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*South America–Caribbean–  
Central Atlantic Plate Boundary:  
Tectonic Evolution, Basin  
Architecture, and Petroleum  
Systems*

AAPG Memoir 123

Edited by  
Claudio Bartolini

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On the Cover:

FRONT: Eastern Caribbean–Central Atlantic–northeastern South America free-air gravity anomaly map based on Sandwell et al. (2014) (offshore) and Pavlis et al. (2012) (onshore). Credit: Antonio Olaiz, potential field specialist, Repsol.

BACK: Northward 3-D perspective view (DEM) showing the Eastern Caribbean region, the Central Atlantic, northern South America, Trinidad, Tobago, and Barbados islands, Lesser Antilles, Venezuela Basin, Grenada Basin, Tobago Trough, Aves Ridge, and Barbados Accretionary Prism. Credit: Mark Norini, Repsol.

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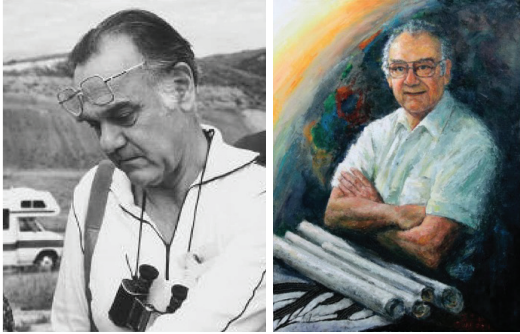
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# Dedication



*A. W. Bally (By Wu, 2012)*

## **Albert W. Bally (1925–2019)**

Albert W. Bally was born in The Hague, Netherlands, on April 25, 1925, and passed away in Houston, Texas, on July 30, 2019. He spent his early years in Indonesia, Italy, and Switzerland. He received a Ph.D. in geology from the University of Zürich in 1952. The Maiella Mountain and adjacent areas of the Central Apennines were the subjects of his Ph.D. dissertation. As student he took a leave of absence in 1949 to work for Gulf Oil on a mapping assignment on southeast Sicily. On weekends and during semester breaks, he helped map the geology of several hydroelectrical projects in the Swiss Alps.

His postdoctoral research in 1953–1954 involved the micropaleontological study of deep-sea sediments of a large piston-core collection at the Lamont Geological Observatory of Columbia University. During this time, he also

taught a course on Alpine geology for graduate students at the Geology Department at Columbia University. Whenever the students giggled, he knew that he had made an English mistake.

Bert, as he was renamed by a personnel manager in Shell, spent most of his career with Shell Oil in Calgary and Houston. He joined Shell Canada in 1954 and was one of the pioneers in the exploration of the Rocky Mountains and their foothills in Alberta. As a novel new exploration approach in a thrust-fold belt at that time, he started to integrate well, seismic, and surface data. From 1961 to 1966, he was the Chief Geologist of Shell Canada helping in the initial projects for the offshore exploration in British Columbia and Nova Scotia. In 1966, he was transferred to Shell Houston and progressed from Manager of Geologic Research to US Chief Geologist in 1968 and later to Senior Exploration Consultant in 1980. During this assignment, he was involved in the exploration of the United States offshore and onshore, and since 1972 with the study of the global geology. By this time, Bert had gathered an enormous amount of experience working with reflection seismic data and regional geological information, which he synthesized into a global basin classification scheme that is still a major reference today.

After Bally retired from Shell, he accepted in July 1981 the position of Harry Carothers Weiss, Professor of Geology at Rice University. He also served as chairman of the department of Geology at Rice until 1986. He successfully managed to make the link between the petroleum industry and academia and brought his experience to the academic world. He supervised numerous M.S. and Ph.D. projects of students coming to Houston from different countries and regions of the world. His students coined the term “Bally’s Barrio” referring to the large group of geologists and geophysicists, often from Spanish-speaking countries, who graduated under his academic guidance. During his tenure at Rice University, Bert collaborated with numerous universities and many oil companies worldwide. His influence and impact on the transformation of the Geology and Geophysics Department at Rice University was crucial.

Bally’s principal research interest was the structural interpretation of seismic reflection profiles, and until his death, he was considered the world’s leading expert in using seismic data to interpret regional geology. His work aimed to show a better reconciliation of the complex structural geology of the upper crust with the presumably less complex nature of the underlying lithosphere (i.e., lower crust and mantle). His main focus was on the geologic definition of regional decoupling levels in compressional as well as extensional and strike-slip regimes. Bally is the father of concepts commonly used today as inversion tectonics, envelopment thrusting, orogenic float, and transfer and listric faults. He is also a pioneer not only in basin classification schemes, balanced cross sections and studies of folded belts, and their forelands but also in understanding continental passive margins and salt tectonics.

Bert also did extensive work on the geology of the Caribbean. He had the opportunity at Rice University to be the director of multiple theses related to the tectonic setting of the Southern Caribbean boundary and the implications for the Venezuelan petroleum systems. This AAPG Caribbean Memoir reflects his contribution as a reviewer and author. After receiving an update on the progress of this book on February 2019, he wrote “This is going to be quite a publication ... I anticipate and hope that the publication of this AAPG volume will herald the beginning of a swift revival of petroleum exploration in Venezuela.”

Albert Bally had numerous publications, but perhaps his most cited article is the one he co-authored with Gordy and Stewart, on the structure and evolution of the southern Canadian Rocky Mountains in 1966. In this work, he introduced the use of regional seismic data to perform balanced cross sections and understand fold-and-thrust belts. With T. Cook he published the Stratigraphic Atlas for North and Central America in 1975, which includes more than 250 maps showing the entire

Phanerozoic stratigraphy of North America. The same year, as an example of the integration of industry and academia, he wrote “A Geodynamic Scenario for Hydrocarbon Occurrences.” It is a worldwide look at types of sedimentary basins and explains the dynamics of the hydrocarbon-bearing basins using the theory of plate tectonics. Two updated versions of this paper were published in 1980.

Most geoscientists are familiar with Bally’s work through his two three-volume sets of seismic atlases published by AAPG: one on structural styles in 1983 and one on seismic stratigraphy in 1987. These atlases highlighted the use of reflection seismic data not only for the petroleum industry but also for academic work. As a counselor with the Geological Society of America, Bert proposed the Decade of North American Geology project (DNAG), a large multivolume encyclopedia for the centennial celebration of the Geological Society of America. Bert co-edited the introductory volume, which many consider to this day the most comprehensive introduction to the geology of North America ever done.

In recognition for his contributions, Albert Bally received many honors, including the William Smith medal (Geological Society of London), the Gustav Steinmann Medal (Geologische Vereinigung), the Sidney Powers Medal from AAPG, the Structural Geology and Tectonics Career Contribution award of the Geological Society of America, and many others. He was also the president of the Geological Society of America in 1988 and president of the Commission of the International Lithosphere Program in 1990–1992; additionally, he was member of numerous geological and geoscience national and international committees, geological societies, and scientific academic institutes worldwide. In 2016, he was awarded a doctorate honoris causa by the University of Fribourg, Switzerland.

However, his former students will not only remember Bally because of his impressive professional achievement and scientific advice but also for his lessons of life. He had an extraordinary ability to make them realize how to approach any problem from a simple and practical side and capturing first the big picture. Bally’s wise advice will always be an eternal guide for them.

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- Roberts, D. G., and A. W. Bally, 2012, Principles of geologic analysis: *Elsevier Regional Geology and Tectonics 1A*, 900 p.



### Harry H. Hess (1906–1969)

While serving in the US Navy during World War II, Admiral Hess became keenly interested in the geology of the ocean basins. Even during the battles of the Marianas, Leyte Gulf, Linguayan, and Iwo Jima, he conducted echo-sounding surveys. Building on the 1912 work of Alfred Wegener and the 1930s work of Arthur Holmes, Hess's research resulted in publication of the ground-breaking "sea floor spreading" hypothesis in his 1962 paper entitled "The History of Ocean Basins," which began the plate tectonic revolution.

In order to further his research on plate tectonics, Hess chose the Caribbean plate as a laboratory. He organized, secured funding for, and directed the Princeton Caribbean Research Project, which was supported by the University, the National Science Foundation, the Office of Naval Research, several oil companies, and the governments of Puerto Rico, Venezuela, and Colombia. This continuing program explored every aspect of Caribbean geology and provided a valuable training ground for graduate students from many parts of the world that produced 34 seminal Ph.D. dissertations on the Caribbean. Most of these Ph.D. recipients continued their Caribbean research and sponsored many additional geological studies of the area.

### Selected Publications

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Hess, H. H., and J. C. Maxwell, 1949, Geological reconnaissance of the Island of Margarita, Part I: *Geological Society of America Bulletin*, v. 60, no. 12, p. 1857–1868.



### Kevin C. A. Burke (1929–2018)

Dr. Kevin C. A. Burke, a world-renowned professor of geology and tectonics at the University of Houston's Department of Earth and Atmospheric Sciences since 1983, passed away at his home in Gloucester, Massachusetts, on March 21, 2018.

He was one of the greatest proponents of plate tectonics and mantle processes in a career that extended over seven decades and influenced multiple generations of geoscientists on many continents. With Burke's passing, a great life force has gone out, but his spirit will live on in all of us that he inspired. Burke was born in 1929 and grew up in London, England, where he received both his B.S. degree and Ph.D. in geology from the University of London in 1951 and 1953, respectively. His Ph.D. study was a mapping and dating study of Barrovian metamorphic rocks and granites in the Connemara area of western Ireland.

From 1953 to 1972, he held a series of geology positions in teaching and research that included postings in Gold Coast, Ghana, the United Kingdom, Korea, Jamaica, and Nigeria. A critical junction in his career occurred in 1972–1973 when he became a visiting professor at the University of Toronto. There, he became a close associate and mentee of Dr. J. Tuzo Wilson, who was one of the most prominent proponents of plate tectonics and hotspot studies at that time. During his time in Toronto with Wilson, Burke began a lifelong study of hotspots, rifting, and mantle processes, which was enhanced by his previous field experiences in Africa and the Caribbean.

In 1973, he was invited by Dr. John Dewey to join a faculty at the State University of New York at Albany, which had assembled a distinguished group of geoscientists interested in the fledgling areas of plate tectonics, hotspot studies, rifting, and field-based ophiolite studies. During his 10-year residence in Albany, Burke produced many seminal papers on continental rifting, hotspots, Caribbean tectonics, and the effects of continental collision in Asia and other continental interiors. In 1983, he joined the faculty of the University of Houston and also worked as director and associate director of the Lunar and Planetary Institute at NASA in Houston until 1988.



In the 1990s and 2000s, in addition to mentoring graduate students and teaching at UH, he held many visiting professorships at NASA, JPL, UCLA, Carnegie Institute, Oslo, and South Africa. He also served on many national committees, including the National Research Council, NASA, and the National Academy of Sciences.

His lifetime achievement awards include the Geological Society of America (GSA) Structure and Tectonics Career Award (2004); the Penrose Medal, the highest award of GSA (2007); and the Arthur Holmes Medal & Membership, one of the most prestigious awards of the European Geosciences Union (2013). Taken from University of Houston Memorial (2018).

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### Gabriel Dengo (1922–1999)

Gabriel Dengo, acknowledged dean of Central American geologists was born March 9, 1922, in the province of Heredia, Costa Rica. Gabriel's formal education began at the University of Costa Rica, where he received a baccalaureate degree in agriculture in 1944. That year he received a scholarship from the Rockefeller Foundation to pursue graduate study in geology at the University of Wyoming, where he earned B.A. (1945) and M.A. (1946) degrees in geology. His Master's thesis was the basis for his first publication: "Geology of bentonite deposits near Casper, Natrona County, Wyoming." He enrolled at Princeton University where he was supported by a prestigious Proctor Fellowship and studied principally under Harry H. Hess, Arthur F. Buddington, and Edward Sampson. He was awarded the Ph.D. in 1949. Gabriel was a well-grounded generalist who made significant contributions in igneous and metamorphic petrology, structure and tectonics, stratigraphy, economic mineral deposits, geologic history, geophysics, and regional mapping and synthesis. For six months in 1950,

Gabriel worked full-time at Princeton as a research associate in the program. In 1950, he returned to Venezuela and served for two years as Senior Geologist in the Ministry of Mines and Hydrocarbons. From 1952 to 1955, Gabriel worked in Costa Rica as a field geologist and supervisor for the Union Oil Company of California. From 1956 to 1962, he was exploration manager in Guatemala. Gabriel returned to Guatemala in 1963 as a consultant for the Organization of American States and was assigned to the Permanent Secretariat of the Central American Economic Integration Treaty (SIECA) as advisor on natural resources. From 1965 until October 1969, Gabriel served as chief of the Geology and Mining Division of the Instituto Centroamericano de Investigación y Tecnología Industrial (ICAITI), Guatemala. From October 1969 to April 1975, he served as General Deputy Director, and from June 1975 through April 1979, as Director. His contributions include editorial service for GSA, AAPG, the Venezuelan Association for the Advancement of Science, and ICAITI. For GSA, he served as councilor from 1970 to 1973 and as a member of the Centennial Committee. He was also an Honorary Fellow of the Society. He was on the committee for the Metallogenic Map of North America and was also senior author. He also edited the DNAG volume on the Caribbean region for GSA. He was a founding member of Sociedad Geológica de Guatemala. Among the many honors and awards he received are AAPG's Michael T. Halbouty Human Needs Award (1995), the Distinguished Services Medal of the Circum-Pacific Council for Energy and Mineral Resources, and Southern Methodist University's Hollis D. Hedberg Award in Energy. The Sociedad Geológica de Guatemala has established the annual Gabriel Dengo Award for Excellence in Earth Sciences, and in 2000, the AAPG executive committee created the Gabriel Dengo Memorial Award to be given to the author of the best paper presented at the annual AAPG International Convention. He was the author or coauthor of more than 60 scientific papers (taken from GSA Memorial, 1999).

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### Paul Mann

I am currently the Robert E. Sheriff Endowed Professor of Geology at the Department of Earth and Atmospheric Sciences at the University of Houston. I obtained my B.A. in geology from Oberlin College in 1978 where I attended the University of Indiana geologic field camp in Cardwell, Montana, as Oberlin did not operate their own summer field camp. The Oberlin geology department was small with four professors and about 5–10 geology majors graduating per year. Most Oberlin classes for geology majors would comfortably fit around a conference table. At Oberlin, I was mentored by Dr. Grant Skerlec, an assistant professor at Oberlin, who encouraged my interests in structure and tectonics and helped steer me in the direction of graduate school. As a liberal arts college and conservatory of music, the Oberlin experience was as much about the arts and music as it was

about the sciences—so I was able to hone skills in writing and critical analysis. I was surprised and pleased to be elected to Phi Beta Kappa in my senior year, which recognized students who had performed equally well in both arts and sciences.

Under the advice of Dr. Skerlec, I visited State University of New York at Albany in the spring of my senior year and met the outstanding tectonics faculty that included Drs. Kevin Burke, John Dewey, Win Means, Bill Kidd, Jeff Fox, Akiho Miyashiro, Steve DeLong, and Mark Harrison. Grant handed me a hardback, dog-eared, mid-1970s Elsevier review volume on ophiolites and advised: “Read this volume before you visit; many of the faculty and grads at SUNY are working on Newfoundland ophiolites.” I recall thumbing blankly through the volume and its specialized vocabulary on the flight from Cleveland to Albany. After a warm reception and productive visit by the grad students and faculty, I applied for admission and a few weeks later received a phone call in Oberlin from Win Means telling me I had been accepted and that SUNY was offering me a three-year graduate fellowship. I was starstruck at his call because we had used Win’s famous structure text in Grant Skerlec’s undergraduate structure class at Oberlin. Three months later, I was sitting in Win Mean’s class on stress and strain where we used his other text on that topic.

My graduate and undergraduate fellow students at SUNY included, among many others: James Pindell, Gary White, Celal Sengor, Keith Mahon, Tim Kusky, Jack Grippi, Bill Bosworth, Janet Fox, Bill Gregg, Jay Ach, Fred Vollmer, Mark Swanson, Rick Livicarri, Bruce Idleman, Mark Hempton, Dave Gallo, Dave Rowley, Andy Bobyarchick, Dwight Bradley, Doug Nelson, Eric Rosencrantz, Jack Casey, and Suzanne Baldwin. What a great peer group I had landed in—and what great mentoring in the transition from sophomore undergrad to beginning grad student. Senior grad students like Bill Bosworth and Bill Gregg would take me aside and say, “OK, listen up, this is how this department works and this is what you need to do.” This group of grads was working in onland areas from Newfoundland, to Turkey, to the coast of Maine, and offshore on spreading ridges and fracture zones in the Atlantic Ocean and Gulf of California. The enthusiasm and pace of both the SUNY faculty and students was feverish: we called it “tectonics fever.”

The SUNY faculty mandate to new graduate students: immediately find an interesting thesis topic—usually structural and tectonic—and figure out to fund the work—usually by writing your own proposal in collaboration with your faculty advisor. In my case, Kevin Burke was looking for a student for a funded NSF project to work in the field in Jamaica. As I timidly entered his office, he barked, “Can you map?” My response: “Yes, I just completed Indiana summer field camp and I got an A in the course.” His reply: “Bring me those maps. I need to need to check that for myself.” I called my parents to have them mail them to me in a large brown envelope. The first “quality time” as a grad student that I spent with Kevin was poring over my summer field camp maps from southwestern Montana. He removed his glasses, put his eyes right up on the map, and quietly studied my maps. He finally commented, “Ah yes, the Laramide orogeny.”

From the icy dead of winter in upstate New York, we flew together to Kingston, Jamaica, in January 1979, with its incredible tectonically controlled geomorphology forming the backdrop of Kingston. Kevin introduced me to all of his Jamaican colleagues

including Trevor Jackson, Ted Robinson, and Grenville Draper, and former students as he had been head of the geology department of the University of West Indies in the 1960s. I immediately acquired a vast, support network who convened most afternoons in the genteel Senior Common Room of the University of West Indies. Occasionally, a stray cow would amble through the bar area.

I was back in the field in the summer and following winter working on the inverted Wagwater rift and the Jamaica restraining bend. In the summer of 1980, Kevin and I again traveled together from Albany to Santo Domingo for the Caribbean conference that is held every three years. Our first night we cautiously made our way through a darkened residential area to the conference center not knowing what the violent crime situation was on the island (it wasn't a problem).

We were introduced to the island-wide geology during an excellent five-day field trip led by the ex-Princeton grad students—including Carl Bowin and Fred Nagle—and local Dominican experts like Romeo Llinas, I was struck by the semi-arid areas of the country, which were such a sharp contrast from the blanketing foliage of Jamaica. My first task was to buy air photos where large structures could be mapped. That trip led to a grant we wrote to NASA that supported our study there and later in Haiti. The Cretaceous–Paleogene geology had been largely mapped but our tack was: *What about the active plate boundary and its Neogene structures?*

The remainder of my Ph.D. study involved mapping in the Dominican Republic and Haiti, along with literature-based review studies of pull-apart basins and Caribbean plate active tectonics. These remaining years of grad school flew by with alternations of long summers in the field, courses at SUNY, and six to eight weeks in the balmy, dry season of the Caribbean during January. I showed up several weeks late for the igneous petrology class of Dr. Akiho Miyashiro, who said to me in his whispering voice, “How can you who show up weeks late and still expect to take and do well my class?” My response was that I was in a hurricane that had severely flooded the island and its roads and bridges so I was unable to return as scheduled. He sighed and gestured for me to take a seat. We all sat in the front row in order to hear his quiet voice.

I arrived in Haiti in the fall of 1982 and appreciate the efforts of a fellow Ph.D. student from France, Thierry Calmus, for patiently showing me how to operate in the field in Haiti. Haiti provided a piece of the jigsaw that allowed connections between my earlier work in Jamaica to the west and Dominican Republic to the east.

After five years of field work and reading every article I could find on Caribbean tectonics, my dissertation ended up being a massive two-volume, phone-directory-like tome, lovingly illustrated with the ink on mylar illustrations and 45 pages of references. I had entered grad school knowing nothing about Caribbean geology; I exited five years later not knowing that much more—but at least having seen many interesting outcrops and knowing how to get there. This five-year whirlwind of activity has served me for decades. I proudly accepted the outstanding dissertation award for the 1983 Ph.Ds. from SUNY, which included a check from SUNY for \$100.

In 1983, I was hired as a research associate by the newly appointed director of the Institute for Geophysics of the University of Texas (UTIG), Dr. Arthur Maxwell. Art had moved from Woods Hole Oceanographic Institution (WHOI) and brought with many of the values and organizational structures of WHOI, which facilitated the expansion and expert management of the research staff at UTIG. UTIG had relocated in that same year from Galveston, Texas, to Austin, Texas, in order to ally with the large geology groups located in Austin (Department of Geological Sciences, Bureau of Economic Geology, which during the early 2000s merged with UTIG to form the UT Jackson School of Geosciences). As young researchers, we were allowed to both teach courses and informally supervise with graduate students from the Department of Geological Sciences—provided we could financially support their studies. For young researchers, this access to highly motivated grad students was invaluable.

It was again by good fortune that I landed amongst an outstanding peer group of land- and ship-based geoscientists at UTIG: Fred Taylor, Cliff Frohlich, David Sandwell, Dale Sawyer, Tom Shipley, Chris Scotese, John Sclater, Jamie Ausitn, Mrinal Sen, Paul Stoffa, Ian Dalziel, Yosio Nakamura, Tosi Matumoto, Mike Coffin, Nathan Bangs, Kirk McIntosh, John Goff, Gail Christeson, and Dick Buffler. The research associate job at UTIG had a simple mandate: write enough proposals to provide six months of our own “soft money” salary support—along with any student support needed—and UTIG would provide the other six months as a hard “state salary.” This system instilled a wonderful sense of focus: write papers, write proposals, get funding, and repeat the process. Art Maxwell and the UTIG administration made no other demands on our time.

At UTIG, projects supported by the Petroleum Research Fund of the American Chemical Society involved a continuation of dissertation-based, basinal studies in the Dominican Republic with University of Texas M.S. students Christoph Heubeck and Rudi de Zoeten and regional studies in Panama and Costa Rica with UH M.S. students Jeff Corrigan and Radim Kolarsky.

It was the hard work and dedication of these early grad students that helped me set the stage to obtain more funded proposals. An early NSF grant with Fred Taylor allowed us to conduct a regional survey of uplifted coral terraces and early attempt of correlating these uplifted coastal areas with depressed basins offshore.

John Ladd and Sandy Shor suggested, why not use a marine geophysical vessel to survey the same faults offshore that you have mapped onshore? This led to other, NSF-funded, offshore mapping collaborations with Eric Rosencrantz, Jim Dolan, and Nancy Grinidlay in Hispaniola and Puerto Rico.

Tim Dixon proposed the idea of a regional GPS survey of the northern Caribbean, which involved Eric Calais, Chuck DeMets, Pam Jansma, Glen Mattioli, and myself. Finally, after many years of controversy, we had a quantitative, velocity framework for the Caribbean plate. During this time, Carol Prentice proposed, why not trench the onland active faults in Hispaniola and Puerto Rico as we routinely do in California? This led to our collaboration that lasted more than a decade of fault trenching in the Dominican Republic and Puerto Rico. In the early 2000s, we applied many of the same type of studies we had done in Hispaniola to the island of Puerto Rico with funding through the USGS-NEHRP program.

In addition of Caribbean work at UTIG, I worked with UTIG colleagues on NSF-funded, marine geophysical surveys of the Macquarie Ridge, Solomon Islands, and conducted fieldwork in the Solomon Islands and Papua New Guinea with Fred Taylor and Brian Horton. In the late 1990s and early 2000s, talented graduate students in the UT Department of Geological Sciences—including Veronica Castillo and Alejandro Escalona from Venezuela and Stephen Babb from Trinidad—led to regional on- and offshore studies of the Maracaibo basin and Trinidad, respectively. The NSF-funded BOLIVAR study of the Venezuelan and Trinidad margins in the early 2000s, ably led by Alan Levander of Rice University, helped expand knowledge of the crustal structure of both the on- and offshore areas of Venezuela and Trinidad.

In the early 2000s, Lesli Wood at the UT Bureau of Economic Geology asked me, why not start using oil industry data to study offshore areas of the Caribbean plate boundary like Trinidad? This question led to an oil industry consortium initially focused on Trinidad, that then expanded to the entire Caribbean in 2005 (Caribbean basins, tectonics, and hydrocarbons), and more recently has expanded beyond the Caribbean basins and to the conjugate margins of the Gulf of Mexico and Atlantic (Conjugate basins, tectonics, and hydrocarbons). In 2011, I moved from research at UTIG to a professor job at the University of Houston where the CBTH continues to operate to the present. We greatly appreciate all for the industry financial support and data that CBTH has received over these years both at UTIG and UH.

Finally, I would like to thank Claudio Bartolini for organizing and editing this AAPG Memoir in the same expert way that he led AAPG Memoir 108 in 2015, and his previous AAPG volumes on the Gulf of Mexico. When I was a first-year graduate student first learning about the northern Caribbean, there was a 1975 volume called *The Ocean Basins and Margins* that was edited by Alan Nairn and Frank Stehli, two gentlemen that I never had the chance to meet. In that volume they had assembled excellent review papers on Jamaica, the Nicaraguan Rise, and Hispaniola that summarized many years of geologic studies in an accessible and well-illustrated way—as this volume will hopefully will do for future workers in the southeastern Caribbean.

### **Selected Publications**

- Carvajal, L. C., and P. Mann, 2018, Western Caribbean intraplate deformation: Defining a continuous and active microplate boundary along the San Andreas rift and Hess Escarpment fault zone, Colombian Caribbean Sea: AAPG Bulletin, v. 102, no. 8, p. 1523–1563, doi: 10.1306/12081717221.
- Gomez, S., D. Bird, and P. Mann, 2018, Deep, crustal structure and tectonic origin of the Tobago-Barbados ridge: Interpretation, v. 6, p. T471-T484, doi: dx.doi.org/10.1190/INT-2016-0176.1.
- Lin, P., D. Bird, and P. Mann, 2019, Crustal structure of an extinct, late Jurassic-to-earliest Cretaceous spreading center and its adjacent oceanic crust in the eastern Gulf of Mexico: Marine Geophysical Research, v. 40, p. 395–418, doi: org/10.1007/s11001-019-09379-5.
- Sanchez, J., P. Mann, L. C. Carvejal-Arenas, and R. Bernal, 2019, Regional transect across the western Caribbean Sea based on integration of geologic, seismic reflection, and magnetic data: AAPG Bulletin, v. 103, no. 2, p. 303–343, doi: 10.1306/05111816516.
- Steier, A. and Mann, P., 2019, Late Mesozoic gravity sliding and Oxfordian hydrocarbon reservoir potential of the northern Yucatan margin: Marine and Petroleum Geology, v. 103, p. 681–701.
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### **James Pindell**

James Pindell took an early interest in plate tectonics while completing a B.A. at Colgate University and continued with an M.S. at SUNY Albany in 1981 on the reconstruction of western Pangea and the evolution of the Gulf of Mexico and Caribbean regions under the incomparable supervision of John Dewey and Kevin Burke. Jim then spent a year in the research arm of Pennzoil in Houston before heading to Durham University in England to complete a Ph.D. in 1985 under John Dewey and Walter Pitman. There, he refined his plate tectonic model for the opening of the Atlantic Ocean basins and the Gulf of Mexico, and the insertion from the Pacific of the Caribbean oceanic crust (Pindell, 1985; Pindell et al., 1988; Pindell and Barrett, 1990; Pindell and Kennan, 2001). This model is now widely recognized as providing the framework for assessments of more local geology across the region (e.g., Pindell and Kennan, 2009; Pindell et al. 2016).

Jim's thesis contributions include: the reconstruction of Atlantic opening history using SEASAT and GEOSAT data sets; the reconstruction of the Alleghanian Orogen through western Pangea; the definition of the two-stage evolutionary model for the Gulf of Mexico, that is, Early and Middle Jurassic northwest–southeast synrift extension followed by mainly Late Jurassic counter-clockwise rotational drift of Yucatan; the recognition of the western GoM as a transform margin; the depiction of the Trinidad-Guyanas margin as a Jurassic, mainly transcurrent continent-ocean margin; the synthesis of plate kinematic and geologic data requiring an Early Cretaceous Pacific origin for most of the Caribbean oceanic crust; the realization that the Bahamas, Yucatán, and northern South America were passive margins through the Cretaceous, and that a “Proto-Caribbean Seaway” or arm of the Atlantic existed between them at that time; the documentation of the relative advance of the Pacific-derived Caribbean plate between the Americas by tracking the eastward-younging development of Caribbean foredeep sections above the American passive margin sections; and the proposal of a two-stage opening history for the South Atlantic in which Africa behaved in the Early Cretaceous as two or possibly three subplates. But the primary underpinning for several of these advances was the drastic (400 km) tightening of the Bullard reconstruction along the Equatorial Atlantic (Pindell and Dewey, 1982; Pindell, 1985). This placed South America 700–800 km closer to North America in the Permian–Triassic, which fundamentally altered our perception of the plate kinematic framework between North and South America during the Triassic–Late Cretaceous, and severely challenged all previous evolutionary models for the Gulf of Mexico.

Professionally, Jim has been fortunate to work with a number of first-rate students and colleagues and has maintained a hand in academia via a series of research appointments at Lamont-Doherty Earth Observatory, Dartmouth College, Oxford University, Rice University, and Cardiff University, the latter two of which are current. In addition, in 1986, Jim formed the exploration research company Tectonic Analysis Inc. to facilitate consortium-style research projects with the oil industry, and in this way began a career-long campaign to document Jim's early interpretation that northern South America was a genuine Jurassic–Cretaceous passive margin with which the Caribbean Plate collided obliquely and diachronously from west to east during Cenozoic time.

Tectonic Analysis thus completed multiple long-term research programs with Ecopetrol (Colombia), PDVSA (Venezuela), Petrotrin (Trinidad and Tobago), and Pemex (Mexico), all funded by industry. Curtis Archie, Julio Cristancho, Jim Granath, Josh Rosenfeld, J. Antonio Escalera, Hans Krause, Roger Higgs, Dick George, John Frampton, Barry Carr-Brown, Bob Erlich, Lorcan Kennan, Alfredo Guzman, Ernesto Miranda, and Jaime Patiño played various instrumental roles in these programs. It is largely from these programs, which integrated and synthesized NOC and Ministry subsurface data with plate tectonic modeling, field work, and lab analyses, that our working models for the evolution of these countries have largely been developed, in tune with the regional Gulf of Mexico and Caribbean plate model (e.g., Pindell et al., 2005). In Trinidad, Sam Algar (Dartmouth College Ph.D. student) dispelled the long-held belief that the Northern Range had undergone Cretaceous orogeny, and in Eastern Venezuela, Johan Erikson (Dartmouth College Ph.D. student) documented passive margin stratigraphic development and relative sea level history from Cretaceous to Eocene time. Tomas Villamil (postdoc) and Claudia Arango determined similar Cretaceous histories from field efforts in Colombia and western Venezuela. From study of these nearly unique exposed Cretaceous passive margin settings, we collectively argued, in keeping with the more theoretical work of Walter Pitman and John Dewey, that eustatic sea level behavior during non-glacial (e.g., Cretaceous) and non-tectonic (passive margin) times lacks high-frequency and large-magnitude (i.e., traditional 3rd order) cyclicity (Pindell and Drake, 1998). In addition, Jim and Roger Higgs focused their field efforts on the palinspastic restoration, Cenozoic arc-continent interactions, and Caribbean foredeep development in northern South America (Pindell et al., 1998). Ken Tabbutt (Dartmouth College postdoc) helped to take that story, and others, farther down the Andes (Pindell and Tabbutt, 1995).

In 1999–2002, Jim developed the Tectonic Analysis Exploration Framework Atlas Series volumes 1–5 with the talented Lorcan Kennan, now at Shell Research. These atlases derived largely from the various national programs and provided concise

paleo-tectonic and paleogeographic summaries and basin assessments for the Andes, Colombia, Venezuela, Trinidad and Tobago, and the Gulf of Mexico–Mexico. Further field and subsurface studies continued with Lorcan Kennan and Roger Higgs through 2008, primarily in Eastern Venezuela, Trinidad, and Barbados, along with progressive upgrades to the original exploration framework atlases.

Since 2010, Jim has focused on Mexico–Central America with Roberto Molina, Uwe Martens, Rod Graham, Diego Villagomez, Gary Gray, Tim Lawton, Bodo Weber, Maria Sierra, Steve Cossey, Henry Coombs, Danny Stockli, and Paul O’Sullivan through his “Cordilleran” industrial research consortium. Also, since 2010, Jim has addressed the processes of rifting and the mapping of crustal architecture in the Gulf of Mexico, the South Atlantic, the SE Caribbean, Panama, and Suriname with colleagues at ION Geophysical (Brian Horn, Adrian McGrail, Ed Haire, Kyle Reuber, Antara Goswami, and Barbara Radovich).

Finally, Jim has assisted with a range of other ongoing academic efforts, such as constraining the origin and migration history of Isla Margarita (southeast Caribbean) with Walter Maresch; gleaning the origins of the Caribbean arcs and oceanic plume with Andrew Kerr, Iain Neill, Douwe van Hinsbergen, and Lydian Boschman; constraining the basements and evolution of Florida, the Bahamas and northern Cuba with Bob Erlich, Paul Crevello, Manuel Iturralde, and Antonio Garcia-Casco; assisting with the interpretation of the Bolivar seismic reflector and refraction experiment in Venezuela and Trinidad with Alan Levander, Hans Avé Lallemand, Gail Cristeson, Jim Wright, and Michael Schmitz; and coleading a western Alps field trip with Rod Graham for the Nautilus training program.

### Selected Publications

- Pindell, J. L., 1985, Alleghanian reconstruction and the subsequent evolution of the Gulf of Mexico, Bahamas, and Proto-Caribbean Sea: *Tectonics*, v. 4, p. 1–39.
- Pindell, J. L., and S. F. Barrett, 1990, Geologic evolution of the Caribbean region: A plate-tectonic perspective, *in* J. E. Case and G. Dengo, eds., *The Caribbean region: GSA Decade of North American Geology H*, p. 405–432.
- Pindell, J. L., S. Cande, W. C. Pitman III, D. B. Rowley, J. F. Dewey, J. LaBrecque, and W. Haxby, 1988, A plate-kinematic framework for models of Caribbean evolution: *Tectonophysics*, v. 155, p. 121–138.
- Pindell, J. L., and J. F. Dewey, 1982, Permo-Triassic reconstruction of Western Pangea and the evolution of the Gulf of Mexico/Caribbean region: *Tectonics*, v. 1, p. 179–212.
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- Pindell, J., M. C. Ernesto, A. Cerón, and L. Hernandez, 2016, Aeromagnetic map constrains Jurassic–Early Cretaceous synrift, break up, and rotational seafloor spreading history in the Gulf of Mexico, *in* C. Lowery, J. Snedden, and N. C. Rosen, eds., *Mesozoic of the Gulf Rim and beyond: New progress in science and exploration of the Gulf of Mexico basin: Transaction of the GCSSEPM Perkins-Rosen Research Conference 35*, p. 123–153.
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- Pindell, J. and L. Kennan, 2009, Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: An update, *in*: K. H. James, M. A. Lorente, and J. L. Pindell, eds., *The origin and evolution of the Caribbean plate: Geological Society (London) Special Publication 328*, p. 1–54.
- Pindell, J. L., L. J. G. Kennan, W. Maresch, K. Stanek, and R. Higgs, 2005, Plate-kinematics and crustal dynamics of circum-Caribbean arc-continent interactions, and tectonic controls on basin development in Proto-Caribbean margins, *in* H. G. A. Lallemand and V. B. Sissons, eds., *Caribbean–South American plate interactions, Venezuela: GSA Special Publication 394*, p. 7–52.
- Pindell, J. L., and K. D. Tabbutt, 1995, Mesozoic–Cenozoic Andean paleogeography and regional controls on hydrocarbon systems, *in* A. J. Tankard, S. R. Suárez, and H. J. Welsink, eds., *Petroleum basins of South America: AAPG Memoir 62*, p. 101–128.

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# About the Editor



**Claudio Bartolini**

**Consulting Geologist, Petroleum Exploration**

Claudio Bartolini is currently a senior exploration advisor at Petroleum Exploration Consultants Americas. On November 15, 2018, Claudio Bartolini was inducted into the prestigious Academy of Engineering of Mexico for his contributions to Mexican geology. As an associate editor of the AAPG Bulletin, he is presently editing a Special Issue on Global Super Basins. Claudio Bartolini was a senior exploration advisor in Repsol's Mexico Exploration Group headquartered in The Woodlands, Texas. For several years, he coordinated technical collaboration agreements between Pemex, Mexican universities, and Repsol, and he was also the international representative for the Mexican Association of Petroleum Geologists (AMGP).

Claudio received his B.S. in geology from the University of Sonora in Mexico in 1983, followed by three years of work as an exploration geologist. He then returned to academia, earning his M.S. in geology from the University of Arizona in 1988, followed by four years as an exploration geologist in Arizona, California, and Mexico with Gold Fields Mining Corporation. In 1992, he resumed his studies at the University of Texas at El Paso, earning his Ph.D. in geology in 1997 and the College of Science's Outstanding Doctoral Student Award. During this five-year program Claudio received a NASA scholarship, as well as financial support from the American Geological Institute, the Houston Geological Society, the Peñoles Mining Company, and the El Paso Mineral & Gem Society. His dissertation fieldwork, which focused in the Jurassic synrift sequence and the Nazas magmatic arc in Mexico, was supported by a research grant from Exxon. In 1994, Claudio did an internship with Amoco in Houston, Texas. While pursuing his doctoral studies, Claudio consulted for several Canadian metal mining exploration companies in Mexico and Central America, and upon completing his doctorate in the summer of 1997, he joined ARCO International Oil and Gas Company's Latin America exploration group, later becoming a basin and field researcher for IHS Energy in Houston, Texas.

Claudio's career with Repsol began with deep-water exploration of the Gulf of Mexico Basin, particularly in Mexico's territorial waters. He worked the Chukchi and Beaufort Seas with Repsol's Alaska exploration team during the 2008 petroleum bid round, and for two years was part of Repsol's Regional Studies Group in Madrid, Spain working on the Llanos Basin of Colombia, while continuing to coordinate the technical collaboration agreement with Pemex on the Campeche area of Mexico. In 2010, he became part of Repsol's New Ventures group Latin America.

Since 1997, Claudio has served as principal editor for several major geological volumes, including the Geological Society of America's Special Paper 340, *Mesozoic Sedimentary and Tectonic History of North-Central Mexico* (1999); AAPG Memoir 74, *The Western Gulf of Mexico Basin: Tectonics, Sedimentary Basins and Petroleum Systems* (2001); AAPG Memoir 79, *The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon Habitats, Basin Formation, and Plate Tectonics* (2003); AAPG Memoir 90, *Petroleum Systems in the Southern Gulf of Mexico* (2011); and AAPG Memoir 108, *Petroleum Geology and Potential of the Colombian Caribbean Margin* (2016). Claudio has now edited this latest AAPG Memoir, entitled *South America–Caribbean–Central Atlantic Boundary: Tectonic Evolution, Basin Architecture, and Petroleum Systems*. These books are all multidisciplinary in nature and are intended to contribute to the knowledge of petroleum geology of Mexico, the Caribbean region, and northern South America. In recognition of these efforts, Claudio was awarded the AAPG Robert H. Dott Sr. Memorial Award for Memoirs 90 and 108. Memoir 90 is a book on the petroleum geology of the Mexican Gulf of Mexico, and Memoir 108 is a pioneering compilation dedicated to the petroleum geology of Colombia.

While collaborating with many international geoscientists, Claudio has received sponsorships from several oil companies actively exploring for oil and gas in Latin America. He has been involved in the organization of international geological symposia. In 2014, Claudio organized a session dedicated to Mexico's deepwater petroleum potential at the annual AAPG meeting in Houston. For the last two years, Claudio has taught a course entitled "How to Write a Scientific Paper" to geology, geophysics, and petroleum engineering students at the School of Engineering of the National Autonomous University of Mexico (UNAM).

Throughout his career, Claudio has reviewed manuscripts for the Geological Society of America, the Journal of Petroleum Geology, International Geology Review, the Mexican Association of Petroleum Geologists, and AAPG. He has contributed geological reports to the AAPG Explorer and coordinated the publication of technical programs and abstract volumes for geological associations across Latin America. He firmly believes that the publication of scientific papers is fundamental for the growth, evolution, and advancement of our profession, and this is the main reason why he continues to pursue these professional activities, spending time beyond his normal professional obligations to work on national and international activities related to geology and hydrocarbon exploration.

## Selected Publications

Bernardo, L. M., and C. Bartolini, 2015, Petroleum source rock in the western Caribbean region: An overview, *in* C. Bartolini and P. Mann, Petroleum geology and potential of the Colombian Caribbean margin: AAPG Memoir 108, p. 201–210.

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Bartolini, C., and M. A. Sanchez, 2008, Regional Mapping of Potential Jurassic Source Rocks in the Deepwater Gulf of Mexico (USA and Mexico): Implications for Hydrocarbons Exploration (abs.): 19th World Petroleum Congress, June 29–July 3, 2008, Madrid, Spain.

Bartolini, C., 2005, The Tampico-Misantla Basin, Mexico: New deepwater plays in a mature basin (abs.): AAPG International Meeting, September 11–14, 2005, Paris, France.

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Bartolini, C., C. Montana, and K. Mickus, 1995, Geological structure of the Parras Basin-Sierra Madre Oriental area, north-central Mexico utilizing geophysical data: American Geophysical Union Transactions, p. 535.

## Personal Dedication

I dedicate this book to my family, particularly to my son Bladimir Ulice and daughter Linda Yolid, for my long absences during their childhood. With all my love to my wife, Gilda Yolid, children, and grandchildren Isabella and Sebastian.



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# Introduction

The discovery of billions of barrels of oil offshore Guyana by ExxonMobil is indeed one of the most important exploratory events to have occurred in the last century near the boundary of the Caribbean and South American tectonic plates. For the first time in history, oil accumulations have been found in Upper Cretaceous sandstone turbidites in Guyana, in the northeast corner of South America. These recent offshore oil discoveries have triggered exploratory activities of international oil companies not only in Guyana but also in contiguous Suriname in the form of awarded blocks, regional seismic surveys, and the drilling of several exploratory wells. Offshore Trinidad, BHP Billiton has acquired extensive 3-D seismic surveys and has drilled four new wildcat wells in blocks recently awarded by the Energy Ministry, and in Barbados, Repsol and BHP Billiton have been awarded several offshore blocks west and south of the island. Thus, this offshore region has emerged as a key area for oil and gas exploration. The integrated 23 papers are critical for the understanding of the petroleum systems and plays, the evolution of the sedimentary basins, and the regional plate tectonic settings of Venezuela, Barbados, Trinidad, Suriname, Guyana, and surrounding geologic provinces (e.g., Tobago Trough). This multidisciplinary AAPG Memoir 123 reflects the world-class research and exploration work conducted for so many years by a large number of geoscientists from different countries in the world.

The complex tectonic origin, the geological framework, and petroleum exploration in the Caribbean region have attracted the interest of hundreds of geoscientists around the world. As a matter of fact, the region has been subject to continued hydrocarbon exploration programs through time, as well as scientific research projects at several universities and research institutions. Even though some areas have been studied in more detailed than others, the present general knowledge of the geologic evolution of the Caribbean Basin is fairly good and comprehensive. There is so much work published and available to our geoscience community that I decided to avoid a section about the geological background and previous studies.

Although very abundant, the literature of the geology and geophysics of the Caribbean Basin is widely dispersed through numerous scientific journals, research papers from Latin and Central America Geological Congresses. Additionally, a lot of theses and dissertations from universities in the United States and some countries in Latin America are another important source of geologic information. Several volumes have been published in the past which are critical for the knowledge of the Caribbean geology; however, there has been a profound need for new integrated volumes reflecting not only the most recent and innovative studies but also the evolution of exploration technology. AAPG Memoir 123 will be an international reference for many years to come.

The geographic area covered by the papers is primarily the offshore basins along the eastern Caribbean margin, mainly Barbados and Trinidad, and the northeastern corner of South America, which includes Venezuela, Guyana, and Suriname. The geological, geophysical, and petroleum systems information contained in this volume comes from different sources in the industry, academia, and research institutions. The focus of this volume is to include all the countries with a history of petroleum exploration and production in this vast region of Latin America. We are all very proud of this first regional integration that contributes to the knowledge of the geology, the geophysics, and the petroleum systems. It is worth mentioning that the book includes several chapters on the geology of Venezuela, a country where scientific publications have been drastically reduced for the last 20 years. One of the key goals of the volume is to emphasize the rise of a new petroleum province in this area of the Americas, with the discovery of billions of barrels of oil in Guyana by ExxonMobil.

This great volume consists of 24 highly technical papers and one field guide from one of the most exciting regions of the Americas: the Caribbean. The technical content and quality of this book were greatly benefitted by the constructive and detailed reviews of a number of volunteer geoscientists who kindly spent their very limited time to improve the manuscripts that constitute this book. Indeed, this book reflects with no doubt the great technical reviews of the following geoscientists: Rick Jowett, Mark Richardson, Stephen Leslie, Raul Ysaccis, Xavier Ravi Moonan, Xiangang Xie, Simon Mitchell, Paul Mann, Rob Govers, Joan L. Latchman, Ronald Steel, Luis Miguel Bernardo, Bill Neal, Joshua Rosenfeld, Gary Prost, William Ambrose, Christian Verard, Joan Flinch, Catherine Homberg, Aline Saintot, Mark Gordon, Jon Blickwede, Peter Bartok, Veronica Castillo, Josgre Salazar, Kevin Mickus, Inessa Yurchenko, Catherine Belgrade, Kevin Burke, Carlos Giraldo, Rasoul Sorkhabi, Albert Bally, Lorena Moscardelli, Randy Keller, Bob Erlich, Joe Curiale, Enrique Hung, and Angel Callejon.

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This new international volume about the sedimentary basins, plate tectonics, and petroleum systems of the Eastern Caribbean and the northeastern corner of South America is dedicated with great respect to the geologists and geophysicists who not only greatly contributed to the Caribbean evolution but who also formed several generations of geoscientists in the Americas. The book honors: Albert A. W. Bally, Harry H. Hess, Kevin Burke, Gabriel Dengo, James Pindell, and Paul Mann.

