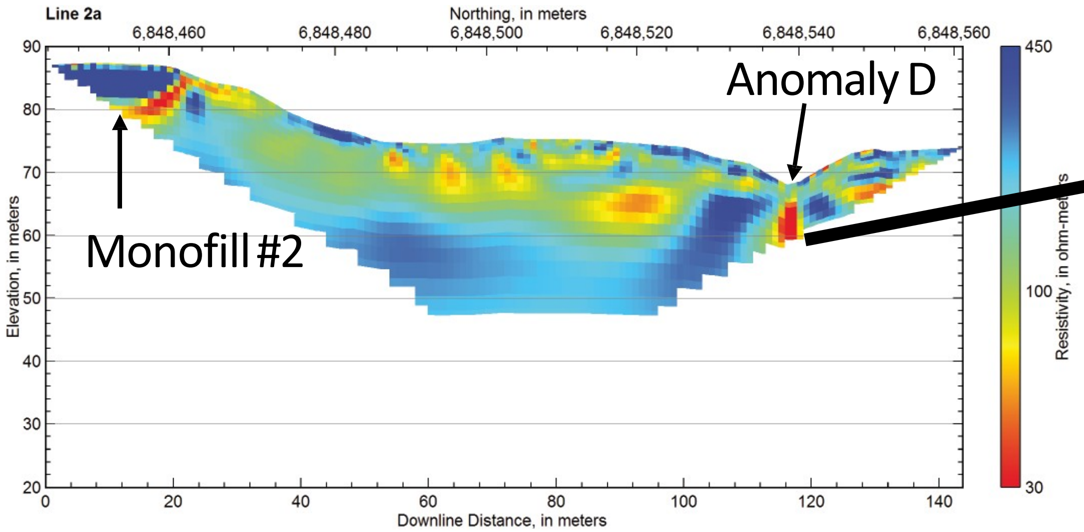


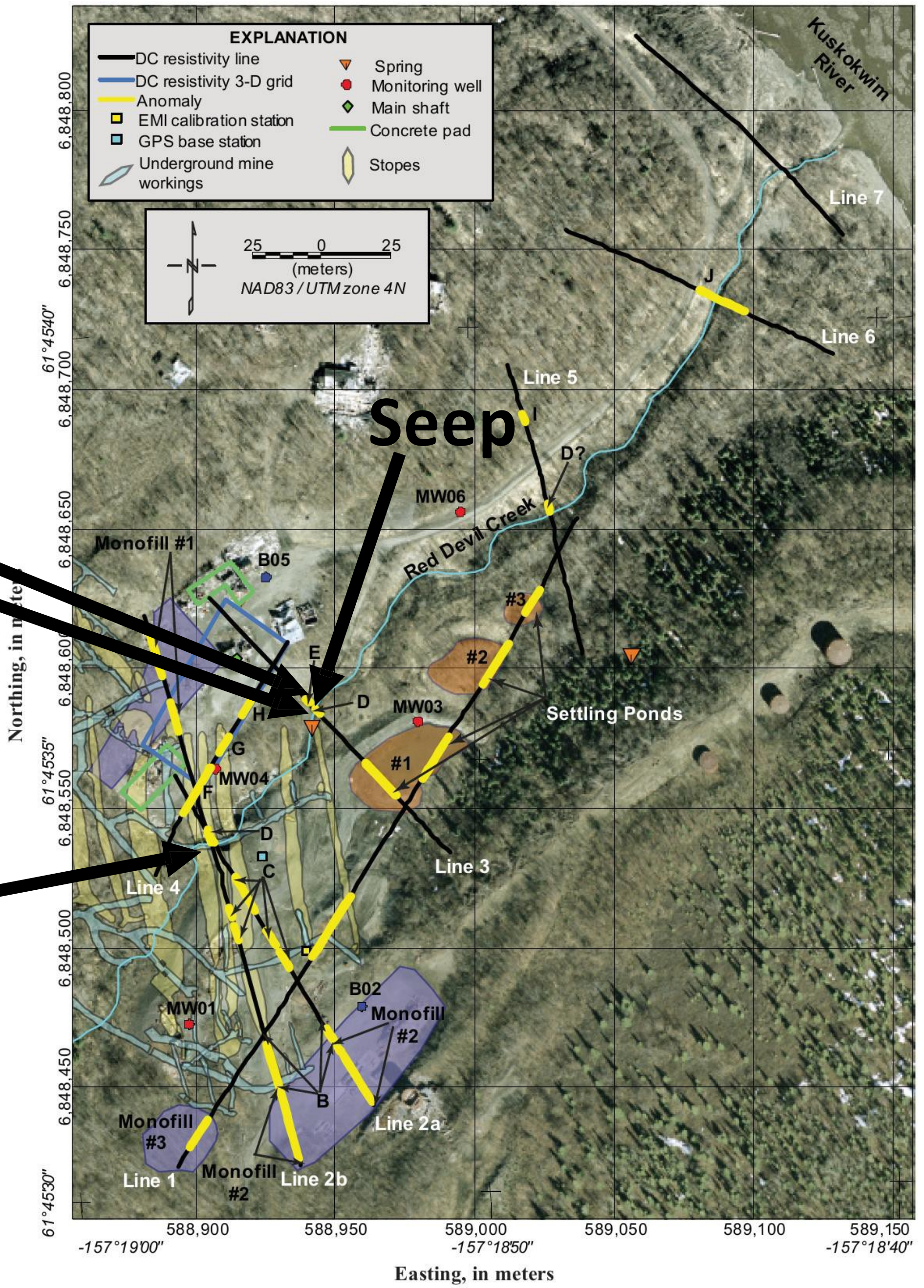
2010 USGS Geophysical Survey

Burton, B.L., and L.B. Ball (2011)

- Strong, conductor (Anomaly D) below creek in lines 2a, 2b, 3, and possibly 5 (further downstream).
- Discrete, nearly vertical conductive anomaly (E) near spring near Red Devil Creek.
- No obvious shallow source of the spring.

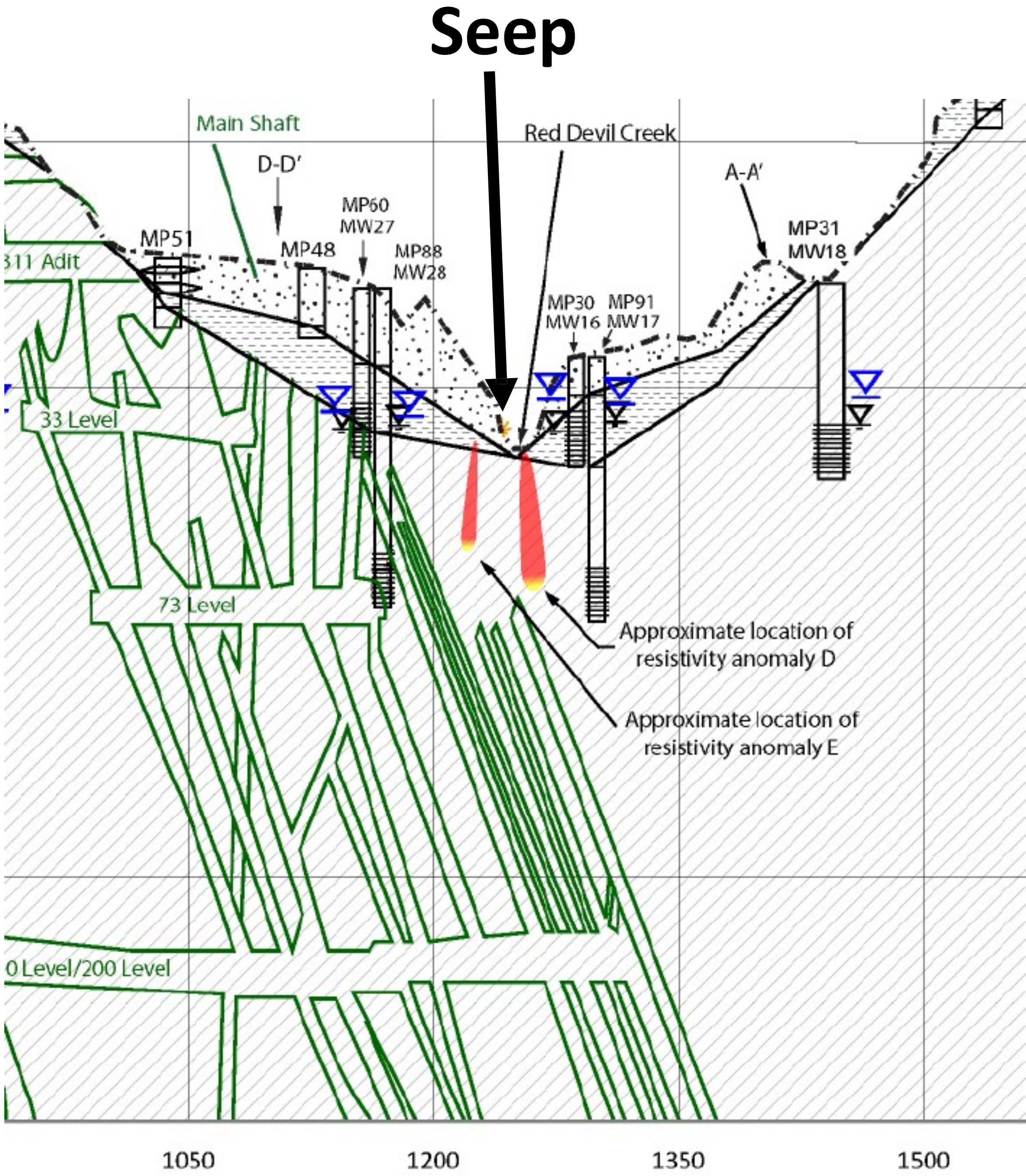






Resistivity Anomalies and Mine Workings near Red Devil Creek and Seep

- Resistivity anomalies D and E appear associated with stopes below creek.



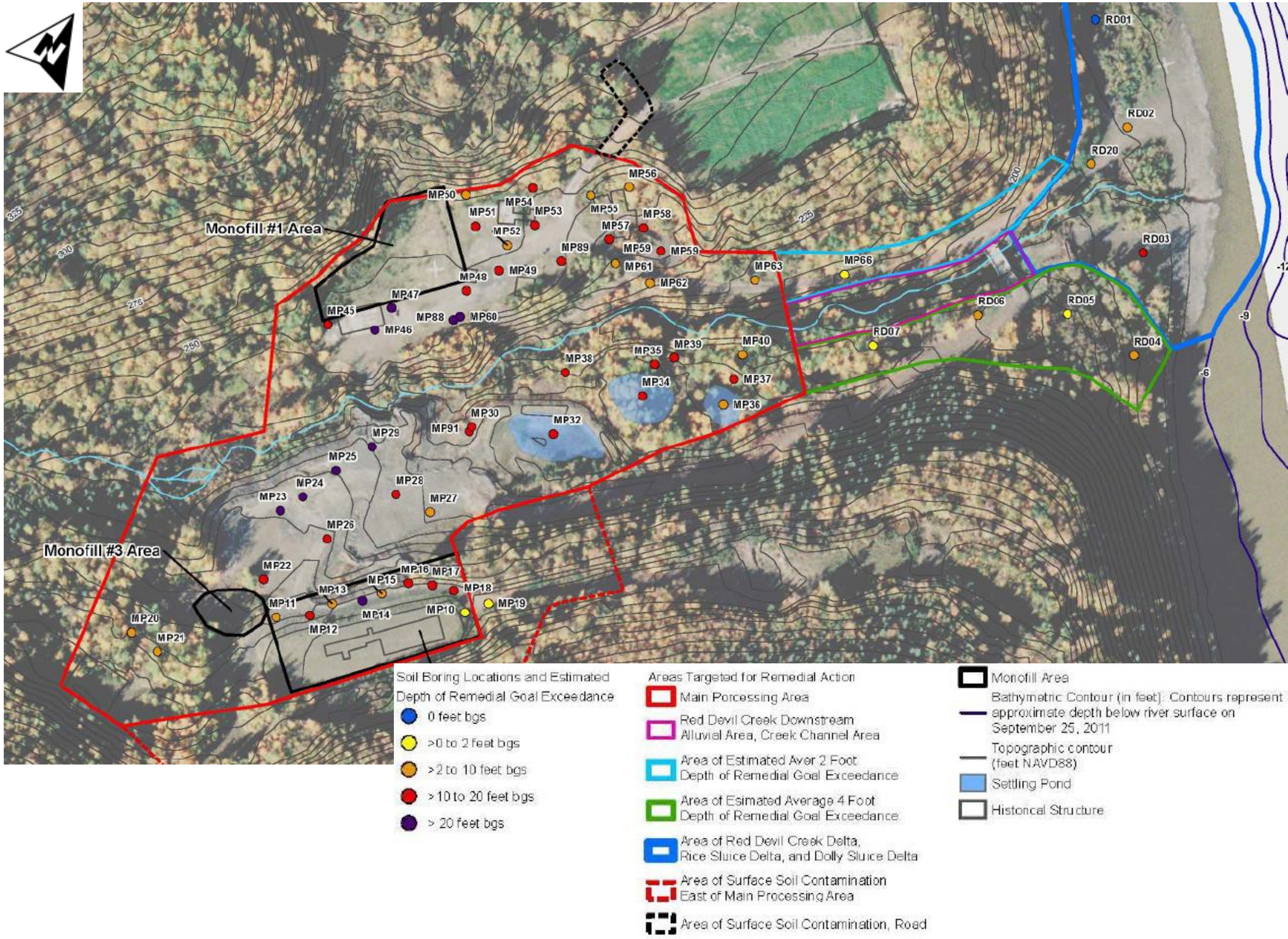
Feasibility Study (2016)

<u>Alternative 1</u>: No Action.

<u>Alternative 2</u>: Institutional and Access Controls.

<u>Alternative 3</u>: Excavation of and Onsite Consolidation of tailings/waste rock, soil, and Red Devil Creek sediment. Includes 4 sub-alternatives.

<u>Alternative 4</u>: Excavation and Offsite Disposal of tailings/waste rock, soil, and Red Devil Creek sediment.



RI Groundwater and Surface Water Characterization Challenges

- Overlap of groundwater and surface water impacts derived from mine waste with those influences derived from naturally mineralized rock/soils and mine workings within the Main Processing Area.

- Lack of information regarding influence of naturally mineralized bedrock and mine workings on groundwater flow paths and quality.

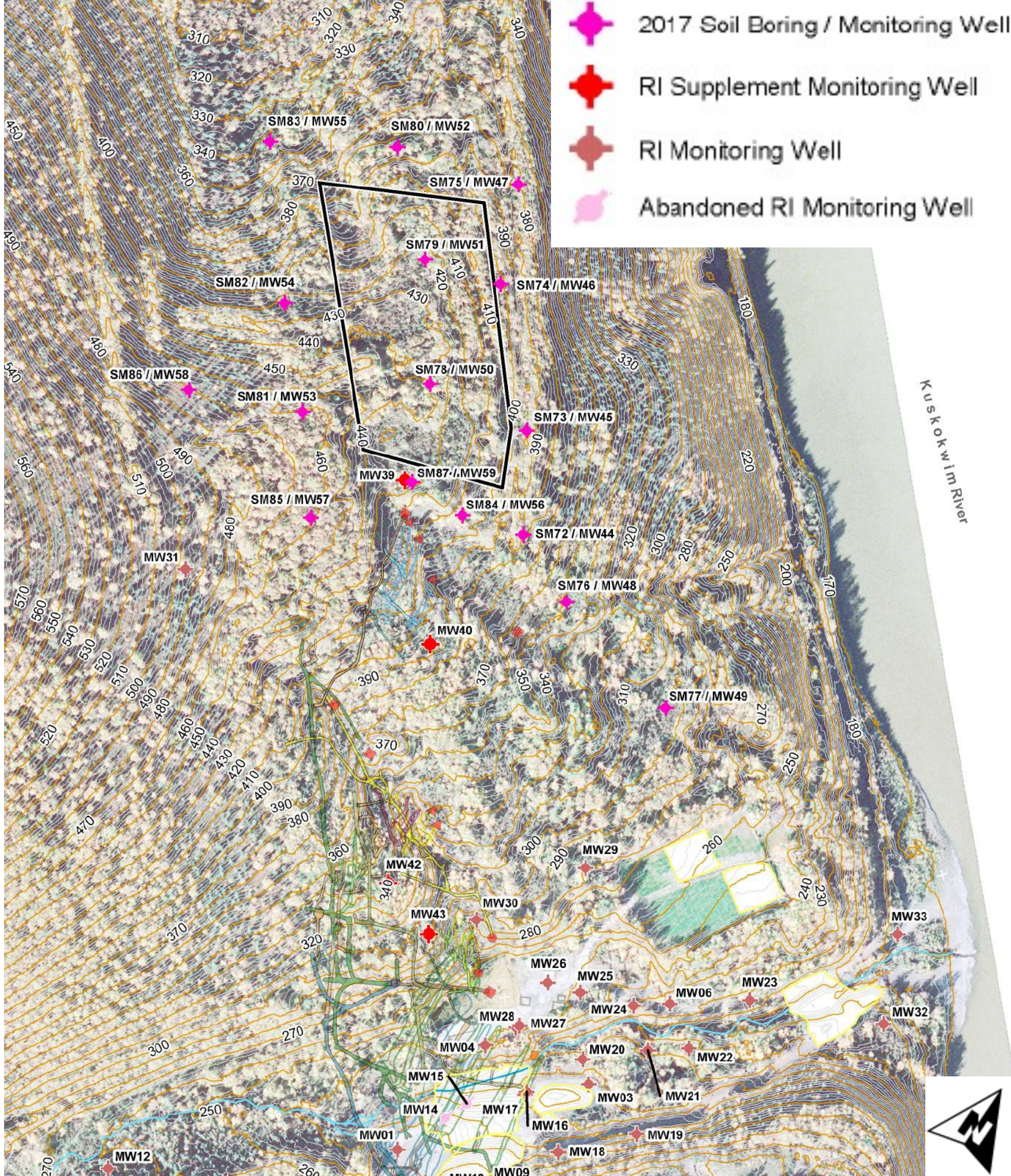
Post-RI Groundwater Characterization

<u>RI Supplement</u>

- Evaluate influence of naturally mineralized bedrock and underground mine workings on groundwater flow paths and COC concentrations.

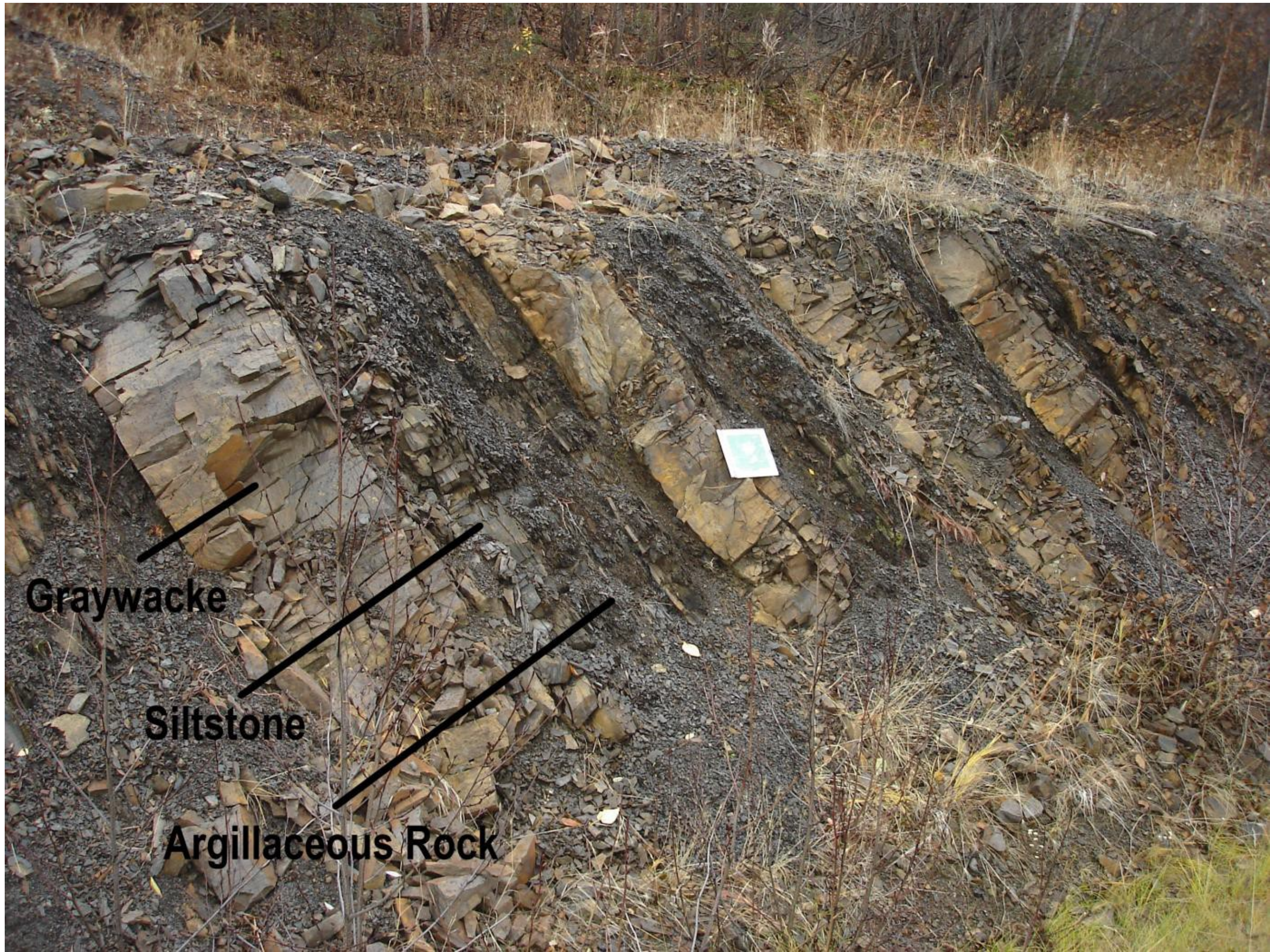
<u>2017 Repository Area Characterization</u>

- Additional characterization of groundwater in the vicinity of proposed repository (FS Alternative 3).
  - Gather Information for more detailed hydrologic analysis of the proposed repository.
  - Generate data necessary to establish detection groundwater monitoring network for the repository.



Bedrock Lithology and Stratigraphy

- Cretaceous Kuskokwim Group. In RDM area comprises a thick marine turbidite sequence consisting of interbedded graded graywacke, siltstone, and argillaceous rock.
- Graywacke beds range from half a foot to about 20 feet thick, commonly 2 to 3 feet thick.
- Most argillaceous rocks underground are argillites but some at and near surface are shale. Some are fissile, and many tend to fracture subconchoidally.



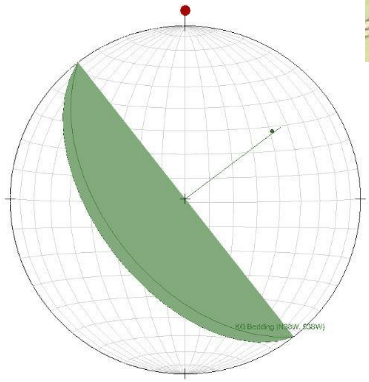
Structural History

1) Folding of Kuskokwim Group (NW-trending Sleetmute anticline) and probable concurrent development of J-1 and J-2 joints.
2) Intrusion of dikes into J-1 joints.
3) Right-lateral strike slip faulting along NW-striking (parallel to sub-parallel to bedding) faults of the Red Devil Fault zone.
4) Further right lateral slip faulting along the NW-striking faults, with introduction of hydrothermal solutions, resulting in ore deposition.
5) Post-mineralization cross faulting.

(MacKevett and Berg 1963)

Folding

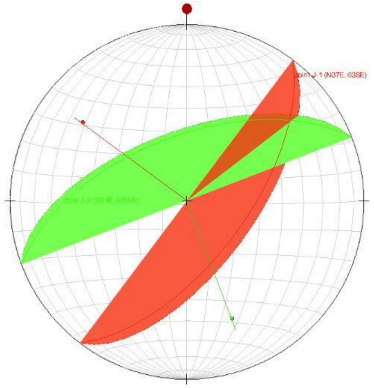
- RDM located on SW limb of NW-trending Sleetmute anticline
- Kuskokwim Group bedding strikes from N 10° W to N 60° W but **strikes predominantly from N 30° W to N 45° W** at the mine. Bedding **dips 45° to 60° SW**.



Cady, W.M., R.E. Wallace, J.M. Hoare, and E.J. Webber. 1955. *The Central Kuskokwim Region, Alaska, An accountof its geography, geology, geomorphology, andmineral resources includingoccurrence and mining of quicksilver*. U.S. Geological Survey Professional Paper 268.

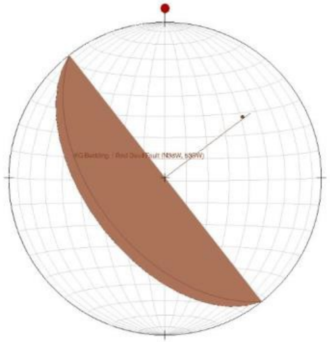
Joints

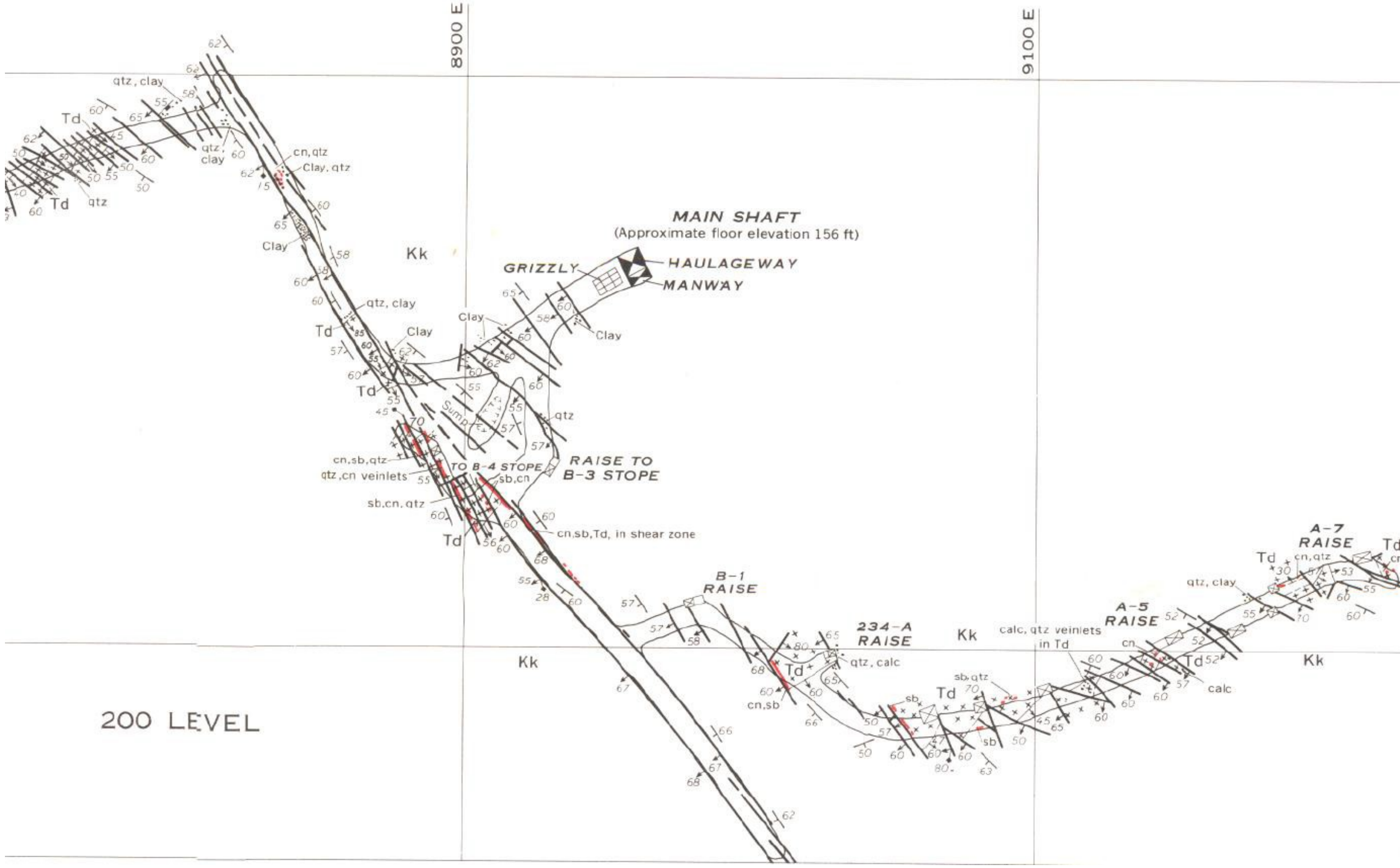
- Two sets of joints (J-1 and J-2) throughout Red Devil Mine.
- At any one place joint orientations vary, but average of many joints within 50-foot radius is close to average elsewhere in the mine.
  - J-1: Ave. strike N 37° E, ave. dip 63° SE
  - J-2: Ave. strike N 69° E, ave. dip 60° NW
- Best developed in the thicker graywacke beds.
- No information specifically regarding joint spacing or apertures.
- Bedrock drill cuttings (RI, RI Supplement, and 2017 additional characterization) indicate fracturing likely associated with joints.
  - Include light-colored veins deposited along planar fractures.
  - Weathering along generally planar fracture surfaces.



Red Devil Fault Zone

- Bedding parallel. NW-striking, SW-dipping. Movement largely right lateral strike slip.
- Well developed and numerous in argillaceous beds.
- Individual displacements range from a few inches to 40 feet. Cumulative displacement is several hundred feet.
- Some individual faults traceable for several hundred feet, but discrete faults generally difficult to trace for long distances.

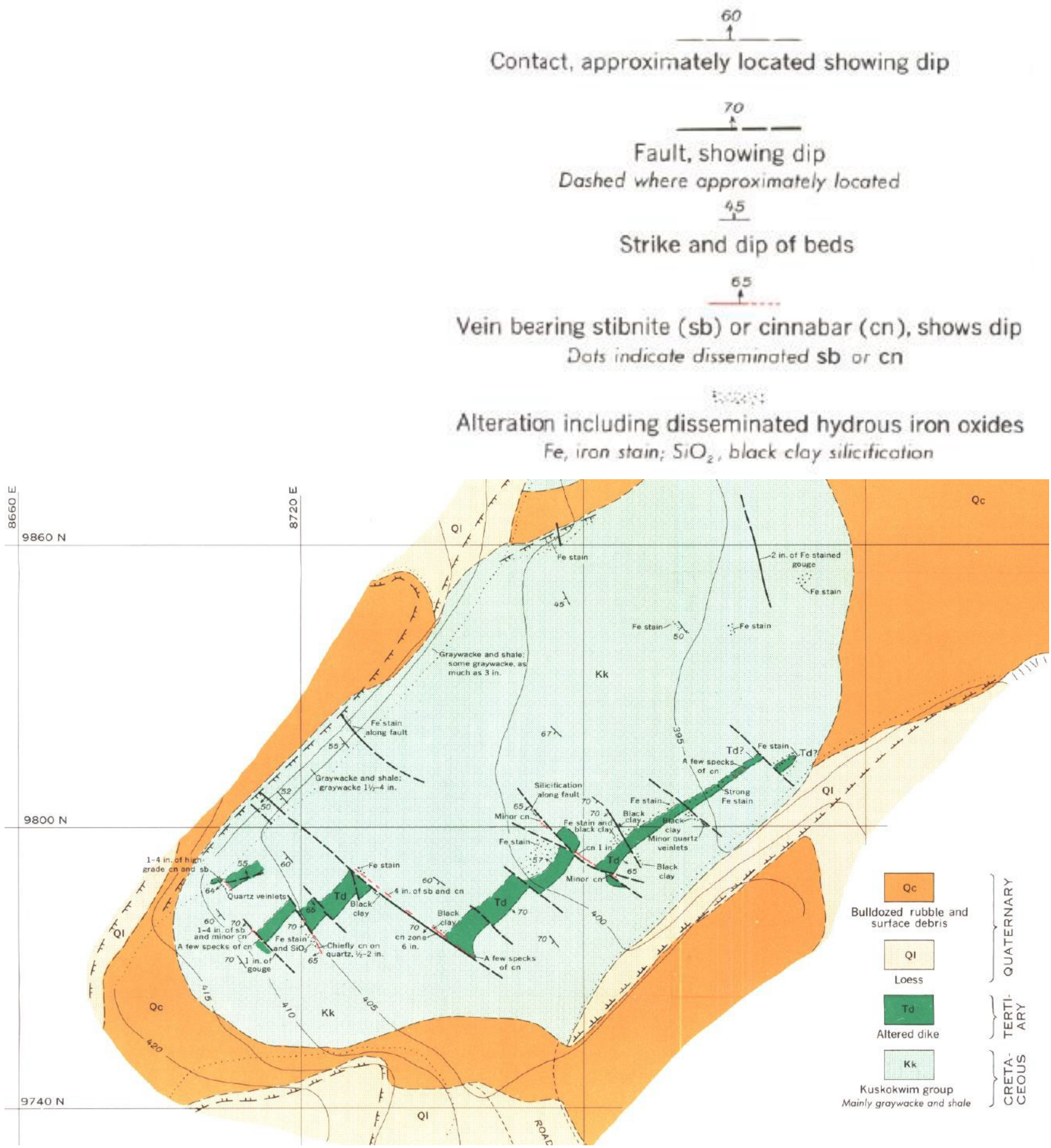




MacKevett and Berg (1963)

Red Devil Fault Zone (cont.)

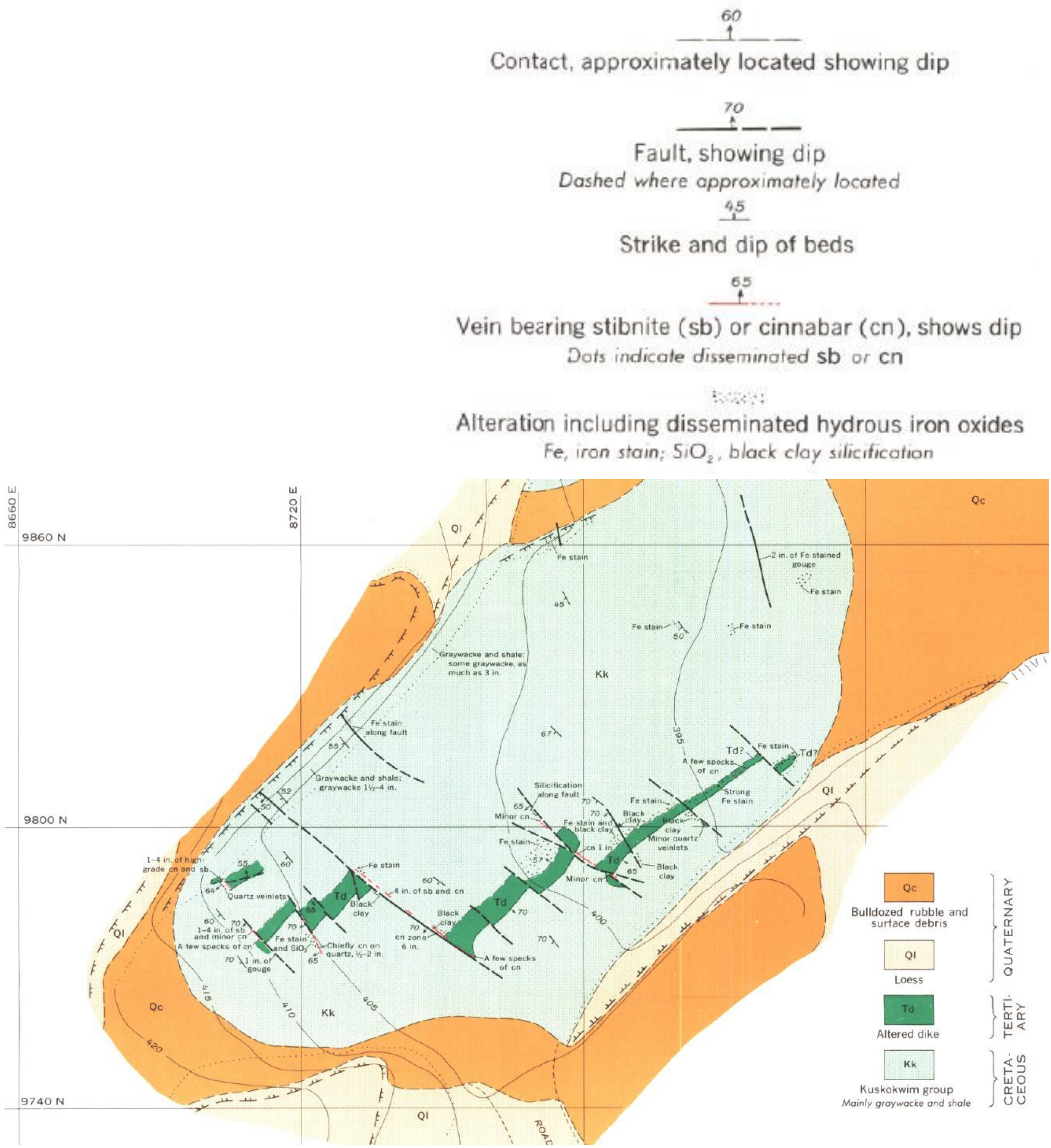
- The total right-lateral movement between dike segments about 800 feet; half or less is in the Red Devil Fault, and the rest is subsidiary fault movements in footwall.
- No information regarding apertures or sealing of the various faults.
- Generally, poor development of open spaces attributed localization of most of the bedding-plane faults in incompetent argillaceous rocks.



MacKevett and Berg (1963)

Dikes

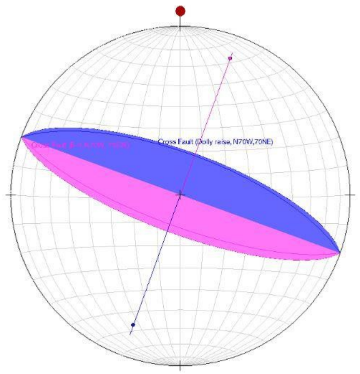
- The Kuskokwim Group rocks intruded by hydrothermally altered dikes. Dikes generally oriented parallel to the J-1 joints.
- Range from 1 foot to about 14 feet thick.
- Three dikes located in the area of the Red Devil Mine played a key role in the development of the ore bodies.



MacKevett and Berg (1963)

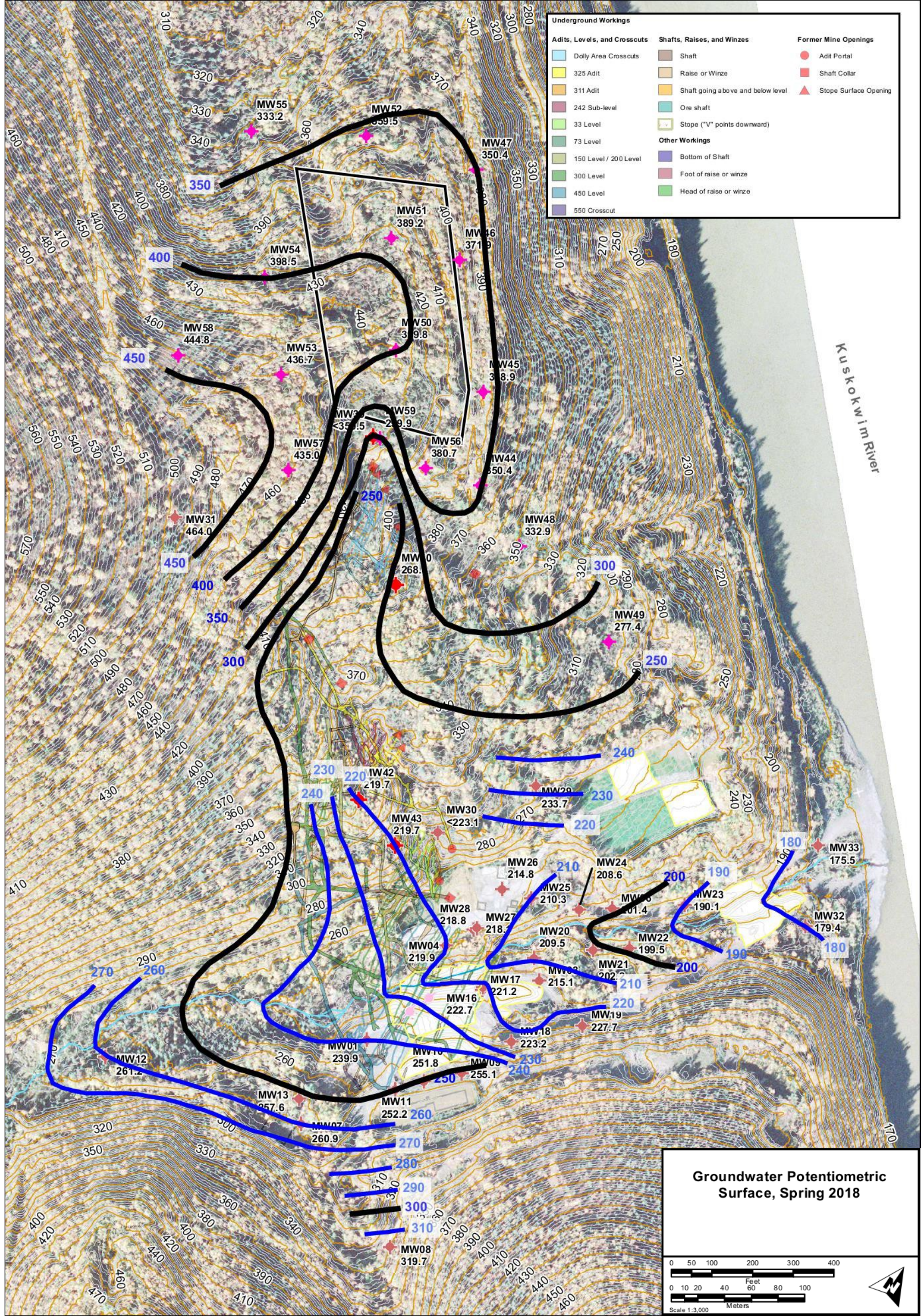
Post-Mineralization Cross Faulting

- Two cross faults postdate both wrench faulting and ore deposition. Both faults are marked by a gray, rubbery gouge a few inches thick (Malone 1962).
  - Fault exposed in the Dolly raise: strike N 70 W, dip 70 NE.
  - Fault in the B-1 stope: strike N 70 W, dip 75 SW.



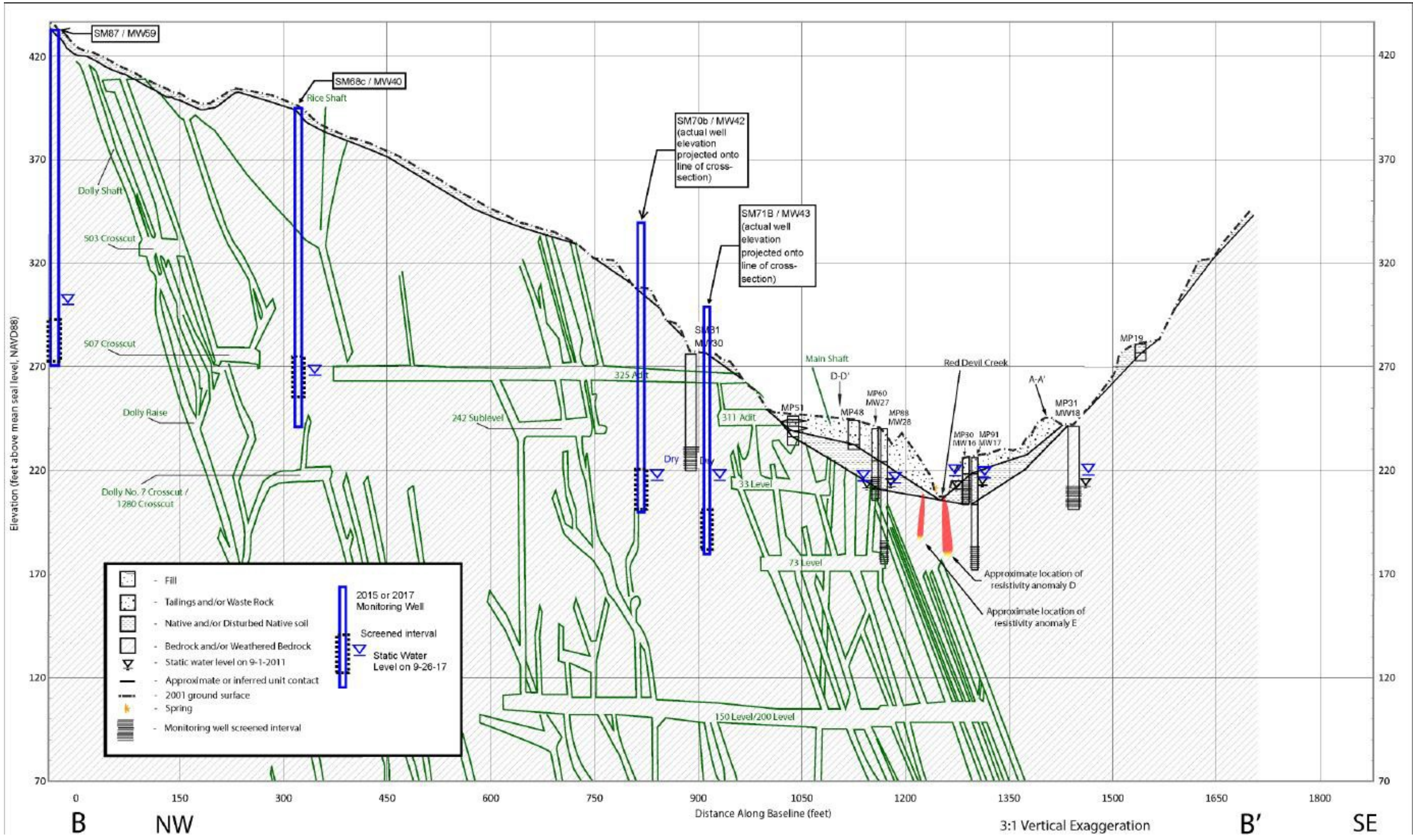
Gradient and Flow Pathways

- In part of the Surface Mined Area, underground workings impart a strong hydraulic gradient (locally about 1V:1H) toward the workings where they lie below the water table within the host bedrock but above the nearby base level of Red Devil Creek.
- Underground mine workings constitute a significant and locally dominant source of bedrock heterogeneity and anisotropy in the bedrock system.



Gradient and Flow Pathways

- The mine workings provide a highly transmissive hydraulic connection between the affected portion of the Surface Mined Area and the Red Devil Creek valley.

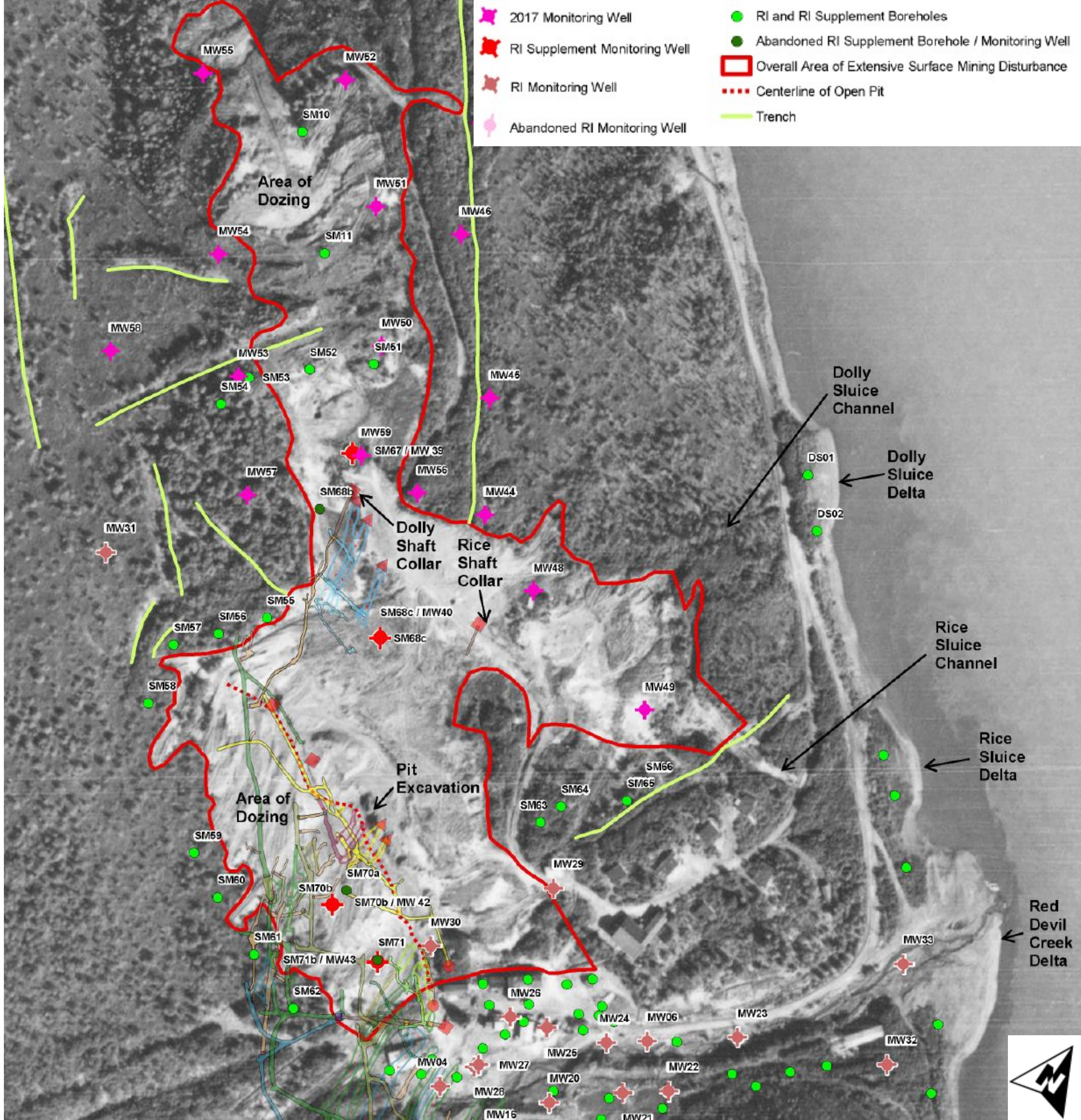


Influences on Groundwater Quality

- Bedrock is mineralized throughout portions of the Surface Mined Area and Main Processing Area, including zones peripheral to mine workings.

- Because mine workings locally impart hydraulic gradient toward the workings, nearby groundwater flows through the mineralized zones peripheral to the workings. Concentrations of COCs in groundwater are locally elevated as a consequence of interaction with naturally mineralized bedrock.

- Evaluation of influence of naturally mineralized bedrock on groundwater quality complicated by superposition of mining-related surface disturbance with the targeted subsurface zones of bedrock mineralization.



Influences on Groundwater Quality

- Once groundwater enters underground mine workings, it is likely further influenced by interaction with the mine workings themselves.
- The magnitude of the influences on COC concentrations attributable to interaction with naturally mineralized bedrock versus flow through mine waste and the mine workings cannot be estimated quantitatively.

Red Devil Creek and Deeper Groundwater

- Groundwater discharges to the predominantly gaining Red Devil Creek as baseflow in the Main Processing Area.

- Some deeper bedrock groundwater below the creek likely discharges into the Kuskokwim River directly. A simple hydrologic analysis (assuming Darcy flow) was performed to assess potential impacts of such deep bedrock groundwater migration to the Kuskokwim River.