

**An extended tribute to Professor George Devries Klein (1933-2018):
A sedimentologic pioneer and a petroleum geologist**



BIOGRAPHY

Introduction

George Devries Klein was an iconic sedimentary geologist. He was born in the Hague, The Netherlands (January 21, 1933), immigrated to the United States in 1947, and passed away in Guam (April 30, 2018). He was one of the foremost sedimentary geologists in the world on the application of many facets of earth science. He was an accomplished process sedimentologist, sequence stratigrapher, sandstone petrologist, tectonics specialist, basin analyst, regional geologist, petroleum geologist, and climate scientist. He had a remarkable career in academia, petroleum industry, and consulting. I had the privilege of getting to know Klein professionally during the past 40 years because of my employment with Mobil Oil Company in Dallas, Texas (1978-2000) and because of our shared interests in subsequent years (2000-2018) on the Ouachita Flysch (USA), submarine fans, tidal currents, deep-water bottom currents, sediment deformation, and climate change. The AAPG Bulletin has accepted a short tribute to Klein for publication (Shanmugam, 2018). However, such a short tribute is not proportional to his

monumental contributions with 12 books and edited volumes and over 380 published works. Therefore, this extended tribute, which is a personal reminiscence based on specific publications and events, is offered.

Professional preparation and experience

1954: B.A. in geology, Wesleyan University, Middletown, Connecticut, USA

1957: M.A. in geology, University of Kansas, Lawrence, Kansas, USA

1960: Ph.D. in geology, Yale University, New Haven, Connecticut, USA

1960-1961: Research Geologist, Sinclair Research Laboratories, Inc., Tulsa, Oklahoma, USA

1961-1963: Geology faculty, University of Pittsburgh, Pennsylvania, USA

1963-1970: Geology faculty, University of Pennsylvania in Philadelphia, USA

1970-1993: Geology faculty, University of Illinois at Urbana-Champaign, Illinois,

USA. He was appointed to a full professorship in 1972 and he retired as Professor Emeritus in 1993.

1993-1996: Executive Director, New Jersey Marine Sciences Consortium and director of the New Jersey Sea Grant College, Fort Hancock, New Jersey, USA

1996-2013: President, SED-STRAT Geoscience Consultants, Inc. Houston, Texas, USA

1961-2016: In addition to his teaching undergraduate and graduate courses at various universities, George Klein taught popular short courses on sandstone depositional models and basins analysis for AAPG, SEG and other professional organizations. He presented technical talks at meetings throughout his professional life.

Awards

George Klein was the recipient of 13 awards, including the following:

1969-70: A Visiting Fellowship to Wolfson College at Oxford University, England, UK

1970: SEPM (Journal of Sedimentary Petrology) "Outstanding Paper Award", USA

1980: A Citation of Recognition from the Illinois House of Representatives, USA

1980: The Erasmus Haworth Distinguished Alumnus Award from the University of Kansas Department of Geology, USA

1983: The Japan Society for the Promotion of Science Fellowship, Japan

1989: Fulbright Fellowship to the Netherlands, The Netherlands

2000: The "Lawrence L. Sloss Award" for Sedimentary Geology by Geological Society of America, USA

2013: The "Legend of Sedimentology" award from The Houston Geological Society, Texas, USA.

Retirement in Guam

Following his consulting work in Houston, George Klein and his wife Suyon Cheong, who is originally from Seoul in South Korea, retired to Guam.

SCIENTIFIC CONTRIBUTIONS

Introduction

George Klein was a prolific author with over 380 published works. His research covered a wide spectrum of topics, including tidal sedimentation (Klein, 1970, 1971), estuarine sedimentation (Klein, 1967), lake sedimentation (Klein, 1959), flysch sedimentation (Klein, 1966), Pennsylvanian cyclothems (Klein and Willard (1989), resedimented pelagic carbonate and volcanoclastic sediments (Klein, 1975), DSDP Leg 58 (Klein, Kobayashi et al., 1980), sandstone petrology (Klein, 1961), diagenesis (Klein, 1985), basin analysis (Klein, 1987), tectonics (Klein, 1993), John E. Sanders (Klein, 2000), and climate change (Klein, 2016).

Most of his contributions are archived at the University of Illinois. Details are available at: <https://archives.library.illinois.edu/archon/?p=collections/controlcard&id=2148>. His contributions during the period 1959-2009 are:

- 1) Number of published scientific books and edited volumes: 11
- 2) Number of published articles: 145
- 3) Number of unpublished technical reports: 49

- 4) Number of published review articles and abstracts: 141.

Published scientific books and edited volumes

Andrews, J. E., Packham, G. H., Eade, J. V., Holdsworth, B. K., Jones, D. L., Klein, G. D., Kroenke, L. W., Saito, T., Shafik, S., Stoesser, D. G. and van der Lingen, G.J. (1975). Initial Reports for the Deep Sea Drilling Project, v. 30: Washington, U.S. Government Printing Office, 754 p.

Klein, G. D. (Ed.), (1968). Late Paleozoic and Mesozoic continental sedimentation, northeastern North America: Geol. Soc. America Spec. Paper 106, 309 p.

Klein, G. D. (1975). Sandstone depositional models for exploration for fossil fuels: Champaign, IL, Continuing Education Publication Co., 109 p.

Klein, G. D. (Ed.) (1976). Holocene tidal sedimentation. Dowden, Hutchinson & Ross, Inc., Stroudsburg, PA., 425 p.

Klein, G. D. (Ed.) (1977). Sedimentary processes: processes of detrital sedimentation: Soc. Econ. Paleontologists and Mineralogists Reprint Ser. 4, 236 p.

Klein, G. D. (1977). Clastic tidal facies. : CEPCO, Champaign, IL 148 p.

Klein, G. D., Kobayashi, K., White, S.M., Chamley, H., Curtis, D.M., Mizuno, A., Dick., H.J.B., Nisterenko, G. V., Marsh, N. G., Waples, D. M., Echols, D. J., Okada, H., Sloan, J. R., Fountain, D. M. and Kinoshita, H. (1980). Initial Reports of the the Deep Sea Drilling Project, v. 58: Washington, U.S. Government Printing Office, 1017 p.

Klein, G. D. (1980). Sandstone depositional models for exploration for fossil fuels, 2nd ed.: Minneapolis, Burgess Pub. Co., 148 p.

Klein, G. D. (1985). Sandstone depositional models for exploration for fossil fuels, 3rd Ed. , IHRDC Press, Boston, MA, 209 p.

Klein G. D. (Ed.) (1994). PANGEA: Paleoclimate, Tectonics and Sedimentation during Accretion, Zenith and Break-up of a Supercontinent: Geol. Soc. America Spec. Paper 288, 295 p.

Klein, G. D. (2009). Rocknocker: A Geologist's Memoir, CCB Publishing, British Columbia, Canada, 431p.

Klein (2003) also published a novel titled "Dissensions", exposing intradepartmental power politics among colleagues in universities.

Tidal sedimentology

George Klein is best known for his pioneering research on tidal sedimentology. His observations and concepts on tidal flats in Bay of Fundy, Canada (Klein, 1963, 1964; Klein and Sanders, 1964) paved a long and illustrious scientific career for Klein. Most importantly, Klein (1971) proposed the "Tidalite" concept for the first time. The genetic term "Tidalites" represents a tidal facies formed in response to global astronomical forcing factors (Klein, 1971, 1977). He showed that increasing shelf width also increased tidal range and thus tidal circulation dominated cratonic seaways. His other work on tidal flats includes the documentation of vertical sequences of rocks and sedimentary structures developed in carbonate banks. Also, he developed new criteria for recognizing features and sediment distribution within tidal flats and the tidal reach in coastal areas. Even today, his publications on tidal sedimentation have a profound impact on facies analysis worldwide (Davies and Dalrymple, 2012).

The Ouachita Flysch, USA: Bottom currents, submarine fans, and sediment deformation

The Pennsylvanian Jackfork Group in the Ouachita Mountains of Arkansas and Oklahoma has conventionally been

interpreted as a classic flysch sequence composed of turbidites in a submarine fan setting (Cline, 1970; Morris, 1977; Moiola and Shanmugam, 1984). In the 1960s, at a time when the turbidite paradigm was in full force, Klein (1966) audaciously advocated an alternative interpretation of sole marks in the classic Ouachita flysch by bottom-current erosion rather than by the orthodox turbidity currents. His 1966 publication was a reflection of his courage, innovation, and independence in thinking.

George Klein was the Editor-in-Chief of *Earth-Science Reviews* (ESR) in the late 1980s. After a decade of evaluating submarine fans worldwide, Shanmugam and Moiola (1988) published their review article in ESR. This was my first major encounter with Klein, although his publications had a major impact on my thinking since the 1970s. He liked our ESR paper because it combined sedimentation and tectonics.

Shanmugam et al. (1988) published a paper explaining the origin of sigmoidal deformation structures (i.e., duplex-like structures) by a sedimentary origin in submarine fan channels than by the conventional tectonic origin. This paper caught the attention of George Klein for three reasons. First, the example was from the Ouachita flysch that he studied earlier (Klein, 1966). Second, we explained the origin of duplex-like structures by integrating detailed field observations with sound theory and laboratory experiments. Third, one of his students recognized similar sediment deformation in the modern Matanuska Glacier, Alaska (Lawson, 1981). Soon after our paper was published, we received a complimentary note from George

Klein with a field photograph from the Matanuska Glacier showing excellent sediment deformation. The geometrical similarity in sigmoidal sediment deformation among the ancient (Shanmugam et al. 1988, their Fig. 2), modern (Shanmugam, 2016a, his Fig. 20B) and experimental (Shanmugam, 2000a, his Fig. 18B) examples is striking. The point is that George Klein was quick to make the link between modern and ancient environments. After 1988, I started receiving frequent communications from him on sediment deformation (e.g., Shanmugam, 2017) and on deep-water sedimentation. He also began to attend my talks at AAPG and SEPM meetings regularly. Klein (2009, p. 314) acknowledged our long-term friendship in his book "Rocknocker: A Geologist's Memoir" with a statement "*I also visited the Mobil Research Lab to meet Dick Moiola and Shan Shanmugam with whom I developed a long-term friendship.*"

In part, following unconventional concepts of Klein (1966), Shanmugam and Moiola (1995) published a controversial reinterpretation of the Ouachita flysch as being composed mostly of debrites and bottom-current deposits. Unlike Newtonian turbidity currents, we argued that plastic debris flows cannot develop typical submarine fans. Our paper resulted in 42 printed pages of five discussions and replies in the AAPG Bulletin (Shanmugam and Moiola, 1997). No other paper in the AAPG Bulletin has generated this much controversy. George Klein, who initiated the Ouachita controversy in the 1960s, was pleased by the AAPG debate in the 1990s.

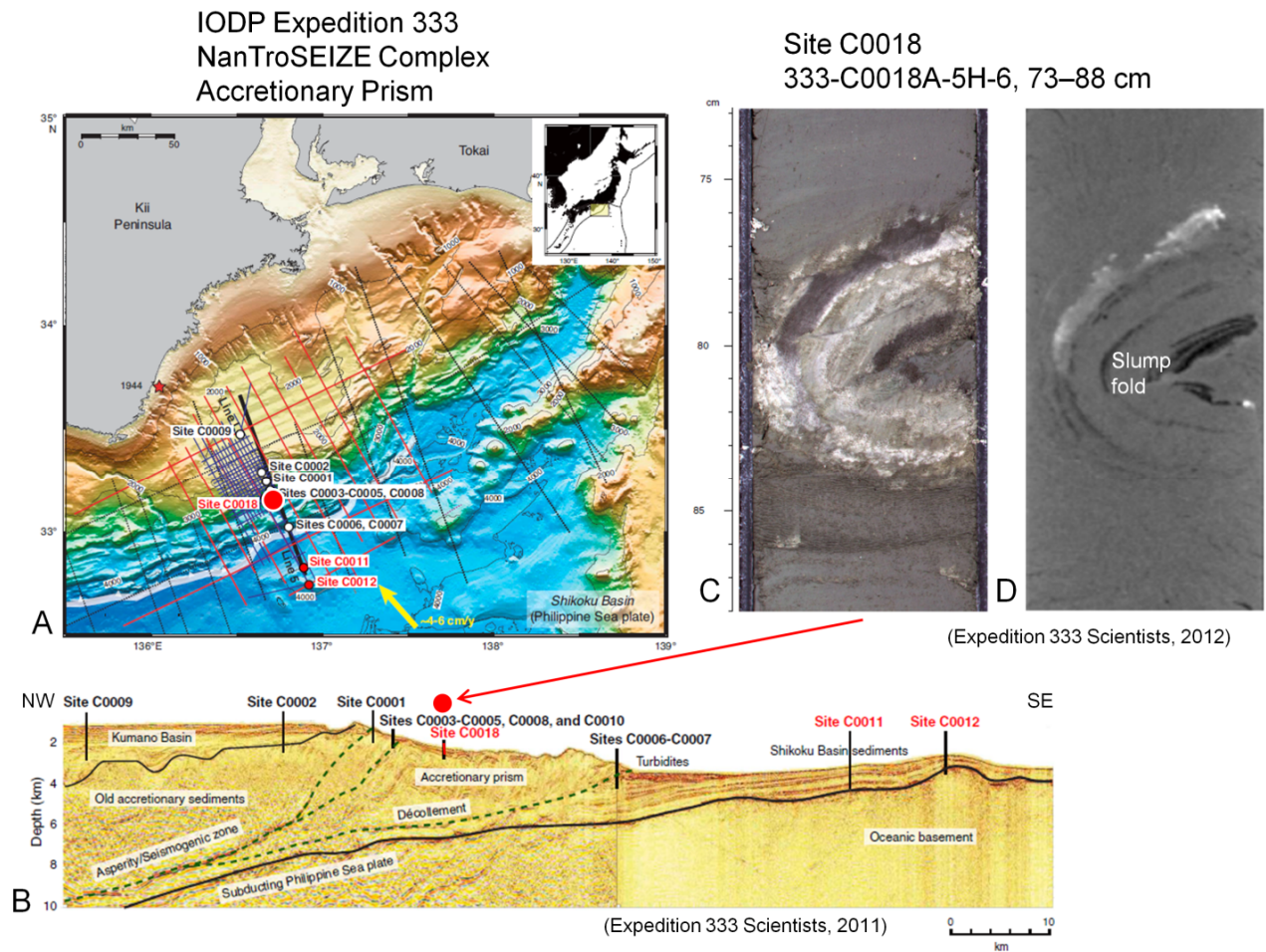


Fig. 1. A - Image showing location of IODP Expedition 333, Site C0018 (filled red circle) in the NanTroSEIZE complex. White barbed line = Position of deformation front of accretionary prism. Yellow arrow = Estimated far-field vectors between Philippine Sea Plate and Japan. Figure from Expedition 333 Scientists (2011), with additional labels by G. Shanmugam. The Shikoku Basin was previously drilled during DSDP Leg 58 (Klein, Kobayashi et al., 1980); B - A NW-SE seismic profile showing position of Site C0018. Note the accretionary prism above the subducting Philippine Sea Plate. Also note location of Site C0012 near the SE end of seismic profile on a Knoll. Figure from Expedition 333 Scientists (2011); C - Core photograph showing slump fold in mudstone. Red arrow points to Site C0018 location; D - CT-Scan image of slump fold in core. Figure from Expedition 333 Scientists (2012), with additional labels by G. Shanmugam. The above composite figure is from Shanmugam, 2017).

George Klein took time to compliment our published works, particularly those that dealt with submarine fans and deep-water sedimentation. After my paper (Shanmugam, 2016b), "Submarine fans: A critical retrospective (1950-2015)" was published, I received an email (5/23/2016 6:20:42 PM Central Standard Time) from him with a note "*Great work Shan and congratulations. Keep the topic moving.*"

DSDP Leg 58 and IODP Expedition 333, Shikoku Basin: Sediment deformation

Klein's multifarious scientific activities included a "Co-Chief Scientist" position of the DSDP Leg 58 that drilled the Shikoku Basin in the north Philippine Sea (4 December, 1977 - 30 January, 1978) (Klein and Kobayashi et al., 1980). IODP Expedition 333 cores from this area showed slump folds. In a recent paper, I documented soft-sediment deformation structures (SSDS) from 140 global case studies, including the Shikoku Basin. In this study, I integrated seismic-scale deformation to core-scale deformation (Fig. 1).

After reading this rather long review paper (71 printed pages), I received an email from Klein (Date: 10/26/2017 9:02:04 PM Central Standard Time) with the following comment, "*I scan-read the paper and it appears to be the most comprehensive one I have seen on the subject. I particularly liked where you had illustration showing map, photo of SSDS and a seismic line or cross-section. Places it all in context for easy visualization and understanding. Keep up the good work. I miss academic research but I don't miss the rest of academe.*" In 2017, Klein was 84 years old and was suffering from a failing health. And yet, he was keeping up with the literature on sediment deformation, which shows his total dedication to science.

John E. Sanders and the turbidite controversy

The late John E. Sanders was George Klein's Ph.D. advisor at Yale University. Sanders' (1965) seminal paper on turbidity currents and their deposits (i.e., turbidites) is still relevant today. In fact, the crux of the turbidite controversy (i.e., whether the basal high-concentration laminar layer is a truly turbidity current or not) today can be traced back to a comment by Ph. H. Kuenen and a reply by J. E. Sanders published at the end of his paper (Sanders, 1965, p. 217-219). In this context on turbidites, Paul Enos, whose Ph.D. advisor at Yale was also John Sanders, received the "Outstanding Paper Award" from SEPM for his paper "Anatomy of a flysch" (Enos, 1969).

Sanders' (1965) concepts on fluid dynamics of turbidity currents had an indelible impact on all my reinterpretations of "turbidites" as "sandy debrites" (Shanmugam, 1996). In particular, my paper (Shanmugam, 1977) "The Bouma Sequence and the turbidite mins set" was reviewed by John Sanders for the journal *Earth-Science Reviews* by the invitation of the then journal's Editor-in-Chief Gerald M. Friedman. John Sanders passed away in 1999. In honoring Sanders' pioneering contributions and those of selected other geologic pioneers, such as James Hall (1811-1898) who co-founded the Geological Society of America, the late Gerald Friedman organized a "Conference on the History of Geologic Pioneers" at the Rensselaer Center of Applied Geology, Troy, New York in 2000. At that conference, Klein (2000) presented a talk "Research guidelines learned from John E. Sanders". George Klein and Gerald Friedman also invited me to deliver a lecture on the influence of John Sanders on my turbidite research. Following my talk "John

E. Sanders and the turbidite controversy" (Shanmugam, 2000b), Gerald Friedman fondly reminisced the pioneering role played by John Sanders during the early stages of the turbidite paradigm (Sanders, 1965; Shanmugam, 2010; Mutti et al., 2009, 2010).

Deep-water sequence stratigraphy

George Klein ran a successful consulting company for the petroleum industry in Houston, Texas. He authored numerous technical reports on sequence stratigraphy for his clients (see University of Illinois Archives, cited above). Houston was also the birthplace of the paradigm of 'Sequence stratigraphy' introduced by the late Peter Vail and his colleagues at Exxon (Vail et al., 1977). Based on sequence-stratigraphic case studies from the North Sea and Norwegian Sea (Shanmugam et al., 1995), I published a critical paper titled "The obsolescence of deep-water sequence stratigraphy in petroleum geology" (Shanmugam, 2007). George Klein felt that local petroleum geologists in Houston should be exposed to my opposing points of view. Consequently, he made arrangements for me to present a lecture on the topic at SIPES (The Society of Independent Professional Earth Scientists) Houston Continuing Education Seminar on January 12, 2009. My talk stimulated a lively debate. George Klein was always willing to consider opposing points of views.

Krishna-Godavari Basin, Bay of Bengal, India: Sandy debrites and tidalites in submarine canyons

As an editor, George Klein invited me to contribute a chapter on "Submarine canyons" to the McGraw Hill Encyclopedia (Shanmugam, 1992). Preparing this chapter paved the way for my future publications on tidal currents in submarine canyons

(Shanmugam, 2003; Shanmugam et al., 2009).

Klein (1975), for the first time, based on studies of DSDP (Leg 30, Sites 288 and 289) cores, suggested that current ripples, micro-cross laminae, mud drapes, flaser bedding, lenticular bedding, and parallel laminae reflect traction and suspension deposition from tidal bottom currents in deep-marine environments. This publication was revolutionary in thinking because traction structures in deep-water deposits were routinely interpreted as "turbidites" in the 1970s. At about the same time, Shepard et al. (1979) measured current velocities of tidal currents in 25 submarine canyons at water depths ranging from 46 to 4200 m by suspending current meters commonly 3 m above the sea bottom. Measured maximum velocities commonly ranged from 25 to 50 cm s^{-1} . Shanmugam et al. (2009) combined the results of Klein (1975) and Shepard et al. (1979) on tidal currents in deep-water environments and applied to the deep-water sands (Pliocene) in the Krishna-Godavari (KG) Basin, Bay of Bengal, India. George Klein served as the primary reviewer for our paper "*Sandy debrites and tidalites of Pliocene reservoir sands in upper-slope canyon environments, offshore Krishna-Godavari Basin (India), implications*" that was published in the *Journal of Sedimentary Research*. The significance is that this case study is a rare example of petroleum-producing debrite-tidalite sandy reservoir.

The contourite problem

Interpretation of traction structures in deep-water deposits has been controversial because their origins have been variously attributed to turbidity currents (Bouma, 1962), contour currents (Hollister, 1967; Shanmugam et al., 1993; Martin-Chivelet et al., 2008), and tidal currents (Klein, 1975).

Furthermore, Lovell and Stow (1981) suggested that contourites can be generated by any kind of bottom currents (i.e., thermohaline, wind, tide or baroclinic) causing additional confusion. I have critically reviewed these issues in a chapter "The contourite problem" (Shanmugam, 2016c) that appeared in the Elsevier Book "Sediment Provenance" edited by Mazumder (2016). Despite his failing health in Guam, George Klein served as the primary reviewer for my chapter. George Klein was chosen as a reviewer because of his established credentials on both bottom currents and provenance.

After his completion of peer review, we exchanged emails on our health issues. In one of his emails (4/30/2016 1:14:49 AM Central Standard Time), Klein wrote "Just remember, Shan, old age is not for wimps." I will miss his wit!

Climate change

Long before climate change became a fad, Klein (1993) was publishing papers on the role of climate on sea-level changes. Even during his retirement years in Guam, George Klein was very active in pursuing research on "Climate Change". He was disappointed that most scientists have failed to take into account all the available data in presenting a balanced account of climate change. He strongly felt that most publications on climate change promoted a false narrative based on computer models, without a robust set of empirical data. In rectifying this problem, he relentlessly gathered data. As a result, he was invited to present a talk, "Some Geological Aspects of Long- and Short-term Climate Change" at the 2016 University of Guam Island Sustainability Conference. He also presented two other talks on the topic, one at the Western Pacific Water and Environmental

Research Institute, and the other at the University of Guam Marine Sciences Laboratory.

Klein (2016) summarized his findings on climate change as follows:

- Geological observations, data and measurements show that throughout the last 600 million years, global temperatures changed independently of changes in CO₂ content.
- The Antarctic Vostok Ice Core shows that during the past 400,000 years increases in temperature occurred ~800-1000 years prior to measured increases in CO₂. Past temperature cycles show that climate always recovered from extremes.
- Evidence for "Tipping Points" and runaway "scenarios" appear absent from the geological record, even though CO₂ content was unusually high during certain past geological periods.
- Pacific Ocean coral reef growth keeps pace with rising sea level; thus barrier and fringing reefs likely can protect islands and island nations from flooding during sea level rise.
- Additional factors contributing to relative sea level change include island thermal subsidence, tectonic uplift, and hydro-isostasy. Mitigation by land-raising is a plausible solution to potentially threatened islands."

George Klein had an uncanny ability to scan through virtually everything that is published on climate change in both print and digital media and to pick out rare nuggets of useful information. He would immediately share the new information with a close circle of 36 scientists worldwide via email. I was fortunate enough to be one among the 36. It was always a delight to

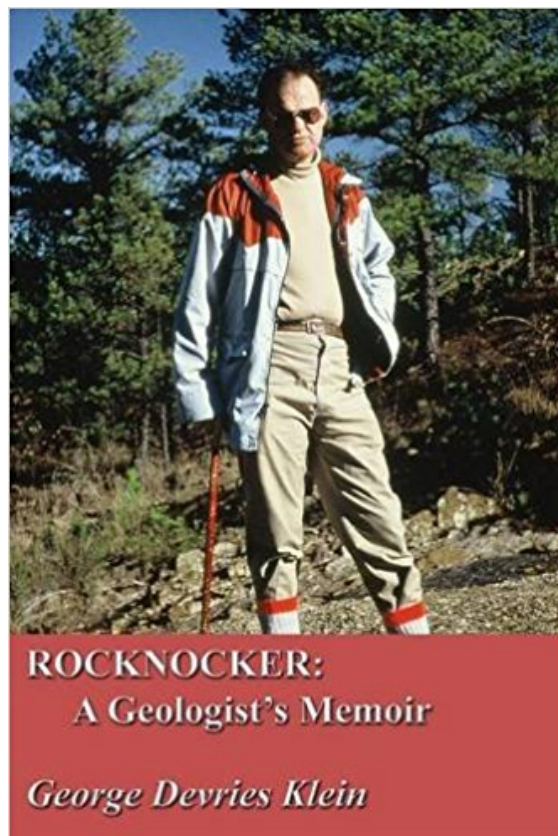
open his frequent emails, expecting some new information on climate change. He was also very sharp in expressing his conservative views on economy, environment, judiciary, media, and politics in the United States.

Petroleum geology

According to Klein (2009), his global consulting work dealing with petroleum reservoirs covered the US Gulf of Mexico, Illinois basin, Appalachian basin, Angola, Senegal, South Africa, East Africa, Brazil, Peru, Venezuela, Mexico, Romania, Russia, and the eastern Mediterranean. It is worthwhile to mention in this context that he discovered on his own or as part of a team some 160 million barrels of oil and some 3 trillion cubic feet of natural gas. By popular demand, a third edition of Klein's (1985) book "Sandstone depositional models for exploration for fossil fuels", was published.

Rocknocker: A geologist's memoir

Klein's (2009) final book appropriately reviewed the life of George Devries Klein. He was an immigrant who made it through the American System as a geologist. The book chronicled his life from early childhood, graduate school, working as an oil company researcher, university professor, science administrator, and as a geological consultant to the petroleum industry. The book included the highs and lows of George's life. Each chapter also summarizes key lessons learned making the book even more useful to young scientists as a career guide.



Book cover: CCB Publishing

EPILOGUE

In his passing, the global geology community has lost a great scientist, teacher, friend, philosopher, critic, guide, and patriot. In an era of 'groupthink', George Klein represented a rare tribe of free-thinking scientists. Fortunately, he left us with a legacy rich in enduring doctrines that future generations will ever be grateful.

ACKNOWLEDGEMENTS

I thank Prof. G. M. Bhat, Managing Editor of JIAS, for encouraging me to submit this tribute. I am grateful to my wife, Jean Shanmugam, for her comments. I also thank CCB Publishing for the use of the cover image of Klein's book "Rocknocker: A Geologist's Memoir".

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