SAND2007-6501P

Rock Mechanics Modeling in WIPP Performance Assessment
(Rock Mechanics in PA)

KHNP Training Program
Module 6: Assembly of a Safety Case

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Sandia National Laboratories
Carlsbad Programs Group

SAND 2007-XXXP

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for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Outline

I. Rock Mechanics in PA

II. Geomechanical Analysis

III. Apply to the Korean Situation

IV. Ending Remarks

Repository

- **Forget how this guy become a criminal.**
- **Life and Toxicity**
- **How long keep this guy in the prison?**
- **To prevent the escape,**
  - **How to design and construct the prison?**
  - **How to operate?**
  - **How to monitor?**

When Escape

- How much damage to public?
- Which pathway?
- How to delay to public?
- Re-arrest?

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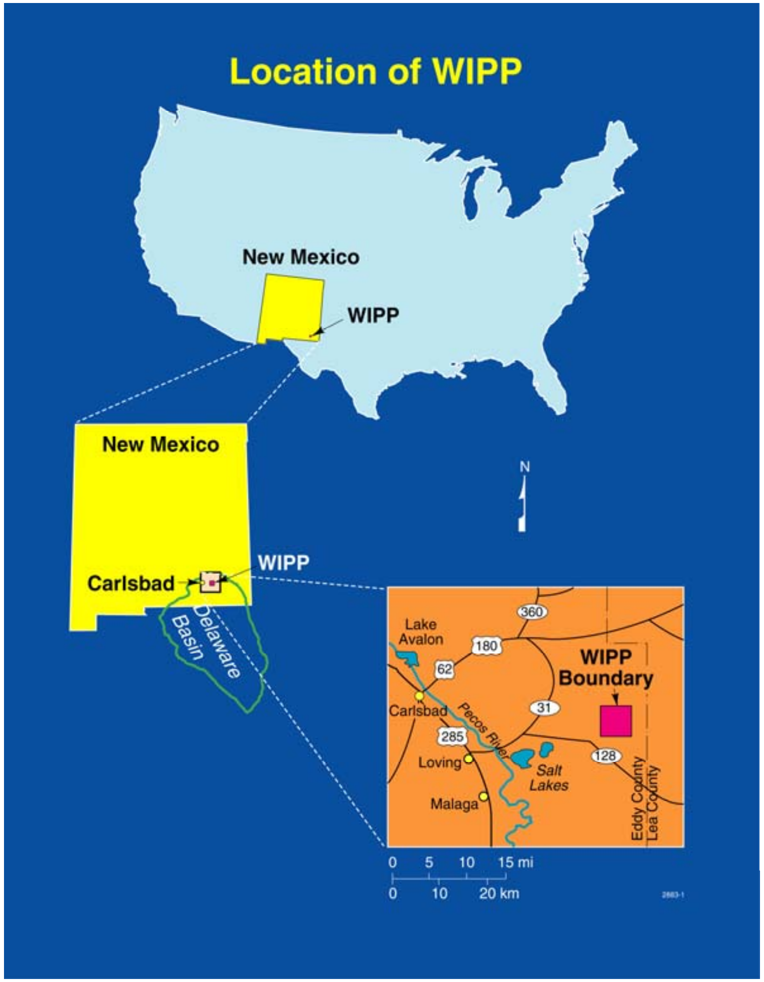
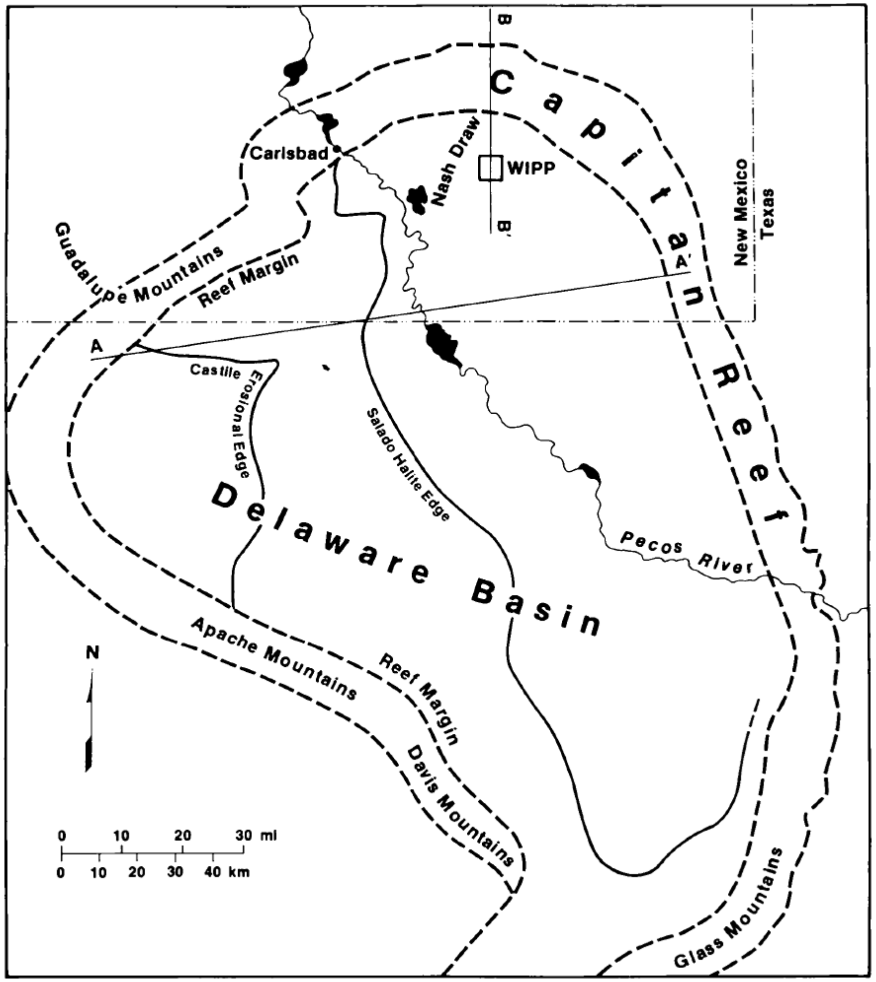
Location of WIPP





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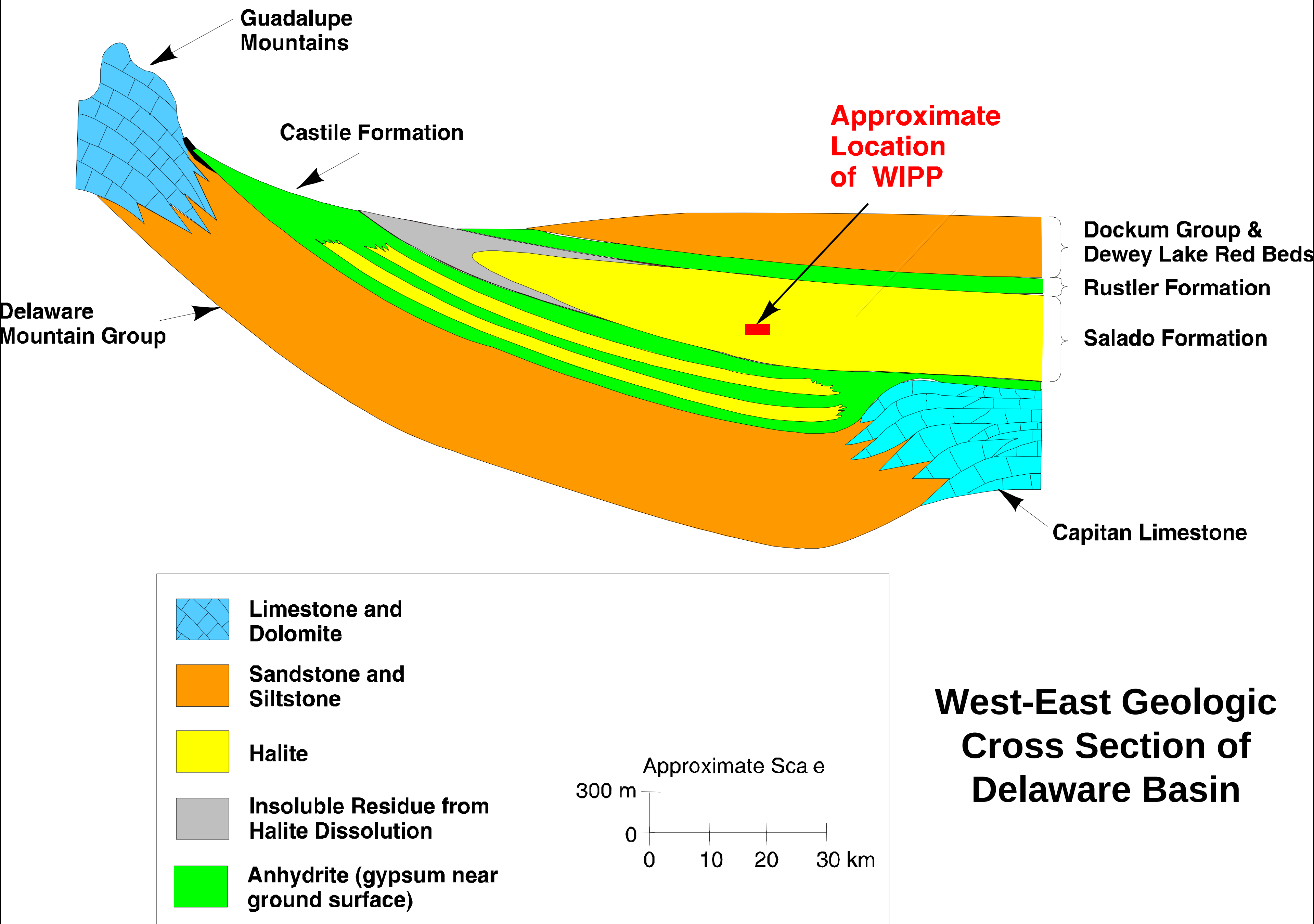
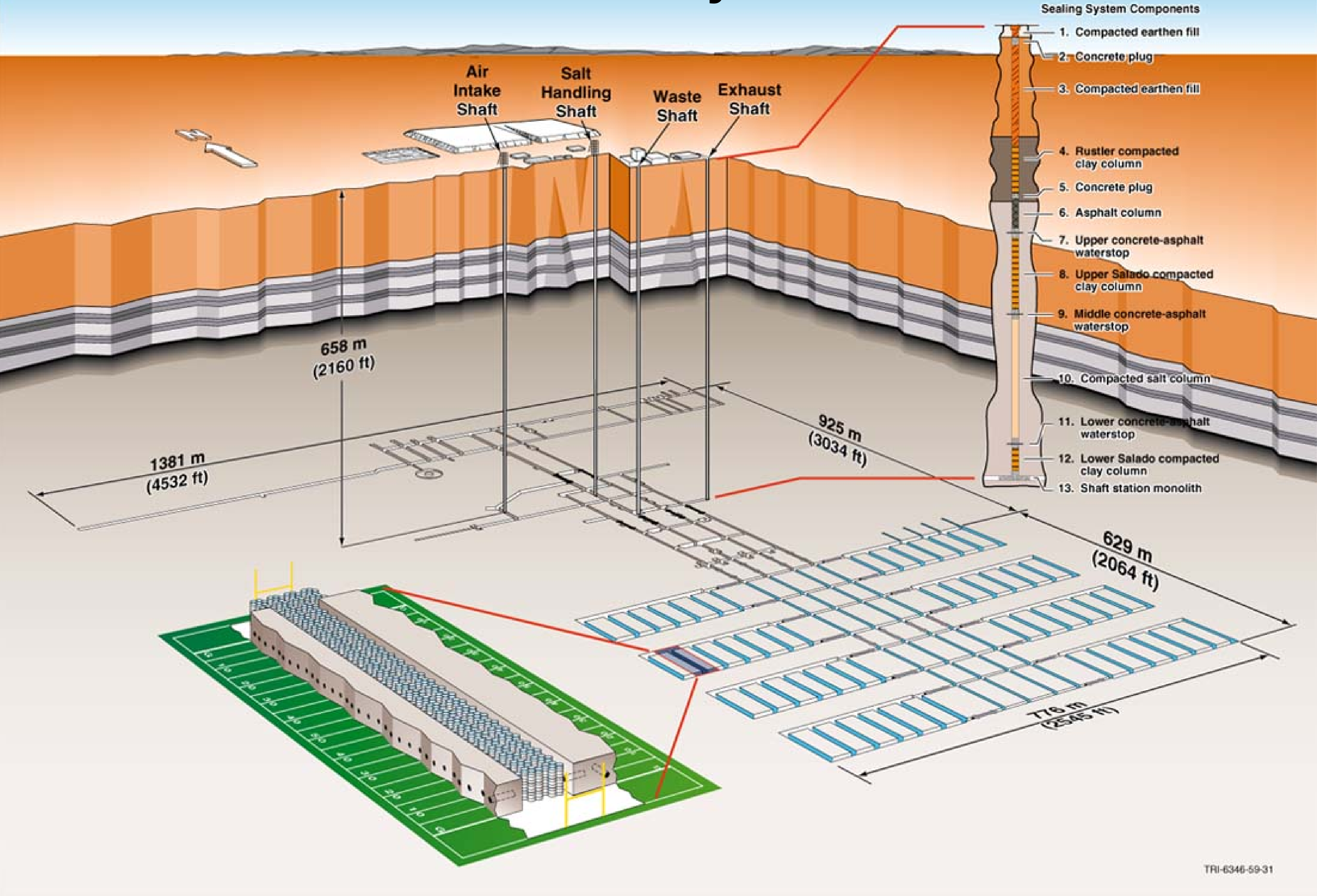


West-East Geologic Cross Section of Delaware Basin

TRI-6342-1076-1

WIPP Layout


Sealing System Components
1. Compacted earthen fill
2. Concrete plug
3. Compacted earthen fill
4. Rustler compacted clay column
5. Concrete plug
6. Asphalt column
7. Upper concrete-asphalt waterstop
8. Upper Salado compacted clay column
9. Middle concrete-asphalt waterstop
10. Compacted salt column
11. Lower concrete-asphalt waterstop
12. Lower Salado compacted clay column
13. Shaft station monolith
Air Intake Shaft
Salt Handling Shaft
Waste Shaft
Exhaust Shaft
658 m (2160 ft)
1381 m (4532 ft)
925 m (3034 ft)
629 m (2064 ft)
776 m (2545 ft)
TRI-6346-59-31

WIPP Regulatory Requirements

- **Regulatory requirements were primary determinant for the development of the PA structure**
  - **The WIPP must be designed to provide *reasonable expectation* that *cumulative releases* of radionuclides to the accessible environment for *10,000 years* after disposal from all *significant processes and events* shall be less than specified *releases limits***

Cumulative Releases

Releases are normalized by radionuclide and by the total inventory

$$R = \sum \frac{Q_i}{L_i} \left(\frac{1 \times 10^6 \, curies}{C} \right)$$

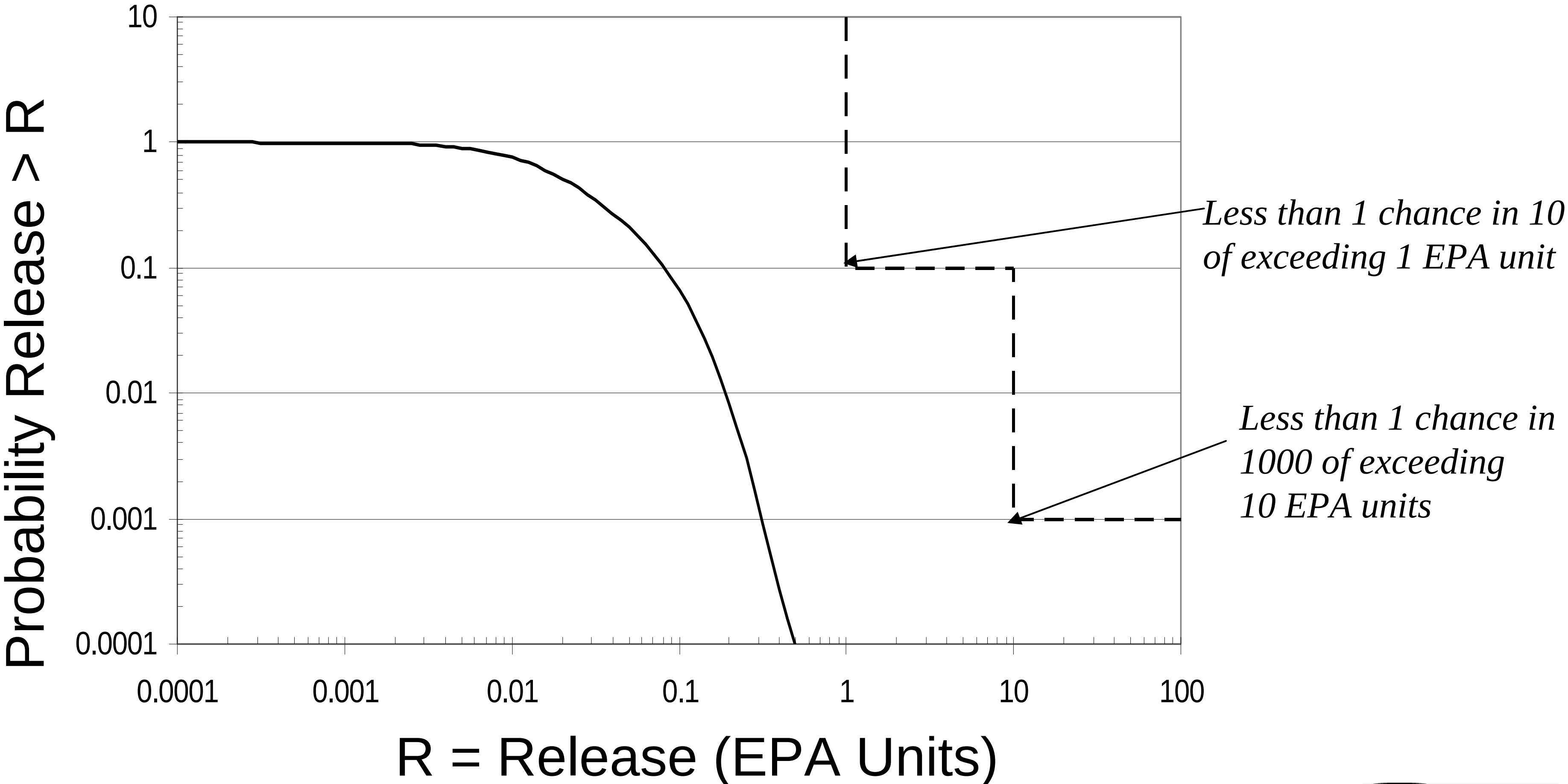
R **= Normalized release in "EPA units"**
Q_i **= 10,000-year cumulative release (in curies) of radionuclide *i***
L_i **= Release Limit for radionuclide *i***
C **= the total transuranic inventory (in curies of α emitters w/halflives > 20 years)**

Table 1 (Appendix A)

Radionuclide	Release Limit (L_i)(in curies) per 10^6 curies of TRU Waste
^{230}Th, ^{232}Th	10
^{241}Am, ^{243}Am, ^{14}C, ^{129}I, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{226}Ra, ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, and other alpha-emitting radionuclide with a half-life greater than 20 years.	100
^{135}Cs, ^{137}Cs, ^{90}Sr, ^{126}Sn, and other radionuclide with a half-life greater than 20 years that does not emit alpha particles.	1,000
^{99}Tc	10,000

Release Limits: CCDF is a Measure of Compliance

Complementary Cumulative Distribution Function



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Overview of PA Objectives

- PA answers three questions about a repository system:
    1. What can happen after permanent closure?
    2. How likely is it to happen?
    3. What can result if it does happen?
- And one question about the analysis
    1. What level of confidence can be placed on the estimate? (uncertainty in analysis)
- Quantitative, probabilistic estimate of the future performance of a system.

Overview of PA Methodology

- **Identify all potential release pathways and calculate the probability and consequences of releases over a 10,000-year regulatory period.**
- **PA Requires:**
  - **Site characterization (conceptual models and parameters)**
  - **Process models (e.g., flow and transport, geomechanical, geochemical, drilling)**
  - **Incorporation of uncertainty**
  - **System-level tool to link everything together**

Features, Events, and Processes

Question: What needs to be considered and included in PA?

Answer: Features, events, and processes (FEPs)

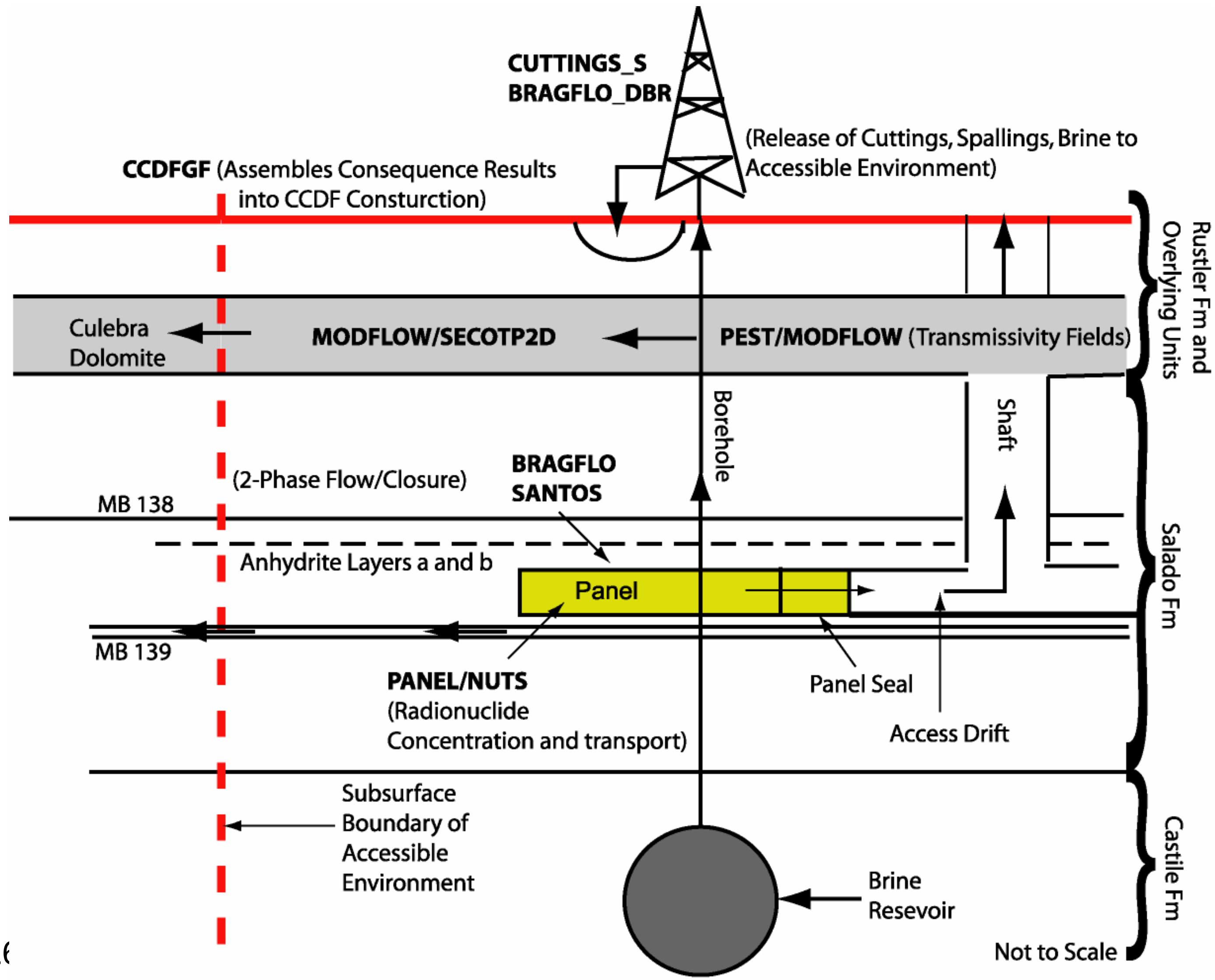
FEPs are screened according to:

- **Probability:** If a FEP has a probability of occurring less than 10^{-4} in 10,000 years it does not have to be included in PA (e.g., meteorite impact)
- **Consequence:** if a FEP is beneficial to performance or is not relevant to WIPP it does not have to be included in PA (e.g., sorption, oceans).
- **Regulation:** Certain FEPs are either screened in or out by regulation (e.g., mining, resource extraction following drilling).

Scenario Development

- All retained FEPs must be accounted for in PA in at least one scenario.
- FEPs can be included by explicit modeling or by parameter assignment.
- Expected FEPs are included in all scenarios
  - Creep closure
  - Brine flow, gas generation
- Disruptive FEPs are included in disturbed scenarios.
  - Drilling, mining, brine pocket

Drilling scenario



Drilling scenarios assume current drilling practices will be applied in the future

Scenario Selection

- **Six scenarios are considered in PA**

Scenario	# of Drilling Intrusions	Time of Intrusion (Years)	Castile Brine Pocket encountered	Intrusion Type
S1	0 (Undisturbed)	NA	NA	NA
S2	1	350	Yes	E1
S3	1	1,000	Yes	E1
S4	1	350	No	E2
S5	1	1,000	No	E2
S6	2	1,000 and 2,000	Only at 2,000	E2 and E1

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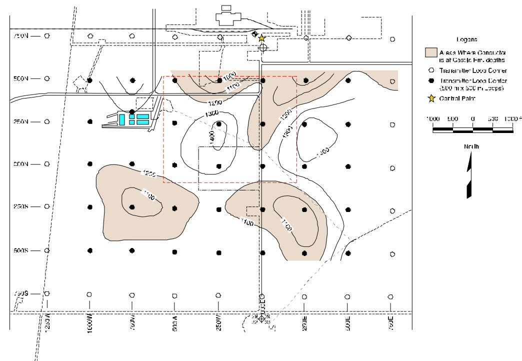
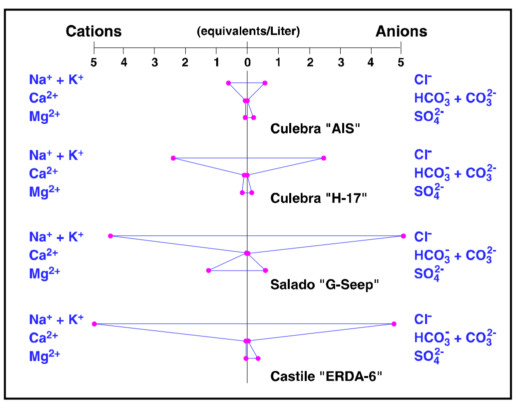
WIPP Site Characterization

Geologic studies



Geophysical surveys

Hydrologic testing



Geochemical sampling and analysis

Geomechanical testing

Surface-based geologic drilling, coring, & geophysical logging

24 WIPP PA Conceptual Models

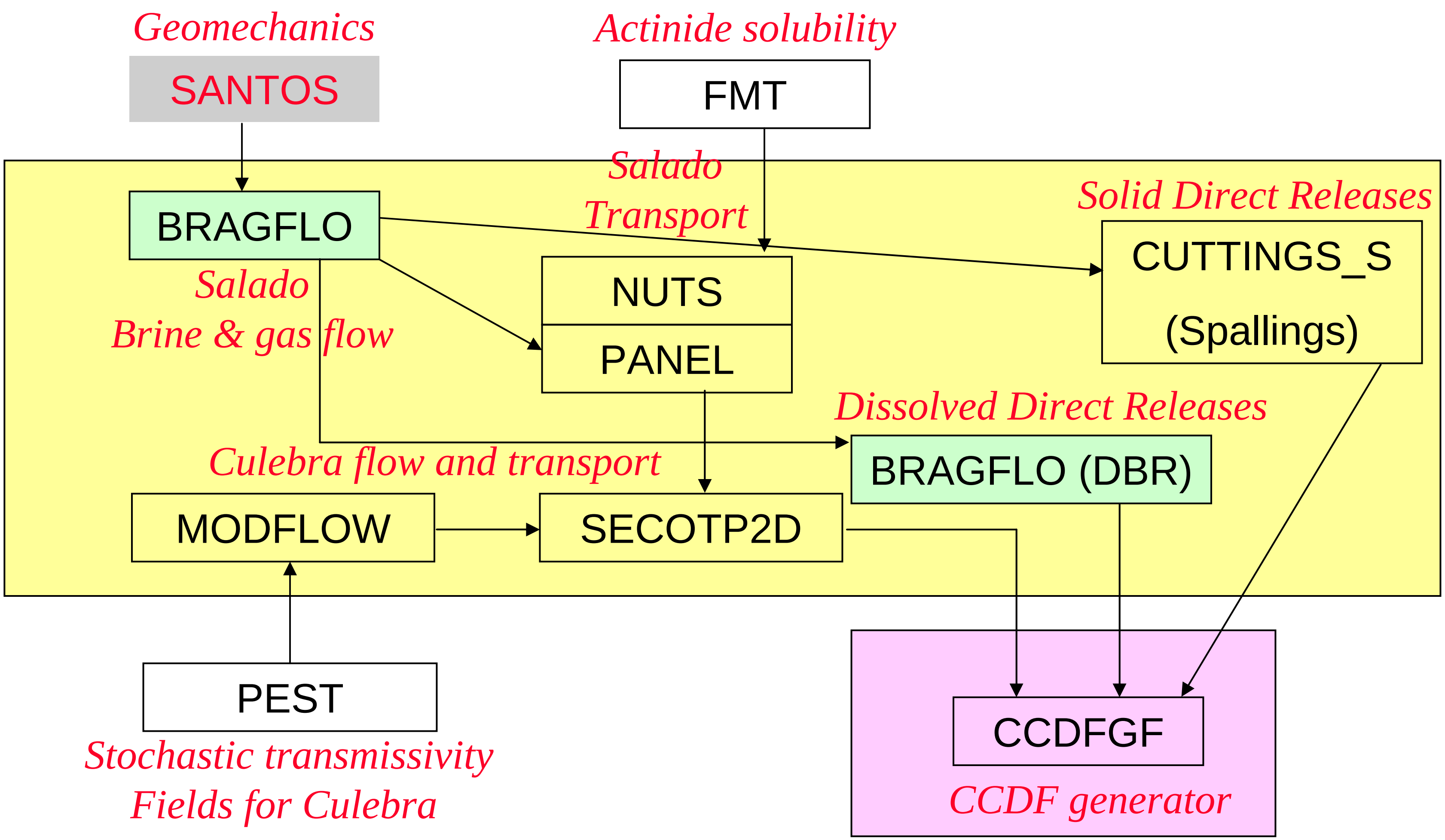
- Disposal system geometry
- Culebra hydrogeology
- Repository fluid flow
- Salado
- Impure halite
- Salado interbeds
- Disturbed rock zone
- Actinide transport in Salado
- Units above the Salado
- Dissolved transport in Culebra
- Colloidal transport in Culebra
- Exploration boreholes
- Cuttings & Cavings
- Spallings
- Direct brine release
- Castile and brine reservoir
- Multiple intrusions
- Climate change
- Creep closure
- Shafts and shaft seals
- Gas generation
- Chemical conditions
- Dissolved actinide source term
- Colloidal actinide source term

Conceptual Models to be Considered by Peer Review

Process Models

- Conceptual models are generally implemented in process models.
- Process models simulate distinct processes or groups of processes such as:
  - Flow of brine and gas in the subsurface
  - Radionuclide transport in the subsurface
  - Gas generation
  - Flow of brine and solids up a borehole
  - Permeability enhancement due to fracturing
  - Room closure
  - Solid extraction by drilling

WIPP Performance Models (CRA)



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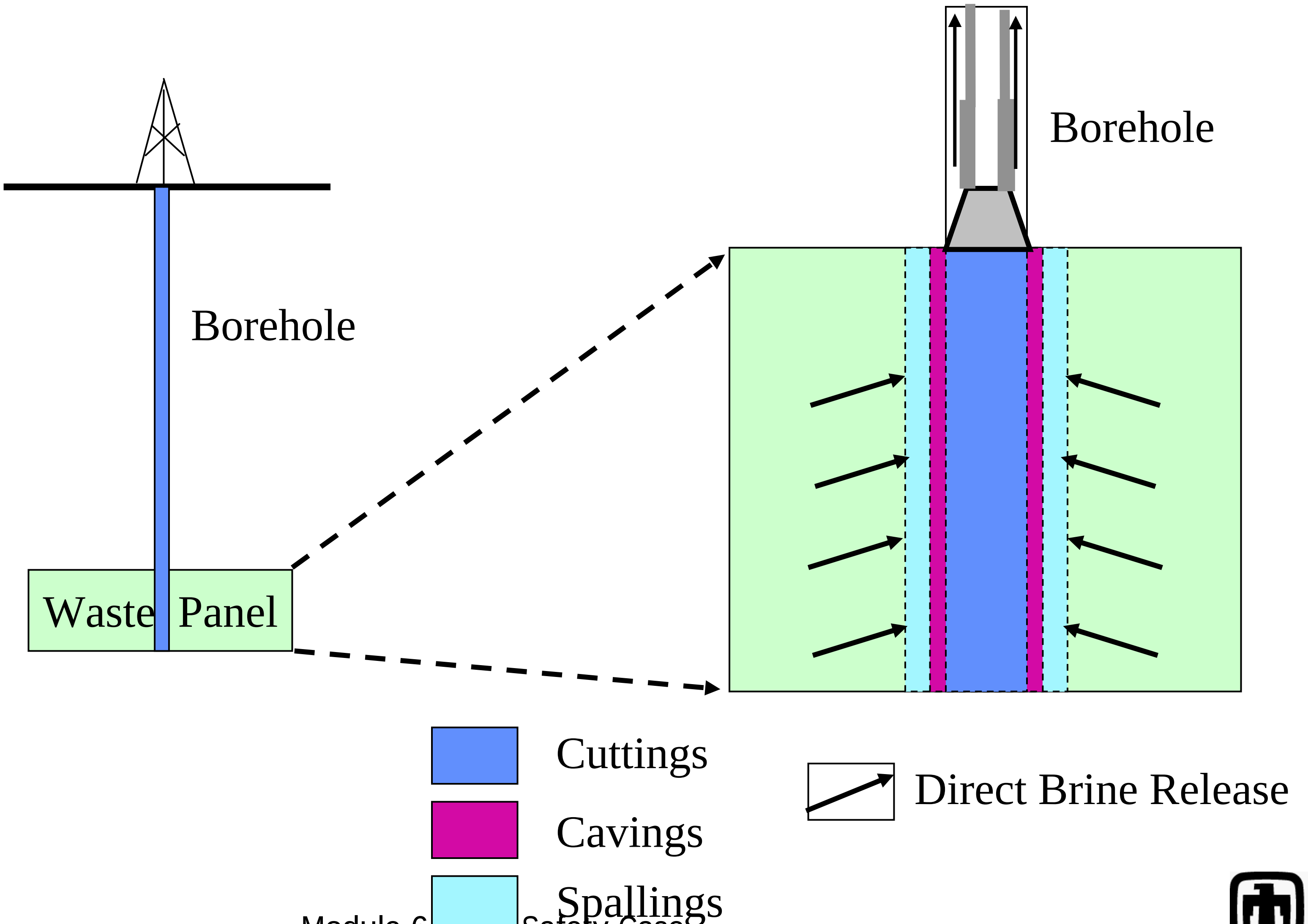
Release Mechanisms

- Direct Releases (occur during or immediately after drilling)
  - Cuttings (Solids from drilling)
  - Cavings (Solids from drilling)
  - Spallings (Solids from pressure release)
  - Direct Brine Release (Brine from pressure release)
- Long-term Releases
  - Groundwater Transport in Culebra
  - Groundwater Transport in Salado

Schematic of Direct Releases



Two Types of Uncertainty

1. Subjective Uncertainty (epistemic)
   - Arises from a lack of knowledge about parameters assumed to have fixed values within the computational implementation of a PA.
     - Examples: permeability, porosity, etc.
   - WIPP PA treats subjective uncertainty in several ways:
     i. Make assumptions that over-estimate releases (conservative assumptions). Example: Waste characteristics
     ii. Sample certain parameter values from probability distributions that cover the range of uncertainty.

Two Types of Uncertainty

2. Stochastic Uncertainty (aleatory)

- Arises from a lack of knowledge about future events.
- Example: Timing and location of future drilling events.

Dealing with Subjective Uncertainty

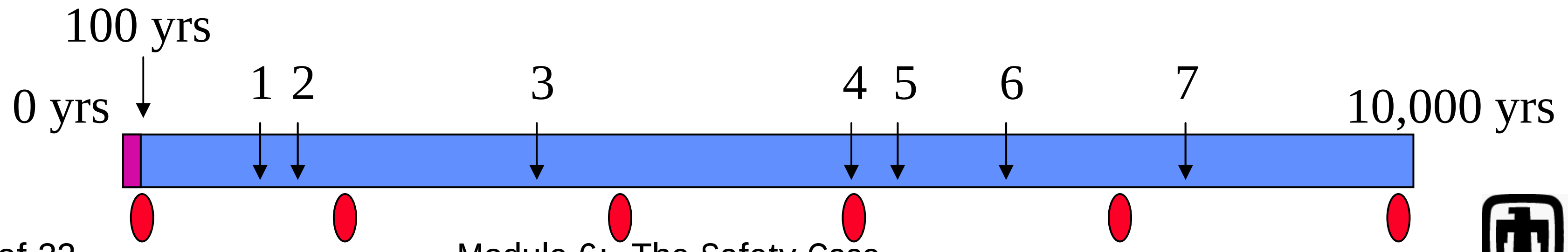
- Latin Hypercube sampling (LHS) is used to define 100 sets of uncertain parameters.
- One realization of the sampled parameters is called a "vector".
- The group of 100 vectors is called a "replicate".
- The replicate essentially covers the full range of all the uncertain parameter distributions.
- LHS minimizes the correlation between parameters unless directed otherwise.
- Typically three replicates are run to demonstrate statistical equivalence.

Dealing with Stochastic Uncertainty

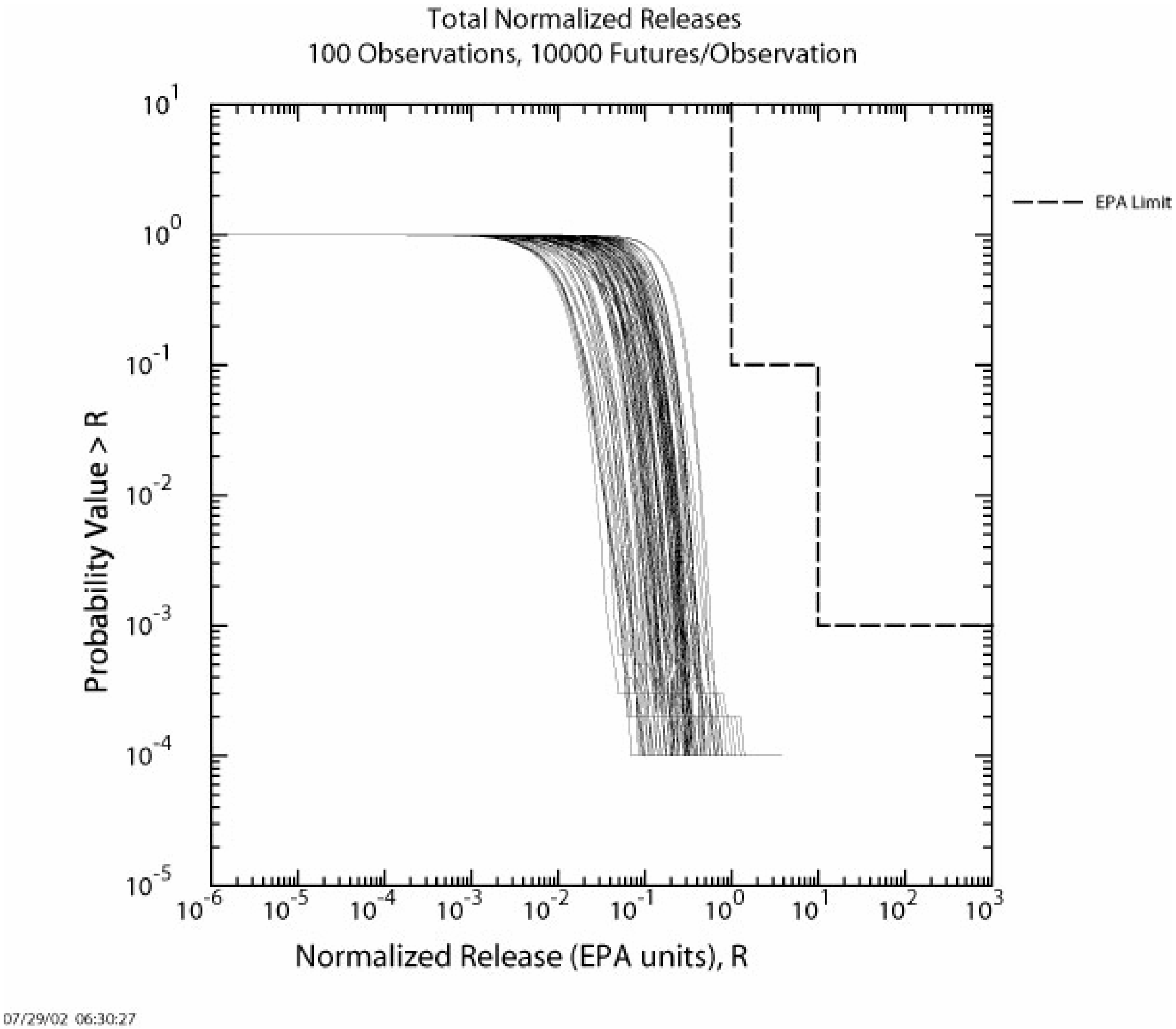
- WIPP PA treats stochastic uncertainty through Monte Carlo sampling on possible futures.
  - 10,000 futures evaluated for each vector to assign a probability to releases
    - Order statistics used to generate complementary cumulative distribution function (CCDF)
  - Results from all 100 vectors combined to determine mean releases (and percentiles).
  - Three replicates used to assign confidence intervals to the mean releases.

Constructing the CCDF

- **CCDFGF generates 10,000 possible futures for each vector.**
  - **A future is the the cumulative release from one possible sequence of events from 0 to 10,000 years.**
  - **Each future consists of a series of randomly occurring drilling intrusions.**
  - **The consequences of drilling intrusions are calculated by interpolating between consequences at discrete times.**

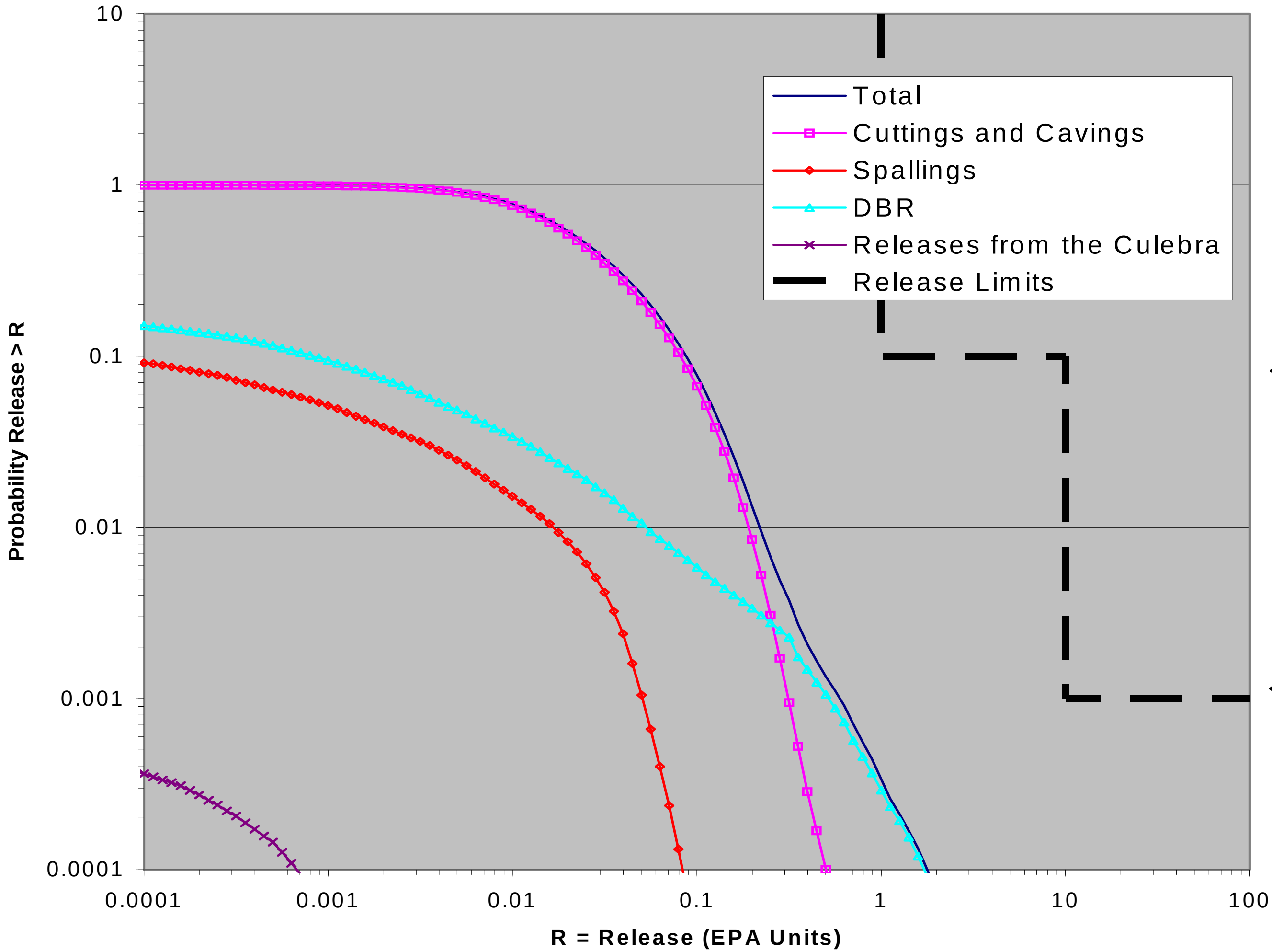


An Example Set of CCDFs



Mean CCDF by Component

Results from CRA-2004 PABC



- CCDF is measure of compliance

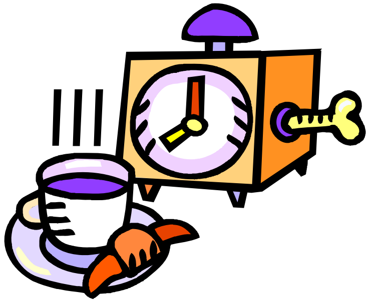
Less than 1 chance in 10 of exceeding 1 EPA unit

Less than 1 chance in 1000 of exceeding 10 EPA units

Summary

- Performance Assessment (PA) is a probabilistic framework to estimate releases to the accessible environment over 10,000 years.
- PA uses a collection site-specific conceptual models, process models, and scenarios.
- PA explicitly includes both subjective and stochastic uncertainty.
- CCDF for mean total releases is the measure of WIPP compliance with EPA release limits.
- PA provides the CCDF for mean releases along with a measure of uncertainty in the analysis.

Break



Rock Mechanics Modeling in WIPP Performance Assessment (Geomechanical Analysis)

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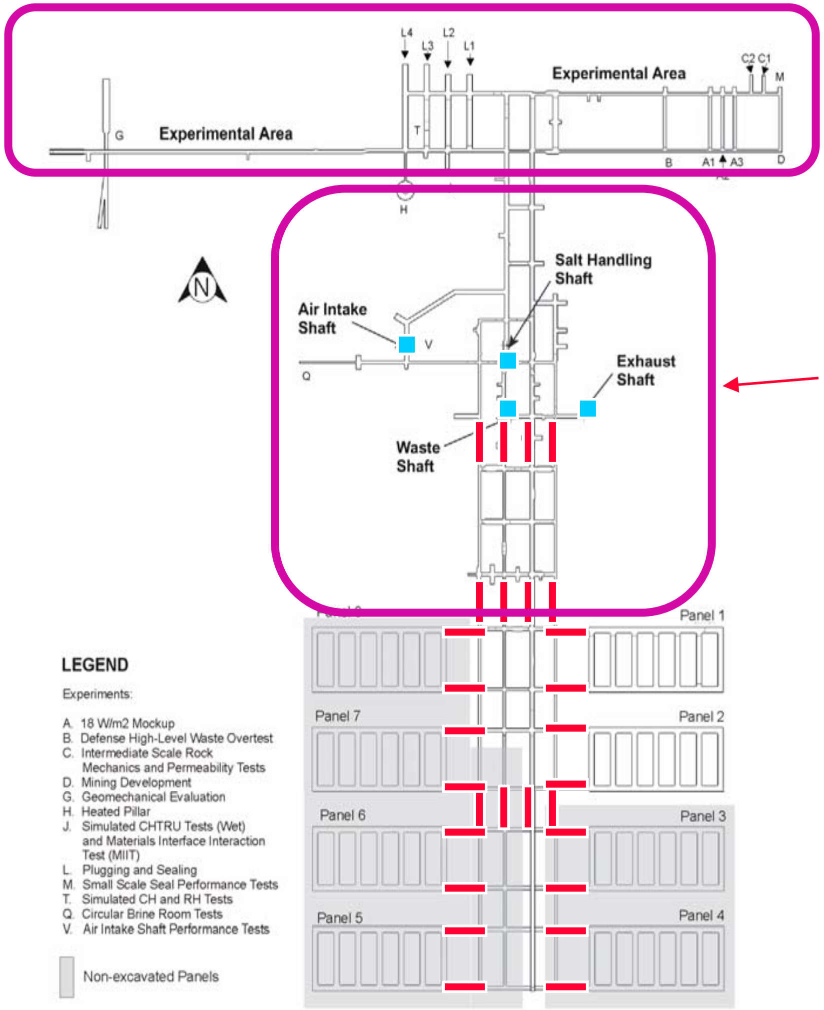
Structural Analysis

- **SANTOS**
  - **SANTOS is a two-dimensional large deformation finite element code which is a internal software developed by SNL.**

- **JAS3D**
  - **JAS3D is a three-dimensional iterative solid mechanics code**
  - **A successor of SANTOS**

Map of WIPP Repository

Experimental area



Operations area

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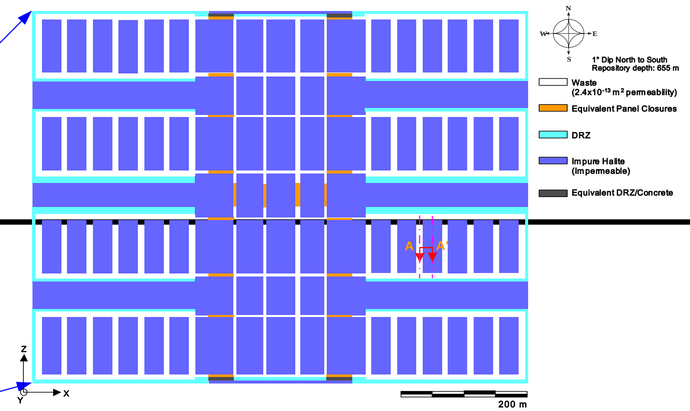
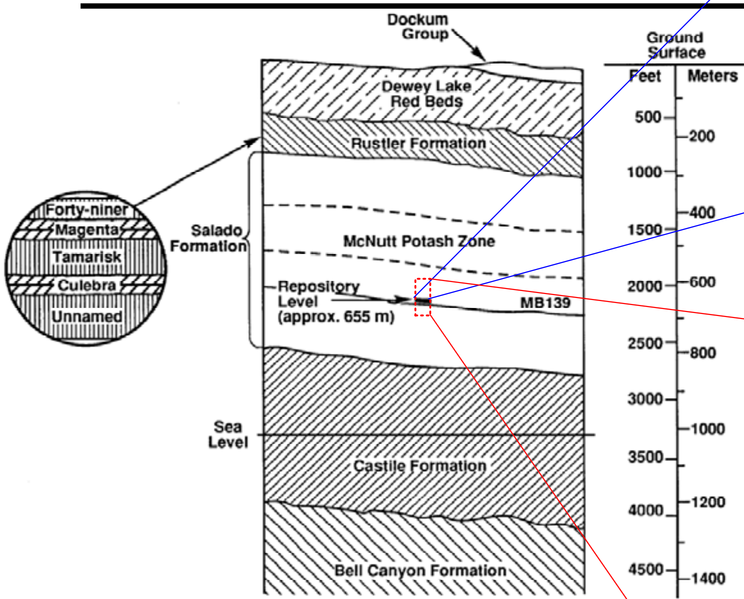
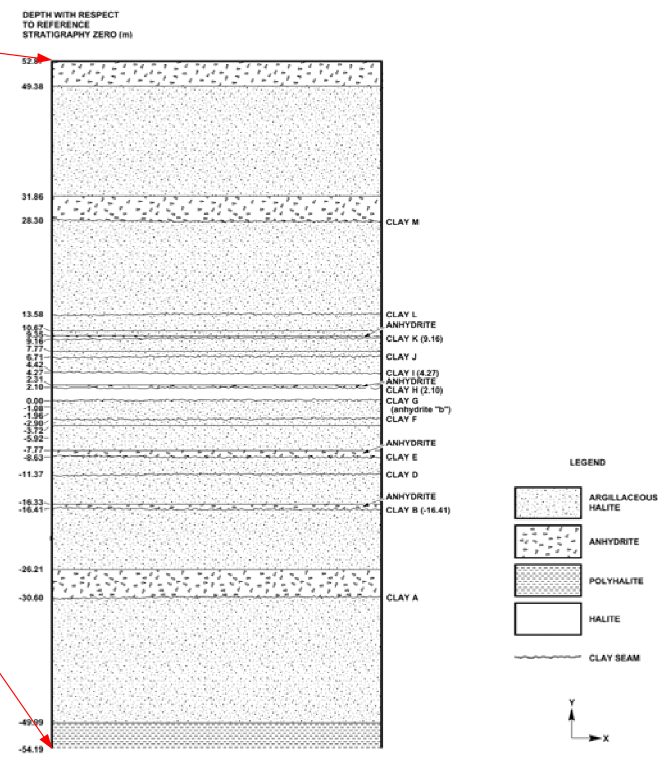


Layout of Disposal Rooms

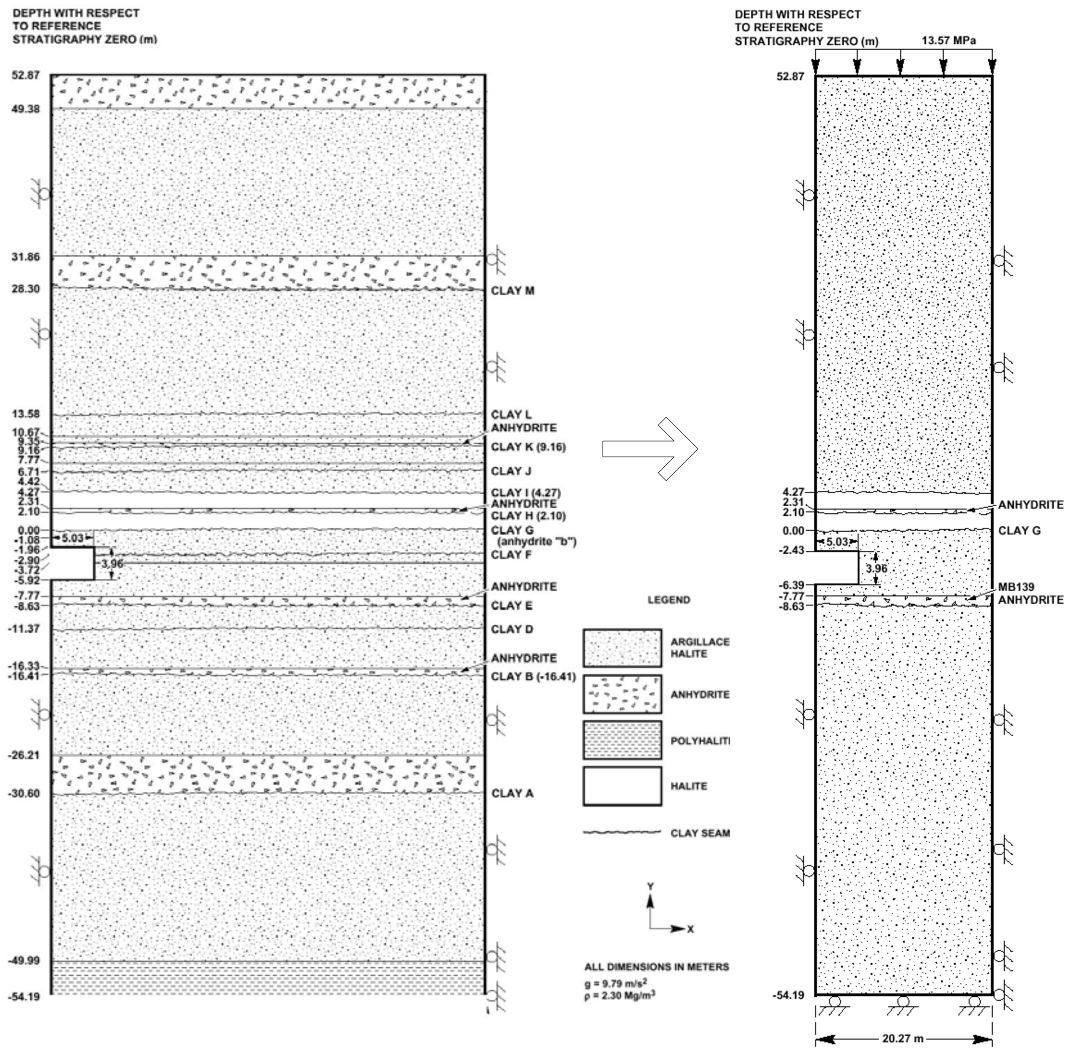


Generalized WIPP stratigraphy



Idealized Stratigraphy Near the Disposal Room Horizon Defined by Munson et al. (1989).

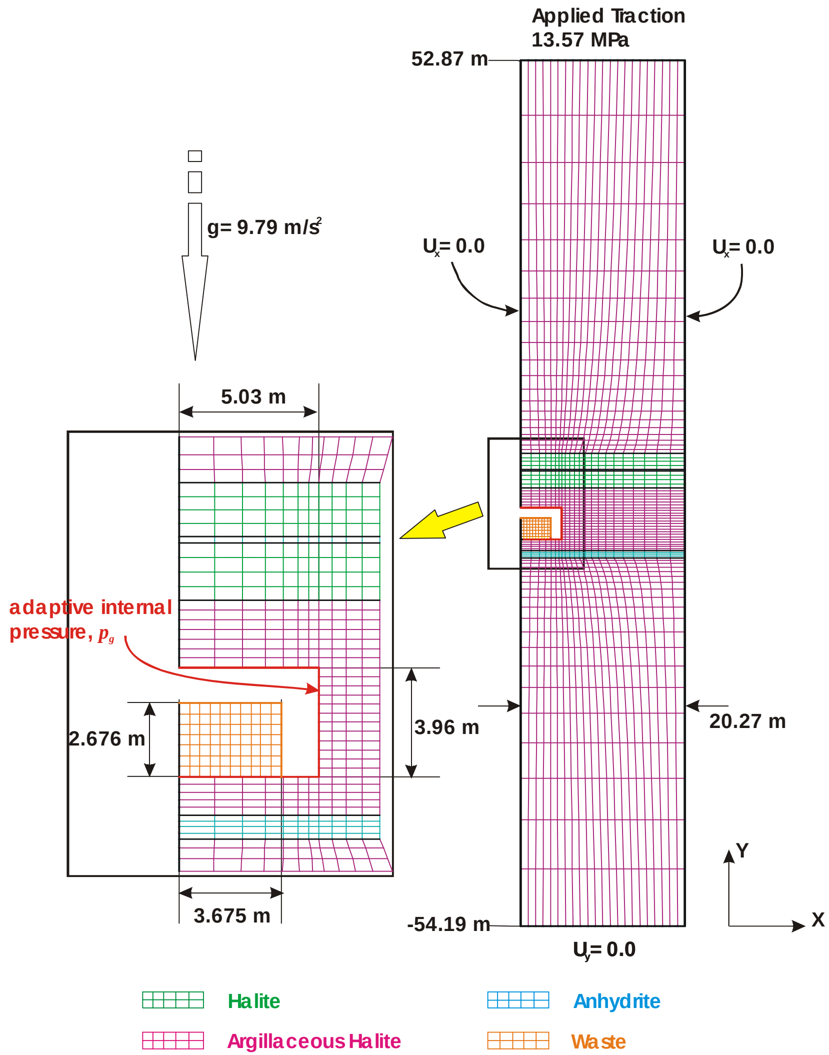
Simplified Stratigraphic Model



(a) (b)

- The bedded stratigraphy in the vicinity of the repository has been mapped in considerable detail as shown in Figure (a).
- A simplified stratigraphic model used for the analysis is shown in Figure (b).
- The simpler model comprises mostly argillaceous salt, with a clean salt layer above the disposal room and a significant marker bed residing below the repository floor.

Mesh Description



- A two-dimensional plane strain disposal room model was converted from the simplified stratigraphy, is used for the SANTOS analysis.
- The discretized model represents the room as one of an infinite number of rooms located at the repository horizon.
- Making use of symmetry, only half of the room is modeled.
- The basic half-symmetry disposal room dimensions are 3.96 m high by 5.03 m wide with a significant portion of this area containing the stored CH-TRU waste.

Constitutive Models

- Halite Constitutive Model
  - A multi-mechanism deformation (M-D) model proposed by Munson and Dawson, has been included in SANTOS to model the creep behavior of rock salt
  - The model can be decomposed into an elastic volumetric part (Eq. 1) and a deviatoric part (Eq. 2)

$$\varepsilon_{kk} = \frac{\sigma_{kk}}{3K}$$

$$\dot{s}_{ij} = 2G\left(\dot{e}_{ij} - F\dot{\varepsilon}_s\left[\frac{\cos 2\theta}{\cos 3\theta\sqrt{J_2}} s_{ij} + \frac{\sqrt{3}\sin\theta}{\cos 3\theta J_2}\left\{s_{ip}s_{pj} - \frac{2J_2}{3}\delta_{ij}\right\}\right]\right)$$

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Constitutive Models

- Anhydrite Constitutive Model
  - The anhydrite layer (MB 139) is expected to experience inelastic material behavior.
  - This is assumed to be isotropic and elastic until yield occurs.
  - Once the yield stress is reached, plastic strain begins to accumulate.
  - Yield is assumed to be governed by the Drucker-Prager (D-P) criterion.

$$\sqrt{J_2} = C - aI_1$$

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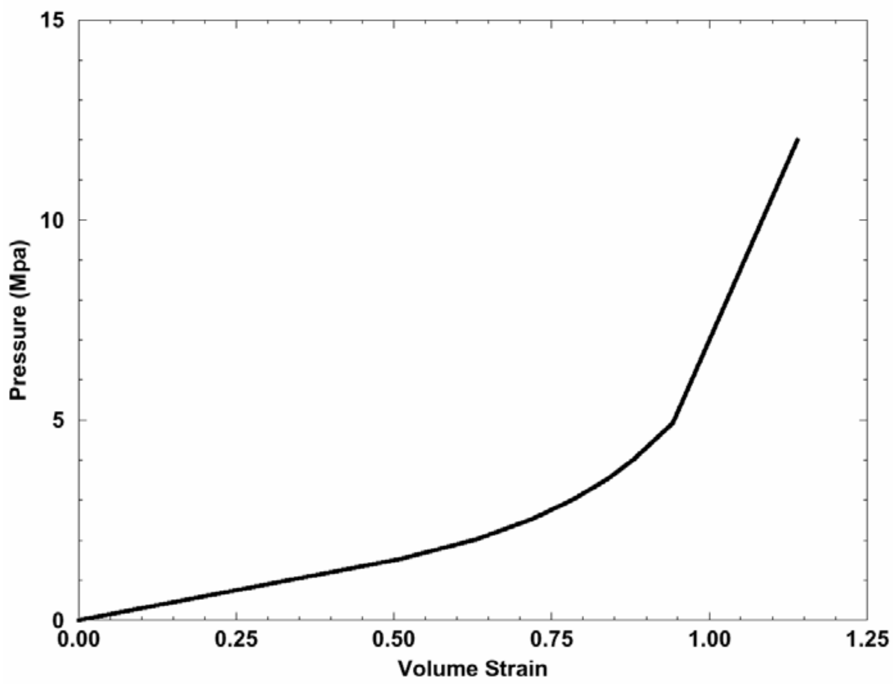
Constitutive Models

- **Waste Constitutive Model**
  - **The stress-strain behavior of the waste was represented by a plasticity model with a piecewise liner function defining the relationship between mean stress and volumetric strain.**
  - **Compaction experiments on simulated waste were used to develop this relationship**

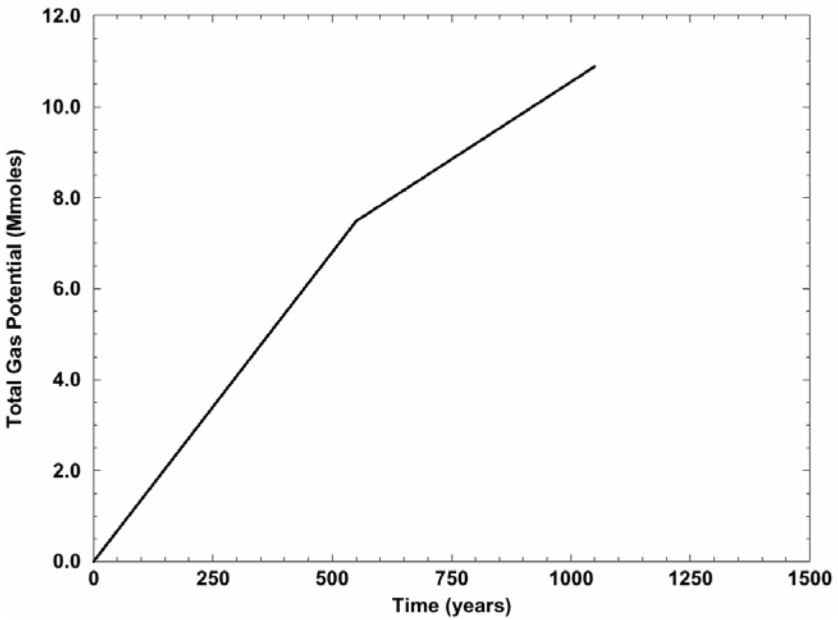


Gas Generation Potential

- The gas generation potential and gas production rate are composed of gas from two sources: anoxic corrosion and microbial activity.
- The gas pressure in the disposal room was computed from the ideal gas law based on the current free volume in the room

$$p_g = f \cdot \frac{NRT}{V}$$

N = mass of gas in g-moles
R = universal gas constant
T = absolute temperature (300 ºK)
V = free room volume
f = gas generation factor



History of the reference gas generation potential Used for the disposal room analysis, *f*=1.0

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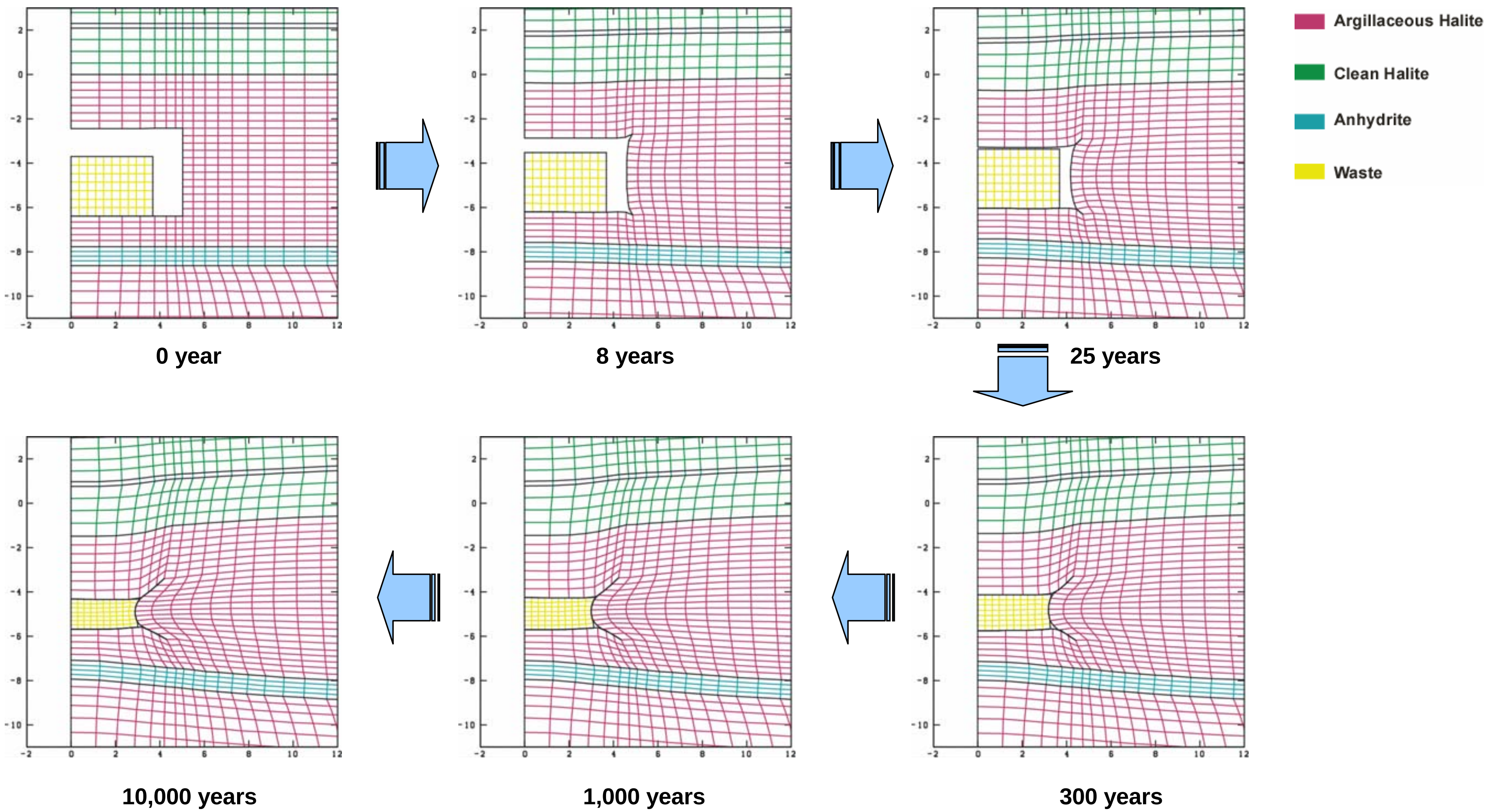
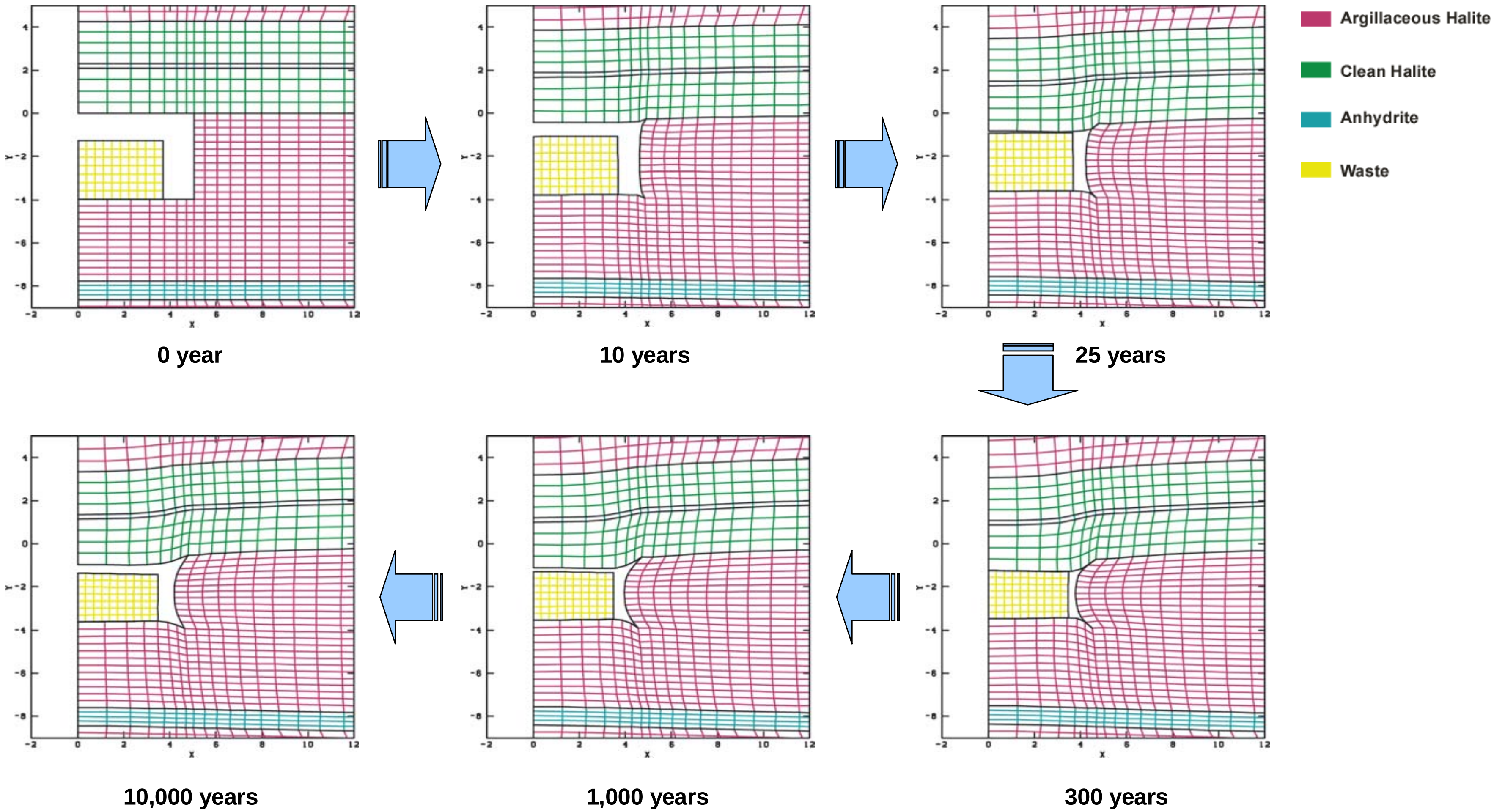
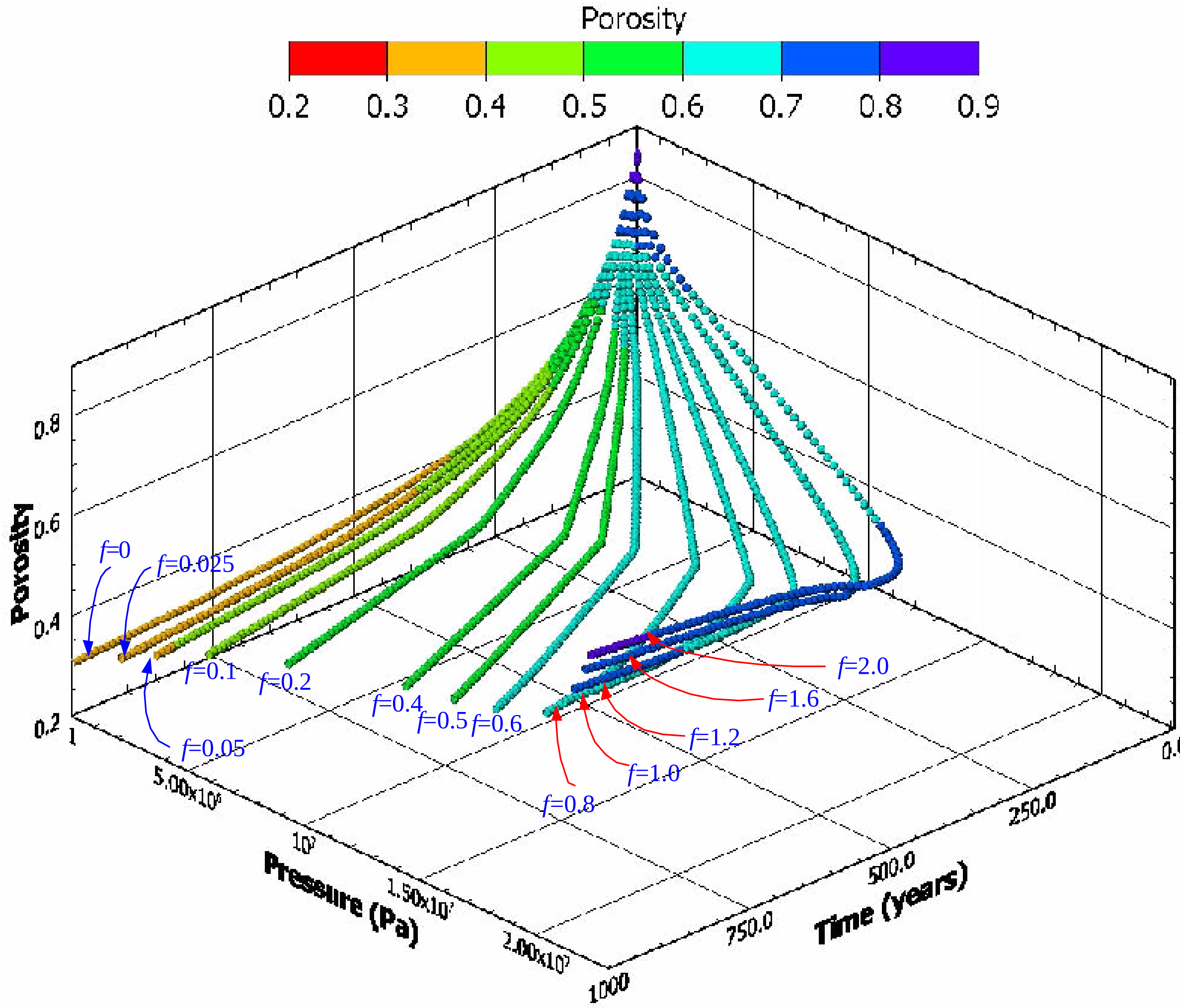
Disposal Room Creep Closure, *f* = 0.0 (Current Room)



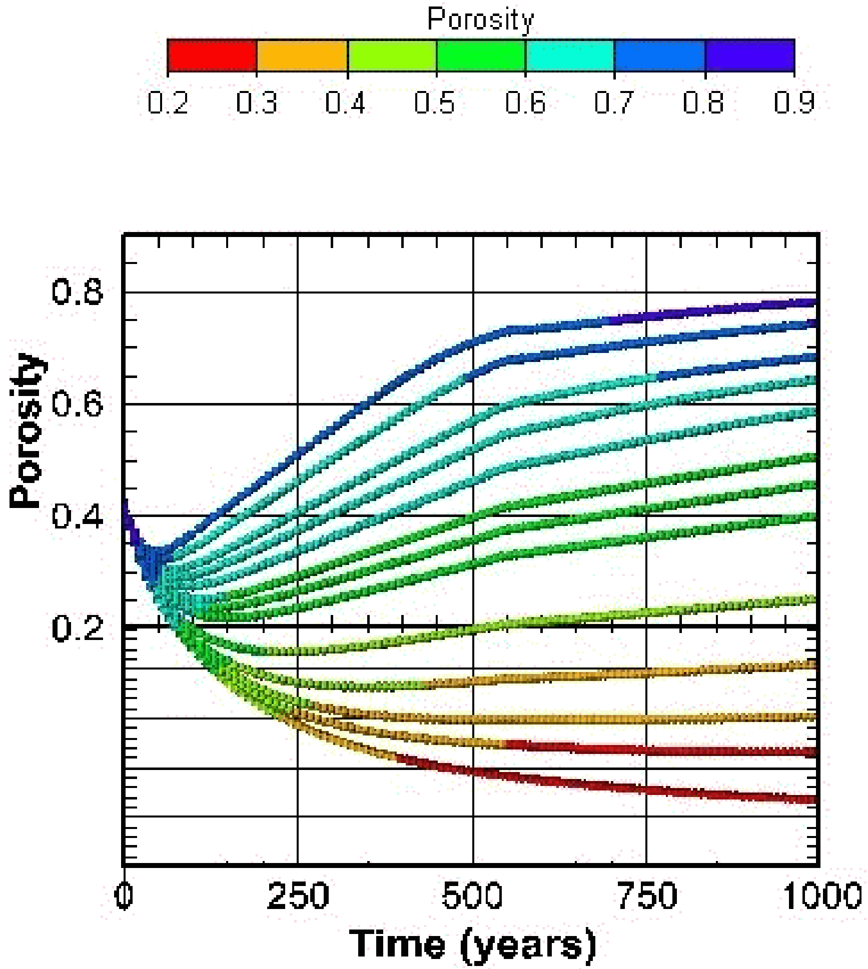
Disposal Room Creep Closure, *f* = 1.0
(Raised Room)



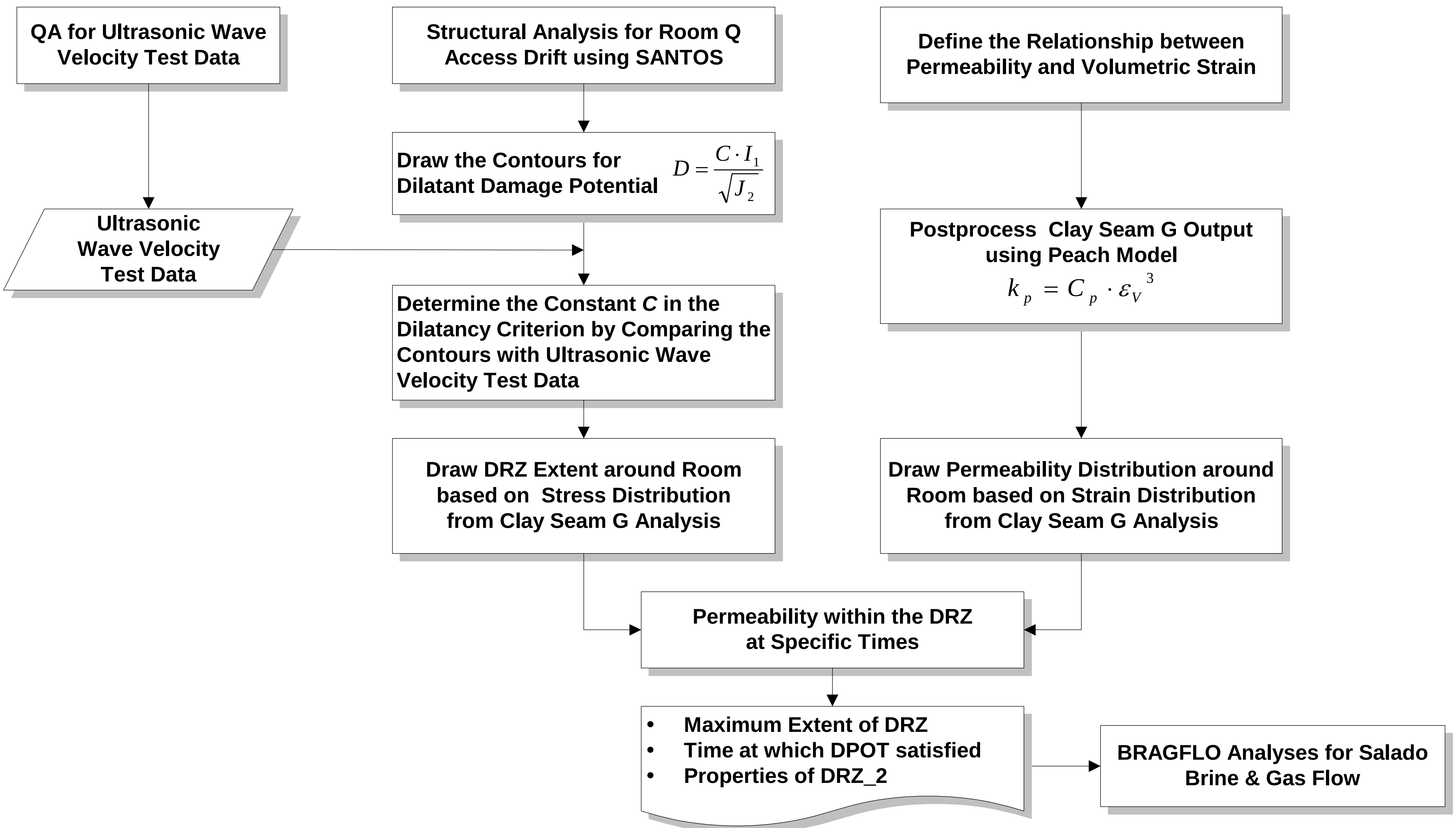
Porosity Surfaces for Rooms Containing Standard Waste



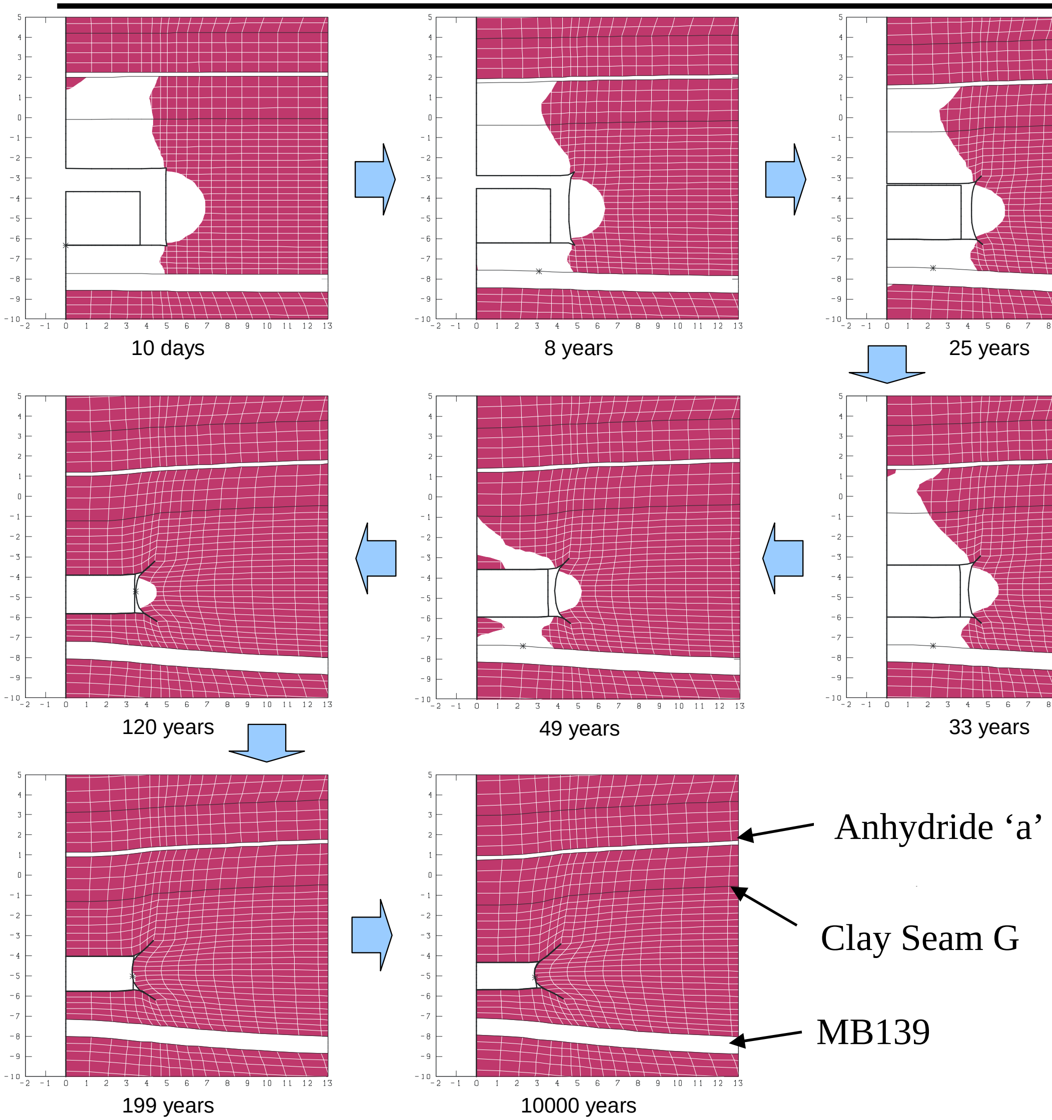
Porosity Surfaces for Rooms Containing Standard Waste



DRZ Calculation



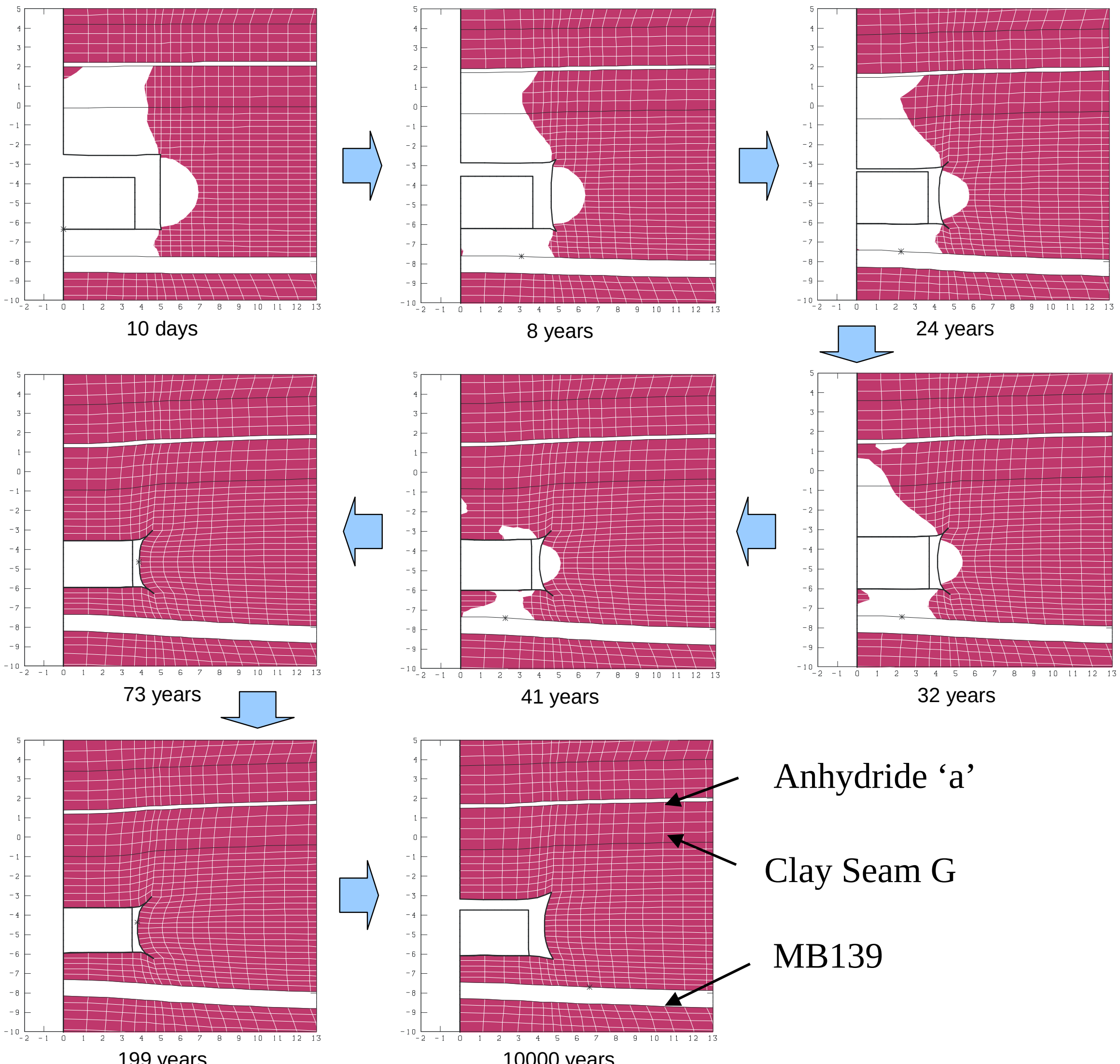
DRZ Extent (*No Gas Generation*)



- **Given the revised value of *C (=0.19)*, the extent of the DRZ is assessed by determining the damage factor (*D*) contour using the data obtained from the Clay Seam G analysis [Park and Holland, 2004]**

$$D = \frac{0.19 \cdot I_1}{\sqrt{J_2}}$$

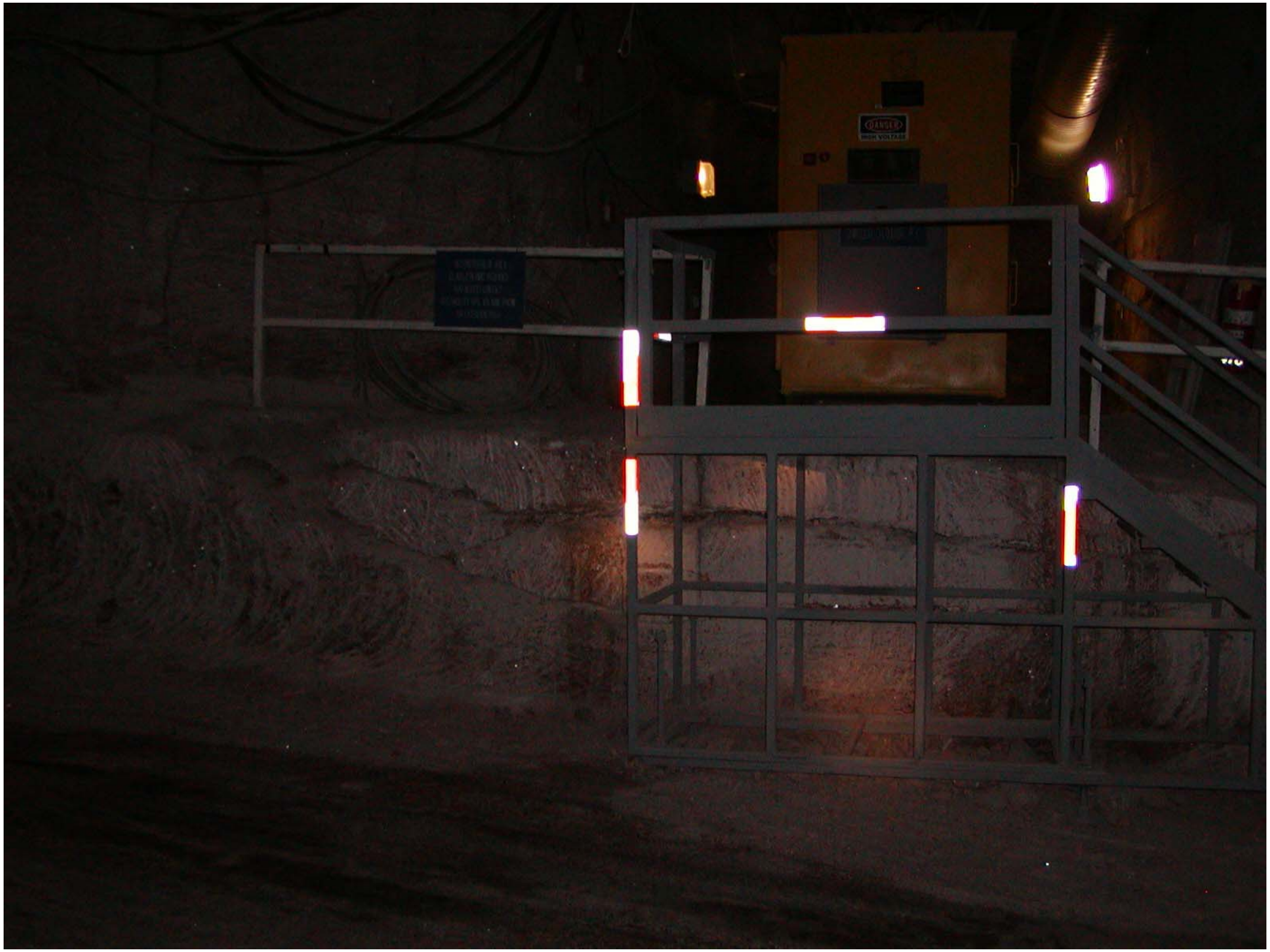
DRZ Extent (*Max Gas Generation*)



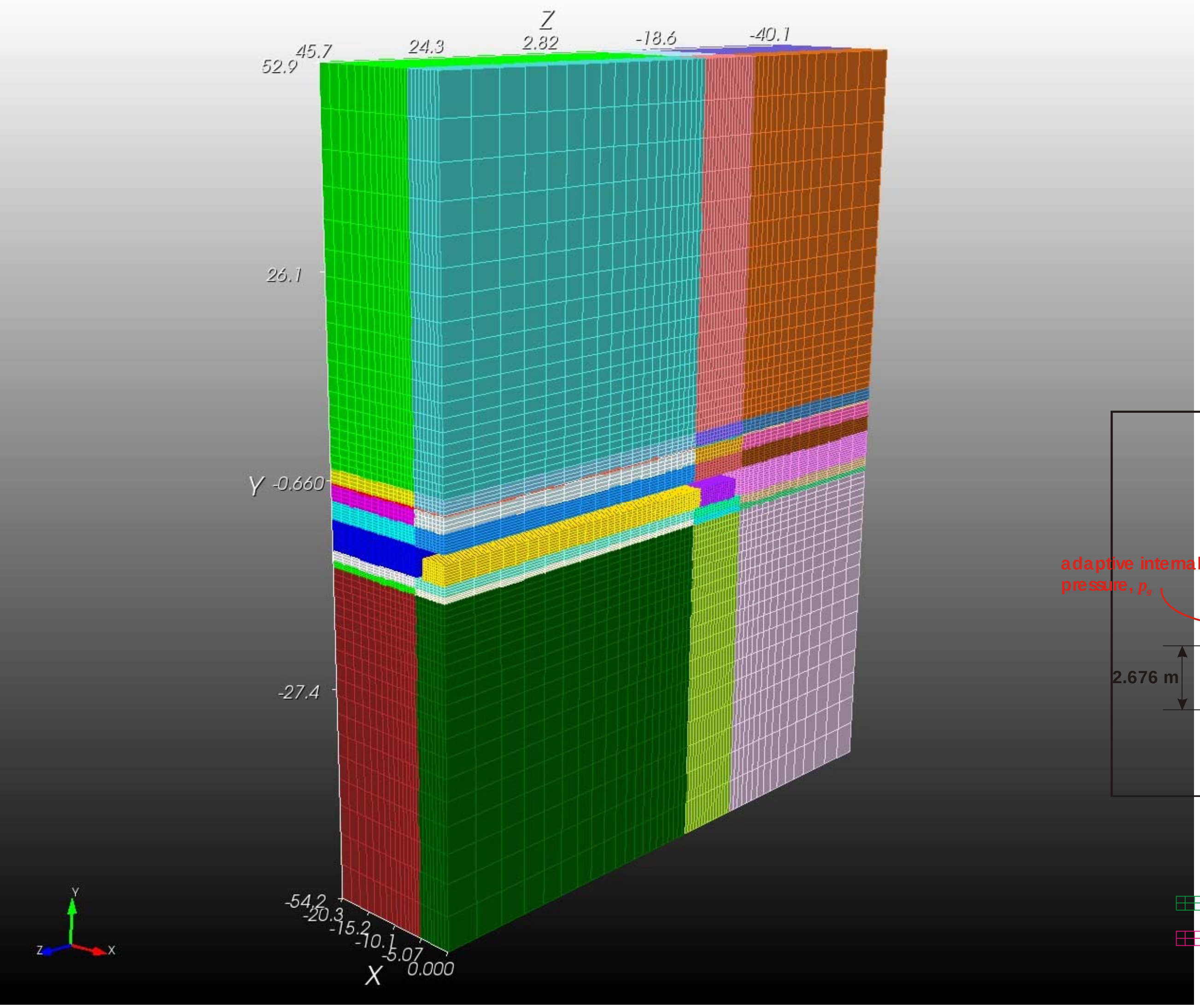
- **The maximum extent of the DRZ calculated for both gas generation cases reaches approximately 1.4 m, the distance to the anhydrite layer (MB 139), below the room.**
- **The anhydrite layer should be included in the DRZ therefore, the thickness of DRZ below the room is 2.24 m.**
- **The maximum extent of DRZ above the room calculated for both cases reaches anhydrite “a”. Thus the thickness of DRZ above the room is 4.74 m**
- **The DRZ does not extend through the anhydrite layer, which acts as a buffer.**

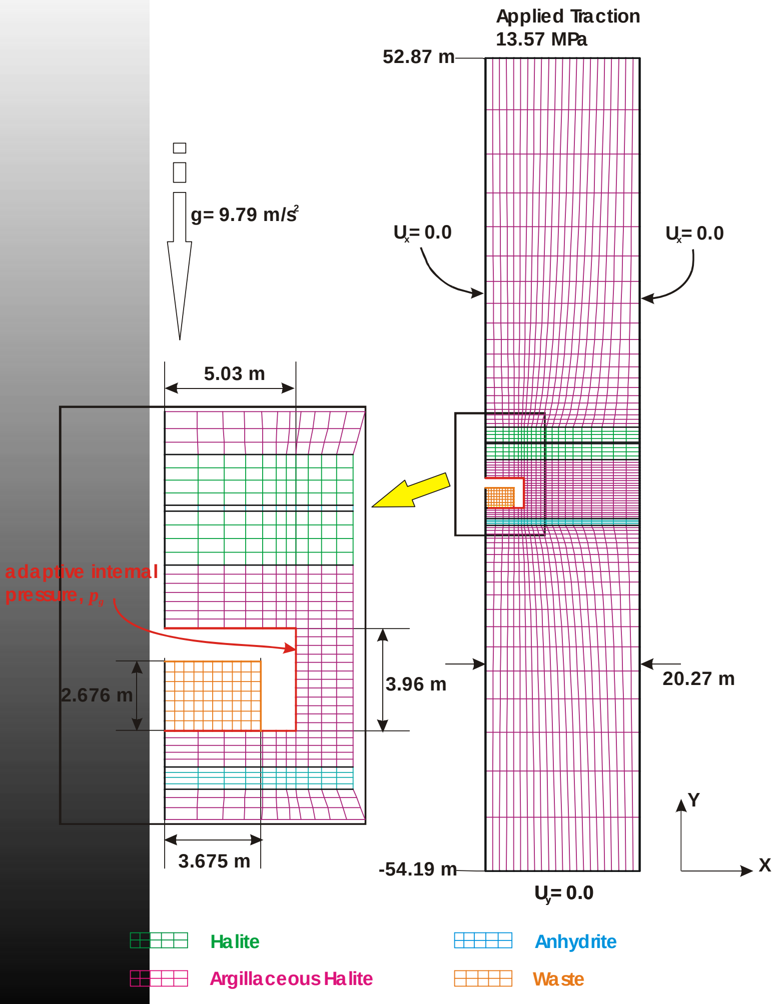
Cracks in the Roof Area of the Room

Cracks in the Bottom Area of the Room



3D Room Mesh for JAS3D





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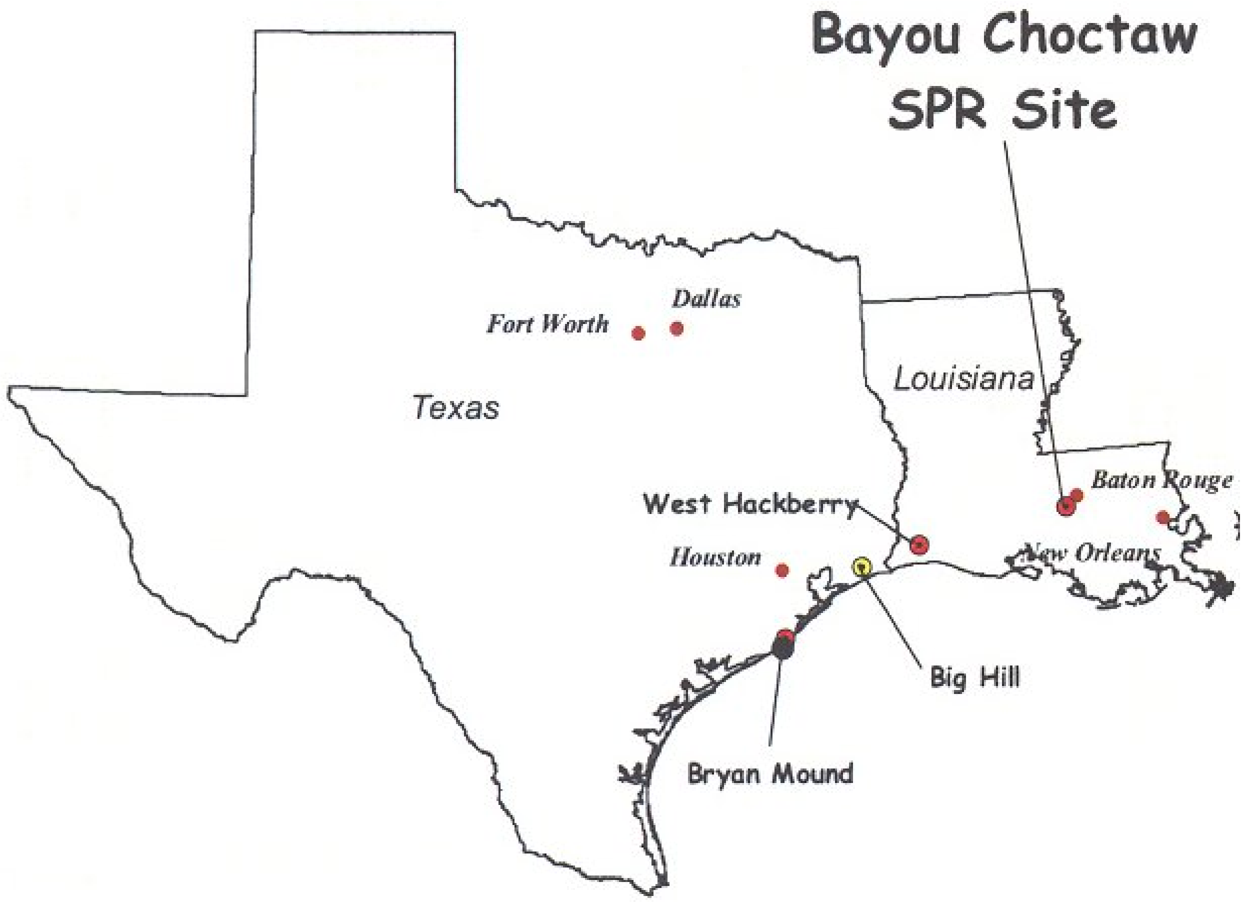
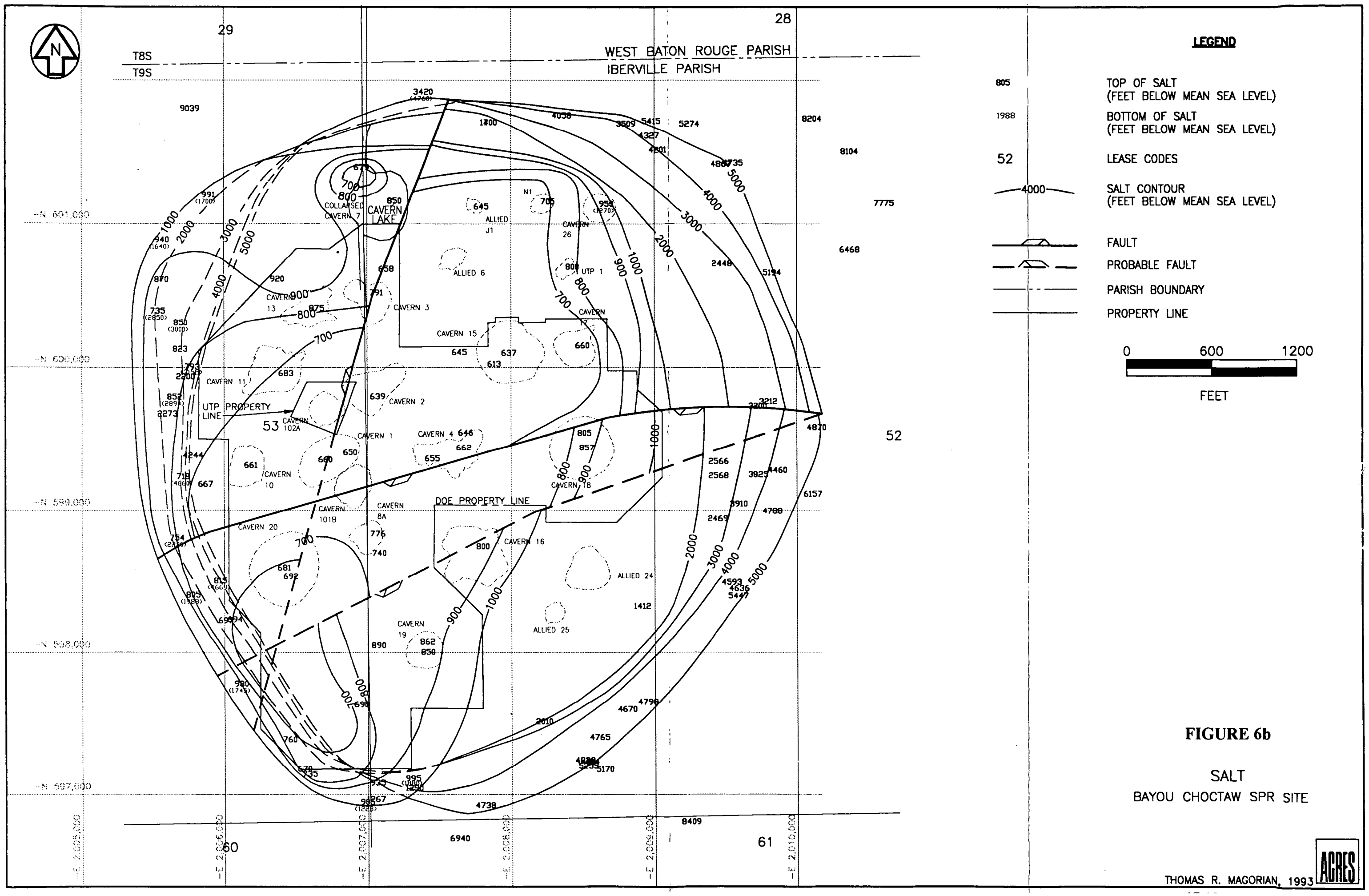
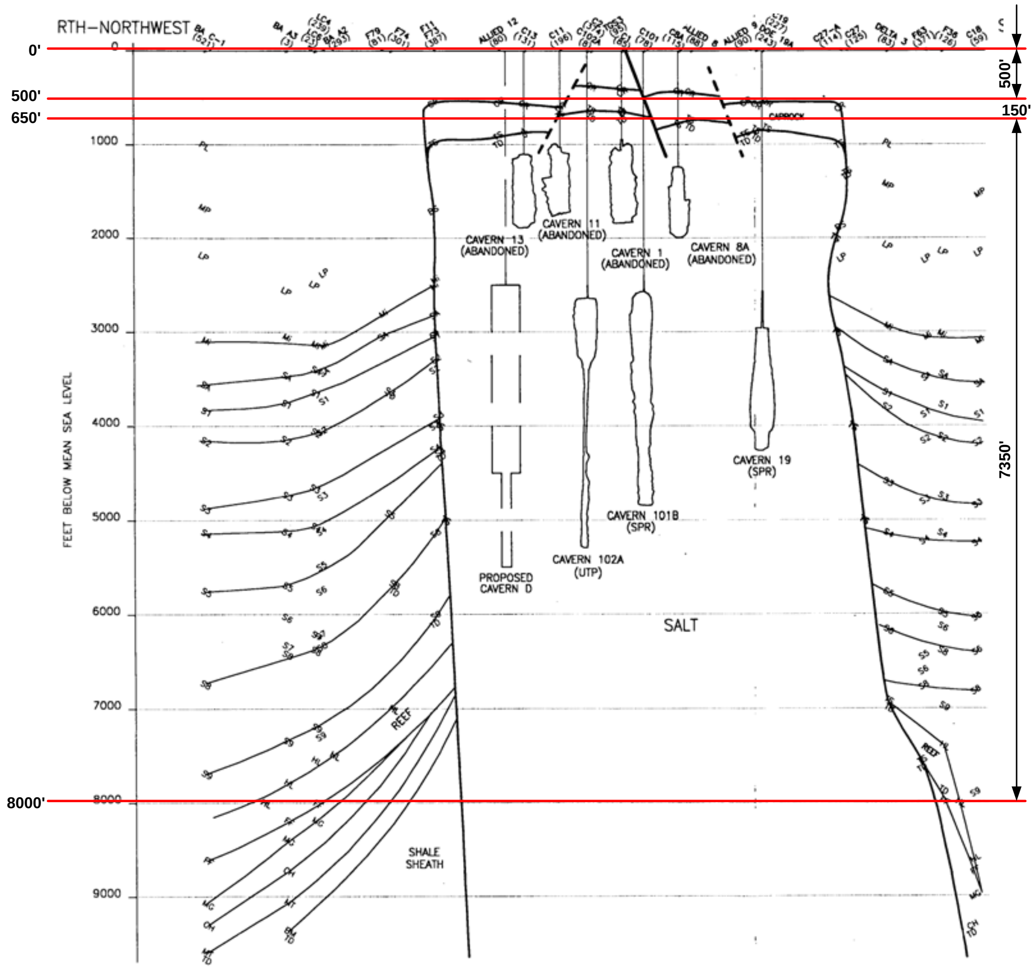
Location of Bayou Choctaw SPR Site



Bayou Choctaw Salt Dome, Louisiana
(Plan View)

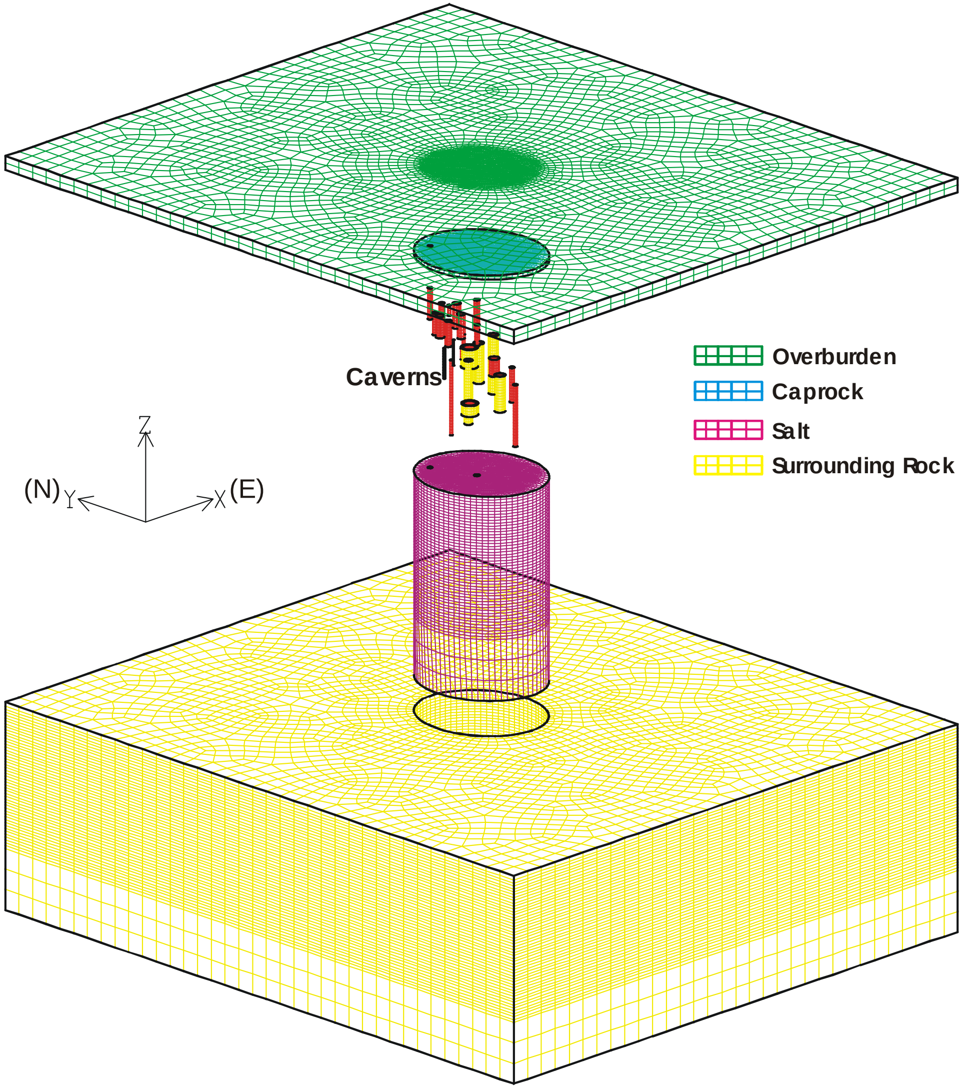


Stratigraphy and Thickness of Each Layer



Overview of the Mesh

(6 SPR, 2 Inactive, 7 Abandoned and 9 UTP Caverns)



Geometry of Cavern A, M and 102

		Cavern A	Cavern M	Cavern 102
UTM Coordinates (ft) (East / North)		2006758 / 597733	2006921 / 600327	2006700 / 599710
Initial Gross Cavern Volume (MMB)		12.6	12.6	23.6
Gross Cavern Volume after 5 Drawdowns (MMB)		25.3	25.3	47.5
Height (ft)		2000	2000	2700
Initial Diameter (ft)	Top/Bottom	110	110	250
	Mid	300	300	
Diameter after 5 Drawdowns (ft)	Top/Bottom	156	156	355
	Mid	426	426	

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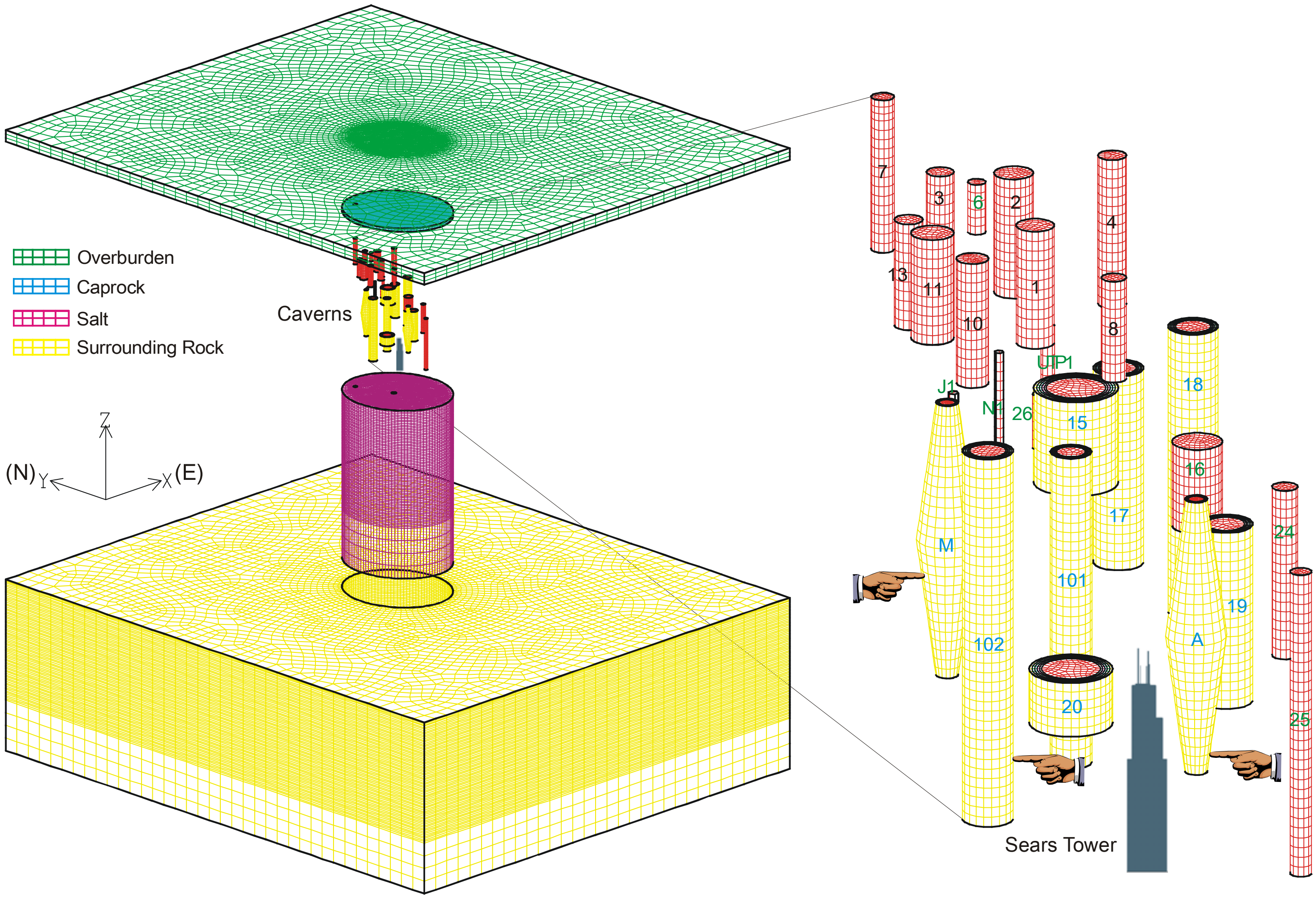
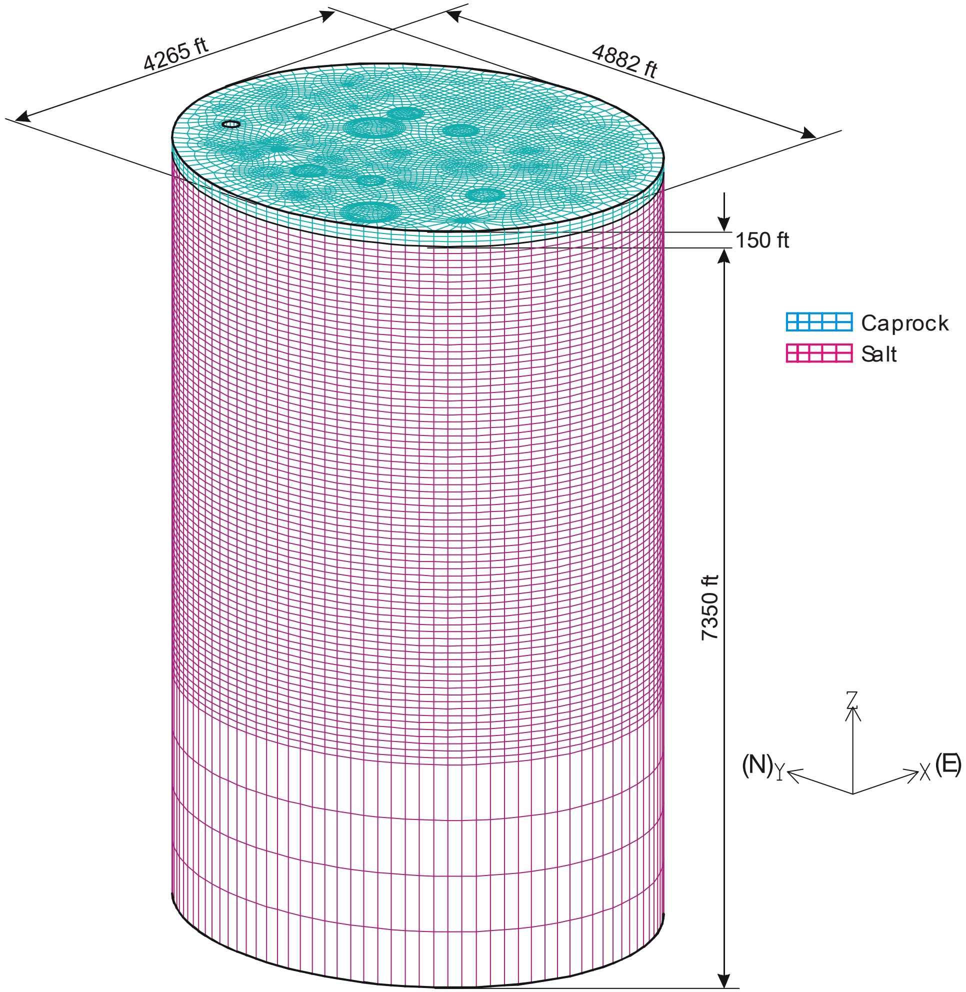
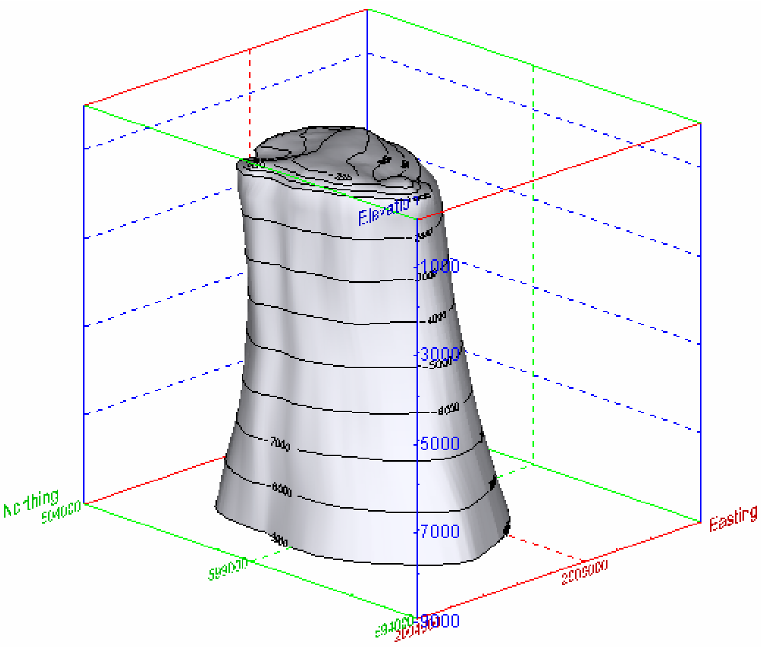
Overview of the Mesh
(9 SPR, 2 Inactive, 7 Abandoned and 8 UTP Caverns)



Comparison of Modeled vs. Actual Salt Dome and Caprock





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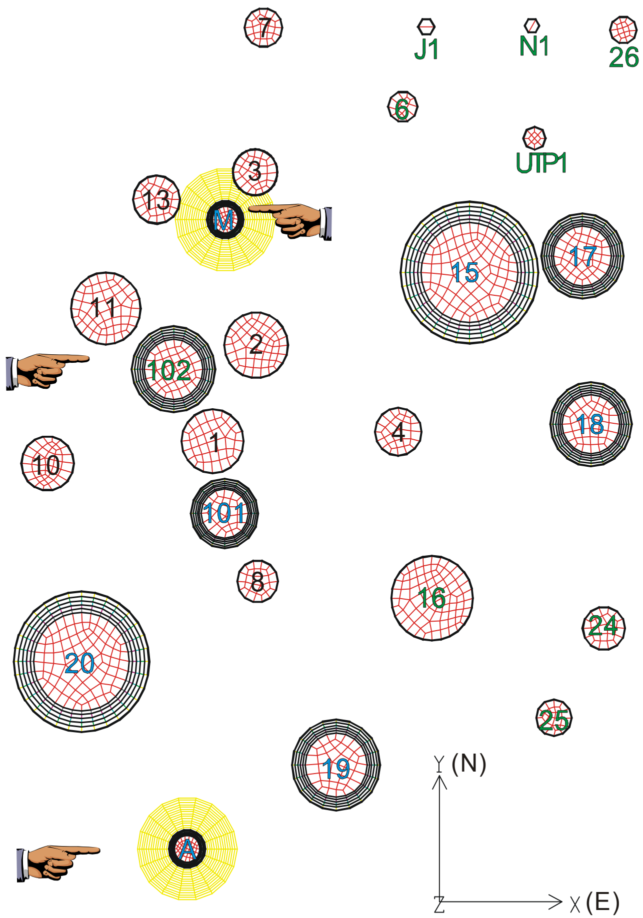
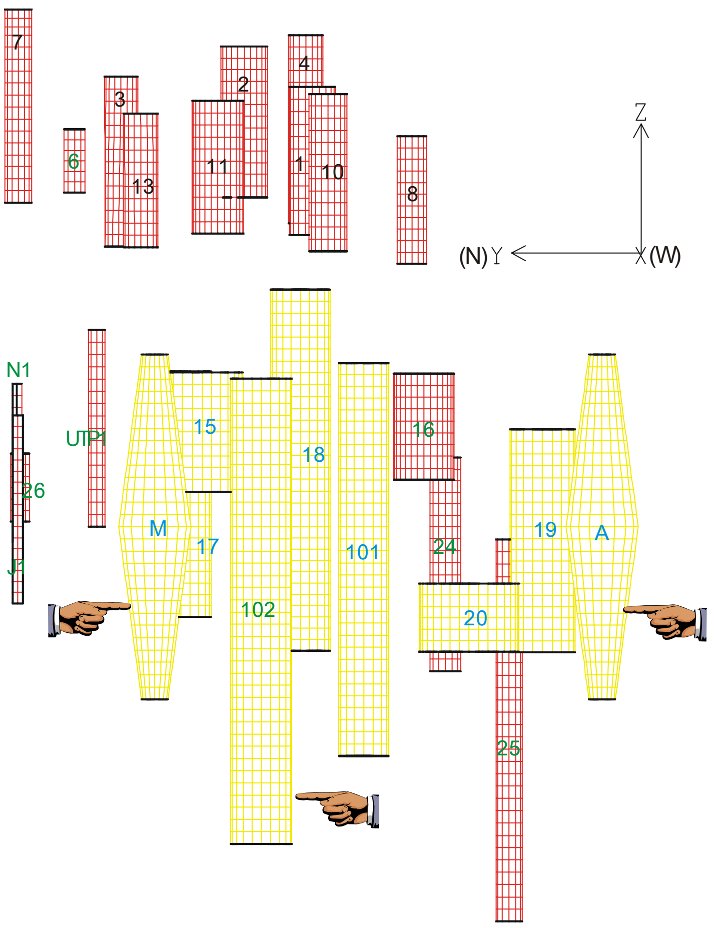
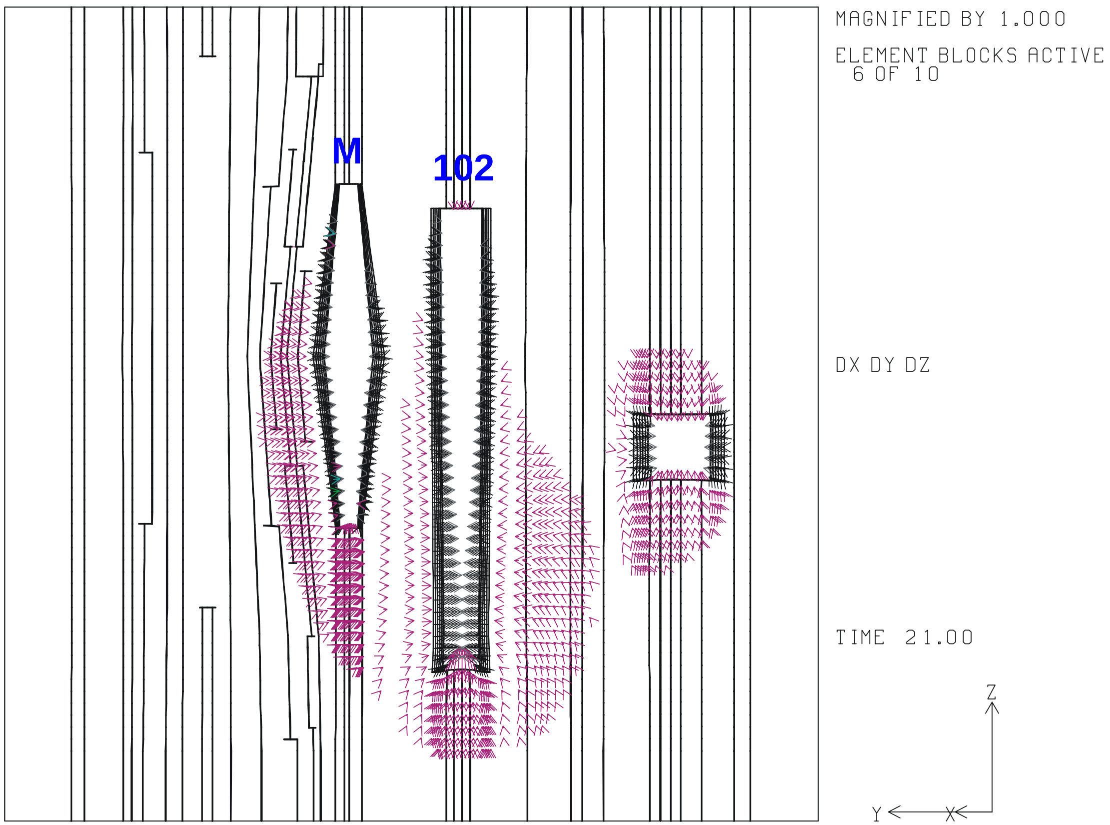
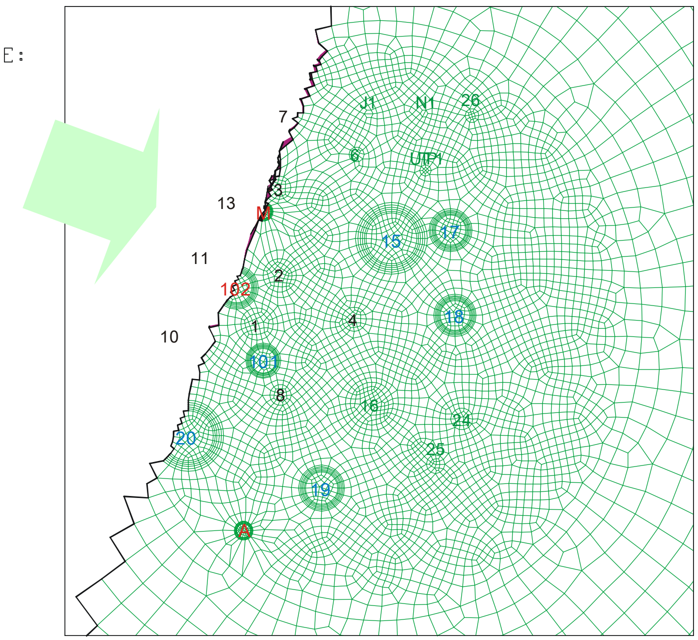
Cavern Layout



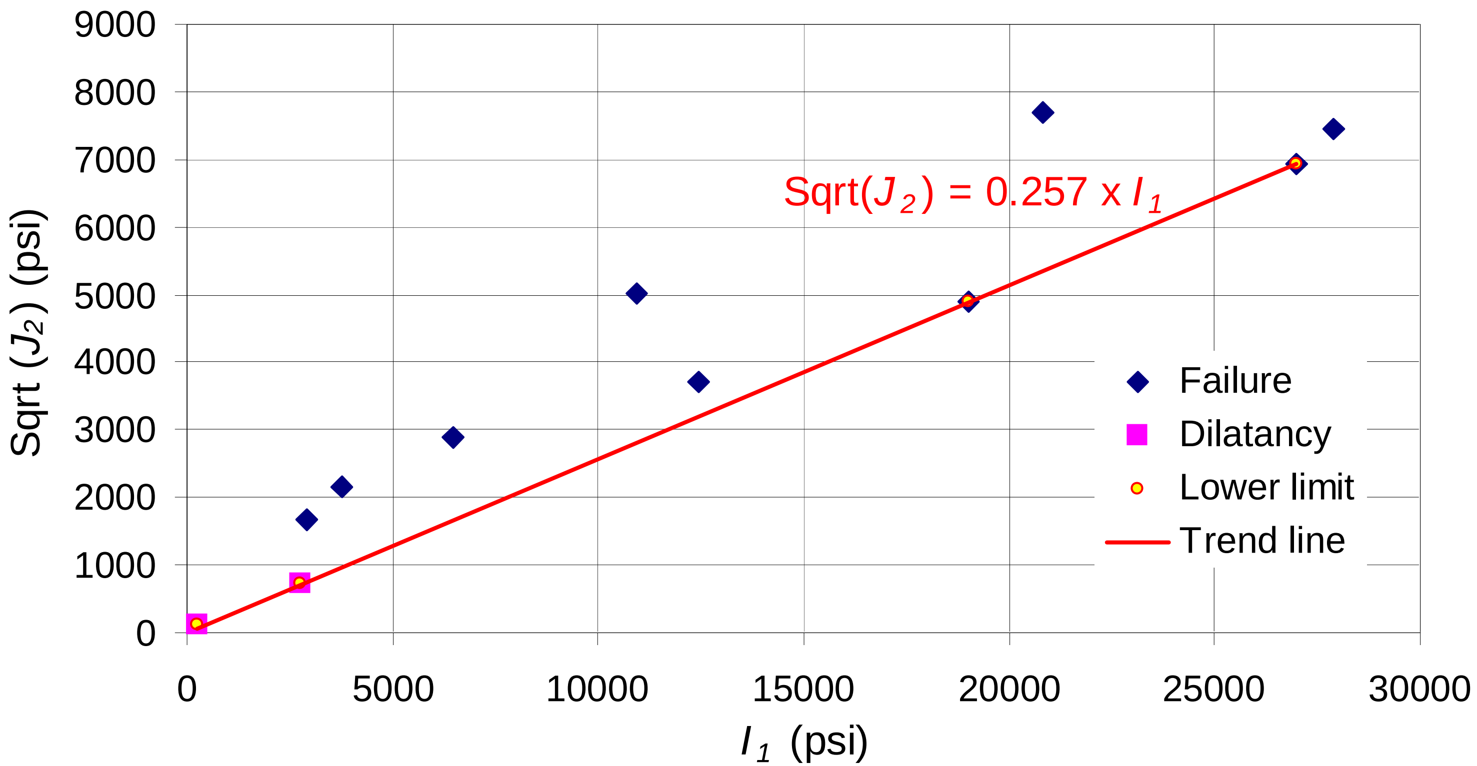


Cavern Deformation (Caverns M and 102)





Dilatancy Criteria for BC salt with Field Data



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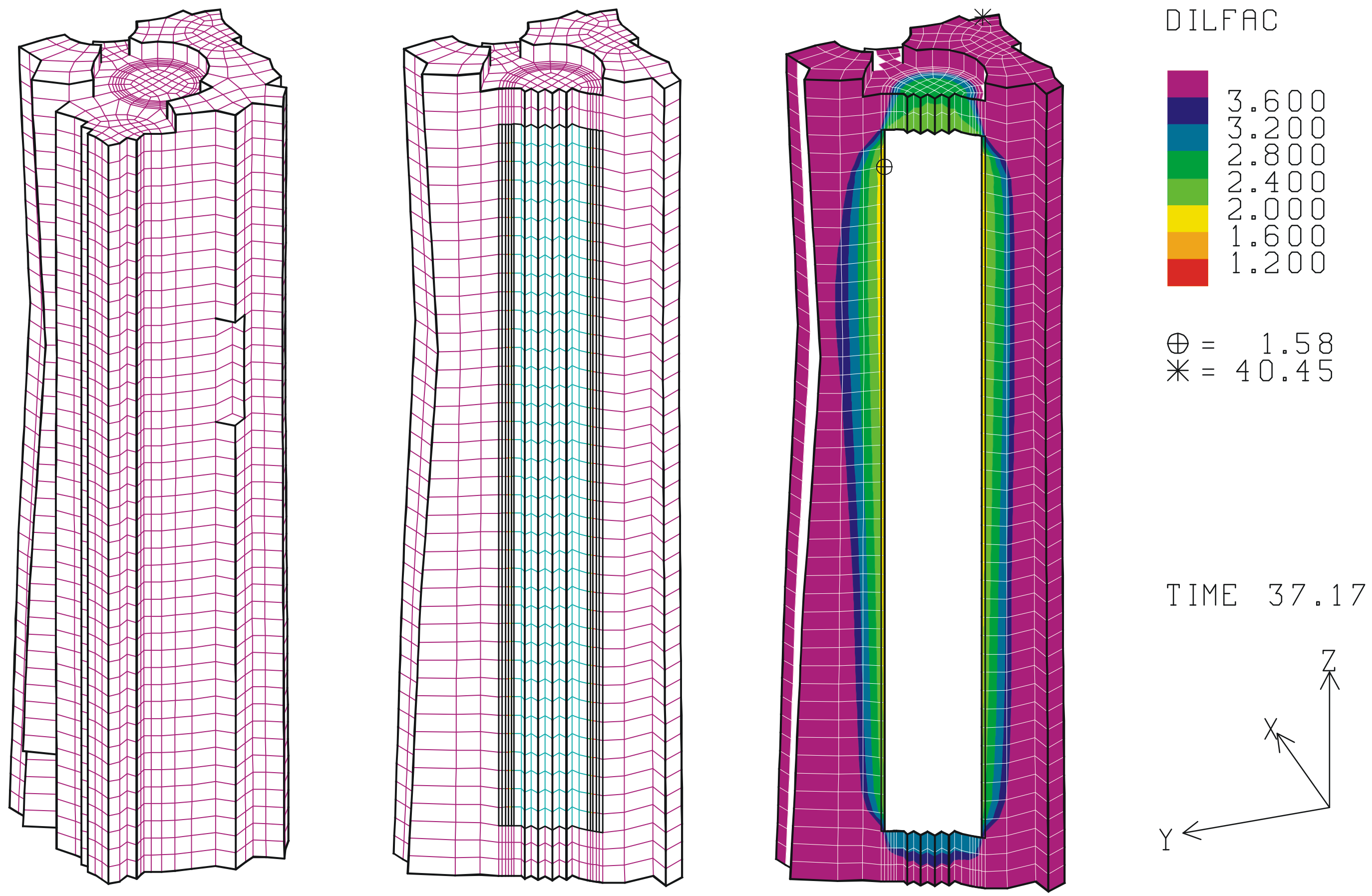
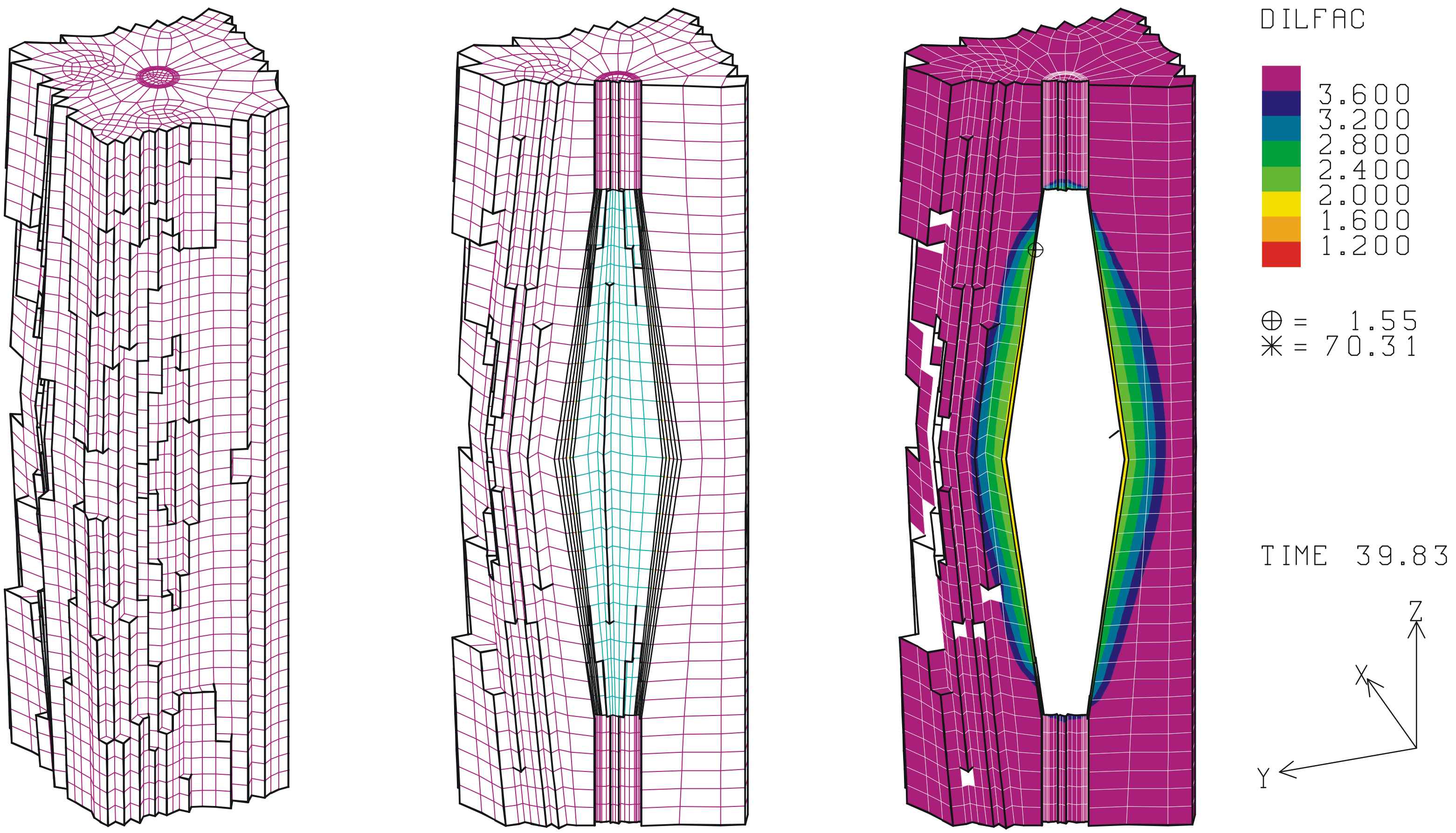
Volume and Dilatancy Safety Factor Contours in the Elements within 131 ft of Cavern 102 (Scenario 1)



Volume and Dilatancy Safety Factor Contours in the Elements within 131 ft of Cavern M (Scenario 1)



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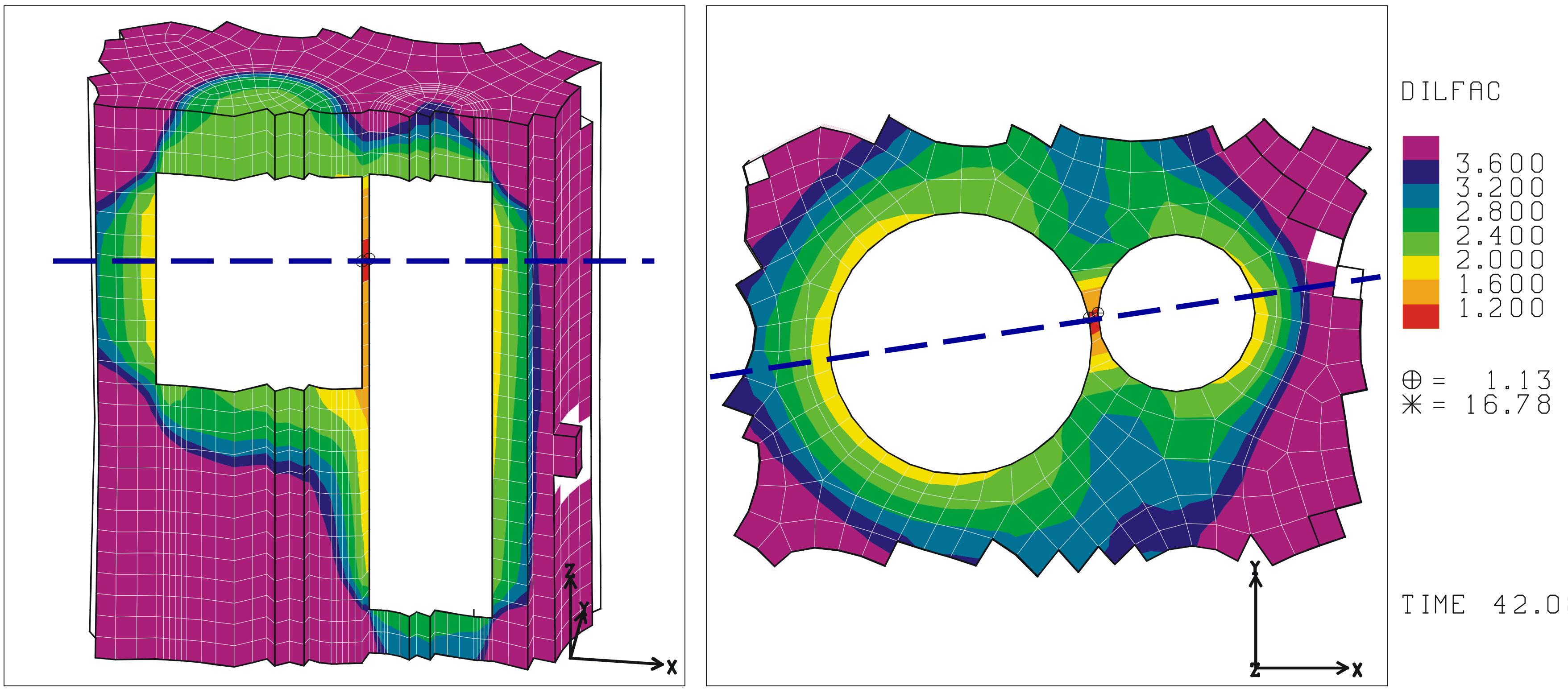
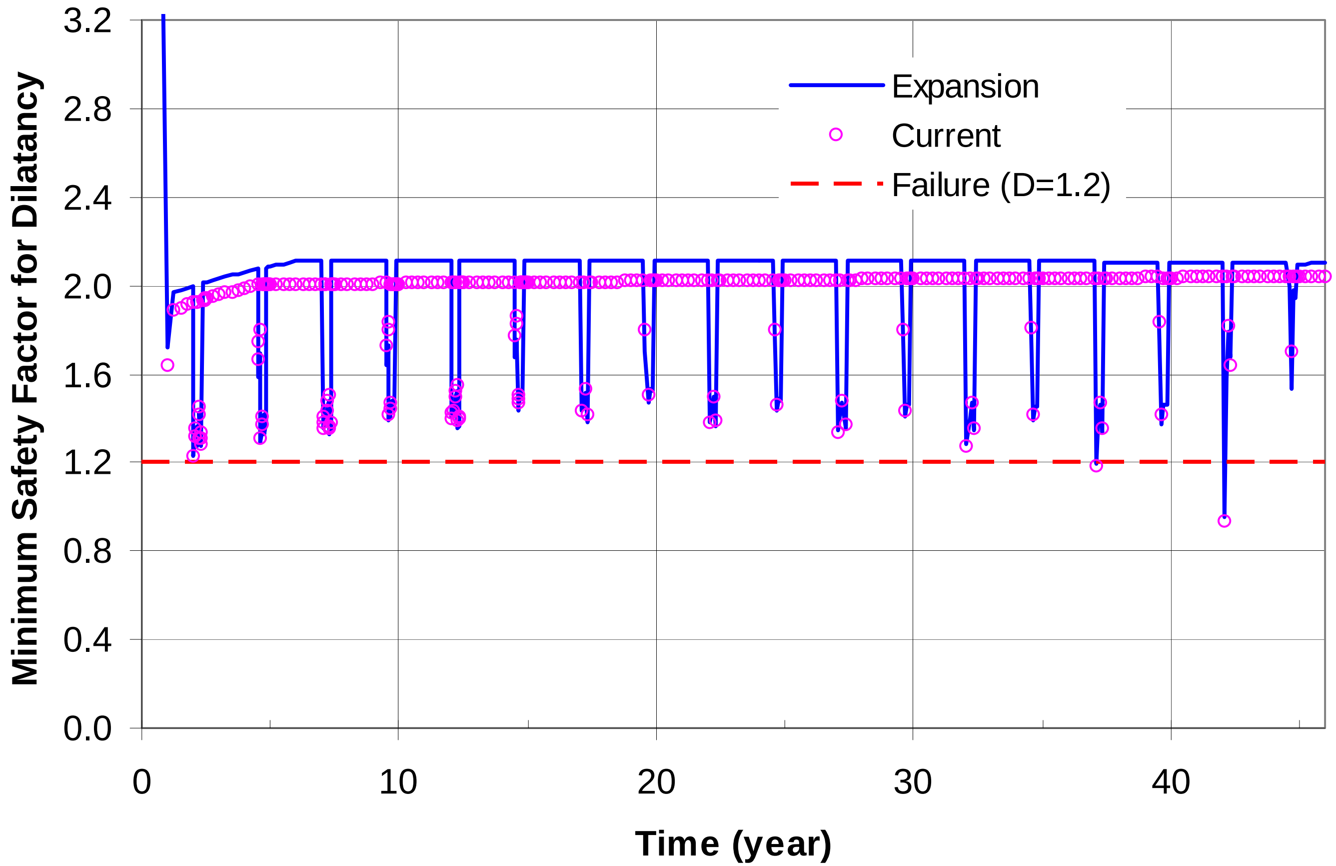
Volume and Dilatancy Safety Factor Contours in the Elements within 131 ft of Cavern 15 an 17 (Scenario 1)



Minimum Safety Factor History for Dilatancy Comparison with Current (Scenario 1)



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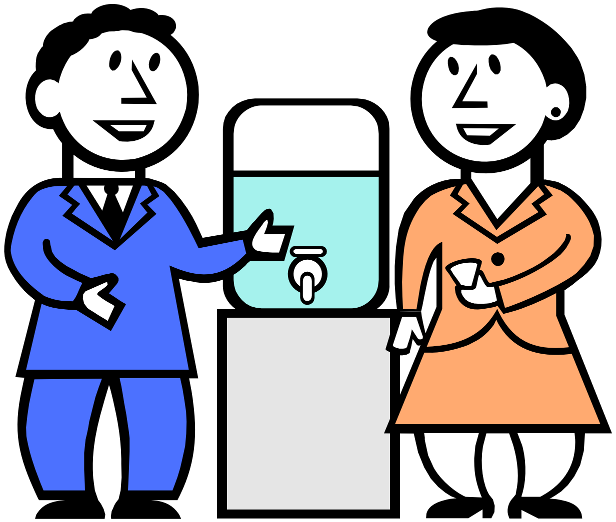
Break



Rock Mechanics Modeling in WIPP Performance Assessment (Apply to Korea)

KHNP Training Program
Module 6: Assembly of a Safety Case

October 15, 2007

Byoung Yoon Park, Ph.D.
Sandia National Laboratories
Carlsbad Programs Group

SAND 2007-XXXP

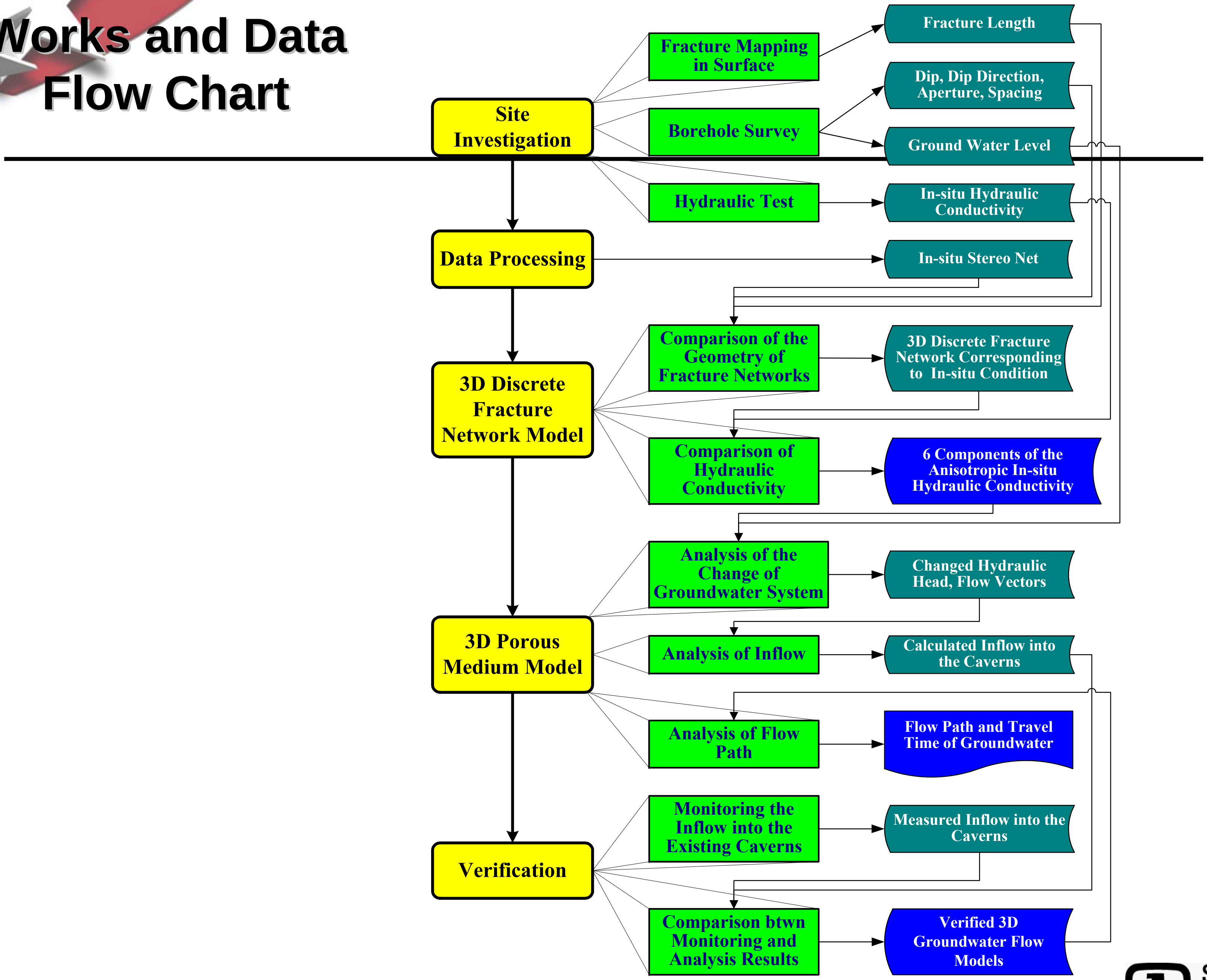
Main Topics

- Introduction
- Site Investigation in the Studied Area
- Data Processing
- 3D Discrete Fracture Network Model
- Calculation results
- Conclusions

Introduction

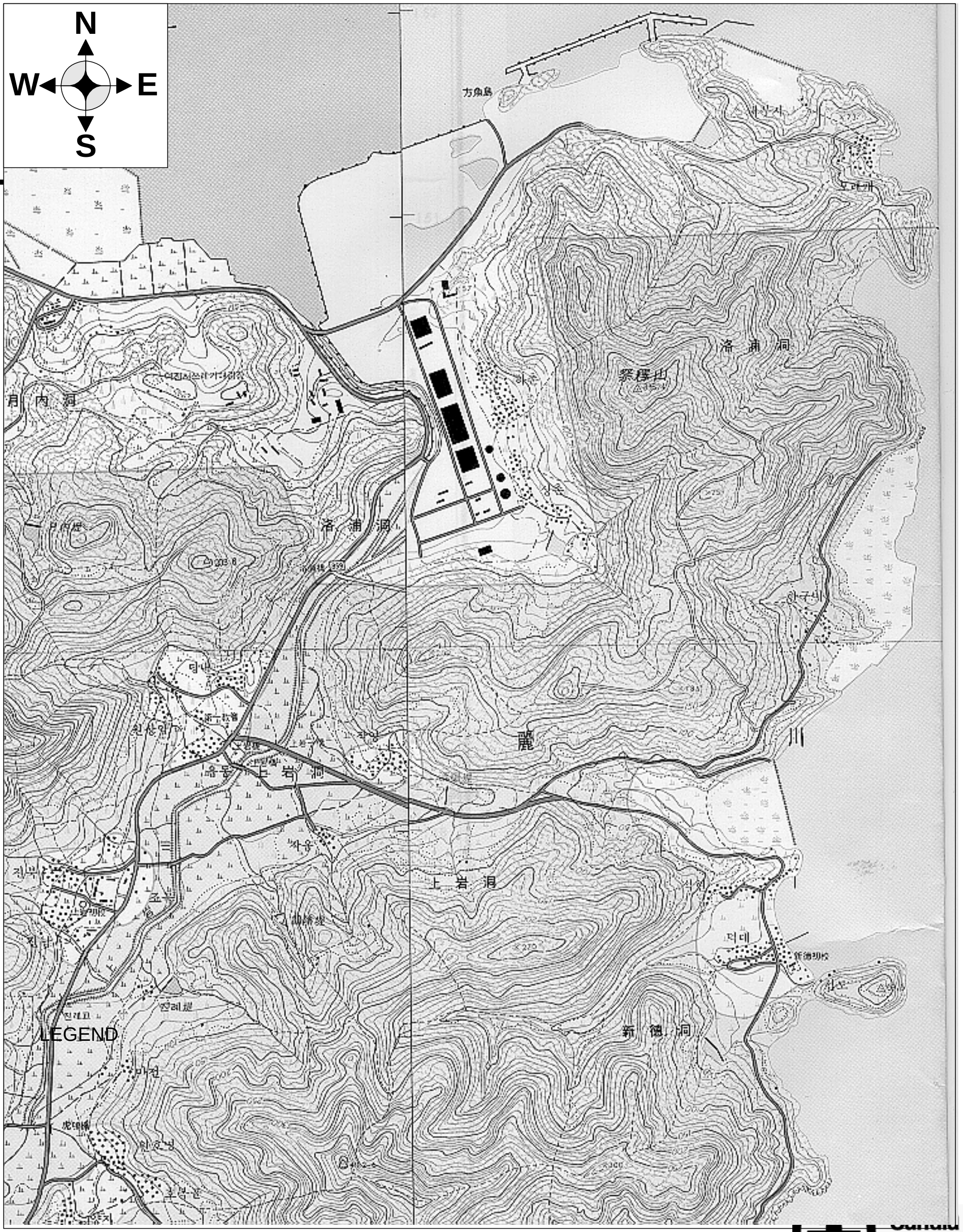
- **Accurate prediction of the pathway, the leakage rate of nuclides from HLW repository is one of the critical factors for PA**
- **Radionuclides are dissolved by groundwater in saturated rock mass**
- **In the case of crystalline rock, groundwater flow is only allowable through fractures**
- **In this presentation,**
  - **3D discrete fracture network could be modeled based on in-situ data by separating geometric parameters and hydraulic parameters.**
  - **Calculating anisotropic hydraulic conductivity from this model**

Works and Data Flow Chart



Studied Area

- Yeosu Peninsula in Chunnam, Korea
- 3 x 5 km Area



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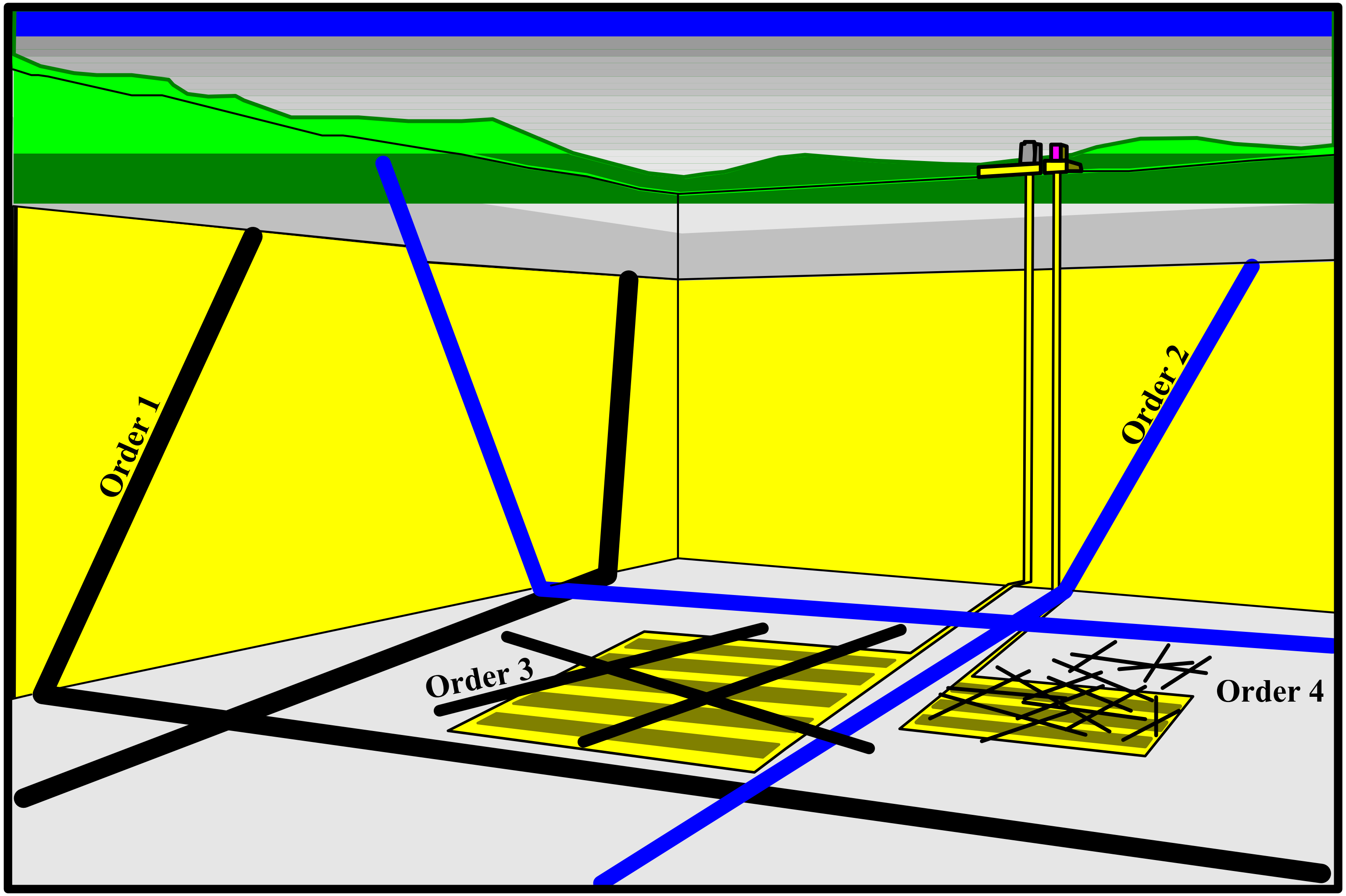
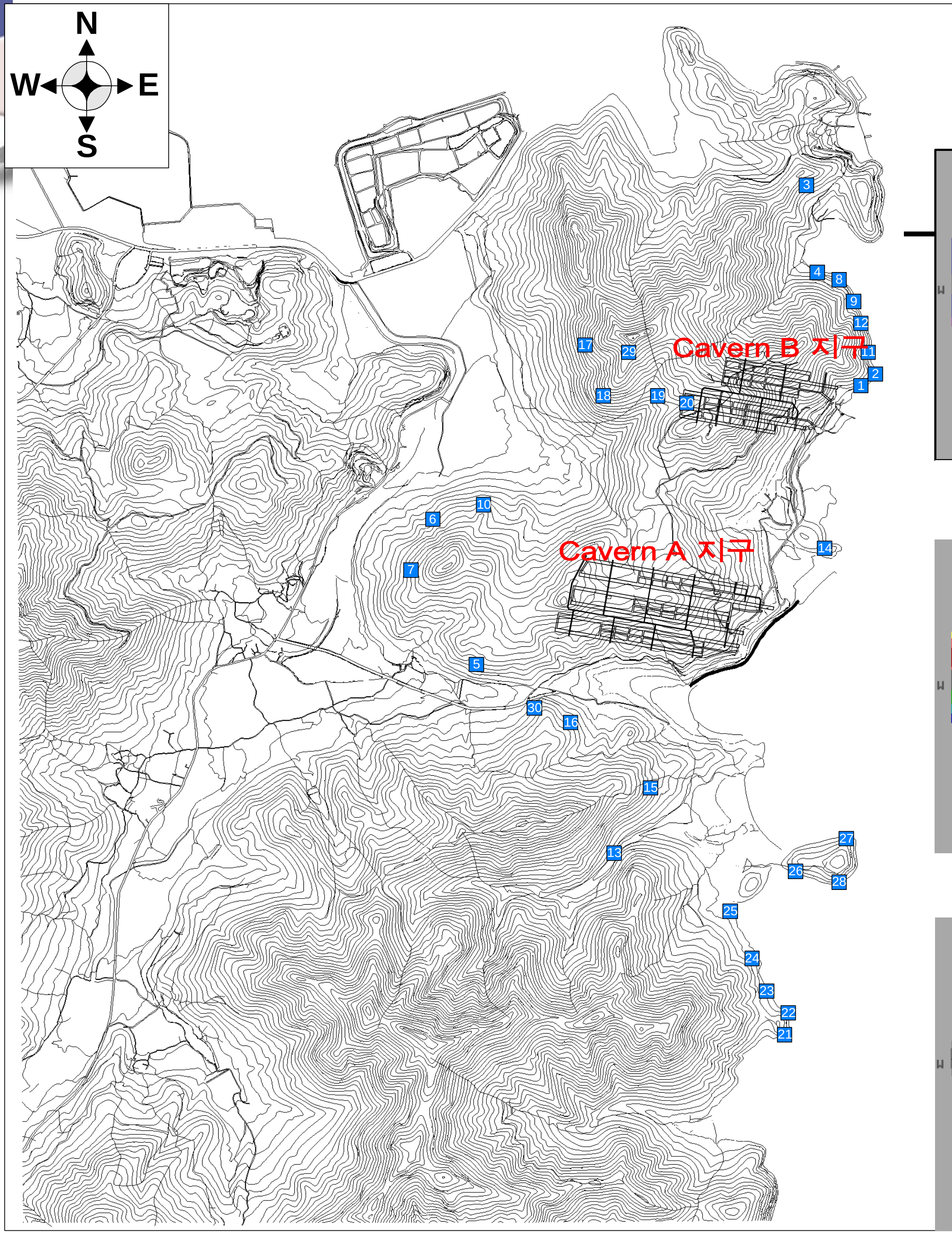
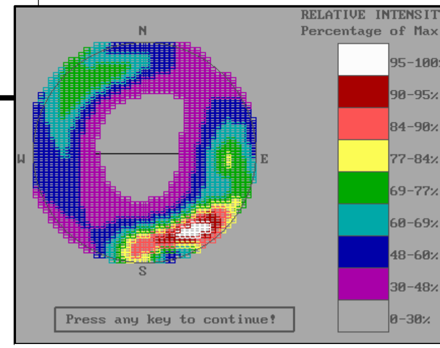
Classification System of the Fracture Zone

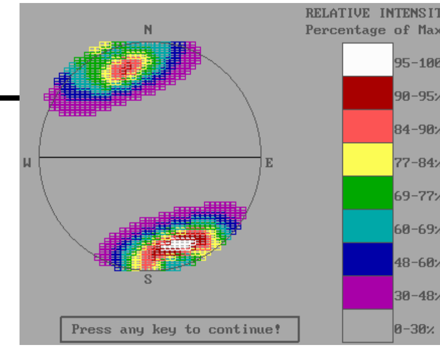




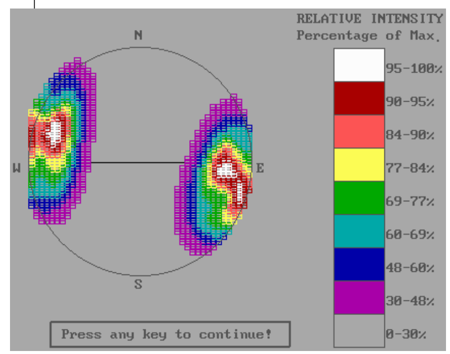
Fracture Mapping in Surface



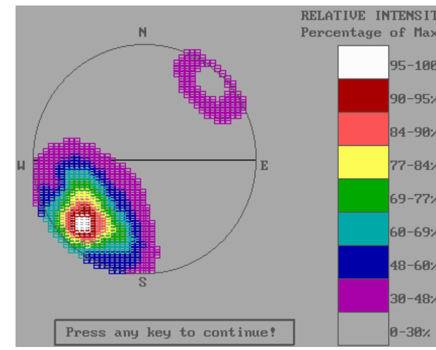
(a) All fractures



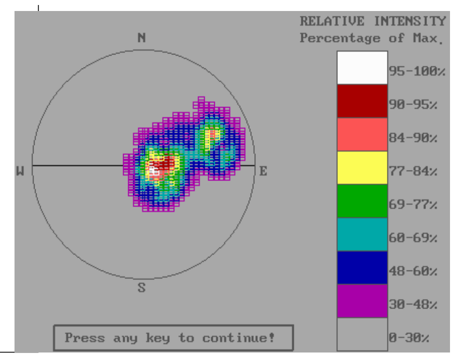
(b) Set 1



(c) Set 2



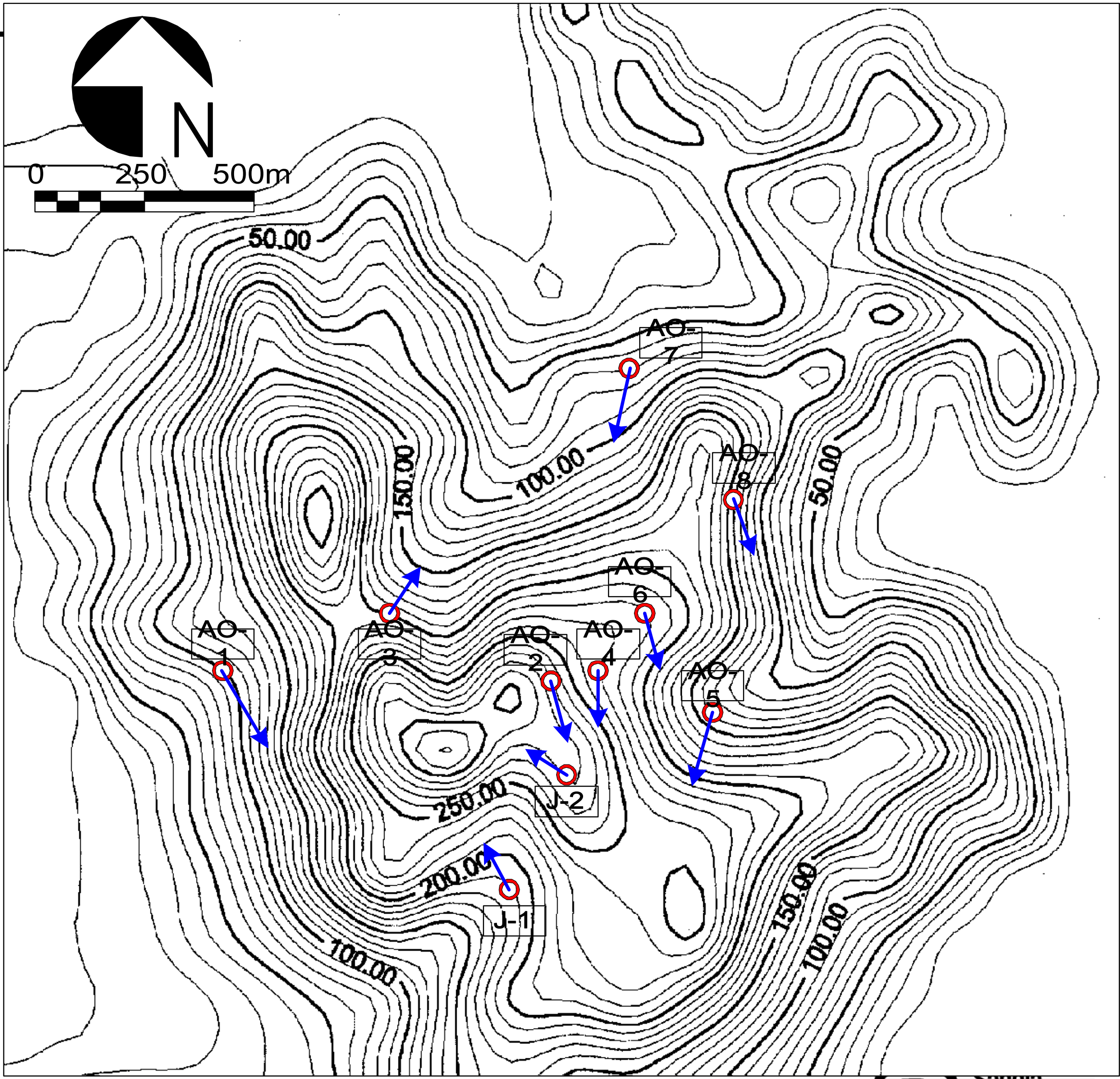
(d) Set 3



(e) Set 4

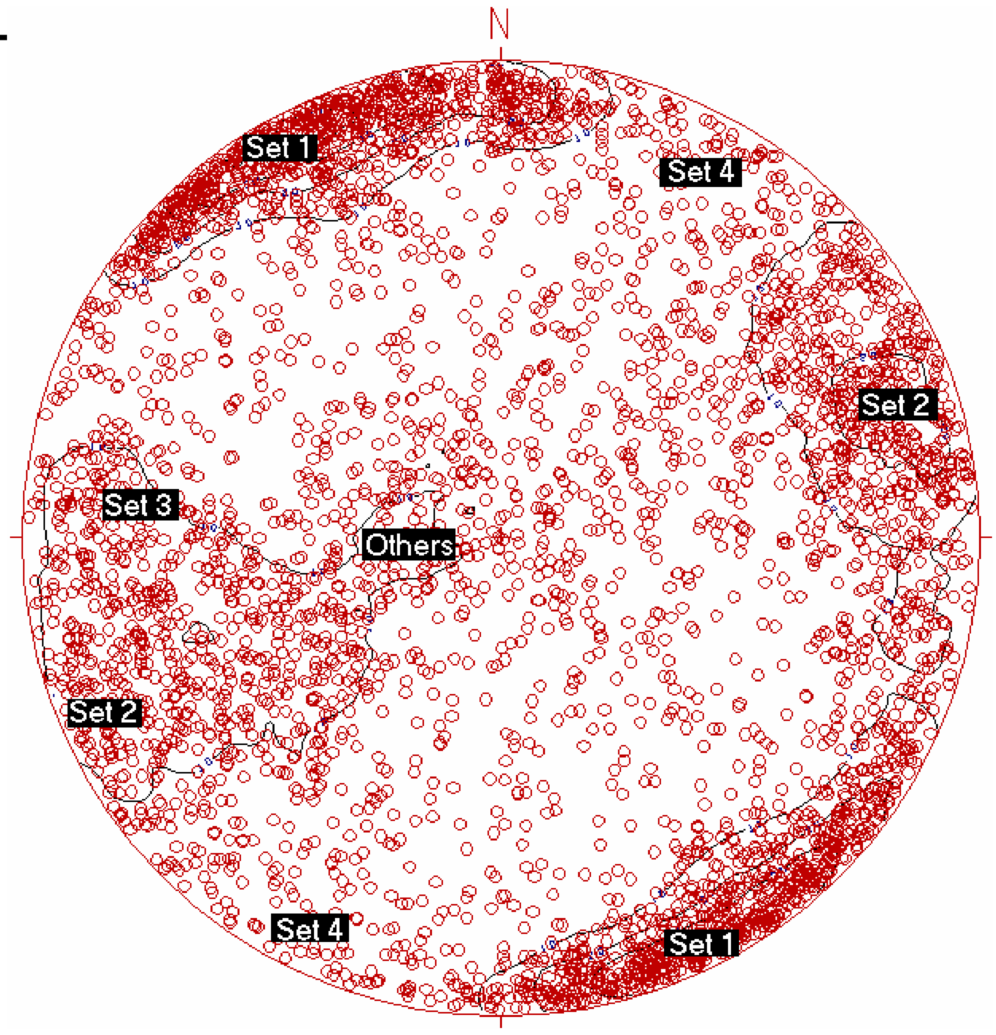
Borehole Survey

- **Ten NX size boreholes were drilled**
- **Total drilling length was 2,361 m**
- **Dip angles of the boreholes were 65° ~ 70°**
- **Total vertical length of televiewer logging was 2,079 m**

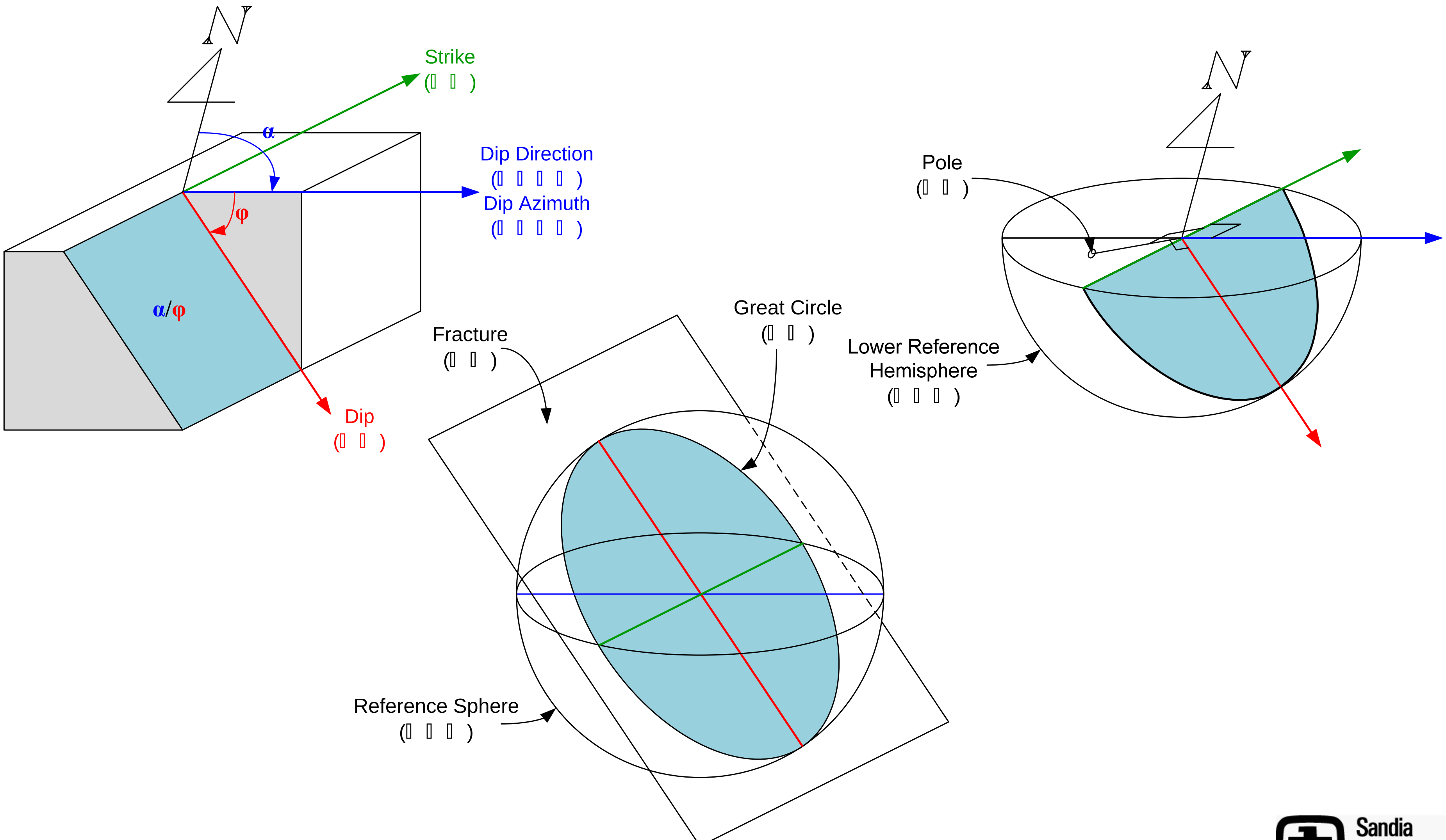


Fractures detected from 10 BHs

- **4,609 fractures were detected from ten BHs**
- **The total number of open fracture is 2,197**
- **The major dip direction of the 5 fracture sets are 148/80, 255/80, 86/65, 28/90, and 140/17, respectively**

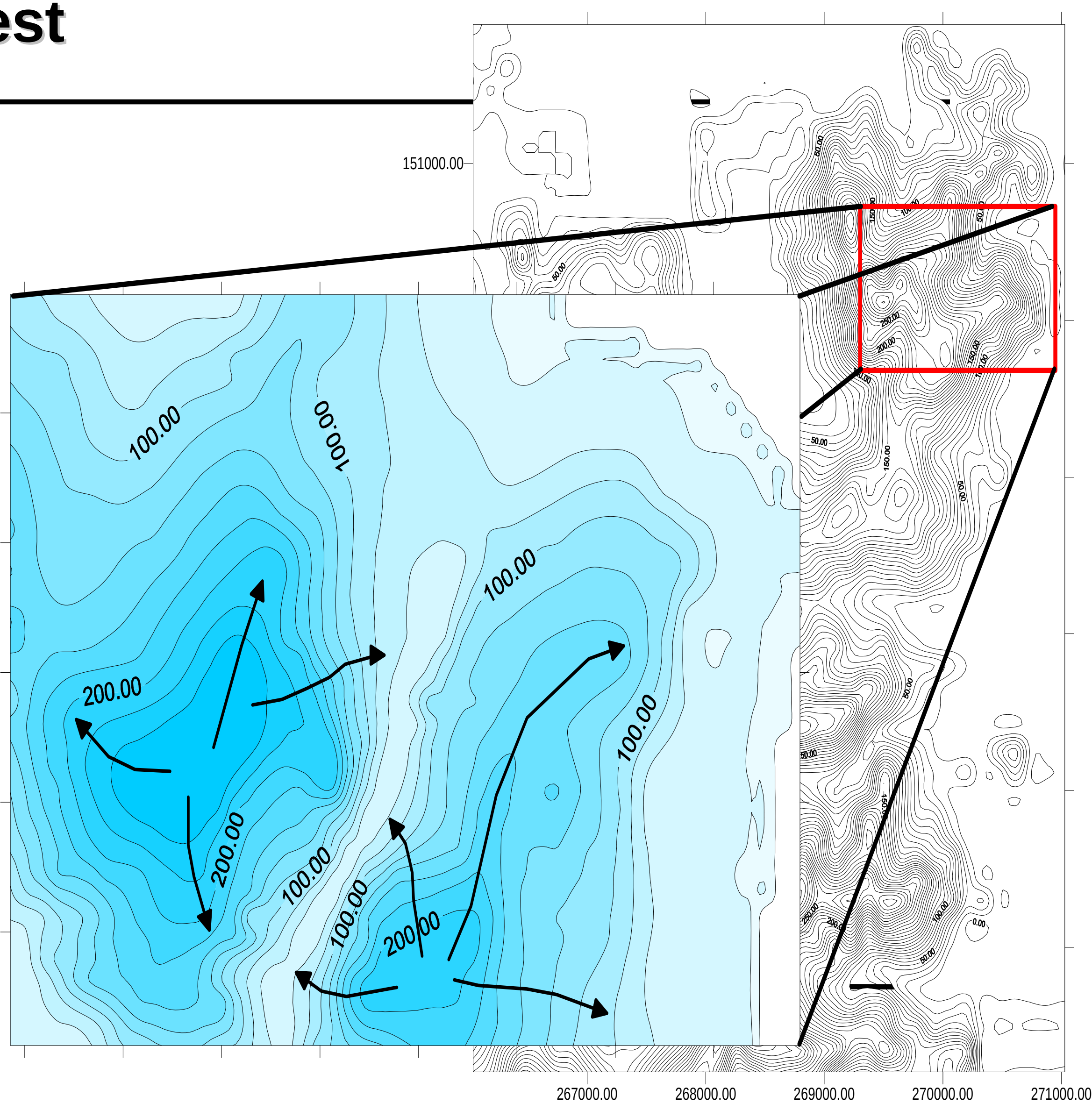


Pole, Dip, Dip Direction, Strike



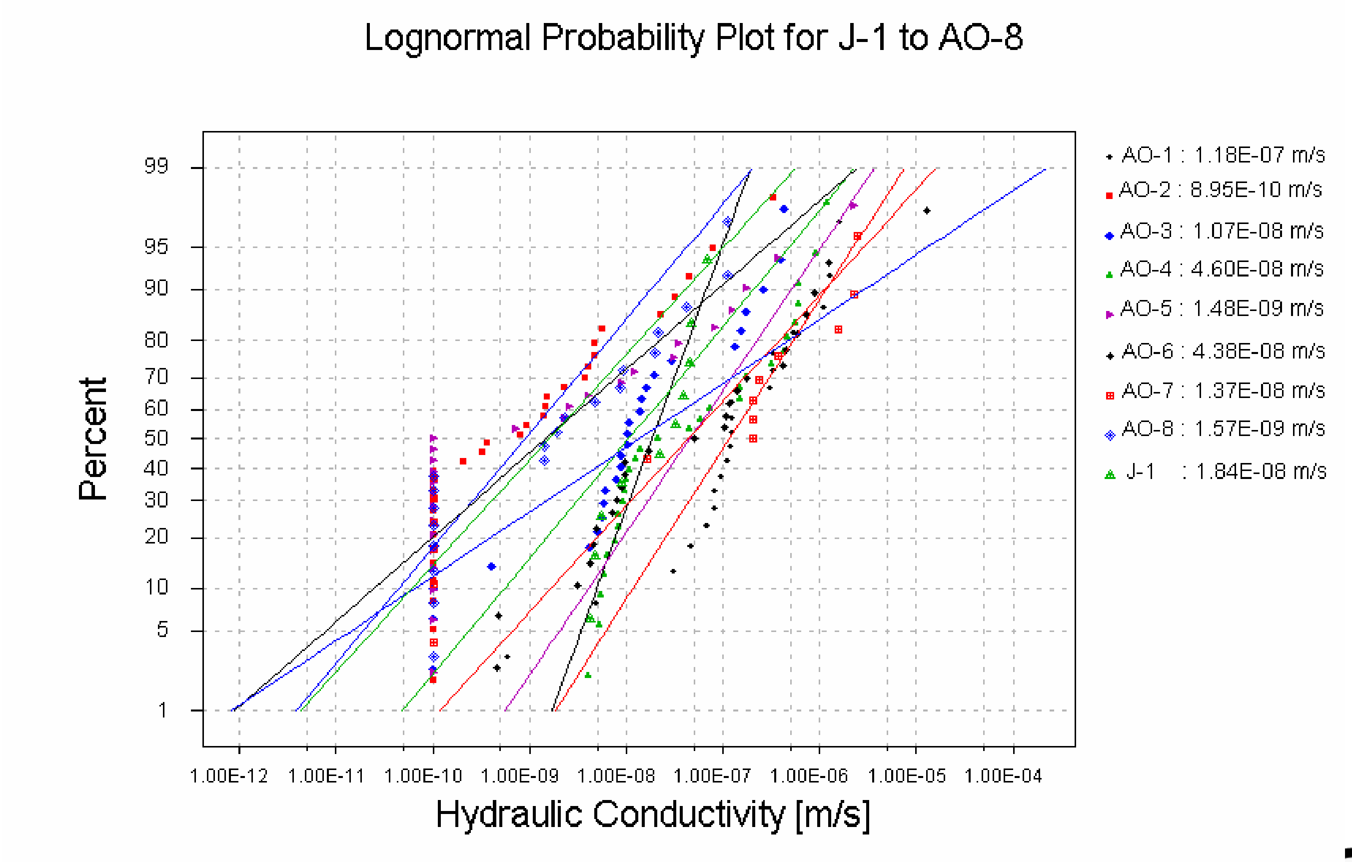
Hydraulic Test

- **205 hydraulic tests in 8 BHs and long term flow tests in 2 BHs**
- **Water table were measured for 9 months**



Effective Hydraulic Conductivity

- The effective hydraulic conductivity ranges from 1.18×10^{-7} m/s at BH AO-1 to 8.95×10^{-10} m/s at BH AO-2
- The geometric mean of the hydraulic conductivities of rock and fracture zone was determined as 5.05×10^{-9} m/s



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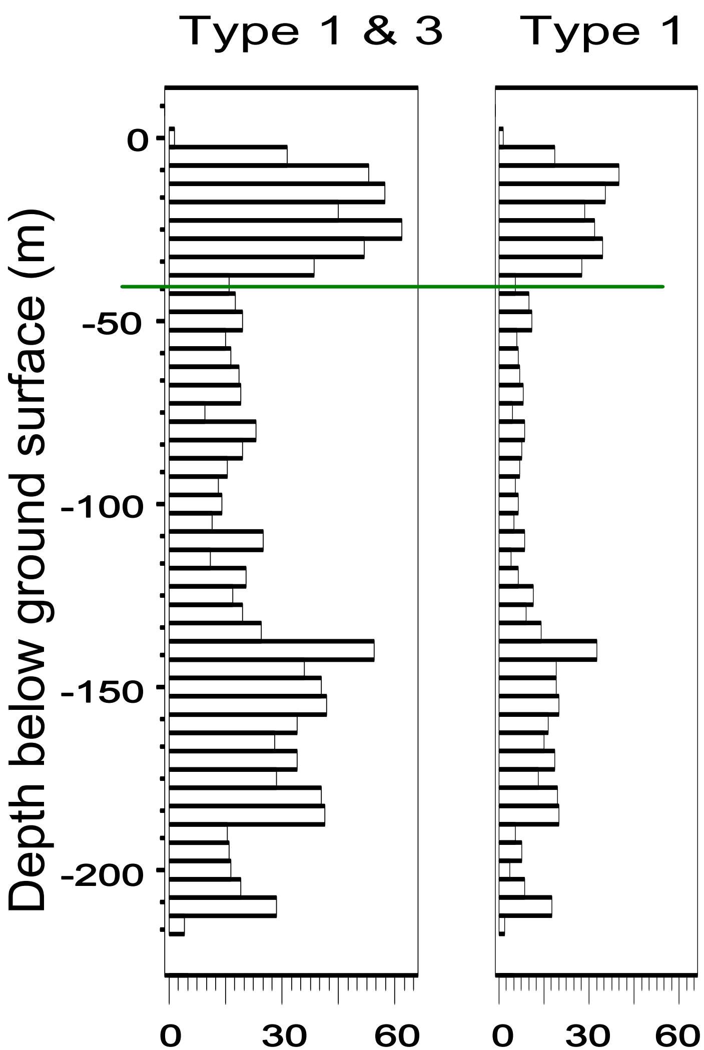
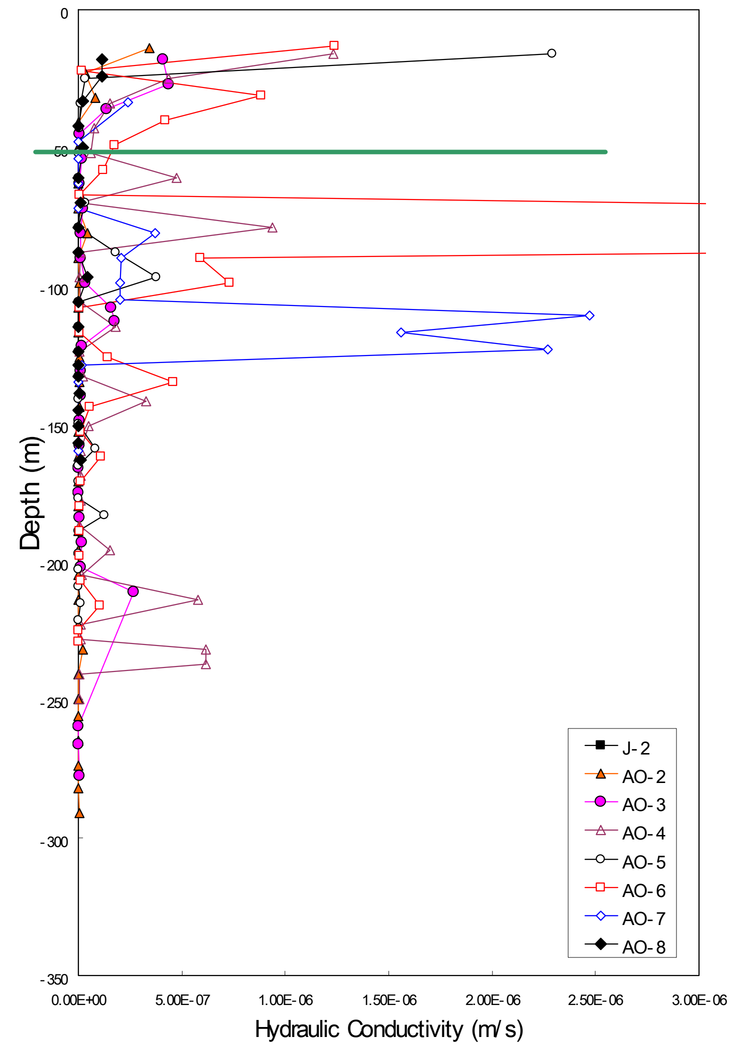
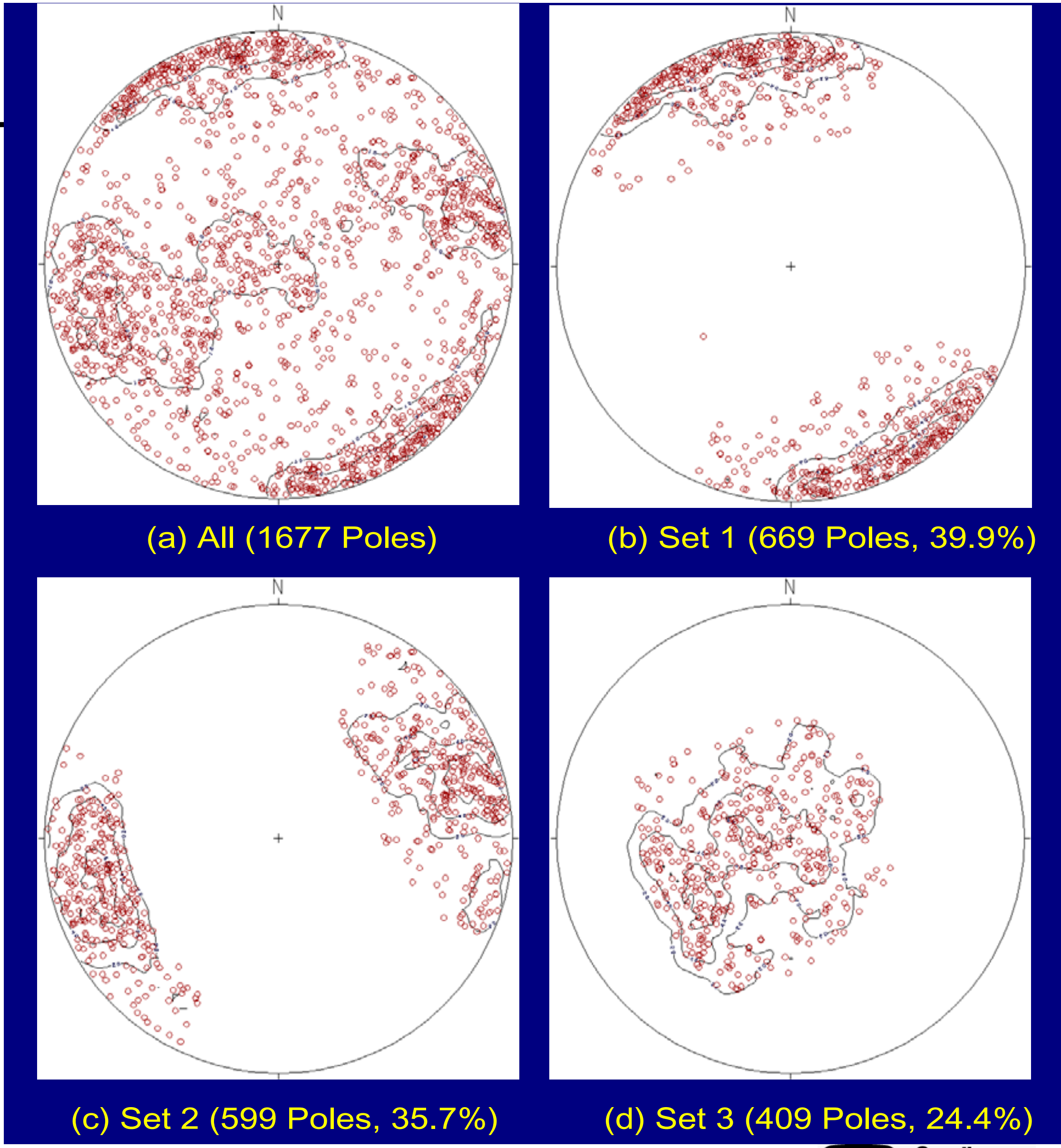
Upper Weathered Zone





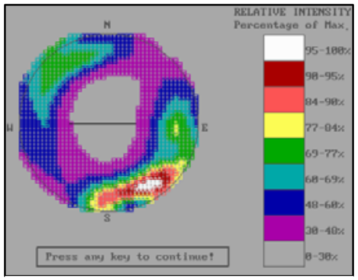
Underground Fracture Sets

- Three fracture sets determined from FracMan
- Major dip directions were 158.6/89.3, 251.4/87.2, 67.8/15.6
- Set 1 and Set 2 is almost vertical fractures
- Set 3 consists of low dip fractures with various dip directions
- Fisher Dispersion K were 9.95, 7.46, 7.17 respectively

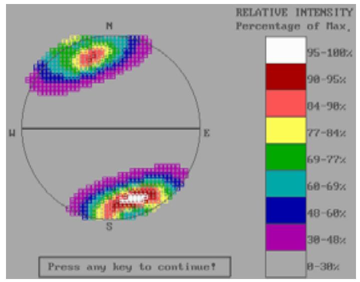


(a) All (1677 Poles)
(b) Set 1 (669 Poles, 39.9%)
(c) Set 2 (599 Poles, 35.7%)
(d) Set 3 (409 Poles, 24.4%)

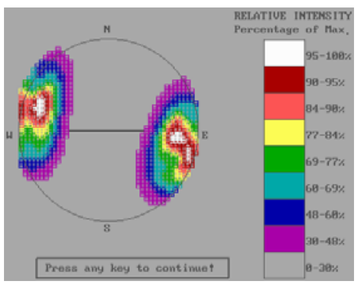
Input Data of Fracture Length



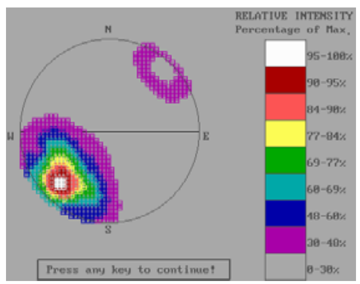
(a) All fractures



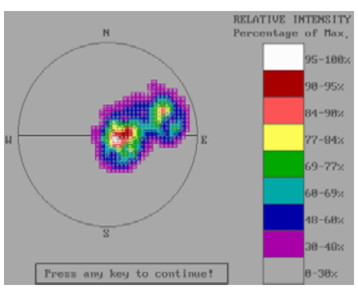
(b) Set 1



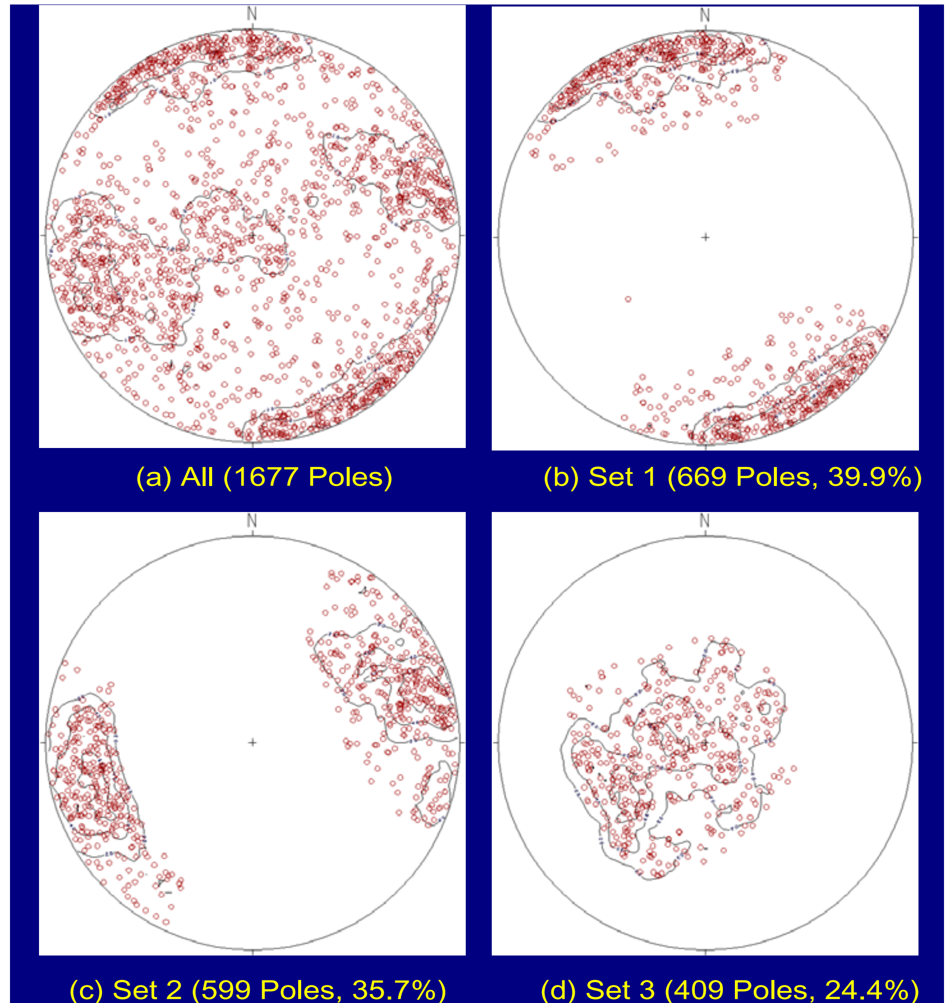
(c) Set 2



(d) Set 3



(e) Set 4



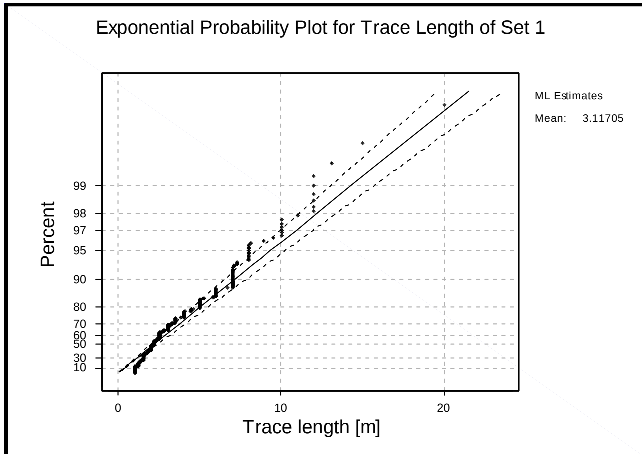
(a) All (1677 Poles)

(b) Set 1 (669 Poles, 39.9%)

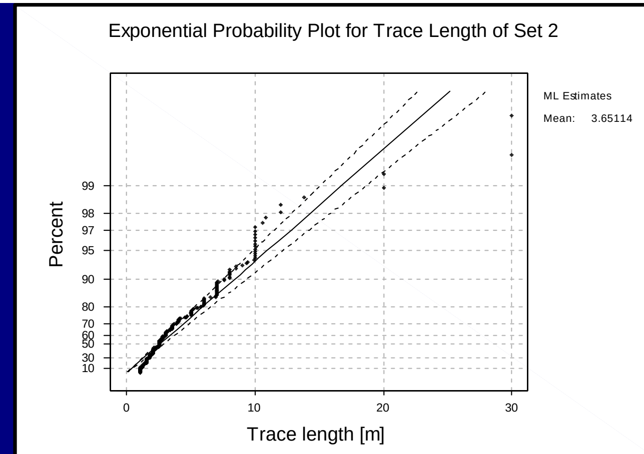
(c) Set 2 (599 Poles, 35.7%)

(d) Set 3 (409 Poles, 24.4%)

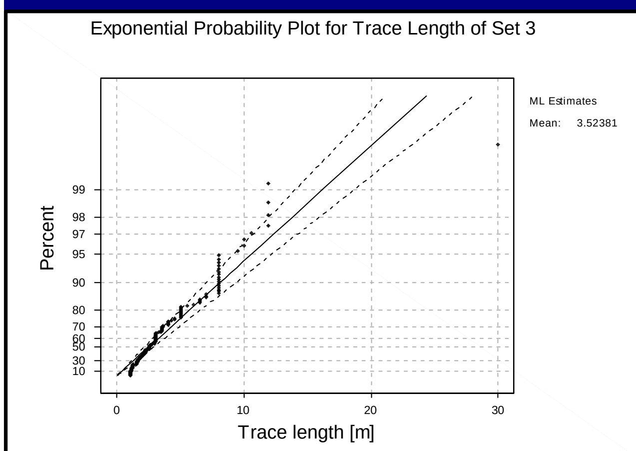
Surface Fracture Trace Length



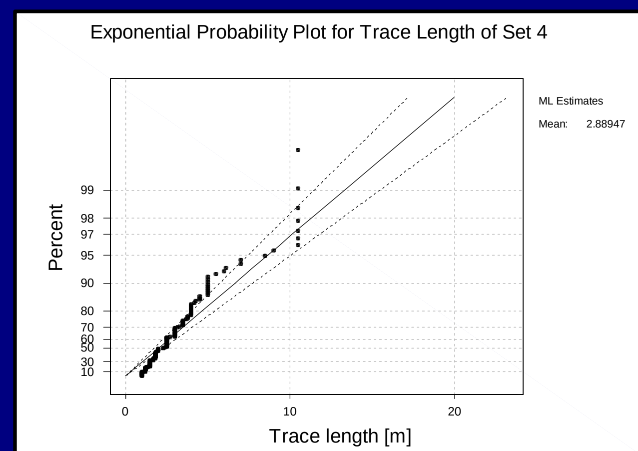
(a) Set 1



(b) Set 2



(c) Set 3



(d) Set 4

Function of Fracture Length

- It can be described using the following equation:
  - Exponential Function: $f(L) = C \cdot L^{-\lambda}$
  - Truncated Power-Law Distribution Function:

$$\text{mean}(L^2) = \frac{1-\lambda}{3-\lambda} \cdot \frac{L_{\max}^{3-\lambda} - L_{\min}^{3-\lambda}}{L_{\max}^{1-\lambda} - L_{\min}^{1-\lambda}}$$

$$C = \frac{1-\lambda}{L_{\max}^{1-\lambda} - L_{\min}^{1-\lambda}}$$

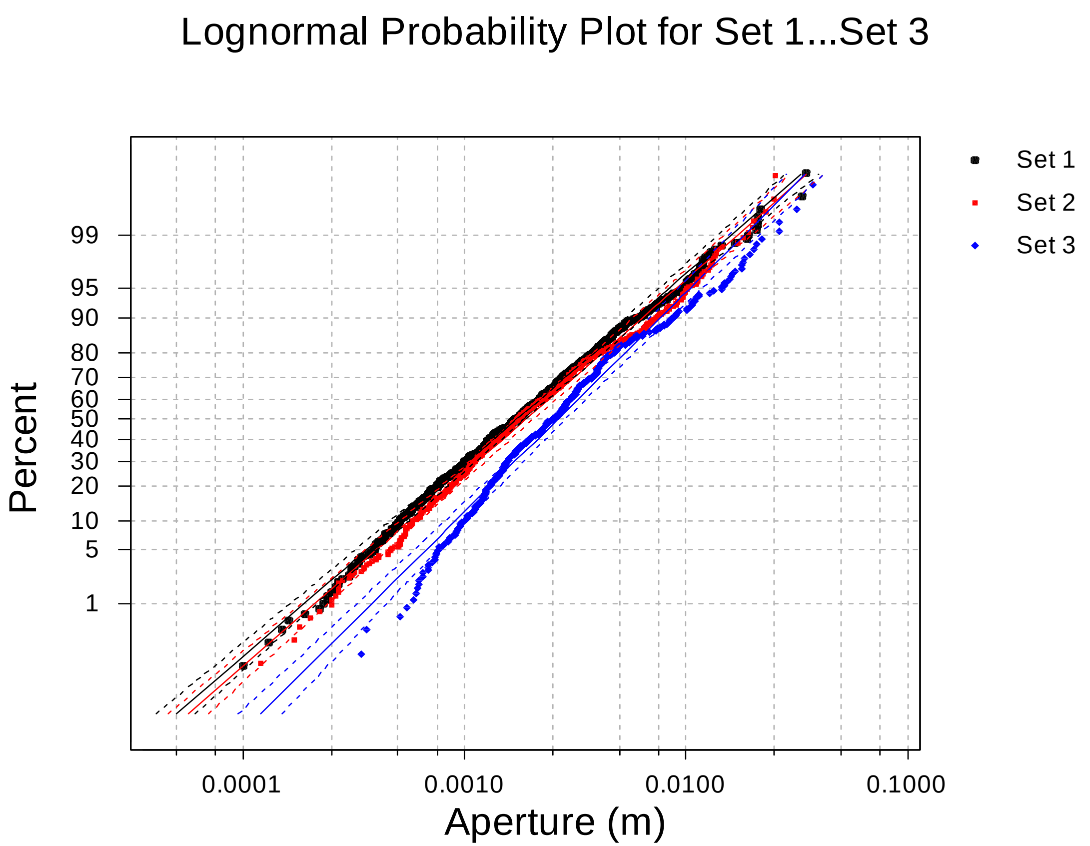
	Set 1	Set 2	Set 3
mean(L^2)	16.5	22.97	13.0
L_{max}	20.0	30.0	10.5
L_{min}	1.0	1.0	1.0
λ	2.147	2.164	1.747
C	1.185	1.186	0.903

Fracture Density

$$\rho = \frac{1}{\text{mean}(s)\cdot\text{mean}(l^2)\cdot\text{mean}(\cos D)}$$

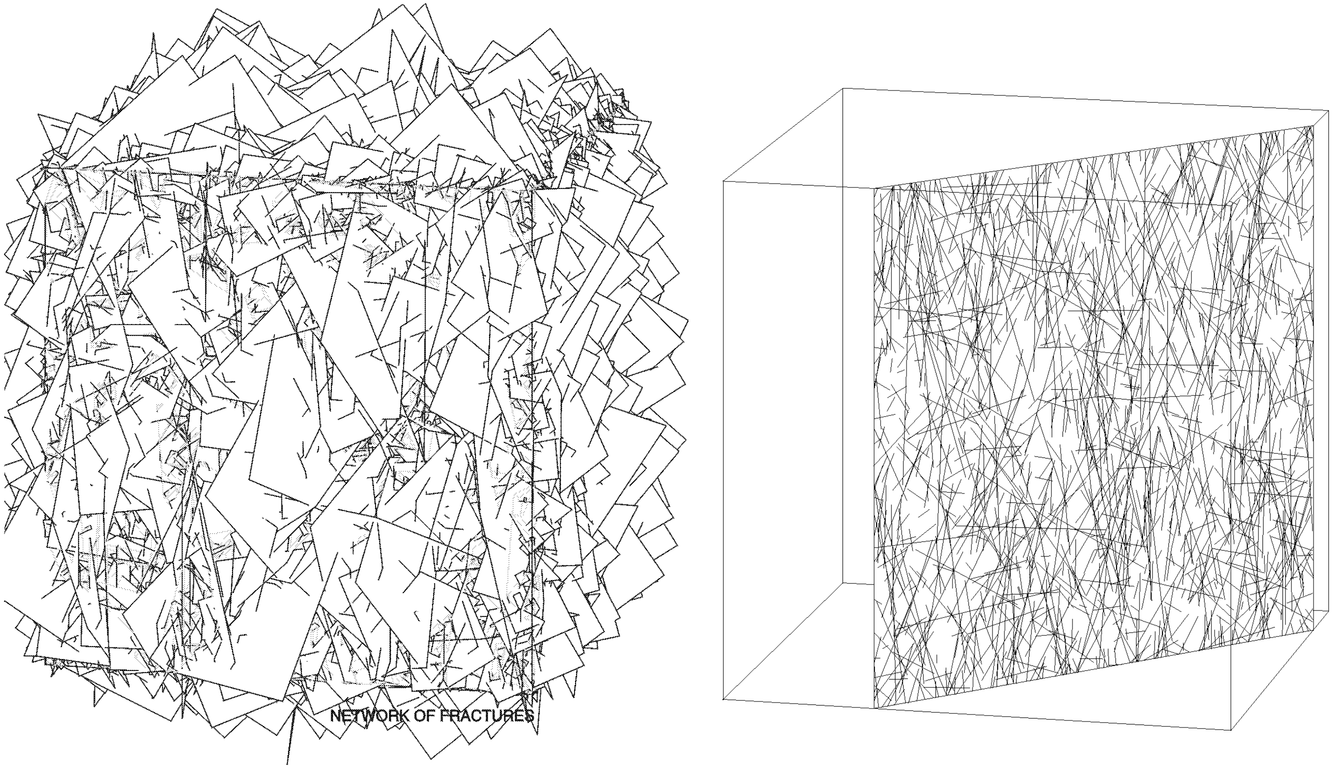
Item	Unit	Set 1	Set 2	Set 3
Number of fractures		669 (39.9%)	599 (35.7%)	409 (24.4%)
Total vertical length of 10 BHs	m	1678.9	1678.9	1678.9
Mean fracture spacing (*s*)	m	2.5096	2.8029	4.1049
Mean fracture area ( )	m^2	16.497	22.970	13.005
Mean cos *D*		0.9179	0.3262	0.8286
Fracture Density	$/m^3$	0.1260	0.0476	0.0226

Fracture Apertures



- **Selecting the open fractures of each fracture set below GL.-40 m**
- **Distribution is Log-normal**

3D Fracture Network Block using in-situ data



(a) (b)

- A lot of vertical trend trace than horizontal one, because the dip angle of Set 1and 2 are close to 90 degrees
- NAPSAC assume that the shape of fracture is rectangular

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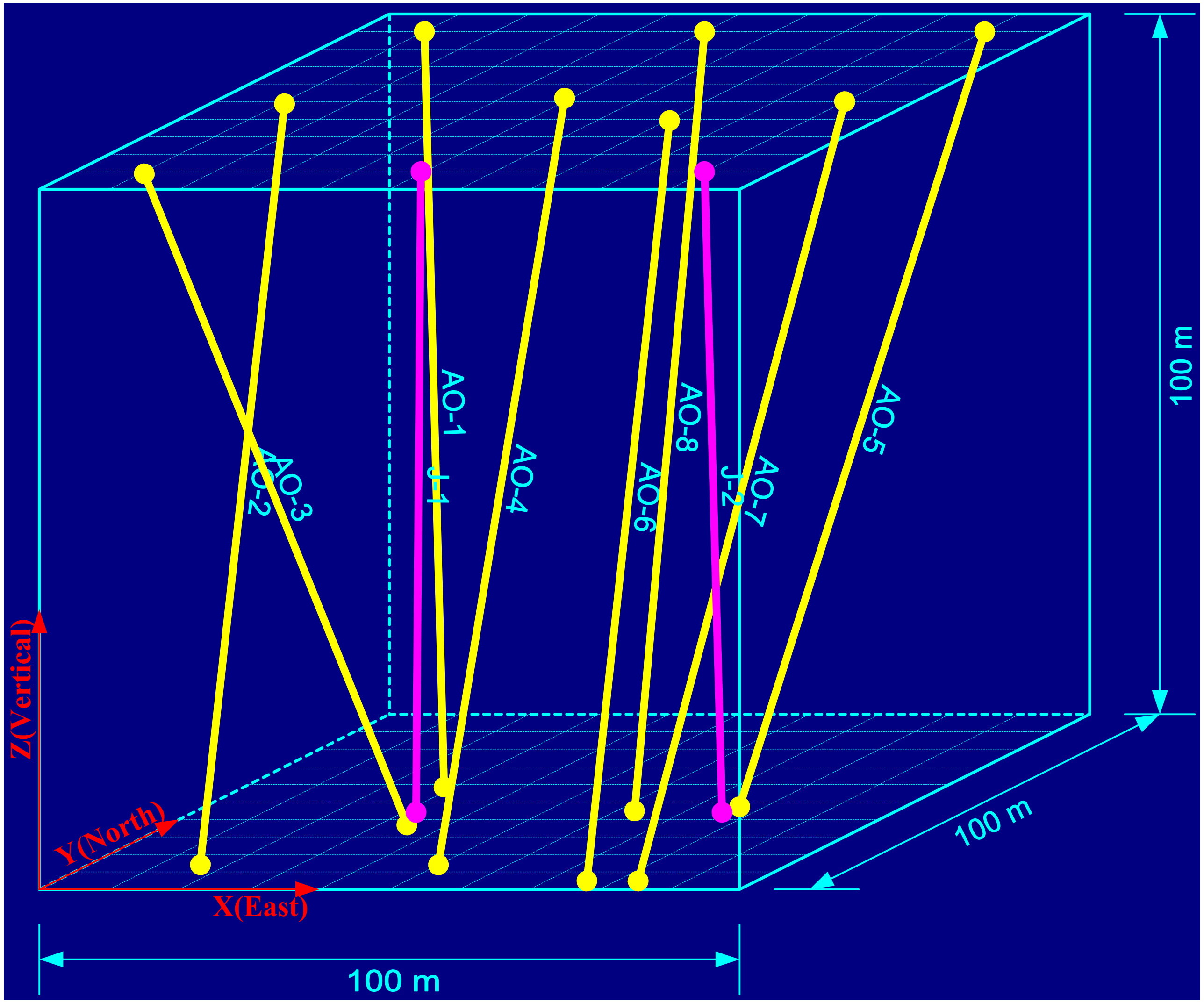
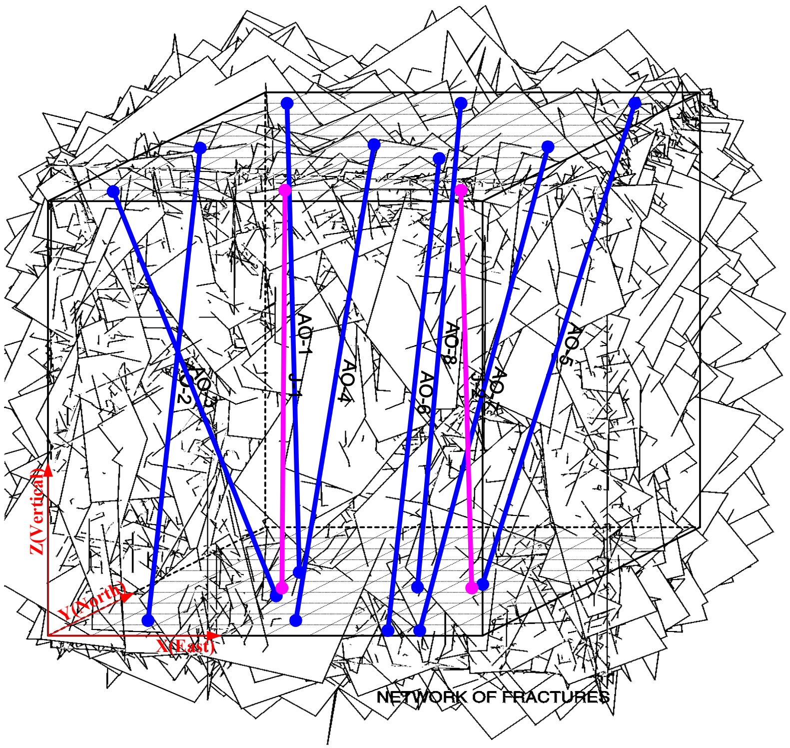
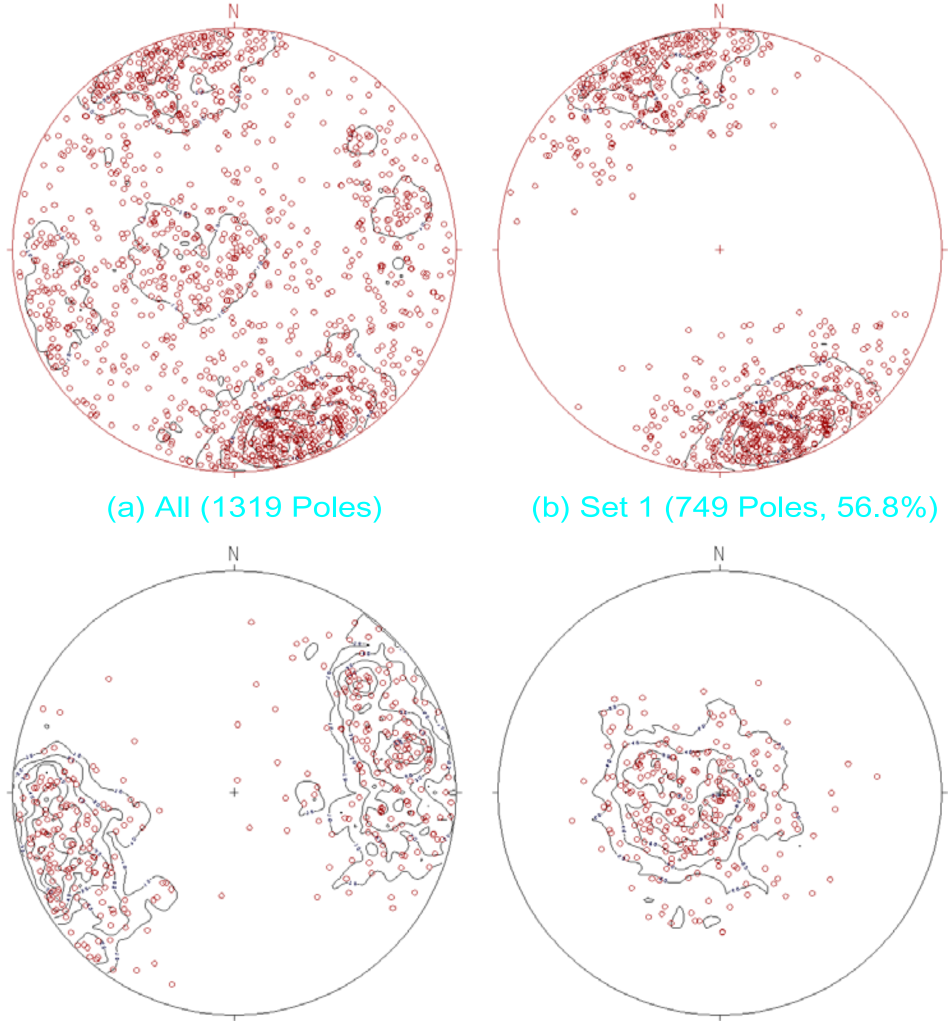
Borehole Details



Stereo net from DFN model using in-situ data





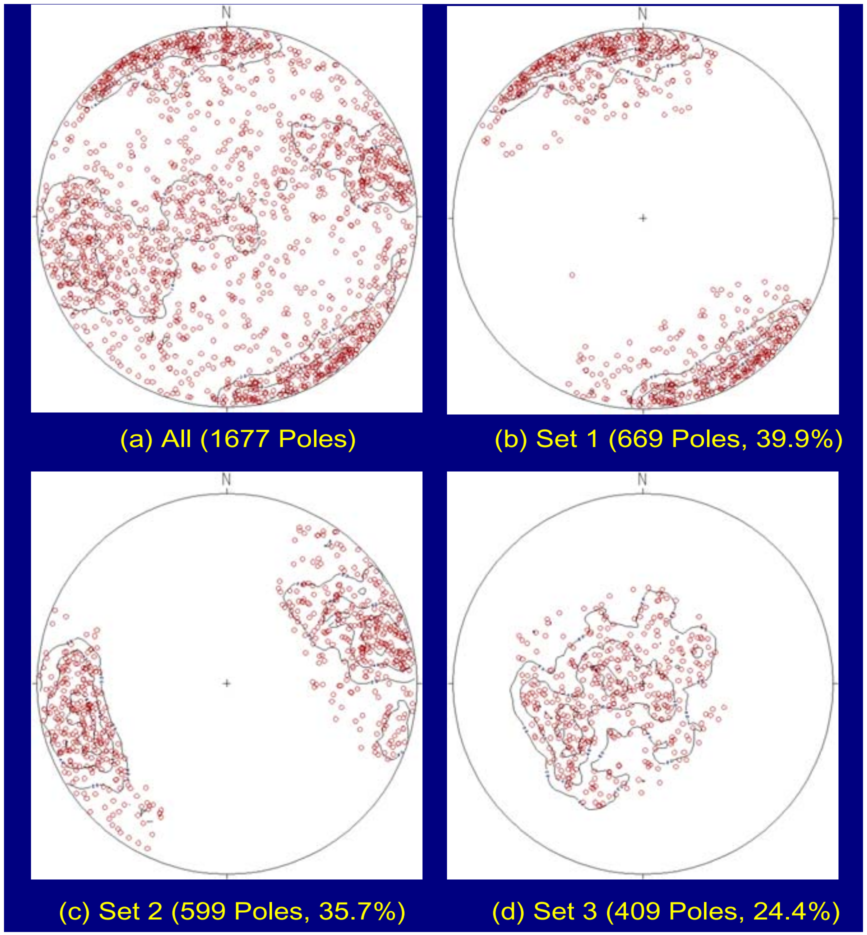
(a) All (1319 Poles)

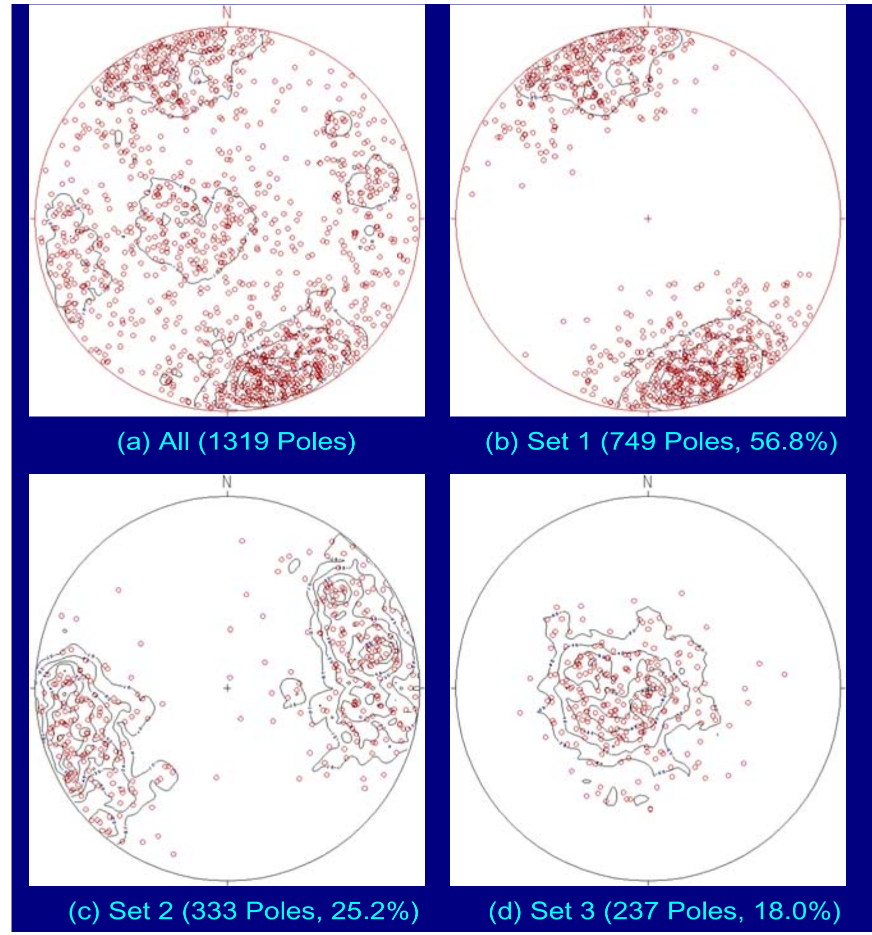
(b) Set 1 (749 Poles, 56.8%)

(c) Set 2 (333 Poles, 25.2%)

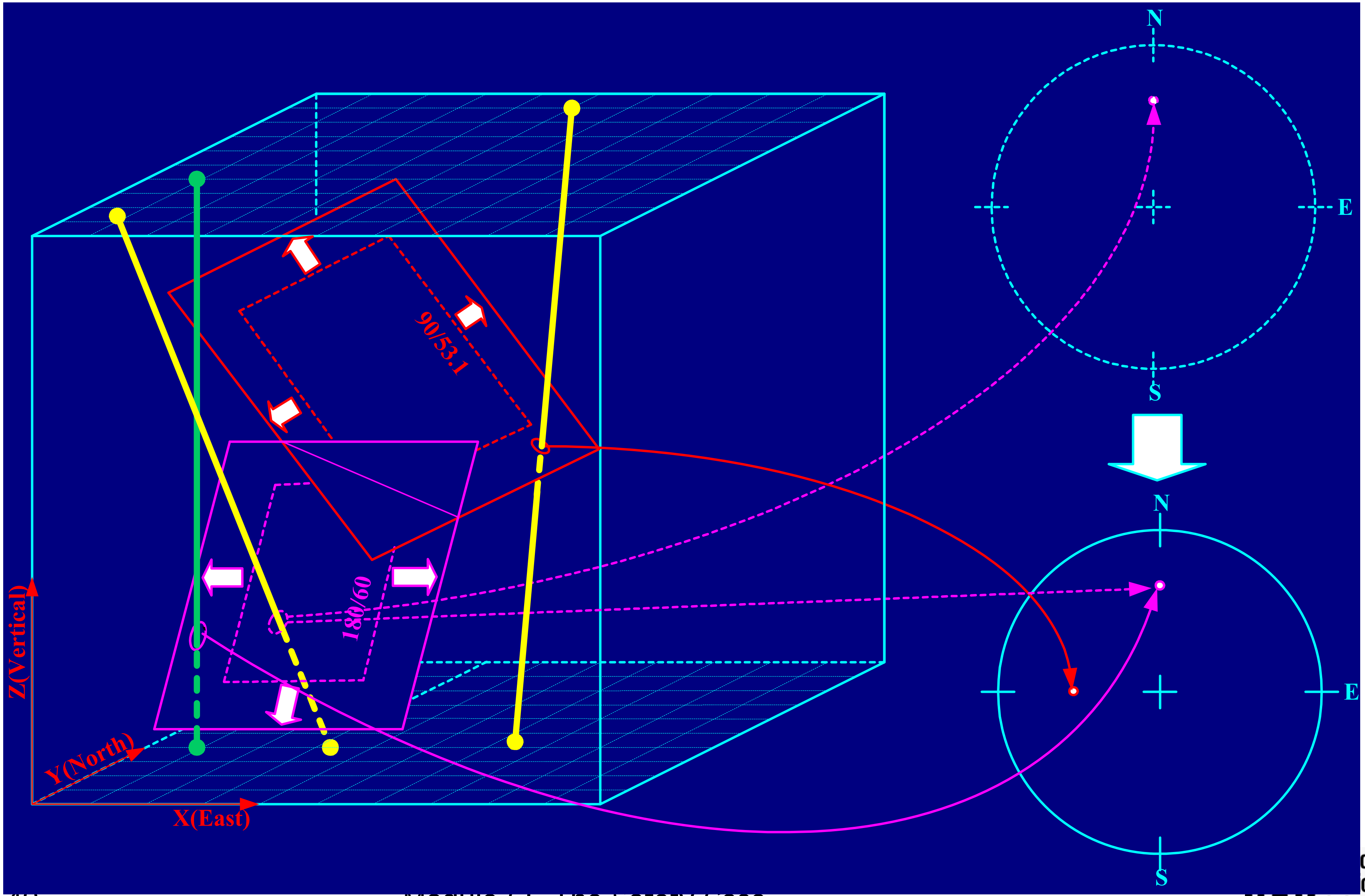
(d) Set 3 (237 Poles, 18.0%)

Comparing real underground with simulated DFN





The larger fractures, the more poles



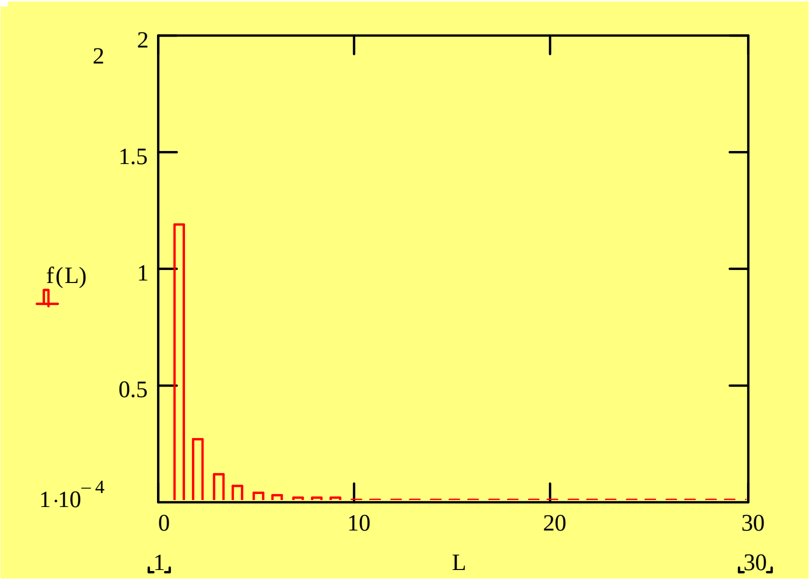
The larger λ, the more short fractures

$$f(L) = C \cdot L^{-\lambda}$$

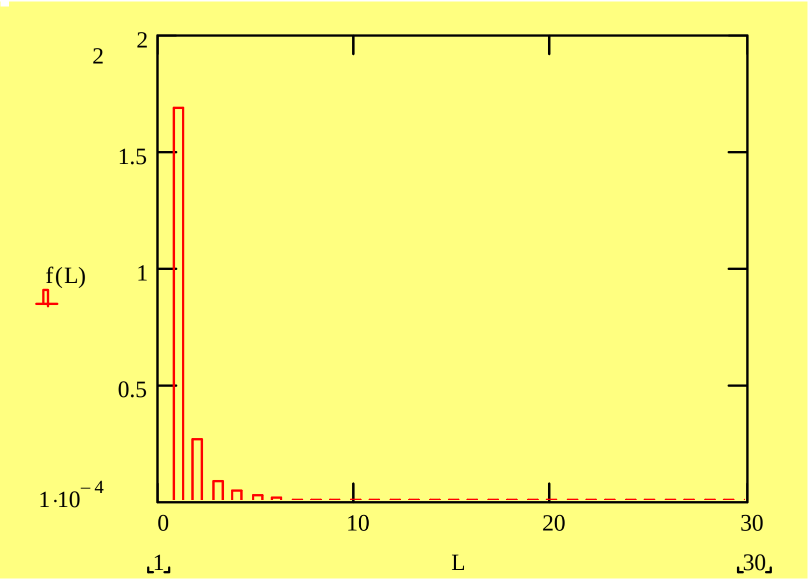
$$\text{mean}(L^2) = \frac{1-\lambda}{3-\lambda} \cdot \frac{L_{\max}^{3-\lambda} - L_{\min}^{3-\lambda}}{L_{\max}^{1-\lambda} - L_{\min}^{1-\lambda}}$$

$$C = \frac{1-\lambda}{L_{\max}^{1-\lambda} - L_{\min}^{1-\lambda}}$$

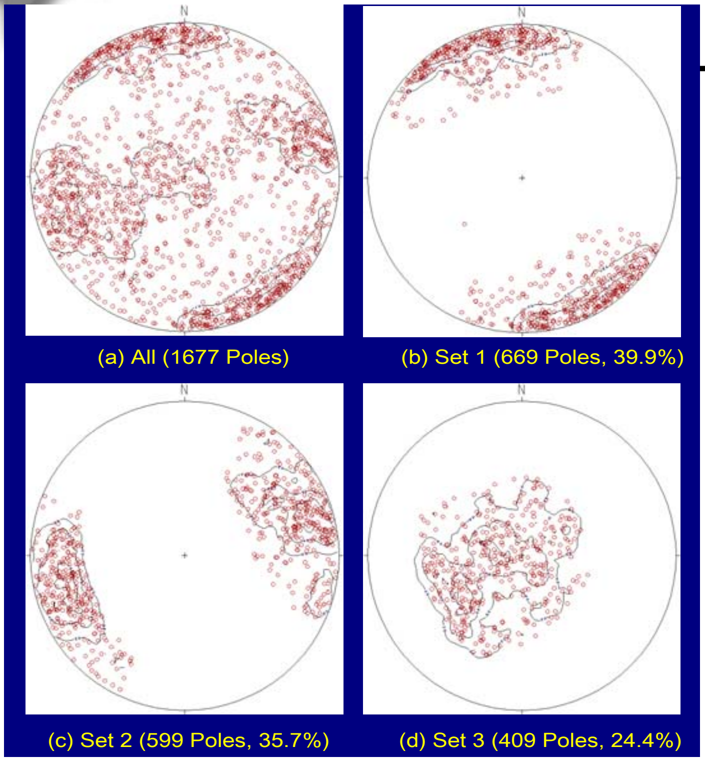
$\lambda = 2.147$



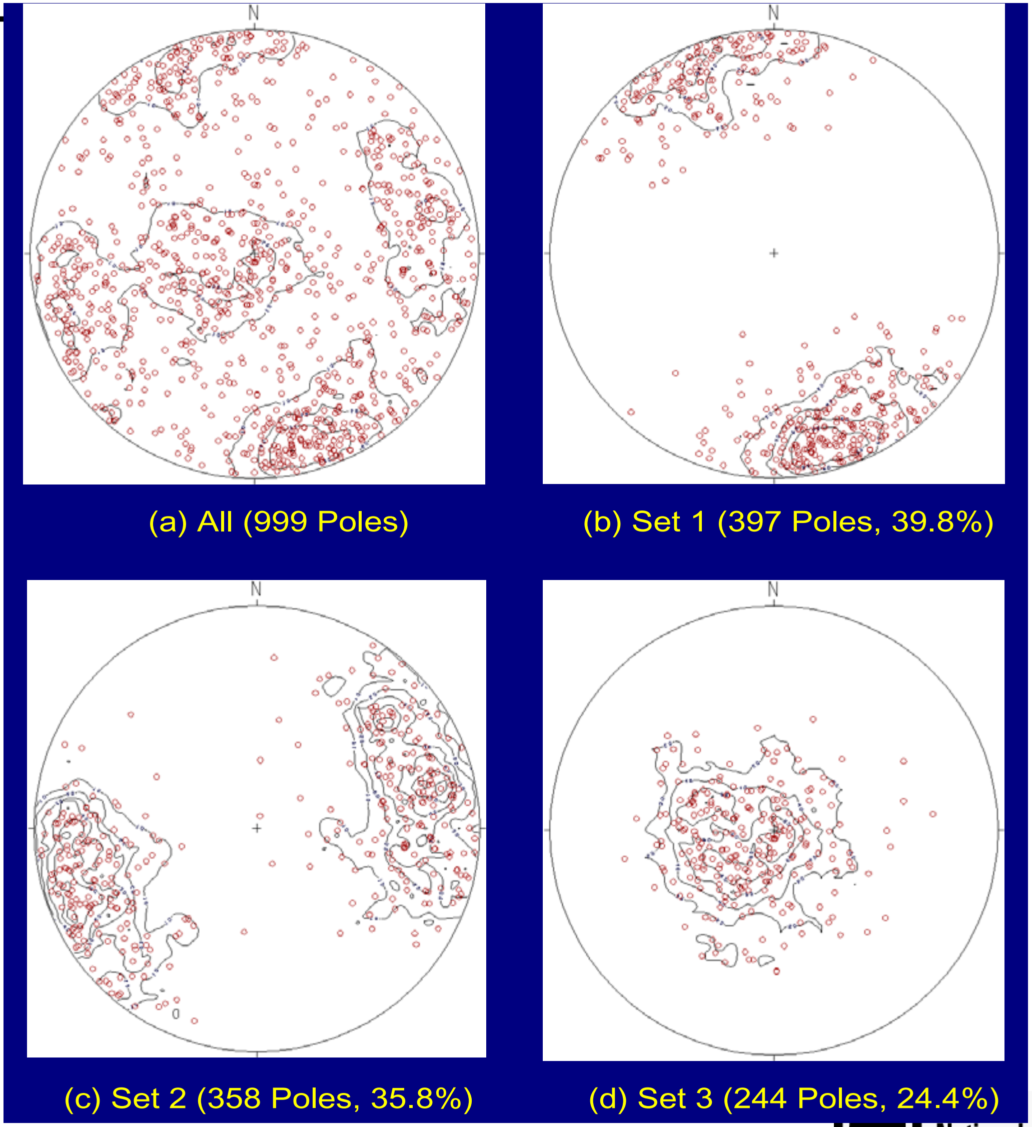
$\lambda = 2.670$



Stereo net for the final simulated fracture network



(a) All (1677 Poles) (b) Set 1 (669 Poles, 39.9%)
(c) Set 2 (599 Poles, 35.7%) (d) Set 3 (409 Poles, 24.4%)



(a) All (999 Poles) (b) Set 1 (397 Poles, 39.8%)
(c) Set 2 (358 Poles, 35.8%) (d) Set 3 (244 Poles, 24.4%)

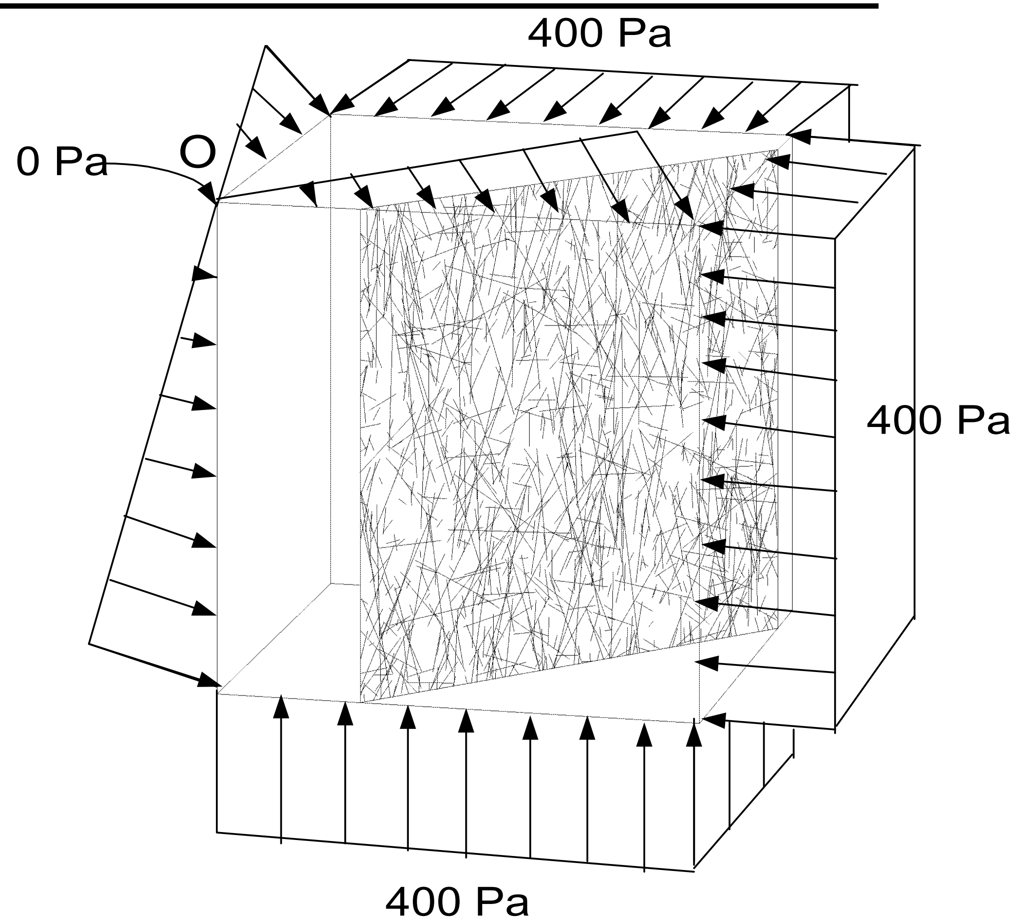
- **Total number of poles is 999 (required 1,000)**
- **The ratios of poles of each set is same as real**

Final Fracture Network

	Set 1	Set 2	Set 3
λ from surface survey data	2.147	2.164	1.747
Finally modified λ	2.670	2.112	1.719

Calculating Hydraulic Conductivity

- **Boundary Condition**
  - **Imposing a certain hydraulic pressure on 3 outside face**
  - **Maintaining zero Pa at the point O**
- **Material Properties**
  - **Density of ground water(ρ) = 998 kg/m^3,**
  - **Viscosity (μ) = 1.003×10^{-3} kg/(m·s) (at 20℃)**
  - **Kinematics' Viscosity (ν) = 1.005×10^{-6} m^2/s**



Why Transmissivity?

- Effective hydraulic conductivity is influenced by:
  - Fracture roughness
  - Microscopic groundwater flow process in fracture
  - Filling material in fracture
  - Overburden pressure, etc.
- In NAPSAC, hydraulic aperture or transmissivity can be specified to define hydraulic response of a fracture
- Physical aperture is different from hydraulic one
- Transmissivities of each Sets are used for determining 6 components of conductivity
- Transmissivity will be determined using in-situ hydraulic conductivity

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Relationship btwn Conductivity and Transmissivity

- **Relationship:**

$$K_e \cong \frac{T}{s}$$

K_e = Effective hydraulic conductivity (m/s)
T = Geometric mean transmissivity of individual fractures (m^2/s)
s = Spacing between open fractures (m)

- **In log space, geometric mean = arithmetic mean**

$$\ln(T) \cong \ln(K_e) + \ln(s)$$

- **Equations were reported to be accurate when the fracture spacing and packer interval are similar**

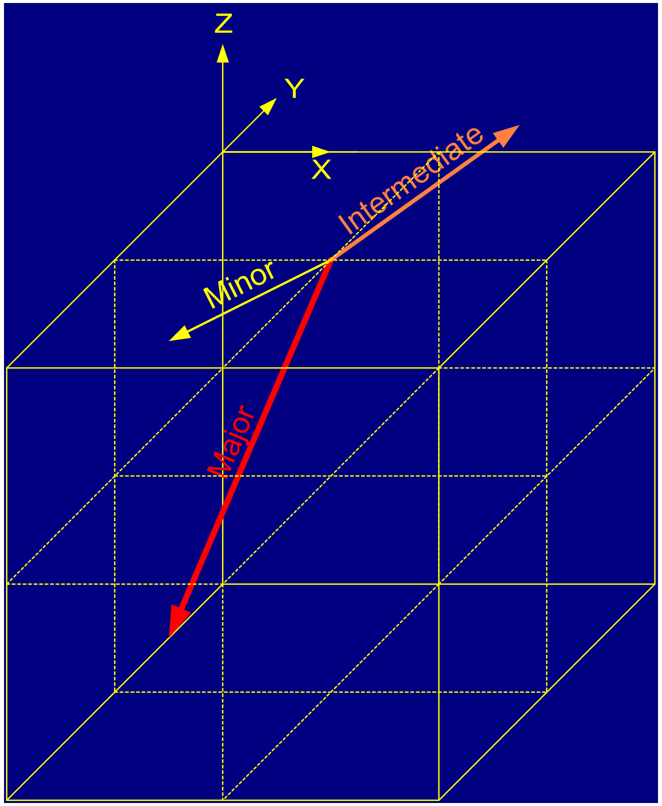
Finally modified 6 components of conductivities and permeabilities

	K_{xx}	K_{yy}	K_{zz}	K_{xy}	K_{yz}	K_{zx}
Components	3.9177E-09	4.7590E-09	7.7854E-09	-1.7449E-10	-1.9403E-10	-1.8320E-09
Major	8.5189E-09					
Intermediate	4.7896E-09					
Minor	3.1536E-09					
Geo. Mean	5.0485E-09					

	k_{xx}	k_{yy}	k_{zz}	k_{xy}	k_{yz}	k_{zx}
Components	4.0056E-16	4.8657E-16	7.9600E-16	-1.7840E-17	-1.9839E-17	-1.8731E-16
Major	8.7100E-16					
Intermediate	4.8970E-16					
Minor	3.2243E-16					
Geo. Mean	5.1617E-16					

Direction cosine of principal permeabilities

	cosαcosβ	sinαcosβ	-sinβ	Trend(deg)	Plunge(deg)
Major	-3.6873E-01	-3.0831E-02	9.2903E-01	274.8	68.3
Intermediate	1.4553E-01	-9.8904E-0	2.4940E-02	8.4	1.4
Minor	9.1807E-01	1.4440E-01	3.6917E-01	98.9	21.7



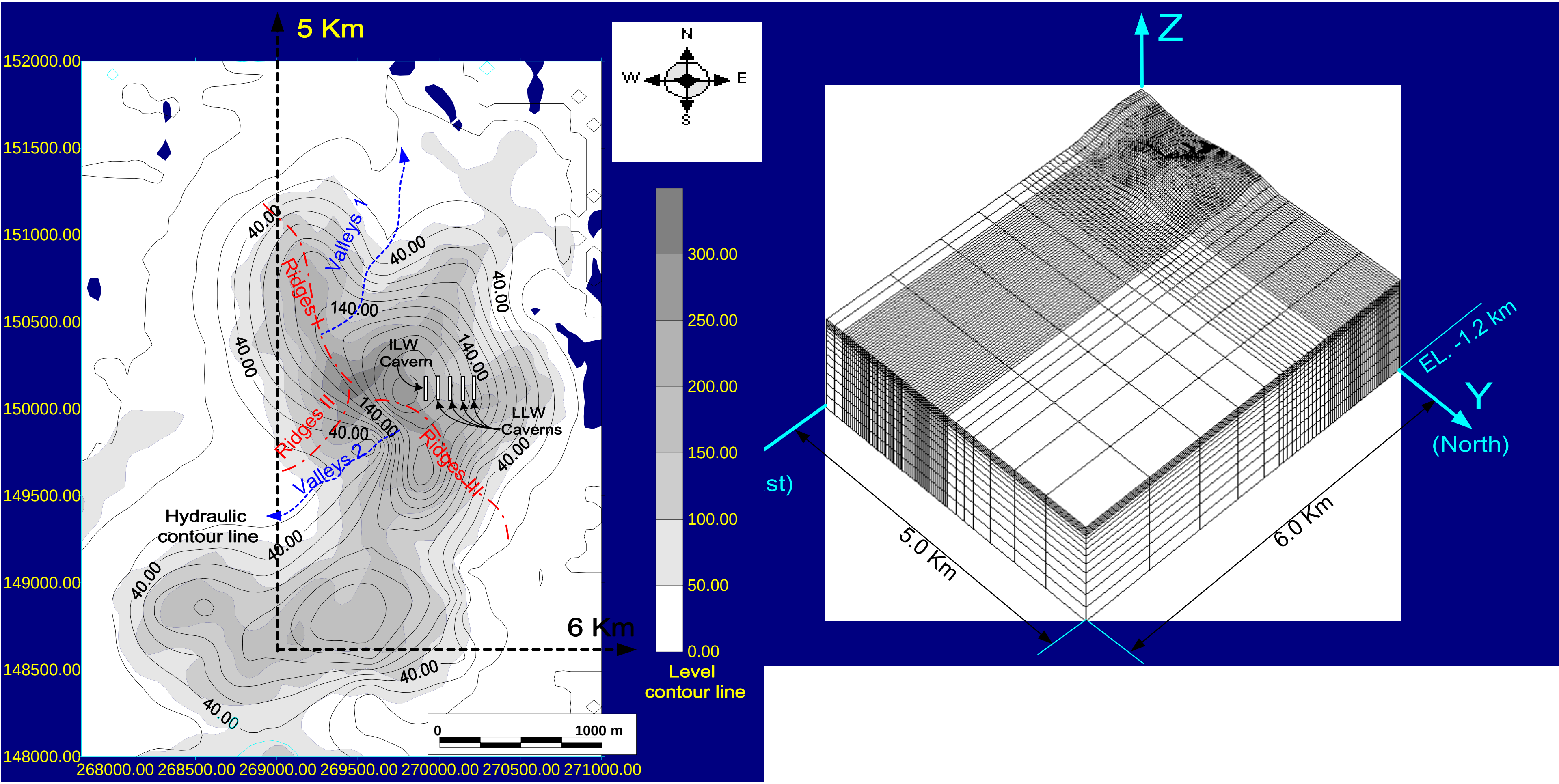
Conclusions

- In order to predict the groundwater flow path more accurately, the anisotropic hydraulic conductivity should be considered

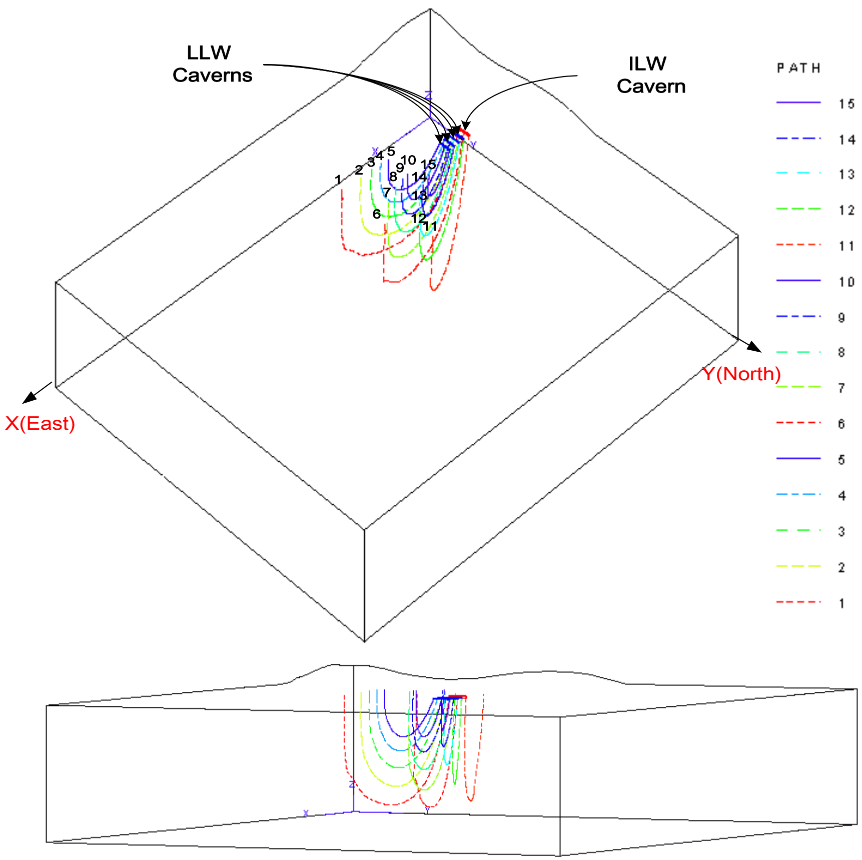
- Following two steps were needed
  1. Generating a geometrically matched 3D DFN model
  2. From this DFN model, finding the hydraulically matched 6 components of permeabilities

- It is possible to calculate the groundwater flow path and travel time more realistically, from the 3D continuum model with the anisotropic hydraulic conductivities

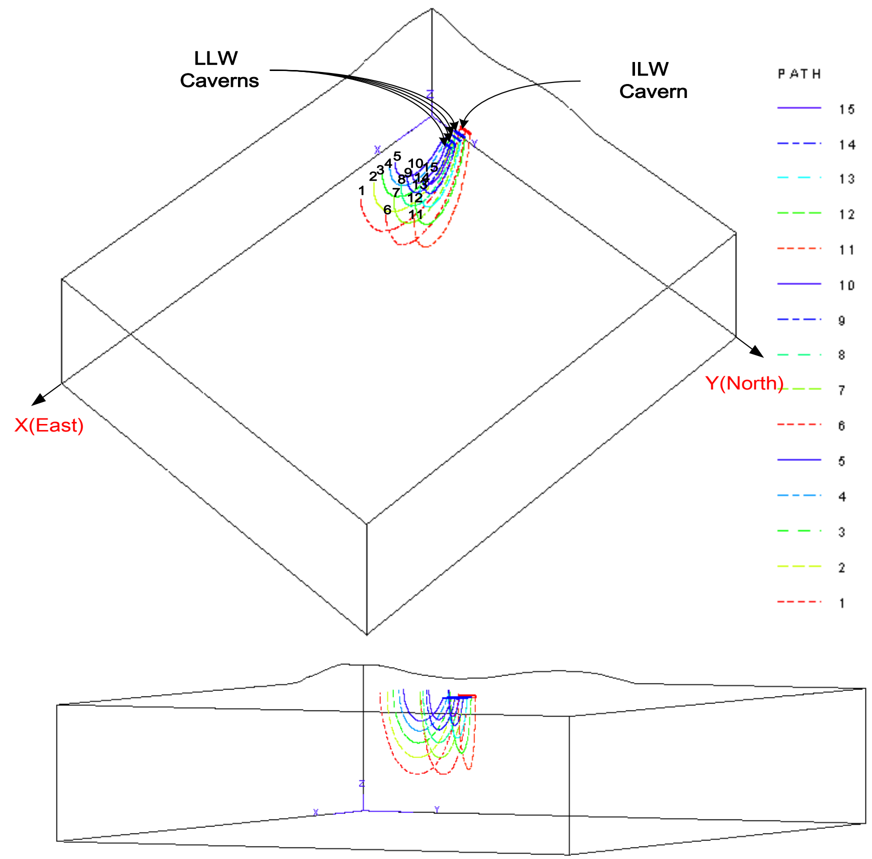
3D NAMMU Model



Final results for Pathway



Using anisotropic conductivity



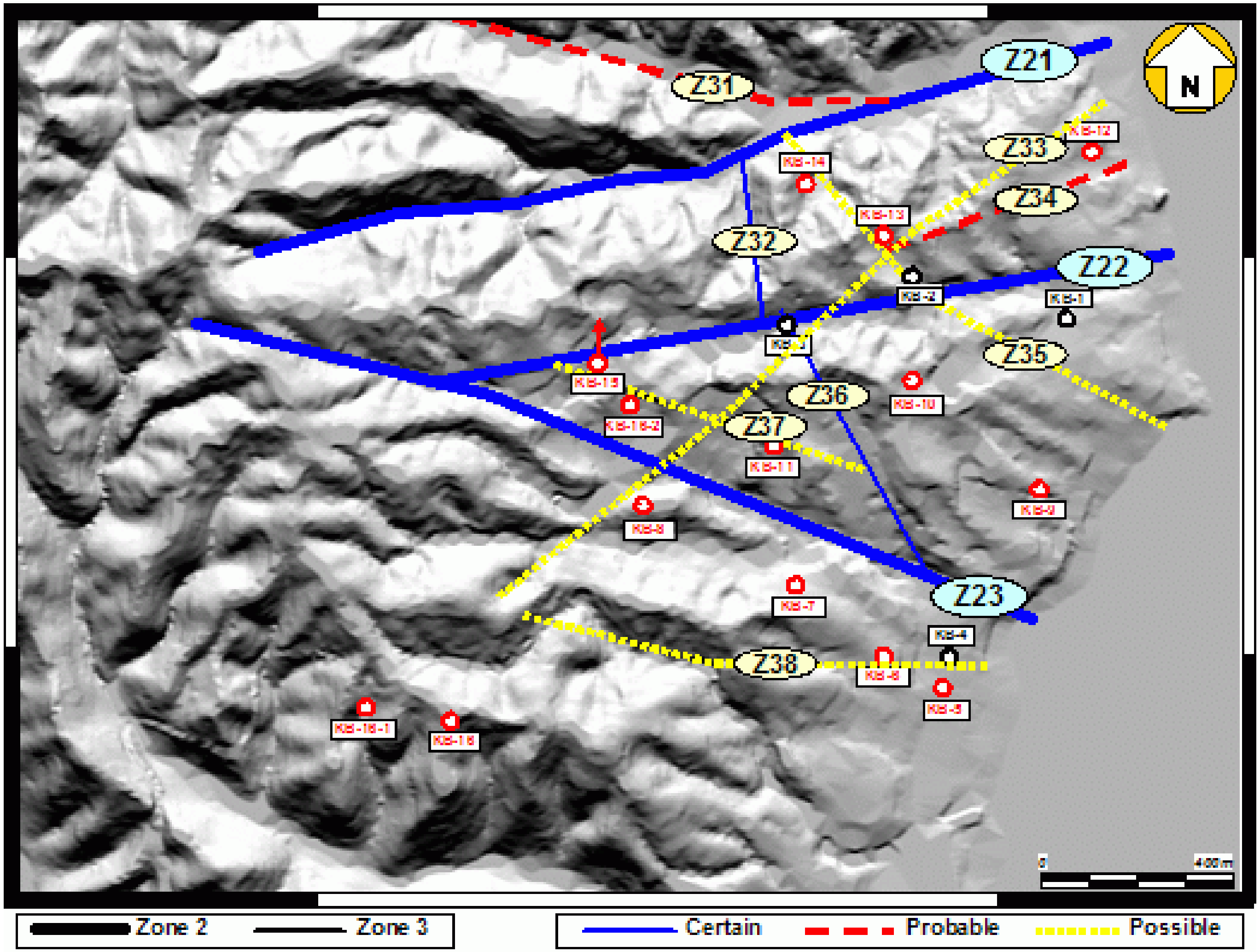
Using isotropic conductivity

시 설 개 요						
수 직 처분동굴 (SILO)	규 모	D26.8M×H48.0M	설치 EL. (M)	(-)80	수 량	6개(SILO)
	용 량	16,700 드럼/개		(-)130		100,000 드럼

지 상 시 설	
주설비	폐기물 인수/검사시설
	폐기물 임시저장시설
	폐기물 처리시설
지원 설비	종합사무실
	지원건물(주제어실, 배전반 등)
	전력공급시설

기상탑	높이 40M/10M
ERMS	MS-1
	MS-2
	MS-3
	MS-4
	MS-5(양북초교)
	MS-6(감포초교)

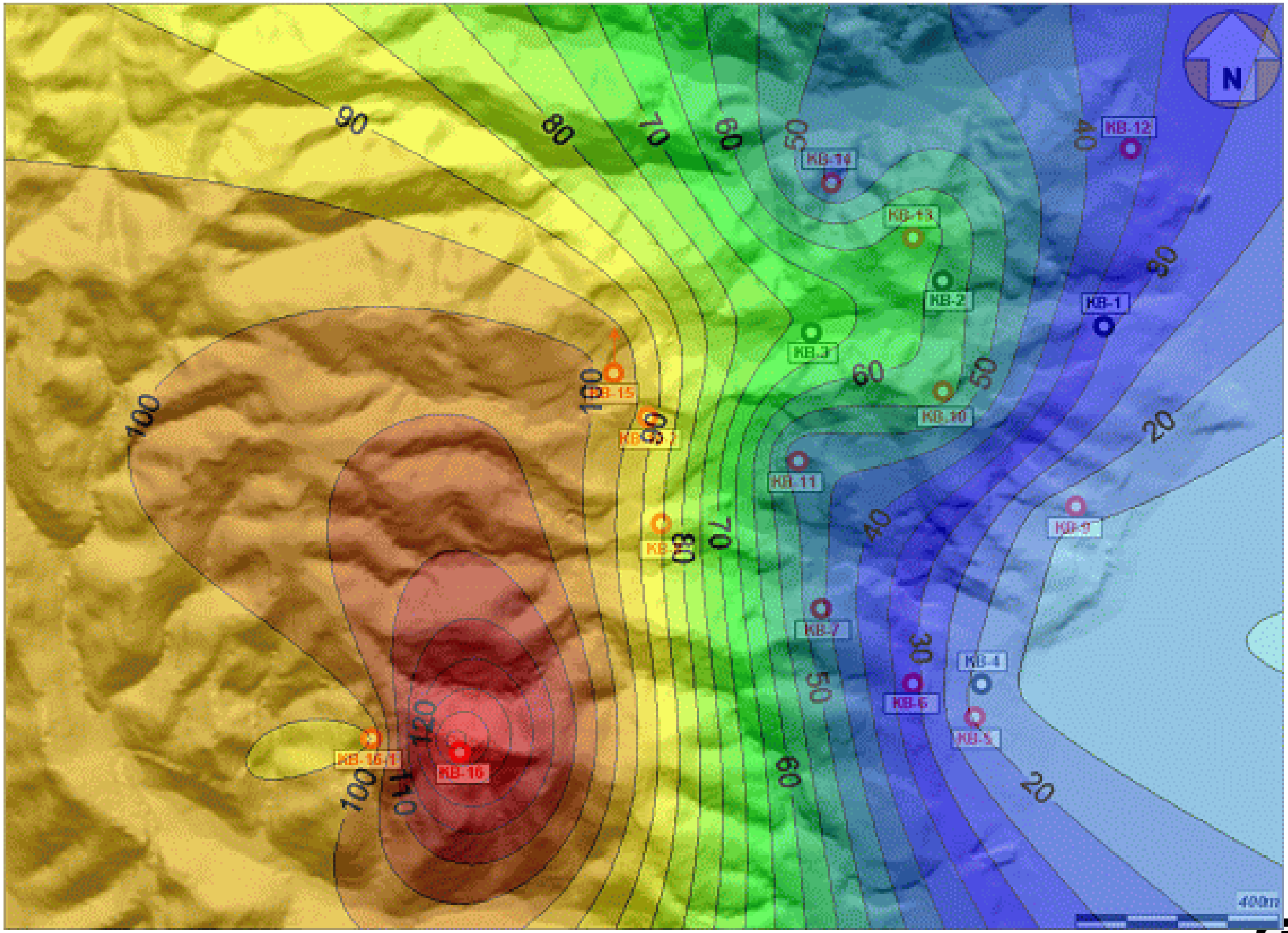
Fracture Zone in Bongkil-Ri



Fracture Zone

	특 성
Zone 1 (Z1)	• 시설의 Unit가 위치할 수 있는 암반규모를 결정해 주는 Zone 2의 경계역할을 하는 광역규모의 단열대로, • 연장길이는 10km 이상, 폭은 100m 이상의 Regional fracture zone에 해당함.
Zone 2 (Z2)	• 시설의 Unit가 위치할 수 있는 암반규모를 결정해 주고 블록의 경계를 이루는 단열대. • 연장길이는 1~10km, 폭은 5 ~100m로 Major fracture zone에 해당함.
Zone 3 (Z3)	• 처분동굴과 교차될 수도 있고 적절하게 터널을 배치하여 비켜갈 수 있으며, • 블록 내에 분포하는 단열대. 연장길이는 10m~1km, 폭은 1~5m로 Minor fracture zone에 해당함

Water Level Contours



Ending Remark