Sixty Years of Rock Mechanics 1956-2016

Charles Fairhurst, Professor Emeritus, University of Minnesota, Minneapolis Senior Consultant, Itasca International Inc.

Introduction

The First Symposium on Rock Mechanics, held April 23-25, 1956 at the Colorado School of Mines was an important milestone for the US. It was the first time an interdisciplinary group of engineers and scientists met in the United States to discuss the special features of engineering in rock *in situ.*[1]

Internationally, the 1950's and 1960's, on the heels of the Great Depression (1929-39) and World War II[2], were periods of optimism - and intense international activity and rebuilding, both physically and intellectually - although tempered somewhat by the Cold War.[3]

Civil construction, mining and petroleum activities expanded globally. In Europe, the Alps offered opportunities for ambitious hydro-electric facilities, highway construction, tunnels linking Northern and Southern Europe by high speed transportation connections.

In 1952, James Robbins then of St. Paul, MN, had designed the first US Tunnel Boring Machine - for work at the Oahe Dam,[4] South Dakota.

Gold mines in India and in South Africa[5], the world deepest mines, were reaching depths of around 2km and encountering hostile working conditions.

In Austria, the 'Salzburg Circle'[6] led by Dr Leopold Müller, a colleague of Dr. Karl Terzaghi [Founder President of the then International Society of Soil Mechanics and Foundation Engineering (ISSMFE)[7]], met regularly to discuss issues in rock mechanics. This 'Circle', predominantly Austrian and German civil engineers, was concerned that problems of rock mechanics were not covered adequately within ISSMFE. Collapse of the Malpasset Dam in France, November 1959, followed by the Coalbrook Coal Mine collapse in South Africa in January 1960 convinced Müller that international attention was needed. He registered the International Society for Rock Mechanics (ISRM) in Salzburg in May 1962[8]. The First ISRM Congress was held in Lisbon in 1966. In his opening address, President Müller identified *discontinuities [joints] and anisotropy* as the most important features distinguishing rock from soil –and of sufficient importance to warrant vigorous international study and discussion.

Rock Mechanics Organization in US. (1962-1995)

Although, as evident from the series of Annual US Rock Mechanics Symposia started in 1956, rock mechanics was a topic of active professional discussion in the US for several years before the International Society for Rock Mechanics (ISRM) was founded in Salzburg, Austria in May 1962, - and the intention to hold the First ISRM Congress in Lisbon in 1966 was announced, establishment of ISRM stimulated vigorous discussion in the US of a national organization for rock mechanics, both to help co-ordinate national activities and to serve as the US national representative to the ISRM.

The following excerpts from a 1965 publication of the US National Academy of Sciences provide a useful insight into some of these early activities. The full report (27 pages plus 55 pages of Appendices) is available on the website https://books.google.com/books/about/Rock_mechanics_Research.html?id=bT4rAAAAYAAJ

Rock-Mechanics Research - A Survey of United States Research to 1965 with a Partial Survey of Canadian Universities.

Committee on Rock Mechanics. W.R. Judd, Chairman. National Academy of Sciences, Washington DC.1966 Publication 1466 Lib. Cong. Catalog No; 66-65791 January 196

Preface.

The need for a better understanding of the physical –mechanical properties of rock and of how stresses in the earth's crust affect these properties becomes ever more apparent with the unprecedented increase in major civil engineering construction now under way. The structural integrity of large buildings, dams, bridges, and many other forms of construction is vitally dependent upon the behavior under stress of the rocks that constitute their foundations. Knowledge of rock mechanics, rock stresses, and geologic structures is also essential to *mining, petroleum engineering, and various other industrial activities. Rock mechanics is of special interest to scientists concerned with the fundamental nature of the materials making up the earth's crust.*

To determine the current status of research and of technical training in the United States, to point out strengths and deficiencies, and to make recommendations to guide future developments, in 1963 the President of the National Academy of Sciences appointed the Committee on Rock Mechanics.[9]

At the time there was neither agreement on the scope of rock mechanics nor a generally accepted definition of it. Therefore, to serve as a basis for both defining the field and evaluating the current state, the Committee undertook a survey of research and education in rock mechanics in the United States.

……

The Committee expresses its appreciation to the 53 companies listed in Appendix H; the Office of Aerospace Research; US Air Force; the Office of Research and Development U.S. Army; the Division of Research, US Atomic Commission; the Bureau of Reclamation, US Department of the Interior; and the National Science Foundation, for financial support of the Committee's activities, including preparation of this report.

August 1966 *William R. Judd.*
Chairman

……

Page 3

The Academy charged the Committee with the following tasks:

1. *Define the field of rock mechanics*
2. *Encourage and improve among scientists and engineers the communication and dissemination of literature concerning rock mechanics*
3. *Determine the present status of professional and academic training in rock mechanics in American universities*
4. *Survey current research in rock mechanics in government, industry, and universities. In order to identify possible gaps in such research*
5. *Serve as a national focus for research*

As a first step, the Committee agreed upon and recommends for general use the following definition of the field

Rock mechanics is the theoretical and applied science of the mechanical behavior of rock; it is that branch of mechanics concerned with the response of rock to the force fields of its physical environment.

*In approaching its second task, the Committee noted that the first symposium devoted wholly to the subject of "rock mechanics" was held in 1956 at the Colorado School of Mines. Since that time, at least 25 United States and 25 international conferences and symposia have dealt entirely or significantly with rock mechanics. (Appendix A lists conferences through 1965 for which proceedings have been or will be published.) Along with a recent increase in the number of meetings concerned entirely with rock mechanics, the number of sessions devoted to this subject at the annual meetings of professional societies has also increased. This growth in interest led the Committee to sponsor several meetings of representatives of those professional societies known to be significantly concerned with rock mechanics. The goal of these meetings was to form a permanent group to coordinate national and regional symposia and to sponsor an annual interdisciplinary symposium. Accordingly, on November 1, 1965, the Intersociety Committee for Rock Mechanics was established **

** The following societies are represented on the Intersociety Committee: (1) American Geophysical Union-Section on Tectonophysics. (2)American Institute of Mining, Metallurgical, and Petroleum Engineers –Committee on Rock Mechanics. (3) Society of Mining Engineers- unit committee on rock mechanics, in the Coal Division and in the Mining and Exploration Division. (4) Society of Petroleum Engineers. (5) American Society for Testing and Materials- Subcommittee 12, on Rock Mechanics, of Committee D-18. (6) American Society of Civil Engineers –Committee on Rock Mechanics. (7) Geological Society of America –Committee on Rock Mechanics in the Engineering Geology Division. (8) Association of Engineering Geologists (9) Highway Research Board - Committee on Soil and Rock Properties. (10) Seismological Society of America. (11) Society of Exploration Geophysicists.*

……

The first paragraph of the Preface by Prof. Judd notes the "*unprecedented increase in major civil engineering construction now under way.*" While acknowledging that mining engineering departments had taken the lead in discussion of rock mechanics, several leading civil engineers were concerned that the profession in the US was not moving forward as rapidly as its European counterparts in recognizing the importance of rock mechanics and rock engineering. [See e.g. the comment on p.13. "*It should be noted that research and education in rock mechanics by departments of civil engineering and petroleum engineering have been confined to relatively few institutions.*"]

The lack of adoption of courses in rock mechanics in undergraduate programs in Civil Engineering curricula at US universities remains a source of concern today. There are several distinguished rock mechanics graduate programs in Civil Engineering in the US.

Although not addressed specifically in this report, rock mechanics was also an important component of several major activities related to National Defense –underground testing of nuclear weapons by the US; efforts to monitor , by geophysics, underground tests being carried out by other nuclear powers, especially the Soviet Union and China; isolation of high level nuclear waste in geological repositories; sub-surface as protection in the event of a nuclear attack (see the discussion of 'Rapid Excavation and Tunneling Techniques' in HFJ. January 2017), etc. This interest is seen in Prof. Judd's acknowledgments to various defense agencies in the final paragraph of his Preface "*The Committee expresses its appreciation……*
The list of professional societies represented on the Intersociety Committee for Rock Mechanics in 1965 illustrates how rapidly interest in rock mechanics in the US had grown from the First Symposium at Colorado School of Mines in 1956.

……….

A note in the journal EOS of the American Geophysical Union (AGU), June 1971, mentions some subsequent developments. http://onlinelibrary.wiley.com/doi/10.1029/EO052i006p00463-02/abstract

> *Three events of major importance for the U.S. National Committee for Rock Mechanics and for the U.S. rock mechanics community have taken place during the past few months. First, at a joint meeting of the U.S. National Committee and the Intersociety Committee for Rock Mechanics (ICRM), held in Rolla, Missouri, on November 15, 1970, both groups agreed unanimously to merge into a single committee that would represent the interests of U.S. activities and workers in rock mechanics both nationally and internationally. Another event of special importance was the election of Leonard A. Obert, of the U.S. Bureau of Mines, Denver, as President of the Society. The third event was ISRM's acceptance of the U.S. National Committee's proposal to host the Third ISRM Congress in Denver in September 1974.*

……….

Formation of the NAE in 1966 as a distinct Academy separate from NAS led to discussions and internal reorganizations within the Academy, but the USNC/RM remained a part of NAS as a Committee under the jurisdiction of the Geotechnical Board of the National Research Council. Around 1993 it became a Standing Committee of the Board of Earth Sciences and Resources (BESR). USNC/RM continued to be the sponsor of the Annual Rock Mechanics Symposium and US representative to the ISRM.

Discussions of internal restructuring continued and, in 1995, NAS management decided that it would no longer sponsor Standing Committees, of which there were several within the Academy. The decision came as a surprise to members of the USNC/RM. Very fortunately for US rock mechanics, Peter Smeallie had joined NAS staff as Director of the Geotechnical Board in May 1990, which included management of the USNC/RM. A group of leaders in the US rock mechanics community formed an *ad hoc* committee to consider how to maintain a national organization for US rock mechanics, including representation on ISRM. Convinced of the importance of rock mechanics as a discipline and the need for a national organization in the US, Peter worked tirelessly to provide organizational leadership as a member of this group. It was decided to form a professional association, the American Rock Mechanics Association (ARMA) with Peter as Executive Director. Incorporated in 1995, ARMA http://armarocks.org/ took responsibility to continue the annual US Rock Mechanics Symposium, and be the US National Group within the ISRM. In 1996, ARMA co-sponsored the 2nd North American Rock Mechanics Symposium 19-21 June 1996, in Montreal, with the Canadian Rock Mechanics Association (CARMA).

Under Peter's direction, ARMA is now recognized internationally as a leading organization in rock mechanics and rock engineering. The 51st US Rock Mechanics Symposium will be held in San Francisco, 25-28 June 2017.

Global developments in Rock Mechanics – post WWII.

The need to improve coal mine safety and technology led, soon after WWII, to establishment of research laboratories in France, Germany and the UK. Advances in coal mine mechanization by German engineers during the war also stimulated change in Western European and US coal mines. 'Hard rock' mines around the globe, many developed by European–based companies, especially from the UK colonial era, were beginning to move towards national ownership. Rock bursts, and high rock temperatures and humidity[10], became formidable obstacles as mines became deeper.

In 1964, the South African Chamber of Mines, Johannesburg, established the Mining Research Laboratory and Coal Mining Laboratory[11] [Later combined as the Chamber of Mines Research Organization, COMRO]. These laboratories applied mechanics to make major contributions.[12] The Energy Release Rate (ERR) approach to design of gold reef extraction patterns, and other design guidelines, are excellent examples of the application of principles of mechanics in rock engineering.

The mines of the Kolar Gold Fields[13] were of comparable depth to those of South Africa, and mining conditions equally hostile and dangerous. The mines were transferred to the Government of India, Ministry of Finance in 1962. In 1972, the government-owned Bharat Gold Mines Limited was formed. R. Krishnamurthy led the rockburst research group.[14] Difficult working conditions led to closure of the mines in 2001[15].

Rockbursts remain a major mining hazard world –wide , and have been the subject of international conferences every four years since 1982 Mining is also an important part of the economy of Australia, Canada, South America (especially Chile.), and these countries became active in rock mechanics and related research, sponsored in large measure by government, with industry support.

Establishment of the Postgraduate School of Rock Mechanics at Imperial College, London in 1966 was an important development - under the leadership of Dr E. Hoek, who held this position until 1975.[16]

Australia, through the CSIRO (Commonwealth Scientific and Industrial Research Organization), established in 1916 [17] has maintained an active program of research in both mining and petroleum engineering; e.g. the Australian Resources Research Center in Western Australia .[18] The

Cooperative Research Center for Mining[19] another joint university/industry partnership, near Brisbane, has conducted basic and applied research on rock fragmentation systems for almost three decades.

Canada supports both basic and applied R&D in mining through the Natural Research Council (NRC) of Canada[20]. NRC, (established 1916) stimulates university/industry collaboration by offering 50% matching support for industry-sponsored research at universities.

Both Australia and Canada recognize minerals as an important element of their economy.

China has emerged onto the World stage of rock mechanics over the last two decades or so, through its massive commitment to hydropower and civil infrastructure development.

The US Bureau of Mines (USBM) was, for many years, a major contributor to rock mechanics research. Founded in 1910 "*to deal with a wave of catastrophic mine disasters*"….. the USBM came to be recognized "*both nationally and internationally, as the focal point for new and emerging science and technology in the minerals field.*"

This high reputation included rock mechanics. A vigorous program of rock mechanics, led by Dr Leonard Obert,[21] was supported by a team of scientists and engineers at several USBM laboratories across the US.

The book: Obert, L. and W.I Duvall (1967) "*Rock Mechanics and the Design of Structures in Rock*", Wiley (New York), was a valuable, early aid to faculty teaching rock mechanics.[22]

In situ extraction from oil shales was also a major research activity of the USBM for many years. A 2008 NETL (Morgantown) report [23] on this program includes the following observation.

> *"The development of oil shale has been hindered by a number of factors. These technical, political, and economic factors have brought about R&D boom-bust cycles. It is not surprising that these cycles are strongly correlated to market crude oil prices. However, it may be possible to influence some of the other factors through a sustained, yet measured, approach to R&D in both the public and private sectors."*

The US mining industry relied on the USBM for R&D in rock mechanics and 'ground control,' –although some mines did conduct 'in –house' R&D, such as the rockburst studies in the hard rock mines of the Coeur d'Alène region, Idaho, Innovation in mining equipment came primarily from manufacturers.

The petroleum industry and service companies, by contrast, had excellent R&D groups in rock mechanics and allied subjects - a tradition that continues. Shell Development Laboratory, Houston, was a prime example. Outstanding scientists and engineers - M.A Biot, J. Geertsma, H.Odé, M.King Hubbert , J.W.Handin, J.B.Cheatham …and others, were all part of the Shell group –an international network of laboratories –making major contributions to petroleum engineering. Although much of the detailed research remained company confidential, development of off-shore rigs, hydraulic fracturing, drilling were active topic in the 1960's. Directional drilling, started in the mid-1980's, has had a transformative, influence in petroleum engineering. As discussed later in these notes, developments in petroleum engineering have major potential for application to other branches of subsurface engineering.

Rock mechanics in the US was also a part of important activities related to national defense. Thus,

- The two-volume publication, J.J. Sullivan (Ed) *Protective Construction in a Nuclear Age (1991),* McMillan Vols. 1 and 2 [Second Conference] 885p. contains numerous rock mechanics contributions.
- The Partial Test Ban Treaty of 1963[24] prohibited atmospheric testing of nuclear weapons, but permitted underground tests. The US conducted over 1000 such tests. The Soviet Union, China and France also had underground test programs. Although the primary purpose of such tests was to assess the effectiveness of weapons development, a great deal was learned relating to the effects of nuclear explosions on rock. The Peaceful uses of Nuclear Energy (PNE) initiative[25] - Project Plowshare [26] in the US helped stimulate interest in using nuclear explosions for such activities as widening of the Panama Canal; stimulating production from petroleum reservoirs, etc. A good discussion of some of the rock mechanics characteristics of underground nuclear explosions can be found in the report *Underground Nuclear Testing in French Polynesia: Stability and Hydrology Issues* (1999)[27]. The Ninth ISRM Congress, Paris (1999) included a discussion of underground nuclear testing experience between colleagues from China, France, Russia, and USA.

The US was also the early leader in establishing, in 1957, [28] that geological isolation in underground repositories was the best option to ensure that the long –lived, highly radioactive waste resulting from the manufacture of nuclear weapons could be safely isolated from the biosphere for the very long times required for the waste to decay to non- toxic levels A remarkable amount of state of the art research in high –level radioactive waste isolation was conducted by the US Department of Energy, with the aid of interdisciplinary teams of leading geoscientists and engineers at US National Laboratories, universities, international colleagues, etc. for both the Waste Isolation Pilot Plant repository at Carlsbad, New Mexico[29] -opened in 1999 -and Yucca Mountain, Nevada[30].

Two excellent examples (of many) to illustrate how challenging rock mechanics issues were addressed by Yucca Mountain scientific and engineering teams can be found in

i. the USGS report "*Extreme Ground Motions and Yucca Mountain*," led by Thomas Hanks. [31] Some details of this report have been presented in the paper *Newton in the Underworld* HFJ January 2017, pp.28-29

ii. the publication *Mechanical Degradation of Emplacement Drifts at Yucca Mountain –a Modeling Case Study*. Int. J. Rock Mech. &Min Sci. Vol.44 (2007) Part 1: *Nonlithophysal Rock* (Lin et al;) pp351-367; Part II: *Lithophysal Rock* (Damjanac et al;) pp 368-399.

Work on Yucca Mountain was halted, by order of President Obama in 2011 – after expenditures of over $10 billion dollars - for political rather than scientific reasons. The future of this site is uncertain.[32] Other countries (e.g. Finland. France and Sweden are now at the stage of developing full-scale geological repositories for permanent isolation of high level waste.

Overall, the US has moved from being at the international forefront of rock mechanics in the 1950-60's, to a significantly weaker position today. Other groups, such as COMRO, once a world leader in mining, rock mechanics and rock engineering R&D have now contracted significantly[33] - especially in hard rock mining. Asian countries, led by China, are moving forward.

US International Collaboration in Rock Mechanics.

Formation of the ISRM in 1962 led the US National Academy of Sciences to establish the US National Committee on Rock Mechanics [USNC/RM (ca 1965)] which then became the official US National Group affiliated with ISRM.[34]

The Third ISRM Congress, Denver, Sept. 1-7, 1974, is the only one ever held in the United States. The US Bureau of Mines was the principal sponsor. The US Corps of Engineers and Bureau of Reclamations were also actively involved in organization of the Congress.

The Congress included five themes. 1-Physical Properties of Intact Rock and Rock Masses. General Reporter J.Bernaix (France); 2. Tectonophysics; A.Nur (USA); 3. Surface Workings; E. Hoek (UK) and P. Londe, (France); 4.Underground Openings ; M.D.G. Salamon;(RSA); 5. Fragmentation Systems C. H. Johansson (Sweden) . The General Reports provide excellent summaries of the State of the Art of Rock Mechanics, internationally, in the early 1970's.

This is the only ISRM Congress at which Tectonophysics was included as a major Theme.

The Swedish-American Stripa project (1978- 1992) was an early joint initiative –the brainchild of Prof. Ingvar Janelid, Prof. of Mining Engineering, (KTH) Royal Swedish Technological Institute, Stockholm, and Dr. Paul Witherspoon, Lawrence Berkeley National Laboratory.[35] This marked the start of a lengthy involvement by the US Department of Energy, through its National Labs, in international research on geological isolation of high –level radioactive waste. The 2001 publication *Geological Challenges in Radioactive Waste Isolation*: *Third worldwide review* P. A.Witherspoon and G.S.Bodvarsson, Editors, Lawrence Berkeley National Lab[36]. provides a comprehensive overview of the status of geological isolation of nuclear waste in 32 countries worldwide. Although the US waste isolation program is now essentially 'on hold', LBNL has continued to maintain contact and awareness of international developments in this important aspect of subsurface engineering. The August 2015 report *Challenging Issues for Nuclear Waste Disposal in Deep Geological Formations: Status Report on Fifth Worldwide Review* is the latest. [37]

Overall, rock mechanics in the mid - 1950's and 60's was characterized by vigorous development both internationally and in the US. Support by government (USBM, NSF, DARPA, Corps of Engineers…) and industry-stimulated university research.

Very few Civil Engineering programs in the US include rock mechanics/engineering as a component of the curriculum[38].

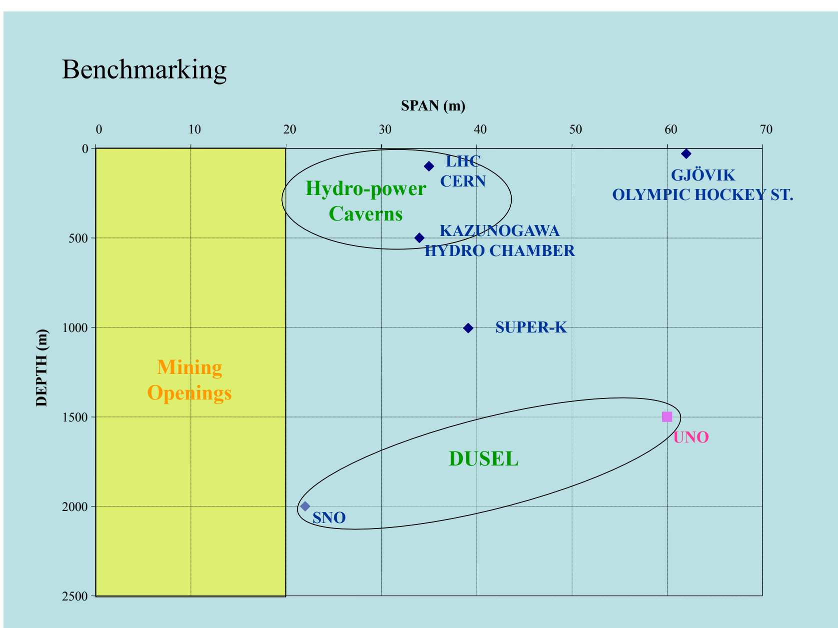


Figure 1. *DUSEL and Similar Physics Projects Need Deep Caverns of Unprecedented Span. Physicists seeking to develop underground research laboratories for neutrino and related studies are keen to establish the feasibility of creating underground excavations at depth larger than any excavated for mining or civil engineering purposes to date.*

DUSEL (The Deep Underground Science and Engineering Laboratory) was a proposal, (ca 2005) stimulated by the National Science Foundation, Mathematics and Physical Science Division and university physics groups, together with the US Department of Energy, through its National Laboratories, to develop a deep underground facility to study neutrino scattering, dark matter etc.

The abandoned Homestake Mine, Lead, South Dakota, was selected to be the site to establish DUSEL. Earth scientists were invited to participate. A report *Geo-Science and Geo-Engineering Research at DUSEL*, December 5, 2006 was prepared and submitted to NSF. A copy of this report can be accessed at the website http://bit.ly/2cNB8tq

Eventually, in September 2011, NSF formally withdrew from the DUSEL project.[39] It is now being carried forward at a reduced level, as the Sanford Laboratory[40], funded by the State of South Dakota and DOE –principally for physics experiments. Rock mechanics experiments are still possible, but must seek funding from other sources. US university research in rock mechanics/engineering is now dependent primarily on the National Science Foundation. Funding is typically of the order of $1-2 million/yr nationally.

The recent (late 2014 –present) dramatic drops in global prices for both petroleum fuels and minerals has forced draconian cuts in funding of research, and layoffs of staffs in US petroleum R&D laboratories. This exacerbates an already serious situation for US rock mechanics. Global mining companies have eliminated virtually all funding for industry-supported university research centers world –wide. Although none of these mineral-industry Centers was located in the US, they illustrate that the ultimate responsibility of a private company is to its shareholders (as it should be) and not to the welfare and security of society in general. This broader concern is a duty of government, both National and State.

Related Advances in Technology. 1956-2016

The developments in Rock Mechanics described above, occurred against a backdrop of remarkable advances in other branches of science and engineering. The International Geophysical Year[41] started July 1, 1957 but came to world attention in dramatic fashion when, on October 4,1957, the Soviet Union successfully launched Sputnik 1, into Earth orbit. This stunned the US, leading President John F. Kennedy to launch the Apollo program, which culminated in astronaut Neil Armstrong stepping onto the surface of the Moon on July 20 1969.[42] – and the dawn of the Space Age [43]. Subsequent developments have brought changes that certainly could not have been imagined, even in 1969 – changes that are continuing. The importance of Engineering, and the challenge of implementing scientific discovery for public benefit, was recognized by the formation of the US National Academy of Engineering in 1964 as "*a private, independent, nonprofit institution that provides engineering leadership in service to the nation*."[44]

The development of medical imaging techniques MRI[45] and CT[46] in the 1970's and on was bringing dramatic change to the practice of Medicine. Concern was also rising that some developments of the Industrial Revolution were resulting in serious harm to the global environment. In the US, the Environmental Protection Agency (EPA) was established in 1971. 'Climate Change'[47] was becoming an important topic of discussion and concern, both within the US and internationally.[48] It is now widely accepted internationally as the leading global technological issue.[49]

In 1995, the US Bureau of Mines was closed by the US Congress; *"almost $100 million, or 66%, of its 1995 programs ceased"*[50] [i.e. equivalent to $158 million/yr in 2016] Some Health and Safety topics were transferred to NIOSH (National Institute for Occupational Safety and Health) a division of the CDC (Center for Disease Control.)

In July2006, Dr Charles Vest was elected President of the NAE. One of his first actions was to convene an International Committee of distinguished engineers and scientists, with former US Secretary of Defense William H.Perry as Chairman, to identify the leading Grand Challenges in Engineering.

Dr. Vest defined a 'Grand Challenge' as *"one that is "visionary, but do-able with the right influx of work and resources over the next few decades"— a challenge that, if met, would be 'game-changing' and have a "transformative" effect on technology."*

The Committee published its report *Grand Challenges in Engineering* in 2008. Fourteen challenges[51] were identified, including four that have a direct connection to both extraction and use of Earth resources viz; *sequestering carbon dioxide; providing access to clean water; managing the nitrogen cycle; restoring and renewing the urban infrastructure*.

Informally, Committee members acknowledged that a different committee may well have chosen a different set of such Challenges, and encouraged colleagues to give further thought to the general topic.

In reviewing the 2008 report, NAE Section 11 (Earth Resources Engineering) members were concerned that the Committee had overlooked grand challenges of Subsurface Engineering. A Committee of Section 11 members was formed to address this oversight.

Four Challenges were identified

- Transparent Earth
- Coupled Processes,
- Minimally Invasive Mining
- Protection of the Environment and the Public.

A brief discussion of these four Challenges was included as part of the HFJ January 2017 issue pp. 33-34

As with the comment above re the 14 Grand Challenges, a different Section 11 Committee might well have arrived at a different – or more extensive – series of Grand Challenges in Earth Resources Engineering.

The comments by of the 16th Century scholar Agricola [52] are as true today as when written

> "*None of the arts is older than agriculture, but that of metals* [minerals]* *is no less ancient...for no mortal man ever tilled a field without implements.* …………………
>
> *If we remove metals from the service of man, all methods of protecting and sustaining health and more carefully preserving the course of life are done away with.*
>
> *If there were no metals, men would pass a horrible and wretched existence in the midst of wild beasts; they would return to the acorns and fruits and berries of the forest.*
>
> *They would feed upon the herbs and roots which they plucked up with their nails.*
>
> *They would dig out caves in which to lie down at night, and by day they would rove in the woods and plains at random like beasts, and inasmuch as this condition is utterly unworthy of humanity, with its splendid and glorious natural endowment, will anyone be so foolish or obstinate as not to allow that metals are necessary for food and clothing and that they tend to preserve life?*
>
> *Agricola (1555)*

* As noted by (former US President) Hoover[53] , in his 1912 translation of Agricola's original Latin text, 'metals' and 'minerals' were synonymous terms in the 16th century.

………

The following comments are indicative of the consequences of this lack of Federal research support

> *"Chronic underinvestment in federal R&D in these subsurface [engineering and geosciences] disciplines has eroded the nation's capacity to educate and train the next generation workforce necessary for industry, academia, and government. As a result, the U.S. faces the prospect of ceding its historic leadership role in these disciplines, and thereby undermining its resource security."*[54]
>
> *".in geo-engineering the funds available for unsolicited investigator-driven research appear to have diminished almost to the point of disappearance"* [55]

In raising this as an issue that should be of concern to the US, it is not unusual to hear the response

> *"This country cannot be the world leader in everything; we must make choices"*

Is it wise therefore to choose to withdraw from the world stage in minerals and related sub-surface technologies? The writer submits that it is, in fact, foolish –and can lead to serious consequences.

Consider, for example, the current national concern with respect to manufacturing

Manufacturing and Minerals

Considerable emphasis is given today to the importance of maintaining/redeveloping a strong manufacturing activity in the United States, as illustrated by the following extract from the 2013 study *"21st Century Manufacturing: The Role of the Manufacturing Extension Partnership Program"* by the US National Research Council

> *"Manufacturing companies in the United States are responsible for over two-thirds of the industrial research and development (R&D), employing the majority of domestic scientists and engineers. Furthermore, manufacturing R&D is a primary source of innovative new service-sector technologies, so that its benefits reach beyond the manufacturing arena."* [56]

Remarkably, little attention is given to the fact that the foundation of the majority of all manufacturing -with the exception only of that part dependent on renewable sources- is an assured supply of mineral resources.

Currently, the US is heavily dependent on imports of minerals. As noted in the Mineral Commodity Summaries 2016 (page 7), published annually by the US Geological Survey,

> *"In 2015, imports made up more than one-half of the U.S. apparent consumption of 47 nonfuel mineral commodities, including some reported only as greater than 50%. The United States was 100% import reliant for 19 of those……. China, followed by Canada*, supplied the largest number of nonfuel mineral commodities." [57]

The concern in 2010 that China, at the time responsible for almost the entire world supply of Rare Earth's, would cease to export them, caused alarm in the US.

> *"Everything from smartphones to iPods to missile systems requires rare earths. Almost every piece of high tech gadgetry contains some combination of rare earths to make volumes louder, E-mails vibrate, and bombs able to hit their targets. Nations that control rare earth production own one of the most capable economic and national security levers in the modern world. Over the last quarter century, that lever has been controlled overwhelmingly by China".*[58]

The complexity of the mineral supply issue is illustrated by the story of the Rare Earth's mine in California - reopened after the 2010 alarm, but now likely to close.[59]

The US Office of Science and Technology has recently started an "*….interagency assessment of critical minerals, intended to indicate what minerals pose a potential risk of being or becoming critical based on availability and susceptibility to supply disruption".*[60]

Minerals are Distributed Globally.

The example of Rare Earths illustrates a key issue with respect to minerals. They occur in geological formations around the world, and are not 'automatically accessible' to the US. How then can the US assure an adequate supply of minerals to sustain its economy?

The most reliable strategy is to ensure that the US is the recognized global leader in Earth Resources Engineering.

Anyone engaged in extraction of mineral resources world –wide will want to use the latest, most cost –effective technology world-wide. Being this leader will provide the US substantial influence in the global mineral resources field. "*Knowledge itself is power.*"[61]

Earth Resources Engineering is a key central component of other major international issues –most notably Global Climate Change. (See Addendum)

The US Department of Energy (DOE), through its National Laboratories, has taken excellent first steps towards development of US technological expertise in Earth Resource Engineering by

1) Requesting the evaluation 'Subsurface Characterization,'[62] (September 2014) by the Jason group. The Jason report resulted in the following conclusion;

   "Our overarching finding is that in addition to the engineered subsurface being important in several of DOE's[63] *mission areas, the science appears ripe for breakthroughs. Disparate research communities working in related areas can benefit from increased coordination (academia, industry, multiple government agencies), and DOE has specific capabilities that can effect these advances. We therefore recommend that DOE take a leadership role in the science and engineering needed for developing engineered subsurface systems."*

2) Developing the program SubTER. The overall goal of this ambitious program, i.e. "Adaptive Control of Subsurface Fractures, Reactions and Flow' is summarized in Figure 2 below.

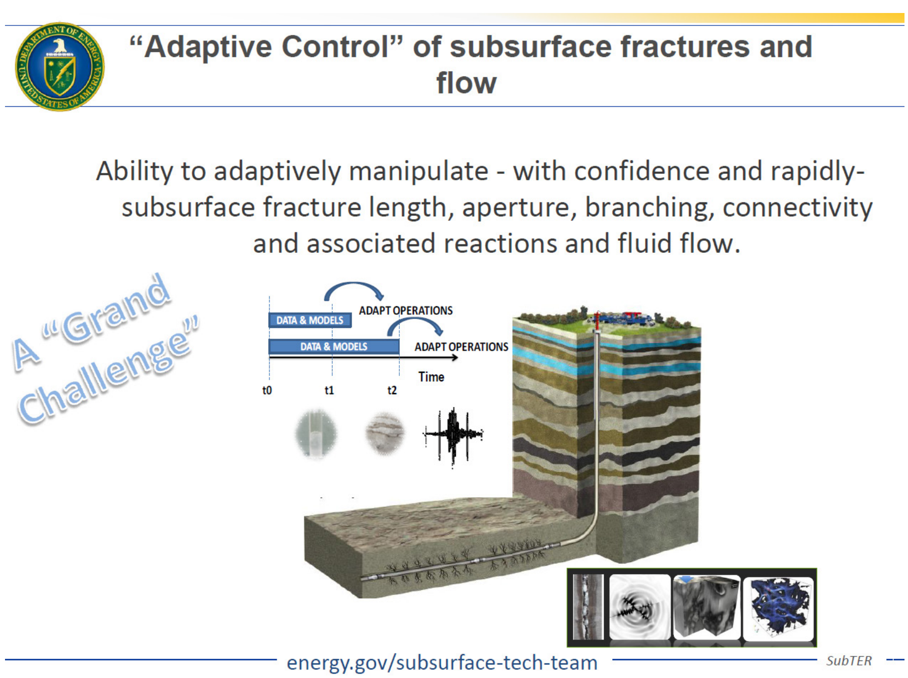


Figure 2. *Adaptive Control of Subsurface Fractures, Reactions and Flow.*

after Dr.M.Walck (Sandia National Laboratory) Courtesy of DOE Geothermal Technologies Office

Numerous key developments are implicit in moving towards the ultimate goal of adaptive control.

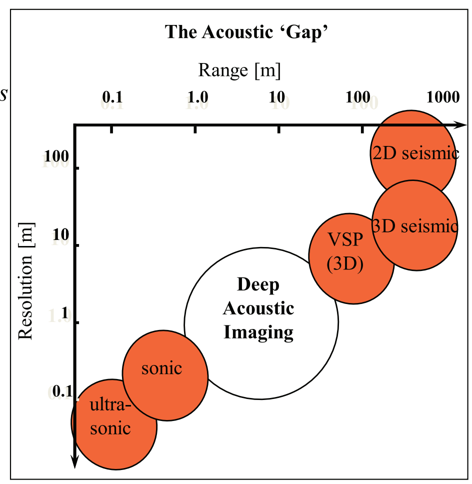
The following are examples of many.

- The major advances of remote-controlled directional drilling in sedimentary rock, as encountered in petroleum reservoirs, must be developed for drilling in the even more challenging environment of hard crystalline rock at depths of the order of 6km and temperatures of the order 150°C-200°C. This implies more robust drilling tools, and improved understanding of drill-string dynamics.
- Development of effective strategies for extraction of geothermal energy in naturally fractured rock, and development of systems economically competitive with other commercial sources of power. This implies integration of understanding of fractured rock systems gained in civil and mining engineering with the borehole-based monitoring systems of petroleum engineering
- Development of rapid feedback between predicted and observed subsurface stimulation response to allow real-time modification of the stimulation parameters.
- Lack of data on key parameters of a rock mass (e.g. natural fracture network orientations and variability, joint properties, intact rock strength, thermal behavior; etc.) suggest that extensive parametric studies will be needed in advance of field tests in order to establish strategies for faster, informed decisions in the field.

....

Figure 3 below is taken from a 2012 paper ilustrating the range of radial distance from a borehole for which petroleum engineers have developed different geophysical techniques to help 'visualize' the rock mass.The white circle, covering the range of the order of 1m-50m radius around the borehole is the one least developed to date. This is the region with which civil and mining engineers are most familiar. This suggests the value of interdisciplinary collaboration between these disciplines –and taking advantage of direct access to the subsurface of mines and civil engineering operations, including direct underground laboratory experiments.

- *Reflections from monopole receivers have been used to successfully image structure and fractures*
- *Depth of investigation can vary greatly, but can be **as much as 140 ft on each side of the borehole.***
- *Bridges the resolution gap between wireline and seismic data.*
- *Complementary data from Stoneley mobility, Anisotropy, Rock properties and potentially Radial Profiling can be acquired in the same pass.*



D.Grael et al; "Borehole Acoustic Reflection Survey (BARS) from Modern, Dipole Acoustic Logs for High-Resolution Seismic-Based Fracture Illumination and Imaging"* SPWLA (Soc. Petrophysicists and Well Logging Analysts), 53rd Annual Logging Symposium, June 16-20, 2012 Cartagena , Columbia .

* *D. Grae, G. A. Ugueto C., J. A. Roberts, H. Yamamoto, T. Oliver and G. Martine*

Figure 3. *Geophysical Techniques used to Image Rock at Various Scales.*

University Interdisciplinary Centers of Excellence in Earth Resource Engineering.

As already noted, there are currently few US university programs in mining engineering or geo-engineering. Petroleum engineering is somewhat better placed, but the recent severe downturn in petroleum markets is having seriously adverse effects on placement of graduates and research support.

The need for the US to be in the forefront of subsurface engineering technology, in order to maintain influence and 'a place at the table' in discussions of allocation of essential mineral resources, has already been noted.

Although the US generates far fewer engineers than is currently the case in many other countries[64], US graduate programs in science and engineering have been a magnet for outstanding engineers from other countries for many decades. Many opt to stay and have contributed in a major way to US pre-eminence in many fields. This was described eloquently, for example, by former NAE President William Wulf [65]

Federal Office of Earth Resource Engineering.

Closure of the US Bureau of Mines in 1995 eliminated approximately $160 million/yr in research on Mineral Resources. Allocation of a similar amount to establish a Federal Office of Earth Resources Engineering would allow, say $130 milion/yr, as a start-up amount for a Federal Office (Funds could be augmented e.g. by requirement of matching industrial support, as in Canadian and Australian programs) plus six University interdisciplinary centers each funded at $5 million/yr.

Given

- the relevance of the research of these Centers to major global problems of the 21st Century, including Climate Control;
- the central importance of US leadership in mineral resources engineering as a way to ensure access to the raw materials essential to industry and national defense systems,
- the availability of knowledge developed in other branches of science and engineering during the past several decades to advance Earth Resources Engineering,

the proposed Centers program should receive Congressional support.

Recognition of the value of interdisciplinary dialog and collaboration between geoscientists and geoengineers is not new. In 1990, Scholz [66] observed,

"It is a consequence of the way in which science is organized that the scientist is trained by discipline, not by topic, and so interdisciplinary subjects such as this one[67] tend to be attacked in a piecemeal fashion from the vantage of the different specialties that find application in studying it. This is disadvantageous because progress is hindered by lack of communication between the different disciplines, misunderstandings can abound, and different, sometimes conflicting schools of thought can flourish in the relative isolation of separate fields. Workers in one field may be ignorant of relevant facts established in another, or, more likely, be unaware of the skein of evidence that weights the conviction of workers in another field. This leads not only to a neglect of some aspects in considering a question, but also to the quoting of results attributed to another field with greater confidence than workers in that field would themselves maintain. It is not enough to be aware, secondhand, of the contributions of another field - one must know the basis, within the internal structure of the evidence and tools of the field, upon which that result is maintained. Only then is one in a position to take the results of all the disciplines and place them, with their proper weight, in the correct position of the overall jigsaw puzzle."

Echoing essentially the same sentiment in his recent book, "*Elements of Crustal Geomechanics*,"[68] Cornet observes,
"Today, Geocientists and Geoengineers must speak the same language."

The need for this broad interdisciplinary approach, and the urgency of moving forward are discussed further in the opening comments 'The Path Forward' in this issue of HFJ.

In closing this discussion of rock mechanics developments over the past sixty years, it is important to note that there has been progress –less than might have been projected had the enthusiasm and support of the 1960's had been sustained - but still progress that should not be overlooked.
A valuable compilation of accomplishments to that time is provided by the 1993 publication

Comprehensive Rock Engineering (1993)J.A. Hudson Editor-in-Chief ; Senior Editors E.T. Brown, C.Fairhurst & E.Hoek. Five Volumes (Vol. 1- Fundamentals; Vol.2 -Analysis and Design Methods; Vol.3 –Rock Testing and Site Characterization; Vol.4 - Excavation ,Support and Monitoring; Vol. 5 - Surface and Underground Project Case Histories. Pergamon Press (Oxford), 1993.

"200 authors from 25 countries, the leading experts in each relevant area, have ensured authoritative coverage of all the main aspects of rock mechanics and rock engineering."

An update to this major effort has been prepared by Professor Xia- Ting Feng (ISRM President 2011-2015) and is scheduled to appear later this year.

Rock Mechanics and Engineering(2017) Xia-Ting Feng (Editor) *(Five Volumes) CRC Press (Forthcoming 2017) https://www.crcpress.com/Rock-Mechanics-and-Engineering-5-volume-set/Feng/p/book/9781138027640*

Endnotes

1 Now an annual event, interrupted only in years of ISRM Congresses and the occasional "North American Rock Mechanics Symposium. (NARMS), held jointly with Canada and Mexico.

2 WWII was preceded by a lengthy era of global depression. https://en.wikipedia.org/wiki/Great_Depression

3 Cold War (1947- 91) The era of mutual suspicion between the USA and the USSR, that the two main technological developments of WWII – the atomic bomb and intercontinental ballistic missiles - would be developed for use by one country against the other . See also https://en.wikipedia.org/wiki/Cold_War Fighting in the Korean War (1950- 1953) had also ended.

4 http://www.therobbinscompany.com/en/about/history/ See also https://en.wikipedia.org/wiki/Oahe_Dam and https://en.wikipedia.org/wiki/Tunnel_boring_machine

5 In South Africa *"over 69,000 mineworkers had died and more than a million were seriously injured –with over 60% of gold mining fatalities due to rockbursts or rock falls" from 1900-93. http://www.klasslooch.com/leon_commission_of_inquiry.htm*

6 https://www.oegg.at/en/the-oegg-2/the-oegg-2/ See also Fourth Int'l Meeting, Int'l Bur. Rock Mech. Leipzig. Int'l. J. Rock Mech. Min.Sci. Vol. 1- pp 117-126 , Pergamon 1963. This group, emphasizing mining in stratified deposits e.g. coal, bedded salt, was disbanded after German re-unification in 1990

[7] Founded in Harvard, Mass, in 1936, ISSMFE was inactive during WWII. It has since been renamed the International Society for Soil Mechanics and Geotechnical Engineering,(ISSMGE)
[8] Salzburg Circle members became ISRM founder members.
[9] This was the second NAS committee to deal with rock mechanics; from 1945 until 1949, the Committee on Experimental Deformation of Rocks, under the chairmanship of Dr. Eleanora B. Knopf, formulated and co-ordinated a program for systematic research on the mechanisms of rock deformation and assisted in establishing and fostering research on rock deformation in various laboratories in the United States.

The Highway Research Board (NRC Division of Engineering) has an active Committee on Soil and Rock Properties (SGF–C2) that has just completed a list of research needs in the area of rock mechanics. The list will soon be published as a part of a highway research circular (Appendix J)
[10] Wyndham, C. N. and N. B. Strydom (1969) *Acclimatizing Men to Heat in Climatic Rooms on Mines.* J. So. Afr..Inst. Min. Met. Oct 1969, pp 60-64 https://www.saimm.co.za/Journal/v070n03p060.pdf NASA scientists consulted Dr.Wyndham in the early stages of the Apollo program to discuss the effects of hostile working environments on Man.
[11] Directed by Drs. N.G.W. Cook and M.D.G. Salamon. respectively (then recent Ph.D. graduates) [Dr Cook joined UC Berkeley in 1976; Dr Salamon joined Colo. Sch. Mines in 1986.]
[12] Cook, N.G.W., Hoek, E., Pretorius, J.P.G., Ortlepp, W.D. and Salamon, M.D.G. 1966. *Rock mechanics applied to the study of rockbursts.* J. S.

Afr. Inst. Min. Metall. 66: 435-528. See also R.J. Durrheim *Mitigating the risk of rockbursts in the deep hard rock mines of South Africa: 100 years of research* http://africaarray.psu.edu/publications/pdfs/SME100_Durrheim_Rockburst%20research.pdf
[13] https://en.wikipedia.org/wiki/Kolar_Gold_Fields
[14] See e.g. *Krishnamurthy*, *R*; Shringarputale, S B. (1988) .Rockburst Hazards in Kolar Gold Fields.. Proc. 2nd Int'l Symp. .R*ockbursts & Seismicity in Mines*, *Minneapolis*, 8–10 June 1988, pp 411–420.1
[15] See *RaSiM Comes of Age—A Review of the Contribution to the Understanding and Control of Mine Rockbursts* W.D. Ortlepp .. March 7-9 2005 http://www.acg.uwa.edu.au/__data/page/2147/Ortlepp_keynote_web.pdf.
[16] Dr Hoek's many contributions to rock mechanics and rock engineering are documented on the RocScience website https://www.rocscience.com/learning/hoek-s-corner
[17] http://www.csiro.au/en/Research
[18] http://www.arrc.net.au/
[19] https://en.wikipedia.org/wiki/Cooperative_Research_Centre http://www.crcmining.com.au/
[20] http://www.nrc-cnrc.gc.ca/eng/
[21] Chief, USBM Applied Physics Laboratory; and ISRM President (1970-74)
[22] This book reports extensively on results of photoelastic studies of stresses around mine openings. The now classic Jaeger J.C. and N.G.W Cook *Fundamentals of Rock Mechanics* ,
[23] http://www.osti.gov/scitech/servlets/purl/915351 See also - Oil Shale Mining (1944-56) USBM Bulletin 611,1964 http://digicoll.manoa.hawaii.edu/techreports/PDF/USBM-611.pdf
[24] https://en.wikipedia.org/wiki/Partial_Nuclear_Test_Ban_Treaty
[25] https://en.wikipedia.org/wiki/Peaceful_nuclear_explosion
[26] https://en.wikipedia.org/wiki/Operation_Plowshare
[27] http://conservancy.umn.edu/handle/11299/162862 (Emphasis is on rock mechanics and hydrology aspects of underground nuclear testing)
[28] See http://www.nap.edu/catalog/10294/the-disposal-of-radioactive-waste-on-land

The Plutonium isotope Pu_{239} for example, has a half-life of 24,100 years – thus requiring almost 100,000- years to decay to $(½)^4$ = 6% of its initial radiation intensity. No fabricated container cam be shown to have a longevity approaching 10,000 years – a very small fraction of the hundreds of millions of years age of most rocks.
[29] https://en.wikipedia.org/wiki/Waste_Isolation_Pilot_Plant
[30] https://en.wikipedia.org/wiki/Yucca_Mountain_nuclear_waste_repository
[31] http://pubs.usgs.gov/of/2013/1245/pdf/of2013-1245.pdf
[32] The two-volume book *Waste of a Mountain* (2016) by Donald Vieth and Michael Voegele provides a detailed chronology of the political and scientific issues associated with this project. Copies are available from Pahrump Library Press, Nevada.
[33] http://www.saimm.co.za/journal-comments/349-mining-research-in-south-africa
[34] The American Rock Mechanics Association (ARMA) was founded in 1996 when the US National Academy of Sciences, decided to eliminate a number of its smaller national committees. The US National Committee on Tunneling Technology (USNCTT) was disbanded at the same time.
[35] See (i) http://hydrology.agu.org/wp-content/uploads/sites/19/2016/06/Witherspoon-eScholarship-UC-item-19s822js.pdf (ii) http://www.nrc.gov/docs/ML0317/ML031740689.pdf
[36] Publication Date: 12-01-2001 Permalink: http://escholarship.org/uc/item/8k17r675
[37] https://publications.lbl.gov/islandora/object/ir%3A188432/datastream/PDF/view
[38] There are several notable exceptions.
[39] http://northernbeacon.blogspot.com/2011/09/dusel-is-dead-long-live-neutrino.html
[40] https://en.wikipedia.org/wiki/Sanford_Underground_Research_Facility
[41] https://en.wikipedia.org/wiki/International_Geophysical_Year
[42] The cost of the Apollo program was reported to Congress as $25.4 billion in 1973 (or ~$138 billion in 2016 dollars).
[43] http://history.nasa.gov/sputnik/

[44] The US National Academy of Science had been established by order of President Lincoln in 1863 http://www.nasonline.org/about-nas/history/?referrer=https://www.google.com/
[45] https://en.wikipedia.org/wiki/Magnetic_resonance_imaging
[46] https://en.wikipedia.org/wiki/CT_scan
[47] https://en.wikipedia.org/wiki/History_of_climate_change_science
[48] https://en.wikipedia.org/wiki/Kyoto_Protocol
[49] http://unfccc.int/paris_agreement/items/9485.php
[50] https://en.wikipedia.org/wiki/United_States_Bureau_of_Mines
[51] See http://www.engineeringchallenges.org/challenges.aspx
[52] https://en.wikipedia.org/wiki/Georgius_Agricola
[53] https://en.wikipedia.org/wiki/De_re_metallica
[54] (U.S. Dep't of Energy, 2009) Energy Research and Development (Document END09278) Strengthening Education and Training in the Subsurface Geosciences and Engineering for Energy Development; Section 33, Subtitle C p.3
[55] US National Resources Council NRC 2006. Geological and Geotechnical Engineering in the New Millennium.(p.150)
[56] Extract from Preface http://www.nap.edu/read/18448/chapter/1#xi
[57] http://minerals.usgs.gov/minerals/pubs/mcs/2016/mcs2016.pdf
[58] http://www.usnews.com/opinion/blogs/world-report/2012/11/20/the-us-needs-rare-earth-independence-from-china
[59] https://www.hcn.org/articles/the-u-s-s-only-rare-earth-mine-files-bankruptcy
[60] https://www.whitehouse.gov/sites/default/files/microsites/ostp/NSTC/csmsc_assessment_of_critical_minerals_report_2016-03-16_final.pdf
[61] "*ipsa scientia potestas est*" ('knowledge itself is power') *Meditationes Sacrae* (1597) Francis Bacon See https://en.wikipedia.org/wiki/Scientia_potentia_est
[62] Subsurface Characterization (September 2014) JSR -14-Task-013 http://www.energy.gov/sites/prod/files/2014/09/f18/2014%20SubTER%20JASON%20Report_1.pdf An earlier JASON report on 'Enhanced Geothermal Systems' (Dec.2013) JSR-13-320 identified other subsurface development challenges and opportunities in rock mechanics. http://www1.eere.energy.gov/geothermal/pdfs/jason.final.pdf
[63] U.S. Department of Energy
[64] http://armarocks.org/documents/newletters_r2/2015_issue_14_winter.pdf See discussion p18 *Mechanics and Rock* pp7-19
[65] (see Attachment).
[66] Extract from Scholz, Christopher, H (2002). *The Mechanics of Earthquakes and Faulting*, Cambridge Univ. Press. 471p. Preface to First Edition (1990), reprinted in the Second Edition.
[67] Although the primary focus of Professor Scholz's book is on *The Mechanics of Earthquakes and Faulting*, his comments apply to rock mechanics in general. As he notes later in his Preface "…*my own specialty is rock mechanics and so this approach is the one most emphasized in this book.*"
[68] F.H. Cornet. (2015) *Elements of Crustal Geomechanics,* Cambridge University Press.

Biography

Charles Fairhurst, Professor Emeritus, University of Minnesota, Minneapolis, USA; Senior Consultant, Itasca International Inc. Minneapolis, obtained his Ph.D. in Mining Engineering from the University of Sheffield, UK in 1955. He joined the University of Minnesota faculty, School of Mines and Metallurgy in 1956, serving as Head for several years to 1970, when the Mining program was joined with Civil Engineering to form the Department of Civil and Mineral Engineering. He served as Head of the joint Department from 1973-87, and retired in 1997.

He has consulted on rock stability problems for tunnels, dams, mines and excavations throughout the world. He remains active in consulting, with a current emphasis on the mechanics of fracture propagation in naturally fractured rock and the effective stimulation of geothermal reservoirs. He served as President of the International Society for Rock Mechanics from 1991-1995, and has been elected to the U.S. National Academy of Engineering (1991) and the Royal Swedish Academy of Engineering Sciences (1979). He is a Fellow of the American Rock Mechanics Association.

Dr. Fairhurst holds honorary doctorate degrees from the University of Nancy, France; St. Petersburg Mining Academy, Russia; University of Sheffield, England; and University of Minnesota, USA; and is Advisory Professor to Tongji University, Shanghai, China.

In December, 2013, he was inducted as Officier, Légion d'Honneur, France.