Industry Affiliates Program
on the Monterey Formation
California State University Long Beach

PROSPECTUS

Monterey and Related Sedimentary Rocks
The Long Beach MARS Project

Director:
Richard J. Behl, PhD

Co-Leaders:
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PROSPECTUS *for a Monterey Formation Research Consortium:*
the Long Beach MARS Project (Monterey And Related Sediments)
http://web.csulb.edu/~behl/MARS/

Project Leader
Richard Behl, PhD, CSULB, Project Director.
- Diagenesis, geochemistry, stratigraphy, sedimentology, lithofacies
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- Mechanical stratigraphy, fractures, faulting, structural geology
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Need for the MARS Project Consortium:
- The Monterey Formation and related sedimentary rocks are the key source and an important reservoir of petroleum in California.
- With the recognition of the staggering potential of shale gas and tight-oil plays, a new look at the reservoir potential of the Monterey and other siliceous deposits is clearly required.
- The last truly broad thrust in research in the Monterey Formation and related siliceous sediments was in the 1970's to 1980's.
- Individual workers (including Behl and Gross) and companies have continued research on aspects of the Monterey Formation, but there has been substantial retirement and overturn of knowledgeable personnel in academia and industry.
- At the same time that there has been loss of expertise, there is a compelling need to address new and more sophisticated questions about the origin, variability, and character of Monterey and related sediments and how the primary composition and distribution controls reservoir characters, such as matrix porosity, permeability and fracture networks.
- Tight operational budgets mandate leveraging resources for R&D and training in industry, increasing the value of a research consortium and joint training program.
- The Monterey Formation, with its varied composition and stratigraphic character, serves as a valuable analog for other shale and non-conventional resource plays. General concepts of mechanical stratigraphy and fracture architecture, which can be observed and studied in great detail in excellent 3D exposures of the Monterey Formation, can be applied to shale gas and shale oil reservoirs in other basins.

Benefits of the MARS Project to Industry Affiliates:
- Development of a focused center of excellence for research into Monterey Formation-related problems, available for consultation and/or contracted research and analyses.
- Sustainable, ongoing university research into the Monterey Formation with ongoing support for graduate student & post-doctoral scholars.
- Annual training and science-sharing events for Affiliate companies.
    - Annual research symposium for presentation of new research results and advances.
    - Annual Monterey Formation field trip, or:
    - Annual training workshop on selected topic based on poll of Affiliate companies, e.g.:
        - Monterey facies
        - Monterey-type lithology and petrology
        - Silica diagenesis
        - Fracture analysis
        - Strain partitioning and Monterey-type lithologies

- Access to cutting edge research prior to publication or general presentation and conferences.
- Ability to interact with Project-members as research plans are developed.
- Access to highly trained and knowledgeable students and post-docs for recruiting purposes.
- Annual membership fee: $25,000 per corporation. <u>Three year initial commitment requested</u> (but not required).

Founding Industry Affiliates – 2011-2014 members:

- Occidental Petroleum, Aera Energy, Venoco, Exxon-Mobil, Breitburn Energy, Plains Exploration & Production, Signal Hill Petroleum, Bayswater Exploration & Production.

Mini-Resumes of Project Leaders

Richard Behl, PhD, CSULB

- Professor & Chair, Geologic Sciences, California State University Long Beach
- Founding member, Institute for Integrated Research in Materials, Environments and Society (IIRMES), a multidisciplinary analytical and research facility at CSULB.
- Distinguished Lecturer, American Association of Petroleum Geologists
- Distinguished Educator Award, American Association of Petroleum Geologists, Pacific Section
- Distinguished Faculty Teaching Award, California State University Long Beach
- Past President, Pacific Section Society for Sedimentary Geology (SEPM)
- President-Elect – Pacific Section American Association of Petroleum Geologists (AAPG)
- Best Oral Presentation Award, Society for Sedimentary Geology (SEPM)
- Regional and International field trip leader for AAPG, SEPM, GSA, ODP, IAS, etc.
- 42 published papers, >100 abstracts, 10 guidebooks and published reports, and 1 book.
- Industry consultant to Mobil, Exxon-Mobil, Arguello Inc. / PXP, Occidental Petroleum.

Michael Gross, PhD, MG Geosciences

- Structural Geology Consultant – fractured reservoir evaluation, training
- Senior Structural Geologist, Shell Exploration and Production
- Associate Professor, Earth & Environment, Florida International University
- 35 peer-reviewed journal publications, numerous abstracts and field guides.
- Field-based, quantitative structural geologist.
- Research focus on mechanical stratigraphy and fracture development.
- Extensive experience describing fractures in core, especially in shale-gas reservoir rocks.
- Committee Member: San Andreas Fault Observatory at Depth (SAFOD), AAPG Technical Advisory Committee.
- Graduate Program Director, Earth & Environment, Florida International University.
- Faculty Excellence in Teaching Award, Florida International University.
- Regional and International field trip leader for AAPG.
- Industry consultant to Occidental Petroleum, Shell Exploration & Production, Baker-Hughes, Devon Energy, Aspect Abundant Resources, Anadarko Petroleum.

Collaboration between Professors Behl and Gross - and their students - has strong potential for linking sedimentology, diagenesis, and structural geology in beneficial and synergistic ways unreachable by studies conducted by researchers separated by discipline.

Synergies for the MARS Project Consortium at CSU Long Beach:

- California State University Long Beach is located at the center of the reinvigorated Los Angeles basin and close to field areas in central California (Ventura/Santa Barbara, San Joaquin, Santa Maria, and Salinas basins) and many other research-focused universities. CSULB hosts the Los Angeles Basin Subsurface Data Center, where over 30,000 well files are archived for public access. In addition to Behl, CSULB faculty members Robert D. Francis and Thomas Kelty both have prior industry experience at major oil companies before coming to teach at Long Beach. Departmental expertise includes tectonics, seismic stratigraphy, geochemistry, and hydrogeology. Mathew Becker – Conrey Endowed Chair in Hydrogeology at CSULB – has special expertise in modeling flow and behavior of aquifers in fractured media. Nate Onderdonk employs the paleomagnetic record on basin-scale and tectonic-block-scale tectonic deformation of California. CSULB is also the host institution for IIRMES (Institute for Integrated Research in Materials, Environments, and Societies) a cutting-edge interdisciplinary analytical and research facility, of which Behl was a founding member.

Monterey Formation research topics in the Long Beach MARS Project

General research topics

- Interaction of pore pressure, dehydration, silica mobility, and pore abundance and morphology at silica phase boundaries.
- Influence of mechanical stratigraphy on fracture development in the Monterey Formation.
- Diagenesis, deformation and reservoir significance of early and stratigraphically out-of-sequence chert formation.
- Influence of depositional setting and process on lithofacies variations, including sediment composition and fabric and properties.
- Variation in the composition and character of diatomaceous sediments resulting from paleoceanographic setting and primary plankton assemblages.
- Relationships of facies and microfacies variations to diagenesis, deformation and reservoirs.
- Integrating subsurface data (core, image logs, petrophysical properties and seismic data) to develop conceptual models of Monterey Formation fractured reservoirs.
- Improved chronostratigraphy of the Monterey employing an integrated approach, including orbital cyclicity derived from well logs.
- Primary vs. structural and diagenetic control of lithology and rock properties.
- Roles of tectonics and paleoceanography in controlling Monterey facies, especially phosphatic, siliceous, dolomitic, and organic-rich deposits.
- Paleoceanographic and paleoclimate records from the Miocene-Pliocene Monterey Formation and related deposits.
- Identifying potential “fracture sweet spots” in Monterey Formation reservoirs based on structural position on folds and proximity to faults.
- Evaluating differences in hydrologic properties between shear fractures (faults) and opening-mode fractures (joints), which are often confined to different lithologic units.
- Provide detailed characterization of throughgoing fracture zones that serve as the major conduits (“backbones”) for reservoir-scale fracture flow.
- Developing conceptual models of reservoir fracture systems through the integration of outcrop studies, core analysis, image logs and seismic surveys.
- Evaluating the containment and geometries of induced hydraulic fractures based on mechanical stratigraphy, rock properties, earth stress and reservoir pressures.

Specific Examples:

1. **Objective: Establish and refine an integrated chronostratigraphy and lithostratigraphy for the Miocene Monterey and Kreyenhagen formations of the San Joaquin Basin, California**.

Scientific reason: Most published literature on the Monterey Formation has focused on excellent coastal outcrops in California. These studies have led to hypotheses and conclusions about the global geochemical impact of carbon, phosphorous, and silica sequestration in the Monterey Formation during the Miocene. However, coastal sections of the Monterey contain numerous hiatuses and condensed sections that make production of geochemical records difficult to create, correlate and evaluate in a global context. This is especially a problem for higher resolution paleoceanographic or geochemical studies. The more proximal San Joaquin Basin has faster and more continuous sediment accumulation rates, potentially making it better suited for stratigraphic and paleoceanographic investigation.

Applied benefit: Better stratigraphic control, correlation, and understanding of genesis of facies. Multi-scale analysis of compositional variation that can be used to calibrate petrophysical models by integration of traditional welllogs, cores, and borehole imaging logs (FMS, etc.).

Approach: Construct a composite subsurface stratigraphic section from drilled oil wells that have available samples (cuttings and cores) or that can be confidently correlated to cores. Integrate additional biostratigraphic methods (nannofossils are underutilized and very useful in Miocene carbonate-bearing deposits), stable isotopes, strontium isotopic ratios and cyclostratigraphy (Milankovitch cyclicity).

Associated studies: Investigate geochemical and paleoceanographic trends and events through the Miocene, including: O and C isotopes, organic carbon abundance and type, phosphate, etc. Study compositional cyclicity at finer scale (bedding to lamination) that reflects millennial to seasonal sedimentary forcing and variations in composition and physical rock properties significant to actual reservoir variation (alternation of shale and porcelanite/chert beds). High-resolution (mm-cm) core analysis by multi-sensor-track analysis of composition and physical properties.

2. **Objective: Petrologic and geochemical characterization of Monterey-type lithology and microfacies.**

Scientific reason: Compositional differences in primary sediment composition control timing, rate, and processes of silica diagenesis. These factors, in turn, control the environment (pore pressure, temperature, compartmentalization, etc.) of silica phase changes that consequently dictate the physical properties of the diagenetic rocks.

Applied benefit: Variations in physical properties (cementation, brittleness) and pore structure are key controls of permeability and effective porosity in reservoir rocks of the Monterey Formation.

Approach: Systematic analysis of lithologies of varying composition at specific diagenetic/stratigraphic levels. ICPMS, XRF and EDS geochemical compositional analysis linked with scanning electron microscopy, confocal laser microscopy, and polarized petrographic microscopy to characterize microfacies and porosity abundance and geometry.

3**. Objective: Investigate variability in genus-level composition of diatomite and influence on physical properties, global.**

Scientific reason: Diatom oozes and diatomites form in many different depositional environments around the world since the late Mesozoic. They consist of a wide variety of diatoms, from hair-like species to silt-like resting spores. These variations in assemblage would reflect paleoceanographic conditions and sedimentary facies. These differences could profoundly influence diagenesis, deformation and reservoir properties, yet they have never been systematically investigated.

Applied benefit: Diatomites have been treated as a single, high-porosity monotype lithology that only varies with detrital content, yet different species compositions should have enormous effect on sediment properties, such as porosity, permeability and fracture character

Approach: Initially compile published physical property data from different locals and investigate species composition. Second, compare correlative diatomaceous deposits in California from distinct paleogeographic settings (e.g., east and west side of San Joaquin basin or Santa Maria vs. San Joaquin basin) for composition and physical properties. Then investigate stratigraphic variation.

4. **Objective: Investigate mechanical stratigraphy and its influence on fracture development in the Monterey and related hemipelagic sediments.**

Scientific reason: Mechanical stratigraphy refers to the subdivision of a stratigraphic sequence into discrete intervals according to the structures or deformation style found in those intervals. Outcrop studies of brittle deformation in sedimentary rocks, including the Monterey Formation, reveal that mechanical stratigraphy plays a critical role in the distribution, geometry and style of fracture development. The scientific goal of this objective is to establish the relationships between components of the mechanical stratigraphy (e.g., bed thickness, lithology, elastic properties) and attributes of the fracture population (e.g., fracture spacing, faulting vs. jointing, ratio of fracture height to length).

Applied benefit: Once specific relationships have been established between mechanical stratigraphy and fracture development, they can be applied to subsurface data collected from core and image logs. For example, fracture spacing can be estimated from measurements of mechanical layer thickness, even where fractures are scarce or absent. Further, based on mineralogical composition, one can infer which layers will develop shear fractures (faults) and which layers will carry opening-mode fractures (joints). Ultimately, one can develop a conceptual model of fracture architecture as a function of mechanical stratigraphy, which in turn provides constraints for modeling fractured Monterey Formation reservoirs.

Approach: Field work will involve collecting structural (fracture orientations, dimensions, spacing, displacement, kinematic indicators, etc.) and stratigraphic data (lithology, bed thickness, bed boundaries, samples for testing of physical properties) from Monterey Formation outcrops along the Santa Barbara and Santa Maria coastlines. Analysis of the data will attempt to correlate properties of the mechanical stratigraphy to attributes of the fracture populations. Quantitative and qualitative guidelines will be developed for application to subsurface datasets.

5. **Objective: Investigate fracture architecture and connectivity in the Monterey Formation.**

Scientific reason: Fractures by themselves do not necessarily enhance reservoir permeability. A conductive fracture network requires connectivity among the many fractures, especially across stratigraphic layers of unfractured rock. Multi-layer, throughgoing fractures in the Monterey Formation are structures that provide the critical linkage among otherwise isolated populations of bed-confined fractures. Our previous work has shown a direct relationship between the development of bed-confined fractures and the larger, throughgoing fractures that may serve as conductive backbones for reservoir fluid flow. New studies will investigate the factors that control the development and distribution of throughgoing fractures in the Monterey Formation.

Applied benefit: The overwhelming majority of fracture flow is accommodated by relatively few, large fractures. In the Monterey Formation, these structures are multi-layer, throughgoing fractures that span numerous mechanical layers. If the development of throughgoing fractures can be placed within the context of tectonic strain and mechanical stratigraphy, then strategies can be developed to identify their occurrence and distribution in the subsurface.

Approach: The field component of this study will investigate the morphology and geometry of throughgoing fractures in outcrops of the Monterey Formation, and how these multi-layer structures interact with the more numerous bed-confined fractures and mechanical layer boundaries. Fracture connectivity will be evaluated at various stages of deformation, from a network of widely-spaced, bed confined fractures (low strain) to a system dominated by multi-layer fracture zones (high strain). Based on results of the outcrop studies, we will attempt to identify throughgoing fractures on image logs, especially from horizontal wells where robust datasets can be collected on their frequency and orientation.

6. **Objective: Establish general principles and rules for mechanical stratigraphy and fracture architecture that can be applied to shale resource plays in other lithologies and basins.**

Scientific reason: World-class exposures of the Monterey Formation provide an unprecedented opportunity to establish fundamental relationships among mechanical stratigraphy and fracture development in layered rocks of varied compositions and bedding character. Parameters critical for the assessment of fractured reservoirs, such as mechanical unit thicknesses, layer boundaries, fracture spacing (or frequency) and fracture and fault scaling relationships (e.g., aperture, length, height, displacement, gouge thickness, fault sealing) can be established through the systematic, quantitative analysis of structures in outcrop and core of the Monterey Formation. Once established, these relationships and techniques can be applied to other formations that share similar elements of mechanical stratigraphy.

Applied Benefit: Many fractured reservoirs, both conventional and unconventional, are difficult to characterize due to a lack of outcrop analogs thereby requiring extrapolation from inherently limited subsurface datasets (e.g., core, well logs, seismic) that may not adequately capture the hydrological and mechanical properties of reservoir-scale heterogeneities. Analysis of fracture populations in mechanically layered rocks may provide the framework for developing viable reservoir models. With its diverse lithology, multi-scale mechanical units and high intensity of brittle deformation, the Monterey Formation is ideally suited to serve as an experimental model. Concepts of mechanical stratigraphy, fracture scaling and strain intensity derived from studies of the Monterey Formation have been applied with success to conventional carbonate reservoirs from offshore Brazil to shale gas and shale oil plays in the Appalachian Basin, the Eagle Ford Formation, and the Barnett Formation. Although each reservoir has its own unique lithologies and geologic history, the resulting fracture network is ultimately controlled by interaction between the internal rock properties and externally applied boundary conditions. These critical relationships can be quantified in the Monterey Formation and applied to other reservoirs where appropriate.

Approach: We will develop techniques to analyze key parameters (e.g., fracture spacing, aperture, gouge thickness) and the factors that control their development (e.g., tectonic strain, fault displacement, mechanical boundaries). These techniques will be applied to outcrops, thin sections, cores and well logs from the Monterey Formation, and perhaps to other formations where data are provided by industry affiliates. Results will form the basis for addressing practical issues of shale resource development, such as upscaling fracture data from core and image logs to enhance reservoir simulations, evaluating potential mechanical barriers to hydraulic fracturing and the selection of optimum landing zones for horizontal laterals.

7. **Objective: Utilize outcrops of the Monterey Formation as an outdoor laboratory for the training of industry geoscientists and engineers in concepts of mechanical stratigraphy, fracture architecture and brittle strain.**

Scientific reason: The development of many domestic shale resource plays requires an understanding of fracture systems and how they relate to such factors as lithology, burial history, earth stress and structural position. Outcrop analogs provide tremendous insight into the three-dimensional geometry of reservoir-scale fracture networks that are not available in limited subsurface datasets. Exposures of the Monterey Formation, especially along the central California coastline, offer unparalleled instructional opportunities to demonstrate the many factors that control fracture development in sedimentary rocks.

Applied Benefit: Through field observations, measurements of outcrops and discussions, geoscientists and engineers will explore the influence of mechanical stratigraphy and tectonic strain on fracture and fault development in a lithologically-diverse formation that serves as both source rock and reservoir. They will examine and understand a variety of issues that pertain to fractured reservoir characterization, including spatial variations in fracture intensity and orientation, multi-scale hierarchy of fracture and fault populations, and the connectivity of fracture zones across lithologic boundaries. Observations and concepts from different members of the Monterey

Formation field experience can then be applied to assess fracture distribution in other formations (e.g., Barnett, Bakken, Eagle Ford, Granite Wash, Marcellus, Niobrara) and to the interpretation of subsurface datasets (e.g., core, well logs, image logs, seismic).

Approach: As noted in the "Benefits of the MARS project" section on p. 1, annual field trips and workshops will be designed according to the specific interests and priorities of the industry affiliates. Field excursions to outcrops of the Monterey Formation in the Los Angeles, Santa Barbara and Santa Maria Basins can be completed in 1-3 days. Different lithofacies of the Monterey have compositional and mechanical similarity to other resource play formations. Topics will include how to define and describe a mechanical stratigraphy (structures, units, boundaries, lithologies, scale-effects), fractures related to folding, the dependence of fracture style on lithology and diagenetic grade and the development of throughgoing fracture zones. Discussions on the outcrop will emphasize features that impact fluid flow and mechanical behavior in the reservoir, strategies to characterize fractured reservoirs, and how structures observed in the field can be properly identified and quantified in core and image logs. In addition to the annual field trips and workshops, company-specific field training may be arranged outside of the normal MARS project affiliate membership program.

Long Beach Monterey and Related Sediments (MARS) Project Industrial Affiliate Agreement

The Long Beach Monterey and Related Sediments (MARS) Project Industrial Affiliate Program at California State University Long Beach (CSULB) is under the direction of Professor Richard Behl. MARS is a research and educational program based in the University's Department of Geological Sciences and administered by the CSULB 49er Foundation.

Interested companies and organizations are invited to become Affiliates on an annual basis. The sponsoring company or organization receives no "deliverable research" for its sponsorship, nor does it direct the activities of MARS. However, the MARS Project is a unique resource for member companies, providing a window into focused, cutting-edge research on the sedimentology, stratigraphy, diagenesis, and structural deformation of the Monterey Formation and related organic-rich and siliceous sedimentary rocks. Membership also provides member companies with access to unique educational and training events outlined below. *Outside* of Affiliate Membership, companies may still sponsor specific research projects, and negotiate terms, conditions, and deliverable results with Principle Investigators and the CSULB Research Foundation. These sponsored projects are separate from the MARS program and the sponsoring company or agency would pay the full cost of the project, including direct and indirect costs.

MARS operates under the Policies and Procedures of the California State University Long Beach and the CSULB 49er Foundation, which provide regulations for operation under compliance with the all applicable Federal, State, and Local laws, codes, regulations, rules, and orders.

Representatives from Affiliate companies are invited to:

- **The Long Beach MARS annual meeting/symposium at which reports are shared with sponsors by faculty and students**. These reports may include theses, research reports and papers, and other publications of current or past years. Materials presented at the annual meeting, or otherwise published or provided to sponsors, are not proprietary and may be copied, distributed, and used by sponsors without restriction. Such materials are available to members to support their own training, exploration or development activities. At least, three representatives from each Affiliate Company may attend.

- **The annual MARS field trip to examine aspects of the Monterey Formation and related sedimentary rocks**. The focus or location of the field trip will vary each year. At least three representatives from each Affiliate Company may attend.

or

- **The annual MARS short course/workshop.** In some years, a 1-day, joint workshop will be held on some aspect of interest to the consortium members. The topic will vary each year. At least three representatives from each Affiliate Company may attend.

- If space allows, additional representatives from Affiliate companies may be permitted to attend the described events for an additional fee.

The Affiliate Company named below agrees to sponsor MARS under the direction of Professor Behl at the California State University Long Beach on an annual basis with a contribution of $25,000 US Dollars. Membership fees provide unrestricted support for MARS project research activities with the benefits outlined above and in the prospectus. Please make payable to **CSULB 49er Foundation**, noting account # N0033 - MARS Project". Send to Mary Ann Messing, CSULB, State University Drive, Suite 332, Long Beach, CA 90815. Tax ID number: 45-2163910. Electronic wiring information available.

ACCEPTED AND AGREED. ***Affiliate Company name***: ....

CSULB 49er Foundation:	***MARS Project Director:***	***Affiliate Company:***
Signature:..	Signature:	Signature: ....
Name: Brian Lawver	Name: Richard Behl	Name: ....
Title: Chief Operating Officer	Title: Professor & Director	Title:..
Date:...	Date:..	Date ....