DUSEL 사례분석을 통한 심부 지하 지질 환경에서의 공동 설계 및 열-수리-역학-화학-생물학적 상호연계 현장실험

세종대학교 에너지자원공학과
김 형 목

Underground Research Laboratories (URLs) Worldwide

- **Blue** : Underground Physics Laboratories
- **Red** : Underground Laboratories for **High-Level radioactive Wastes (HLW)**

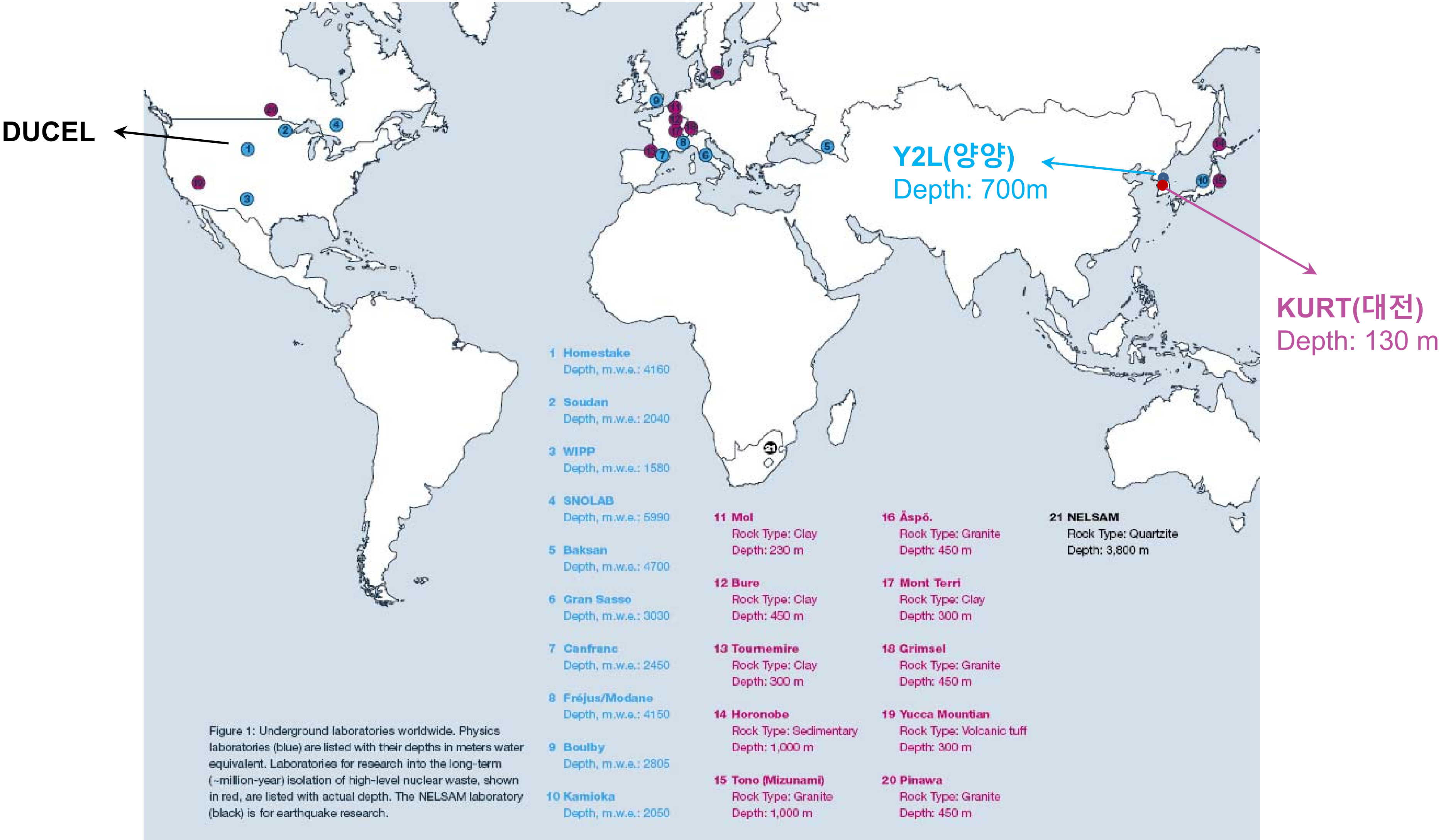


Figure 1: Underground laboratories worldwide. Physics laboratories (blue) are listed with their depths in meters water equivalent. Laboratories for research into the long-term (~million-year) isolation of high-level nuclear waste, shown in red, are listed with actual depth. The NELSAM laboratory (black) is for earthquake research.

(http://www.deepscience.org/contents/facilities_popup01.shtml)

URL Networking Commission in ISRM

- ISRM established Commission on **Underground Research Laboratory (URL) Networking** in 2011
- Focus on Linking Rock Mechanics with
  - **Engineering** – Civil, Mining, Petroleum (ARMA, ARMS, EUROCK, ISRM …)
  - **Geoscience** – HM, THM, THMCB, GTHMCBE (IAEA Network, AGU, …)
  - **Physics** – DM, neutrinos (TAUP bi-annual, ASPERA, …)
- Technical sessions in URL workshop
  - I. Challenges of Deep/Large Excavations
  - II. **Physics Deep Laboratories**
  - III. **Radioactive Waste URLs**
  - IV. Injection & Withdrawal, Borehole URLs
  - V. **Coupled Process** Testing, Mine URLs
- Differences in Engineering, Geoscience, Physics Requirements
- Similarities in Needs to **Optimize Cost**, Schedule, **Safety**, …

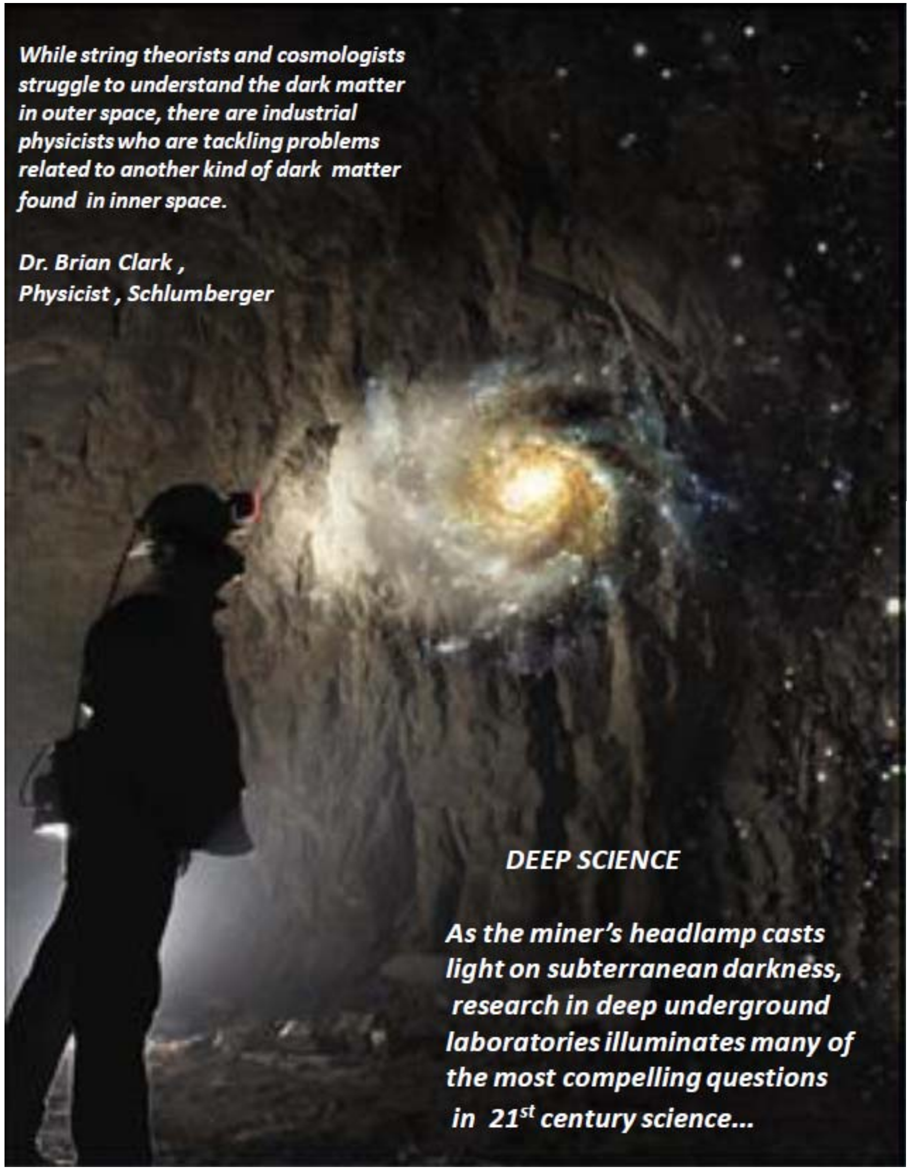
ISRM
International Society for Rock Mechanics

(Wang, 2012)

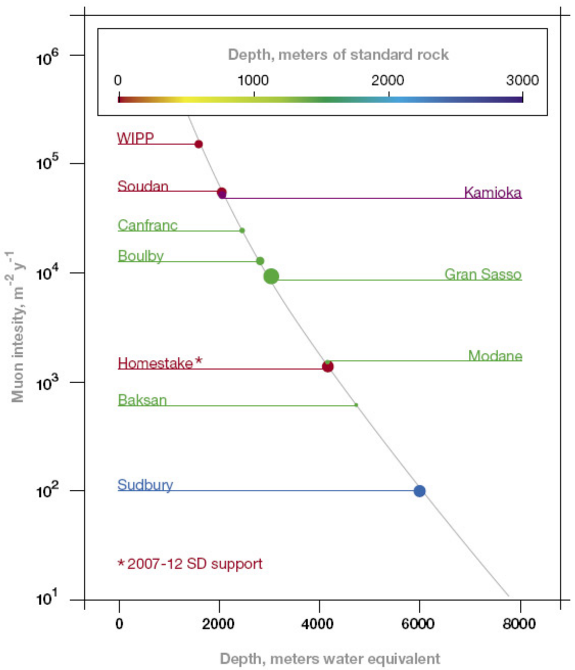
Purpose and Types of URLs

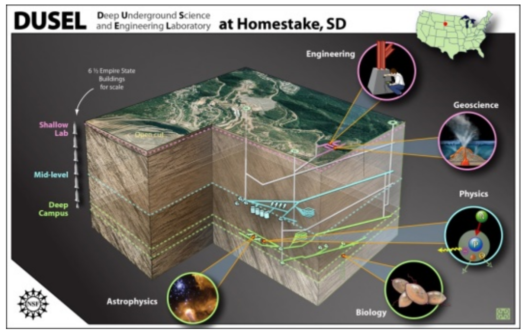
- A URL is '*an underground facility in which **site characterization** and **testing activities** are carried out along with **technology development** and **demonstration activities** in support of the **development of deep geological repositories** for radioactive waste'* (NEA, 2013).
- Purpose of URLs
  - Develop the technology and methodology required for **underground experimentation**;
  - Provide data to understand the behavior and **assess the performance of the repository system** and of their interactions;
  - **Demonstrate the robustness of the design** and to show the potential areas of optimization of engineering components and processes;
  - **Train personnel** for safe operation of a future repository;
  - **Build confidence** with stakeholders for their understanding of the important processes governing repository performance.
- Types of URLs
  - **Generic**
    - Facilities that are developed for generic research and testing purposes at a site that will not be used for waste disposal, but provide information that may support disposal elsewhere.
  - **Site-specific**
    - Facilities that are developed at a site that is considered as a potential site for waste disposal and may, indeed, be a precursor to or the initial stage of developing a repository at the site. e.g. ONKALO(Finland), WIPP(USA), Yucca Mt. (USA)
  - Although many **experiments** and engineering applications **are generic (; multi-disciplinary)**, any single **underground research site** is a case in a **specific** geological setting.
    - DUSEL: a metamorphic rock in a low tectonic environment
    - Research in subsurface engineering, geoscience and biosciences (EGB) would benefit from **international cooperation**.

Underground Universe: Physics and Astrophysics



- Physicists and astrophysicists have a strong tradition of **underground research**.
- There is an emerging consensus that underground facilities also play an important role in addressing key questions in **biology, geoscience** and **engineering**.
- Deep Underground Science and Engineering Laboratory (DUSEL) is necessary.





(http://www.deepscience.org/)

DUSEL Timeline: 2000-2007

- 2000 Homestake mine closure announced
  - First meeting of Earth science and physics communities
- 2001
  - Underground science meetings; Earth science, physics and geomicrobiology workshops
- 2002
  - NSF visit to Homestake
  - NESS meeting in Washington DC ~200 BGE participants
- 2003
  - EarthLab Report/ ARMA-NSF Report
  - **ARMA-NSF 1st Workshop at ISRM Congress – Johannesburg, South Africa**
- 2004
  - NSF S-process announcement
  - S-1 Workshop 1 (Berkeley)/ S-1 Workshop 2 (Blacksburg)
- 2005
  - S-1 Workshop 3 (Boulder)
  - S-2 Site submissions [Cascades, Homestake, Henderson, Kimballton, San Jacinto, Soudan, WIPP, SNOLab]
  - S-1 Workshop 4 (Minneapolis)
  - S-2 Site selections: Henderson and Homestake
- 2006
  - S-2 Workshops
- 2007
  - S-3 Submissions (January)
  - **ARMA-NSF 2nd Workshop at ISRM Congress – Lisbon, Spain**
  - **S-3 Selection (July) Homestake**
  - Post S-3 Town Meeting (November – Washington DC)

(Ellsworth et al., 2012)

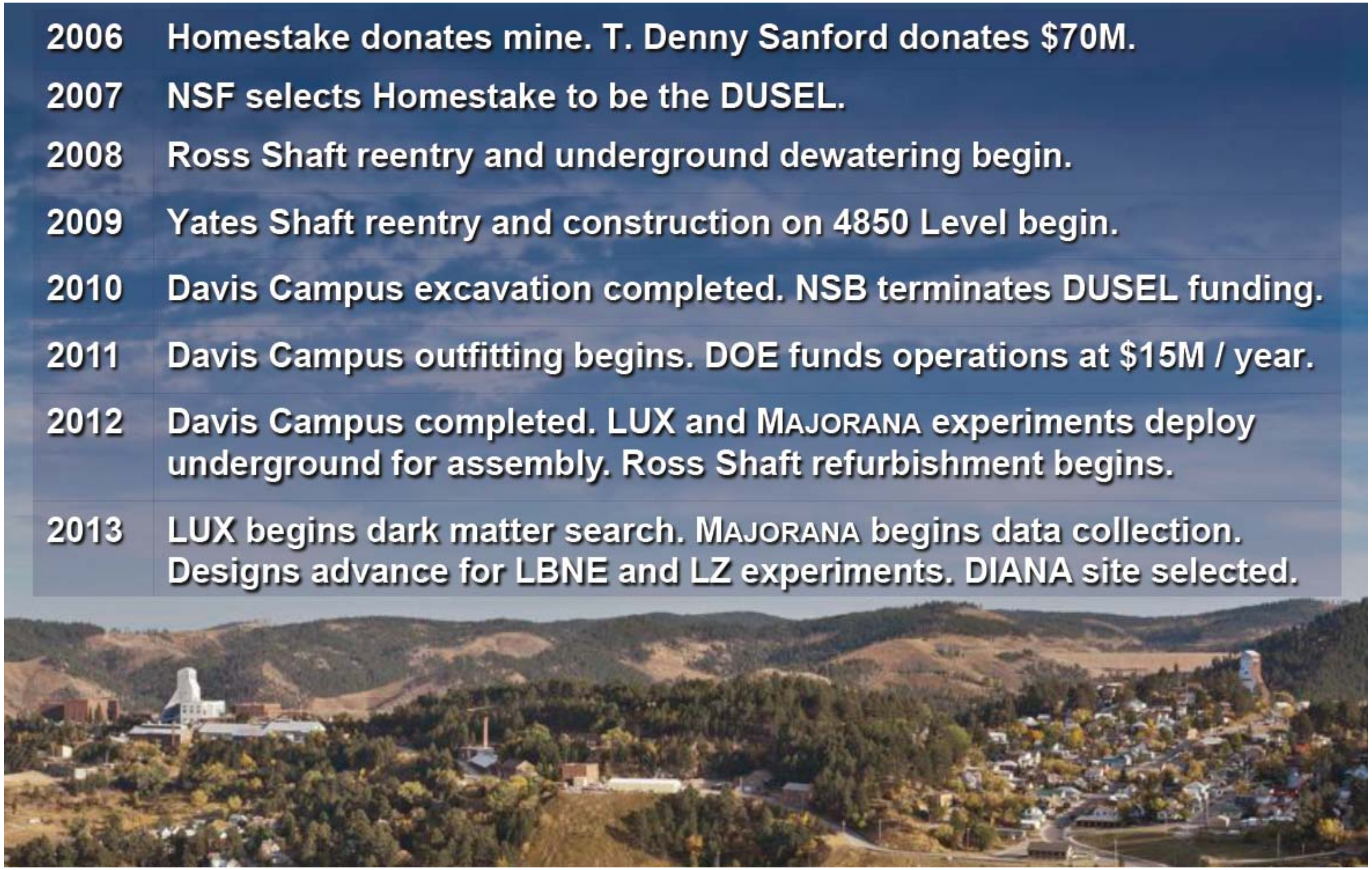
DUSEL Timeline: 2008-2012

- 2008
  - DUSEL Experiment Development Committee formed (DEDC, with 3 BGE and 3 physics members)
  - NSF Project Review (July)
  - DUSEL-DEDC Meeting (September – Lead, SD)
  - S-4 Solicitation (October)
- 2009
  - NSF Project Review (January)
  - S-4 Solicitation closes (January)
  - S-4 Awards ~71 BGE senior investigators and ~230 physics senior investigators
- 2010
  - DEDC transitions to DURA (March, with 2 new BGE members on the Executive Committee. 131/1000 DURA members as of February 2011)
  - NSF Project Review (April)
  - NSF Reverse site visit for BGE Projects (August)
  - DUSEL-DURA 1st Meeting (September – FermiLab, IL)
  - NRC Review (December-June)
- 2011
  - PDR Review (March) and Submission (June)
  - **ARMA-NSF 3rd Workshop at ISRM Congress – Beijing (October), China**
  - **ISRM Commission on URL Networks (October)**
- 2012
  - DUSEL-DURA 2nd Meeting (January – FermiLab, IL)
- 2015
  - **4th Workshop on Underground Research Laboratory (URL) at ISRM Congress – Montreal (May), Canada**
    - A field visit to Sudbury Neutrino Observatory Lab (SNOLab), at Sudbury, Canada
    - Infrastructure plans among Asian, European, and North American laboratories
    - An informal meeting with ARMA and NSF

(Ellsworth et al., 2012)

SURF Chronology: 2006-2013

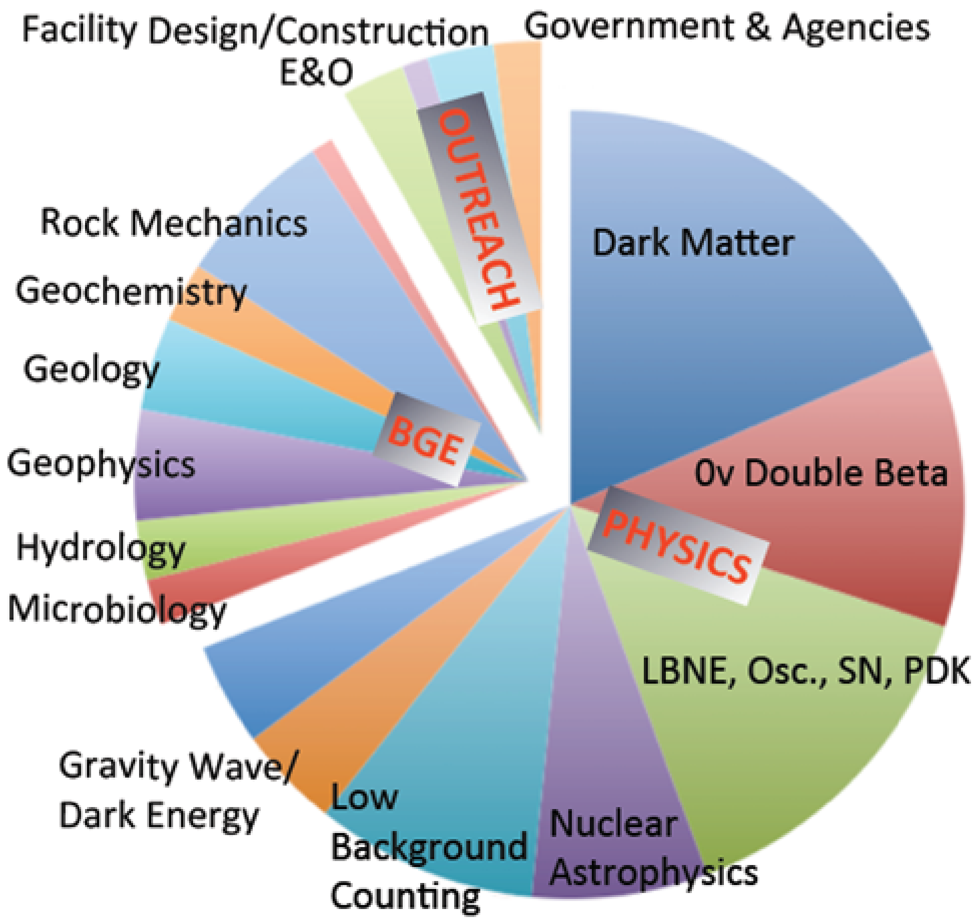
- "DUSEL gets caught up in heavy SURF (Sanford Underground Research Facility)", *D. Ellsworth et al.*, on the ARMA News Letter, 2012
  - DUSEL project at Homestake has been renamed the SURF in July 2011.
  - Funding: from NSF to DOE



(Jaret Heise, 2013)

Deep Underground Research Association (DURA)

- DUSEL User's Research Association (DuRA) endures as DURA in 2011.
  - DuRA membership:
    - Solicitation 4 (S4) for potential DUSEL experiments: 25 proposals received; 300 senior researchers; 91 institutions



- **Nine proposals funded in physics:**
  - **Dark matter (4)**
  - **Neutrino-less double-beta decay (2)**
  - **Large water Cerenkov detector (multipurpose)**
  - **Underground accelerator**
  - **Assaying sub-facility**
- **Total physics awards: $21M over 3 years.**

- **Seven proposals funded in BIO, GEO & ENG sciences:**
  - **Fracture processes**
  - **Coupled processes**
  - **Subsurface imaging and sensing**
  - **Fiber optic strain monitoring**
  - **CO_2 sequestration**
  - **Eco-hydrology & deep drilling**
  - **Underground monitoring**
- **Total BGE awards: $3M.**

(Rick Gaitskell, 2012)

Costs & Uncertainties

- Cost effective?
  - Excavation costs proportional to the volume
  - Rock stabilization costs proportional to the surface (increasing with depth)
  - Costs of services are not a large fraction of the total

DUCEL at Homestake

116M$

-Reopening the mine

-Underground safety, rehabilitation, dewatering and providing safe access to levels greater than 8,000 ft below ground

~50M$ for ~ 18 months

-**Regaining underground access** & **dewatering** the entire facility

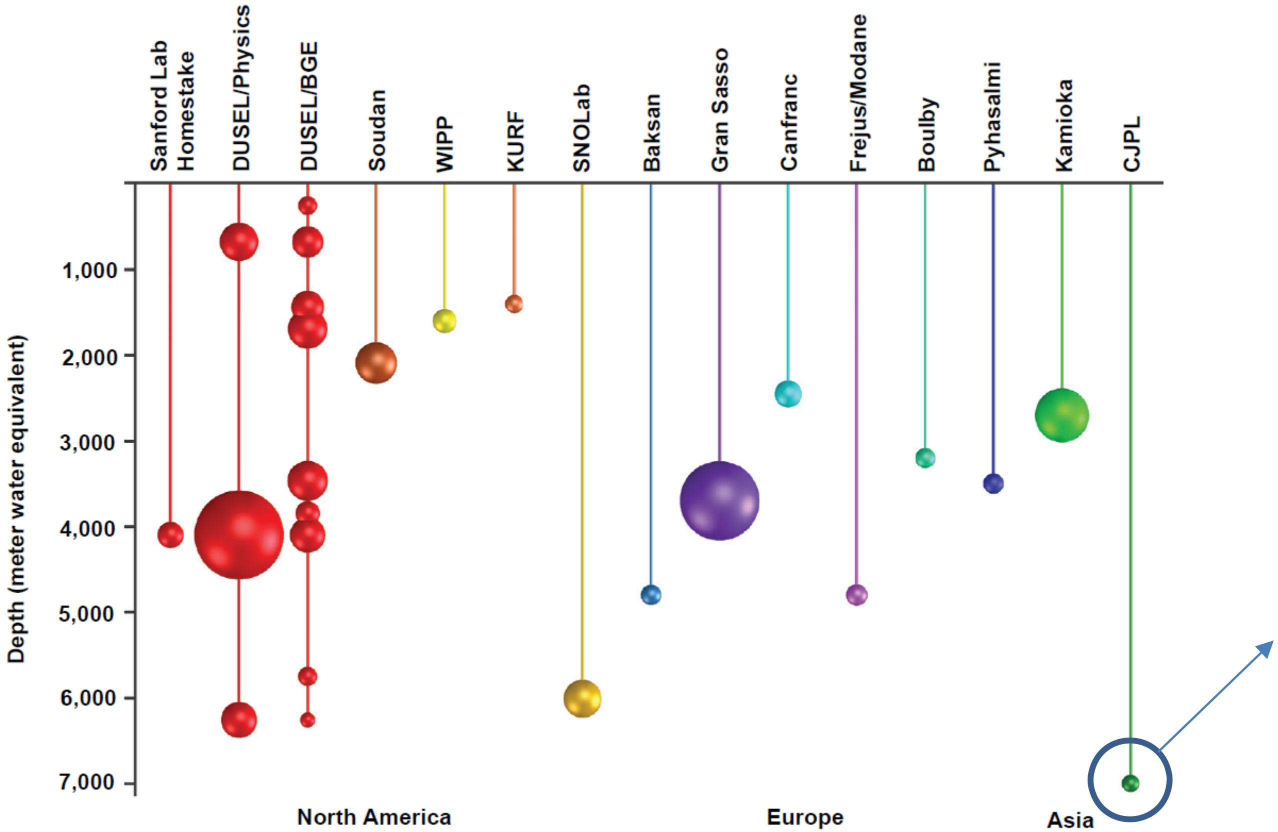
DUCEL

Refurbish shaft an general structures	311M$
Halls for two experiments (1/3 LNGS Hall or Ulisse [15M€])	159M$
Infrastructure for one water Cherenkov	not found

Costs have large **uncertainty**, due to the **incomplete knowledge** of the status of the old (and needed) structures

Underground Observatories in the World

- Depth and relative volumes, represented by the size of the spheres.



~ 96,000 m^3 in CJPL-II

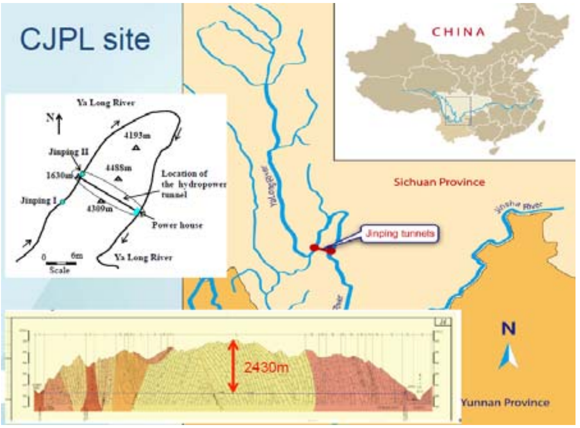
@DUSEL

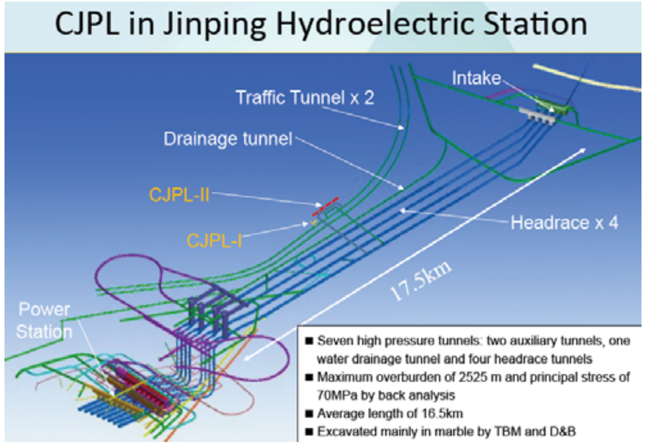
(K. Lesko, 2010)

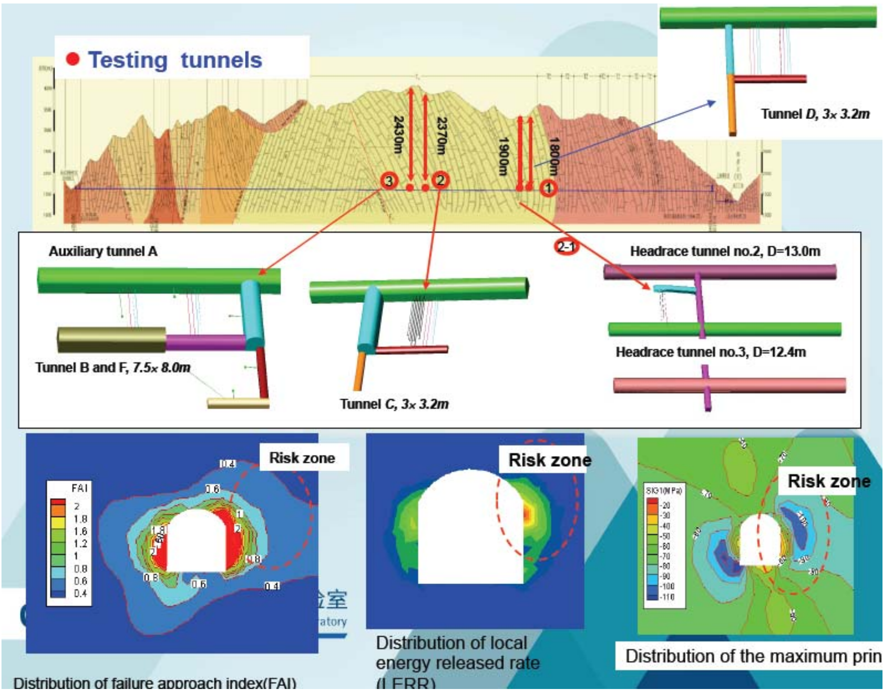
Level Below Ground	Laboratory Floor Space (m^2)	Laboratory Volume (m^3)	Common Space (m^2)	Common Space Volume (m^2)
300 ft (91~233m)	640	6,800	150	1,500
4,850 ft (1,478~4,100m)	7,200	65,000	2,800	40,000
7,400 ft (2,256~6,400m)	4,500	40,500	1,500	15,000
8,000 ft (2438~7,000m)	100	1,000	-	-

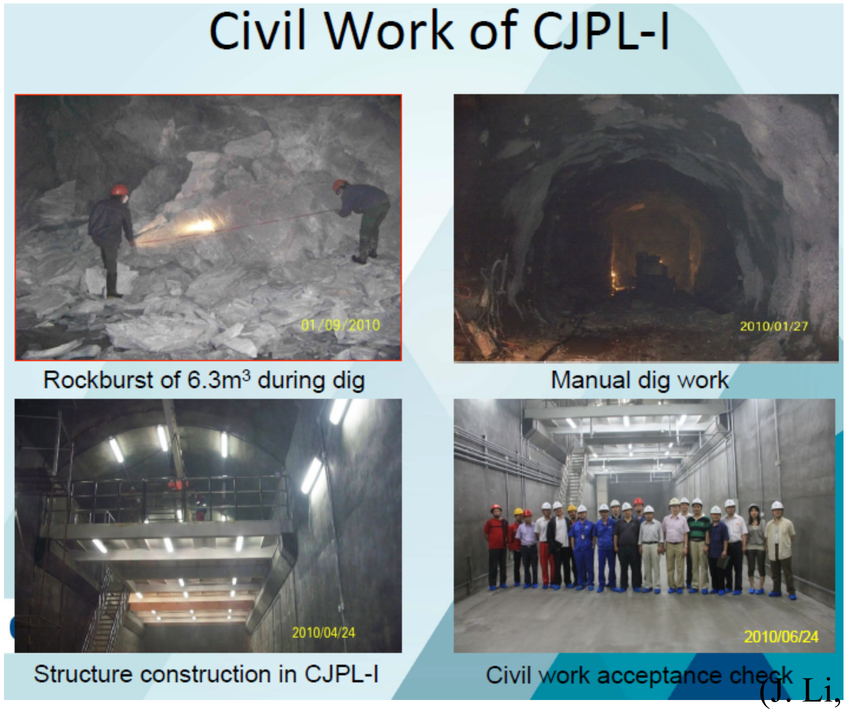
CJPL Underground Observatory in China

- Rock Mechanics studies at JinPing, China





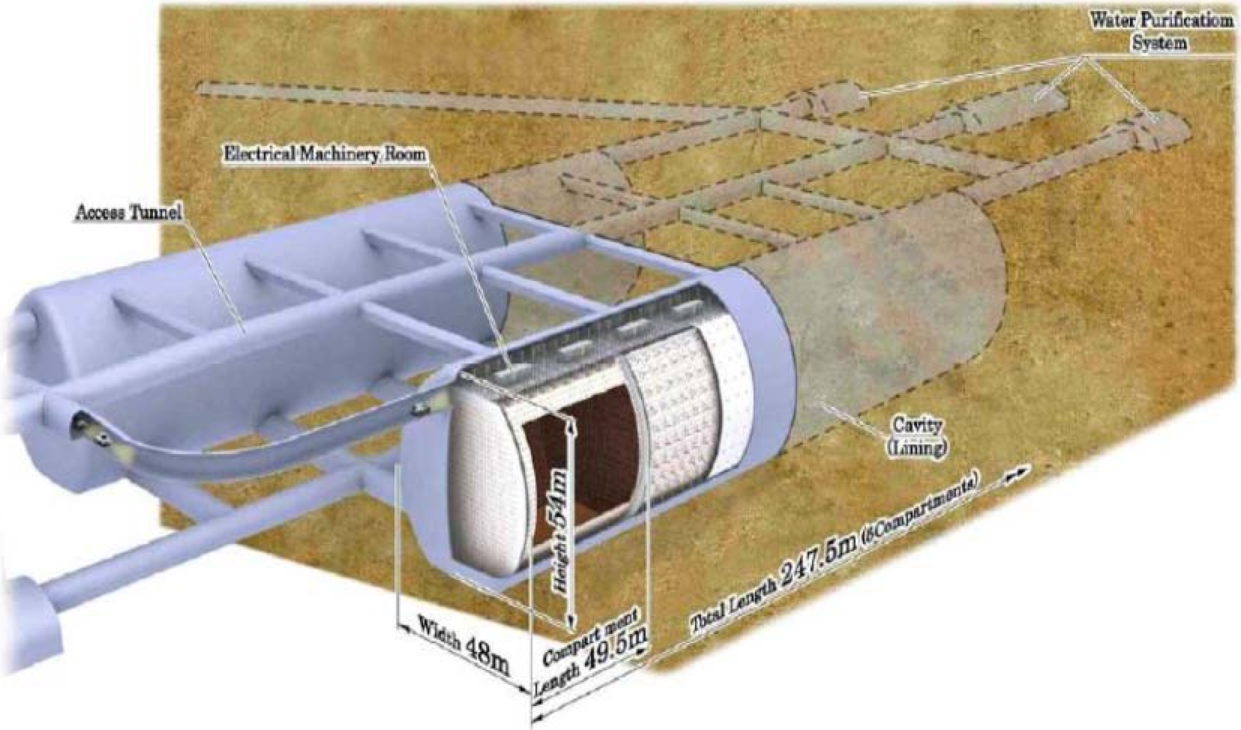


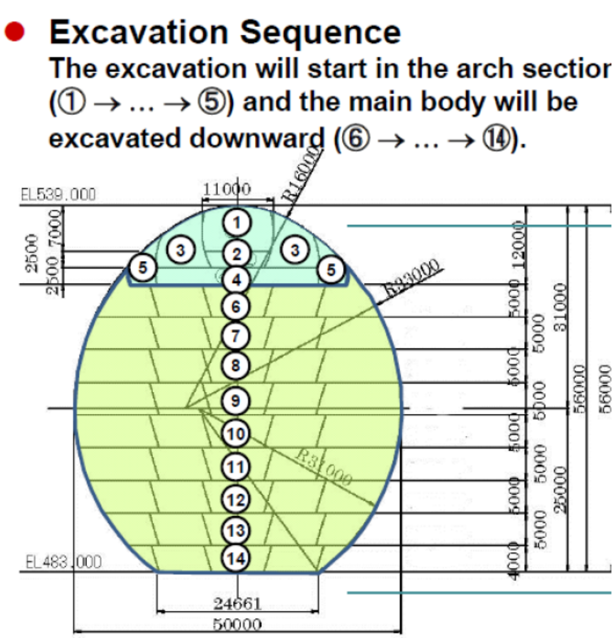


(J. Li, 2015)

Hyper-Kamiokande in Japan

- The next generation of neutrino observation after Kamiokande and Super-Kamiokande
- The volume of HK is planned to be 20 times as large as the SK tank.

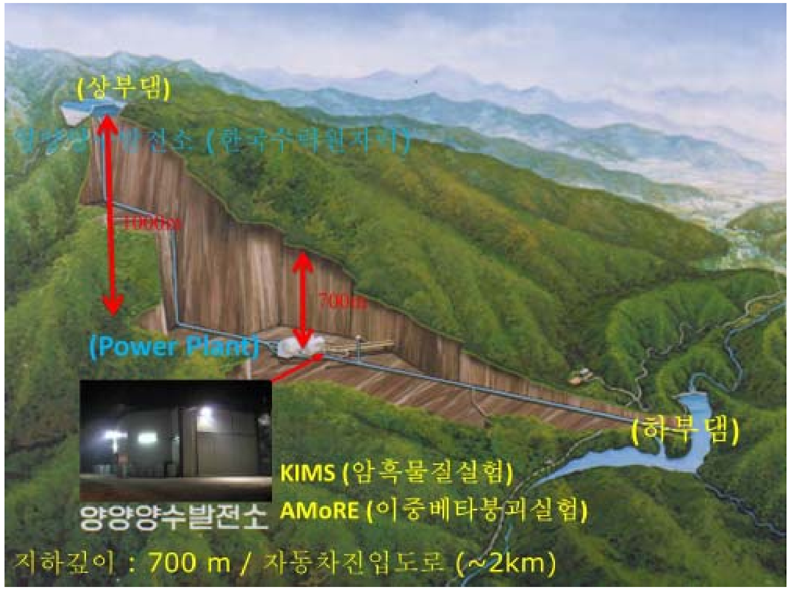


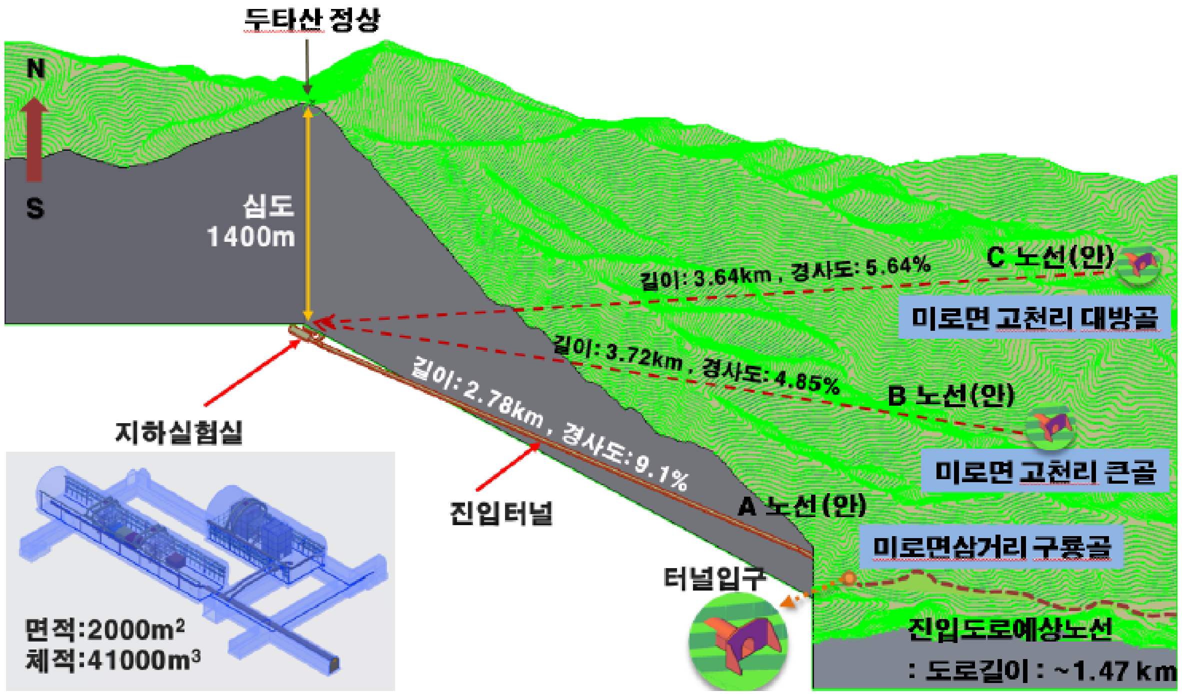


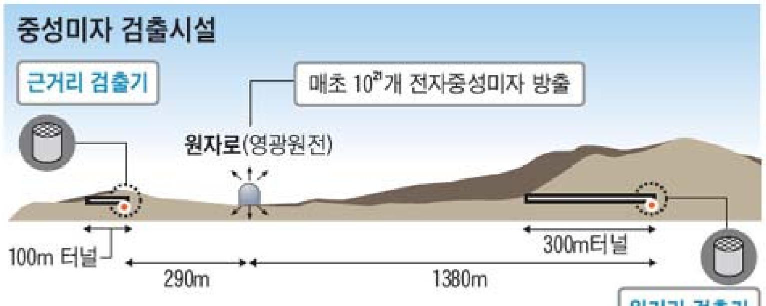
Hyper-K: 48 m wide twin caverns. 1,000,000 m^3, 500-700 m design framework, site characterization on-going
Super-K: 40 m wide cylinder, 1/20 volume, 1000 m deep

(Wang, 2014)

Underground Observatories in Korea

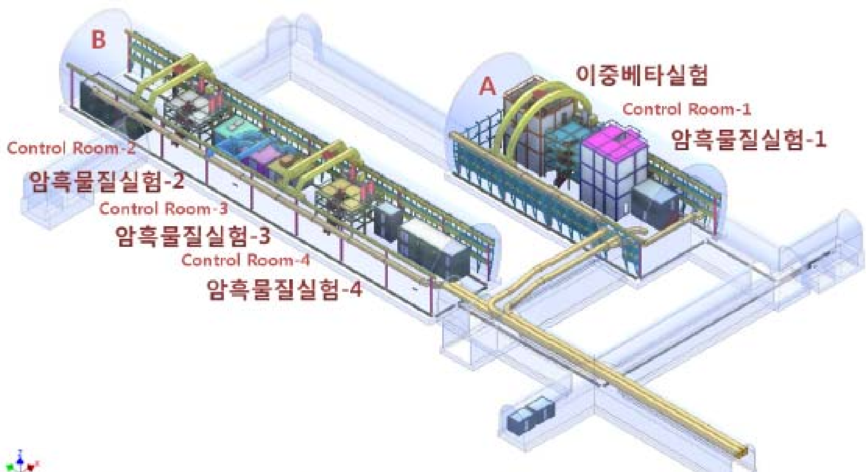






원자로(원전)에서 약 300m 지점에 검출기를 지하에 설치해 원자로에서 방출된 중성미자 양을 측정하고 약 1400m 위치에 동일한 검출기를 설치해 중성미자가 도중에 다른 종류로 바뀌어 줄어드는 정도를 파악.

(http://www.chosun.com)



* A터널 : 20m(가로)×40m(세로)×17m(높이) = 800 m² 넓이

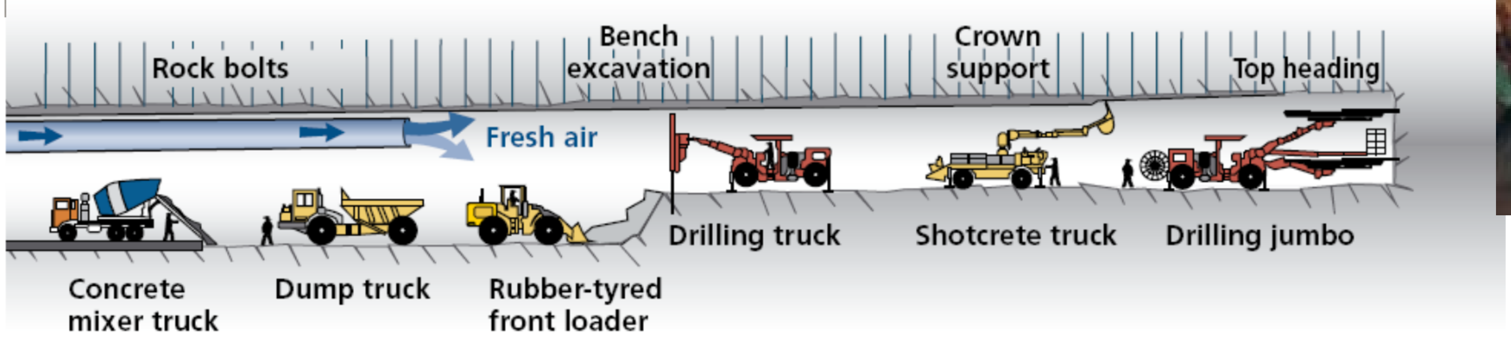
* B터널 : 15m(가로)×80m(세로)×13m(높이) = 1,200 m² 넓이

(박강순 & 최선호 , 2014)

Types of Excavation in Rocks

- Drill & Blast (using Explosives)
  - NATM (New Austrian Tunneling Method)
- Mechanical Excavation
  - Tunnel Boring Machine (TBM)
  - Roadheader

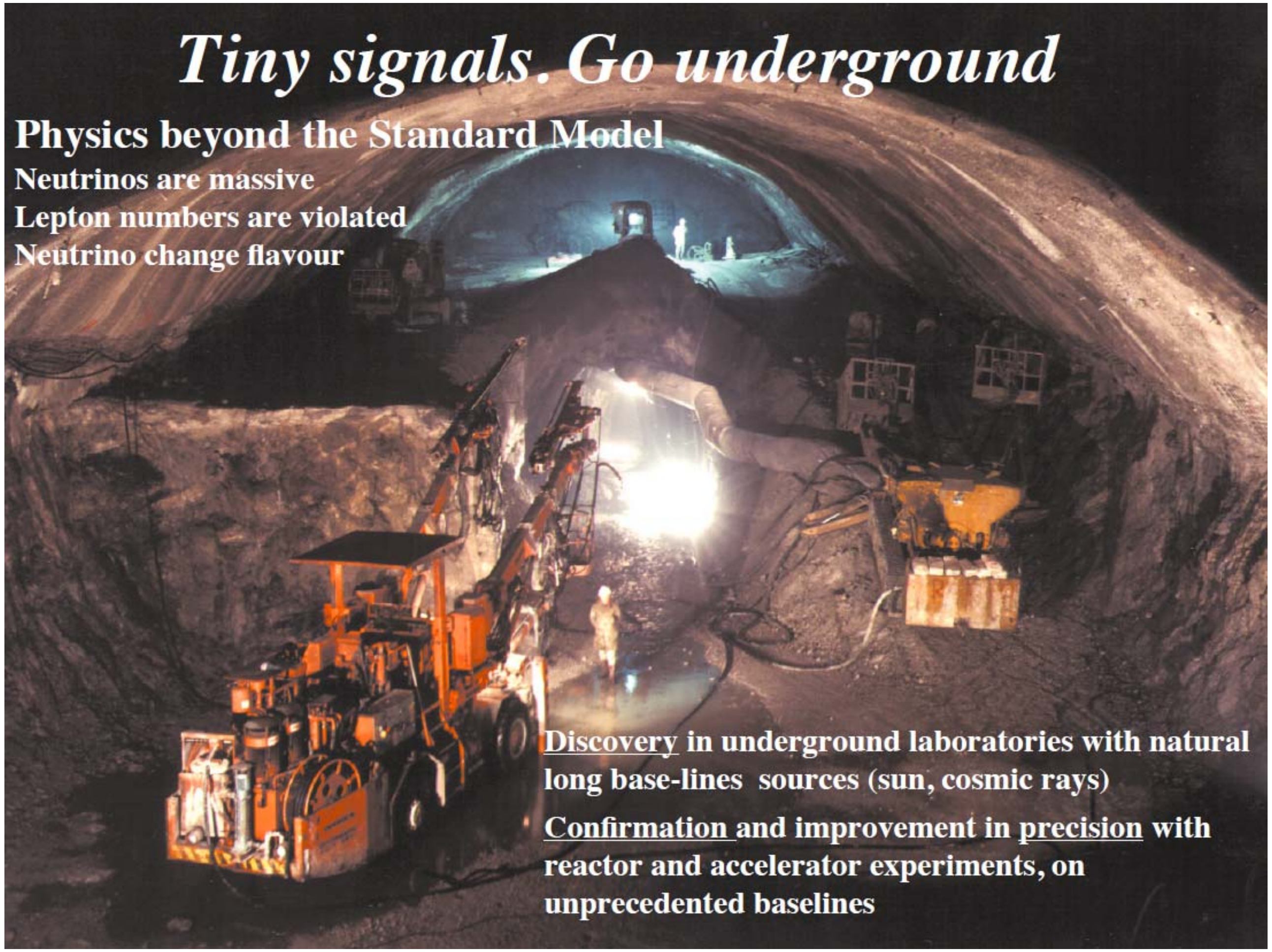
(http://www.grimsel.com)



(http://www.google.com)

Underground Physics and Rock Mechanics

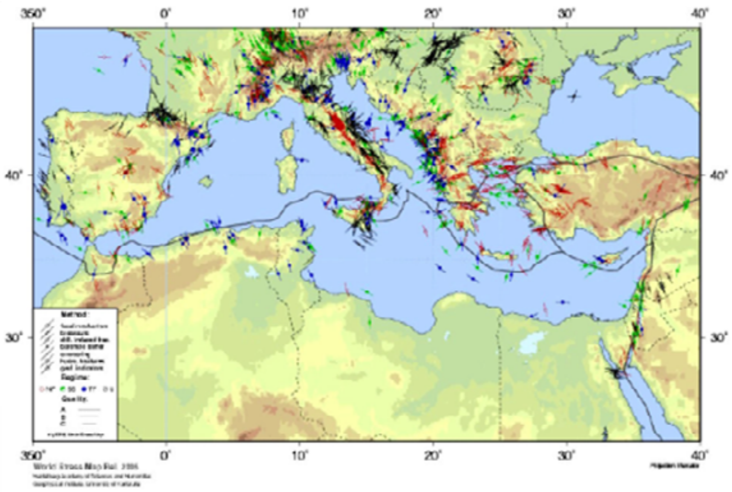
- In-situ and induced stresses
- Scale effect and Uncertainty in fractured rock mass
- Complex coupled processes in underground rock mass

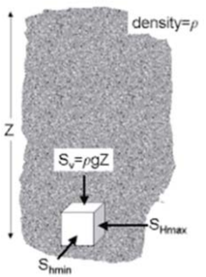


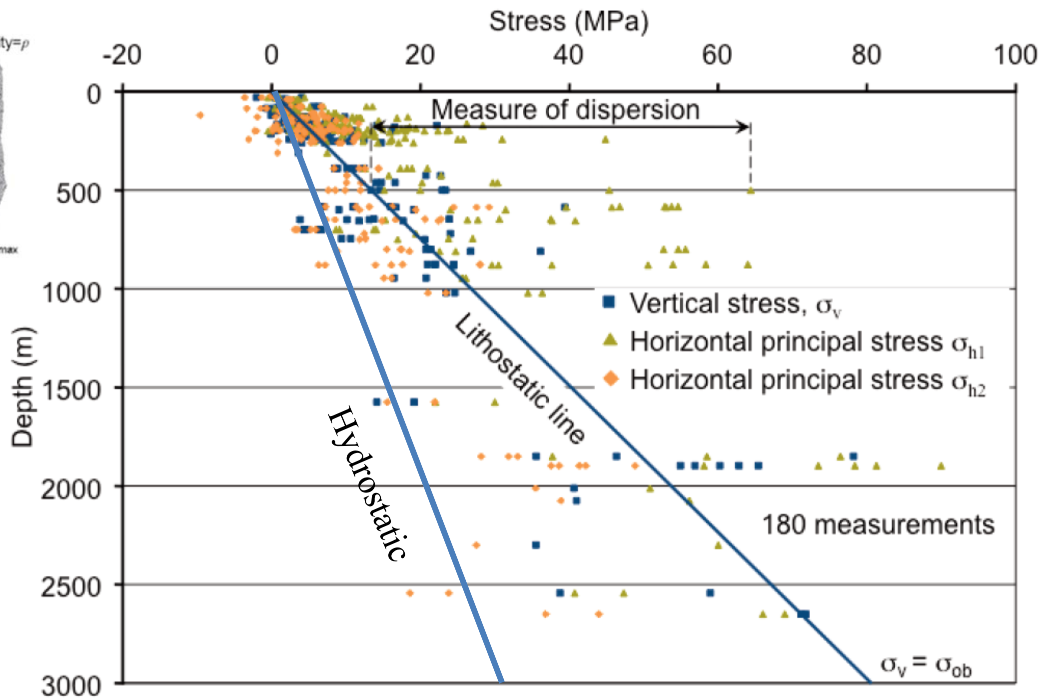
(A. Bettini, 2012)

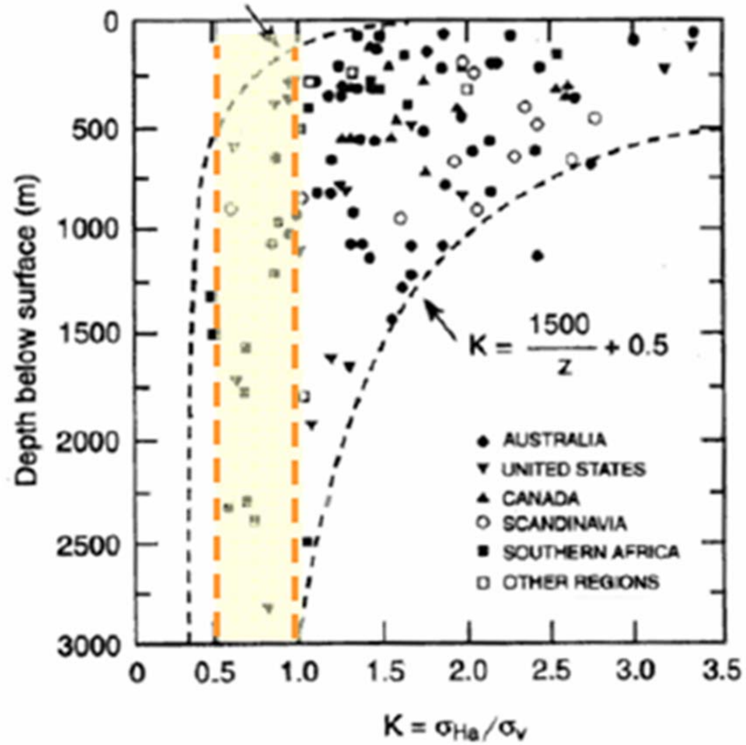
In-Situ Stress (초기응력)

- Rock at depth is subjected to stresses resulting from the weight of overlying strata (vertical) and tectonic forces (horizontal).
  - Depth-dependent
  - Anisotropic
- Knowledge of the **magnitudes** and **directions** of **in situ** and **induced stresses** is an essential component in designing underground caverns.





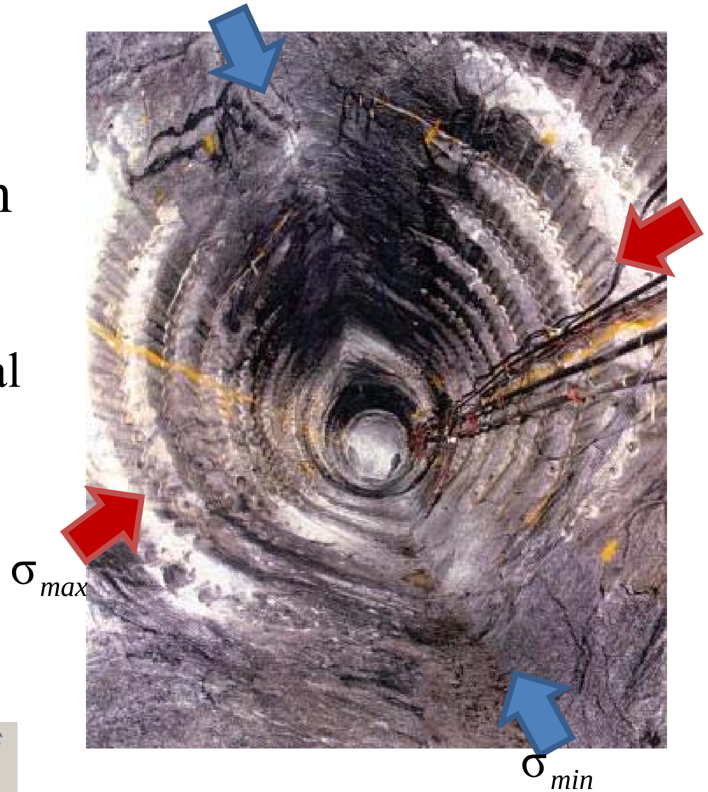




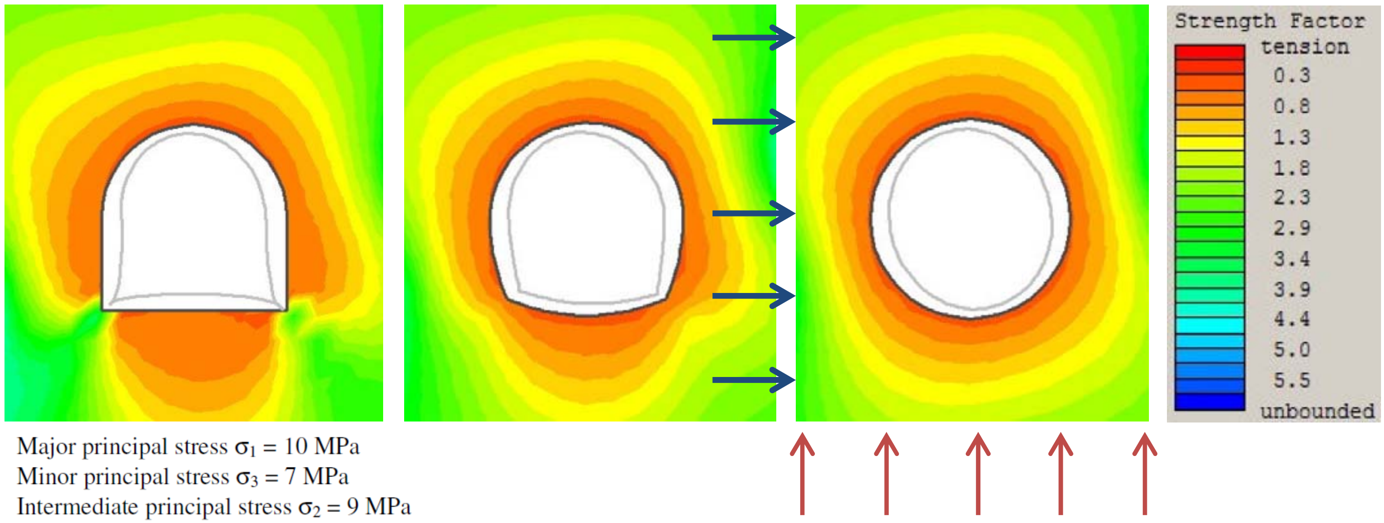
(Hoek & Brown, 1980)

Induced Stress (유도응력) and Harmonic Holes

- Stresses are **redistributed** and **concentrate** around excavated openings and caverns.
  - e.g. A cylindrical test tunnel with a length of 46 m and a diameter 3.5 m at a depth of 420 m at the Aspo URL, Canada
    - The tunnel axis is parallel to the intermediate principal stress (; promoting the maximum development of excavation induced damage)
- **Harmonic holes (조화공동)**
  - The concept of 'excavation shape around which stresses are uniformly distributed'



(http://www.civil.engineering.utoronto.ca)



Major principal stress σ_1 = 10 MPa
Minor principal stress σ_3 = 7 MPa
Intermediate principal stress σ_2 = 9 MPa
Inclination of major principal stress to the horizontal axis = 15°

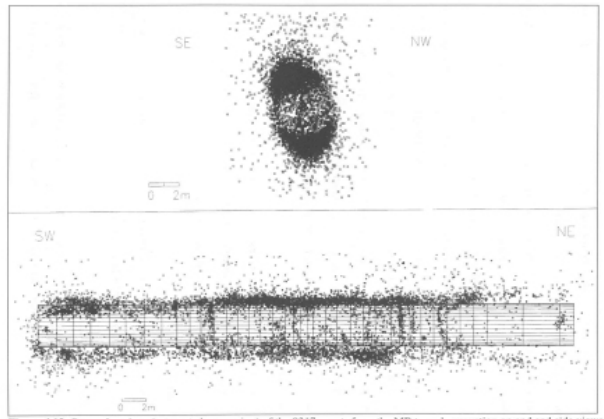
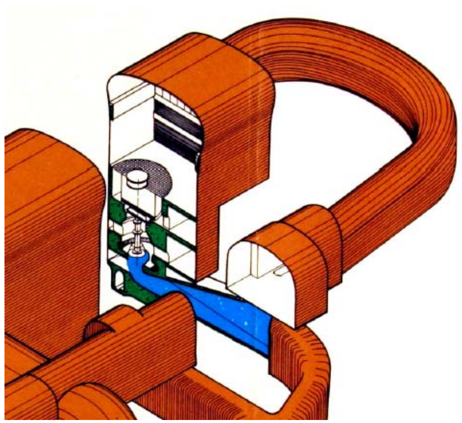
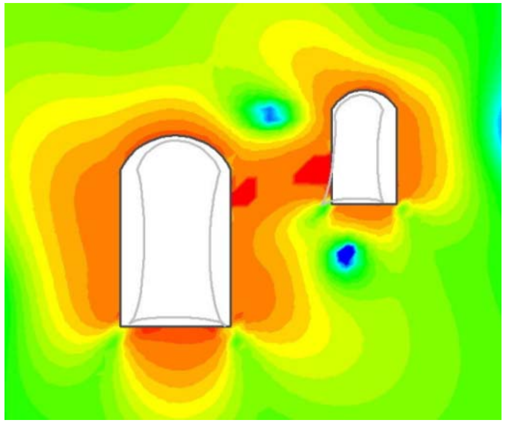


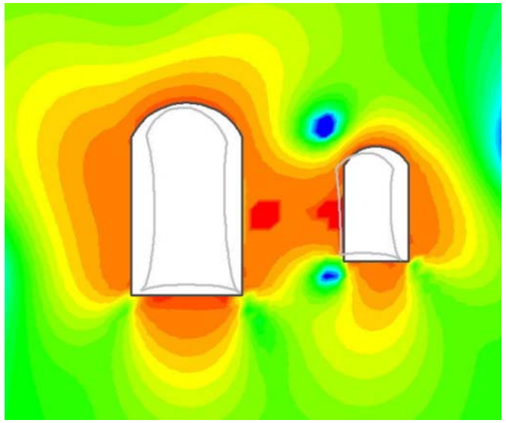
Figure 4.12: Source locations (automated processing) of the 9317 events from the MB tunnel excavation on end and side views.

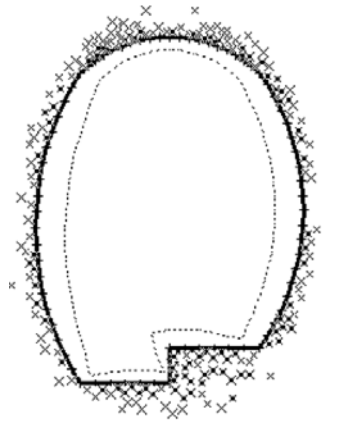
Basic Concept of Large Underground Cavern

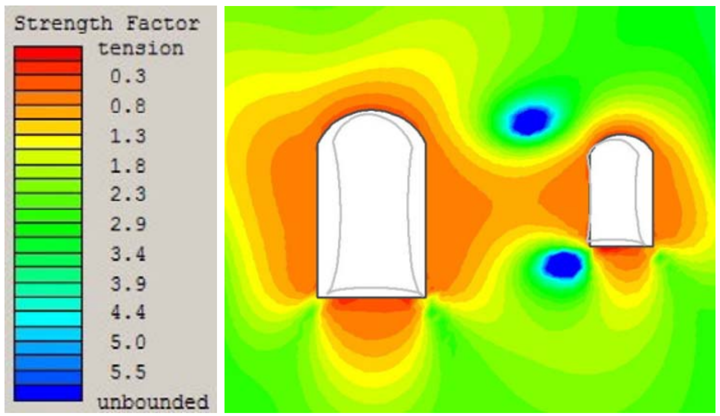
- Practical limitations of the ‘harmonic holes’ concept
  - The underground excavation engineer seldom has complete freedom in selecting the excavation shape.
  - Surrounding rock masses are **not elastic**, usually **fractured**, and contain high **uncertainty**.
- Underground excavation shape optimization
  - Appropriate **support** and **reinforcement** design for stability
  - **Communication** between rock engineers and end-users

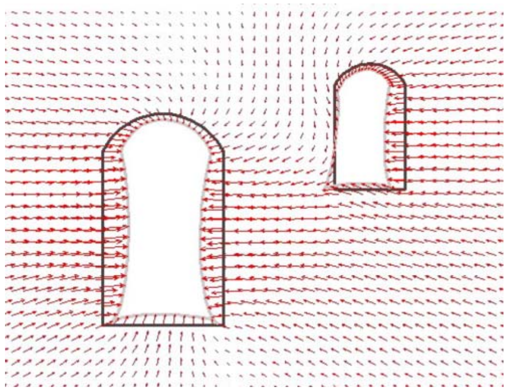


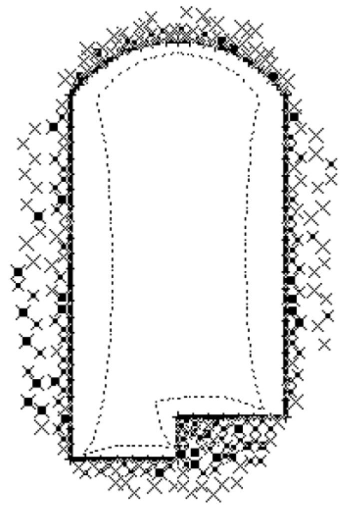






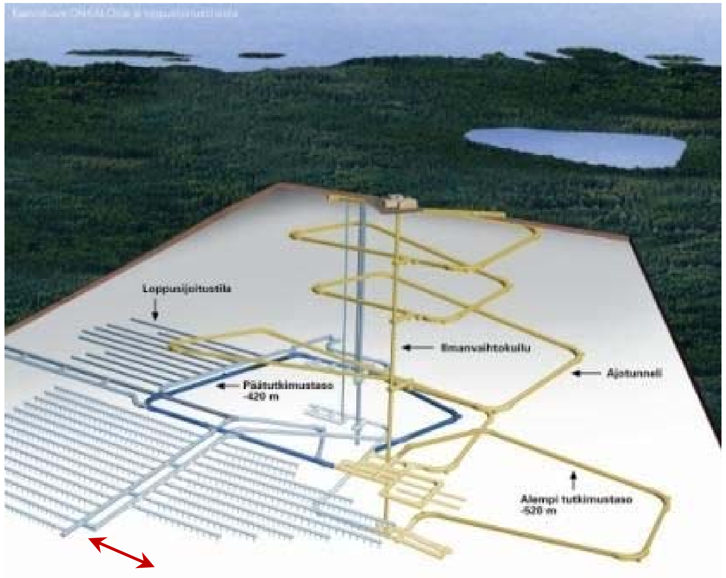




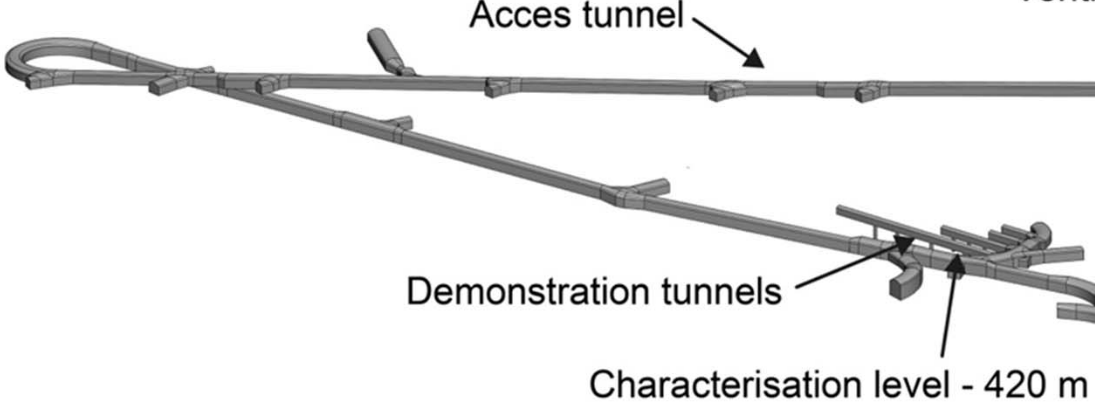
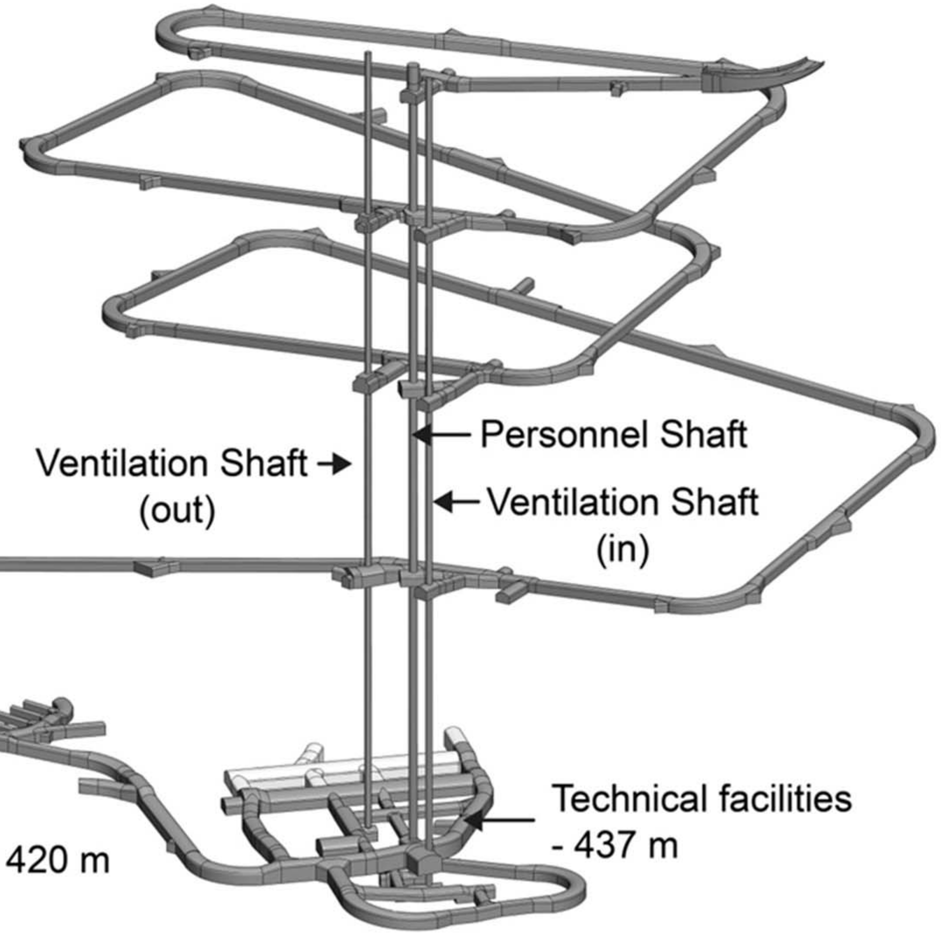


(http://www.rocscience.com)

ONKALO (Finland)



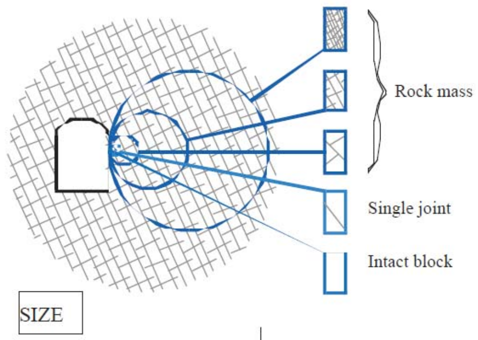
Max. principle (in-situ) stress direction

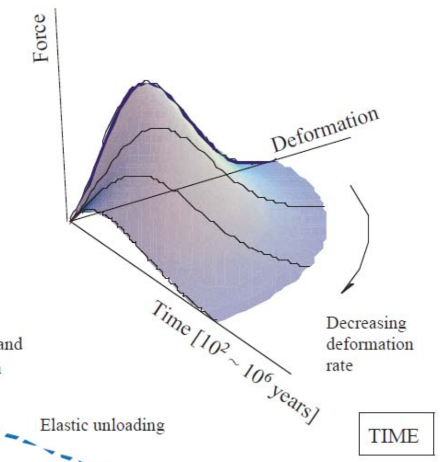



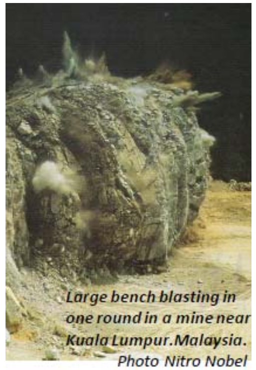
(http://www.posiva.fi)

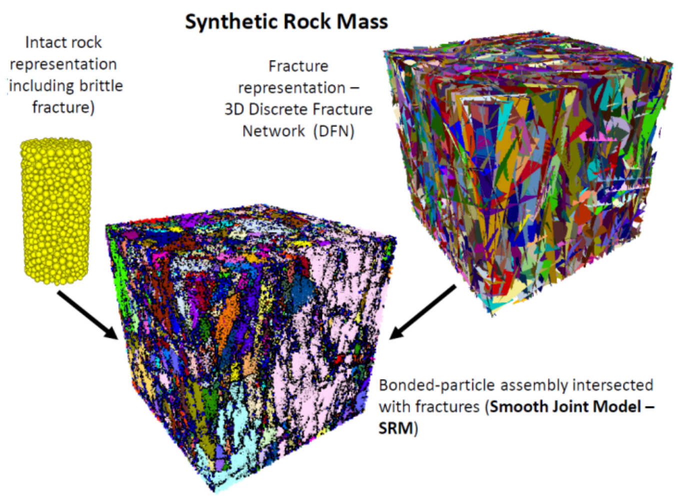
Effects of Size and Time Scales in Rock Mechanics

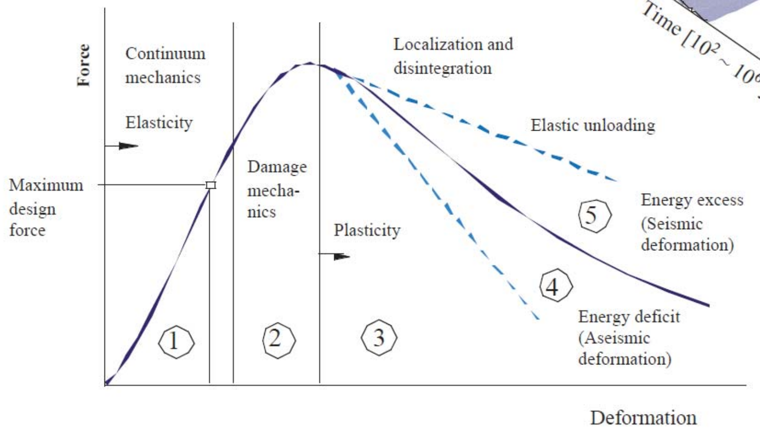
- ***Do we know the strength of rock? "For a rock mass, no. This is why we need an international society, ISRM"*** : L. **Muller**, May 24, 1962.
- Much of earth resource engineering has relied on **empirical rules** because of the complexity of the processes and the inadequacy of closed form **continuum** solutions.
- Advances in computing power now allow strength of rock mass to be computed. **Field (in-situ) verification of predictive numerical models** is now the challenge! : **C. Fairhurst**, Sept. 2010.
  - **URL** is a key element







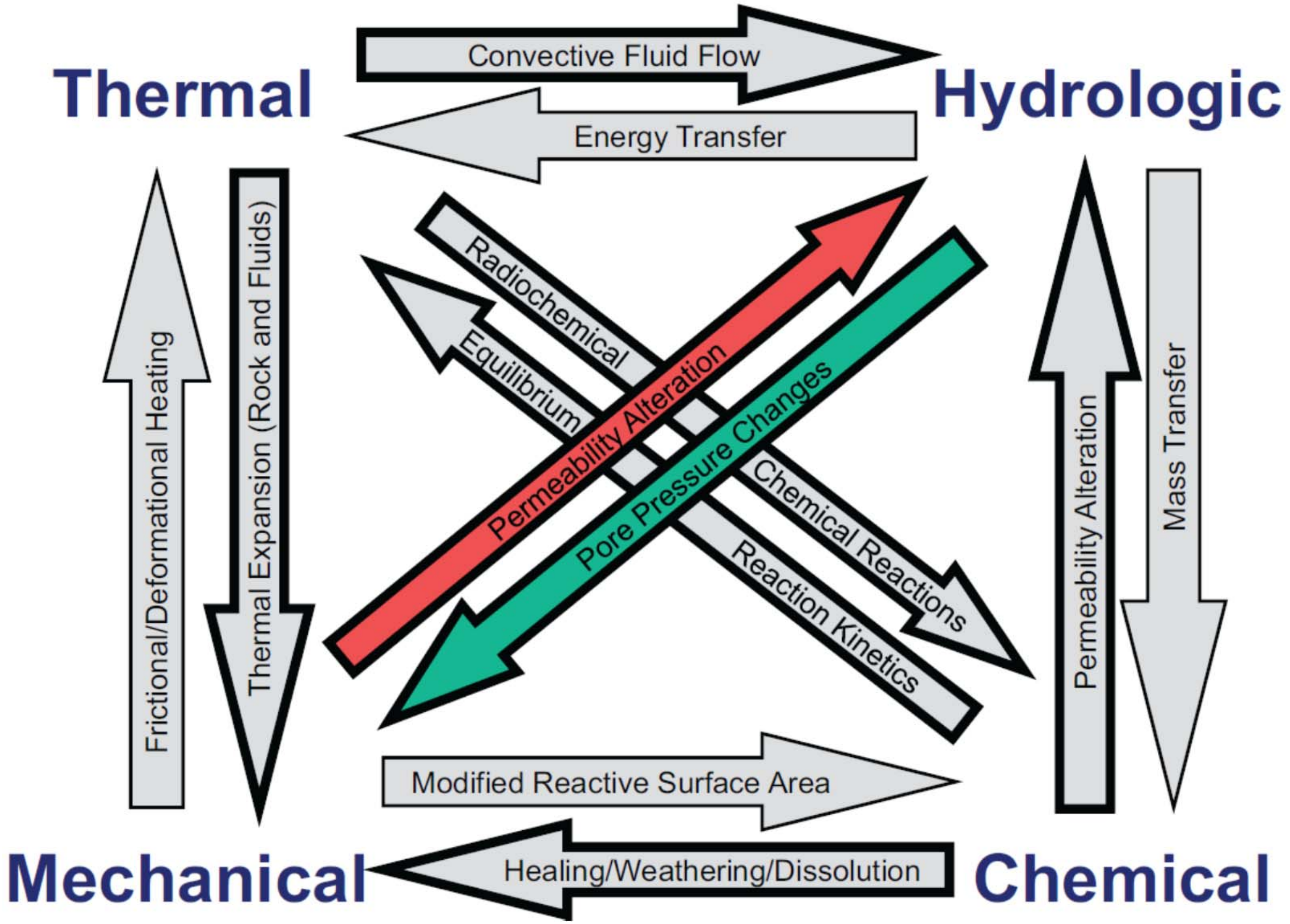




(Fairhurst, 2010)

Coupled THMC(B) Processes in Subsurface Systems

- “Fluid (water, gas, chemically reactive) flowing at depth through hot (deforming) rock under high pressure”

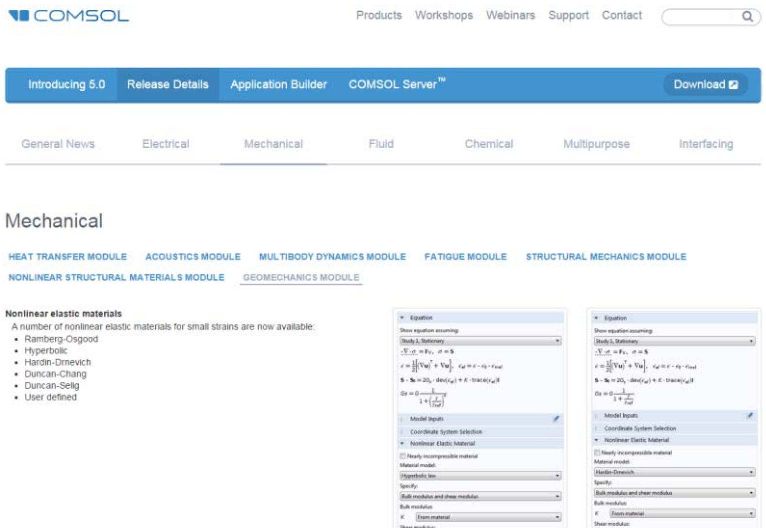


(J.L. Yow and J.R. Hunt, 2002)

THMC Modeling Software in Rock Mechanics

- OpenGeoSys(OGS)
  - Helmholtz Center for Environmental Research-UFZ, Germany
- CODE_BRIGHT
  - Polytechnic University of Catalonia (UPC), Spain
- COMSOL Multiphysics
  - COMSOL group, Sweden
- **TOUGH-FLAC**
  - Lawrence Berkeley National Laboratory, USA
- FRACOD
  - FRACOM, Finland

http://www.opengeosys.org/



http://www.comsol.kr/release/5.0

https://www.etcg.upc.edu/recerca/webs/code_bright/

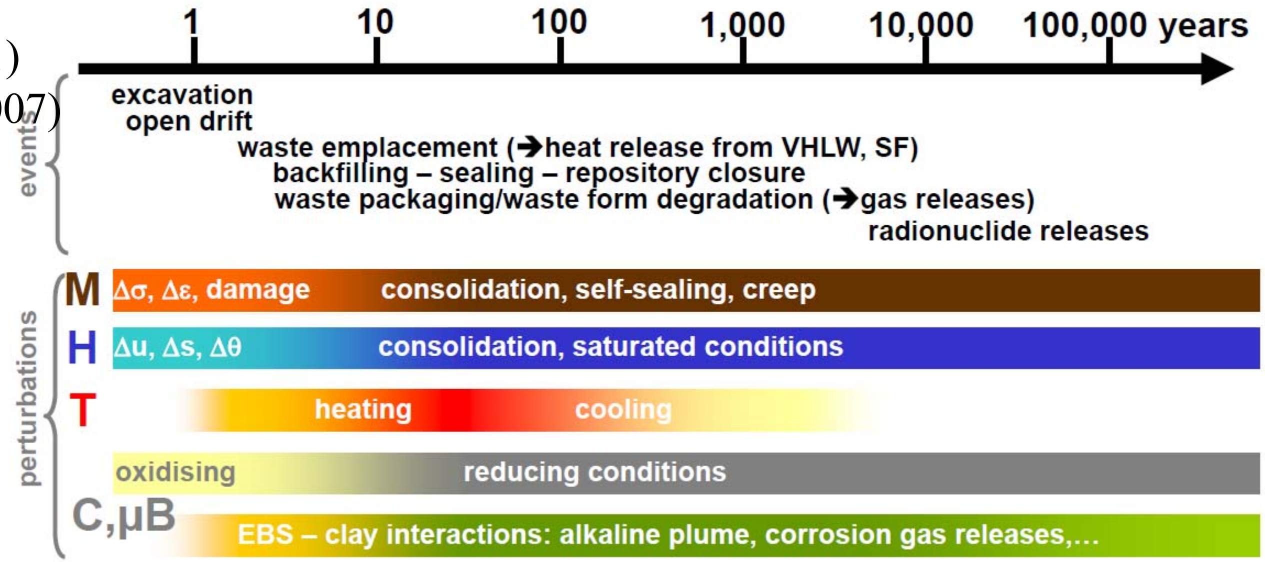
DECOVALEX Projects

- DECOVALEX
  - **DE**velopment of **CO**upled models and their **VAL**idation against **EX**periments
  - An international research and model comparison collaboration, initiated in 1992, for advancing the understanding and modeling of **coupled thermo-hydro-mechanical (THM)** and **thermo-hydro-mechanical-chemical(-biologica) (THMC(B))** processes in geological systems.
- DECOVALEX 2015
  - 6th project phase and runs from 2012 through 2015
  - Task A: The SEALEX Experiment
  - **Task B: HE-E Heater Test**
  - Task B.2: Horonobe EBS experiment
  - Task C.1: THMC Processes in single fracture
  - Task C.2: Bedrichov Tunnel Test Case

DECOVALEX 2015

http://www.decovalex.org/

- Past Phases
  - DECOVALEX 2011 (2008-2011)
  - DECOVALEX THMC (2004-2007)
  - DECOVALEX III (2000-2003)
  - DECOVALEX II (1995-1999)
  - DECOVALEX I (1992-1994)



Concluding Remarks

- For an affordable price, (Wang, 2014)
  - Reliable early estimates of $ and Days
    - Practical, cost-effective and safe designs
  - Demonstrating research values for $
    - Multi-disciplinary studies
    - Need to integrate (DUSEL or …) into world network of URL's
- Need to have **our own URL** in order to play a leading role in science and engineering principles of Underground Physics & Rock Mechanics
  - **Depth**, **Access** (vertical or horizontal), Environmental control (dust, humidity), **Safety**, **Expansion capability**, Cost
  - Need **experimental verification of models** in different rock types at deep depth
- A deep underground laboratory will **inspire** and **educate the nation's next generation** of science and engineering.

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