SEPM

2018 Garrison Research Conference

Four decades of research on the Monterey Formation and Neogene marine units

May 8th
Santa Cruz, California USA

Technical Program Committee Leaders

Ivano Aiello, Moss Landing Marine Laboratories
Christina Ravelo, UC Santa Cruz

Pre-Conference Field Trip Leader

Richard Behl, California State University Long Beach

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SEPM – Society for Sedimentary Geology
SEPM – Pacific Section
Moss Landing Marine Laboratories
University of California Santa Cruz

INTRODUCTION

The 2018 Garrison Research Conference was held in Santa Cruz on May 7th and was preceded by a 3 days field trip (between May 5th to May 7th) to key outcrops of the Monterey Formation along central California coast.

The Monterey Formation is a Miocene marine unit that occurs extensively in the Coast Ranges and in the continental margins of California and analogous biosiliceous deposits are found around the Pacific Rim and elsewhere in the world. The diatomaceous deposits that characterize the hemipelagic/pelagic facies of the Monterey Formation have been the subject of classic studies exploring the oceanographic and tectonic conditions that promote deposition and preservation of large volumes of organic-rich hemipelagic biosiliceous sediments along continental margins. The Monterey deposits are also known for the “Monterey hypothesis” that links carbon isotopic enrichment events to intense episodes of marine organic matter burial and to the global carbon budget.

In 1981, Robert Garrison, Robert Douglas, Ken Pisciotto, Caroline Isaacs and Jim Ingle were the editors of the keystone SEPM Special Volume " The Monterey Formation and related siliceous rocks of California, Volume 15, Society of Economic Paleontologists and Mineralogists, Pacific Section, Special Publication." Since the publication of the Special Volume there have been significant progresses in our understanding of Miocene climate and oceanography, upwelling sediments such as the Monterey, the evolution of the California Margin and other active/transform upwelling basins: the talks presented during the Conference offer numerous examples of these new exciting new studies.

The Conference was also an opportunity to honor Robert Garrison because his life and career are an example for the science community of a combination of science at its highest-quality, altruism, and humanity. Bob has nurtured the careers of many European and US scientists as well as young scientists across the globe.

Ivano Aiello
Christina Ravelo

SEPM Garrison Monterey Formation Research Conference

May 8th, 2018

Dream Inn Hotel and Conference Center
175 W Cliff Dr.
Santa Cruz, CA

Conference Program

7:30 am	**Registration, badge pick up, and coffee**
8:30 – 9:00 am	Opening remarks
9:00 – 9:20 am	*Tectonic and climate imprint on the regional expression of the Monterey Formation and related biosiliceous rocks in California –* **John Barron**
9:20 – 9:40 am	*Re-visiting the tectonic disruption of a Miocene petroleum system in coastal northern California: a possible Santa Barbara–Santa Cruz–Point Reyes connection –* **Rick Stanley**
9:40 – 10:00 am	*Monterey Formation Lives On In the Bering Sea –* **Dave Scholl**
10:00 – 10:20 am	*The influence of strike-slip tectonics on petroleum system development in the Santa Cruz County Coast area –* **Allegra Hosford Scheirer**
10:20 – 10:40 am	**Coffee break (Poster Viewing)**
10:40 – 11:00 am	*Influence of original sediment composition on the mechanical properties of rocks in the Monterey Formation of the Santa Maria basin, Santa Barbara County, California –* **John Dunham**
11:00 – 11:20 am	*Enhanced upwelling and phosphorite formation during the Late Oligocene warming event in the Eastern Pacific realm: depositional mechanisms and environmental conditions –* **Iris Schollhorn**
11:20 – 11:40 am	*The Monterey Formation in the Santa Barbara, Santa Maria, and Pismo Basins, and "Monterey Beds" in Baja California Sur: an update –* **Karl Follmi**
11:40 – 12:00 am	*Phosphatic, Organic-Rich, and Biosiliceous Facies of the Triassic in Northwest Alaska: Transect Across a High-Latitude, Low-Angle Continental Margin –* **Julie Dumolin**
12:00 – 1:30 pm	**Lunch break (on own, Santa Cruz Wharf or local fare) Poster Viewing**

1:30 – 1:50 pm	*Understanding the Diagenesis and Development of the Mechanical Stratigraphy of the Woodford Shale of Oklahoma Using the Siliceous Mudrocks of the Monterey Formation: Siblings on the Same Road to Brittleness –* **Craig Hall**
1:50 – 2:10 pm	*Multi-Basin Paleoredox Reconstructions from the Miocene Monterey Formation –* **Leanne Hancock**
2:10 – 2:30 pm	*From Depositional Environment to Rock Properties in the Highly Siliceous Sediments of the Miocene Monterey Formation, California –* **Rick Behl**
2:30 – 2:50 pm	*Evolution of Pacific denitrification since the Miocene –* **Christina Ravelo**
2:50 – 3:10 pm	**Coffee break (Poster Viewing)**
3:10 – 3:30 pm	*Relationship of Organic Carbon Deposition in the Monterey Formation with the Monterey Excursion Event –* **Gregg Blake**
3:30 – 3:50 pm	*You can observe a lot by just looking—the utility of sequence-stratigraphic analysis of outcrops in deciphering depositional and diagenetic processes of the Monterey Formation –* **Jon Schwalbach**
3:50 – 4:10 pm	*Nanometer-Scale Pore Structure and the Monterey Formation: A New Tool to Investigate Silica Diagenesis –* **Cynthia Ross**
4:10 – 4:30 pm	*Uranium Isotopes in Organic-Rich Shales as a Proxy for Oxygen in the Ancient Oceans: A Case Study from the Miocene Monterey Formation –* **Kimberly Lau**
4:30 – 5:00 pm	**Closing Remarks** **Poster take down**
7:00 – 10:00 pm	**Dinner – Honoring Bob Garrison** **Dream Inn Hotel, Surf & Beach View Ballroom** Dinner and drink coupon included in conference registration.

POSTERS
Poster Viewing during Breaks and Lunch

- *Hazardous scenarios for Monterey Canyon Geological State Development*
  Nepeina Kseniia

- *Large, Calcite-Cemented Sandstone "Chimneys"; in the Santa Margarita Sandstone, Scotts Valley, California: Solving A Gold-Rush Era Mystery*
  Hilde Schwartz

- *Deciphering the Tectonostratigraphic History of the Ventura Basin using Detrital Zircon Geochronology*
  Clark Gilbert

- *GRA bulk density an indicator of diatom valve abundance and preservation in Pleistocene biosiliceous sediments in the Bering Sea*
  Michelle Drake

ROBERT (BOB) E. GARRISON: A SHORT BIOGRAPHY

Ivano Aiello, Richard Behl and Christina Ravelo

Anyone who has had the pleasure to interact with him, whether as a former student or as a colleague, will tell you that Bob Garrison is not only an extraordinary scientist and a superb teacher, but is also one of the nicest and selfless people that they have ever met. Bob and his wife Jan Garrison have positively impacted the lives of many people with their kindness, open-mindedness, and welcoming attitude. During his long and productive career, Bob has helped to change sedimentologists' understanding of the origin, distribution and diagenesis of fine-grained marine sediments, most notably of siliceous, calcareous and phosphatic rocks. He has generated enormous international goodwill, cooperation, integration and scientific progress with his tireless efforts to involve scientists from all institutions, regions, and countries in the understanding of the sedimentary deposits of the deep sea.

Robert E. Garrison (1975)

Bob is also very modest, and so it fell to us to highlight and share his biography with you for the occasion of the SEPM Garrison Monterey Research Conference held in Santa Cruz on May 8th, 2018.

Bob's life and the different steps of his career coincide with the socio-economics events and the rapid growth in many fields within Earth Sciences and Oceanography during the second half of the 20th century.

Bob was born in 1932 in Texas during the Great Depression when a large part of the population, including his parents were struggling because of the harsh economic situation and the lack of jobs. Looking for a brighter future, his family had moved from Indiana to Texas, because they heard that there were jobs in the oil fields. While doing manual labor at the Texas Oil Company (Texaco), his father studied to become an accountant at a night school in Dallas to improve his status. Opportunity came during World War II when his father was sent to work in Saudi Arabia where Texaco purchased a share in the Arabian-American Oil Company, Aramco. After his father returned from Saudi Arabia the entire family moved to San Francisco when Bob was a teenager.

The early part of Bob's life as a student was in the Bay Area, and he received a B.S. from Stanford University in 1955. Like his father, Bob had to work hard to support himself, and worked day and night serving meals in dormitories while in college. His first inspiration to study marine geology came during a Scripps cruise to the Juan de Fuca Ridge towing magnetometers and mapping magnetic anomalies several years before the idea of seafloor spreading was formulated in 1962 by Harry Hess and others.

While Bob was at Stanford, geologist Bob Compton was an Associate Professor and the main teacher of a field geology course in the Santa Lucia Mountains: it is during mapping on one of these field courses that Bob Garrison had his first encounter with the biosiliceous sediments of the Monterey Formation.

During the Korean War Bob joined the Reserve Officers Training Core (ROTC) Program at Stanford, and after receiving his B.S., he became an Officer in the U.S. Air Force. He served for two years (1955-57) at the Otis Air Force Base on Cape Cod and lived for a time in Woods Hole where he made connections with marine geologists at the Woods Hole Oceanographic Institution.

After receiving a M.S. in Geology at Stanford University in 1958, he was awarded a Fulbright Scholarship at the University of Innsbruck in Austria through 1959. There in the Alps, Bob developed a deep interest in shallow-water back-reef lagoonal limestones. This was the trip of lifetime for another reason, too. It was during this trip to Austria that he met Jan who became his lifetime partner.

Following the Fullbright period Bob worked for two years (1959-61) as a professional Geologist at Sunray DX Oil Co. in Wyoming where he gained an appreciation for the commercial applications of geology and learned how to keep his desk clean.

Unken Valley (Unkental), 1962. Picture of Bob Garrison during his Ph.D. thesis in Austria. The outcrop is a Jurassic pelagic limestone (Ammonitico Rosso facies) overlain by very coarse breccias

Bob was a Ph.D. student from 1961 to 1964 at Princeton University under the mentorship of Alfred Fischer. As Bob often mentions at the end of his talks, finding the right mentor is fundamental for a scientist's career, and for Bob (as well as many others) Al Fischer has been a mentor, a dear friend and an inspiration. Unfortunately, Al Fisher has recently passed away at the age of 96.

For his Ph.D. research, Bob went back to Austria initially to study the Lofer limestones (Early/Middle Triassic Tethyan carbonates), but later to focus on Jurassic pelagic sedimentary rocks. Bob and Al, through the careful examination of Jurassic limestones, demonstrated the biogenic origin of fine-grained pelagic limestones, using pioneering approaches that combined transmission electron microscopy and detailed field stratigraphy. Previously, most geologists thought these to be inorganic sediments. Al and Bob found abundant coccolith remains; to their surprise, they also uncovered a little known and neglected old article by Gustav Steinmann that contained a microphotograph of coccoliths in a thin section of a Tethyan limestone. Their discovery revived one of Steinmann's fundamental contributions to modern geology and plate tectonic theory, namely, the concept of the "Steinmann Trinity", which interpreted the sedimentary covers of ophiolites as deep-sea deposits and not chemical precipitates as previously suggested. Bob continued at Princeton as a Research Associate for a year after completion of his PhD.

Jan and Bob were married in 1963 in the UK during a summer in Europe where Bob was doing PhD fieldwork in Austria. Unfortunately, within a year of their marriage, both of Bob's parents died even though they were still very young. Later, Bob was able to take Jan back to the UK as a Guggenheim Fellow at Oxford University from 1972 to 1973.

The 60's included some of the most exciting years in Bob's career and life. His collaboration with Al Fisher inspired Bob's studies on the origin of bedding in siliceous formations such as the Monterey Formation, and at the same time Bob was exposed to new radical theories in Earth Science. For instance, Bob was a student at Princeton when Harry Hess was giving lectures on his 'crazy' seafloor spreading ideas. That decade also marked the beginning of the Deep Sea Drilling Project (DSDP) in which Bob was one of the earliest participants having sailed on Leg 6 in the Western Pacific in 1969.

Bob's career in academia continued as an Assistant Professor at the newly formed campus of the University of California, Santa Barbara, in 1965 and then after one year he moved on to become an Assistant Professor at the University of British Columbia were he worked between 1966 and 1968.

Earth Sciences faculty at the University of California Santa Cruz (around 1990)

It was in 1968 that Bob and Jan returned to US to make their home in California when he became Associate Professor at the University of California in Santa Cruz only three years after the campus was established. UCSC's first Chancellor, Dean McHenry, persuaded Aaron Waters to move from UC Santa Barbara to UCSC in 1967 to create a program in the Earth Sciences. Between 1968 and 1973, Waters, who was a renowned petrologist, structural geologist and educator, built a faculty of mostly young, energetic earth scientists. In 1973 Bob become

Professor at UCSC and stayed in his role until 1994 when he retired and acquired the Emeritus status.

If the 60's were an exciting time in Bob's life, the 70's were very active and productive. Between 1970 and 1971 he was co-Investigator of lunar rocks returned by the Apollo 12 mission. In 1975, Bob sailed as sedimentologist on Leg 42A of the DSDP in the Mediterranean Sea with a group of scientist including Daniel Bernoulli, Maria Cita, Ken Hsü who then became life-long colleagues and friends. Since their discovery in 1973, the interpretation of the Messinian evaporites was a highly controversial and emotional topic, and during the cruise Bob acted as patient moderator between the proponents of the deep basin shallow-water origin and those who were proposing the shallow basin–shallow water model.

Coffee break in the core lab of the Glomar Challenger during DSDP Leg 42a in the Mediterranean (1975). From left to right: Bob Garrison, Kenneth Hsü, Maria Cita and Daniel Bernoulli

During his career as Professor at UCSC, as a participant in the DSDP and then the Ocean Drilling Program (ODP), and as an active member (including President) of the Pacific Section of the SEPM, Bob has consistently addressed fundamental sedimentologic problems in fields that had previously been inadequately resolved because of the lack of appropriate methodology or due to being outside of popular trends in research. Bob contributed importantly to understanding the origin, diagenesis and distribution of fine-grained, deep-sea and biologically generated or mediated sediments. These are the kinds of sediments that were not easily understood by either physical or paleontological studies alone, but required an integration of traditional methods with modern marine biology, oceanography and paleoclimatology. These sediments include radiolarites, diatomites, porcelanites and cherts, deep-sea and shelfal chalks and limestones, organic-rich mudstones (black shales), and phosphorites.

In the 1980's Bob organized and edited a collection of superb Pacific Section SEPM and AAPG symposium volumes, including the iconic SEPM Special Volume " The Monterey Formation and related siliceous rocks of California". The volume was a transformative approach to sedimentology and included ground-breaking papers written by some of the most innovative geologists of the time like Bob, Jim Ingle, John Barron and others. Their work is the basis for a modern 'paleoceanographic' approach to understanding the Monterey Formation and similar biosiliceous deposits, Miocene climate and the significance of biosiliceous upwelling sediments and phosphorites. The special volumes that Bob edited are still fantastic sources of insight for modern workers.

Bob has been at the center of a group of colleagues investigating the origin and significance of phosphatic rocks who have documented in detail the early diagenesis of pelagic chalks and the significance of hardgrounds, omission surfaces, nodular limestones, and the associated glauconitic or phosphatic condensed intervals in the Monterey Formation and similar upwelling deposits around the world including Egypt, Israel, Oman, The United Arab Emirates, England, Columbia, the Peru margin, California, and Mexico. He feels blessed in having worked collaboratively with talented colleagues, including Daniel Bernoulli and Karl Föllmi in Switzerland, Azuma Iijima in Tokyo, Miriam Kastner in La Jolla, Jim Kennedy in Oxford, and Yeshu Kolodny in Jerusalem: and also with dozens of bright and energetic students in the U.S., Canada, Latin America, Europe, the Middle East, and the Far East.

Jan and Bob Garrison in 2011

After his retirement in 1994 Bob served as Director of the Geology and Paleontology Program of the NSF in 1994 and 1995. In the last two decades while finally being able to spend more time with Jan, Bob has continued his research activity and has made a number of scientific contributions. Following a new interest in fluid and gas seeps, he and colleagues have investigated Miocene seep structures in the Santa Cruz area. In 1999 he was editor of a Pacific Section AAPG publication on fluid seeps in Monterey Bay. In 2001 and 2002, he was also involved in organizing a conference in Azerbaijan on submarine gas seeps and later edited two volumes of Geo-Marine Letters reporting the results of this conference. His recent papers on the role of the Mediterranean region in the development of modern sedimentology and cyclostratigraphy have become required reading in many geology classes in the US and Europe. Bob's contributions were recognized by the national Society for Sedimentary Geology (SEPM) in 2000 with the Pettijohn Medal for Excellence in Sedimentology. In 2012, he was awarded with Honorary Lifetime Membership for his contributions to the Pacific Section SEPM and California geology.

We conclude this short biography of Bob Garrison by plagiarizing the end of one of Bob's seminars on the development of sedimentary geology in the Mediterranean region, in which he advises students what they need to have a rewarding career.

WHAT DO WE NEED?

Encouragement/Support

New Perspectives

The Right Colleagues

Freedom

SELECTED BIBLIOGRAPHY OF R. E. GARRISON

1967 A. G. Fischer, S. Honjo and R.E. Garrison, Electron micrographs of limestones and their nannofossils: Princeton University Press, Princeton, New Jersey, 141 p. (book).

1969 R.E. Garrison and A.G. Fischer, Deep-water limestones and radiolarites of the Alpine Jurassic: *in* Soc. Economic Paleontologists and Mineralogists, Spec. Pub. no. 14 "Depositional Environments in Carbonate Rocks", P. 20-56 (reprinted in *Depositional Processes in Ancient carbonates*, S.E.P.M. Reprint Series).

1971 A.C. Waters, R.V. Fisher, R.E. Garrison and D. Wax, Matrix characteristics and origin of lunar breccia samples 12043 and 12073: *in* Proceedings of the Second Lunar Science Conference, **1**:695-709, M.I.T. Press.

1974 R.E. Garrison, Radiolarian cherts, pelagic limestones and igneous rock in eugeosynclinal assemblages: *in* "Pelagic Sediments: On Land and Under the Sea", Intern. Assoc. Sedimentologists, Spec. Pub. No. 1, p.319-351.

1975 W.J. Kennedy and R.E. Garrison, Morphology and genesis of nodular chalks and hardgrounds in the Upper Cretaceous of southern England: *Sedimentology*, **22**:311-386.

1978 R.E. Garrison, et al., Sedimentary petrology and structure of Messinian evaporitic sediments in the Mediterranean Sea, Leg 42A, Deep Sea Drilling Project: Initial reports of the Deep Sea Drilling Project, v. 42, ch. 32, p. 571-611

1981 K.A. Pisciotto and R.E. Garrison, Lithofacies and depositional environments of the Monterey Formation, California: in Garrison, R.E. and Douglas, R.G. (eds.): The Monterey Formation and Related Siliceous Rocks of California, Pacific Section, Soc. Economic Paleontologists and Mineralogists, Spec. Public., 97-122.

1983 C.M. Isaacs, K.A. Pisciotto, and R.E. Garrison, Facies and diagenesis of the Miocene Monterey Formation, California, in Iijima, A., *et al*., (eds.): Siliceous Deposits of the Pacific Region, Developments in Sedimentology, **36**: 247-282.

1985 K.F. Watts and R.E. Garrison, Sumeini Group, Oman - evolution of a Mesozoic carbonate slope on a South Tethyan continental margin:*Sedimentary Geology*, **48**:107-168.

1987 R.E. Garrison, M. Kastner, and Y. Kolodny, Phosphorites and phosphatic rocks in the Monterey Formation and related Miocene units, coastal California, *in* Ingersoll, R.V. and Ernst, W.G. (eds.), Cenozoic Basin Development in Coastal California, vol. 6 of the Rubey Volumes: Prentice-Hall, Inc., Englewood Cliffs, NJ, p. 348-381.

1987 R.E. Garrison, W.J. Kennedy, and T. Palmer, Early lithification and hardgrounds in Upper Albian and Cenomanian calcarenites, southwest England: *Cretaceous Research*, **8**:103-140.

1990 R.E. Garrison, and M. Kastner, Phosphatic sediments and rocks recovered from the Peru Margin ODP Leg 112 : *Proceedings of the Ocean Drilling Program, Scientific Results*, Volume 112, p. 95-134.

1990 M. Kastner, R.E. Garrison, Y. Kolodny, C.E. Reimers and A. Shemesh, Coupled changes of oxygen isotopes in $PO_4{}^{3-}$ and $CO_3{}^{2-}$ in apatite, with emphasis on the Monterey Formation, California, *In* Burnett, W.C. and Riggs, S.R. (eds.), Phosphate Deposits of the World, Vol. 3, Neogene to Modern Phosphorites: Cambridge University Press, Ch. 23, p. 285-299.

1991 K.B. Föllmi and R.E. Garrison, Phosphatic sediments, ordinary or extraordinary deposits? The example of the Miocene Monterey Formation (California), *in* Mueller, D., McKenzie, J., and Weissert, H. (eds.), *Controversies in Modern Geology*: Academic Press, Ch. 5, p.55-84.

1994 Y. Kolodny and R.E. Garrison, Sedimentation and diagenesis in paleo-upwellingzones of epeiric sea and basinal settings: a comparison of the Cretaceous Mishash Formation of Israel and the Miocene Monterey Formation of California, *in* Iijima, A., Garrison, R.E. and Abed, A.M. (eds.), Siliceous, Phosphatic and Glauconitic Sediments of the Tertiary and Mesozoic: Symposium Volume, 29th International Geological Congress (Kyoto), VSP International Science Publishers, Zeist, The Netherlands, p. 133-157.

1994 R.J. Behl and R.E. Garrison, The origin of chert in the Monterey Formation of California (USA), *ibid*, p. 101-132.

2003 C.R. Glenn and R.E. Garrison, Phosphorites, in G. V. Middleton (ed.), Encyclopedia of Sediments and Sedimentary Rocks, Kluwer Academic Publishers, p.519-526

2009 A.G. Fischer and R.E.,Garrison, The role of the Mediterranean region in the development of sedimentary geology: a historical overview: Sedimentology, v. 56, p. 3–41 doi: 10.1111/j.1365-3091.2008.01009.

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Four decades of research on the Monterey Formation and Neogene marine units

ABSTRACTS

Tectonic and climate imprint on the regional expression of the Monterey Formation and related biosiliceous rocks in California

John A. Barron and Richard G. Stanley
U.S. Geological Survey, Menlo Park, CA 94025

Diatom biostratigraphy constitutes the main biochronologic tool for dating the Monterey Formation and related biosiliceous rocks, although calcareous nannofossils are very useful in lower middle Miocene sections where calcium carbonate is more common. In porcelanites and cherts, post burial diagenesis severely affects diatom preservation, but diatom assemblages sufficient for age control can often be recovered in calcareous concretions and dolomite beds. Here we present an updated review of the Monterey Formation and overlying biosiliceous rocks in the context of changes in global climate and regional tectonic events. Figure 1 shows the ages of various key sections of the Monterey Formation and overlying biosiliceous rocks in coastal California as determined by the diatom and calcareous nannofossil biostratigraphy. The boundaries of the California Benthic Foraminiferal Stages (BFS) are referenced based on their correlation with these zones. The benthic foraminiferal oxygen isotope curve of Zachos et al. (2008) provides a context for generalized climatic change between 20 and 4 Ma with heavier values coinciding with high latitude ice growth and/or cooling of higher latitude regions.

The onset of deposition of the terrigenous sediment-poor organic shales of the Monterey Formation typically falls between about 17 and 16 Ma (early Relizian to earliest Luisian BFS). Climatic warming associated with onset of the Miocene Climatic Optimum marks this period. In the Santa Monica Mountains section of the northern Los Angeles Basin, however, the onset of Monterey Formation deposition (locally called the Modelo Formation) is delayed by as much as three million years due to the continued deposition of clastic sediments of the Topanga Formation. In most coastal sequences, lower middle Miocene (~16.0 to 13.5 Ma, Luisian BFS) sediments are rich in both calcareous and siliceous microfossils and appear to be uninterrupted by unconformities. Overlying lower Mohnian (BFS)(~13 to 10 Ma) sequences in coastal and offshore southern California are typically condensed, coinciding in time with falling eustatic sea level and uplift of structural highs in the southern California Continental Borderland. Coeval deepening of the northern part of the Los Angeles Basin (Santa Monica Mountain section) resulted in deposition of the biosiliceous Modelo Formation.

The overlying upper Miocene interval (~10 to 8 Ma, late Mohnian BFS) is well represented in southern California Monterey sections and is characterized by an increased deposition of diatoms at the expense of calcareous microfossils. Within the Salinas Valley and Santa Cruz Mountains to the north, however, sandstones of the Santa Margarita Formation represent this interval. Continuing up section, the uppermost Monterey Formation (~8 to 6.7 Ma, lower Delmontian BFS) contains rapidly accumulating diatomaceous sediments largely devoid of calcareous microfossils. Included here is the Santa Cruz Mudstone of the Santa Cruz Mountains and Point Reyes areas and the mineable deposits in the Lompoc diatomite quarry. In the eastern equatorial Pacific, this ~8 to 7 Ma interval coincides with a marked increase in diatom deposition, suggesting a regionally extensive increase in Pacific upwelling. This ~8 to 7 Ma interval, however, has yet to have been encountered in surface exposures of the Salinas Valley and may possibly have been removed at an unconformity.

An abrupt transition from the diatom-rich uppermost Monterey Formation to more terrigenous-rich sediments of the overlying Capistrano (Newport Beach), Sisquoc (Santa Barbara coast and Santa Maria Basin), Pancho Rico (Salinas Valley), and Purisima (Santa Cruz Mountains and Point Reyes area) Formations occurs ~7.0-6.7 Ma, where it is often marked by an angular unconformity. The widespread nature of this unconformity throughout coastal California suggests that it may be associated with a major eustatic or tectonic event, for example a change in Pacific-North American plate motion to convergence that is variously estimated as ~8 Ma; (Atwater and Stock, 1988, Int. Geol. Rev. 40, 375-402) to ~5.2-4.2 Ma (DeMets and Merkouriev, 2016, Geophys. J. Int. (2016) 207**,** 741–773). Diatoms commonly disappear in these post-Monterey sediments in the earliest Pliocene coincident with an increased input of clastic sediments. Studies of offshore cores taken by the Ocean Drilling Program suggest that climatic warming in the earliest Pliocene was also responsible for a decline in diatom productivity and deposition along the California margin.

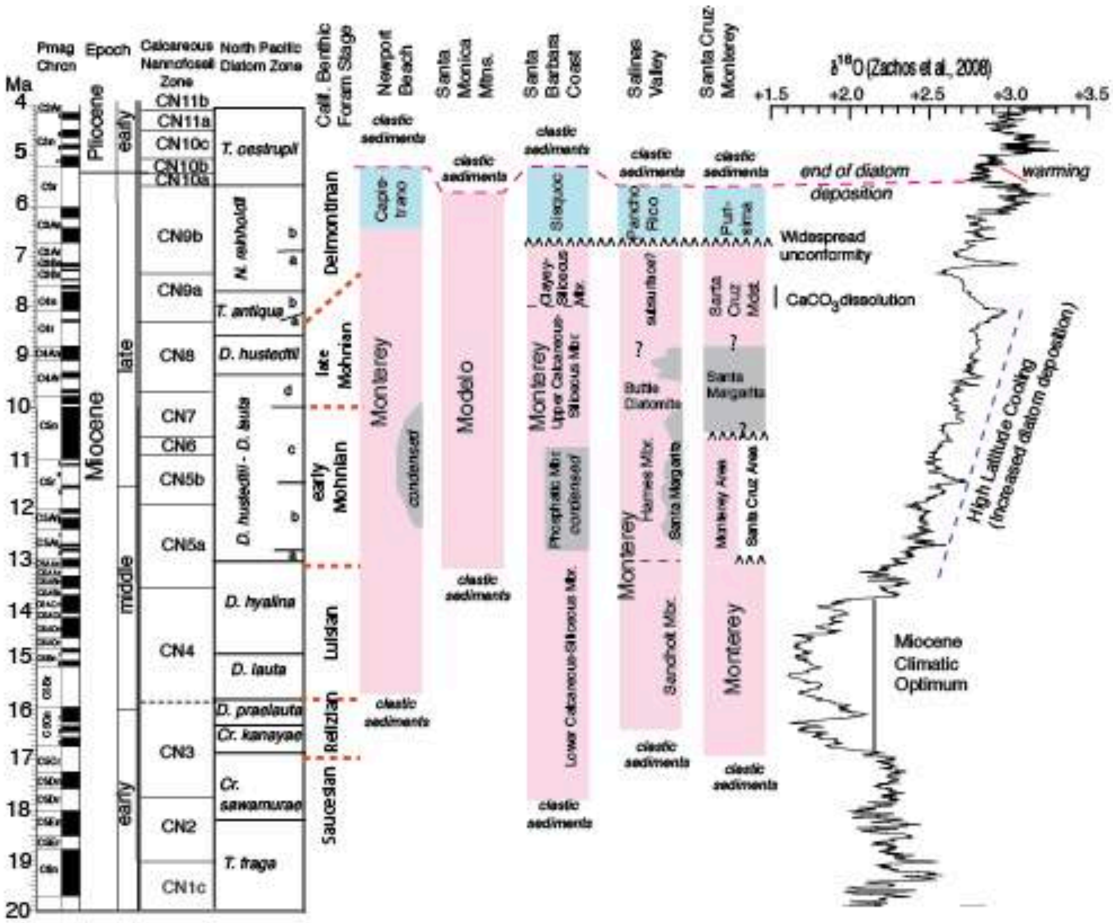


Figure 1. Correlation of key sections of the Monterey Formation (pink) and overlying biosiliceous rocks (light blue) through calcareous nannofossil and North Pacific diatom zones (Barron, 1981; Barron and Gladenkov, 1995) to the geologic time scale of Gradstein et al. (2004). The global deep sea oxygen isotope record of Zachos et al. (2008) is shown for climatic contex. Correlation of California benthic foraminiferal ages is based on their correlation with calcareous nannofossil and diatom zones.

Barron, J.A., 1981. Late Cenozoic diatom biostratigraphy and paleoceanography of the middle latitude eastern North Pacific, DSDP Leg 63. DSDP 63, 507-538.

Barron, J.A. and Gladenkov, A.Y, 1995. Early Miocene to Pleistocene diatom stratigraphy of Leg 145. Sci. Res., ODP 145, 3-19.

Gradstein F., Ogg. J., Smith, A., 2004. A Geologic Time Scale 2004. Cambridge University Press, Cambridge, 589 p.

Zachos, J., Pagain, M., Sloan, L., Thomas, E., Billips, K., 2008. Cenozoic Global Deep-Sea Stable Isotope Data. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series # 2008-098. NOAA/NCDC Paleoclimatology Program, Boulder CO, USA.

From Depositional Environment to Rock Properties in the Highly Siliceous Sediments of the Miocene Monterey Formation, California

Richard J. Behl
California State University, Long Beach, California, USA

Biosiliceous sediments and their diagenetic equivalents display a greater range of physical rock properties (e.g., porosity, hardness, compressive strength, etc.) than any other kind of sedimentary rock. The geologic consequences of this variability are amplified by the high degree of stratigraphic and spatial heterogeneity and contrast produced and preserved by hemipelagic /pelagic sedimentation into oxygen-depleted settings like that which much of the Miocene Monterey Formation was deposited. Although previous studies demonstrated the influence of composition on porosity and styles of structural deformation, the diagenetic evolution of these and other properties has not been followed from depositional facies at macro- and micro-scales.

We seek to clarify the linkage between sedimentology, stratigraphy, burial history, diagenesis and structural deformation in the Monterey Formation and similar siliceous sedimentary deposits. Understanding the evolution of diagenetic rock properties is critical to both clarifying obscured sedimentary histories and to more effective economic utilization of these important source and reservoir rocks. For example, in addition to stratigraphic variation in lithofacies with time, we observe significant lateral variation in composition (biogenic/diagenetic silica, clay, organic content, silt/sand), thickness, bedding heterogeneity and sedimentary fabric over distances as short as 1-2 km in multiple tectonic settings and basins. Primary sedimentary composition and fabric (homogeneous, thin-bedded, laminated, speckled, etc.) resulting from different sedimentary processes and environments influence original porosity and permeability, and these variations are inherited through successive diagenetic stages; even the spatial distribution of pores in opal-CT- and quartz-phase porcelanites mimics that in the primary diatomaceous sediments although the size and shapes of pores are transformed by silica diagenesis through 2 steps of dissolution of the silica framework.

Primary sediment composition (silica/detritus ratio) resulting from depositional environment is also the principal control of rock hardness at any burial depth or diagenetic stage. Hardness generally increases with steps between silica phases, but does not increase between opal-CT- and quartz-phase rocks where diagenetic silica is >70%, suggesting that above this threshold, the crystalline silica framework is critically linked and continuous. Doubling burial (2,000'-4,000') within opal-CT-phase rocks does not decrease porosity or increase hardness, but doubling burial after conversion to quartz (6,000'-12,000') leads to harder rocks by reduction of porosity. Heterogeneously stratified siliceous sediments like those that accumulate in isolated settings or by repeated diatomaceous gravity flow deposits are prone to diagenetic enhancement of bedding which leads to the contrasting mechanical behavior critical to the formation of intense fracture networks that are important pathways for water, solutes and hydrocarbons through the formation.

Relationship of Organic Carbon Deposition in the Monterey Formation with the Monterey Excursion Event

Gregg H. Blake
Blake Geological Services, Marble Falls, TX USA

The Monterey Formation is an extremely complex lithostratigraphic unit consisting of siliceous and calcareous biogenic sediments deposited in marginal basins formed during a tectonic reorganization of the California borderland in the late Oligocene to early Miocene. As the marginal basins subsided and sea level rose in late early Miocene, terrigenous-rich sedimentation was replaced by the deposition of calcareous and bio-siliceous marls that marked the start of Monterey deposition (Issacs 1983).

The deposition of the Monterey Formation occurred during an important time in the climate and oceanic evolution of the mid to late Cenozoic; the transition from a relatively warm greenhouse climate in the early Miocene to cooler temperatures of icehouse climatic conditions during the middle to late Miocene. The Miocene Climatic Optimum (MCO) in the early Miocene represents an interval of global warming which interrupted the overall Cenozoic cooling trend for more than 2 m.y. (Holbourn et al., 2015). In the late early to middle Miocene, there were global paleoclimatic and oceanic changes that resulted in the deposition of organic-carbon rich sediments into the marginal basins of California and around the Pacific margin (Ingle, 1981). During this time, there is a long lasting positive carbon isotope trend called the Monterey Excursion, which started around 16.9 Ma and ended at ~ 13.5 Ma, about 400 kyr after a major expansion of the Antarctic ice sheet at 13.9 Ma (Vincent and Berger, 1985).

Flower and Kennett (1993; 1994) selected the Naples Beach section as an excellent location to test the synchronicity between the organic carbon-rich deposition within the Monterey Formation and the positive $\delta^{13}C$ trend of the Monterey Excursion. Located along coastline at the mouth of Dos Pueblos Canyon about 15 km west of Santa Barbara, the Naples Beach exposure contains the entire interval of the Monterey formation, (age range of ~ 17.85 to 7.5 Ma), only interrupted by stratigraphic breaks at Dos Pueblos Canyon (~ 30 m of section not exposed) and in a condensed section. This section has well preserved benthic foraminiferal assemblages, limited diagenetic effects and age control from benthic foraminifera, calcareous nannofossils, diatoms, magnetostratigraphy, and strontium isotope stratigraphy.

In the deep-sea record, high resolution time series spanning this critical climatic transition are limited because deep sea sedimentary sequences have been strongly affected by carbonate dissolution, and/or burial diagenesis and/or proven incomplete due to major changes in ocean circulation. The original oxygen and carbon isotopic studies used age models for the Miocene time interval that relied often on sparse biostratigraphic control and magnetostratigraphic data not directly calibrated to an astronomical timescale. Recent studies of Pacific deep-sea sites use astronomically tuned chronologies that have resolution of ~4-9 kyr (Holbourn et al., 2007).

In the deep-sea benthic foraminifera oxygen isotopic record, there is a sharp decrease (~ 1‰) in the benthic and bulk carbonate $\delta^{18}O$ curves and onset of a pronounced (-0.6‰) negative shift in benthic and bulk carbonate $\delta^{13}C$ ca. 16.9 Ma which represents the start of MCO, a rapid global warming and/or polar ice cap melting event (Holbourn et al., 2015). Rapid recovery in benthic and bulk carbonate $\delta^{13}C$ after 16.7 Ma is associated with improved carbonate preservation. This recovery signals the onset of the first carbon isotope maximum within the Monterey Excursion (Vincent and Berger, 1985). The first $\delta^{13}C$ maximum is >1.4‰ (CM1) is recorded at ~16.8 Ma (Holbourn et al., 2007) and represents the earliest δ13C maxima in Monterey Excursion.

Based on the integration of orbital variations in climate proxy signals $\delta^{13}C$ and $\delta^{18}O$ and carbon from several ODP and IPOD sites in the central, southern and southeastern Pacific Ocean, there appears to be three distinct climate phases developed in the Miocene (Holbourn et al, 2007). Each phase is based on the oxygen isotopic record and its relationship to Miocene water mass characteristics.

Phase 1 broadly corresponds to the early Miocene climate optimum (prior to 14.7 Ma), and consists of peak minimum values in benthic foraminiferal $\delta^{18}O$. This phase equates to minimum ice volume and to poor ventilation in the deep Pacific water masses.

Phase 2 (~14.7 to 13.9 Ma) starts the long-term trend towards heavier $\delta^{18}O$ values associated with punctuated climate cooling. This phase ends with rapid ice growth and global cooling at the onset of the last and most pronounced $\delta^{13}C$ increase. During this transitional phase $\delta^{13}C$ continues to show high amplitude 400 kyr variability and indicates improvement in Pacific deep-water ventilation. Phase 2 culminated with massive stepped increase in $\delta^{18}O$ at 13.8 Ma marking entry into icehouse climatic conditions.

Phase 3 continues after 13.9 Ma, when $\delta^{18}O$ exhibits a long term increasing trend and final entry into icehouse climatic conditions. This phase culminated with a substantial improvement in deep water ventilation and intensified production of southern source deep and intermediate waters. Initially in this phase, $\delta^{13}C$ displays the highest values of whole middle Miocene at 13.8-13.6 Ma but subsequently shows reduced amplitude variations and long term declining values (Holbourn et al., 2007)

In the Naples Beach section, the Monterey Formation has generally been divided into the following members: a lower calcareous-siliceous marl, overlain by a carbonaceous marl, overlain by a transitional member, overlain by the upper calcareous to predominantly siliceous marl, and finally a siliceous member at the top of the interval (Issacs 1981, 1983). Benthic foraminiferal $\delta^{18}O$ values at Naples Beach are low throughout the lower calcareous-siliceous member averaging between ~0.0 – 0.5‰ (Flower and Kennett, 1993, 1994). The first increase in $\delta^{18}O$ occurs at the top of the first organic carbon-rich subunit within the lower Carbonaceous Marl member. There is a large permanent $\delta^{18}O$ increase of ~ 1‰ found within the upper part of the Carbonaceous Marl member, which clearly precedes the phosphatic condensed interval. Above the condensed section, within the uppermost part of the Carbonaceous Marl member, the oxygen isotopic values reach ~1.5-2.0‰ (Flower and Kennett, 1994). Based on the age constraints at the time, Flower and Kennett (1994) proposed that the major increase in $\delta^{18}O$, was associated with the organic carbon-rich Organic Shale, and is the main step of the well-known middle Miocene oxygen isotopic increase, now dated at 13.9 Ma. However, it now appears that this first large increase is associated with the first increase in $\delta^{18}O$ that occurs at 14.7 Ma, at the base of Phase II interval (Holbourn et al, 2015). The main $\delta^{18}O$ increase and end of the Monterey Excursion occurs within the Condensed Zone at approximately 13.9 – 10.2 Ma and represent the change into the icehouse climatic conditions. This is also the switch from calcareous dominated deposition to predominately siliceous deposition. Oxygen isotopic correlations of these organic carbon-rich intervals within the Naples Beach section of Monterey Formation suggest episodic increases in organic carbon deposition coincided with deep sea $\delta^{18}O$ and $\delta^{13}C$ maxima and synchronous global cooling events including the start of cooling at 14.7 Ma and the major middle Miocene cooling and expansion of the Antarctic ice sheet at 13.9 Ma.

Improved correlation of Naples Beach section shows that phosphatic condensed interval (13.9 -10.2 Ma) is clearly followed the major middle Miocene sea level drops of the Ser 1 (13.8 Ma) and the Tor 1 (11.8 Ma). There could be a relationship between major sea level falls and formation of this condensed section, although another possibility is that it represents a tectonically influenced bank-top and associated phosphatic hardgrounds; similar to the bank-tops that form in borderland style margins.

Phosphatic, Organic-Rich, and Biosiliceous Facies of the Triassic in Northwest Alaska: Transect Across a High-Latitude, Low-Angle Continental Margin

Julie Dumoulin[1], Katherine J. Whidden[2], William A. Rouse[3], Richard Lease[1], Paul O'Sullivan[4]
[1]Alaska Science Center, U.S. Geological Survey, Anchorage AK 99508 USA
[2]Central Energy Resources Science Center, U.S. Geological Survey, Denver CO 80225 USA
[3]Eastern Energy Resources Science Center, U.S. Geological Survey, Reston VA 20192 USA
[4]Geosep Services, 1521 Pine Cone Road, Moscow, ID 83843 USA

The Shublik Formation (Middle and Upper Triassic) is a mixed siliciclastic-carbonate-phosphatic unit in northern Alaska. It generated oil found in Prudhoe Bay and other accumulations and is a prospective self-sourced resource play on Alaska's North Slope. Its distal, deeper water equivalent—the Otuk Formation—consists largely of radiolarian chert, mudstone, and limestone, and contains potential gas accumulations in the Brooks Range foothills to the south. New petrographic, fossil, geochemical, and spectral gamma ray data yield insights into facies changes in these units, which were deposited across a shallowly dipping shelf margin in a high-latitude setting. Samples come from four localities along a transect that extends 425 km from present-day northeast (proximal) to southwest (distal) in northwest Alaska.

The most proximal section is the Brontosaurus 1 well, which penetrated ~120 m of Shublik Formation (lower 40 m were cored), overlain by the Sag River Sandstone (Upper Triassic shallow marine siliciclastic strata) and underlain by the Sadlerochit Group (Lower Triassic and older shallow marine to fluvial siliciclastic rocks). The cored Shublik section consists of medium gray mudstone to fine-grained quartz sandstone and light gray to white calcareous mudstone to fine-grained limestone, interbedded on a scale of ~2-30 cm. Darker intervals are finely laminated in the lower Shublik but become increasingly bioturbated upwards. White limy layers have sharp bases and may represent event (storm) beds. Bioclasts are mainly halobiid and monotid bivalves, with subordinate ostracods and benthic foraminifers. Phosphate is abundant (up to ~20-30% volume estimated in core and thin section) in the basal 30 cm of the Shublik and in a 10-m-thick zone near the top of the cored Shublik interval; it occurs as sand-sized peloids and coated grains, pebbles and nodules ≤2 cm in diameter, and less common phosphatic and phosphatized bioclasts. Mudstones have relatively low (≤1.6 wt %; n=8) total organic carbon (TOC). Sedimentologic and fossil data (Mickey et al., 2006) indicate an inner to middle shelf setting for the Shublik in the Brontosaurus 1 well.

A unique exposure of Triassic rocks at Surprise Creek, 325 km to the southwest of the Brontosaurus 1 well near the Chukchi coast, shows facies transitional between those of the Shublik and Otuk Formations and provides a potential outcrop analog for source rocks in the main Chukchi shelf hydrocarbon exploration play. The base of the condensed, ~25 m thick section is the core of an anticline (no underlying strata are exposed) and the top is a Jurassic unconformity overlain by Oxfordian to Valanginian Kingak Shale. The main Triassic lithofacies is siliceous to calcareous mudstone that is variously organic-rich (0.3-9.5 wt % TOC; >2 wt % TOC for 22 of 44 samples) and contains sparse to abundant Middle (Ladinian) and Late (Carnian-Norian) Triassic bivalves. An especially organic-rich zone of late Carnian-early Norian age is ~ 2 m thick and has 1.9-9.5 wt % TOC (>5.3 wt % TOC for 7 of 12 samples). Subordinate lithologies include phosphatic nodules (typical of the Shublik but rare in the Otuk) and siliceous radiolarite (characteristic of the Otuk but absent from the Shublik). Yellow-weathering bentonite(?) layers (2-3 cm thick) are similar to beds seen elsewhere in the Otuk. Concentrations of large (≥500 μm diameter) *Tasmanites* algal cysts in Ladinian or older mudstone resemble ~coeval occurrences in hydrocarbon source rocks in Svalbard, the Barents Shelf, and Siberia and we have seen similar forms in Ladinian strata of the Shublik in the offshore Phoenix 1 well, northwest of Prudhoe Bay. The Surprise Creek section formed within the proximal part of the Hanna Trough, a failed rift initiated in Devono-Mississippian time that intersects the Northern Alaska shelf margin. The section is most like the "Shublik equivalent sequence" (TOC 2-8 wt %) in the Klondike well, which was drilled on the west flank of the Hanna Trough ~200 km to the northwest (Sherwood et al., 2002).

The third locality in our transect is a complete penetration of the Otuk Formation in a continuous drill core (DDH 927) from the Red Dog Zn-Pb-Ag District, ~100 km south of Surprise Creek. The Otuk here is ~82 m thick, overlies siliceous mudstone of the Siksikpuk Formation (Permian), and underlies black organic-rich mudstone of the Kingak(?) Shale (Jurassic?). Informal shale, chert, and limestone members of the Otuk are recognized (Dumoulin et al., 2013). The lowest (shale) member consists of 28 m of black to light gray, silty shale with as much as 6.9 wt % TOC and bivalve fragments (*Claraia* sp.?) consistent with an Early Triassic age. Gray radiolarian chert dominates the middle (chert) member (25 m thick) and yields radiolarians of Middle (Anisian and Ladinian) and Late (Carnian-late middle Norian) Triassic ages. Black to light gray silty shale, like that in the lower member, forms interbeds (a few mm to 7 cm thick) that are most abundant in the lower half of the middle member. A distinctive, 2.4-m-thick interval of black shale and calcareous radiolarite in the upper part of the member has as much as 9.8 wt % TOC, and a 1.9-m-thick interval of limy to cherty mudstone immediately above this contains radiolarians, foraminifers, conodonts, and halobiid bivalve fragments. The upper (limestone) member (29 m thick) is lime mudstone with monotid bivalves and late Norian radiolarians, overlain by gray chert that contains Rhaetian (latest Triassic) radiolarians. Rare gray to black shale interbeds in the upper member have as much as 3.4 wt % TOC. A suite of $\delta^{13}C_{org}$ (carbon isotopic composition of carbon) data (*n*=38) from the upper Siksikpuk Formation through the Otuk Formation and into the Kingak(?) Shale in DDH 927 shows a pattern of positive and negative excursions similar to those reported from many other Triassic sections worldwide. Both lithologic and fossil data indicate that the Otuk section in DDH 927 was deposited in oxic to dysoxic, outer shelf settings. Thin graded layers of silty shale to fine-grained sandstone found throughout the section likely formed as distal turbidites; coarse grains are mainly quartz but locally include feldspar crystals that could reflect a tuffaceous component.

New data from two Otuk Formation sections on Cape Lisburne (CL1 and CL3), ~125 km to the west of Surprise Creek, provide additional insight into Triassic facies patterns in this area. The composite Otuk section at Cape Lisburne is >55 m thick (base not exposed). It generally resembles that in the Red Dog area, and likely formed in similar outer shelf settings. The shale member (>10 m thick) is mainly non-calcareous mudstone with rare carbonate layers bearing middle Smithian (late Early Triassic) bivalves (*Peribositria mimer*) in a matrix of calcareous radiolarite. Radiolarian chert predominates throughout the chert member (~20 m thick) and contains thin interbeds of mudstone (TOC 2-4.2 wt % in 13 of 25 samples) and fine-grained limestone; radiolarians and daonellid and halobiid bivalves indicate an age of Middle through Late Triassic for this member. The limestone member (>25 m thick) is mainly fine-grained limestone with locally abundant monotid bivalves of late Norian age, interbedded with siliceous limestone, lesser mudstone, chert, and yellow-weathering bentonite(?) layers.

The upper part of the Otuk Formation in section CL1 at Cape Lisburne is distinctive and comprises a 10-m-thick interval of sandstone interbedded with bivalve wacke-packstone and cherty mudstone. New fossil and detrital zircon data indicate that this sandstone is ~coeval with the Sag River and Karen Creek Sandstones (latest Triassic) but differs in composition, provenance, and setting. Cape Lisburne sandstone yields abundant young (~206-330 Ma) detrital zircon U/Pb ages, is heterolithic, and formed as turbidites. In contrast, Sag River/Karen Creek sandstone lacks detrital zircons younger than Devonian, is quartz-rich, and formed in shallow marine settings. Two new detrital zircon samples support and expand previous findings of Miller et al. (2006). The young age populations of 206 and 209 Ma from our samples define maximum depositional ages that are close to the Norian-Rhaetian boundary and consistent with fossil age constraints from our CL1 section. Structural analysis indicates that the Otuk at Cape Lisburne was deposited in a distinct sub-basin west of the Hanna Trough that received siliciclastic input from the (present-day) northwest (Gottlieb et al., 2014). Detrital zircon U/Pb age spectra from the Cape Lisburne sandstone resemble those of Triassic sandstones of St. Lawrence Island (western Alaska; Dumoulin and Amato, 2017), Chukotka and Wrangel Island (eastern Russia), and the northern Sverdrup basin (Canada) but differ greatly from those of Triassic strata elsewhere in northern Alaska (Gottlieb et al., 2014). The abundance and wide range of Triassic detrital zircon ages in our new Cape Lisburne samples support the suggestion (Midwinter et al., 2016) that the northwest source area had a protracted history of magmatism through the Triassic.

Factors that shaped Triassic facies patterns in northwestern Alaska include sea level change, climate, and regional tectonism. Spectral gamma ray data and a revised stratigraphic framework for the Triassic of northern Alaska (Whidden et al., in press) indicate that Middle and Upper Triassic strata of the Shublik and Otuk Formations represent five transgressive-regressive sequences. These sequences correlate with those recognized in other Arctic basins, implying regional and perhaps global significance. The Shublik Formation contains the largest phosphorite accumulation of Triassic age (Trappe, 1994), which has been interpreted as forming in response to a marine upwelling system initiated in the Middle Triassic (e.g., Parrish et al., 2001). Warm greenhouse conditions characterized the Triassic and would likely have produced lower latitudinal temperature gradients and more sluggish global circulation (Holz, 2015), leading Whidden and Dumoulin (2016) to question the importance of upwelling as an influence on Shublik deposition. However, the high paleolatitude (~+45–60° N) proposed for northern Alaska during the Triassic (e.g., Colpron and Nelson, 2011), in concert with a worldwide shift of phosphorite sedimentation into high latitudes during the Triassic (Trappe, 1994), could resolve this paradox; upwelling of nutrient-rich waters may have been limited to high latitudes during this period. Other causes likely contributed to accumulation of organic-rich strata in northwest Alaska during the Triassic. Volcanic ash can supply biolimiting nutrients such as iron, and the presence of bentonites and abundant Triassic age detrital zircons in our sections suggest volcanic input as an additional driver of high productivity in the Shublik-Otuk depositional system. Fossils in all of our sections are predominantly pelagic (radiolarians) or opportunistic benthic bivalves suited to oxygen-deficient environments (McRoberts, 2010), implying dysoxia was prevalent and may have contributed to the abundance of organic-rich mudstone. Lastly, Triassic facies of northern Alaska also reflect regional tectonic events, which produced pulses of siliciclastic detritus that accumulated primarily on proximal parts of the shelf during the Early and latest Triassic. Organic-rich facies developed best in times (Ladinian-Norian) and settings (distal shelf, Hanna Trough) where dilution of organic matter by other detritus was minimized.

References

Colpron, M., and Nelson, J.L., 2011, A Palaeozoic NW Passage and the Timanian, Caledonian and Uralian connections of some exotic terranes in the North American Cordillera, *in* Spencer**,** A.M., Embry, A.F., Gautier, D.L., Stoupakova, A.V., and Sørensen, K., eds., Arctic Petroleum Geology: Geological Society, London, Memoirs, 35, p. 463–484; doi: 10.1144/M35.31

Dumoulin, J.A., and Amato, J.M., 2017, Petrologic, fossil, and detrital zircon data from Devonian-Triassic strata on St. Lawrence Island, Alaska: Links to northwestern Alaska and eastern Russia: Geological Society of America Abstracts with Programs. v. 49, no. 6; doi: 10.1130/abs/2017AM-297991

Dumoulin, J.A., Burruss, R.C., and Blome, C.D., 2013, Lithofacies, age, depositional setting, and geochemistry of the Otuk Formation in the Red Dog District, northwestern Alaska: U.S. Geological Survey Professional Paper 1795-B, 32 p.

Gottlieb, E.S., Meisling, K.E., Miller, E.L., and Mull, C.G., 2014, Closing the Canada Basin: detrital zircon geochronology relationships between the North Slope of Arctic Alaska and the Franklinian mobile belt of Arctic Canada: Geosphere v. 10, p. 1366**–**1384.

Holz, M., 2015, Mesozoic paleogeography and paleoclimates – A discussion of the diverse greenhouse and hothouse conditions of an alien world: Journal of South American Earth Sciences, v. 61, p. 91–107.

McRoberts, C.A., 2010, Biochronology of Triassic bivalves, *in* Lucas, S.G., ed., The Triassic Timescale, Geological Society, London, Special Publication 334, p. 201–219.

Mickey, M.B., Haga, H., and Bird, K.J., 2006, Micropaleontology of selected wells and seismic shot holes, northern Alaska: U.S. Geological Survey Open-File Report 2006-1055, 11 p.

Miller, E.L., Toro, J., Gehrels, G., Amato, J.M., Prokopiev, A., Tuchkova, M.I., Akinin, V.V., Dumitru, T.A., Moore, T.E., and Cecile, M.P., 2006, New insights into Arctic paleogeography and tectonics from U-Pb detrital zircon geochronology: Tectonics, v. 25, TC3013.

Midwinter, D., Hadlari, T., Davis, W.J., Dewing, K., and Arnott, R.W.C., 2016, Dual provenance signatures of the Triassic northern Laurentian margin from detrital-zircon U-Pb and Hf-isotope analysis of Triassic–Jurassic strata in the Sverdrup Basin: Lithosphere, v. 8, p. 668–683.

Parrish, J.T., Droser, M.L., and Bottjer, D.J., 2001, A Triassic upwelling zone: The Shublik Formation, Arctic Alaska, U.S.A.: Journal of Sedimentary Research, v. 71, p. 272–285.

Sherwood, K.W., Johnson, P.P., Craig, J.D., Zerwick, S.A., Lothamer, R.T, Thurston, D.K., and Hurlbert, S.B., 2002, Structure and stratigraphy of the Hanna Trough, U.S. Chukchi Shelf, Alaska, *in* Miller, E.L., Grantz, A., and Klemperer, S.L., eds., Tectonic Evolution of the Bering Shelf–Chukchi Sea–Arctic Margin and Adjacent Landmasses, Geological Society of America Special Paper 202, p. 39–66.

Trappe, J., 1994, Pangean phosphorites – Ordinary phosphorite genesis in an extraordinary world?, *in* Embry, A.F., Beauchamp, B., and Glass, D.J., eds., Pangea: Global Environments and Resources, Canadian Society of Petroleum Geologists Memoir 17, p. 469-478.

Whidden, K., and Dumoulin, J.A., 2016, An alternative hypothesis for the development of organic-rich strata in the Triassic Arctic Alaska Basin: Geological Society of America Abstracts with Programs, v. 48, no. 7; doi: 10.1130/abs/2016AM-279845

Whidden, K.J., Dumoulin, J.A., Rouse, W.A., in press, A Revised Triassic Stratigraphic Framework for the Arctic Alaska Basin: AAPG Bulletin.

Influence of original sediment composition on the mechanical properties of rocks in the Monterey Formation of the Santa Maria basin, Santa Barbara County, California

John B. Dunham P.G.
Dunham Professional Geology, Ventura, California USA

I measured outcrop-sections and described cores from the Monterey Formation in the Santa Maria basin for Union Oil Company. It was common to see fractured-rock layers interlayered with non-fractured layers (Figure 1). Research showed that variations in original sediment composition ultimately determined the mechanical properties of these rocks. The first studies of rock mechanics came from the field of Engineering Geology, since weak rocks had caused repeated problems with construction projects. That effort led to development of a formal engineering classification of rock strength, based on Uniaxial Compressive Strength (UCS).

UCS was recognized as an important property that predicted whether a rock mass might cause trouble, or not. The UCS Test applies compression to a rock cylinder, while at the same time, measuring the change in length of the cylinder, thereby producing a stress-strain curve. Initially, strain is elastic; the rock-core will return to original length if stress is removed. Eventually the elastic limit is reached, where the rock begins to deform permanently (plasticly). Finally, the yield point is reached, where strain becomes rapid with little additional applied stress. The slope of the straight line on the stress strain curve is Young's Modulus, which is a measure rock stiffness, or how much the rock squeezes per each unit of stress; imagine squeezing a cube of granite, or a marshmallow, between your fingers.

UCS tests provide a formal definition for <u>brittle</u> versus <u>ductile</u> rocks. Rocks defined as <u>brittle</u> undergo little plastic deformation and will fail by fracture soon after reaching the elastic limit. Rocks that are <u>ductile</u> will continue to deform by plastic flow without fracturing, long after the elastic limit is reached. Classic end-members of the brittle to ductile rock-spectrum are seen in comparison of UCS tests of granite and rock salt cores. A granite core shows very little plastic deformation prior to fracturing, while a rock-salt core displays major plastic deformation and never does fracture. Extensive research (Deere and Miller, 1966; Hoek and Brown, 1997; Nelson, 2001; Sone and Zoback, 2013, among many others) has shown that rocks with high compressive strength tend to be brittle, while rocks with low compressive strength tend to be ductile. The properties of rocks with high compressive strength include having <u>low porosity</u>, <u>low clay content</u>, <u>low kerogen content</u>, <u>high mineral toughness</u> where mineral toughness is a function or mineral hardness and crystal cleavage (consider halite versus quartz as an example), and <u>high degree of interlocking of crystals</u> in the rock matrix. Rocks with the opposite properties have low compressive strength. Examples on the high side include granite, chert, and silica-cemented sands. Carbonates are lower because of low mineral toughness. Weak rocks include porous sands, evaporites, and mudstones. In any sequence of Monterey rocks, it would not be unusual to encounter cherts and carbonates with high strength that are interlayered with claystones with low strength. The concept of mechanical stratigraphy subdivides stratified rock into individual mechanical units defined by differences in rock strength, stiffness, and brittleness (Laubach et al., 2009).

Uniaxial Compressive Strength forms the basis for the National Engineering Classification of Rocks (NEH, 2017). Rock classes that are defined by UCS rock strength also show differences in ability to withstand blows with a rock hammer. Hard to very hard to extremely hard rocks are the ones that "ring" when struck with a rock hammer, and may require many hammer-blows to break, if they break at all. Rock-hardness properties correlate with rock stiffness and strength. Within the Monterey Formation, Isaacs (1981a) reported that quartz cherts and opal-CT porcelanites, both brittle rocks, emitted high-pitched rings when struck with a hammer, while siliceous mudstones that showed ductile behavior emitted a dull thud when struck with a hammer. Audible sound correlates with Young's Modulus and rock strength.

The basic Monterey story is that upwelling stimulated growth of calcareous and siliceous plankton in surface waters. In the California Borderland (Blake, 1981), there are sills that isolate individual basins and keep out the deep oxygenated bottom water; these silled basins accumulate and preserve sediments with TOC's of 5% to over 20% that are the source for most of the oil in the Santa Maria, Santa Barbara, Los Angeles, and San Joaquin basins. Some of these basins were proximal to sources of terrigenous silt and clay, and others were more distal. The Santa Maria and Santa Barbara basins accumulated purer biogenic sediments, while the Los Angeles and San Joaquin basins received more terrigenous clay, silt, and sand. During burial, siliceous plankton dissolved and re-precipitated as opal-CT and quartz silica phases, while calcareous nanno-plankton dissolved and re-precipitated as microcrystalline dolomite. Both diagenetic tracks resulted in major decreases in porosity.

Monterey dolostones are "bacterial dolomites" as described by Garrison et al. (1984) that replaced calcareous nannoplankton soon after burial, at shallow depths below the water bottom. Silica phase changes occurred at greater depth where increasing temperature drove the dissolution-reprecipitation reactions (Isaacs, 1980, 1981b; Behl and Garrison, 1994; Behl, 1999) at specific depths below the water bottom. The result of these burial-diagenetic carbonate and silica phase changes is the reduction of original high-porosity sediment to a sequence or very low porosity chert and dolostones interlayered with claystones with higher porosity.

The mechanical behavior of these different rocks can be explained in terms of rock-matrix properties. Chert is a rock composed of quartz, with high mineral toughness, in a matrix of fine, tightly interlocked crystals, with low porosity; all leading to high strength. Dolostone is a rock composed of dolomite crystals with lower mineral toughness, in a matrix of tightly interlocked crystals with low porosity. Mudstone is a rock composed of some amount of silica and dolomite microcrystals in a matrix of clay and kerogen; mudstone does not have an interlocked crystal mosaic and it has high porosity, resulting in low strength. Why don't all the sediments become hard dolostone or chert layers? The answer is that the original depositional sediment contained a mix of siliceous plankton, calcareous plankton, and detrital clay. Figure 2 summarizes data from Santa Maria basin cores. Rocks fitting the field description of dolomite or chert plot at the points of the triangle, only the purest siliceous or calcareous sediments became transformed into chert or dolomite. Any sediment that contained more than about 10 weight percent detrital clay, evolved into a calcareous or siliceous shale. These shale rocks have fissility and retain high porosity, and tend deform plastically without fracturing. The presence of 10 weight percent clay is observed to be the dividing line that determines whether the rock is brittle or ductile, regardless of whether the silica-phase is opal-A, opal-CT, or quartz. Chert and dolostone are hard rocks that ring when hit with a hammer; siliceous mudstone, calcareous mudstone and claystone are soft rocks that dent when hit with a hammer. 10% clay appears to mark the dividing line.

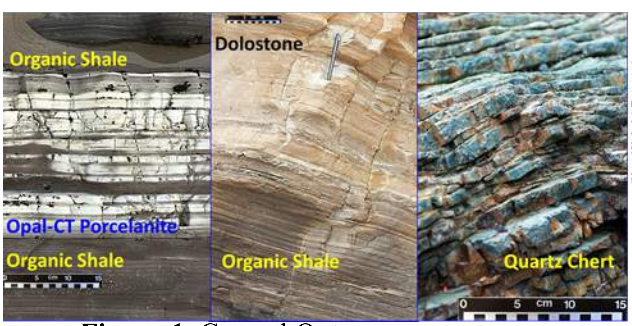


Figure 1. Coastal Outcrops

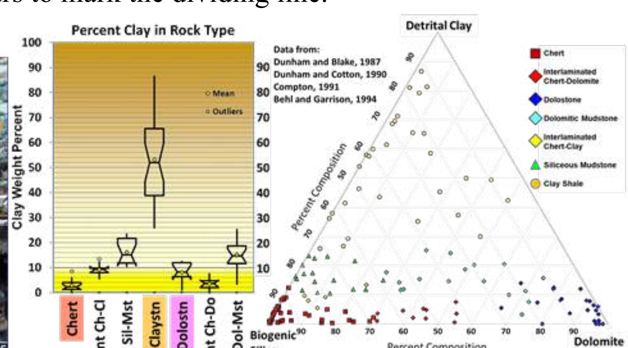


Figure 2. Rock Composition Data

The system of natural fractures seen in Monterey outcrops shows the direction of the maximum compressive stress, which is horizontal compression, ultimately related to transpression along the San Andres fault system. The fractures are arranged in very orderly patterns that can be predicted from the shapes of folds visible on seismic lines, and horizontal wells can be oriented to intersect an optimal number of fractures. As horizontal compression is applied at geologic-time rates, chert and dolostone will form brittle fractures, while organic shale will deform plastically and not develop natural fractures.

However, it is very possible to induce tension fractures in organic shales via hydraulic fracturing, where a borehole is inflated in a geologic instant. To summarize, the Monterey Formation contains layers of fractured and non-fractured rock since diagenesis has reduced porosity in original low-clay calcareous and siliceous sediments, while mudstones with high clay and kerogen content are micro-porous and ductile and do not develop natural fractures.

References

Behl, R.J., and Garrison, R.E., 1994, The origin of chert in the Monterey Formation of California (USA): Proceedings of the 29th International Geological Congress, Part C, A. Ijima, A., Abed, and R. Garrison (eds), Utrecht, p. 101-132.

Behl, R.B., 1999, Since Bramlette (1946): The Miocene Monterey Formation of California revisited: Geological Society of America Special Paper 338, p. 301-313.

Blake, G.H., 1981, Biostratigraphic relationship of Neogene benthic foraminifera from the southern California outer continental borderland to the Monterey Formation: in Garrison, R.E., Douglas, R.G., Pisciotto, K.E., Isaacs, C.M. and Ingle, J.C. (eds.), The Monterey Formation and Related Siliceous Rocks of California: Pacific Section, Soc. Econ. Paleontologists and Mineralogists, p. 1-13.

Compton, J.S., 1991, Porosity reduction and burial history of siliceous rocks from the Monterey and Sisquoc Formations, Point Pedernales area, California: Geological Society of America Bulletin, v. 103, p. 625-636.

Deere, D.U., and Miller, R.P., 1966, Engineering Classification and Index Properties for Intact Rock: USAF Technical Report no. AFWL-TR-16-116 (this can be found by copying this reference into Google Search).

Dunham, J.B., and Blake, G.H., 1987, Guide to coastal outcrops of the Monterey Formation of Western Santa Barbara County, California: Pacific Section, Soc. Econ. Paleontologists and Mineralogists, Book 53, p. 1-36.

Dunham, J.B., and Cotton, M.L., 1990, Lithology of the Monterey Formation in the Western Santa Maria Valley Field, Santa Maria Basin, California: SEPM Core Workshop v. 14, p. 203-243.

Garrison, R.E., Kastner, M. and Zenger, D.H., (eds.) 1984, Dolomites of the Monterey Formation and Other Organic-Rich Units: Pacific Section, Soc. Econ. Paleontologists and Mineralogists,
215 p.

Hoek E, Brown T (1997) Practical estimates of rock mass strength: International Journal of Rock Mechanics and Mining Sciences, Vol 34, No 8, 1997, pages 1165-1186.

Isaacs, C.M., 1980, Diagenesis in the Monterey Formation examined laterally along the coast near Santa Barbara, California: Stanford University, Ph.D. dissertation, 329 p.

Isaacs, 1981a, Field characterization of rocks in the Monterey Formation along the coast near Santa Barbara, California: Guide to the Monterey Formation in the California Coastal Area, Ventura to San Luis Obispo, Pacific Section AAPG Volume 52, p. 39-53.

Isaacs, 1981b, Porosity reduction during diagenesis of the Monterey Formation, Santa Barbara coastal area, California. In Garrison, R. E., and R.G. Douglas, eds., The Monterey Formation
and Related Siliceous Rocks of California. Pacific Section SEPM pp. 257-271.

Laubach, S.E., Olson, J.E., and Gross, M.R., 2009, Mechanical and fracture stratigraphy: AAPG Bull. v. 93, p. 1413-1426.

NEH, 2017, National Engineering Handbook Part 631, Chapter 4, Engineering Classification of Rock Materials: https://directives.sc.egov.usda.gov/viewerFS.aspx?id=3848

Nelson, R.A., 2001, Geologic Analysis of Naturally Fractured Reservoirs, 2nd ed.: Gulf Professional Publishing, Houston Texas, 332 pages.

Sone, H. and Zoback, M.D., 2013, Mechanical properties of shale-gas reservoir rocks – Part 1: Static and dynamic elastic properties and anisotropy: Geophysics, v. 78, p. D381-D392.

The Monterey Formation in the Santa Barbara, Santa Maria, and Pismo Basins, and "Monterey Beds" in Baja California Sur: an update

Karl B. Föllmi
Institute of Earth Sciences, University of Lausanne, CH-1015 Lausanne, Switzerland

The Miocene Monterey Formation in the borderlands of central California is largely composed of laminated, biosiliceous, organic-rich, and phosphatic sediments, which are intercalated with carbonates and volcanogenic deposits. In general, these lithologies reflect strong upwelling, enhanced primary productivity, and the presence of an oxygen-minimum zone, which is indicated by ubiquitous lamination, a general absence of bioturbation, high pyrite, Mo, and U concentrations, and molar ratios of total organic carbon and organic phosphorus (TOC/P_{org}) of up to 2000. The presence of erosional surfaces, angular unconformities, and reworked clasts and nodules suggests that bottom-current activity and gravity-flow deposition were instrumental in sediment accumulation. The phosphatic laminae were precipitated at a very early stage of diagenesis, during periods of non-sedimentation. They formed less permeable sedimentary lids and may as such have contributed to enhanced organic-carbon (OC) preservation. The thus formed phosphatic laminae were frequently subjected to subsequent sediment winnowing and reworking, resulting in the formation of condensed phosphatic beds.

Oxygen depletion was particularly severe during the early Langhian, and the late Serravallian and early Tortonian, and favored the preservation of organic matter. Phosphogenesis occurred throughout the time interval considered (approximately 17.5–6.5 Ma), and phosphate-rich sediments formed especially during periods of sedimentary condensation in the Langhian and earliest Serravallian, and the latest Tortonian and early Messinian. A comparison of temporal trends in the type and quantity of deposited sediments between the two sections at Shell Beach and Mussel Rock, and three sections of the Santa Barbara Basin (El Capitan State Beach, Naples Beach, and Haskells Beach) confirms that towards the top of the Monterey Formation, sediments become enriched in biosilica in all three basins. The transition into this lithology occurred diachronously, during the Serravallian in the Pismo and Santa Maria basins and Tortonian in the Santa Barbara Basin, and was probably related to a diachronous shift to more intense upwelling in all three basins. A phase of important condensation and phosphogenesis terminated Monterey-‘‘type’’ sedimentation during the latest Tortonian and early Messinian in both the Santa Maria and Santa Barbara basins. The uniform expression of this phase is interpreted as the result of improved connections between the two basins.

Upper Oligocene and Lower Miocene, siliceous, organic-, and phosphate-rich sediments are widespread in the northern and central regions of Baja California Sur (Mexico). We analyzed a representative section at La Purísima and a core from the ROFOMEX mine in San Juan de la Costa for its sedimentology, stratigraphy, geochemistry, and mineralogy, and obtained a radiochronologic framework by LA-ICP-MS U-Pb dating of zircons from a representative set of ash layers. The sediments were deposited in an upwelling-dominated, hemipelagic setting, for which the presence of lamination, the scarcity of benthic organisms (except for in gravity-flow deposits), and redox-sensitive trace-element enrichments indicate the prevalence of oxygen-depleted conditions, which were particularly well developed around 27 and 24-22 Ma. Gravity-flow deposits predominantly composed of phosphatic coated grains and coprolites occur frequently, and were likely generated by seismic and volcanic activity, as is seen by the close association with volcanic ash layers. The phosphatic coated particles were generated in a shallower, better oxygenated and partly condensing shelf environment. They were also formed within the hemipelagic sediments, where they were often subsequently concentrated by winnowing processes, indicating that phosphogenesis also occurred in situ. This process was also responsible for partly cementing the phosphate-rich gravity-flow deposits.

Phosphogenesis and the accumulation of phosphate-rich sediments coincide with an episode of globally increased phosphorite formation during the Late Oligocene and Early Miocene. At the two studied sites, phosphogenesis occurred throughout the time interval investigated and was particularly important in around 28-25.5 Ma, and 23.5- 21.5 Ma. These time intervals correspond to the Late Oligocene glacial maximum and the Oligocene-Miocene and Early Miocene glacial intervals Mi1 and

Mi1a. This indicates the increasing importance of glacial denudation during the Oligocene, which led to a more than doubled phosphorus flux into the oceans, and the efficient transfer of phosphate through the oceans to thermocline waters by increased upwelling. Subordinate phosphogenesis during the intervening warm periods is explained by the weathering of glacial legacy sediments during deglaciation and warming. This all indicates that with the transition from green- to icehouse conditions during the Oligocene and Miocene, new ways of weathering, nutrient mobilization, and distribution pattern within oceans affected and partly inverted feedback mechanisms between climate, geochemical cycles, and life, which profoundly influenced the biosphere and its evolution.

Deciphering the Tectonostratigraphic History of the Ventura Basin using Detrital Zircon Geochronology

Clark Gilbert and Zane Jobe
Department of Geology and Geological Engineering
Colorado School of Mines, Golden, CO, USA

Spatial and temporal changes in sediment routing patterns can signal shifts in basin evolution and regional tectonics, and can also significantly affect hydrocarbon reservoir quality. Therefore, it is imperative to integrate tectonic, sedimentary and geochronological approaches into a source-to-sink framework to interpret sedimentary basin evolution. The complex tectonic history of southern California created sedimentary basins of various structural styles throughout the Cenozoic. The Ventura basin in southern California is a Miocene strike-slip basin that experienced multiple episodes of source-area reorganization due to changes in regional tectonics. The timing of Cretaceous and Eocene forearc deposition in southern California is somewhat constrained to 80-24 Ma. Strike-slip movement between the North American and Pacific plates historically began after 30 Ma, but recent findings may suggest initiation as early as 38 Ma. Questions remain about the timing and character of transtension, transpression, and transrotational tectonics caused by complex strike-slip movement in the Ventura and Los Angeles basins and the Transverse Ranges in southern California. The Ventura basin's proximity to many igneous and metamorphic terranes in the Basin and Range, the Sierra Nevada batholith, and the Transverse Ranges makes it an ideal place to study source-to-sink dynamics in a tectonically complex basin using detrital zircon geochronology. The provenance of basin sediments can be inferred by dating detrital zircons and matching the age peaks to possible sediment source areas.

We used U-Pb geochronology to date detrital zircons from 5 samples in a transect from the Eocene Juncal Formation through the Miocene Modelo Formation in the eastern Ventura Basin. We also used two different un-mixing methods (top-down and bottom-up sediment un-mixing) to identify possible parent sources and interpret sediment routing patterns in the Ventura basin. These results help to determine how source areas and structural styles changed during reorganization of the plate margin and to demarcate the paleogeographic margins of the Ventura Basin. We also incorporate the stratigraphic architecture of the Mohnian-aged (13.5-7.5 Ma) Modelo Formation in the Ventura Basin to help constrain spatial and temporal sediment routing. The Modelo Formation contains sandy turbidites encased in siliceous shale similar to the age-equivalent Monterey Formation to the west. We use the stacking patterns of these main lithofacies (coarse grained sandstones versus the Monterey-like shales) to explore controls on sediment routing into and within the Ventura Basin. We hope that these results can also be used to better understand sediment routing variability and its impacts on paleoceanography,

Understanding the Diagenesis and Development of the Mechanical Stratigraphy of the Woodford Shale of Oklahoma Using the Siliceous Mudrocks of the Monterey Formation: Siblings on the Same Road to Brittleness

Craig D. Hall Ph.D
Core Laboratories, Houston, Texas, USA

The Woodford Shale in the Arkoma Basin in Oklahoma, is a heterogeneous mix of chert and siliceous mudrock in the late oil to dry gas window. These two facies may occur separately or in a thinly (1cm-10cm) interbedded facies association. The siliceous shale is mostly very dark gray and laminated, possesses common cm-scale pyrite nodules, and contains varying amounts of silt and compacted algal cysts; average total clay volume is around 17 volume percent. Correlation of XRD data and thin section petrographic observations suggests that the siliceous shales contain additional quartz over and above what can be accounted for in the visible detrital silt fraction. Most of the chert in the Woodford is present as mostly massive to faintly laminated beds containing abundant, vertical, bed-limited, mineralized fractures. The dominant color of the chert beds in the subsurface is black, to very dark bluish gray due to the presence of clay (which averages 7 volume percent) and organic matter, and the author and other workers have found intact radiolaria in the chert beds suggesting their origin as radiolarites. In outcrop in the northern Arbuckle Mountains in southern Oklahoma the chert beds weather to a buff or light tan color similar to the Monterey porcelanite exposures along the California coast and near Arroyo Seco. They also exhibit a dense, orthogonal fracture system that can contain bitumen. The depositional setting for the Woodford is interpreted as a restricted shelf overlain by a stratified water column, and is bordered on the south by a deep, open marine basin that developed during the approach of Gondwana from the present day south in the Late Devonian. The chert beds are interpreted to have originated as siliceous oozes of opal-A derived from radiolarian blooms that were episodically transported up out of the basin onto the outer shelf by upwelling currents.

The presence of bed-limited fractures in the Woodford cherts was initially enigmatic. It was noted that many of the mineralized fractures often had short “tails” of the mineral-fill material that extended only a few millimeters outside of the host chert bed. In many cases these “tails” were frequently folded and contorted due to compression suggesting deformation prior to reaching maximum burial depth/compaction. Recent work by Weller and Behl (2017) documents the heterogeneity in mechanical properties and porosity of Monterey Formation mudrocks in the San Joaquin Basin in California and correlates the same to heterogeneity in bulk composition, and “stepwise” diagenetic changes in silica phase. In light of their observations and conclusions, and given the similarity in original composition, and stratigraphic architecture between the Monterey and Woodford, I interpret a similar diagenetic history in the Woodford, and that it has gone through similar processes and relative timing, ie the same stepwise changes in attributes documented by Weller and Behl (2015 and 2017). The Woodford chert beds became sufficiently brittle to host the ubiquitous fractures that characterize these beds during a period of burial when the adjacent, more argillaceous mudrock facies was still too ductile for the fractures to propagate through.

Multi-basin paleoredox reconstructions from the Miocene Monterey Formation

Leanne G. Hancock[1], Timothy W. Lyons[1], Noah J. Planavsky[2], Richard J. Behl[3]
[1]*University of California Riverside, Riverside, CA, USA*
[2]*Yale University, New Haven, CT, USA*
[3]*California State University Long Beach, Long Beach, CA*

The Miocene Monterey Formation, an organic-rich deposit found along the coast of California, was deposited under oxygen minimum zones in numerous sediment-starved basins with varying degrees of connection with the open ocean. The Monterey's organic-rich nature has been linked to a global positive carbon isotope excursion between ~13 and 18 Ma, and constraining oxygen availability within these diverse basins is crucial for unraveling the magnitude of its role in organic carbon accumulation and the various other controls such as levels of primary production and sedimentation rates. This study includes water column paleoredox indicators—iron speciation and molybdenum concentrations and isotopes—from both drill core and outcrop samples from the Santa Barbara, Santa Maria, and San Joaquin Basins. These basins capture an environmental gradient spanning from settings well connected with the open ocean to relatively restricted depocenters. Bottom-water redox is constrained by high-resolution iron speciation and trace metal concentrations, which suggest continuously anoxic and occasionally euxinic conditions were achieved in all three basins, although these relationships manifest in different ways due to local basin dynamics such as sedimentation rate and degree of condensation.

The San Joaquin Basin had strongly euxinic conditions as suggested by both the elevated highly reactive to total iron (>0.5) and pyrite to highly reactive iron (>0.8). However, Mo concentrations, another euxinic indicator, are <50 ppm except in one interval where they reach 200 ppm. Other redox-sensitive trace metals such as uranium and vanadium are similarly enriched in this interval. The combination of the iron speciation and molybdenum data suggest that basin restriction limited the input of Mo and quantitative removal of Mo to sediments could have been achieved. The Mo-enriched interval may represent a period of increased connection with the ocean, allowing both increased Mo input to the basin and concomitant burial in sediments. The Santa Maria and Santa Barbara Basins show more variable and wider ranges of iron speciation data and likely had unstable redox conditions that fluctuated on various timescales between anoxic and euxinic. Molybdenum concentrations in both of these basins are also variable between 10 and 50 ppm, with some scattered intervals approaching 150 ppm. Despite the marginal marine settings with varying degrees of restriction and differing redox histories, δ^{98}Mo is homogenous and relatively invariant within and among the basins. Invariant Mo isotope signals are rare outside of modern strongly euxinic basins like the Black Sea where the sediment Mo isotope signatures capture seawater values. δ^{98}Mo values from the Monterey Formation are on average ~1.1‰, lighter than seawater values of 2.3‰. Despite the systematic observed behavior for δ^{98}Mo, the inter-basin relations are counter-intuitive relative to conventional views of the Mo proxy, leading to two primary conclusions: 1) the Monterey's overall δ^{98}Mo composition suggests more pervasive oxygen deficiency in the Miocene on an global scale relative to today's oceans, and 2) the array of depositional gradients expressed temporally and regionally within the Monterey Formation provide an ideal test bed for further developing the Mo proxy for general use.

A global context for Miocene peak warmth and subsequent cooling

Timothy Herbert
Dept. of Earth, Environmental and Planetary Sciences, Brown University, Providence RI 02912

Bob Garrison's scientific contributions span a very broad range. For this presentation, I will consider aspects raised particularly by Bob's work with the Monterey Formation and the deposition of siliceous and carbon-rich marine sediments along the Pacific Rim from mid to late Miocene time. These sequences raise fascinating questions on the relationship of the marine carbon cycle to carbon sequestration and paleo-CO_2 levels in the atmosphere, and on the relationship of the development of regional stratigraphic packages to global climatic changes.

My presentation will take advantage of data sets not available during the formulation and publication of seminal papers on Monterey deposition and the "Monterey hypothesis" linking carbon isotopic enrichment events to unusually intense episodes of marine organic matter storage. New information includes the development of high resolution and continuous stable isotopic records that place carbon cycling and Miocene ice volume events in an orbital framework, and the application of high precision methods of reconstructing past ocean surface temperatures in many locations over late Miocene time. Students, post-docs and I at Brown have particularly contributed in the latter effort- my presentation will therefore emphasize the emerging relations global temperature patterns to questions of ice volume history, carbon cycling, and ecological change in the middle to late Miocene.

It is now clear that the Middle Miocene climatic Optimum saw global surface temperatures at least $10^{o}C$ warmer than today. The change was particularly striking at higher latitudes. Approximately coincident with the "refrigeration" of East Antarctic, global temperatures began to decline. This cooling trend was gentle until ~ 8 Ma, at which point it sharply accelerated into the late Miocene (Messinian stage). From ~6.3-5.5 Ma, ocean temperatures approached Holocene levels in both hemispheres. Orbitally- paced cold excursions map to late Miocene glaciations recognized in high resolution $d^{18}O$ records and by physical evidence of ice rafting in the North Atlantic, North Pacific, and off the West Antarctic ice sheet. The very latest Miocene and most of the Pliocene saw average ocean temperatures rebound above late Miocene levels.

Late Miocene temperature evolution evidently charts global cooling between the temperature "set points" of Antarctic and Northern Hemisphere (stable Greenland ice cap?) glaciation. During this time, equator-pole temperature gradients increased strongly, presumably a forcing factor influencing coastal upwelling systems. Global cooling provides an environmental context for widespread evidence for increasingly arid climates seen in the sub-tropics in late Miocene time (expansion of C4 grasslands, desertification). This new temperature evidence suggests that the hypothesis of a significant late Miocene decline in atmospheric CO2 levels first proposed by Thure Cerling is likely correct. Evidence will be presented here in further support of Miocene global environmental changes as the result of reduced levels of CO_2.

The Evolution of Indian and Pacific Ocean Denitrification and N dynamics since the Miocene

A.C. Ravelo
University of California, Santa Cruz

The feedbacks between geochemical cycles and physical climate change are poorly understood; however, there has been tremendous progress in developing coupled models to help predict the direction and strength of these feedbacks. As such, there is a need for more data to validate and test these models. To this end, the nitrogen (N) cycle, and its links to the biological pump and to climate, is an active area of paleoceanographic research. Using N isotope records, Robinson et al. (2014) showed that pelagic denitrification in the Indian and Pacific Oceans intensified as climate cooled and subsurface ventilation decreased since the Pliocene. They pointed out that a more ventilated warm Pliocene contrasts with glacial-interglacial patterns wherein more ventilation occurs during cold phases, indicating that different mechanisms may occur at different timescales. Our objective is to better understand the nature of the feedbacks between the oceanic N cycle and climate by focusing on the large dynamic range of conditions that occurred during and since the Miocene, which includes major perturbations and changes in biogeochemistry and climatic conditions. We used new cores from across the tropical Pacific and find that N isotope trends since the Pliocene are in agreement with previous studies showing increasing denitrification as climate cooled. In the Miocene, the records show a trend that is roughly coupled to changes in global climate suggesting that pelagic denitrification in the Pacific was strongly influenced by greater ventilation during global warmth. However, there are notable deviations from this coupling during several intervals in the Miocene, and there are site-to-site differences in trends. These deviations and differences can be explained by changes in tropical productivity (e.g., late Miocene biogenic bloom), which drove changes subsurface oxygenation and denitrification, and by changes in regional nutrient utilization. Our study provides fundamental data that can be used to validate conceptual and numerical models of the long-term coupling of climate, biological productivity and ocean chemistry.

The influence of strike-slip tectonics on petroleum system development in the Santa Cruz County Coast area, California

Allegra Hosford Scheirer and Leslie B. Magoon
Stanford University, Stanford, CA, USA

The fossil petroleum system on the Santa Cruz County coast provides a natural lab for examining how strike-slip tectonics influences the migration of oil in the subsurface. Coastal exposures lie east of the offshore San Gregorio-Hosgri Fault, a right-lateral strike-slip fault of the North America-Pacific Plate boundary system that has accumulated about 150 km of slip since the mid-Miocene. The essential elements of the petroleum system—source rock, reservoir rock, seal rock, and overburden rock—appear in outcrops north of the city of Santa Cruz: the Monterey Formation is the likely source rock (although on the coast it crops out only on the "wrong" side of the fault for this petroleum system at Pt Año Nuevo); the Santa Margarita Sandstone is the reservoir rock, and the Santa Cruz Mudstone is the seal and principal overburden rock. The key in unraveling how these elements coalesced into a successful (though noncommercial) petroleum system lies in understanding how the timing of fault movement impacted the paleo sedimentary depocenter.

We developed a simple basin and petroleum system model to better understand the interplay between sedimentation and tectonics in the area. The model is guided in part by observations from the deepest well on the coast, the Texaco Poletti NCT-1, drilled in 1956 to a total depth of 9201 ft (2.8 km). In the basin model, we defined the Monterey Formation as dominantly Opal-CT rock with 3 wt% Total Organic Carbon, 700 mg HC/g TOC Hydrogen Index, and default kinetics for petroleum generation. Other modeling inputs included paleowater depth, seawater-interface temperature, and basal heat flow through time. Two calibration points guided model parameterization. What makes this modeling effort unique is our hypothesis that the slip history of the San Gregorio Fault determined the critical moment of the petroleum system, that time that best depicts the generation-migration-accumulation of petroleum. Piercing points indicate that fault movement in the area occurred between about 9 and 7 Ma. Our modeling results indicate that the base of the Monterey Fm entered the oil window ~7.5 Ma when overburden thicknesses were sufficient to generate sufficient thermal stress. However, the petroleum system was only active for about 1 Myr, when fault slip dissected the paleo depocenter and ceased thermal maturation of the source rock. The Monterey Formation only reached about 60% transformation (vitrinite reflectance of 1.0%) before the petroleum system became inactive. For this conference, we plan to examine how strike-slip fault movement influenced petroleum system development with a simple 3D geodynamic model to reconstruct both the geometry and thermal conditions of the paleo depocenter through time.

Uranium Isotopes in Organic-Rich Shales as a Proxy for Oxygen in the Ancient Oceans: A Case Study from the Miocene Monterey Formation

K. V. Lau[1], L. G. Hancock[1], K. Maher[2], S. Severmann[3], A. Kuzminov[3], R. J. Behl[4], T. W. Lyons[1]
[1]*Department of Earth Sciences, University of California, Riverside, California, USA*
[2]*Department of Earth System Sciences, Stanford University, California USA*
[3]*Department of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey USA*
[4]*Department of Geological Sciences, California State University, Long Beach, California USA*

Redox-sensitive trace metals and their isotopes can serve as important proxies for tracking the degree of oxygenation of past oceans. When recorded in organic-rich shales, these archives can provide quantitative information about redox conditions for the sedimentary basin in which the strata were deposited, as well as elucidate patterns of changing ocean oxygenation and de-oxygenation through Earth history. The uranium isotope proxy ($^{238}U/^{235}U$, commonly denoted as $\delta^{238}U$) has emerged as a promising tool for constraining changes in global redox conditions, in contrast to many other proxies that speak only to local conditions. However, our current understanding of the controls on the uranium paleo-redox proxy is limited, complicating interpretations of $\delta^{238}U$ fluctuations in the rock record. Variations in productivity-driven upwelling, basin connectivity, and sedimentation rate can influence the isotopic fractionation of uranium into organic-rich shales—the largest lever on the $\delta^{238}U$ composition of seawater. To investigate the interplay of these factors on uranium cycling, we focus on the phosphatic, carbonaceous, and silica-rich shales of the Miocene Monterey Formation. We specifically compare $\delta^{238}U$ and U concentration data in strata deposited in the San Joaquin and Santa Barbara Basins, taking advantage of each basin as a natural laboratory for testing the importance of various environmental factors on uranium accumulation and related isotopic fractionation.

The $\delta^{238}U$ patterns in the two basins differ significantly: in a core drilled from the southern San Joaquin Basin, the $\delta^{238}U$ and U concentration data covary, whereas in the Naples Beach section in the Santa Barbara Basin, the $\delta^{238}U$ and U concentration values are inversely correlated. We hypothesize that these differences can be explained by depositional conditions unique to each basin: The San Joaquin Basin experienced greater degrees of restriction from the open ocean, whereas the Naples Beach section in the Santa Barbara Basin was deposited under exceptionally low sedimentation rates. To further test our hypotheses, we developed a reactive transport model and will demonstrate that these factors can result in the patterns in uranium isotope fractionation observed in each basin. More broadly, this work provides important new constraints on the major controls on $\delta^{238}U$ in the past oceans as a critical step in the development of an emerging paleo-redox proxy.

Nanometer-Scale Pore Structure and the Monterey Formation: A New Tool to Investigate Silica Diagenesis

C. M. Ross[1] and A. R. Kovscek[1]

[1]*Stanford University, Stanford, California, USA*

The Monterey Formation of California has been the subject of field and laboratory studies on silica diagenesis. Often these studies rely upon compositional measurements such quantitative XRD and FTIR to detect silica alteration. Quantitative XRD is limited in that it requires calibration, which is challenging with an amorphous silica phase. In addition, the results are dependent upon the relative weight percentage of components and their grain densities. Using nanometer-scale pore structure as an indicator of silica alteration, specialized calibrations are not required, sample preparation and measurements are easy, and initial and subtle changes (≤ 1 wt%) are readily detected using the resulting data.

Silica phase transitions of the Monterey Formation originate with biogenic silica, predominantly comprised of planktonic algae or diatoms, deposited as opal-A (amorphous silica; $SiO_2 \cdot nH_2O$). As these biogenic silica-rich deposits are buried and subjected to increasing temperatures, opal-A progressively dewatered and became more ordered converting into opal-CT (amorphous silica with distinct XRD peaks for cristobalite and tridymite), and, eventually, the final crystalline phase, quartz (SiO_2). In thin section, opal-A and opal-CT samples are readily distinguished from each other based on their distinct pore structure and rock fabric. For samples in the early transformation stages, image-based distinctions are not possible and other methods such as XRD and FTIR are not sensitive enough. Nanometer-scale pore structure measures provide an alternative method.

Nitrogen desorption isotherms collected after low temperature outgassing and processed using the BJH method (Barrett et al., 1951) provide pore size distributions of nanometer-sized pores (nPSD; ~3.5 to about 200 nm) as well as nanometer-scale pore volume (nPV) and surface area (nSA). When applied to diatomaceous rocks and their alteration products, the resulting data reveal two distinct trends in the evolution of nanoscale porosity with respect to silica alteration as described by Ross et al. (2016; Fig. 1). Samples with more surface area per unit volume lie parallel to the steep trend (Fig. 1) with opal-A samples near the base of the trend (nSA < 50 m^2/g), opal-A to opal-CT transitional samples containing 1 to 11 wt% opal-CT (XRD) further up the trend (50 m^2/g < nSA < 100 m^2/g), and opal-CT samples with some opal-A as well as fully converted samples in transition to quartz (opal-CT 50 to 78 wt% and quartz 17 to 31 wt% XRD) occur at the uppermost portion of the steep trend (> 100 m^2/g). These distinct trends are also apparent in the nPSD in which all of the samples have a peak at ~ 3.8 nm, the steep trend samples exhibit a second peak between 5 and 10 nm in diameter, and the second peak on the shallow trend samples occurs between 10 and 100 nm (Fig. 2).

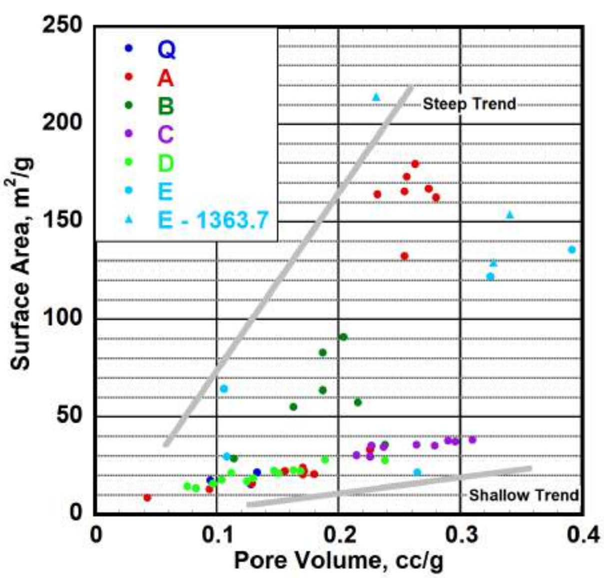


Figure 1. BJH pore volume vs surface area for naturally occurring study samples* (from Ross et al., 2016). For visualization, lines approximate the orientation (but not location) of the shallow and steep trends. Samples include: Quarry samples (Q; Lompoc,

This new application was developed using diatomaceous and siliceous shale samples from the Monterey Formation of the Santa Maria and San Joaquin Basins. The rocks types studied include clean diatomite from Lompoc, California, diatomaceous mudstones, calcareous diatomaceous mudstones, opal-CT porcelanites, and quartz porcelanites. Aside from the quarry samples, the remaining samples are reservoir samples. A few of the reservoir samples have been exposed to thermal oil recovery methods and exhibit induced silica alteration. Samples are discussed with respect to their nanometer-scale pore structure, composition (rock type, mineralogy, and elemental data), physical properties (such as porosity, grain density, and their macro pore structure), and thermal history.

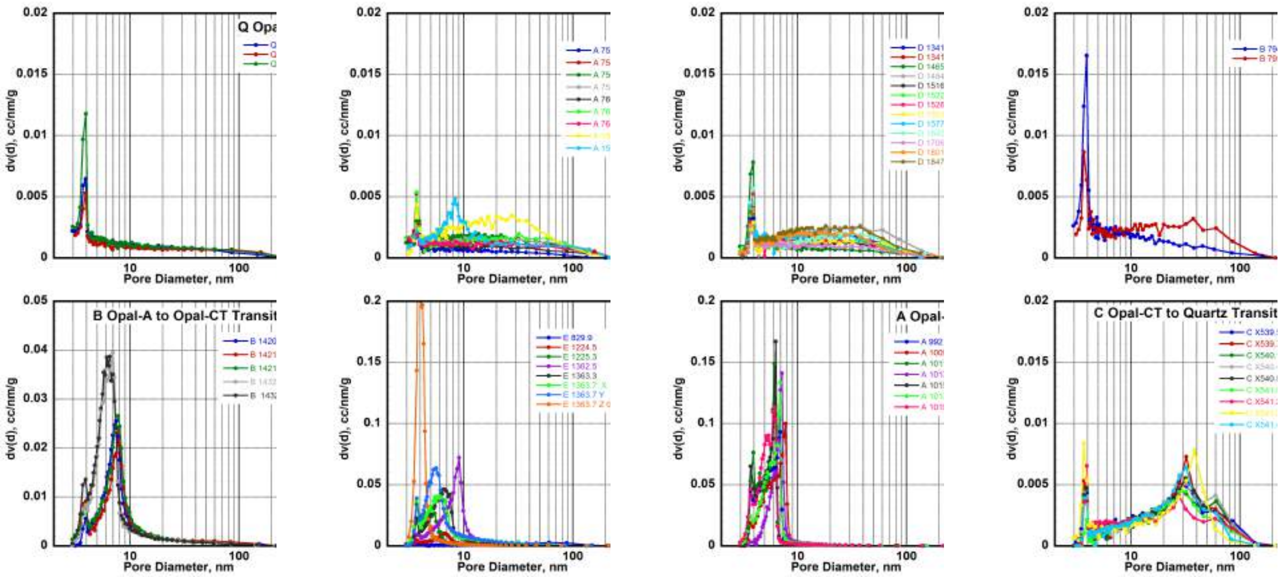


Figure 2. BJH pore-size distributions for natural diatomites* by source and silica phase (either known or interpreted; Table 3; from Ross et al., 2016). Note: Scale changes were necessary for high pore volume samples. Samples include: Quarry samples (Q; Lompoc, CA) and samples from five fields (designated by A, B, C, D, and E) in the San Joaquin Basin. (* - A few samples may have been altered in situ by thermal recovery methods.)

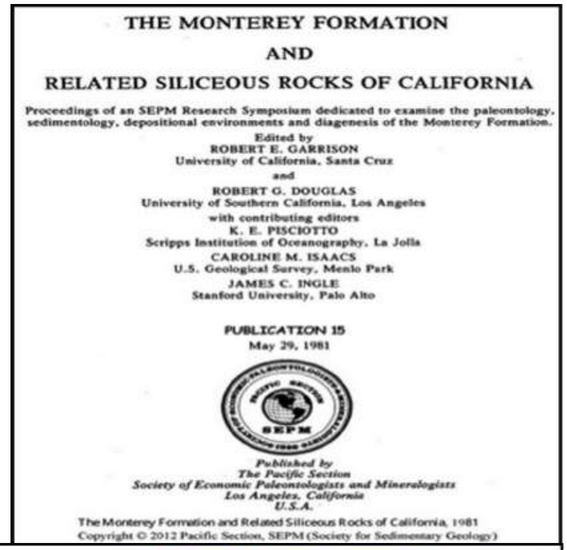
References

Barrett, E. P., Joyner, L. G., and Halenda, P. P. 1951. The Determination of Pore Volume and Area Distributions in Porous Substances. I. Computations from Nitrogen Isotherms. J Am Chem Soc 73: 373-380.

Ross, C. M., B. Vega, J. Peng, M. Ikeda, J. R. P. Lagasca, G.-Q. Tang, and A. R. Kovscek, 2016. Detecting Opal-CT Formation Resulting from Thermal Recovery Methods in Diatomites. Presented at the SPE Western Regional Meeting, Anchorage, AK, 23-26 May. SPE-180369-MS doi:10.2118/180369-MS

Monterey Formation Lives On In the Bering Sea

Dave Scholl
University of Alaska Fairbanks, Emeritus



THE MONTEREY FORMATION
AND
RELATED SILICEOUS ROCKS OF CALIFORNIA

Proceedings of an SEPM Research Symposium dedicated to examine the paleontology, sedimentology, depositional environments and diagenesis of the Monterey Formation.

Edited by
ROBERT E. GARRISON
University of California, Santa Cruz
and
ROBERT G. DOUGLAS
University of Southern California, Los Angeles
with contributing editors
K. E. PISCIOTTO
Scripps Institution of Oceanography, La Jolla
CAROLINE M. ISAACS
U.S. Geological Survey, Menlo Park
JAMES C. INGLE
Stanford University, Palo Alto

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The sine-qua-non for the middle and late Miocene Monterey Formation of California is its siliceousness. Up and down coastal California, rocks with this attribute were described and explored by Bob Garrison and his colleagues in their iconic Publication No. 15 of the Pacific Section of the SEPM (Garrison et al., 1981; Fig. 1). Prior to the appearance of this comprehensive work, the earth science community widely understood that one of the singular characteristics of California's Monterey Formation was it diatomaceous sequences, e.g., Bramlette, (1946).

Discovering the "Monterey Formation " in the Bering Sea

Offshore geological and geophysical studies in the Bering Sea did not get underway until the mid 1960s. In the deep water (3000-4000 m) Aleutian Basin, initial discoveries included the recording of a 2-10-km-thick section of basin fill overlying a basement of oceanic crust (Fig. 2). Although prominently striped by magnetic anomalies, the basement age this backarc basin was undetermined but most likely was Mesozoic or earliest Tertiary. In the late 1960s and early 70s, dredging of the Beringian continental margin and scientific drilling in the Aleutian Basin (DSDP Leg 19) determined that its bordering continental slopes and basin floor were, respectively, draped and underlain by thick (100s to 1000s of m) sections of diatomaceous or formerly diatomaceous beds (Figs. 2 and 3).

Below a subfloor depth of about 1 km, silica transformation of Opal A to Opal CT had converted weakly consolidated diatom-rich sections to lithified porcelaneous shale and mudstone, and at greater depth, to microcrystalline quartz. These beds were generally of ~late Miocene and older age (Fig. 2).

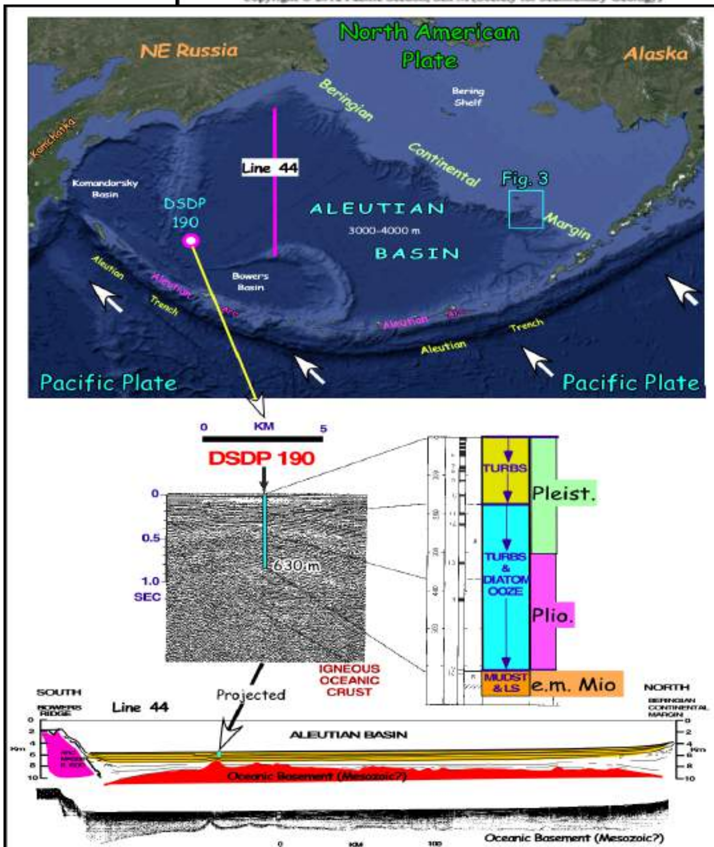

Figure 2

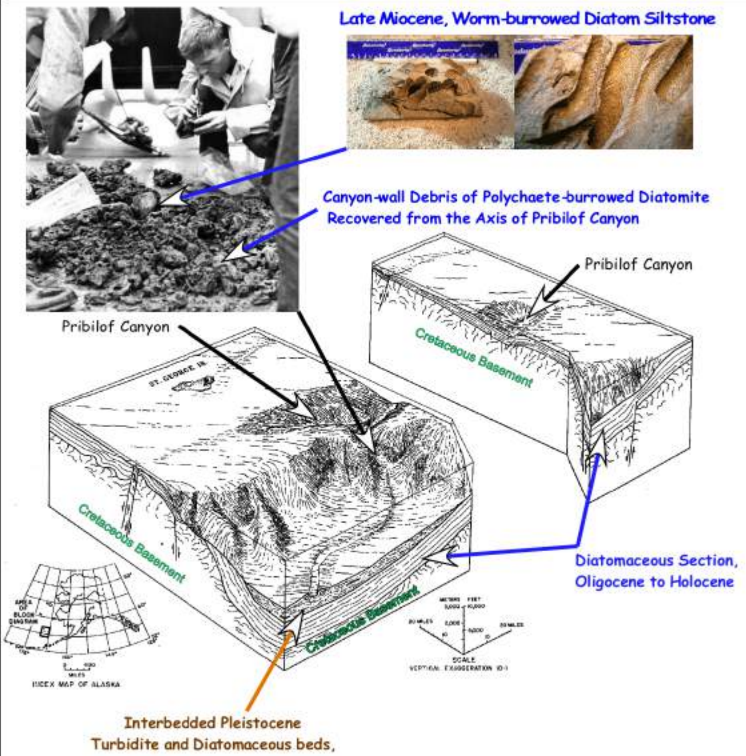

Figure 3

In now vintage publications, these early drilling and dredging discoveries were described by Scholl et al., (1968, 1973) and Scholl and Creager (1973).

They revealed that the Aleutian Basin was, in effect, a large (~500,000 km^2) Pacific-rim basin that since at least the earliest Oligocene had, along with terrigenous sediment, been continuously accumulating the siliceous biogenic debris characteristic of the Monterey Formation. But whereas California's Monterey Formation accrued along the tectonically active Pacific-North American plate boundary zone of western California, coeval and younger siliceous sequences of the Aleutian Basin amassed within the tectonically quiet setting of a backarc basin (Fig. 2).

Summing Remarks

During the middle and late Miocene, the siliceous deposits of California's Monterey Formation accumulated in multiple basinal settings formed along the active Pacific-North American transform boundary zone. Miocene and younger boundary tectonism deformed and widely exposed these deposits along coastal California.

In contrast, coeval and younger siliceous deposits of the Bering Sea's Aleutian Basin accrued in a tectonically stable backarc basin that largely remains undeformed and unexposed. After the Miocene and to the present, siliceous deposits continued to pile up over the basin's flanks and floor, although, during the Pleistocene (past ~2.6 Myr), interbedded with basin-floor turbidite units (Figs. 2 and 3).

Thus, since at least the early Oligocene, the Monterey Formation's depositional setting has been maintained in the Aleutian Basin. This setting requires up-welling SiO_2-rich waters supporting a productive siliceous ecosystem thriving distant (hundreds of km) from the input of terrigenous detritus. Along the Beringian margin, upwelling water rich in dissolved silica nourishes seasonal diatom blooms separated from riverine outfalls by a minimum of ~500 km.

References

Bramlette, M. N., 1946, The Monterey Formation of California and the Origin of Its Siliceous Rocks; USGS Professional Paper 212.

Garrison, R. E., R. G., Douglas, K. E., Pisciotto, C. M., Issacs, and J. E., Engle, 1981, The Monterey formation and related siliceous rocks of California; Publication 15, Pacific Section, S.E.P.M., 327 pp., Los Angeles, CA.

Scholl, D. W. and Creager, J. S., 1973, Geologic synthesis of Leg 19 (DSDP) results; far North Pacific and Aleutian Ridge and Bering Sea, in Creager, J. S., Scholl, D. W., and others, Initial Reports of the Deep Sea Drilling Project, v. 19: U.S. Government Print. Office, Wash., D. C., p. 897-913.

Scholl, D.W., E. C., Buffington, and D.M., Hopkins, 1968, Geologic History of the Continental Margin of North American in the Bering Sea: Marine Geology, v.6, p. 297-330.

Scholl, D.W., E.C., Buffington, and M.S., Marlow, 1975, Plate Tectonics and the Structural Evolution of the Aleutian-Bering Sea Region; Geological Society of America, Special Paper 151, pp 31.

You can observe a lot by just looking—the utility of sequence-stratigraphic analysis of outcrops in deciphering depositional and diagenetic processes of the Monterey Formation

Jon R Schwalbach[1], Kevin M Bohacs[2]
[1]*Consultant, Oxnard, CA, USA*
[2]*ExxonMobil Upstream Research Company, Spring, Texas, USA*

Sequence stratigraphy has proven to be an invaluable tool for the analysis of coarse-clastic depositional systems and for integrating observations across scales from reflection seismic to SEM. Applications to mudstone-dominated depositional sequences have been more limited, despite the fact that mudstones make up more than sixty percent of the sedimentary volume and generally provide the most complete record of sedimentation in a basin. The “shale revolution” has brought increased emphasis recently, and a number of studies have highlighted the benefits of the sequence-stratigraphic approach to help unravel the depositional and diagenetic complexities of mudstone-dominated systems. Direct observations from outcrops and cores are readily integrated with other subsurface data, as well as a wide variety of information and proxies derived from paleontologic, chronostratigraphic, geochemical and compositional analyses.

Some of the earliest investigations of mudstone sequence stratigraphy focused on the slope and basinal environments of the Monterey Formation (e.g., Bohacs, 1990; Schwalbach, 1992; Schwalbach and Bohacs, 1992). Much of the geologic framework required for these initial investigations was provided by researchers associated with Bob Garrison and UCSC (Pisciotto, Omarzai-Khan, White, Behl, Coe, and Grimm, among others). Critical elements included analysis of facies and composition, paleoceanography, diagenesis, regional stratigraphy, and detailed chronostratigraphy including paleomagnetic studies. Each of these elements plays an essential role in our understanding of the depositional sequences of the Monterey Formation.

California’s Neogene basins present a unique challenge for sequence-stratigraphic analysis. Topographic relief isolated many of the basins and sub-basins from large-scale mainland drainages and their associated clastic-dominated systems. These basins were dominated by hemipelagic sedimentation including a significant biosiliceous component, and thus provide an excellent setting to evaluate the influences of biological productivity and preservation on fine-grained sediment assemblages. The water-depth component of accommodation, which plays a major role in depositional patterns of many clastic-dominated systems, would not be expected to impact slope and basin sedimentation significantly. The impact of eustatic change and sediment supply must be considered differently in these settings and related to mechanisms such as paleoceanography and geochemistry. Even on shallow-marine shelves, accommodation is not defined by sea level but by the marine profile of equilibrium that reflects the regional marine-energy regime (e.g., Jervey, 1988). Analogously, in deep-marine settings, bottom energy and oceanic circulation are the key components of accommodation, because of their strong influence on the level to which sediment can accumulate (Gorsline, 1981; McCave, 1983, 1984; Bohacs, 1990).

Outcrop studies linking global events such as the transition from equable climates of the early Miocene to the glacially active ice-house world facilitate developing a big picture understanding of paleoceanography and productivity responses in the Neogene basins. This in turn enables us to use sedimentologic observations to interpret factors such as sediment accumulation rates and bottom-energy levels, as well as lithofacies successions, to identify key chronostratigraphic surfaces. The identification of these sequence boundaries and downlap surfaces are essential for evaluating the record of the depositional systems preserved in the Monterey Formation because they enable us compare time-equivalent stratal packages across different slope and basin settings. Outcrop gamma-ray profiles, collected from many of the outcrop sections along the California coast, provide a reliable means to project the interpretation into the subsurface, and greatly expand the geographic area of our depositional models.

Interpreting more detailed variation in the stratal succession is more challenging because our understanding of the links between paleoceanography, productivity, and diagenetic processes are evolving – but the rock record provides us with many clues on the interaction of these factors at the parasequence and parasequence-set scale. For example, dolomites formed at or near the sediment-water interface commonly mark times of pauses or lower rates of sediment accumulation in the basin, and can be interpreted in terms of parasequence boundaries. Thus early-stage diagenesis becomes an important influence on lithostratigraphic successions.

Within these slope and basin settings, we have identified distinct stratal stacking patterns within highstand, transgressive, and lowstand systems tracts. The lithofacies associations are partly a function of geographic position within the basin, and thus lithofacies distributions are diachronous. Stratal stacking patterns reflect variations of interpreted bottom energy levels and composition, including organic and inorganic components. The Monterey stratal succession is ultimately the result of an interplay of biological productivity, preservation, and dilution with numerous components that can vary singularly or collectively. Sequence-stratigraphic analysis of outcrop sections have changed the basis of the study of fine-grained rocks from proxies alone to direct observation and full integration of analytical insights that has proven so valuable for understanding the influences on rock properties. This integrated approach was inspired by the vision of Bob Garrison who taught us to see the Monterey Formation through the lens of oceanography, climate, and biology.

References

Bohacs, K.M., 1990, Sequence stratigraphy of the Monterey Formation, Santa Barbara County; integration of physical, chemical, and biofacies data from outcrop and subsurface. SEPM Core Workshop, v. 14, p. 139-200.

Gorsline, D.S., 1981, Fine sediment transport and deposition in active margin basins. - In: Douglas, R.G., Colburn, LP., Gorsline, D.S., editors, Depositional systems of active continental margin basins. – Pacific Section SEPM Short Course notes, p. 39-59.

Jervey, M.T., 1988, Quantitative geological modeling of siliciclastic rock sequences and their seismic expression, in Wilgus, C.K., Hasting, B.S., Kendall, C.G.St.C, Posamentier, HW, Ross, CA, and Van Wagoner, JC, editors, Sea-level changes: an integrated approach: Tulsa, OK, Society of Economic Paleontologists and Mineralogists, Special Publication No. 42, p. 47-69.

McCave, I.N., 1983, Particulate size spectra, behavior, and origin of nepheloid layers over the Nova Scotian continental rise. Journal of Geophysical Research v. 88, p.7647-7666.

McCave, I.N., 1984, Erosion, transport and deposition of fine-grained marine sediments. in Stow, D.A.V., and Piper, D.J.W., editors, Fine-grained sediments; deep-water processes and facies. Geological Society of London Special Publication 15, p. 35-69.

Schwalbach, J.R., 1992, Stratigraphic and sedimentological analysis of the Monterey Formation: Santa Maria and Pismo Basins, southern California: unpublished Ph.D. dissertation, University of Southern California, Los Angeles, California, 360 p.

Schwalbach, J.R., and Bohacs, K.M., 1992, Sequence stratigraphy in fine-grained rocks: examples from the Monterey Formation: The Pacific Section-SEPM, Bakersfield, California., SEPM Field Guide v. 70, 80 p.

Large, Calcite-Cemented Sandstone 'Chimneys' in the Santa Margarita Sandstone, Scotts Valley, California: Solving A Gold-Rush Era Mystery

Hilde Schwartz[1], Frank Perry[2], Carlos Bazan[3]

[1]*Earth and Planetary Sciences, Univ. of California, Santa Cruz, Santa Cruz, California, USA* [2]*Santa Cruz Museum of Natural History, Santa Cruz, California, USA*

[3]*Mining and Mineral Exploration, British Columbia Institute of Technology, Vancouver, British Columbia, Canada*

An outcrop of the upper Miocene Santa Margarita Sandstone in Scotts Valley, California, contains abundant calcite-cemented concretions that resemble authigenic structures found at cold seeps, including chimney-like columns up to 2 m in diameter.

The site first caught the attention of settlers during the 1850s. The sandstone columns were mistaken for the remains of a massive building, presumably constructed by some ancient civilization like those of Mexico or South America. Dubbed "The Ruins," the site made national news, and a company was formed to excavate for buried treasure. Fifty columns were found, but no treasure. Nevertheless, the site remained a tourist attraction during the rest of the 1800s. Natural explanations for the building-like features at "The Ruins" were soon favored, including the possibility that the columns formed like stalagmites. By the twentieth century, geologists agreed they were concretions, but their columnar shape was problematic. In 1982 the area's curious history prompted archaeologists to once again investigate a possible human origin, but no cultural resources were found.

Figure 1: Bob Garrison near the tallest remaining chimney at "The Ruins" (rock hammer for scale in lower left)

We recently mapped, sampled and analyzed 12 chimneys and numerous slab-like concretions, which are exposed over ~160 square meters in the uppermost portion of the otherwise poorly indurated Santa Margarita Sandstone. The surviving columns crop out along a SW-NE trend on a sandy hillside and are distinctly chimney-like, with circular cross sections and central cavities; the tallest rises 1.5 m above the surface (see Figure 1). A broad horizon of discontinuous, slab-like concretions, 0.2-1.7 m in length, stratigraphically overlies the chimneys. All concretions consist of coarse-grained sandstone cemented by low-Mg calcite (1.5-2% $MgCO_3$), and they typically contain abundant remains of the echinoid *Astrodapsis spatiosus*. The stable isotope values of the cements ($\delta^{18}O$ from -5.15‰ (chimney) to -2.32‰ (slab); $\delta^{13}C$ from -19.89‰ (chimney) to -1.95‰ (slab)) are consistent with a cold seep origin.

A geological enigma for 150 years, the once-famous "Ruins" represent an exhumed, localized seep field that included focused rising columns (chimneys) and diffusive flow (slabs) of methane-rich fluids through shallow marine sediments. The chimneys overlie and follow the trend of the middle Miocene-aged Bean Creek Fault, suggesting that fluid flow was fault/fracture controlled. This sole example of hydrocarbon seepage in the Santa Margarita Sandstone occurred during a period of complex transpressional deformation in the southern Santa Cruz Mountains and foreshadowed regional development of an extensive fluid system (marked by seepage, oil migration and injection of Santa Margarita sands/fluids into overlying sediments) in the latest Miocene.

Revisiting the tectonic disruption of a Miocene petroleum system in coastal northern California: a possible Santa Barbara–Santa Cruz–Point Reyes connection

Richard G. Stanley[1], Paul G. Lillis[2], and Joseph P. Colgan[2]
[1]*U.S. Geological Survey, Menlo Park, California USA*
[2]*U.S. Geological Survey, Denver, Colorado USA*

Here we build on pioneering work by Bob Garrison and his colleagues to consider how a Miocene petroleum system in coastal northern California may have been tectonically disrupted by right–lateral displacement along the northern part of the San Gregorio–Hosgri fault. Further, we hypothesize that slip on the northern San Gregorio–Hosgri fault may have been kinematically linked to clockwise rotation of the western Transverse Ranges that began after about 18–17 Ma in the Santa Barbara area.

Outcrops of oil–stained Miocene strata occur east of the San Gregorio–Hosgri fault near Santa Cruz and west of the fault near Point Reyes (Fig. 1). Much of the oil in the Santa Cruz and Point Reyes areas is found in sandstone dikes and sills that intrude fine–grained strata of the upper Miocene Santa Cruz Mudstone, a siliceous unit that was deposited about 9–7 Ma and is correlative with the upper part of the Monterey Formation of the Santa Maria and Santa Barbara basins (Barron, 1986). The sandstone intrusions near Santa Cruz and Point Reyes are thought to have formed when petroleum– and water–charged sands from the upper Miocene Santa Margarita Sandstone were intruded upward into the overlying Santa Cruz Mudstone, in some cases reaching the late Miocene sea floor (Thompson, Garrison, and Moore, 1999, 2007; Boehm and Moore, 2002).

Samples of oil from the Santa Cruz and Point Reyes sandstone intrusions and from the nearby La Honda and Half Moon Bay oil fields were analyzed for stable carbon isotopic composition and biomarkers by Stanley and Lillis (2000). The results show that (1) all oil samples analyzed were derived from source rocks of Miocene age, and (2) the Santa Cruz and Point Reyes oil samples are similar in composition to each other but different from the La Honda and Half Moon Bay oil samples (Fig. 2). The specific source rocks from which the oils originated have not been conclusively identified, but geological and organic geochemical information indicate that the likely source of oil in the Santa Cruz and Point Reyes areas is the Monterey Formation, whereas the likely sources in the La Honda and Half Moon Bay oil fields are the Monterey Formation and the lower Miocene portion of the Lambert Shale (Stanley and Lillis, 2000).

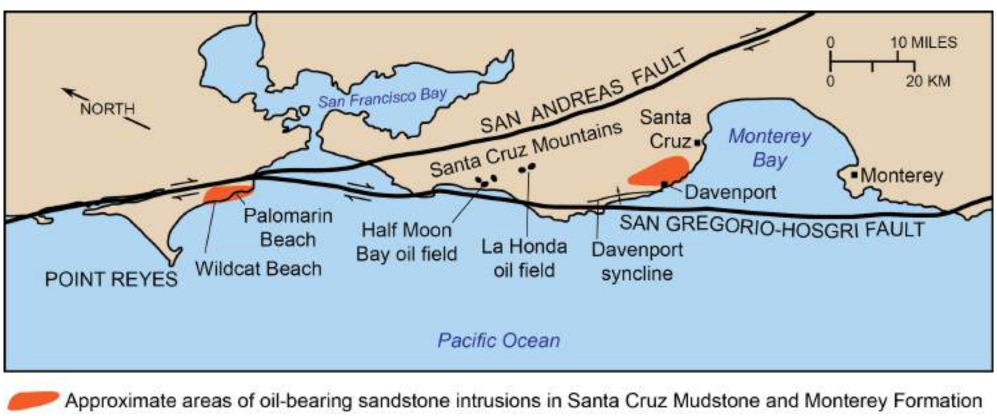

Figure 1. Location map for the northern part of the San Gregorio–Hosgri fault.

These results suggest the possibility that oil–bearing sandstone intrusions in the Santa Cruz and Point Reyes areas share a common origin and that the two areas were formerly contiguous. We hypothesize that oil in both areas was generated from thermally mature, organic–rich Miocene source rocks in the vicinity of the Davenport syncline northwest of Santa Cruz (Fig. 1), that oil migration and sandstone intrusion happened about 9–7 Ma during deposition of the Santa Cruz Mudstone, and that the Santa Cruz and Point Reyes areas were subsequently separated by about 115 ± 10 km of right–lateral displacement along the northern San Gregorio–Hosgri and northern San Andreas faults.

Right–lateral slip on the northern San Gregorio–Hosgri fault may have been kinematically linked to clockwise rotation of the western Transverse ranges near Santa Barbara in the manner proposed by Colgan and Stanley (2016; see Fig. 3). The amount of right–lateral displacement along the San Gregorio–Hosgri fault increases northward, possibly because of slip added by right–lateral faults located east of the San Gregorio–Hosgri fault and west of the Salinian block (Langenheim and others, 2012, and Fig. 3).

The time of initial slip along the northern San Gregorio–Hosgri fault is uncertain. Clark (1997, p. 7) proposed that Miocene bathymetric shallowing recorded by benthic foraminifers in the Monterey Formation on the Monterey Peninsula may indicate uplift that accompanied the initiation of displacement along the fault about 10 Ma. A possible alternative interpretation is that slip along the northern San Gregorio–Hosgri fault may have begun at about the same time as initial clockwise rotation of the western Transverse Ranges, an imprecisely–dated event that occurred after about 18–17 Ma (Luyendyk, 1991) and is shown on Fig. 3 as 16 Ma. If rotation and fault slip began at the same time, then initial slip along the northern San Gregorio–Hosgri fault may be recorded by a regional unconformity that has an approximate age of 17.5–15 Ma and is overlain by the Lompico Sandstone and Monterey Formation in the Santa Cruz Mountains.

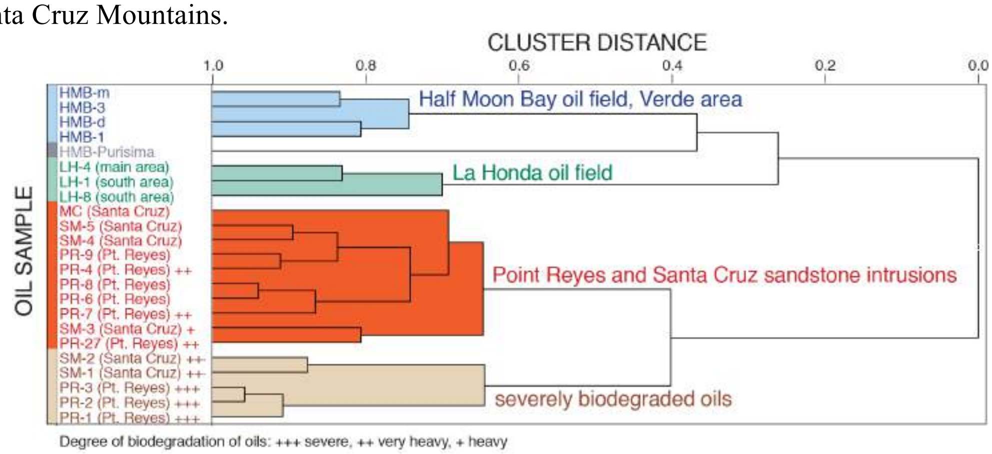

Figure 2. Dendrogram showing the genetic relationship between oils in the Santa Cruz and Point Reyes areas based on statistical analysis of source–related geochemical data, from Stanley and Lillis (2000). Cluster distance is a measure of genetic similarity indicated by the horizontal distance of any two samples to their branch point.

References

Barron, J.A., 1986, Updated diatom biostratigraphy for the Monterey Formation of California SEPM Pacific Section Book 45, p. 105–119.

Boehm, Anja, and Moore, J. C., 2002, Fluidized sandstone intrusions as an indicator of paleostress orientation, Santa Cruz, California: Geofluids, v. 2, p. 147–161.

Clark, J.C., 1997, Neotectonics of the San Gregorio Fault Zone—age dating controls on offset history and slip rate: Final technical report, National Earthquake Hazards Reduction Program, Program element I—Evaluating national and regional hazard and risk (Award No. 1434–HQ–96–GR–02741), 30 p.

Colgan, J.P., and Stanley, R.G., 2016, The Point Sal–Point Piedras Blancas correlation and the problem of slip on the San Gregorio–Hosgri fault, central California Coast Ranges: Geosphere, v. 12, no. 3, p. 1–14.

Langenheim, V.E., Jachens, R.C., Graymer, R.W., Colgan, J.P., Wentworth, C.M., and Stanley, R.G., 2012, Fault geometry and cumulative offsets in the central Coast Ranges, California: evidence for northward increasing slip along the San Gregorio–San Simeon–Hosgri fault: Lithosphere, v. 5, no. 1, p. 29–48.

Luyendyk, B.P., 1991, A model for Neogene crustal rotations, transtension, and transpression in southern California: Geological Society of America Bulletin, v. 103, p. 1528–1536.

Stanley, R.G., and Lillis, P. G., 2000, Oil–bearing rocks of the Davenport and Point Reyes areas and their implications for offset along the San Gregorio and northern San Andreas faults: Stanford University Publication Geological Sciences, v. 21, p. 371–384.

Thompson, B.J., Garrison, R.E., and Moore, J.C., 1999, A late Cenozoic sandstone intrusion west of Santa Cruz, California: fluidized flow of water and hydrocarbon saturated sediments: Pacific Section AAPG Book GB–76, p. 53–74.

Thompson, B.J., Garrison, R.E., and Moore, J.C., 2007, A reservoir–scale Miocene injectite near Santa Cruz, California: AAPG Memoir 87, p. 151–162.

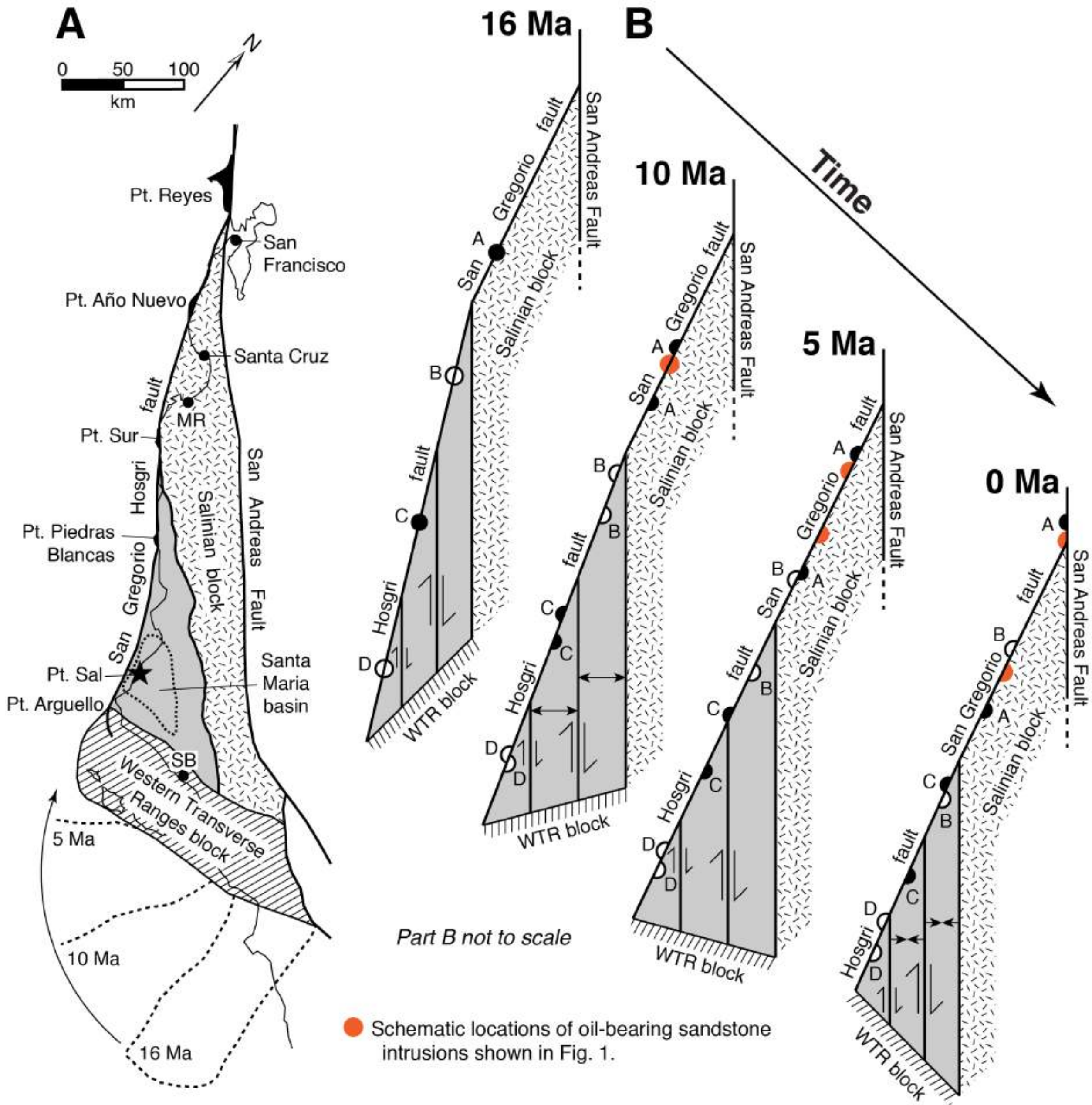

Figure 3. Model for evolution of the San Gregorio–Hosgri fault system requiring low–magnitude slip on the southern part of the fault while permitting 150–160 km slip on the northern part of the fault, from Colgan and Stanley (2016). Gray shaded region—Franciscan basement; hatched pattern—Salinian block; MR—Monterey; SB—Santa Barbara. ***A***, present–day configuration of Coast Ranges tectonic elements, with rotation of the western Transverse Ranges shown from 16 Ma to 0 Ma. ***B***, Cartoon diagram illustrating the relative positions of points A, B, C, and D on both sides of the San Gregorio–Hosgri fault from 16 Ma to 0 Ma, as rotation of the western Transverse Ranges (WTR) block was accommodated by right–lateral slip that was ultimately transferred onto the northern San Andreas fault. Horizontal arrows show local crustal extension during the early history of rotation, followed later by contraction.