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A Tribute To Jean-Claude Roegiers

Ahmad Ghassemi, University of Oklahoma
John McLennan, University of Utah



Professor Dr. Jean-Claude Roegiers, one of the top Geomechanics Engineers in the profession, passed away on 8 February, 2022, at the age of 76. Dr. Roegiers was recognized worldwide in industry and academia. He made multiple contributions to the science and practice of geomechanics, particularly related to petroleum and geothermal energy. He was the founder of the Rock Mechanics Institute at the University of Oklahoma, designed and built the hydraulic fracturing characterization facility at that University and has been a leader in the development of the science of borehole stability and fracture mechanics. During his career he published more than 250 technical papers, and graduated more than 85 masters and PhD students -- probably his greatest legacy. At last count, his CV contained 53 pages. Jean-Claude was a founding member of the American Rock Mechanics Association (ARMA) in 1995. He was ARMA's first Treasurer and one of the nine members elected to the inaugural class of ARMA Fellows (2008). Dr. Roegiers was also a member of the Science and Technology Analysis Team for the Frontier Observatory for Research in Geothermal Energy (FORGE) project.

As an educator, Dr. Roegiers was recognized for his creative yet analytical thinking and the innovation that he brought to challenging subsurface problems, while enfranchising, mentoring, encouraging and inspiring students and colleagues along the way.

This edition of ARMA Letters provides a tribute to the life, profession, students and colleagues, friends and family of Jean-Claude -- demonstrating the many ways that he affected their lives.

Co-editors:

Ahmad Ghassemi (University of Oklahoma) | John McLennan (University of Utah)

The Jean-Claude Roegiers Fellowship Fund has been established at the University of Oklahoma. To contribute, please visit the following link:
<https://giving.oufoundation.org/OnlineGivingWeb/Giving/OnlineGiving/devmain>

When submitting your contributions make sure to mention the Jean-Claude Roegiers Fellowship Fund and please send a reminder to ahmad.ghassemi@ou.edu Thank you.

Jean-Claude Roegiers

July, 1945 – February, 2022

Beginnings in Belgium

Jean-Claude Roegiers was born 6 July, 1945 to Henri Roegiers and Rosa Claus of Courtrai (now Kortrijk), Belgium. Growing up in a ravaged post war environment with limits and necessitating simplicity, his toys were his books, stamp collections and comic books. He was raised in a Flemish/French speaking home, and he became an avid reader and excelled in school -- always selected as the top student in his class. Being an only child, he especially loved family gatherings with his multitude of cousins. In high school, he chose Greek and Latin studies while pursuing his love of acting. When he graduated from high school, his father encouraged him to spend an extra year with the Jesuits studying mathematics in order to better prepare for his collegiate studies. He graduated magna cum laude in 1969 with a Civil Engineering degree from the University of Liège.

He was known for his out-going and ebullient personality. One example where his larger-than-life personality took hold was at a school dance, where he charmed his future wife, Jeanne Biémar.

He was smitten by her elegance and willingness to put up with his attempts to dance in spite of “one of his toes nailed to the floor.” With a twinkle in his eye, as a pre-requisite to marriage, he enrolled her in cooking classes, for he was a man whose palate knew no limit. They married in August 1969 in Mélen, Belgium. From the beginning, he kept life interesting for his bride. They were on their way to Lebanon for their honeymoon just as violent military clashes broke out and they had to narrowly escape through Syria. He continued the shock and awe by shortly thereafter taking his non-English speaking bride to brave the extreme cold in St. Paul, Minnesota for graduate studies.

“Minnesota Mafia”

Jean-Claude, or “J-C,” as he was known affectionately to his colleagues, was a member of the early group of both international and U.S. graduate students in the Rock Mechanics program at the University of Minnesota (UMN). As he began to gain recognition internationally for his research and scholarship, and especially his role in developing the field of petroleum geomechanics, his early graduate studies attracted the attention of staff at the Los Alamos National Laboratory (LANL). In 1972, he obtained an exemption to the “US citizens only” rule, to allow him to be part of that group from 1972 to 1974. He joined this



Reunion of an early UMN Rock-Mechanics Group (in rows from left): Bezalel Haimson, Charles Fairhurst, Steve Crouch (first row); Wolfgang Wawersik, Jaak Daemen, John Hudson, Jean-Claude Roegiers (middle row); and François Cornet, Emmanuel Detournay, and Michael Hardy (top row).

top-secret government effort, participating in the Hot Dry Rock project field studies at Fenton Hills - while also continuing to develop his stress determination technique.

In 1974, he was the 19th Ph.D. graduate of the University of Minnesota program. He was awarded his degree in Geo-Engineering for his research leading to a technique for determining the state of stress in rock at depth (~2km) from a borehole. He was also the one who introduced the term *Minnesota Mafia* to describe graduates of the program. With now close to 120 Ph.Ds and numerous Master graduates, the term is now recognized internationally.

During his Minnesota years, he and Jeanne began their family. Their first daughter, Natasha, was born in 1973; described as fiery, she proudly gave him his first grey hairs. Two more children came: practical Sebastien and docile Emmanuelle. With his 3 children he returned to Europe as a Von Humboldt Fellow in Bockum, Germany. Their youngest child, Joshua, was born in 1984.

Time in Toronto, Settle in Oklahoma

In 1974, Jean-Claude joined the Department of Civil Engineering, University of Toronto as Assistant Professor; he was later promoted to Associate Professor with tenure. During this time, he took a sabbatical year, and traveled the globe giving conferences in China, Japan, India, Egypt, Hawaii, Greece, and the Holy Land. In 1981 he joined the Dowell Technology Group, Rock Fracture Mechanics Division, in Tulsa, Oklahoma. The Dowell group joined with Schlumberger in 1984 to form the Dowell Schlumberger Technical Center in Tulsa. This called for interaction with the Schlumberger research group in Cambridge UK, focusing on mechanics applied to petroleum engineering.

In 1988, Jean-Claude accepted appointment as McCasland Chair and Professor in the School of Petroleum and Geological Engineering, University of Oklahoma, Norman, OK. He remained at the university until his retirement as Professor Emeritus in 2016. While there, he quickly became one of the top Geomechanics Engineers in the industry. It was during this period that Jean-Claude made his most important professional contributions -- such as designing and building the hydraulic fracturing characterization facility, and

was a leader in the development of the science of borehole stability and fracture mechanics.

Early developments in rock mechanics tended to emphasize civil and mining engineering applications. Although educated originally as a civil engineer, Jean-Claude's association with borehole technology and the challenges of remote subsurface engineering faced in petroleum engineering led him to develop the field of Petroleum Geomechanics. Early (i.e., 1990's) ARMA Symposia included few papers on the topic. Today, it is the dominant topic at these annual meetings.

He campaigned tirelessly -- with remarkable success -- to obtain over \$28 million in external financial support for his Rock Mechanics Institute, part of the Mewbourne School of Petroleum and Geological Engineering. The large hydraulic fracture characterization facility in his laboratory was a consequence of these efforts. He traveled extensively to all corners of the globe, presenting papers and consulting on engineering projects -- and indulging his keen interest in local cultures. He was appointed an Honorary Professor at China University of Geosciences in Wuhan and an International Fellow in Japan. In 2000-01, he was selected as SPE Lecturer on the subject "*Importance of Rock Mechanics to the Petroleum Industry*." and travelled extensively, both in the US and internationally, to lecture on this topic.

Joyful Personality

Although a dedicated and accomplished professional, for J-C there was always more to life, and it should be lived to the fullest. As noted by daughter Natasha, he was the consummate '*bon viveur*', and always a lively companion. To his many friends in rock mechanics, his incorrigible penchant for practical jokes earned him another French title -the '*enfant terrible*' of rock mechanics. He often said that some of the best times in his life were when he practiced this talent. Never malicious and often quite clever, these jokes could be embarrassing to the victim. Many practical jokes were played in return by his students. One of the most memorable involved a fictitious graduate student named Oran Utan from Mongolia, whom his colleagues eventually divulged was only an orangutan.

He never bragged about his achievements and

made use of every moment. He supported and loved the Arts throughout his life—theatre, ballet, opera, & music. He had an extensive library collection, was well-read and had a passion for travel. He was well respected amongst his colleagues and graduate students and in a maverick sort of way he continuously ameliorated the lives of many immigrants in the United States.

In his retirement he devoted much of his time, talents and generosity to Saint Thomas More Parish in Norman, Oklahoma. He conducted conferences on God and Science and How God Illumines Professional Life. He helped produce a book on all the artwork at St. Thomas More and proudly took part in the refurbishment of its 1923 Organ. In 2019 he enjoyed celebrating his 50th wedding anniversary in Breckenridge, Colorado, surrounded by all of his cherished children and grandchildren.

Jean-Claude Roegiers is survived by his wife, Jeanne; his children Natasha (Joseph Barrett) and their children Isabella, Chloé, Eva-Maria, Gabrielle, Isaiah, Evelina from Phoenix, Arizona; Sebastien (Carri Stevenson) and their children

Brecken, Sawyer, Harper from Edmond, Oklahoma; Emmanuelle (Todd Wilhelm) and their children Jacob, Annalysia, Lucas, Emily, Natalie from Sarasota, Florida; and Joshua from Tulsa, Oklahoma; and his Belgian brothers-in law, sisters-in law, nieces, nephews and many cousins.



Jean-Claude and Jeanne Roegiers



Jean-Claude (second person, left side) surrounded by his considerable family.

Note: This account of Jean-Claude Roegiers' life and career was based on the obituary prepared for his memorial service by his family and a tribute article published in the newsletter of the Department of Civil, Environmental and Geo-Engineering of the University of Minnesota (with input from Professor Emeritus, Charles Fairhurst), and other sources.

Selected ARMA Fellow



Jean-Claude Roegiers (second from right) elected member of the initial class of ARMA Fellows, at the 2008 ARMA Symposium, San Diego. Other members of the initial class (left to right) are Charles H. Dowding, Herbert H. Einstein, Charles Fairhurst, Richard E. Goodman, Sidney J. Green, Bezalel C. Haimson, François E. Heuze, Jean-Claude, and Bernard Amadei.

Dinner with Former Students, ARMA Houston, 2016.



Giving Advice



Eulogy for Jean-Claude Roegiers

*Submitted by Natasha Roegiers (daughter);
presented at memorial service on 18 February, 2022*

We can all agree that Jean-Claude was ONE OF A KIND-- in capital letters -- he was the life of the party, ornery, cheeky, charming, stubborn, very intelligent, passionate, high energy, unstoppable, antagonistic with a twinkle in his eye, and incredibly generous. He was very loved by many. Dad was "a salt of the earth" kind of man. His world-renowned status as a scientist never tempted him to boast about his accomplishments. I won't be summarizing his work accomplishments here -- a quick internet search can expound on his prolific work. I will instead elucidate the imprint his joyous soul left on our hearts. His brilliance came from humble beginnings and he developed a charm and a wit that commanded the attention of a room. But his greatest gift, apart from his incredible generosity, was his wonderful way of making everyone feel equal, welcome and at ease.

However -- he was a bit of maverick -- a maverick that tweaked the system to his advantage. Did you know: He never roughed it the first years in college as 99% of us did. No dorm life for J-C! Nope. I am sure it would make some of you chuckle to know that he had a full time cook and launderer as a college freshman. He lived with a widow who had nothing else to do but to shower him with three-course meals. He was an excellent foodie but a terrible cook. He burned everything he was in charge of -- and his excuse would always be "Well, I like my meat black. It's good for my complexion." When Mom wasn't looking, he loved to add all sorts of surprises into her soups/ stews/ dishes. He especially enjoyed seeing Mom's expression when she sat down and tasted the first bite. "Gosh Lapin," she would say. "What did you add? It's too spicy." Then he -- with a giant smile on his face, would plead the 5th. He also skipped out of the required Belgian 2-year military service. He did this by going overseas for graduate school and advertised this loophole to everyone. Military service would have done him some good but then maybe he wouldn't have been so colorful or politically incorrect.

He was like a bull in a china shop, yet ironically his most famous line was that everything in life was "all under control". When Mom would go into surgery -- Dad would call and say "It's all under control,"

When grandchildren were being born, his first phone call to the father was "It was all under control." When his friends and neighbors would drink a little too much of his special Christmas punch, "It was all under control." When Sebastien ran through the porch screen while running away from Dad, "It was all under control."

He always tried to bend the rules. He would joke that something only became wrong if one got caught. Dad loved practical jokes. One of his favorite stories to tell was when he was a student at the University of Liège. He was the winner in the grand student drinking contest -- no surprise there. As a reward, he earned the right to set up the next practical hazing joke on the first-year students. So he decided to load the first-year students in a truck and headed to the main city square in Liège. There he told them that they had to run naked across the square to the awaiting truck containing their clothes on the other side. Except, there was no truck on the other side. "Those poor students"-- Dad would chuckle --"you should have seen their faces." And he would laugh a deep belly laugh.

But you know --'what goes around comes around' and over the years, his students and colleagues played jokes on him too. At the bereavement meal today, we will have a mic set up and we invite you to tell us some jolly stories. He so loved being surrounded by humor and joy.

When he referred to any number of individuals of more than one -- he dropped names and just summoned us as "you people". "You people have got to get going" -- was his way of pushing us to make decisions. He never quite mastered the "th" pronunciation in English nor was he able to distinguish the difference between an idea and an ID. When referring to his third idea, he could be heard saying, "I fink I have a fird ID."

He was a strict disciplinarian with high expectations. As children, we would bemoan his Saturday 8:00 a.m. jobs -- weeding the yard, washing his cars, mowing the lawn, or washing windows. He would antagonize us with all the spots we missed. I loathed these tasks as a child (I think my siblings would concur) but looking back -- it did build character, strength against adversity, patience, and humility.

Traveling was his passion because he cherished experiencing the world around him and he savored knowledge about other cultures and their history. His library would be brimming with historical books

from all the places he visited. His tales from far-away lands would fill our heads with stories of him breaking bread with Amazonian Indians, Tibetans, Indonesians -- eating all sorts of wild food -- such as snakes and monkey brains. Sometimes he brought back art contraband and like a kid would gleefully explain how he had snuck the pieces out of a particular country. The adventure of it was just as fun as owning the art piece. He truly was a Renaissance man. Well read, studied many languages, well-traveled, and believed the exposure to the Arts was a fundamental component to savoring life. He especially loved music. He was certainly a closeted opera singer. His early weekend tenor voice would boom often in our home. He sang until the very end of his life!

Reading the tribute messages of people he touched over the course of his life has been so heartwarming. He was a champion for the underdog, encouraging others to see their potential. So many of you mentioned how he made a point to ameliorate your lives because he truly cared for his neighbor. I am also learning that he took advantage of this system -- bending the rules as to what graduate students' jobs entailed. Apparently, he was successful in getting some of you to build his back porch, finish his basement and provide babysitting duties. Graduate students who did free manual labor. What a coup!

Family was very important to Dad. He integrated Leah from the Philippines to make his family more special and more beautiful. He hosted several international students. He absolutely lived for family reunions not only for his immediate family but for his extended Belgian family too. He loved to be surrounded by people and laughter. Mom mentioned he was a peacemaker in many work settings -- always seeking to help others forgive their grievances toward others.

We chose a coffin made of pecan wood. Pecan trees are so prevalent here in the state of Oklahoma. I recently learned that the name "pecan" is a Native American word of Algonquin origin that was used to describe "all nuts requiring a stone to crack." Oh, how relevant for your life -- you the stone whisperer -- cracking rocks your entire career. You were the pecan tree of our lives! The words of the Prophet Jeremiah ring true for your life. Daddy: "Blessed is the one who trusts in the Lord, whose hope is the Lord. He is like a tree planted beside the waters that stretches out its roots to the stream: it fears not the heat when it comes: its leaves stay green; in the year of drought it shows no distress, but still bears fruit." You bore great fruit, Dad.

I see your generosity and goodness in my sister Emmanuelle -- she like you would give the shirt off her back to help one in need. I see your passion for building things and love of travel in my brother Joshua, I see your hardworking perseverance and financial sense in my brother Sebastien. I see your desire to debate, in myself-- not for conflict, but from intrigue in knowing how and why others think. And your humor is certainly peppered in each one of us. As for Mom -- you made her so resilient! You would often say: "Lapin, aiey-aiey-aiey you give me all these grey hairs you know. I have nothing to say around here." We all knew you were the head of the family but Mom was the neck that turned your head! Mom, be at peace knowing Dad has seen the face of God and that he now knows that we don't come from monkeys.

Jean-Claude gave us the example of God the Father when he welcomed the stranger, fed the poor, loved his neighbor, and consoled those that were burdened.

The end of Dad's life was marked by a lot of suffering especially of the loss of his brilliant mind through the devastating disease of Parkinson's. He endured great emotional pain as he recognized that his ability to communicate was waning. However, something so beautiful arose from his suffering. The man who once commanded a room and had the last word on every decision, retreated into a quiet humility -- a dying onto himself. He graciously accepted to be fed, washed, dressed, held, lifted and transported. The last four months of his life in our home were the sweetest. I saw in him the suffering Christ, the humble Christ, the peaceful Christ. But the most powerful lesson was to witness God's merciful love for him. Thank you God for this gift!

We will miss your phone calls, your quirky demands, your jubilant smile, your gregarious personality, your interest in our lives.

A one of a kind of light has blown out in this world but we will still hear him say "I personally believe it's time to go... "C'mon let's go!"

Dad -- May the Lord surround you with His love and may your soul Rest In Peace.

J-C's family put together an 18 minute slide show, with photos from many stages of his life and showing many personal relationships. It can be viewed at the following link.

https://www.youtube.com/watch?v=M1vcJ5y7O_w

Hello from Sapporo!

Personal correspondence from Jean-Claude Roegiers

As most of you know, I have been spending my sabbatical leave from the University of Oklahoma here in Hokkaido University, as guest of Professor Yoji Ishijima of the Department of Mineral Development Engineering.

Upon arrival here on January 10th, I quickly realized that my clothes from Oklahoma would not suffice! I had also to "re-train" for sliding on snow and ice rather than walking swiftly. And after a few memorable falls, I followed the Dean's advice...and found some spikes to fit my leather soles. However, I have to admit that winter had its charms, especially during the Snow Festival. For me it was Christmas all over again. Spring has now finally arrived and the cherry trees are starting to blossom.

After a few weeks of "cultural shock," mainly caused by the fact that I could not relate Japanese to any other language I knew, I started to settle down and appreciate this very different culture. I also decided to take some Japanese lessons after getting frustrated from not understanding the messages on the phone, nor when the Xerox machine wanted to tell me some obvious mistakes I was making! Although I am far from being able to converse, or even to understand Hiragana and Katakana, I have gained some appreciation for the way Japanese think and express themselves. As with French grammar, there are rules -- but as many exceptions. I can honestly say that "counting" is a nightmare...and that the usage of "wa, ga, no, ni, o" still leave me perplexed! But the Japanese language has intrigued me to the point that I will probably pursue its challenge as a hobby upon return to Norman; my plan is to write a *Konnichiwa Oklahoma Daigaku Kare* in the near future.

Most of my time was spent in starting to write a book on *Rock Mechanics for Petroleum Engineers*, based on the notes I have accumulated over the years. Although this task will not be completed before I leave Japan, I still intend to have it about two thirds done by June. This would certainly not have been possible without the moral and financial support provided by Professor Yoji Ishijima and the Japanese Ministry of Education. I was also fortunate to be in Sapporo when the tragic accident

of the Toyohama Tunnel occurred. I sincerely hope that the little help I could provide to elucidate the slope failure will contribute somewhat to avoid such disasters in the future. From a professional point of view I like to thank the authorities for allowing me to visit the site at such early and busy times.

I would also like to take this opportunity to thank the many colleagues and friends I met and made during this stay in Japan. Professor Ishijima gave me the opportunity and arranged for a number of diversified visits. The welcome and the reception received at most sites was outstanding; often the projects were new to me and broadened my scope. I can guarantee that I will become an "unofficial" Japanese ambassador when talking in the future about some of the projects I had the opportunity to visit. Special thanks should be extended to Professor Yoshiaki Mizuta from Yamaguchi University, who not only accepted me to attend his traditional Japanese wedding, but made me understand the real meaning of a "sister university."

Last, but not least, I need to thank Dr. Yoshiaki Fujii, who had to suffer throughout my stay. He was always available and ready to solve my "not so trivial and regular" problems. He also tried to help me understand the differences between our cultures.

There is no doubt that I will miss karaoke and sashimi when I return to Norman, but the memories will last forever.



How did a world class rock mechanics genius like Jean-Claude Roegiers ever end up in Oklahoma?

*Submitted by Carl T. Montgomery,
NSI Technologies.*

My name is Carl Montgomery, and it is my fault that J-C came to Oklahoma. The following is the story of how that happened. Believe it or not, it all started because of the Hanford Plutonium plant in the State of Washington. The Dow Chemical Company used brine produced from wells in Michigan to make its fortune. These wells needed to be stimulated from time to time so Dow developed the technology and equipment to do this and founded a company they named the Dow Well Servicing company which became Dowell. Dowell had the equipment to hydraulically fracture wells but really lacked the engineering expertise to optimize the treatments, so decided they needed to start a Rock Mechanics lab, probably because of competitive pressure. They went to an Ivy League university and recruited a young Ph.D. who had some expertise in Rock Mechanics and brought him to Tulsa to set up a Rock Mechanics lab at Dowell's International well servicing facility. This young engineer was in Tulsa about a year and ordered about two million dollars' worth of TerraTek testing and rock preparation equipment, hired a geologist and built a special building to hold it all. After going to a prestigious out-of-state university, this young engineer was somewhat disenfranchised with working in Tulsa, Oklahoma on a project which was not up to the intellectual challenge he wanted. Through his contacts he found out that the Hanford site was looking for someone to help them with the disposal of all the radioactive waste they had generated; he applied for the job, got it and off he went.

No one really paid much attention to this until about six months later when all this rock testing equipment started showing up and nobody knew what it was for or what to do with it. At the time I was just a spectator watching all this happen while working on Cement and Sand Control research. One day Dowell's VP of Technology, Ted Pumpelly, came in the lab and told me I had a new job and that was to figure out what all this equipment was for and to

find someone that could help turn it into a working laboratory.

I knew absolutely nothing about Rock Mechanics but did find out that the International Society of Rock Mechanics (ISRM) was having its annual conference in Austin, Texas. I hopped on a plane, registered for the meeting, and just sat in the back of the conference hall listening to the papers and watching the people. There were three people that asked a lot of challenging questions and seemed to lead a lot of the discussion. That evening there was a mixer, so I went and bought eight drink tickets and started looking up the three people that had impressed me.

The first was Mike Cleary. I asked him if he would like to have a drink and if he had any students that I could recruit. He said he didn't want a drink, didn't have any students but did have a JIP on hydraulic fracture modeling which Dowell later joined. The second was Bezalel Haimson. He also didn't want a drink but did have a M.S. student, Nae Kan Ren, who Dowell later hired and was the first person in the Rock Mechanic group. The third was, of course, J-C. He not only drank up all eight of my drink tickets but about ten more on top of that. I convinced him to come to Tulsa as a consultant and help us set up the group.

Following that first contact J-C consulted with Dowell and myself for about three years. After this time J-C had, of course, made a tremendous impression on a lot of people including Ted Pumpelly, again the VP of Technology. Pumpelly asked me one day if I could set up a dinner date with J-C the next time he came to town, which I did. I was not at that dinner but the story I got from J-C was that Pumpelly took him to the best restaurant in Tulsa, bought the most expensive bottle of wine the restaurant had to offer and, after a couple of malt scotches, passed J-C a paper napkin and asked him to write down what it would take to convince him to come to Tulsa and run the Rock Mechanics facility. Apparently, J-C wrote something down on the napkin, passed it back, Pumpelly looked at it, stood, put out his hand and said "Done" and as J-C put it, "I was trapped." Before finalizing the offer, he called his Ph.D. advisor, Charles Fairhurst, to get his thoughts. Dr. Fairhurst told J-C that he thought it was a good idea for him to get some industry experience; that finalized the decision for J-C. That is how he and his lovely family left the very cosmopolitan, French speaking Toronto and landed in a place famous for country and western music and wild Indians.



Leisure time with Jean-Claude and Carl Montgomery

From this beginning J-C built from scratch a world class Petroleum Rock Mechanics Group. The people he recruited into that group include John McLennan, Emmanuel Detournay, Luc Van Damme, Rob Jeffery, Joe Carvalho, Mark Thiercelin, Kamel Ben Naceur, Steve Cobb, Richard Keck, plus some more. That group of people is certainly at the top of their game today and it all started with J-C. After leaving Dowell he went to the University of Oklahoma and did the same thing there. The number of Petroleum Geomechanics engineers that studied under J-C is large and I see and hear from them often.

I worked and played with J-C for over thirty years and would describe him with three words. The first is “Hustle”. Everything he did – no matter if it was working, challenging the technology, driving his car, or enjoying the opera – it was at his top speed. The second was “Family”. Not only did he challenge and fully enjoy his family here in the States but also his extended family in Europe. I went with him several times to visit his family in Europe and it was always a party. The third is “Food and Wine”. As with his work he always enjoyed and shared his appetite for good food and the best of wine.

Dr. Prof. Jean-Claude Roegiers was my best friend and companion, and I will miss him dearly. It all started over a beer, and I will end with a salute saying, “Thank you J-C for a life well lived.”

Life-long Connection

Submitted by Joe Carvalho, Golder Associates. (a division of WPS, Seattle, Washington)

My connection with Jean-Claude Roegiers was through the University of Toronto. Jean-Claude was a Professor at the University of Toronto during my undergraduate years and by the time I reached graduate school, Jean-Claude had gone on sabbatical and had taken a position at the Dowell Technology Group in Tulsa, Oklahoma. Luckily for me, Jean-Claude kept very close ties with U of T and, through Dowell, sponsored a number of graduate students, of which I was the last. The research focused on fracture mechanics, more specifically, fractured propagation coupled with fracture flow. My turn to continue the research came at a time when the industry was very interested in poroelastic behavior in fracture propagation, and I was given the opportunity to work on Displacement Discontinuity solutions in poroelastic media. This work earned me my Doctoral degree. I am forever grateful for the encouragement and the support from Jean-Claude and Dowell during this time.

But Jean-Claude was not quite done with me. When I completed my degree (I was actually not quite done yet), he offered me a position at the Dowell-Schlumberger Research Center in Tulsa. I joined a group of very talented engineers and researchers that Jean-Claude had attracted. You see, Jean-Claude had this contagious energy and excitement that made one want to be a part of it. This was my first “real” job and I owe it to Jean-Claude to have launched my career in a way that opened so many doors.

Thank you Jean-Claude.

Measurement of Opening Mode Hydraulic Fracturing in Hard Naturally Fractured Rock

Submitted by Rob Jeffrey, Principal Research Scientist (retired), CSIRO.

Jean-Claude Roegiers recruited me in 1982 to work at the Dowell Technology Center in Tulsa. He started me on a path of research into hydraulic fracture growth in naturally fracture rock, a topic that occupied me for the rest of my career. J-C. also had an ongoing interest in stress measurement and geothermal energy. I dedicate this ARMA letter to his memory.

Introduction

The stimulation of Hot Dry Rock (HDR) and Enhanced Geothermal Systems (EGS) has relied on dilation of natural fractures, produced as they undergo shear deformation (Duchane and Brown, 2002, Jung, 2013). The shear deformation is produced

as a result of fluid injection reducing the effective normal stress acting on natural fractures (Pine and Batchelor, 1984). Injection induced seismicity is one expression for the shear fracture process. However, stimulation of HDR reservoirs was initially planned to use opening mode hydraulic fracturing, but difficulty was experienced in establishing connections between wells. This led to shear fracturing as the preferred method of stimulation (Jung, 2013; McClure and Horne, 2015). This letter presents data showing that hydraulic fractures do form and extend as opening mode fractures in strong and hard naturally fractured rock when the injection is focused into a small zone and when the injection rate is sufficient to maintain a pressure in excess of the minimum stress magnitude (Jeffrey et al., 2010).

Measured Opening Mode Hydraulic Fractures (HF)

This letter provides a summary of measured stress change near a propagating hydraulic fracture and mineback mapping of hydraulic fractures that confirms opening mode hydraulic fracture growth. The data presented here support the conclusion

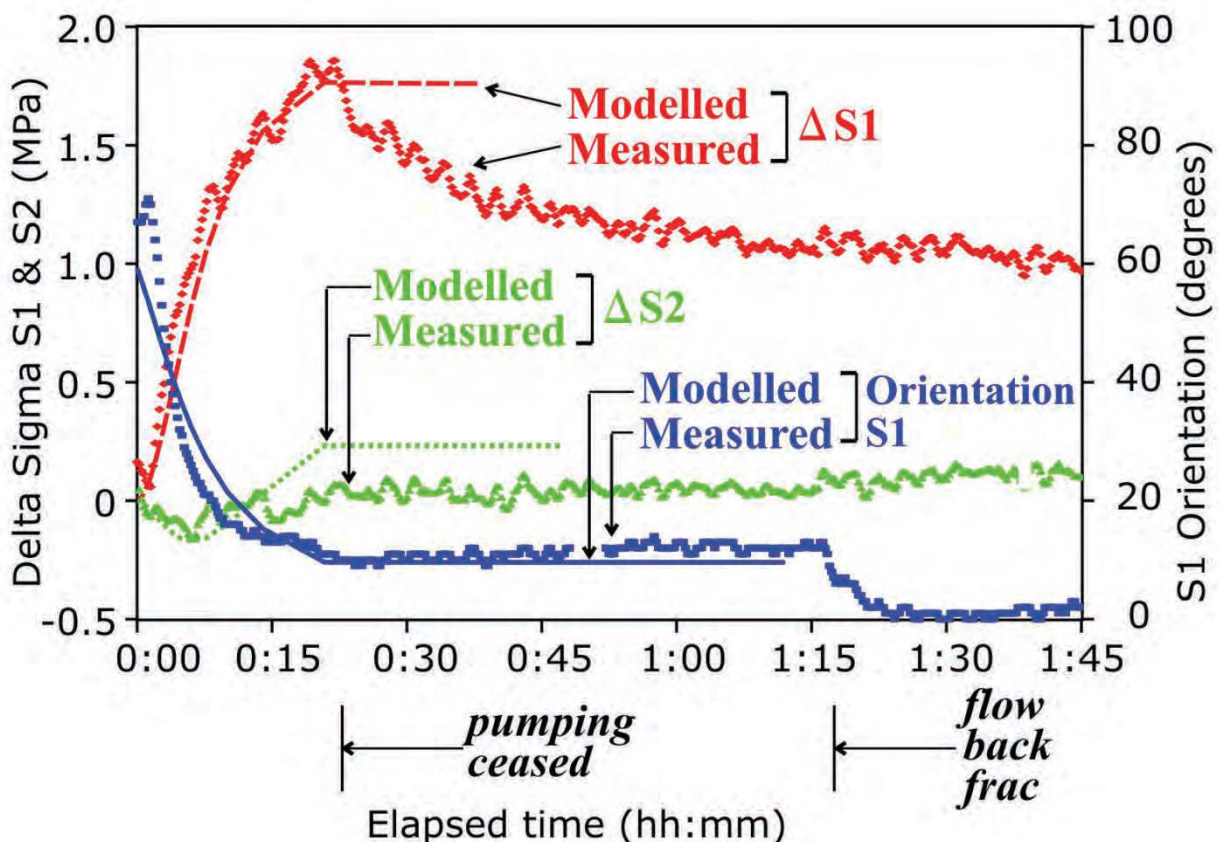


Figure 1: A comparison of the measured and calculated stress change occurring as the hydraulic fracture grew past the location of the stress change cell. S1 and S2 are the maximum and minimum principal stresses induced by the pressurized fracture (after Mills et al., 2004). A radially symmetric fracture geometry is used in the calculation.

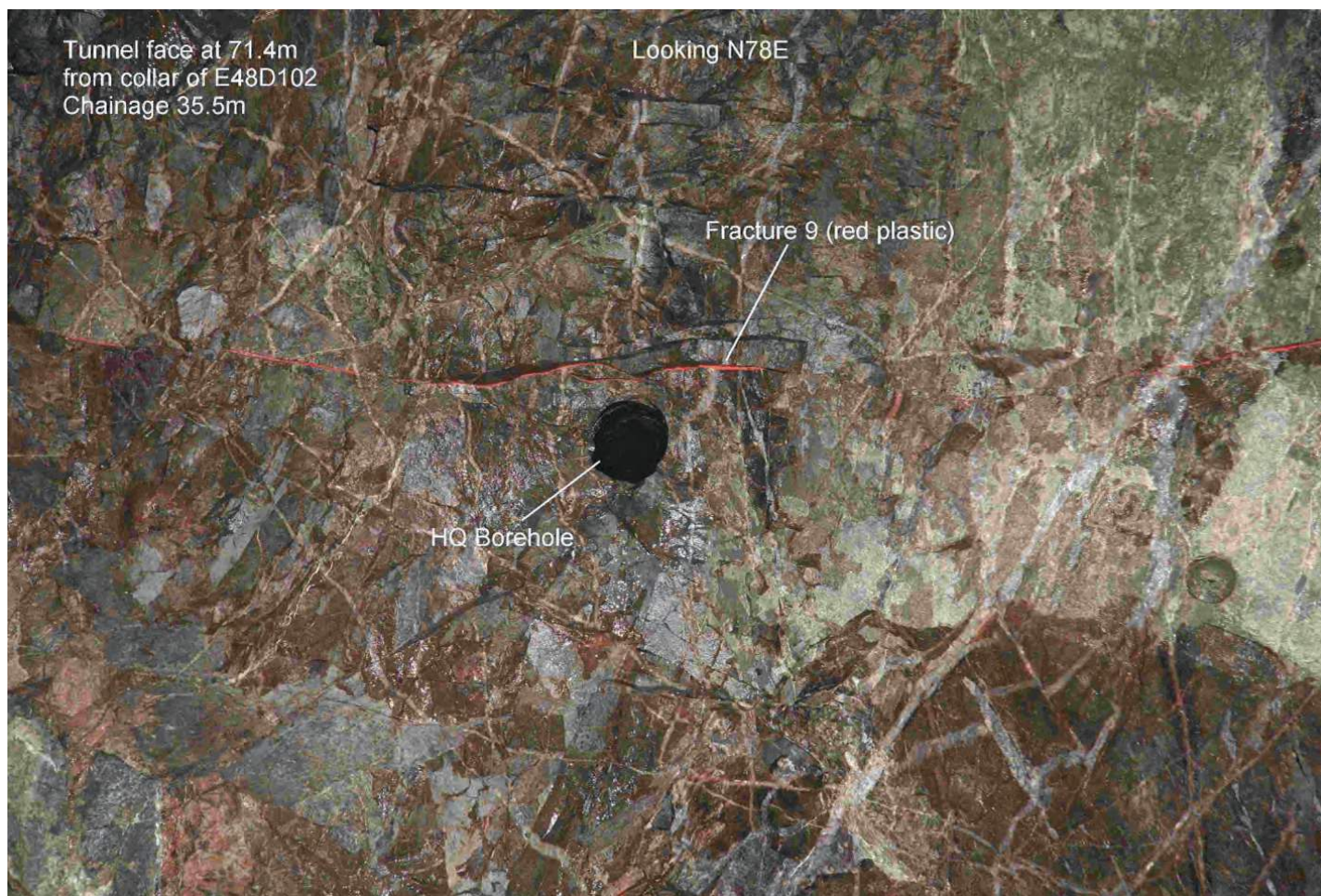


Figure 2: Hydraulic fracture propped with red plastic at Northparkes E48 mineback site (Jeffrey et al., 2009a).

that opening of the fracture channel is the dominant mode of deformation occurring during HF stimulation of naturally fractured rock when injections are carried out at pressures in excess of the minimum stress magnitude.

The stress change data was obtained by using an ANZI strain cell, described by Mills et al. (2015). Two of these cells were installed approximately 16 meters from the anticipated plane of the HF. The measured stress change at this location, as the hydraulic fracture propagated past the strain cell location, is compared in Figure 1 to the calculated stress change produced by a uniformly pressurized radially symmetric hydraulic fracture (Sneddon, 1946). The fit between the measured stress change and calculated stress change is very good when using the Sneddon pure opening mode fracture solution, suggesting that little shearing is occurring along or around the hydraulic fracture (Mills et al., 2004). Note that the post shut-in stress change was not modeled. The site was in a naturally fractured Andesite orebody at Codelco's Salvador mine in Chile. Additional details of this site

can be found in Mills et al. (2004) and in Chacon et al. (2004).

Many hydraulic fractures have been placed into coal seams and mapped after mining, where the fractures were placed to pre-drain gas from the seams or to produce the gas as coalbed methane. The compilation by Diamond and Oyler (1987) provides examples showing propped, opening mode HFs in coal. Coal is a soft naturally fractured rock. Indeed, thousands of opening mode HFs have been placed, with proppant, into gas and oil shale over the past decade. These treatments into naturally fractured rock create shear fracturing around the main propped fracture. However, coal and shale are not similar (other than being naturally fractured) to the hard and strong crystalline rocks that typically are targets of geothermal stimulations.

Results from mapping of HFs in the hard naturally fractured rock of metalliferous orebodies, similar in many ways to geothermal reservoir rocks, confirm opening mode fracture formation. Figure 2 is a photograph from a site 550 meters below the

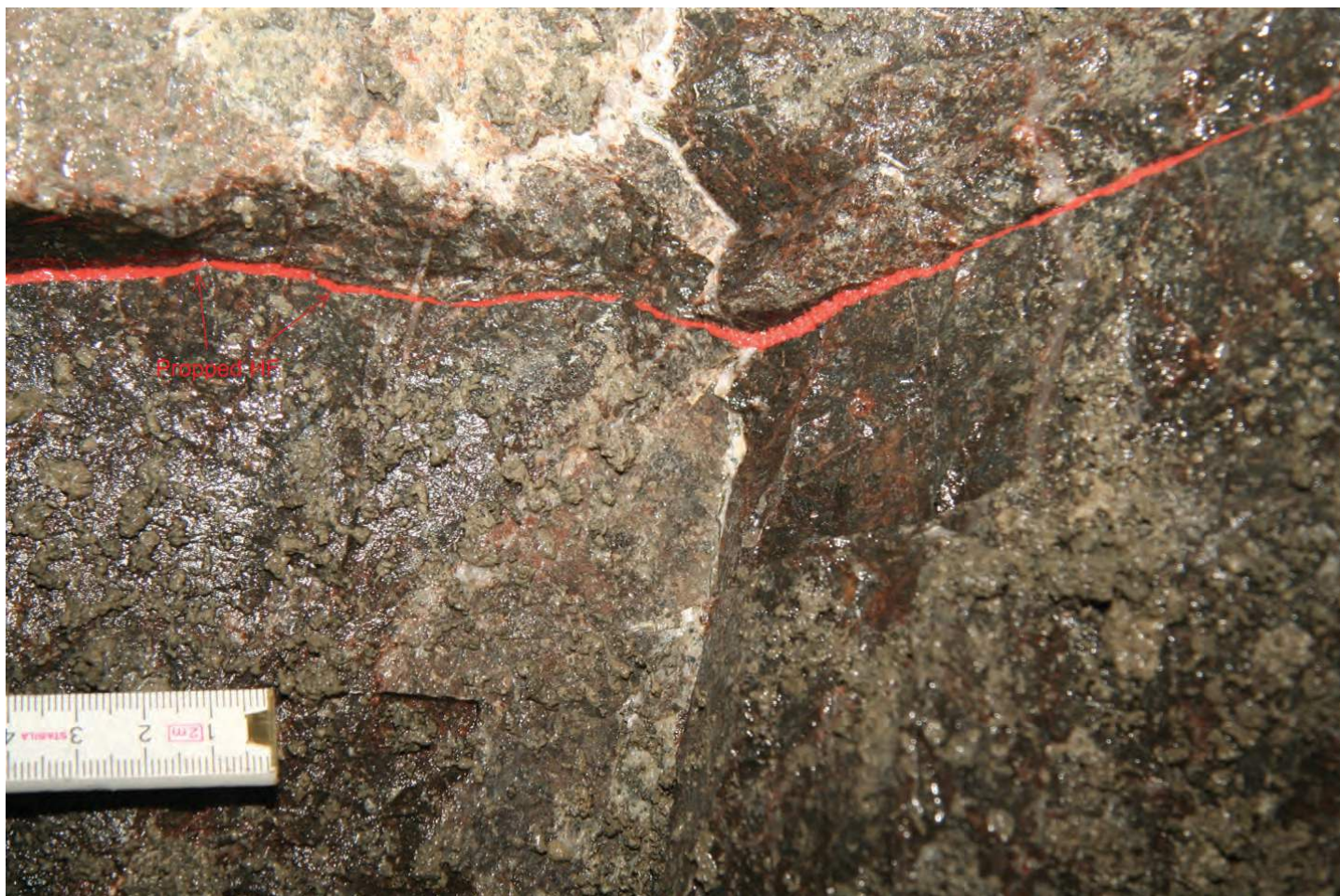


Figure 3: A close-up view of the propped hydraulic fracture shown in Figure 2. The red plastic has propped the fracture to a width of between 1 mm and 3 mm.

surface, showing a fracture which was propped with red plastic as a marking agent, in lithified volcanic sediments. Water was injected into an interval located approximately two meters out of the page along the HQ borehole shown. This fracture and other HFs mapped at this site were primarily single propped channels. Branches and offsets did occur at some locations where they crossed veins, shears or natural fractures (Jeffrey et al., 2009a, Jeffrey et al., 2009b). A small branch can be seen on the right side of the fracture in Figure 2 where the fracture crosses an inclined vein.

Figure 3 contains a close-up view of the fracture shown in Figure 2, at a location to the right of Figure 2. The image in Figure 3 includes a scale in centimeters and millimeters and it can be seen that the propped width of the fracture is 1 mm to 3 mm. This propped width is after compression of the soft particulate plastic proppant by the 15 MPa closure stress acting at this site. The hydraulic opening of the fracture during the injection is therefore estimated to have been 5 mm to 7 mm.

The treatment that created this fracture screened out near the end, which provides an explanation for part of the width. A standard planar HF model predicts a hydraulic width at the wellbore of approximately 1 mm for this treatment.

Mineback data from the Salvador site and from a trial at a Newcrest mine in Australia (Bunger et al., 2011) also show opening mode hydraulic fractures forming in these hard rock orebodies. This data supports the conclusion that opening mode HFs can be formed and extended in such rocks and the injected fluid is not dissipated into a network of shear fractures. However, shear fracturing does occur during such injections as a significant portion of the injected fluid is lost into the permeable natural fracture system.

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Tribute to Jean-Claude Roegiers

Submitted by Kamel BenNackeur; CEO, Nomadia Energy Consulting; Chair, DAMORPHE; and President, Society of Petroleum Engineers, 2022.

I had been informed of Jean-Claude's deteriorating health condition, but when I received the news of his passing away, it was a shock not only to myself, but also to my wife Najoua. To her, he was one of the most extraordinary characters she had met during our 34 years with Schlumberger. And his death is a loss also to many colleagues who knew him during and after the Dowell times in Tulsa, and to many former students all around the world.

I met J-C in the early 1980s, when he was heading the rock and fracturing group at the Dowell Center in Tulsa (OK), and I had a similar role at the Dowell Schlumberger group in Saint Etienne (France). With his charisma, he had created a very talented group that included John McLennan, Emmanuel Detournay, Luc Vandamme, Rob Jeffrey and Nae Kan Ren. Both teams across the Atlantic were developing, among other technologies, three-dimensional fracture propagation models as well as integrated pseudo-3-dimensional fracturing codes. J-C's team was using the displacement discontinuities method (DDM), which is an indirect boundary element method developed a few years earlier by Crouch et al., while we were developing an integro-variational scheme using finite elements; this was a generalization of the technique introduced by Clifton and Abou Sayed. We had regular coordination meetings, where I discovered J-C as a fantastic colleague! His visits to France for project reviews were an opportunity to combine science, business, and certainly to enjoy selected food and wine from one of the most renowned regions for its cuisine (the Lyon area).

Following the acquisition of the remaining half of Dowell by Schlumberger in 1985, it was decided to combine the research and engineering teams of Tulsa and St Etienne, distributing the centers of excellence among the 2 Centers. Given the importance of hydraulic fracturing in North America, it made sense to move my team from France to Tulsa. J-C was an extraordinary host, providing great advice on how to facilitate the integration into the Oklahoman world. This was certainly from his own experience, having moved from Europe to

North America a few years earlier. He had asked if I could bring a few bottles of nice French wine in my shipment to Tulsa. I managed to find some great bottles of Bordeaux 1982, which happened to be one of the best years in the century. Unfortunately, the moving company decided that they could make better use of the beverage, and none of the carefully selected bottles arrived in Tulsa, to our common disappointment!

We were among a few families that moved from St Etienne to Tulsa. The group included talented geomechanical experts, such as Dr Marc Thiercelin, and Dr Jean Claude Hujoux. J-C made us all feel welcome, organizing social events in his nice house in Tulsa. We enjoyed the great hospitality of his wife Jeanne, and were treated to J-C's superb home-made bread and collection of cheese!

During his time in Tulsa, he had developed extraordinary camaraderie with another Dowell colleague, Carl Montgomery, who was heading the engineering department. Carl brought his applied operational knowledge to complement J-C's science. This collaboration was one of a lifetime, and it is best to describe it was using the French expression "comme des larrons en foire." The Tulsa Center remembered for years the extraordinary going away party organized by J-C for Carl in 1986!

J-C always managed to create such a great collaborative spirit within his team, with his enthusiastic character. We continued developing the 2 P3D and the 3D hydraulic fracturing models, and published together several papers in the Goemechanics and the Society of Petroleum Engineers conferences. In our first joint paper[1], we assessed the impact of fluid rheological properties on three-dimensional fracture propagation, using the integro-variational code. We then worked together to publish the first edition of the "Reservoir Stimulation" book [2] in 1987, where J-C co-wrote the third chapter. The first edition came out in record time. J-C also had chapters in the 2nd and 3rd editions of the Reservoir Stimulation book.

In 1988, we worked together to develop a better understanding of multiple hydraulic fractures and their interactions, using displacement discontinuities. The original SPE paper[3] was rapidly accepted for publication in the 1990 SPE Production and Operations Journal, and it had many of the thoughts that are applicable to the

multiple fracture designs in today's unconventional formations. We also analyzed together the mechanisms affecting pressure decline during fracturing, which was subsequently published in the *International Journal of Rock Mechanics and Mining Sciences* [4].

JC was the initiator or was involved in so many projects, including the evaluation of the impact of poro-elasticity and fracture toughness on hydraulic fracturing, combining both numerical and experimental work.

After he moved from Schlumberger at the end of 1988 to become Professor at the University of Oklahoma, we continued our collaboration, and we later published a paper on stress relief by hydraulic fracturing.

In 1993, our paths crossed again, this time in Venezuela. The national oil company (PDVSA), through its subsidiaries Corpoven and Lagoven, was faced with a major production issue in eastern Venezuela. Prolific wells were seeing a major production decline due to the deposition of asphaltenes and the production of sand from very consolidated formations. J-C led the rock mechanics characterization, alongside INTEVEP (PDVSA's research arm), and we jointly recommended hydraulic fracturing to bypass near wellbore damage, and to transform the production's radial flow into a linear regime. The latter would induce a much smaller pressure drop at the wellbore, therefore reducing the risks of asphaltene drop and sand particle transport. We used the fracturing technique very successfully, despite the challenges created by the formation temperatures and the treating pressures. Thanks to J-C's gift of persuasion, fracturing became the completion technique in the whole deep eastern Venezuelan fields.[5]

Throughout the years, we stayed in touch, and he would always have new ideas for research funding, which allowed his department to get a record level of financial resources. Because of this, it led to financing a whole generation of talented geomechanics around all continents. Whenever I would move to a new position, J-C would be among the first colleagues to call me to congratulate me, and propose areas of collaboration!

For me J-C represents a great combination of a

very talented scientist, a team builder, a teacher, a family-person, and ... the ultimate "bon-vivant"! Rest-in-peace Jean Claude ! We will greatly miss you !

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The Energy Transition, 2022

Submitted by Sidney Green; CEO, Enhanced Production, Inc (EPI) and Research Professor, University of Utah.

Purpose

This essay is intended as a tribute to Jean-Claude Roegiers. During his life, he made many outstanding accomplishments, affecting many persons and contributing not just to the science and technology of rock mechanics and geo-engineering, but ranging as well from free, even provocative expression of his ideas and views to his numerous mentored students that are currently engaged in academia and industry.



The picture is of Sid and Mimi Green with Jean-Claude and Jeanne Roegiers in Salt Lake City, Utah after a dinner sponsored by Dr. Xiaochun Jin, a student from J-C's university.

In tribute to J-C, this discussion is about the current and necessary transition of the world economy to new and additional sources of energy. J-C was not hesitant to speak freely and to share his feelings. In that same spirit, the author has followed J-C's example and speaks openly about something very important to the world, with direct ties to J-C's field of rock mechanics-geomechanics.

The author notes that energy production and consumption and new and potentially new energy sources are changing rapidly, with more facts emerging and new perceptions being formed almost daily. It is also noted that this writing is not a complete presentation on each topic, but it speaks to today's observations and

understandings that the author feels are worthy to note, and provided here in tribute to J-C.

Introduction

The problem leading to the current energy transition is greatly important. Carbon emissions from current primary energy sources are contributing to global warming. This is a huge worldwide problem, one that is not easily solved, particularly in the near-term. Although not obvious at first thought, rock mechanics and geomechanics -- the strengths of J-C for whom this tribute is written -- play a critical role.

Current primary energy sources of oil, natural gas, and coal come from the subsurface, as do critical minerals required to provide both current energy and new primary and secondary energy sources. And, in this move to new energy sources, it is important to remember that current energy sources provide the energy to develop the new energy sources and the large amounts of minerals and metals that will be required. Additionally, the large scale of energy must be appreciated, a large-scale that requires the use of the subsurface as a key part of the energy transition. Indeed, rock mechanics and geomechanics to characterize and understand the subsurface are important for the energy transition.

What is the Fuss about Climate Change

There is justifiably much fussing about climate change, with global warming a confirmed fact. The planet-warming culprit is generally perceived to be primarily the world's majority primary-energy source of coal, oil, and natural gas. Currently, about 36 billion metric tons of carbon dioxide gas is emitted into the atmosphere annually by burning coal, oil, and natural gas.

However, just as global warming and the contribution from burning fossil fuels are facts, so too is the critical role of primary energy for life and to increase the quality of life throughout the world. Worldwide, a nation's energy consumption is directly tied to gross domestic product (GDP). Life itself and the quality of life is tied to GDP. And, although over the last fifty years the world has become much more efficient at producing GDP with less energy, GDP has increased so drastically that energy consumption -- and corresponding

carbon dioxide emissions -- has steadily grown over the same time period.

These two facts of carbon emissions from burning coal-oil-natural gas and the requirement of energy for life and increased quality of life creates a highly complex conundrum. They tend to be much competing.

What are the Facts about Energy

Energy is economically and physically very large with the world currently consuming nearly 100 million barrels of crude oil daily, over 300 billion standard cubic feet of natural gas daily, and over 24 million short tons of coal daily. It is globally complicated economically and technically, and is a world issue in many ways beyond just climate change.

The complications of energy can lead to misunderstandings -- for example, how the U.S. grid electricity is produced. Figure 1 below shows U.S. electricity production over the past fifty years. This is not a projection, but a fact. In the past few years, production of electricity by coal has decreased, electrical production by wind power has increased noticeably, and electricity produced by natural gas has greatly increased. Today about 40% of all U.S. electricity produced is from natural gas. Solar electricity is in the "All Other" category.

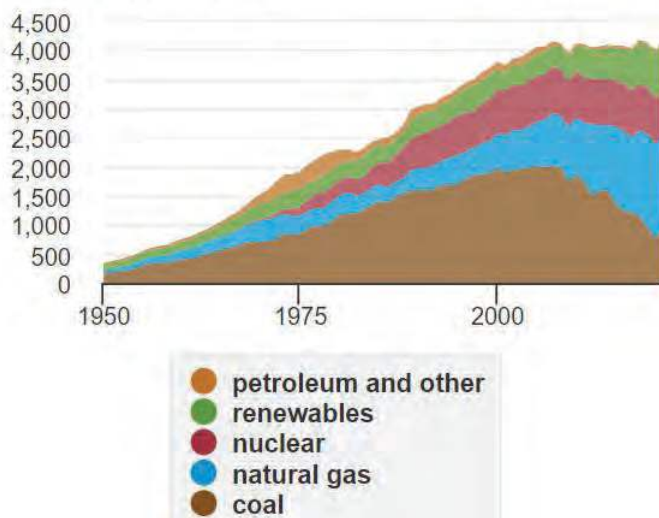
What is the Greatest Complexity Regarding New Energy

For any new energy source to be successful, it must ultimately be evaluated in light of its complete cycle, considering emissions and other environmental impacts, weighing the coupling of technologies and economics, and carefully weighing unintended consequences. Unfortunately, the strong need and desire for world rapid carbon emissions reduction in order to mitigate global warming has not fostered widespread full understanding of new energy options. Even more confusing at times is a lack of appreciation of what is a primary-energy source, such as oil, natural gas, coal, geothermal, solar, or wind, versus what is a secondary energy source such as hydrogen or battery storage. Additionally, discussions of "zero emissions" are at times taken as "no emissions" even though there is no emissions-free energy source, further leading to misunderstandings.

The complete cycle analysis must heavily weigh economics, as economics tend to be a strong driver for adaption worldwide. In considering economics, any new energy source competes with coal, oil, and natural gas, no matter what governments may do in the way of regulations, taxes, or subsidies. That doesn't mean that

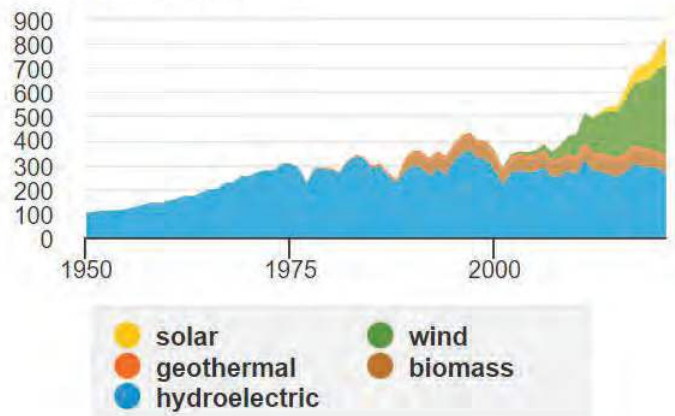
U.S. electricity generation by major energy source, 1950-2021

billion kilowatthours



U.S. electricity generation from renewable energy sources, 1950-2021

billion kilowatthours



Source: U.S. Energy Information Administration, *Monthly*

Figure 1 - US electricity production over the past fifty years.

the new energy source has to be cheaper, but it nevertheless does compete cost-wise and politically for whatever actions governments or private industry take regarding research, regulations, taxes, and subsidies. Government actions can be powerful, but they are far less effective than economics.

What are Current Drivers for Solar, Wind, and EV's

The energy transition is aggressively moving forward with solar and wind electricity and electric vehicles ("EV's"). Solar photovoltaic and wind-turbine electricity direct-electricity-costs have been greatly reduced over the last decade. Likewise, chemical batteries for EV's have increased in energy density while manufacturing cost has been greatly reduced. Of these three initiatives, wind grid electricity has made the greatest impact to date, particularly offshore wind turbines. Worldwide over eighty new offshore wind-farms and over 3000 wind turbines added over 18 gigawatts of capacity in 2021 alone. An even larger number of wind-turbines is under development or planned at present.

For both solar and wind electricity and for EV's, two important technical-economic factors were relatively less examined, but both are now gaining in attention. Promising research is underway, but no clear solutions yet exist.

The first is the intermittent nature of solar radiation and wind speeds. This has led to excess solar and wind electricity being available at some times, yet long-range uncertainties due to prolonged weather changes such as smoke conditions from forest fires or reduced winds in a given region. For large-scale grid electricity, the intermittent electricity production requires large-scale and long-term storage.

Chemical batteries -- primarily lithium-ion batteries -- are being added in some cases for limited short-term storage (a few hours storage). Such high-density energy batteries, however, are cost-wise and scale-wise not possible for the large-scale and long-term storage needed. Flow batteries, particularly iron and vanadium, are being developed, and appear to have possibilities. Several compressed air underground storage facilities are in operation and others are being planned. Hot water storage in sedimentary basin high-porosity formations has been researched

and appears in some ways a possibility for long-term storage. Other novel storage concepts are being researched.

The second factor is the availability and cost of required minerals and metals for large-scale solar, wind, and EV adaption. Critical minerals costs have greatly increased in the past year and supplies are being stretched. Neither new minerals availability nor large-scale practical and economic recycling of minerals is yet clearly on the horizon. Some suggest that for minerals currently available, world EV production may be near capacity at about or slightly higher than ten million plug-in electric cars and light trucks manufactured annually.

Unfortunately the intermittent nature of solar and wind electricity and the rising costs of required minerals and metals, make both solar and wind produced grid electricity and EV battery costs difficult to be further reduced. Costs may in fact increase in the near-term, and world availability of copper, aluminum, lithium, cobalt, nickel will at least somewhat limit solar, wind, and EV's expansion.

What about Hydrogen as an Energy Source

Hydrogen as an energy source has what would appear to be two very attractive features; it can be produced from water and when it 'burns' it produces only water. However, hydrogen is not a primary fuel, but must be produced. This energy, which in the future may possibly be from solar or wind energy requires energy to produce.

About 90 million metric tons of hydrogen is currently produced worldwide per year, nearly all made from natural gas. Hydrogen is today primarily used for refining crude oil and for chemical processes including producing ammonia for fertilizer.

Commercial electrolyzers are being manufactured to produce hydrogen from water using electricity, primarily increasing scale as opposed to breakthroughs in efficiency of hydrogen production. Some hydrogen production cost reduction estimates of fifty percent in the next half decade have been made, but this would still leave hydrogen from electrolyzers more expensive than production today from natural gas.

Hydrogen is a high energy density source by

weight, but a low energy density by volume. This requires that in many applications hydrogen must be compressed to high pressures or liquefied to increase its energy density by volume. For example, hydrogen at atmospheric pressure and temperature has about 325 BTU's per cubic foot of volume, while methane has slightly over 1000 BTU's; gasoline has about 900 thousand BTU's per cubic foot, and coal about 784 thousand BTU's per cubic foot. Hydrogen compressed to 10,000 psi has about 245 thousand BTU's per cubic foot, and liquefied at atmospheric pressure about 275 thousand BTU's per cubic foot. Hydrogen fuel cells for electricity production have some advantage in efficiency with about 60 percent efficiency of BTU's to KWhs, while heat to electricity is only about 20-35 percent efficiency BTU's to KWhs.

Because of the low energy density by volume, hydrogen as a transport fuel seems difficult, at least for cars and small trucks. Hydrogen for use in chemical processes where hydrogen is required, and possibly large transportation vehicles on scheduled runs where liquid hydrogen could be used, may offer better opportunities.

At present storage and handling hydrogen are limitations, requiring special materials and substantial new safety requirements. Underground storage is being pursued aggressively, and high-pressure low-weight tanks are being developed for broad commercial applications.

What about Natural Gas in the Energy Transition

Natural gas ("NG"), mostly methane, has been broadly embraced worldwide as a primary energy source, so much so that demand now exceeds supply. Worldwide NG has somewhat replaced coal, leading to a measured reduction in carbon dioxide emissions growth over the past half-decade. At the same time, NG has become the "fill-in" for grid electricity supporting solar and wind grid electricity. Indeed today, solar electricity would much be limited if NG powered turbines were not available. Natural gas has become the largest U.S. electricity producer today, as noted earlier. It has also led to the European Union to consider including NG as a "sustainable clean fuel". And, recent Europe events have moved forward the important role of NG regarding energy security. NG at present is indeed a key player in the energy transition.

NG requires large-scale and long-term storage, as wellhead-to-market poses problems for all-times delivery. For example, the Texas grid electricity issues of February 2021 again showed the risks of NG without near-market storage. The U.S. does already store underground about 4 trillion standard cubic feet of NG annually. Additional storage is needed as NG is more relied on for a primary fuel source, particularly for grid electricity. Unfortunately, local NG storage is not without issues, as demonstrated by the Aliso Canyon, California NG storage well leak in 2017.

What about Carbon Capture

Carbon dioxide capture and storage ("CCS" or "CCUS") is aggressively being pursued. Currently worldwide about 40 million metric tons of carbon dioxide annually are being collected by over a hundred different projects. Many additional carbon capture projects are under development or planning that could more than double the current annual carbon capture. And, recent U.S. government programs present goals of capturing even more carbon dioxide, upwards of an additional one hundred million tons annually. Unfortunately, nearly one-hundred times current annual capture would be needed to remove even ten percent of world carbon dioxide emissions resulting from today's burning fossil fuels.

With respect to CCS or CCUS, two questions seem to emerge, in addition to the scale of the capture required to make a significant impact on carbon dioxide emissions. First, it would seem logical that large point sources—such as large coal-fired electricity generation plants—would be most easily adapted technically and economically. Yet CCS for even the large point sources has not been easy technically or economically. This observation is particularly bothersome. Second, the disposal of huge amounts of carbon dioxide will not be technically, environmentally, or cost-wise easy. Certainly subsurface disposal would seem to be required, and this requires better understanding of subsurface characterization and rock-carbon interactions. With respect to carbon dioxide collection, a concept of injecting entire flue-gas streams is again being considered. Although this would reduce the cost of capturing the carbon dioxide, the large gas volumes to be injected pose issues.

What about Required Minerals for the Energy Transition

Solar, wind, geothermal, hydrogen, EV's, and carbon capture all will require critical minerals, and large amounts of copper, aluminum, and steel metals. This requirement occurs before there is substantial reduction in oil, natural gas, and coal consumption, and before recycling can contribute substantial amounts of re-usable minerals (as noted earlier). Potential demand projections are already raising questions of from-where and how will these minerals and metals be supplied, at what cost, and what will be the emissions and other environmental impacts from their productions. This is particularly complicated in that the energy transition requires minerals and metals that are both energy intensive and with high emissions/ environmental impacts. An additional issue, but not discussed here, is required water, as mineral recovery tends to be water intensive, and often the minerals are found in water stressed regions.

The most advanced weather prediction calculations are at best estimates, while historical trends require significant time in order to develop a “trend”. Of these two methods to estimate weather events, the most reliable may be identifying the “trends”, which weather experts suggest are trending to more frequent and more severe weather related events.

Person and property losses tend to be due to more people and property in more dangerous locations, made worse by any climate-warming caused more frequent and severe events. It would seem important to focus separately on mitigating climate warming -- i.e. the energy transition -- and in managing and preparing for weather related events whatever the cause. Climate related events are long-term related and will not be changed quickly; severe weather events for whatever cause are here today. The energy transition is aimed to help mitigate climate warming in the long term, not to manage today’s weather related events.

Underground Energy Related Storage and Containment			
Storage		Containment	
Compressed Air Storage		Carbon Dioxide Sequestration	
Crude Oil Storage		Drill Cuttings Disposal	
Hot Water-Cold Water Storage		Nuclear Waste Disposal	
Hydrogen Storage		Oil/Gas Produced Water Disposal	
Natural Gas Storage		Waste / Toxic Materials Disposal	
Pumped Hydro Water Storage			
Propane / Light Hydrocarbons Storage			
Engineered Cavern Storage or Disposal		Rock Pore-Space Storage or Disposal	
Compressed Air Storage		Carbon Dioxide Sequestration	
Crude Oil Storage		Drill Cuttings Disposal	
Hydrogen Storage		Hot Water-Cold Water storage	
Nuclear Waste Disposal		Hydrogen Storage	
Propane / Light Hydrocarbons Storage		Natural Gas Storage	
Pumped Hydro Water Storage		Oil/Gas Produced Water Disposal	
		Waste / Toxic Materials Disposal	

Figure 2 – Underground Storage and Containment

What about More Frequent and Severe Weather Events

Climate-change weather events that may be caused by climate warming are not directly a part of the energy transition. However, the energy transition is being somewhat driven by severe weather events such as forest fires, floods, tornadoes, hurricanes, high tides and ocean surges, and extreme hot or cold periods.

What is the Role of Rock Mechanics-Geomechanics

Regarding rock mechanics-geomechanics, the subject of this tribute, two important areas emerge. Both are critical for the energy transition.

First has to do with the production of currently required energy sources, oil, natural gas, coal, and geothermal energy, particularly natural gas from unconventional resources. As noted earlier, natural gas is clearly a key player in the energy

transition. With respect to natural gas production, the low recovery factor of natural gas (and oil) from the abundant unconventional formations is an opportunity for technology advances that could have a large favorable impact on the world, allowing a faster energy transition with lower environmental impacts (i.e. more oil/gas from the same drilling and fracking and at lower cost). Also as noted above, is the requirement for critical minerals to support the energy transition. Providing energy and minerals for the energy transition requires rock mechanics-geomechanics.

Second is the great importance of underground storage and containment required by current energy and for the energy transition. The importance of the subsurface arises with the appreciation of the large scale of the required storage/containment. It's huge; whether storage for subsequent retrieval or for containment for permanent isolation.

Regarding underground storage and containment, there are many projects underway throughout the world, some with decades of experience. Today U.S. examples include storage up to 170 million barrels of crude oil in the Strategic Petroleum Reserve, underground injection of most of the 21 billion barrels of oil/gas produced water (mainly salt water) each year; storage and withdrawal of about 4 trillion [standard] cubic feet of natural gas each year; and underground nuclear waste storage used for certain military waste disposal.

Underground storage and utilization currently in practice or in the R&D stage, divided into "storage" and "containment" and into "engineered caverns" or "rock pore-space" storage categories is shown in Figure 2 above. The energy transition is requiring more storage—much more—and has different storage requirements.

Even with the experience that exists and the projects underway, some technical experts, practicing businesses, and investment groups are drawing attention to "storage"—or really, the lack of storage. For examples, carbon capture planning and investments are moving forward while containment technology for large amounts of carbon dioxide isn't so clear; solar electricity capacity is being installed but without storage for anytime electricity needed to manage its intermittent nature and the underground offers the potential for large-scale and long-term

storage. The same is true with respect to gaseous hydrogen storage, with required storage driven largely by the low energy density of hydrogen by volume. And, certainly nuclear electricity has for decades been deterred by lack of acceptable nuclear waste permanent storage. Overall, some economists are noting that the energy transition may see limitations caused by lack of proven and developed storage and containment.

For underground storage, cost, safety, and environmental considerations require application of sophisticated rock mechanics-geomechanics applications. The "underground container" may be the most difficult to assure, and poses substantial up-front costs. Experience has shown that the subsurface is the source of the highest cost uncertainty and the highest risks in many cases.

With respect to rock mechanics/geomechanics needs, industry practices presented by experts in technical papers, panel discussions, and invited presentations are helpful to establish research priorities. Highlights of these priorities that seem to have emerged are the following:

1. Better deployment of the vast oil and gas technology for subsurface storage applications,
2. Improvements in site characterization including practical workflows, particularly for accessing seals/cap rocks, location of faults, deep formation layer interfaces, and interconnections of offsetting reservoirs,
3. Development of better understanding of rock-fluid chemical interactions, both immediate reactions and long-term effects including mineralization and high-temperature reactions for given applications,
4. Development of better understanding of cyclic applications on rock integrity and on rock-fluid chemical reactions, and
5. Development of risk analysis and of long-term monitoring protocols, particularly considering induced seismicity.

What Recent Observations have Emerged

For the energy transition, two very profound matters have recently emerged. Neither is new, but events and better understandings of the energy transition have moved these to the forefront.

First, is the importance of energy security, and how the energy transition can affect energy security. Energy is not a luxury; it is essential for survival. Europe's energy transition, the conflict in Europe, and the cost of energy in the U.S. have clearly again shown the great importance of energy supply. This was shown so well in the 1970's energy crisis in the U.S., and certainly is shown again today.

Second, is the appreciation of the requirements needed to allow a rapid energy transition. Available and low cost energy and critical minerals and metals are required. It takes energy to achieve an energy transition, and equally critical, are the minerals and metals needed for the new energy sources.

Conclusions

The warming of the planet is a measured fact, and that the burning of fossil fuels for energy contributes to this warming is a scientific fact. The carbon dioxide content in the atmosphere is a fact, and recent measured carbon dioxide amounts are the highest ever in recorded history. An energy transition toward more sustainable and lower greenhouse gas emissions is underway led to a large extent by the U.S. and Europe. Its aim is to replace as much as possible oil, natural gas, and coal as quickly as possible. Unfortunately, the competing interests of world beneficial effects of abundant and low-cost energy versus huge environmental impacts are worldwide very complex.

In this energy transition, natural gas is providing a larger part of world energy, while a strong focus is being placed on solar and wind renewable energy sources. Geothermal energy, carbon dioxide capture and sequestration, and hydrogen as a replacement for some oil and gas are all being advanced. Nuclear energy is being considered, but at a slow pace. R&D on a variety of additional energy related technologies is underway, with some in the field demonstration or early commercial small-scale stage.

How much the current energy transition will slow world carbon dioxide emissions growth in the near term is not clear, as the demand for energy continues to grow at a high rate while current high energy costs limit resources that could be used for an energy transition. Furthermore, forest fires

and volcanos are annually adding large amounts of carbon dioxide into the atmosphere, while reduced world forests are lowering the carbon dioxide up-take -- these are large compared to today's solar and wind electricity and EV impacts on reduced carbon dioxide emissions, the parts of the energy transition receiving the most attention.

A complete-cycle analysis of each energy transition option is greatly needed -- not just a complete cycle emissions analysis, but an analysis coupling technology and economics with all environmental impacts, and considering unintended consequences. To the author's knowledge, this is not being done.

It would appear to the author that today only two primary energy sources may exist that could have a worldwide impact to lower carbon dioxide emissions in the medium and long-term. These include natural gas, to a large extent somewhat replacing coal, and nuclear energy. Natural gas is already being deployed, and seems to only be limited by supply and cost. U.S. natural gas from unconventional formations has been the world driver for this. The rapid deployment of small-scale nuclear power -- sometimes referred to as "micro-reactors" -- possibly could provide almost unlimited energy. A first (to the author's knowledge) has recently gone on line in China using helium as the heat-transfer fluid. Nuclear energy would appear to be a high immediate priority; however, this cannot be accomplished without broad public support, which requires a better understanding of risks and safety offered by the newest nuclear reactors.

Unfortunately, neither natural gas nor nuclear offer a "free lunch," so to speak, but would require a big, big effort to make happen. For each, the public and governments must both play a strong role making compromises based on realistic deployment times considering realistic technology, economics, and consequences.

Mentor, Colleague, Friend

Submitted by Ahmad Ghassemi, University of Oklahoma

Shortly after joining the faculty of the University of Oklahoma (O.U.) in November 1988, Jean-Claude Roegiers (J-C) started the O.U. Rock Mechanics program. My interactions with him began as a student strongly interested in poroelasticity and hydraulic fracturing. I had heard J-C was starting a petroleum geomechanics program with a large rock mechanics lab (which continues to be the largest academic rock mechanic lab in the U.S. -- if not the world). On my way to a Texas university, I stopped at O.U. to visit with him to explore graduate research opportunities. When he generously offered me a R.A. position, I made the decision to stay.

J-C's group grew rapidly with many graduate students and post-docs supported by multi-million-dollar funding from the NSF and the petroleum industry. This led to the formation of the O.U. Rock Mechanics Institute, a major national/international center for petroleum geomechanics. As is well-known, J-C was very much interested in poroelasticity, both in wellbore stability and hydraulic fracturing (HF). In relation to the latter, he would emphasize the need to do away with the leak-off coefficient by developing advanced coupled poroelastic models. He had a

broad R&D vision and could quickly discern the practical significance of scientific discovery.

As evident by the breadth and depth of work during his years as an O.U. faculty member, he had a grand research plan dealing with different aspects of petroleum geomechanics. Each student worked on a portion of this plan, from wellbore stability to hydraulic fracturing to naturally fractures reservoirs and rock fractured mechanics, with major emphasis on modeling or experimental research. On the other hand, he always encouraged students to get exposed to both modeling and experimental work. Due to my familiarity with displacement discontinuity, he encouraged me to do 3D poroelastic HF modeling, building on the works of Vandamme and Carvalho. This culminated in a 3D poroelastic HF model. Of course, fracture driven interactions (FDI) were not a major issue of concern back then, but the experience has been very useful since. I was also fortunate to have the opportunity to spend a good amount of time on measuring poroelastic properties of sandstones and limestones while working for J-C.

As a supervisor and a mentor, J-C had a student-friendly philosophy, reflecting his own personality as well as his experience with his own advisor, Prof. Charles Fairhurst. He was generous and moved barriers to achieving goals -- from simple things like access to the copy machine and the Rock Mechanics Library to mitigating the infamous university bureaucracy, including funding for attending conferences and, of course, enjoying



Attending a gathering of rock mechanics graduate students during retirement, Norman, 2014.

some fun times together. He always encouraged us to aim high, to persevere, and to keep pressing, and always encouraging our professional success.

J-C always enjoyed a good debate and was open to controversy and dissenting opinions. Of course, one understood the situation and got the message when hearing “I personally believe....” He loved to be involved with graduate students even after retirement, serving as a committee member and attending group functions -- particularly if a party was on the horizon. The following brief technical note is dedicated to his memory as the “Sooner” in the petroleum geomechanics rush.

On Poroelasticity and Hydraulic Fracture Swarms in Unconventionals

Coring adjacent to a hydraulically fractured horizontal well in HFTS-1 and HFTS-2 has revealed several closely spaced parallel hydraulic fractures propagating in the direction perpendicular to the wellbore axis (Figure 1). The observation contrasts with the conventional practice of hydraulic fracture modeling, where a single fracture is assumed to propagate from each perforation cluster. This assumption stems from a simplified concept of the stress shadow that inhibits the growth of multiple parallel fractures under very tight spacing.

An earlier study (Sesetty and Ghassemi, 2019) demonstrated that correct modeling can in fact capture the field observed fracture clusters or swarms of closely spaced hydraulic fractures. Using a 2D fracture model, the study showed that closely spaced fracture clusters or swarms can occur for a certain range of conditions and operational parameters. The in-situ stress differential or contrast, perforation conditions, and injection rates exert a significant influence. Under

the right conditions, closely spaced fractures can extend to distances exceeding tens of feet from the wellbore (Figure 2).

Early termination and/or coalescence of closely spaced fractures can also occur when the above conditions are not met.

The actual cause of the initiation of these multiple fractures is not clear and a number of mechanisms have been proposed, including poroelasticity (e.g., Savitski, 2020), near-wellbore branching, mixed-mode propagation from rock fabric features, and distressing of the stimulated volume and neighboring jobs (Ghassemi, 2020 - ARMA TCHF Robe Talk). In the next section, we reexamine the potential role of coupled poroelastic effects on initiation of fractures in the vicinity of a hydraulic fracture.

A Poroelastic Cause for Fracture Swarms?

Poroelastic effects play an important role in geomechanics of reservoir development including creating a stimulated volume, fracture driven interactions (FDI), induced seismicity and refrac design, and utilization of pressure data to draw conclusions regarding the in-situ stress and the net pressure. These problems are strongly affected by the mutual coupling between rock deformation and fluid pressure (deformation/diffusion phenomena). The fracture driven interactions and refrac design are driven by the rock volumetric deformation in response to pore pressure changes via Biot's effective stress coefficient, $\Delta V/V = \alpha(\Delta p/K)$. On the other hand, pore pressure monitoring for managing fracture-wellbore communication (“frac-hit”) and net pressure estimation are driven by the pore pressure resulting from increased applied mean stress via the Skempton's pore pressure coefficient, $\Delta p = B\Delta P$. Can stress shadow and

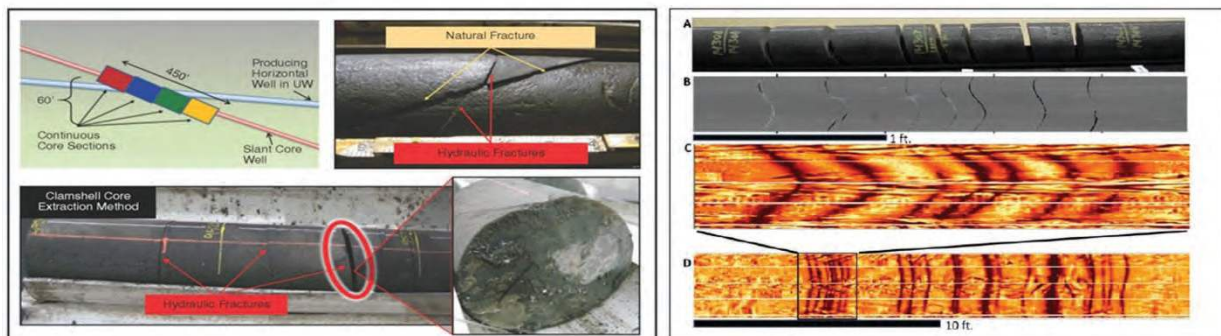


Figure 1. Left: HFTS core from Ciezobka et al., (2018) Frac Facts; Right: tightly spaced hydraulic fractures observed (Rateman et al. 2017).

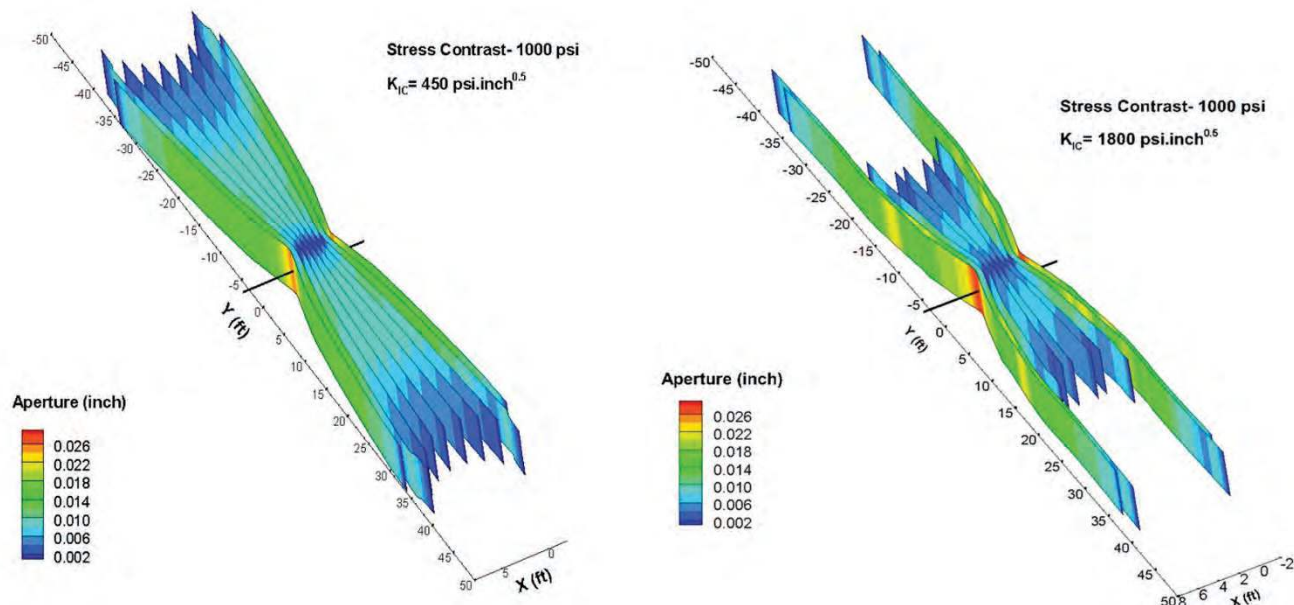


Figure 2. Numerical simulation of closely spaced hydraulic fracture propagating from a cluster. Impact of stress differential and fracture toughness. High stress differential and low toughness promote extensive growth of swarms (Sesetty and Ghassemi, 2019).

the resulting pore pressure caused by the latter mechanism induce sufficient tensile stress to initiate and propagate fractures parallel to the hydraulic fracture? To address this question the problem of a pressurization of fracture in poroelastic shale is studied next.

Although coupled poroelastic effects of interest in refrac generally demand 3D numerical modeling (Safari and Ghassemi, 2010; Kumar and Ghassemi, 2017; Kumar et al., 2018a and 2018b; Masouleh et al., 2020), the current problem can be effectively treated in 2D if the characteristics of such a treatment are noted. Nevertheless, even the less elaborate 2D solution required numerical treatment. The 2D poroelastic DD method (Curran and Carvalho, 1987; Ghassemi and Zhang, 2006) is used in this work to explore the occurrence of significant tensile stresses away from the tip regions to assess the possibility that stress-and leakoff-induced pore pressure would cause fracture initiation in the neighborhood of a hydraulic fracture.

To examine the stress and pore pressure conditions around a hydraulic fracture, the effects of diffusion and stress shadow are each isolated by considering their impact individually i.e., calculating the stress distribution around a fracture using the usual mode 1 and mode 2 loading decomposition (Figure 3). The fracture is assumed to be 2 m and to be in Eagle Ford type shale with properties shown in Table 1.

When the fracture is formed, it is subject to a net pressure; to maximize the effect of the applied stress we choose a relatively high value of 5 MPa for the net pressure. The fracture opens under the applied load and a pore pressure field is generated in its vicinity ($\Delta p = B\Delta P$).

Table 1. Rock mechanical properties and in-situ stresses for Eagle Ford type formation.

Parameter	Value
Young's modulus, E (GPa)	25.1
Poisson's ratio, ν	0.25
Skempton's coefficient, B	0.5
Biot's coefficient, α	0.7
Permeability, k (darcy)	1.76×10^{-6}
Undrained Poisson ratio, ν_u	0.328
Fluid viscosity, μ (Pa.s)	0.001
In-situ pore pressure, p (MPa)	50.0
Min. horizontal stress, σ_h (MPa)	55.0
Net pressure, P (MPa)	5.0

These are plotted in Figure 4 for a short time of 360 seconds. It can be noted that aside from the tip region no significant tensile zones develop. Induced tension is observed away from the fracture surfaces but the values are small and when the background stresses are added they would have minimal impact (unless the minimum in-situ stress and pore pressure are nearly equal in magnitude). If tensile fractures are initiated, they would have to reorient during propagation to become parallel

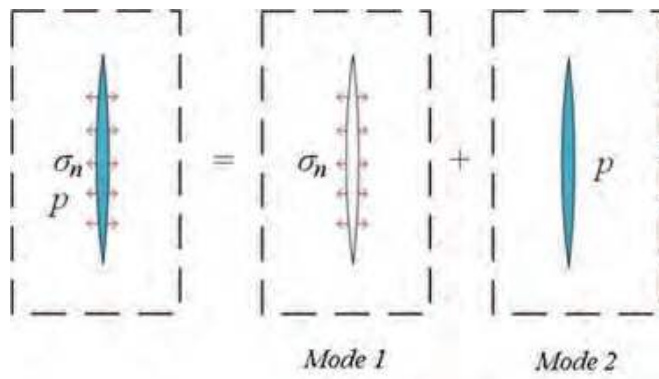


Figure 3. A pressurized fracture in poroelastic formation (Cheng, 2016).

to S_{Hmax} requiring a pressure higher than or of the order of the net pressure in the main fracture, and thus direct communication with the main hydraulic fracture. Evidence of such communication (in terms of proppants in the swarms for example) has not been observed. So that this scenario seems unlikely to generate HF-parallel swarms.

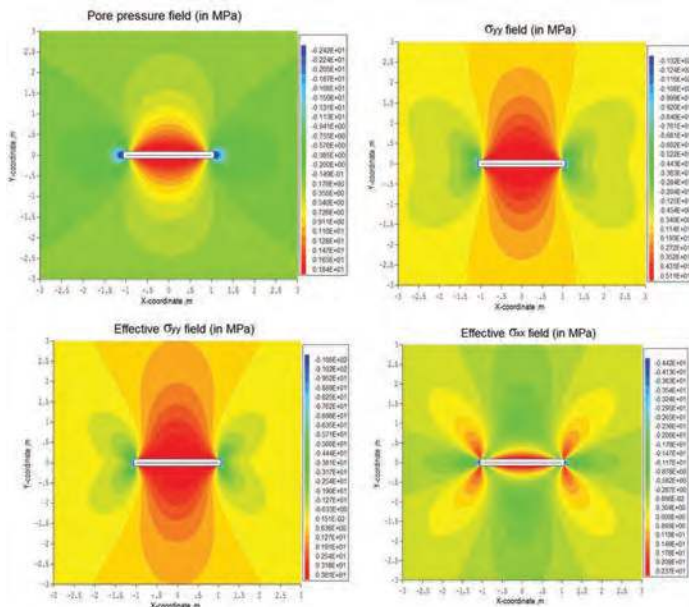


Figure 4. Induced pore pressure and stress components around a pressurized fracture in Eagle Ford shale after 360 sec of pressurizations (mode 1 only).

On the other hand, a scenario can be envisioned whereby the hydraulic fracture is pressurized for a relatively long time (long term mode 2 or the pore pressure loading of the fracture) and then the stress shadow is removed by suddenly depressurization of the fracture. This scenario can occur in the operations once the hydraulic fracture is depressurized after having been pressurized for some time allowing the pore pressure induced by stress and leakoff to spread into the formation. Another possibility is the rapid action of the net

pressure within an intersecting natural fracture (Ghassemi and Kuma, 2022) or a thin permeable layer (Savitski, 2020). To simulate the removal of the stress shadow due to net pressure, only a small (0.01 MPa) net stress is applied while a pore pressure of 5 MPa acts on the fracture surfaces for a long time to simulate the full diffusion effect.

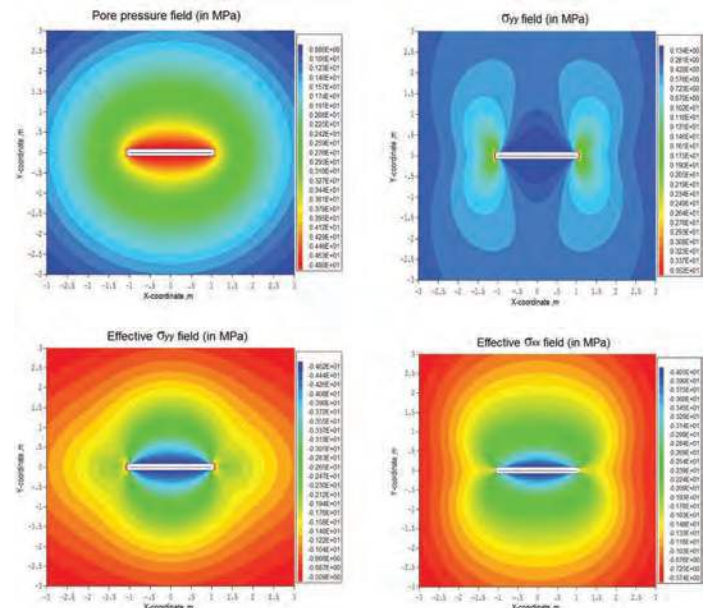


Figure 5. Induced pore pressure and stress components around a pressurized fracture in Eagle Ford shale after 360,000 sec of pressurizations (mode 2 only).

The resulting induced pore pressure and the associated effective stress components are shown in Figure 5. Clearly, there is about 1-4 MPa of tension to a notable distance from the fracture surfaces. The tensile S_{yy} component would tend to initiate fractures parallel to the main hydraulic fracture. The tensile S_{xx} would facilitate opening of fissures and hydraulic communication between the main fracture and newly formed ones. However, it is important to emphasize that the actual stress state (sum of the background and induced values) would still be compressive unless the in-situ pore pressure magnitude is very near S_{Hmin} . Even then these mudstones have a high a tensile strength (2000 psi) so that fracture initiation requires the presence of weak fabric features within the formation with pore pressure values that are close to the S_{Hmin} . One could consider a situation where the Skempton's pore pressure coefficient would be close to unity maximizing the total induced pore pressure. But laboratory measurements of related poroelastic parameters (Zhou and Ghassemi, 2017-2020) do not support this conjecture.

Similarly, examining the potential role of coupled poroelastic effects on fracture initiation in the vicinity of a hydraulic fracture using a fully coupled 3D model (Ghassemi and Kumar, 2022) shows that strong discernments of favorable to swarm formation due to poroelasticity can be caused by the 1D nature of the analysis predicting a significantly higher pore pressure around the hydraulic fracture. Although 3D simulation of a HF connected to a permeable NF demonstrates that under special reservoir pressure and stress conditions a potential for the formation of tensile fracture swarms exists. However, a more likely scenario related to poroelastic effects is the rapid depressurization of a hydraulic fracture after the pore pressure has built up at some distance under the combined influence of the Skempton effect and leakoff. Finally, the common occurrence of swarms in different formations would tend to suggest other causes such as near-wellbore branching, mixed-mode propagation from rock fabric features, and stressing/distressing of the stimulated volume and neighboring stimulation jobs.

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