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In this issue

ARMA LETTERS

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Editor's Note

Haiying Huang, Interim Editor

Time flies! It has been twelve years since the inaugural issue of ARMA e-Newsletter was published in Fall 2010. What started as a modest undertaking has now flourished and become a flagship publication of ARMA. Over the years, much has changed. The earlier issues typically included one or two featured technical notes together with reports of the annual symposium and an assortment of news items. Since Spring 2014, various initiatives were undertaken to expand the technical notes section. The outcome was eleven special issues consisting of both unsolicited and solicited articles in various themes. The triannual ARMA e-Newsletter was consequently renamed ARMA Letters in Fall 2018 to reflect this emphasis on publishing the newest developments of most interest to our members in the field of rock mechanics/ geomechanics. In the last few years, the so-called "special" issue has in fact become the norm. In addition, ARMA Letters also published a series of reflections of our pioneers on their lives careers, and tributes honoring our colleagues and friends. These have showcased the role of the Letters in building strong bonds in our community.

Tribute to Bezalel Haimson

We owe all this success primarily to Professor Bezalel Haimson. As the Editor-in-Chief, he worked tirelessly to reach out and solicit technical articles. He kept members of the publication committee and special issue editors on their toes in order to maintain a rigorous review process and timely publication schedule. His uncompromising focus on quality is the reason that ARMA Letters more than stayed relevant in this fast-paced digital age.

We dedicate this special issue to Bezalel to honor his distinguished career and to share his extraordinary life stories. This issue consists of two parts. The first half includes tributes written by Bezalel's former students: Thomas Doe, Paul LaPointe, Chandong Chang, Insun Song and Xiaodong Ma. They present their personal reflections of Bezalel as a researcher, educator, mentor and colleague, as well as the long-lasting impact of Bezalel's research on using hydraulic fracturing and wellbore breakout for *in situ* stress measurement and on the development of true triaxial testing. The article on Bezalel's early life from me was primarily based on a sit-down interview conducted by Judith Pierotti of Voice Treasures. In the second half -- as Bezalel would certainly not like to see the usual business of producing a newsletter being interrupted -- we bring you the Santa Fe reports of the 56th ARMA Symposium by Douglas Blankenship and DFNE 2022 by Sergio Sarmiento.

Prospects for ARMA Letters

As for the prospect of the Letters, earlier this year an ad-hoc Strategic Committee on Journal Publication, led by Professor Herb Wang of the University of Wisconsin, took a comprehensive look at the ARMA publication portfolio. They recommended to enhance ARMA Letters as ARMA's news magazine. A new editorial team, consisting of a chair, a lead editor, one member representing each of the major technical areas relevant to ARMA and one member of the Future Leaders should be formed. We therefore call upon all of our readers to volunteer if you are interested. Details on the duty and term of service will be announced soon. I will serve as the Interim Editor until the new editorial team is formed and approved by the ARMA Board.

So, please stay tuned!

Haiying Huang, Interim Editor

Reflections on a Successful Career in Rock Mechanics

Submitted by Thomas Doe, Golder Associates (WSP-Golder)

I am pleased to provide a contribution to this special issue of ARMA Letters celebrating the successful career of Bezalel Cecil Haimson. I was surprised to look at the calendar and realize that it was nearly fifty years ago in 1973 that I walked into Professor Haimson's office at the University of Wisconsin to see if it was possible for a geology graduate student without engineering prerequisites to take his rock mechanics course. Unlike other professors in the College of Engineering, Professor Haimson welcomed me with open arms, and my life has not been the same since.

What defines a successful career?

- For an engineering academic, success is how one's work has improved the way we design and build things;
- For a scholar in the geosciences, success is how one's work has changed the way we understand the earth;
- For a consulting engineer, it is how one's work has helped our clients achieve their project objectives safely and within cost;
- For a member of an engineering profession, success is how one has facilitated networking, information sharing, and promoting best practices in our chosen field;
- For an educator, success is how one's teaching has positively changed lives of their students.

Most people in our field can be satisfied if they have achieved one or two of these success measures. This article asserts that Bezalel Haimson has achieved *all* of them.

Engineering Academic

As an engineering academic, Bezalel Haimson's work in rock stress measurement,

borehole breakouts, true triaxial testing and more has proven transformative. When Professor Haimson began his graduate studies in the 1960's, rock mechanics was a technical discipline in its infancy. The International Society for Rock Mechanics had just been formed in the aftermath of the terrible dam disasters at Vajont in Italy and Malpasset in France. ARMA was multiple decades away from its inception, and at the University of Minnesota, Professor Charles Fairhurst was assembling a remarkable cadre of students funded in part by contracts with U.S. Army Corps of Engineers to solve one of the stickiest problems in rock structure design -- understanding and measuring the rock stresses at distances deeper than ten meters or so. In addition to Bezalel Haimson, the group included John Hudson, "Fritz" Rummel, François Cornet, Bill Hustrulid, Jean-Claude Roegiers, and Hilmar Von Schönfeld -- among others. To have been a fly on the wall in that grad student office!

Bezalel Haimson's PhD dissertation tackled the question of poroelastic effects on breakdown pressure, which he addressed both theoretically and experimentally (Haimson, 1969). After leaving Minnesota, he served a short stint at Halliburton in Oklahoma and then landed at the University of Wisconsin-Madison. There he continued his experimental work and added a field component as one of the key developers of hydraulic fracturing as an effective and accepted means of measuring rock stress.

Bezalel Haimson with Jay Avasthi and Lok Sing Cheung inspecting packers for stress measurements, Waterloo, Wisconsin, 1976 (Photo by Thomas Doe)

Geosciences Scholar

In addition to engineering research, Bezalel Haimson made basic contributions to geosciences. Besides the founding of rock mechanics as an engineering discipline, the 1960's found the earth sciences upended by the new theories of plate tectonics and earthquake source mechanisms. Bezalel Haimson was quick to ascertain the applications of stress measurement to these fields. Armed with a new capability for organizing and interpreting field tests, he was able to perform some of the original work in these areas. Starting with the seminal experiment in earthquake triggering by elevated pore pressure at Rangely, Colorado, for which he did the stress measurements, and deep hole tests in exploratory borehole in the Michigan Basin, the Iceland mid-ocean ridge, and a deep borehole in northern Illinois, among others (Haimson, 1975a, 1975b, 1977), he was a pioneer in this nascent field. Besides ARMA, Haimson has been an active publishing member of the American and European Geophysical Unions.

Engineering Consultant

As a consultant in the mid-1970's, Bezalel Haimson adapted his field capabilities to provide stress measurement services for the design of underground structures. Pacific Gas and Electric Company (PGE), northern California's major power producer, was building one of the first pumped hydroelectric storage and generation projects involving a large underground powerhouse in the USA at Helms Creek in the Sierra Nevada Mountains. Berkeley professor and member of PGE board of advisors, Professor Tor Brekke, strongly recommended Bezalel Haimson to apply hydraulic fracturing stress measurement for the rock mass characterization. This was

the first of many similar critical infrastructure projects performed by Bezalel Haimson. Since that time hydraulic fracturing has become a standard method for pressure tunnel design (Haimson, 1978).

Supporter of the Rock Mechanics Profession

Throughout his career, Bezalel Haimson has been a strong supporter of the professional and academic organizations associated not only with rock engineering but also with earth sciences. With François Cornet, he wrote the ISRM suggested practices for hydraulic fracturing stress measurement and contributed a key chapter to John Hudson's encyclopedic work on rock mechanics (Haimson and Cornet, 2003; Haimson, 1993a). Bezalel Haimson was co-chair with Mark Zoback on a National Academy of Sciences (NAS) workshop on hydraulic fracturing stress measurement in 1981 that produced a seminal NAS proceedings volume (Zoback and Haimson, 1981). Bezalel Haimson further promoted stress measurement through a 1988 workshop, Hydraulic Fracturing Stress Measurements, held in Minneapolis, producing a two-volume proceedings co-edited by Jean-Claude Roegiers and Mark Zoback (Haimson et al, 1988). Bezalel Haimson served on the U.S. National Committee on Rock Mechanics of the National Academy of Engineering, the predecessor of ARMA. He organized and chaired the 34th Symposium on Rock Mechanics in 1993, which still stands as the one symposium which published its proceedings in a refereed journal (Haimson, 1993b). Bezalel Haimson's multi-decade editing of the ARMA Letters is covered in the Editor's Note to this issue.

Educator

Finally, as an educator, Bezalel Haimson has an impressive record of successful graduate students. You will find testimonies to Professor Haimson as a mentor to graduate students elsewhere in this issue. Perhaps his most impressive, outside-the-box achievement was the founding of the University of Wisconsin's Geological Engineering program (GLE). GLE started partly in response to the end of Wisconsin's mining engineering program, of which Professor Haimson was a part. This followed the lead of many other universities in closing those programs in the 1980's and 1990's. According to UW's Emeritus Geotech Prof. Tuncer Edil, "GLE was established in 1988 as a 'virtual' department within the College of Engineering, but with a strong linkage and relationship with the College of Letters and Science. Professor Bezalel Haimson was the founding Chair of the GLE and continued to serve as Chair until 1999. Creation of GLE required broad interdisciplinary faculty participation for the degree program from colleges outside of Engineering (notably, but not exclusively, the College of Letters and Science)." Herbert Wang, of the UW Geosciences Department and longtime GLE faculty member, notes that the creation of such an unusual program, which not only cuts across discipline but even college boundaries, was an effort of nearly a decade requiring approvals at the highest levels of university administration. The GLE program has graduated dozens of students annually since that time. Most graduates

Bezalel Haimson receiving a teaching award, Madison, 2012 (Photo by Moo Lee)

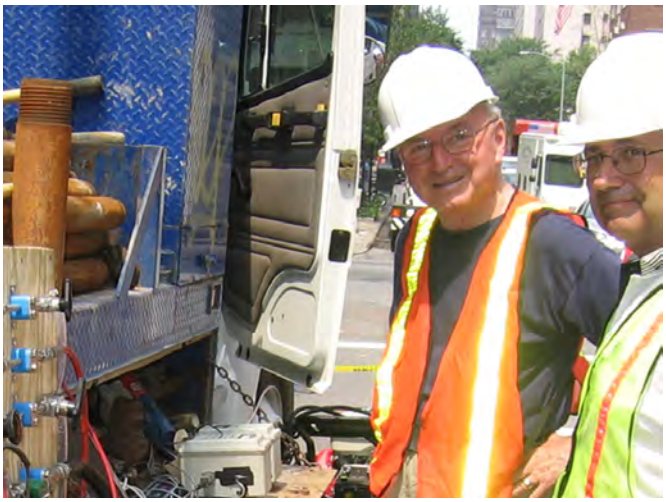
complete dual degrees with Geosciences, and they are in high demand among earth engineering consulting firms and users of earth engineering services.

Because of his illustrious career, Bezalel has received many honors and awards. He has received the 2006 American Rock Mechanics Association Award for Research in Rock Mechanics, the 2000 US National Committee for Rock Mechanics Applied Research Award, the 1997 Society of Mining, Metallurgy and Exploration (SME) Rock Mechanics Award for the development of hydraulic fracturing as an engineering method of *in situ* stress measurement, the 1975 American Society for Testing and Materials (ASTM) Award for contributions to rock and soil mechanics, and the 1970 US National Committee on Rock Mechanics Research Award in recognition for research achievements in rock mechanics for the development of the hydraulic fracturing stress measurement method. He is the editor of three books on rock mechanics, and the author of over 200 professional papers. He was elected as an ARMA Fellow in the first class formed in 2008.

"Tom Doe introducing Bezalel Haimson at the 1st International Reunion (2012) of UW-Madison Geological Engineering alumni (Photo by Moo Lee)".

On a personal note, I am privileged to have had Bezalel Haimson as a mentor, co-consultant, and collaborator over the half-century span that I have known him. I came to the University of Wisconsin-Madison from a liberal-arts geology background with an interest in geological engineering and only a vague idea of how to make that a reality. Bezalel Haimson made that possible and helped with the later connections that built my own career. He has served as a personal role model of how to be a successful rock mechanic.

There is more. Bezalel Haimson is well known as lover of good food. The highlight of any American Geophysical Union meeting (usually December in San Francisco) or ARMA symposium was joining him for dinner at whatever renowned restaurant he had recently discovered in the New York Times. One time he worked with me on a stress measurement project near Fayetteville, Arkansas. Even there, he had scoped out the AAA guides to find the best places to eat.



Testing in New York City for the 2nd Ave. subway, 2005 (Photo by Thomas Doe)

Lunch by the drill rig during testing for the 2nd Ave. subway, New York City, 2005 (Photo by Thomas Doe)

Bezalel Haimson discussing a deep overcoring stress measurement probe with Lars Strindell, Stripa Mine, Sweden, 1980 (Photo by Thomas Doe)

He especially loves New York both for food and for the Met Opera! The photo (previous page) shows the intersection of all these loves. I worked with Haimson in 2005 on stress measurements for the 2nd Avenue Subway (now built and running). Our drilling support rig occupied the sidewalk at East 70th and 2nd Avenue, where a restaurant normally had outdoor dining. I asked if they could set up a table for us next to the drill rig and serve lunch. Now that's field work! My back is to the camera, and the other face besides Bezalel's is Gene Simmons, MIT geophysicist and PhD advisor to fellow Wisconsin Badger, Herbert Wang. Gene was part of the consulting company running the geophysical logs.

The photo above is from a project Bezalel Haimson worked with me for the underground research facility at the Stripa Mine in Sweden,

Betsy and Bezalel visiting Albuquerque in July 2013 (Photo by Moo Lee)

where we did the first hydraulic fracturing stress measurements in Scandinavia in 1980 (later to be greatly superceded by the excellent group under Ove Stefansson). With Haimson was Lars Strindell discussing his deep overcoring probe, the predecessor to the Swedish Borre tool.

On the human side, Bezalel Haimson could be a very demanding advisor with a drive that could sometimes exceed student capacities. He has not been one to suffer quietly when expectations were not met. Mitigating these all-too-human characteristics has been his partner in life, Betsy Haimson. She has provided strong and loving support that has gone far to enable the successes in his career. Our gratitude to you, too, Betsy!

Betsy and Bezalel visiting Albuquerque in July 2013 (Photo by Moo Lee)

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Snakes!

Submitted by Paul LaPointe, Manager, Petroleum Services, FracMan Technology Group, Golder Associates.

I remember that late Spring day in the late 1970's, standing near the Longyear drill rig, as the quarry floor became alive with small snakes emerging from the nooks in the quarry walls after a long winter's hibernation. As they made their way across the quarry floor into the nearby field, we stopped drilling, and just looked at this unexpected scene before our eyes. We were a group of grad students born in many countries, but I think that all of us felt a bit of magic, and I felt my own wonderment in being in that time and place so unexpectedly. I was thankful that I seemed to finally be on a good path - even if there were a few snakes now and again.

The imperfectly remembered words of Robert Frost's poem about two roads diverging in a yellow wood came unbidden to mind while we were waiting for the snakes to pass. The poem is about a moment of choice in life where there are two diverging roads, and one of them is the more well-worn, broad and safe road taken by many. The other is somewhat overgrown and less trodden, and it is uncertain what lies at its end.

I had been working in Professor Haimson's group for about three years at that time, and the data we were obtaining drilling a NQ core hole through the Paleozoic Section in Eastern Wisconsin would become part of my doctoral thesis.

Soon the last of the little snakes vanished into the nearby fields, and I set about with the pipe wrenches to unscrew the next section of drill rods. I could never have imagined that this is where I would have been only a few years earlier.

When I entered Graduate School at the University of Wisconsin – Madison in 1974, it was not to study engineering, but rather to explore the possibilities of the nascent field of Hydrogeology in the College of Letters and Sciences. I had been captivated by some work that I did as an undergraduate on water resources in the northern Yucatan Peninsula, partly by the adventure of doing the work in a foreign country in its pre-Cancun stage - a fairly undeveloped portion of the world at that time - for its potential to make a difference in the lives of the people living there.

Matters do not always go as planned; sometimes there are unexpected snakes. When I arrived to start my MS, the hydrogeology professor with whom I hoped to work had left the university over the summer, and there was no replacement yet hired. As a consequence, I pursued a MS thesis in structural geology. I learned much, and had a

wonderful summer of field work in the mosquito-infested, bear-trodden Chequamegon Forest in northern Wisconsin. Despite the enjoyment of the field work and subsequent data analysis for the thesis, I had trouble convincing myself that the work made any difference to anyone. With the classic altruistic blinders of a person starting out in life, I didn't see the societal value of any future work that might be open to me to pursue for a PhD in the Geology Department. I successfully defended my thesis in the summer of my second year, and spent the Fall semester as a University Special Student, primarily to continue to take courses at a reduced rate (my RA job had ended with the completion of my thesis) while I figured out what to do next. I contemplated getting a job locally while my wife finished her PhD, or maybe getting a Master in Water Resource Management.

As I said, matters do not always go as planned. Sometimes, they go much better than planned, and this was the case during that Fall. My erstwhile office mate in the Geology Department, whom I rarely encountered as he was taking courses and doing work over in the Engineering College and spent a lot of time there, told me about the project at a quarry with which he was involved. He and his colleagues were drilling holes, logging core, running hydrologic tests and measuring the *in situ* rock stresses as part of a broader site investigation program for constructing an underground energy storage magnet system. It sounded fascinating. He invited me to talk to the professor in charge of the site engineering work. That professor was Dr. Bezalel Haimson, and my office mate was Thomas (Tom) Doe, who became a life-long friend and professional colleague for the past 30 years at Golder Associates.

When I spoke then with Professor Haimson, he told me all about the activities in his group, which extended beyond the field work that Tom had told me about, to cutting-edge laboratory rock mechanics work. I didn't have the standard engineering coursework background that most students entering an engineering PhD program would have had. Professor Haimson and I devised a program to remediate my engineering coursework deficiencies. I matriculated into the College of Engineering and joined his group to start the Spring semester of my third year in grad school. Moving into the world of engineering was not the path that I ever envisioned taking. It involved a lot of risk from my perspective and a lot of faith from Professor Haimson's part to take a chance on me.

When I look back now that I am 70, over a professional career that satisfied my intellectual curiosity and allowed me to live easily, I can see the importance of skills that I learned during my graduate years under Professor Haimson that I wasn't aware of at the time. Of course, I learned a lot of cutting-edge rock mechanics; that goes without saying. But I learned many as equal, or probably more valuable skills. Among them how to work in an engineering group; how to publish papers; how to work with funding agencies and present results; and how to flourish in a highly diverse environment where we all came from a myriad of different countries, spoke many different first languages, and came from different social, political and religious backgrounds. When I consider my undergraduate, MS and PhD years, the overwhelming majority of those with whom I still keep in contact professionally or as friends come from my time with Professor Haimson's group.

Though I've never been a professor at an academic institution, I have been a parent and hopefully a half-way decent mentor. What I hope for my kids and those starting out in their careers seeking advice is that if I am able to empower them to find the best in themselves, to have self-confidence to meet the challenges that they will inevitably face, and to foster a desire to achieve their dreams, along with useful facts and knowledge, they will be well-served.

I'm not sure that I have succeeded, but Professor Haimson succeeded with me. He believed in me when I did not believe in myself. He encouraged me often, and provided support, both financial and professional. He gave me the freedom to fail, as I did in my first effort to find a thesis topic, and then supported me when I found a problem to work on that fascinated me, although it had little direct linkage to his own research interests. I think that one of the greatest gifts that a professor can give

a graduate student, besides believing in them and showing it, is freedom to imagine, freedom to fail, and to offer the support to follow a different road that is unknown to both as to where it might lead. Professor Haimson was there with me as I started down that road less trodden.

These seeds sprouted and grew over the years in my professional life, and when I look back to relish how grand I was or how clever, I always realize instead that what enabled me to achieve whatever I may have accomplished came from the academic and practical knowledge that Professor Haimson shared with me, and more importantly, his belief in me, and that curious and wonderful place that was his research group in the 1970's. I have been able to do work over the decades that I think may have some societal value, at least I hope so, and my professional career has been satisfying to me. That has been a wonderful gift!

Indeed, the road that I took was more uncertain, but someone encouraging you to take it, and giving you support to take it, has been one of the great gifts in my life.

As Robert Frost concluded: "And that has made all the difference."

Thank you, Professor Haimson for that gift!

Professor Haimson (white hat, blue coveralls) getting ready to measure stresses at the Valders Quarry in June, 1979, with three of his grad students. Hands-on engineering work in the field was a great part of working in Professor Haimson's group in the 1970's.

True Triaxial Testing: Personal Remembrance of Professor Bezalel Haimson

Submitted by Chandong Chang, Chungnam National University, South Korea

Bezalel Haimson successfully served as the Editor of the ARMA Letters for over a decade. The editorial work needs earnestness, responsibility, and enthusiasm for rock mechanics, which I believe all express his scientific and academic characteristics properly. Here I would like to summarize my personal experience with him as my Ph.D. advisor.

When I joined Bezalel's rock mechanics laboratory in 1995, one of his major research interests was rock failure and deformability under true triaxial stress conditions. Our first research was to explore such rock behaviors through laboratory true triaxial experiments, with an ultimate goal to obtain the *in situ* stress state from borehole breakouts. Reliable true triaxial rock strength data are essential for estimating the *in situ* stress from the breakout analysis. The specific target borehole was the 9.1 km deep KTB hole in Germany, where the stress-induced breakouts developed almost continuously in the amphibolite borehole wall.

The initial version of the University of Wisconsin true triaxial testing apparatus had just been built, requiring all kinds of calibrations before its first use. I recall that we spent almost two years on calibrations and modifications of the apparatus to ensure its functionality, including the uniformity of loading, reduction of friction between pistons and rock, and optimal loading paths. During this period, we only tested using strain-gauged metal samples (aluminum and brass).

Bezalel was always painstaking and extraordinarily meticulous about laboratory testing. He had to resolve every calibration issue, one by one, before we moved forward. Only after we were completely satisfied with

the work done for about two years were we able to commence the true triaxial testing with rocks, but still not with the amphibolite. Again, Bezalel had to make sure that the brand-new testing apparatus would work fine with real rocks, the material properties of which were known. We chose Westerly granite, a rock mechanics "standard" type of rock for these "preliminary" tests.

These tests produced a dataset sufficient for us to publish our first paper (Haimson and Chang, 2000). After all these efforts, the testing with the KTB amphibolite finally became routine, although not so simple by the nature of true triaxial testing. We published two consecutive papers: one for general rock failure under true triaxial stress (Chang and Haimson, 2000) and one for rock failure applicable to borehole wall conditions (Haimson and Chang, 2002).

Our collaboration continued after my graduation. We worked together on true triaxial testing in different rocks: ultra-fine-grained meta-sedimentary rocks (hornfels and metapelite from the Long Valley Caldera) (Chang and Haimson, 2005) and rhyolite from Korea (Chang and Haimson, 2007). Particularly, the ultra-fine-grained rocks exhibited a unique non-dilatant failure process, which might be linked to rock strength behavior independent of the intermediate principal stress. Such an independency of strength on the intermediate principal stress is in fact consistent with the conventional Mohr-type failure criteria. This research outcome brought us the 2006 ARMA Award for Research in Rock Mechanics.

Whenever he had opportunities for collaboration, he shared them with me and his other students. We kept on working together on failure criteria and true triaxial testing systems until recently (Haimson and Chang, 2005; Chang and Haimson, 2012; Haimson et al., 2017; Feng et al., 2018). All the outcomes from these co-works constituted an important foundation for my career; I am indebted to him for that.

Throughout this journey, I realize that Bezalel showed me model cases of how to do research and do it properly. It was sometimes tough and exhaustive, but it became eventually rewarding. I have not been very active in ARMA recently because of the pandemic and have not yet read the recent issues of ARMA Letters. I think I am going to read through the past ones that Bezalel organized, like catching up on my homework. Congratulations on your work for the ARMA Letters, Bez!

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Standing from left to right: Chandong Chang, Insun Song, Xiaodong Ma; sitting from left to right: Sun-sook (Insun's wife), Myung (Moo's wife), Haimson, Moo Lee, at an AGU meeting in San Francisco (photo by Betsy Haimson)

In Honor of Dr. Bezalel C. Haimson's Life-Long Dedication to the Development of Wellbore Breakout Technology for *In Situ* Stress Determination

Submitted by Insun Song, Korea Institute of Geoscience and Mineral Resources and Chandong Chang, Chungnam National University; Daejeon, Republic of Korea

Dr. Bezalel C. Haimson's insight and commitment to the research of wellbore breakouts revolutionized the technology of *in situ* stress determination for the last four decades. Based on an analysis of compressive *in situ* stress direction observed by Bell and Gough (1979) in Alberta, Canada, Dr. Haimson at the University of Wisconsin-Madison formulated a new indicator. The new indicator was the cross-sectional elongation of oil wells oriented to the minimum horizontal stress direction, later known as "wellbore breakouts". Bezalel and his students demonstrated visible evidence through a series of experiments by subjecting limestone blocks with a vertical hole to true triaxial compression (Haimson and Herrick, 1985, 1986; Haimson and Song, 1993). Their experimental works showed for the first time that borehole breakouts are produced by preferential compressive failure of rock at the wellbore wall, resulting from excessive compression and become larger in size with increasing far-field horizontal stress.

In the 1990s, Bezalel's Rock Mechanics Research Group modified their biaxial apparatus (Figure 1a) to be applicable for more (stronger) rock types such as granites and sandstones for the scalability of breakout experiments. Careful observations of microphotographs of thin sections suggested some different mechanisms of breakout formation depending on rock types, such as the extensile failure model, shear failure model, and compaction band model (Haimson and Song, 1993; Lee and Haimson, 1993; Haimson and Song, 1998).

Meanwhile, Bezalel realized that subjecting a predrilled block to external forces did not truly replicate the *in situ* condition, where a wellbore is drilled into the ground that is already subjected to *in situ* stresses. He conceived of a new device to drill into a prestressed rock block that is subjected to a true triaxial state of stress (Figure 1b). As a result, his students were able to conduct much more realistic simulations of drilling wellbores into the rock subjected to *in situ* stresses. Their research found that the breakout widths do not change during drilling for a set of far-field stresses, and it could be a reliable indicator for *in situ* stress magnitudes as well as their orientations if the rock strength is known (Haimson and Song, 1995; Song and Haimson, 1997).

A basic premise of this technique is that the stress condition at the margin of breakouts is in equilibrium with rock strength, which has

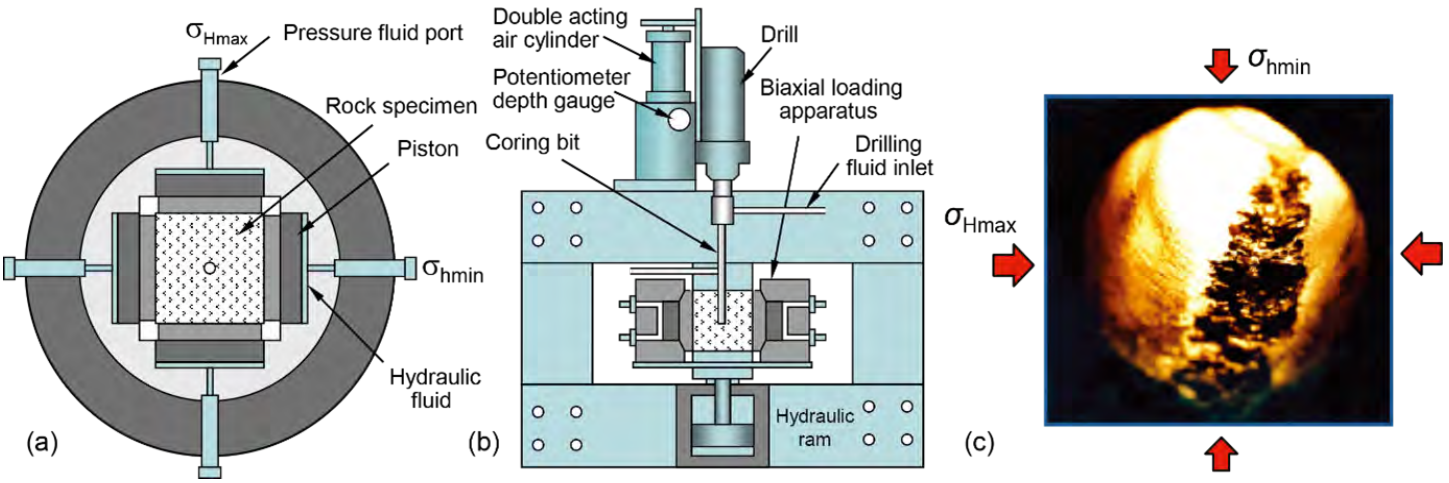

Figure 1. (a) Biaxial loading apparatus for subjecting a predrilled cubic specimen to two horizontal stresses orthogonal each other, (b) the new device for drilling into a prestressed rock block subjected to true triaxial far-field stress ($\sigma_1 \geq \sigma_2 \geq \sigma_3$), and (c) a typical example of borehole breakout produced from a prestressed test on Westerly granite (Song and Chang, 2018).

been comprehensively demonstrated in the experimental studies at Bezalel's laboratory. Such a long-standing technique using breakout dimensions to estimate one of the horizontal principal stress magnitudes, when the other is known, became a widely utilized method. In addition, their research found that the true triaxial rock failure criterion should be obtained, instead of the conventional triaxial failure criterion to define the rock strength

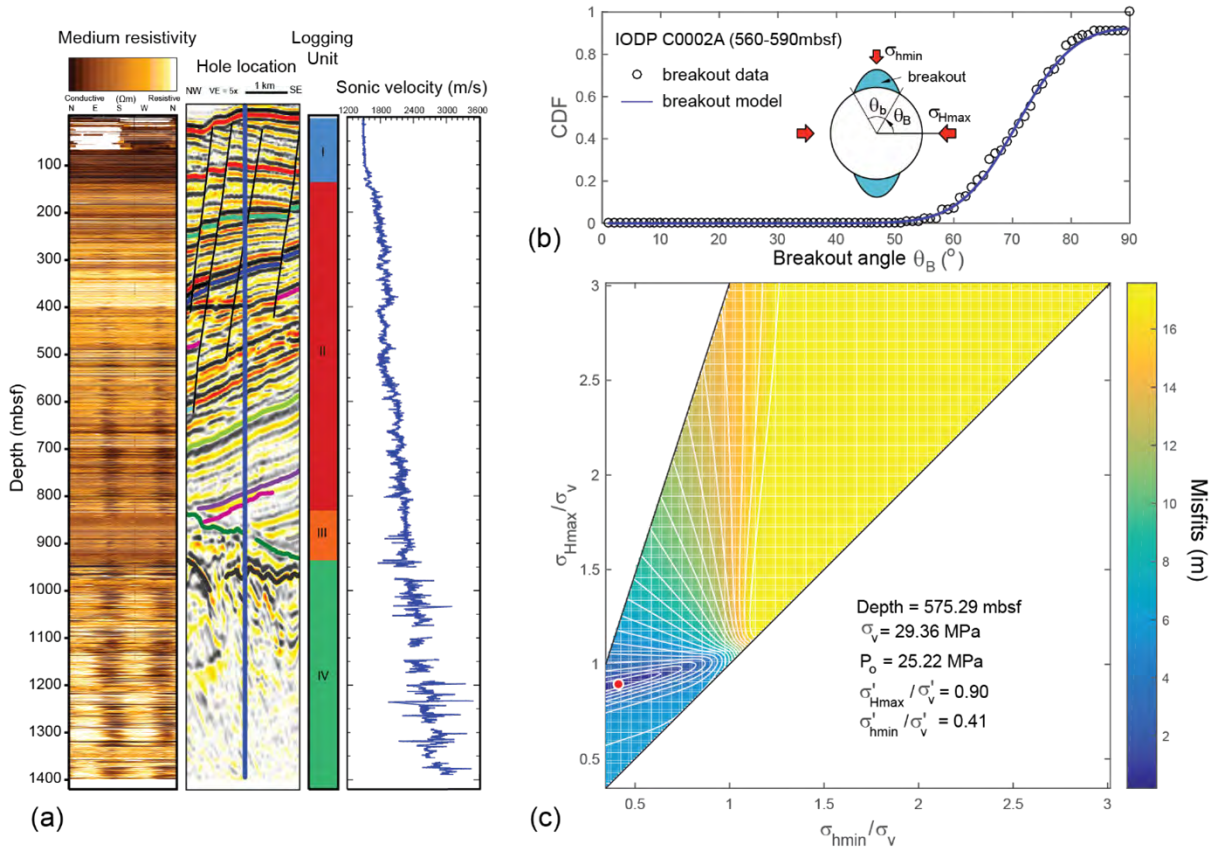

Figure 2. An example of the stochastic method for the determination of in situ stress magnitudes at IODP Hole C0002A near Nankai Trough showing (a) wellbore logging data of borehole breakout image and sonic velocity from the vertical wellbore (middle), (b) the best fits between breakout model (solid line) and observed breakout data (open circles), and (c) stress polygon representing contours of misfits mapped from the objective function and the optimized coordinate (red dot) of σ'_{hmin}/σ'_v versus σ'_{Hmax}/σ'_v with the minimum misfit (Song and Chang, 2017).

at the breakout margins at wellbore wall. Such promising results motivated Bezalel's group to start conducting true triaxial compression strength tests (Haimson and Chang, 2000).

The methodology developed by Bezalel's group had a lasting impact on the field, and it has been applied to constrain tectonic stresses in different regions: KTB, Germany (Haimson and Chang, 2002), Chelungpu Fault zone, Taiwan (Haimson et al., 2010), and Nankai Trough, southwest Japan (Chang et al., 2010).

Throughout his career, Bezalel remained passionate in contributing to the development of his students and leaving a lasting impact on the field of rock mechanics through their success. This commitment to his students resulted in the development of various experimental devices that they would utilize in their research for years to come. The pioneering laboratory experiments on wellbore breakouts at his lab inspired his students to extend the technique further; i.e., estimating both magnitudes of the horizontal principal stresses at once from breakout width and rock strength. Rock strength of sedimentary formations varies vertically to some degree because of generic mechanical heterogeneity of strata, which can be determined either by direct measurements or more practically by indirect estimation using empirical relations between rock strength and rock properties measurable from geophysical logs (Chang et al., 2006). If the basic premise holds, the size of breakouts would also vary depending on rock strength.

Recently, Song and Chang (2018) analyzed close-up views of logged breakouts and showed that their width variation is closely linked with rock strength variation. This observation enabled them to develop a stochastic optimization method to constrain both horizontal principal stress magnitudes simultaneously using probabilistic model of rock failure at the wellbore breakout margins (Figure 2). First, a cumulative density of breakout data as a function of breakout angle (open circles in Figure 2b) is obtained from wellbore wall image in a certain interval of the well (Figure 2a). Second, breakout models are generated from the strength variance model and numerous sets of the far-field stress virtually given in the same hole interval. Then we can determine the magnitudes of a far-field stress set that are used for the best fitting breakout model (solid line in Figure 2c) with the observed breakout data (open circles in Figure 2b). Figure 2c shows the objective function as misfits between the breakout data and the breakout model in the given range of the normalized horizontal far-field stresses ($\sigma'_{hmin}/\sigma'_{v}$ versus $\sigma'_{Hmax}/\sigma'_{v}$). This method has been applied to constrain the tectonic stress magnitudes near the seaward edge of the Kumano basin, offshore from SW Japan (Song and Chang, 2017).

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Twelve Years (2010-2022) of Fun Reading– A Young Professional's Perspective on ARMA Letters

Submitted by Xiaodong Ma, ETH Zurich

As his official last PhD student, I feel well-qualified to comment on Professor Bezalel Haimson's service as the inaugural Editor-in-Chief of the ARMA Letters. I am pleased to dedicate this article to him as he is stepping down from that post. In recognition for a decade of tireless service to ARMA, he deservedly was awarded the first ARMA Distinguished Service Award (Senior category) in 2020.

I started my PhD working with Professor Haimson at UW-Madison in Fall 2010 -- coinciding with the publication of the first issue of ARMA Letters (formerly ARMA e-Newsletter, renamed in Fall 2018). I remember that, from then on, the printed proof of the upcoming ARMA Letters would appear on Haimson's desk, typically for a couple of weeks. The bold red cover of ARMA Letters was eye-catching, quite a contrast from the piles of other documents on his desk. As a new graduate student who had just arrived in the U.S., I had little interaction with ARMA and did not pay much attention

Bezalel at work. On his desk, one could easily tell the stratigraphy of the piles of documents. Often times, on top of the pile there was a proof of upcoming ARMA Letters (not pictured).

to these colorful publications. I had other priorities. Nevertheless, those printouts made quite a visual impression on me, as I recall my first few meetings with Haimson in his office. A more printer-friendly design of ARMA Letters was adopted in Winter 2014; by then, I was an avid reader of the Newsletter.

As I settled down in Madison, I found myself with time to browse through all the ARMA Letters. It was fun, and for a young professional, it was the window to the ARMA community. Thank you, Professor Haimson for introducing me!

Some memorable reads are:

• 'OPINIONS: Hydraulic fracturing gets a BUM RAP' (2011 Winter Issue, pages 4-6)) by Bezalel Haimson

It appears that Hydraulic Fracturing (HF) was at the center of a public debate. In responding to a number of inquiries and doubts, Professor Haimson attempted to clarify the differences between HF (or "fracking") for stimulating hydrocarbon reservoirs and the synonymous *in situ* stress measurement technique he pioneered. This article coincided with my PhD qualifying exam, for which I was assigned to read and present the classic paper 'The Mechanics of Hydraulic Fracturing' by Hubbert and Willis (1957). Since then, HF has become the keyword that appears in almost every issue of ARMA Letters. But back then, HF hardly concerned a new resident of Wisconsin like me, since the state has few to no hydrocarbon reservoirs to frack (nor associated seismicity), except for piles of good-quality proppant sands exported elsewhere.

• 'DUSEL gets caught up in heavy SURF' (2012 Winter Issue, pages 1-2) by Derek Elsworth

DUSEL was the main attraction for me to pursue my PhD in the U.S., first learning about it a talk given by Elsworth during his visit to my home university in China, circa. 2008. Although in the end, my PhD research was not related to underground experiments at all, it was still a pity to see the uncertain future of DUSEL for geoscientists. Going forward, key words such as DUSEL, SURF, kISMET and EGS Collab, as they evolve, frequently appear in ARMA Letters. A long-standing interest in carrying out *in situ* experiments in underground facilities is evident, and these activities are essential in answering some of the fundamental questions in geosciences and engineering. Recently, two relevant special issues of ARMA Letters were dedicated to the underground laboratory efforts in Europe and the U.S., edited by myself and Matthew Ingraham, respectively (2021 Winter and Spring Issues).

• 'My career in rock mechanics' (2013 Spring – 2014 Fall Issues) by Charles Fairhurst

In his four-part article, Fairhurst succinctly touched on many topics. For someone new to the field of rock mechanics, these articles presented a personal perspective on the early history of rock mechanics internationally and in the U.S. Apart from many valuable insights, I learned about the "Minnesota Mafia". It is amazing to see how foundational those PhD theses are from Professor Fairhurst's research group. Many of the topics they have pioneered are still being actively studied today!

In 2020, I signed up for ARMA's Fellows Mentoring Program with Professor Fairhurst, thanks to the organization of the Fellows and the Future Leaders. It is always nice to meet the advisor's advisor, and I enjoyed our dialogue. I sincerely hope the mentoring program continues, in order to create opportunities for young professionals to interact with the veterans in rock mechanics.

So, what is the future for ARMA Letters? In 2021, an ad hoc committee was formed to address issues related to ARMA's publications, including the ARMA Letters. I participated in this effort and was able to provide my perspective as a junior professional. I am optimistic about the future of ARMA Letters. Among many other exciting improvements and new initiatives within ARMA, we will probably see ARMA Letters with new contents, new appearances, and perhaps new formats. I sincerely hope that the ARMA Letters will continue to be fun to read for all members, and particularly for young professionals in ARMA!

Becoming Professor Haimson

Submitted by Haiying Huang, Georgia Institute of Technology

Like history, timelines of our lives comprise many different events, often with world-changing moments in the background. Together, these events make our lives unique. Here is part of Bezalel Cecil Haimson's life story before he became Professor B.C. Haimson.

Bezalel was born in Bucharest, Romania in 1936. His mother's side was from Moinești, a city near Iași, which was the second largest city in Romania and the main economic and business center of Romania's Moldavian region. His father's side came from Galaţi, a southern city in Moldova. His parents met in Bucharest, married in 1929 and had two children, Efraim, the older, and Bezalel, the younger. Growing up, Bezalel was strongly influenced by his maternal grandfather, who was a rabbi in Bucharest. Many of his childhood memories were related to time spent in the synagogue. His grandfather prepared him for his Bar Mitzvah at the age of thirteen and inspired his Bar Mitzvah sermon.

Bezalel with his parents

At a very early age, Bezalel was quite studious. Prior to his formal schooling, he'd often hide under the dining room table where his brother was memorizing homework out loud and would impress his family by reciting poems that were his brother's assignments. Efraim would bring his kid brother along to study at the public library in Bucharest. Bezalel was proud to be treated as someone older than his given age.

In 1943, under the Nazi regime, Jewish children were forbidden to attend Romanian schools. Bezalel started attending a Jewish elementary school at the age of seven. The Jewish school had only one classroom with fifty some students in all grade levels. There was only one teacher for all subjects except for music and physical education. Though there was not much personal attention, Bezalel did not feel they suffered from it in any way.

After the war was over, Bezalel attended fourth grade at a Romanian school. Perhaps due to a shortage of teachers after the war, the local government obliged university professors to also teach in elementary schools. Looking back, Bezalel viewed his mathematics professor from fifth grade as someone who made a great difference for him. With his exceptional depth of knowledge, not only was the professor able to make complex subjects straightforward, he also had a great sense of humor. He pushed the students hard and yet was incredibly gentle with them. The way he was able to make learning math fun without gimmicks stuck with Bezalel for the rest of his learning years. Bezalel prided himself on being a good student. He actually attended lyceum (secondary school) with a substantial stipend, which was even more than his father's meager income provided at that time. Even though Romania was still suffering after WW II, the importance

Bezalel (left) and his brother Efraim in early 1940's

of education was highly regarded by the government. Those who did well in school were thus rewarded.

Bezalel's life was, however, about to take a drastic turn. In 1944, with WW II still raging, Bezalel's brother, Efraim, decided to move to then British Palestine with his best friend's family. On August 3rd, Efraim boarded the *Bulbul*, one of the three old merchant ships carrying Jewish refugees on the journey from Romania to Istanbul, Turkey. En route another of the three ships, the *Mefküre*, which was leading the way, came under attack and eventually sank in the Black Sea with a loss of nearly 300 passengers, many of them children. (There are several conflicting versions of the historical details of how the ship was sunk.) The *Bulbul* arrived at the scene shortly afterward, rescuing the few surviving passengers and crew members. Fortunately, Efraim narrowly avoided being placed on the ill-fated refugee ship where mostly young people were on board. Efraim was still a minor then. Romanian law required that he be officially adopted by a family in order for him to obtain paperwork to leave the country. As he was the same age as his best friend, their family could not help. He was eventually adopted by a childless Polish refugee couple who vociferously insisted that their son travel with them and not on another boat.

However, the voyage on the *Bulbul* was not without incident. The ship in fact ran ashore in Bulgaria. They were rescued and eventually transported to Istanbul by rail. From there, they journeyed from west to east across the entire country of Turkey and then Syria and Lebanon before finally arriving in Palestine some six weeks later. Bezalel's family was already at a loss when Efraim departed. Hearing the tragic news of the *Mefküre* and not knowing which ship Efraim was on dealt them an even greater blow. While Bezalel's father, Haim, suffered silently, his mother, Miriam, became hysterical. They were relieved only after receiving a postcard in Efraim's own handwriting several weeks after he arrived in Palestine.

About a year or two after Efraim's departure, the family decided to join him in Palestine. As a result of that decision, Bezalel's father lost his job as a wine buyer. Bezalel's student stipend became the family's sole source of income.

In January 1950, the family arrived in Haifa, Israel. They were sent to a quarantine camp before the government decided where to place them next. The family had lost communication with Efraim. He did not know they were coming. Their reunion was by pure coincidence. About three weeks after their arrival, one day as Bezalel was walking around the camp, he spotted someone in military uniform who looked like his brother. It was a warm and emotional reunion.

Efraim ensured that Bezalel resumed his education without delay. In mid-February, he was admitted to Ahavah (Love), the same secondary boarding school that Efraim himself had attended. The curriculum there consisted of half academic study and half labor activities. Students worked in a three-month rotation of activities such as kitchen patrol duty, laundry detail, barn assignment

which included caring for and riding the horses and keeping the barn clean, or apprenticing in the machine shop or the carpentry shop. That was very good training of life skills.

Bezalel in the Ahavah school (back row, 3rd from the left). The man in the center is the founder of the school

.

After finishing eighth grade in 1951, Bezalel's parents insisted that he attend high school. However, high school tuition was expensive. The cost was almost equal to that of college. Efraim's solution: Bezalel would work during the day at a construction company and attend Alliance evening school, a subsidiary of Alliance Française, the French immersion day school. While the school did not have a full-fledged curriculum, they provided a solid education with six core courses required for students to pass the Baccalaureate exams.

Bezalel graduated from high school in 1955 and spent three years fulfilling the mandatory

Bezalel on his Vespa in Israel (undated)

Barn duty at Ahavah (Love) boarding school in Kiriat Bialik, Israel, sometime in the early 1950's.

military service requirement before he was able to apply for college. He was accepted by the Department of Math and Physics at the Technion - Israel Institute of Technology after a comprehensive entrance exam. He excelled in his first year and started to attend seminars regularly in his second year. One day, they were visited by two MIT professors. During the Q&A session of the seminar, a student asked what he could do with a Bachelor's degree in math and physics. One of the professors replied, "Oh, nothing. You'll have to go on to get your Master's and Ph.D." Another five years beyond college were more than Bezalel was ready to take on. He had already lost one year because he was not fluent in Hebrew when he arrived in Israel, and another three years because of army service. Besides, the concept of a graduate degree was almost unheard of at that time. He reluctantly explored options outside the Math and Physics Department and decided to switch to Civil Engineering as it was easier to get into than others and the courses had more overlap with what he already had taken.

In the following Fall semester of his Junior year, Bezalel was barely surviving with

Bezalel in the Israeli army in the 1950's

the change of major and a three-week interruption of military service. One day, he saw a big poster from the South African Friends of the Technion Society advertising one fully financed scholarship to study Mining Engineering at the University of the Witwatersrand in Johannesburg. Both Bezalel and his friend, Shlomo Carmi, thought it was a joke. Even though they had no idea about mining, they applied anyway and both were accepted. Being young and fearless, they went to South Africa. They were prepared academically for what to expect there. Still, being the first time far away from their families was not easy emotionally.

In his Senior year at the University of the Witwatersrand, Bezalel's advisor and department chair was an Englishman named R.A.L. Black (aka Ral Black). For his sabbatical year, he traveled around the world to visit other universities with a mining engineering department. His itinerary included Australia, the United States and England. He had a week or two visiting the United States. Of all places, he visited the University of Minnesota, where the young English Professor, Charles Fairhurst, was just building his rock mechanics program. Professor Fairhurst, who would never miss a great opportunity to recruit excellent graduate students, asked Professor Black for recommendations. Professor Black suggested Bezalel Haimson and Shlomo Carmi.

Bezalel at a soccer game in South Africa (early 1960's)

In August 1963, Bezalel embarked on his journey to the Twin Cities together with Shlomo who was going to study with Professor Daniel Joseph at the Department of Aerospace Engineering and Mechanics. They arrived after a 24-hour bus ride from New York. The next day, Bezalel went to introduce himself to Professor Fairhurst. Fairhurst welcomed him to the University and then said, "I must tell you one thing. I am leaving tomorrow on a sabbatical for one year in England." But Fairhurst assured Bezalel that there was nothing to worry about as he had arranged for Dr. Neville Cook to serve as a replacement for this one year. Fairhurst described Cook as a brilliant student who had just received his Ph.D. in Mechanical Engineering and Geophysics from the University of the Witwatersrand at the same time Bezalel graduated with his Bachelor's degree. Needless to say, there was some disappointment. (As affectionately recounted by many of Fairhurst's former students years later, this type of interaction upon a new graduate student's arrival at

Bezalel and Shlomo Carmi in a mine in Southern Africa (early 1960's)

Minnesota would become almost a "hallmark" of his advising (Sikora, 2018)).

The first year went by quickly. Not only did Cook successfully advise Bezalel for his M.S., he also sold Bezalel his Fiat 1100D, a new model then, before his return to South Africa. Cook being a mechanical engineer by training loved cars and was a skilled mechanic. He set the condition that Bezalel, who only had a motorcycle license in Israel previously, could buy the car only after he got a driver's license and learned how to service the car. For several weeks, the two met at least once a week. Cook would put Bezalel on the floor under the car to teach him how to do oil changes and routine repairs and maintenance.

Bezalel viewed his Ph.D. research as the most important in his professional career. The U.S. Army Corps of Engineers had awarded a research contract to Professor Fairhurst to investigate potential methods for measuring rock stress at depth – a hitherto unsolved problem in rock mechanics. Inspired by the work of Hubbert and Willis (1957), Charles suggested that Bezalel work on the connection between hydraulic fracturing and *in situ* stress measurement for his research, hence the groundbreaking work of Haimson and Fairhurst (1967) establishing the borehole breakdown pressure criterion. Bezalel finished his Ph.D. in 1968 with his thesis *"Hydraulic Fracturing in Porous and Nonporous Rock and its Potential for Determining In-Situ Stresses at Great Depth."*

After Romania, Israel and South Africa, Bezalel's life in Minnesota was relatively easy and comfortable, especially with the love and support of Betsy, whom he met on a blind date in his second year. They were married in 1965 in St. Paul with Shlomo Carmi as Best Man and Charles and Margaret Fairhurst and Wolfgang Wawersik standing in for Bezalel's family. Internship and job opportunities came from Halliburton as a result of his research. In 1969, after 18 months in Duncan, Oklahoma, Bezalel finally settled down with Betsy in Madison, Wisconsin and life as Professor B.C. Haimson began.

Acknowledgements

This article was written based on a sit-down interview conducted by Judith Pierotti of Voice Treasures in 2016. Betsy and Bezalel Haimson kindly shared the interview with me; all of the photos were provided by Betsy. I would like to thank them for their review and for entrusting me to write their story. I would also like to thank Thomas Doe and Paul LaPointe for their careful review of this article.

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Santa Fe – We're Back! The 56th U.S. Rock Mechanics / Geomechanics Symposium

Submitted by Douglas Blankenship, Symposium Chair

The 56th U.S. Rock Mechanics/Geomechanics Symposium was held in Santa Fe, New Mexico from 26-29 June, 2022; this was the first in-person symposium in three years and was also the first time the symposium returned to Santa Fe since the 33rd U.S. Symposium –organized by Joe Tillerson and Wolfgang Wawersik- on Rock Mechanics in 1992. Covid related travel restrictions continued to affect our members.To accommodate those that could not travel, opportunities for remote presentations and publication only options were offered to registrants. Over 600 people registered with about 400 people attending in person.

As in past Symposia, technical tracks covering areas of Civil, Mining, Conventional and Unconventional Petroleum, Geothermal, and Interdisciplinary applications were offered to the community. A very wet technical tour of the Valles Caldera and the Fenton Hill Geothermal Site was fully subscribed, and a number of special activities focused on Santa Fe and Northern New Mexico were enjoyed by many. Following the Symposium, the 3rd International Discrete Fracture Network Engineering (DFNE) Conference was held from 29 June to 1 July. The Santa Fe Community Convention Center proved to be an outstanding and intimate venue for the meeting. It was great to see people again.

Authors Breakfast at the Santa Fe Community Convention Center. (Photo by Hill Montague)

Laura Pyrak-Nolte of Purdue University opened the symposium with a Keynote Address entitled *Fractures: Form & Function* that provided an intriguing look at the role of fracture geometry on the functional response of fractures to external stresses. Fred Dupriest, Texas A&M University, provided a Keynote Address on *How to Change Performance: Knowledge Deployment, Not Technology* describing the common gap between technology development and the deployment of knowledge to practitioners. The Early Career Keynote Address was provided by Ingrid Tomac from U.C. San Diego on the topic of *Micromechanics of Rock Fracture Propagation under Coupled Processes*. Mark Zoback delivered the 3rd ARMA Distinguished Lecture where he examined the role of *Lithologically-Controlled Variations of the Least Principal Stress with Depth and Its Effect on Multi-Stage Hydraulic Fracturing and Earthquake Propagation*.

Geothermal Panel Discussion. (Photo By Doug Blankenship)

Panel sessions have proven popular and there were three separate panel discussions offered during the Symposium. The Geothermal Energy Panel offered perspectives from the government, industry, and academia. A panel that addressed Industry Perspectives on Current Rock Mechanics Challenges included representatives from the mining, civil, and petroleum sectors. A third panel provided perspectives on Diversity in Rock Mechanics. Five separate workshops were well attended both the weekend before and immediately following the Symposium. The themes of the workshops were: 1) Damage Mechanics Challenge, 2) Best Practices for Induced Seismicity Risk Assessment, 3) Distributed Fiber Optical Sensing in Geomechanical Applications, 4) Machine Learning for Flow, Geomechanics, and Subsurface Energy Practices, and 5) Emerging Opportunities in Carbon Sequestration and Hydrogen Storage Geomechanics. Additionally, an ARMA Educational Session was offered that provided an overview of the Fundamentals of Experimental Rock Mechanics.

One of many podium presentations. (Photo by Hill Montague)

Mark Board and John Curran were named as the new ARMA Fellows and the ARMA Future Leaders gained another 15 members. A Presidential Citation was awarded to the ARMA Middle East Blue Ribbon Group. The Applied Research Award was presented to Y. Samarkin, M. Desouky, M. Aljawad, A Amao, T. Soling, K. Al-Ramadan, M. AlTammer, and K. Alruwaili for the paper *Hydraulic Fracture Conductivity Sustenance in Carbonate Formations through Rock Strengthening by DAP Solution*. The MS Thesis Award was given to Mustafa Can Suner from West Virginia University for his thesis *The Effect of Natural Fractures on the Mechanical Behavior of Limestone Pillars: A Synthetic Rock Mass Approach Application*. The Cook Dissertation Award was received by Huang Yao from the University of Pittsburgh for *Analysis of Sleeve Fracturing and Burst Experiments for Measurement of In-Situ Stress and Rock Fracture Toughness.* Distinguished Service Awards were presented to Hill Montague (ARMA Staff), Bisheng Wu (Tsinghua University) and Aly Abdelaziz (University of Toronto).

Taking it outside. (Photo by Hill Montague)

A sincere thank you is extended to this year's Symposium Sponsors which included Rocscience, Aramco, Geobrugg, Itasca Consulting Group, MetaRock Laboratories, Sandia National Laboratories, WSP Golder, and the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences. We are also grateful to all the exhibitors: Geobrugg, Itasca Consulting Group, MetaRock Laboratories, Rocscience, Sandia National Laboratories, WSP Golder, Floxlab, GCTS Testing Services, Geomechanica, Rock Mass Technologies, and Wille Geotechnik.

We hope the Symposium met the standards set by Tillerson and Wawersik.

Third International Discrete Fracture Network Engineering Conference (DFNE 2022)

Submitted by Sergio Sarmiento, Acting-chair DFNE 2022

The third International Discrete Fracture Network and Engineering Conference DFNE https://www.dfne2022.org/ took place along with the 56th American Rock Mechanics Association annual symposium in Santa Fe, New Mexico from 30 June to 1 July, 2022.

Even with the current travel restrictions due to the covid pandemic, the Third DFNE Conference brought a very vibrant group of participants who shared their expertise and groundbreaking results. Thirty-eight talks and four posters were presented in the following theme sessions: DFN Fundamentals, DFN Oil & Gas, DFN Mining, DFN Nuclear and DFN Civil and Geothermal.

The conference featured two keynote speakers. The opening keynote speaker was Dr. Hari Viswanathan from Los Alamos National Laboratory. The title of his talk was *"Emergent Flow Phenomena from Fracture Coalescence, Branching and Network Geometry."* Dr. Viswanathan discussed the research advances on characterizing fluid flow on fracture branching/coalescence systems as they reflect the nature of fractures as rough, branched, and segmented structures rather than the traditional way to represent them as planar features. He shared how the lab experiments they are currently conducting on shear-generation of *en échelon* fracture structures provide direct measurements of permeability in both shear- and tensile-dominated deformation. He also discussed graph-based machine learning emulators to accelerate DFN simulations and how large system of linear equations are being solved with quantum computers and using state-of-the-art quantum algorithms.

Fractures play a significant role in a low carbon energy economy from carbon capture, utilization and sequestration to the enhanced production of heat exchange and power generation from hydrothermal systems. The second keynote speaker was Dr. Thomas Doe from Golder Associates-WSP, who addressed the role of fractures on hydrothermal systems. The title of his talk was *"Influence of Fracture Networks on Engineered Geothermal Systems (EGS) Performance."* Dr. Doe summarized the major conclusions of a panel commissioned by the U.S. Department of Energy (DOE) to study the behavior of engineered geothermal systems (EGS) using discrete fracture network (DFN) approaches.

Dinner reception with 2022 DFNE attendees in Santa Fe, New Mexico.

Dr. Bill Dershowitz (left) is presented the award by Thomas Doe.

He discussed how power production depends on the production rate and temperature, and time until the onset of significant production temperature decline, which depends on flow rate and heat exchange area. He presented how analytical solutions show the time to thermal decline has a second power relationship with ratio of surface area to rate. He highlighted the use of DFN models to show how the heterogeneity between and within fractures reduces the effective heat-exchange area. The talk concluded with how DFNs can help to better manage EGS systems that likely will require multiple stimulations and considerations of the injector-producer layouts to optimize heat exchange area and power production.

Characterizing, measuring and modeling fracture intensity and fracture size are among the inherent uncertainties of Discrete Fracture Networks. As a way to share experiences and lessons learned from fracture intensity and fracture size, two discussion panels as plenary sessions took place with panelists coming from the Oil & Gas, Engineering, Nuclear and Mining industries. The first panel was titled *"The Challenges of Multiscale and Multisource data integration in the modeling of Fracture Intensity and Fluid Flow in fractured media"* and the second panel was titled *"Coping with Fracture Size."*

This Third DFNE conference marks the beginning of a new tradition in our DFN community. The work that our international DFN members do for the advancement of fracture state of the art research and applications in science, engineering and society is paramount and needs to be peer recognized.

Two Inaugural awards were established. The first Award is the "Bill Dershowitz DFN Founders Award" to honor the work of Dr. Bill Dershowitz as the pioneer in DFN modeling. The second award is the "Transformational Achievement in DFN Technology Award" to recognize a colleague whose work significantly contributes to the advancement of the understanding of fracture fundamentals, fracture characterization, fracture modeling and new technologies in DFN.

There were two recipients of the inaugural awards. Dr. Bill Dershowitz from GeoFractal LLC was awarded the "Bill Dershowitz DFN Founders Award." Dr. Nataliia Makedonska from Los Alamos National Laboratory is the first recipient of the "Transformational Achievement in DFN Technology Award." The two award winners are given full congratulations. The following is the link of the inaugural award ceremony followed by their bios.

https://www.dfne2022.org/inagural-awards

Dr William (Bill) Dershowitz studied with

Dr. Nataliia Makedonska Award and Photograph.

Professors Herbert Einstein and Greg Baecher in the 1970's and early 1980's. He has worked for the past forty-five years extending Professor Einstein's Discrete Fracture Network (DFN) approaches for probabilistic and geological simulation in Rock Mechanics and Hydrogeology. Dr. Dershowitz is the Founder of Golder Associates /WSP FracMan Technology Group (www.fracman.com), and the developer of many of the key algorithms for Discrete Fracture Network (DFN) analysis, including geological simulation, *en echelon* and wedge slope stability, fracture network connectivity / compartmentalization analysis, multiple porosity DFN flow and solute transport, grouting, induced seismicity, and hydraulic fracturing. Dr. Dershowitz served as Treasurer of ARMA for six years, and is currently the President of the ARMA Foundation. He has served as co-chair of the 52nd ARMA Symposium, and of three International Discrete Fracture Network Engineering Conferences. Dr. Dershowitz is currently adjunct faculty at the University of Washington, and Principal of GeoFractal LLC.

Dr. Nataliia Makedonska is a scientist in the Computational Earth Science Group at Los Alamos National laboratory. Her main expertise lies in discrete fracture network (DFN) modeling, design of fracture network generation algorithms and development and implementation of flow transport in fractures, in particular 3D Lagrangian Particle tracking method. Nataliia is one of the core developers of dfnWorks. Her research focuses on prediction of oil and gas production at subsurface reservoirs, CO_2 sequestration problems, understanding heat and mass transport in enhanced geothermal systems (EGS), and modeling the safe disposal of nuclear waste.

The Discrete Fracture Network Engineering Community owes recognition to the DFNE 2022 conference organizing committee members: Bill Dershowitz, GeoFractal LLC (chair); Sergio Sarmiento, Fracture Consultant (acting chair), Sherilyn Williams-Stroud (Illinois State Geological Survey), Evan Earnest (Chevron), Nataliia Makedonska (Los Alamos National Laboratory), David DeGagne (Itasca), Mark Cottrell (WSP Golder), Steve Rogers (WSP Golder) and many other DFN community members that support the DFNE conference. Special thanks are due to ARMA President Gang Han (Aramco) and ARMA Executive Director Peter Smeallie for their support as well as the logistics provided by Lisa Reny and Emily Fournier (Karma Link).

The conference would not have been possible without the generous support of the 2022 ARMA symposium sponsors and the exhibitors Itasca and WSP/Golder. The support of the ARMA staff is greatly appreciated.