Abstract

The Miocene Monterey Formation is an exceedingly heterogeneous, biogenic-rich (siliceous, calcareous and carbonaceous) deposit and only a minor fraction of its volume would be considered a true “shale”. It is California’s primary petroleum source rock and an important “conventional” reservoir in many areas, primarily exploiting naturally fractured rocks. Recently, due to its great thickness, broad areal extent and organic-richness, the Monterey was recently estimated to hold more than half of all the recoverable shale oil resources in the lower 48 states. This significance raises the following fundamental and applied research questions: How much of the Monterey’s varied lithostratigraphy reflects global vs. local environmental conditions? How do facies in the formation vary laterally? How does porosity and permeability vary with diagenetic setting and timing - not just silica phase and composition? How does diagenesis and deformation vary with depositional environment, primary composition and structural setting?

As part of the CSU Long Beach Monterey and Related Sedimentary rocks (MARS) Project, we are investigating stratigraphic, geochemical, diagenetic, and structural aspects of this important formation with the following goals: Refine the chronostratigraphy lithostratigraphy for the Monterey Formation of the San Joaquin Basin, applying chemostratigraphic, cyclostratigraphic and tephrochronologic methods. Investigate compositional variability in facies of the "Nodular Shale" or "Black Shale" of the Los Angeles Basin. Characterize Monterey lithologies and microfacies petrographically, including unusually porous diagenetic siliceous rocks. Investigate variability in genus-level composition of diatomite related to depositional environments and the influence of diatom assemblage on physical properties and diagenetic potential. Study mechanical stratigraphy in different lithologies and stratigraphic architectures and their influence on fracture development in the Monterey Formation. Develop a genetic model of lithologic composition and cyclicity that can be predictive of mechanical stratigraphy and fracturability in different lithofacies. Hopefully, with
success in these endeavors, the Monterey Formation, with its varied composition and stratigraphic character, can serve as a valuable analog for other “shale” and non-conventional resource plays.

References


Davies, R.J., M.T. Ireland, and J.A. Cartwright, 2009, Differential compaction due to the irregular topology of a diagenetic reaction boundary; a new mechanism for the formation of polygonal faults: Basin Research, v. 21/3, p. 354-359.


Website

The Monterey Formation of California: New Research Directions
(some in old places..)

Richard J. Behl
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Monterey Research Directions

1. Understanding global vs. local control of lithology & stratigraphy
2. How can we better date & correlate the Monterey?
3. What really happens at the silica phase transitions?
4. Unifying genetic sedimentology with mechanical stratigraphy.
Tectonic subsidence from ~17 or 18 Ma
Global sea level rise to ~14 Ma
Ice sheet expansion ~14-12 Ma
Much learned, but too much focus on Santa Barbara Basin.

Need to work in:
- Los Angeles
- Salinas
- San Joaquin
- Santa Maria
- other basins
The Long Beach MARS Project
(Monterey And Related Sedimentary rocks)

Monterey Research Projects
Monterey Research Directions

1. Understanding global vs. local control of lithology & stratigraphy
   - *Expand geochemical characterization of members to unstudied basins*
   - *Detailed characterization of good sections in outcrop and subsurface*
   - *Tie oceanographic & bathymetric setting to sediment character*
How similar is Monterey stratigraphy in:

- Inboard and outboard basins?
- North to south?
- Across individual basins?
Influence of bathymetry and basin setting?

San Pedro Basin - Santa Ana Mountains

(C) 2023

San Pedro Basin

(future) Palos Verdes Hills

Palos Verdes Fault

Wilmington Graben

Newport - Inglewood F.Z.

(future) San Joaquin Hills

Capistrano Embayment

Cristianitos Fault

Pacific Ocean

footwall

Late Miocene

(not all features to scale)

0 km

10

20

(horizontal = vertical scale)

Catalina Schist (Franciscan belt)

Peninsular Ranges granitic WFH belt

Fore-arc (GVS belt)

Eocene-E. Miocene Sespe-Vaqueros

Miocene San Onofre Breccia

Miocene igneous rocks

Miocene strata

Crouch & Suppe (1993)

Long Beach MARS Project: Monterey and Related Sedimentary rocks
Rapid change in muddy sediment accumulation in modern analogs

Santa Barbara Channel

Dramatic changes in sedimentation *in just 0.1-0.2 Myr*

Next talk!

Marshall, 2012

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Long Beach MARS Project: Monterey and Related Sedimentary rocks
Patchy upwelling leads to uneven distribution of plankton (diatoms, etc.).

Upwelling strongly controlled by margin shape.
Diatoms highly varied

Chang et al. and Pike & Kemp studies
Long Beach MARS Project: Monterey and Related Sedimentary rocks

Blakey (1997)

Early-Mid Miocene

Late Miocene

[Maps showing geographic features and geological structures related to Miocene geological events.]
Monterey Research Directions

Time-transgressive benthic biostratigraphy

2. How can we better date & correlate it?
   • Planned approaches:
     • Isotope stratigraphy
     • Chemostratigraphy
     • Tephrochronololgy
     • Sequence stratigraphy
     • Cyclostratigraphy
Climate Cycles & Litho-cyclicity

Evolution of Earth, atmosphere and biosphere:
- Tectonic cycles: mountain building and weathering
- Orbital (Milankovitch) cycles
- Dansgaard-Oeschger cycles
- NAO, PDO, ENSO
- Annual solar forcing
- Annual harmonics, synoptic weather, diurnal cycle
- Diurnal harmonics

Variance increasing over time (years):
- $10^9$ to $10^8$
- $10^7$
- $10^6$
- $10^5$ to $10^4$
- $10^3$
- $10^2$
- $10^1$ to $1$ day
- $0.1$ day
- $0.01$ day
- $0.001$ day
Lithologic Cyclicity & Climate

Shown at all scales:

- Composition
  - CaCO₃, silica, clay, organic carbon
- Sedimentary fabric
  - Bedding thickness and ratios
  - Laminations, bioturbation
Microlaminations

1 cm
Thick laminations & bundles
Meter-scale (2-4’)
beds or bed sets

1 m
**Long Beach MARS Project: Monterey and Related Sedimentary rocks**

10' cycles

20 30 40 50 60 70 80 90 100

5300 5350 5400 5450 5500

Gamma Ray (API units)

Depth (ft) KB

OCS-0437 #1

Point Pedernales Field, Offshore Santa Maria Basin

Estimated sed. rate = 100 ft/m.y. (2.77 cm/k.y.)

Aziz et al. (2004)

Milankovitch cycles drive climate and sedimentation

Mid-Miocene, Orera, Spain

Pam Hill, MS research
Monterey Research Directions

3. What really happens at the silica phase transitions?
   • Geochemical rearrangement
   • Fluid expulsion
   • Formation of pressure compartments
   • Diagenesis-related deformation
Long Beach MARS Project: Monterey and Related Sedimentary rocks
Long Beach MARS Project: Monterey and Related Sedimentary rocks
Dissolution of opal-A diatom test

Precipitation of opal-CT infilling microfossil void
Well structured opal-CT
Opal-CT Porcelanite
Quartz Porcelanite

Related Sedimentary rocks
Silica phase transition zones are not simple

Long Beach MARS Project: Monterey and Related Sedimentary rocks

Opal-A
diatomite

Opal-CT
porcelanite
Laminated, but massive-bedded diatomite

Ribbon-bedded cherty porcelanite
Bed-to-Bed Diagenetic Segregation of Silica at Mussel Rock

Opal-A

Opal-A + Opal-CT

Charlotte Deason, MS research

Long Beach MARS Project: Monterey and Related Sedimentary rocks
Theoretical Fluid Loss & Volume Change for Opal-A to Opal-CT to Quartz for Chert and Porcelanite

Pure diatomite
- Grain density: 1.8 gm/cc
- Porosity: 80%

Impure diatomite
- Grain density: 1.8 gm/cc
- Porosity: 65%

Diatomite
- Grain density: 2.3 gm/cc
- Porosity: 15%

Chert
- Grain density: 2.3 gm/cc
- Porosity: 40%

Porcelanite
- Grain density: 2.7 gm/cc
- Porosity: 15%

Long Beach MARS Project: Monterey and Related Sedimentary rocks
Do geochemical and pressure compartments form at the phase boundaries?

Could these help explain:

- localized diagenesis?
- localized fractures and faults?
- unusually porous rocks?
- Would they differ at the A/CT and CT/Quartz transitions?
What are the controls of the geometry of silica phase boundaries?

*Diagenesis induced deformation*

Ireland et al. (2009)

*Long Beach MARS Project: Monterey and Related Sedimentary rocks*
Monterey Research Directions

4. Linking genetic stratigraphy with mechanical stratigraphy

- If climatic cyclicity and depositional setting control lithologic composition and stacking pattern, then mechanical stratigraphy should follow.

*Can we predict where and when lithologic type and bedding ratios would be optimal for maximum fracture development?*
Stacking Patterns for Silica-Clay cycle

Long Beach MARS Project: Monterey and Related Sedimentary rocks
Fracture density depends on lithology and layer thickness

So, where in the basin and where in the cycle is the sweet spot for maximum fracture development?
The Long Beach MARS Project
(Monterey And Related Sedimentary rocks)

1. Development of a focused center of excellence for research into Monterey Formation geology

2. Provide sustainable support for ongoing research into the Monterey Formation for graduate student & post-doctoral scholars

3. Develop well-trained graduate students, ready for entry into the petroleum industry

4. Encourage fruitful intellectual interaction between industry and academia on real problems
Acknowledgements – thank you!

2011-2012 MARS Project Founding Members

• Occidental Petroleum
• ExxonMobil
• Aera Energy
• Venoco, Inc.
• BreitBurn Energy Partners
• PXP - Plains Exploration & Production
• Signal Hill Petroleum
• Bayswater Exploration & Production