Case Study: 25 Years of Historic Hydrocarbon Seep Studies in Santa Maria Basin, Offshore California Using Seismic and Stratigraphic Data (1995 through 2020)*

Joseph Saenz¹, Thomas O'Neil¹, and Frank Denison²

Search and Discovery Article #11346 (2020)**
Posted August 24, 2020

*Adapted from oral presentation prepared for the 2020 AAPG Pacific Section Convention, 2020 Vision: Producing the Future, Mandalay Beach, Oxnard, California, April 4-8, 2020 (Cancelled)
**Datapages © 2020 Serial rights given by author. For all other rights contact author directly. DOI:10.1306/11346Saenz2020

¹Oxnard College, Oxnard, California (jsaenz@vcccd.edu)
²Consultant, Bakersfield, California

Abstract

Historic seismic and stratigraphic records were used to understand the relative effects of active tectonics on hydrocarbon seeps in the Santa Maria Basin (SMB), offshore California. The study confirms that hydrocarbon seeps are associated with the Hosgri-Purisuma-Lompoc Fault zones tapping into a single major reservoir, the Monterey Formation. In the northern and central areas, these Monterey reservoirs occur in growing anticlinal folds that are faulted and fractured by the Hosgri Fault zone, acting as a major conduit for gas and oil seeps. In the southern area, heavy oil migrating up-dip in the Monterey Formation is found near (or at) the seafloor in the hanging-wall of the Santa Barbara Basin along North Channel Fault. The stratigraphy of the offshore SMB is known from seismic surveys, cores, electric logs, and 73 mud logs within the basin.

More than 60 multi-sensor, shallow drilling hazard and deep seismic reports provided data sets of seeps, seafloor features, and geologic structure. We find an abundance of evidence to suggest continuous or episodic upward movement of fluids as migrating gas plumes from deeper sediments into surface sediments. The analysis shows that bright spots on the seismic reflection profiles are gas-plumes, linked to the highest geothermal gradients and controlled by active tectonics. Gas, deeply sourced in the Monterey Formation, migrates upward along faults, anticlinal folds, and steeply dipping beds into shallow sediment. Gas chromatographic analysis from mud logs samples in wells near gas plumes show the highest concentrations of methane, ethane, propane, and butane. Temperature changes induced by geothermal heating during burial caused in-reservoir thermal cracking of the oil to lighter-end hydrocarbon gases that migrate as gas plumes into shallow burial depths.

Records indicate that Monterey Formation API oil gravities range from 3° to 35°. Oil gravities are related to zones of shallow gas-charged sediments, and variable geothermal gradients ranging from 1.7°F/100 ft to 3°F/100 ft, with downhole temperatures ranging from 118°F to 248°F. Within close proximity to the Hosgri Fault zone, lithologic analysis revealed three areas where siliceous Monterey rocks have been
diagenetically altered to glassy cherts related to high geothermal gradients and reservoir pressures (2115 psig to 3385 psig). Active tectonics has fractured these brittle reservoir rocks, forming migration pathways that serve as conduits for seafloor hydrocarbon seeps.

Selected References


Saenz, J. M., 2007, Geological Controls of Hydrocarbon Seeps in the Santa Maria Basin Offshore California, Oxnard College Lecture Series, "Addressing natural oil and gas seeps, including methane in the Santa Maria Basin –what causes it and the potential effects this phenomenon may have on global climate and the stability of seafloor sediments resulting in submarine landslides", February 2007.


Joseph M. Saenz
Ventura Community College School District
Oxnard College

Frank Denison
Frank Denison Consultant
Westlake, California

In Honor of Peter Fischer, Ph.D.
Department of Geological Sciences,
California State University, Northridge
1931–2012

In Honor of James W. Vernon, Ph.D.
GEO III
Camarillo, California
1922 – 2009
Acknowledgements

• Peter J. Fischer*, Ph.D., California State University, Northridge, Professor Emeritus
• Gerry Simila*, Ph.D., California State University, Northridge, Professor
• Dan Francis*, Ph.D., California State University, Long Beach, Professor
• Fred Piltz*, Ph.D., U.S. Minerals Management Service, Pacific OCS Region
• James Vernon, Ph.D., GEO III – Research Vessel
• Mark Legg, Ph.D., Legg Geophysical, Inc.
• Satish Pullammanappallil, Ph.D., University of Nevada, Reno, Seismological Laboratory
• Rick Behl, Ph.D., California State University, Long Beach
• Tom O’Neil of Oxnard College
• Jim Caesar formerly of Clean Seas
• U.S. Department of the Navy, D. B. Chan, Ph.D, K. Zaiger, Ph.D., R. Nordahl, and others
• U.S. Coast Guard, Commander Bill Drelling, LT Commander Michael Hunt, and others
• U.S. Drug Enforcement Administration, T. Gorshe and others
• U.S. Geological Survey, Tom Lorenson and Janet Watt
• Combined Joint Task Force Horn of Africa, Admiral Richard Hunt, Admiral Moon, CDR Paul Vandenberg, Major Tim Collier, and others

References Cited
- U.S. Coast Guard - Johnson, 1971;
- Fischer, P. J., and A. J. Stevenson, 1973;
- Fischer, P. J., 1977;
- InterOcean Systems Inc, 1981-1984;
- Sigalove, 1985;
- Hovland and Judd, 1988;
- Saenz, 2001, and 2002;
- Saenz, 2006.
Background
U.S. Minerals Management Service
1982 to 2010

Formed in December 1982
Dissolved in June 2010
Agency existed for 28 years.

MMS Focus Facility Inspection Team, Pacific Outer Continental Shelf Region - 1999

Deep Water Horizon Explosion
April 20, 2010

Under President Obama’s Administration:

Due to perceived conflict of interest and poor regulatory oversight following the Deepwater Horizon oil spill and Inspector General investigations, the Secretary of the Interior Ken Salazar issued a secretarial order on May 19, 2010 splitting MMS into three new federal agencies:

1) the Bureau of Ocean Energy Management (BOEM),
2) the Bureau of Safety and Environmental Enforcement (BSSE), and
3) the Office of Natural Resources Revenue.
Background:
In 1995, the U.S. Coast Guard requested a hydrocarbon seep map of the Santa Maria Basin, offshore California from the U.S. Minerals Management Service, Operations Section.

No hydrocarbon seep maps existed for the SMB, Offshore California.

Several maps were generated upon the U.S. Coast Guard’s request.

Eventually, this seven year effort lead to my Masters Thesis obtained from CSUN in 2002.
Data Set Used in this Investigation

- Seafloor features (hydrocarbon seeps, pockmarks, mass movement deposits, buried channels, and seafloor mounds, rubble, and hummocks) mapped from multi-sensor, high-resolution geophysical surveys from over 60 Lease Blocks, well and core data.

- SNIFFER data (Sigalove, 1985; and Ocean Engineering International, 1985).

- Mesozoic and Cenozoic Formation thickness from 73 offshore exploratory wells interpreted from mud logs, electric logs, dip meter logs, unpublished micropaleontological analyses, well correlations, and other data.

- A structural synthesis (anticlines, synclines) and a brief assessment of recent fault activity from multi-sensor, high-resolution geophysical surveys and other sources.

- Assessments of API oil gravity, geothermal gradient, and average temperatures, and distribution of chert types based upon 73 offshore exploratory wells.

- An assessment of glauconite and phosphate in Quaternary and Neogene Formations.

- An assessment of seismic activity in the region (e.g.: November 4, 1927 M 7.3 Lompoc Earthquake)
Data Set Used in this Investigation

- Mud Logs
- Temperature Logs
- Dual induction Logs
- Compensated Neutron Formation Density Logs
- Micro-later Log / Micro Logs
- Natural gamma ray tool Logs
- SP Logs
- Borehole compensation sonic Logs
- Neutron litho-density Logs
- Computer processed Logs
- Sonic waveform Logs
- High Resolution Continuous Dip-meter Logs
- Drill Stem Tests
- Completion reports / Daily reports
Offshore Exploratory Wells

- Locations of the 73 offshore exploratory wells in the offshore SMB study area.
- Exploratory wells were drilled from 1965 through 1989. Geophysical logs, mud logs, micropaleontology controls and other data that were used to define the stratigraphy of the offshore SMB study area.
- Mud log data are the most abundant geochemical data available. In general, they are an adequate representation of vertical variations of light gases and fluorescing compounds. Showing orders of magnitude of changes in a few feet to tens of feet, and rapid compositional shift of light compounds to heavier compounds.
- High values are related to the occurrence of mature source rocks, top of over pressured zones, faults, and reservoirs (Saenz et al, 2005).

Pacific Outer Continental Shelf Lease Blocks and Bathymetry of the Offshore SMB Study Area

Geologic structures, rock stratigraphy, and seafloor features were identified and confirmed from high resolution geophysical survey data collected within the POCS lease blocks. Blocks with lease numbers were surveyed by industry consultants and are listed in unpublished reports in Saenz 2001 and 2002.
Generalized stratigraphic column

Stratigraphy of the offshore SMB study area, generalized from offshore well data (Appendix B of Saenz, 2002) (Note; the top of the “lower part” of the Monterey Formation (T) is the mapped horizon of Figure 2 (Saenz, 2002).

<table>
<thead>
<tr>
<th>Age</th>
<th>Offshore Stratigraphic Units for the Santa Maria Basin</th>
<th>Description of Rock Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holocene</td>
<td>Quaternary deposits</td>
<td>Dominantly marine to non-marine (?), mud, sand, and gravel</td>
</tr>
<tr>
<td>Pleistocene</td>
<td>Foxen Fm.</td>
<td>Marine sandstone and conglomerate</td>
</tr>
<tr>
<td></td>
<td>Sisquoc Formation</td>
<td>Marine mudstone, siltstone, and sandstone</td>
</tr>
<tr>
<td></td>
<td>Monterey Formation (T) (low part)</td>
<td>Distomaceous mudstone, sandstone, conglomerate, siltstone grading with depth</td>
</tr>
<tr>
<td></td>
<td>Point Sal Formation</td>
<td>Siliceous shales</td>
</tr>
<tr>
<td></td>
<td>Lospe Formation</td>
<td>Cherts, porcelanites with dolostones</td>
</tr>
<tr>
<td></td>
<td>Vajencias Formation (equiv.)</td>
<td>Phosphatic mudstones with dolostones</td>
</tr>
<tr>
<td></td>
<td>Anita Shale</td>
<td>Carbonaceous siliceous mudstone, dolostones and siltstone</td>
</tr>
<tr>
<td></td>
<td>Erosional remnants</td>
<td>Limeymudstone, dolostone, sandstone, and volcanic rocks</td>
</tr>
<tr>
<td></td>
<td>Jalama Formation</td>
<td>Rhyolitic tuff, tuffaceous volcanic clastics, and sands</td>
</tr>
<tr>
<td></td>
<td>Espada Formation</td>
<td>Non-marine to marine sandstone and mudstone with some tuff beds</td>
</tr>
<tr>
<td></td>
<td>Franciscan Complex</td>
<td>Shallow marine siltstones, sandstones, and conglomerates</td>
</tr>
<tr>
<td></td>
<td>Erosional remnants</td>
<td>Marine shales interbedded with sandstones</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Erosional remnants: marine siltstone, sandstone, and reworked volcanic and Franciscan fragments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thick bedded clay shales and sandstones with metamorphics and volcanic fragments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thick bedded shale, sandstone, and conglomerate with metamorphics clasts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Metamorphic and sedimentary rocks in a sheared, serpentinite matrix</td>
</tr>
</tbody>
</table>

Holocene 0.010 Ma to 0 Ma (10,000 yrs. ago to 0 yrs. ago)
Pleistocene 2.6 Ma to 0.010 Ma (10,000 yrs. ago)
Pliocene 5.3 Ma to 2.6 Ma
Miocene 23 Ma to 5.3 Ma
Oligocene 33.9 Ma to 23 Ma
Eocene 56 Ma to 33.9 Ma
Paleocene 66 Ma to 56 Ma
Cretaceous 145 Ma to 66 Ma
Jurassic 201 Ma to 145 Ma
Triassic 252 Ma to 201 Ma

Note: Times picks from GSA Geologic Time Scale v. 4, 2012
Stratigraphic Correlation and Migration Pathways for Hydrocarbon Gases Originating from Monterey Formation Source Rocks

Assessment of Glauconite and phosphate in Formations

Index map showing locations of stratigraphic columns for the northwest, central, south, and southeast portions of the study area.
Stratigraphic Correlations - Fence Diagrams

Northern Area

Central Area

Southern Area

Southern-Most Area

Formation determinations after Frank Webster, William Roberts, Scott Drewry of the MMS (1982-1984)
Isochore Map of the Monterey Formation

- Offshore SMB rapidly subsided from Oligocene (?) into late Miocene time.
- Accumulations of Monterey Formation, formed in two depocenters where 2900 to 3700 ft of sediment were deposited.
- Monterey Formation thins to the west, a series of highs trend northwest.

Isochore Map of the Foxen Formation

- A northward migration of the northern depocenter. Basin was filled with over 3400 ft of Foxen Formation.
- The southern depocenter trend becomes elongate and trends NW-SE. It was filled with over 3700 ft of Foxen mudstone.

Isochore Map of the Sisquoc Formation

- The northern depocenter became larger and broader, and filling in of the basin trough with more than 4100 ft of sediments.
- The southern depocenter became steeper and narrower; sedimentation was controlled by the Amberjack high; filling up with 3000 ft of sediments.

Isochore Map of the Quaternary Deposits

- The northern depocenter shifts westward and the southern depocenter has been filled. A new depocenter to the NW of Point Arguello has formed with 3200 ft of Quaternary deposits.

The Amberjack high does not show thickness variations of Quaternary sediments during Quaternary time, it was no longer active.
Gas Migration Pathways: Faults in Shallowest Horizons Offsetting Seafloor and Gas Migration Pathways

Mapped mass movement deposits and seafloor features to include rock outcrop, buried channels, and seafloor offsets due to faulting (Richmond and others, 1981; modified by Saenz, 2002).

Geologic structure interpreted and mapped from structure contour maps by Saenz, 1995-2002.

Base Map from National Oceanic Atmospheric Administration National, Geophysical Data Center Coastal Relief Model Vol. 06 Shaded Relief Images.
Geothermal gradients for the offshore SMB ranges between 3.0 to 1.7 °F per 100 feet.

The highest geothermal gradients for the offshore SMB ranges between 3.0 to 2.2 °F per 100 feet.

Geothermal gradient is a measure of temperature increase with depth. Geothermal gradients are normally 1.0 to 1.7 °F 100 feet. For example: If a well has a surface temperature of 75 °F and bottom hole temperature is 175 °F at a depth of 10,000 feet, the geothermal gradient is 1.0 °F per 100 feet (WellLog, 2003, Resistivity Logging, Revised 05-02-2001, © 2003 - 2011 WELLOG).

Glassy Cherts and Porcelaneous Cherts are associated with highest geothermal gradients, the highest average temperatures in Monterey Formation, and highest Methane gas concentrations.
Gas Migration: Three Dimensional Perspective
Using Highest Geothermal Gradients, and Gas-Charged Sediments

The average geothermal gradient is about 1.4 °F per 100 feet of depth. Geothermal gradient are normally 1.0 to 1.7 degrees per 100 feet. (http://www.wellog.com/webinar/interp_p1_p6.htm) (Saenz, 2002; Saenz et al, 2005; Saenz et al, 2007; Saenz et al, 2020)

(Surfer by Golden Software, 2000)
Gas Migration: Average Temperature in the Monterey Formation: High Heat Flow Volatilizing Hydrocarbon Gases Upward through Fault Zones and Stratigraphic Sections

Map based on temperature logs, dual induction logs, compensated neutron formation density logs, micro-later log / micro logs, natural gamma ray tool logs, SP logs, borehole compensation sonic logs, neutron lithodensity logs, computer processed logs, sonic waveform logs, high resolution continuous dip-meter logs, completion reports, daily reports, and other documents collected from 63 exploratory wells (Saenz, 2002; and Saenz et al, 2005)

The offshore SMB is host to numerous oil and gas fields with average temperatures ranging from 118 °F (47.7 °C) to 248 °F (120 °C) and reservoir pressure that ranges from 2115 pounds square inch gauge (psig) to 3385 psig. We believe that several of these oil accumulations have undergone in-reservoir thermal cracking, resulting in a lighter, single-phase fluid, together with a pyrobitumen residue in the pore volumes. With several traps at or near their leak-off pressure, the likelihood of top seal failure and gas leakage is prevalent (Saenz, 2007).
Three Dimensional Perspective of the Average Temperatures in the Monterey Formation

The Glassy Cherts and Porcelaneous Cherts are associated with:

- the highest geothermal gradients,
- the highest average temperatures in Monterey Formation,
- and highest Methane gas concentrations.

Surfer by Golden Software, 2020
Gas Migration: Three Dimensional Perspective of the Average Temperature in the Monterey Formation and Gas Chromatographic Results

Well P-0395-1
Average Temperature = 188 °F (86.7 °C)

<table>
<thead>
<tr>
<th>Methane</th>
<th>Ethane</th>
<th>Propane</th>
<th>Butane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Tf</td>
<td>+10,000</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Ts</td>
<td>+32,000</td>
<td>310</td>
<td>400</td>
</tr>
<tr>
<td>Tm</td>
<td>25,000</td>
<td>1,800</td>
<td>1,600</td>
</tr>
</tbody>
</table>

Well P-0093-1
Average Temperature = 225 °F (107.2 °C)

<table>
<thead>
<tr>
<th>Methane</th>
<th>Ethane</th>
<th>Propane</th>
<th>Butane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Tf</td>
<td>+18,000</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Ts</td>
<td>20,000</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Tm</td>
<td>5,000</td>
<td>300</td>
<td>500</td>
</tr>
</tbody>
</table>

Well P-0409-3
Average Temperature = 229 °F (109 °C)

<table>
<thead>
<tr>
<th>Methane</th>
<th>Ethane</th>
<th>Propane</th>
<th>Butane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Tf</td>
<td>+4,000</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Ts</td>
<td>+10,000</td>
<td>600</td>
<td>550</td>
</tr>
<tr>
<td>Tm</td>
<td>10,000</td>
<td>+10,000</td>
<td></td>
</tr>
</tbody>
</table>

Well P-0425-1
Average Temperature = 167 °F (75 °C)

<table>
<thead>
<tr>
<th>Methane</th>
<th>Ethane</th>
<th>Propane</th>
<th>Butane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Tf</td>
<td>15,000</td>
<td>900</td>
<td>500</td>
</tr>
<tr>
<td>Ts</td>
<td>95,000</td>
<td>4,500</td>
<td>2,900</td>
</tr>
<tr>
<td>Tm</td>
<td>70,000</td>
<td>6,300</td>
<td>3,800</td>
</tr>
</tbody>
</table>

Well P-0320-1
Average Temperature = 226 °F (107.2 °C)

<table>
<thead>
<tr>
<th>Methane</th>
<th>Ethane</th>
<th>Propane</th>
<th>Butane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Tf</td>
<td>+20,000</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Ts</td>
<td>30,000</td>
<td>650</td>
<td>700</td>
</tr>
<tr>
<td>Tm</td>
<td>20,000</td>
<td>825</td>
<td>475</td>
</tr>
</tbody>
</table>

Well P-0250-1
Average Temperature = 120 °F (49 °C)

<table>
<thead>
<tr>
<th>Methane</th>
<th>Ethane</th>
<th>Propane</th>
<th>Butane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Tf</td>
<td>10,000</td>
<td>1,050</td>
<td>200</td>
</tr>
<tr>
<td>Ts</td>
<td>18,000</td>
<td>150</td>
<td>20</td>
</tr>
<tr>
<td>Tm</td>
<td>10,000</td>
<td>700</td>
<td>650</td>
</tr>
</tbody>
</table>

Well P-0450-1
Average Temperature = 225 °F (107.2 °C)

<table>
<thead>
<tr>
<th>Methane</th>
<th>Ethane</th>
<th>Propane</th>
<th>Butane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tc</td>
<td>13,000</td>
<td>780</td>
<td>1000</td>
</tr>
<tr>
<td>Tf</td>
<td>920</td>
<td>650</td>
<td>700</td>
</tr>
<tr>
<td>Ts</td>
<td>11,000</td>
<td>1000</td>
<td>850</td>
</tr>
<tr>
<td>Tm</td>
<td>12,000</td>
<td>1000</td>
<td>720</td>
</tr>
</tbody>
</table>

Well P-0441-1
Average Temperature = 205 °F (96 °C)

<table>
<thead>
<tr>
<th>Methane</th>
<th>Ethane</th>
<th>Propane</th>
<th>Butane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt</td>
<td>13,000</td>
<td>NA</td>
<td>4,200</td>
</tr>
<tr>
<td>Tf</td>
<td>12,000</td>
<td>NA</td>
<td>2,200</td>
</tr>
<tr>
<td>Ts</td>
<td>13,000</td>
<td>NA</td>
<td>20</td>
</tr>
<tr>
<td>Tm</td>
<td>7,900</td>
<td>350</td>
<td>150</td>
</tr>
</tbody>
</table>

Well P-0427-1
Average Temperature = 188 °F (87 °C)

<table>
<thead>
<tr>
<th>Methane</th>
<th>Ethane</th>
<th>Propane</th>
<th>Butane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Tf</td>
<td>100,000</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Ts</td>
<td>4,000</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Tm</td>
<td>7,900</td>
<td>350</td>
<td>150</td>
</tr>
</tbody>
</table>

Well P-0397-2
Average Temperature = 218 °F (103.3 °C)

<table>
<thead>
<tr>
<th>Methane</th>
<th>Ethane</th>
<th>Propane</th>
<th>Butane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Tf</td>
<td>+60,000</td>
<td>800</td>
<td>200</td>
</tr>
<tr>
<td>Ts</td>
<td>-95,000</td>
<td>2,800</td>
<td>600</td>
</tr>
<tr>
<td>Tm</td>
<td>25,000</td>
<td>1,800</td>
<td>1,600</td>
</tr>
</tbody>
</table>

Well P-0396-1
Average Temperature = 197 °F (91.7 °C)

<table>
<thead>
<tr>
<th>Methane</th>
<th>Ethane</th>
<th>Propane</th>
<th>Butane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Tf</td>
<td>+40,000</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Ts</td>
<td>+100,000</td>
<td>400</td>
<td>90</td>
</tr>
<tr>
<td>Tm</td>
<td>+10,000</td>
<td>600</td>
<td>550</td>
</tr>
</tbody>
</table>

Well P-0392-1
Average Temperature = 216 °F (102 °C)

<table>
<thead>
<tr>
<th>Methane</th>
<th>Ethane</th>
<th>Propane</th>
<th>Butane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Tf</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Ts</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Tm</td>
<td>25,000</td>
<td>1,800</td>
<td>1,600</td>
</tr>
</tbody>
</table>


(Surfer by Golden Software, 2000)
Three Dimensional Perspective of Vertical Distribution of % Argillaceous Chert in Monterey Formation from OCS Wells

Surfer by Golden Software, 2020
MUDLOGS:
Argillaceous chert is a hard chert, a less pure chert, with higher amount of clay, and conchoidally fractured. It is vitreous or non waxy in texture. Rock fragments hardness on Mohs scale ranges from 5 to 7. Generally, taken as less pure than porcelaneous chert.

Three Dimensional Perspective of Vertical Distribution of % Argillaceous Chert in Monterey Formation from OCS Wells

(Surfer by Golden Software, 2000)
Three Dimensional Perspective of Vertical Distribution of Percent Porcelaneous Chert in Monterey Formation from OCS Wells

Surfer by Golden Software, 2020
Well P-0444-1
Average Temperature = 205°F (96.1°C)
%Chert OCS Well = 100%

Well P-0439-1
Average Temperature = 163°F (73°C)
%Chert OCS Well = 97.7%

Well P-0427-1
Average Temperature = 188°F (86.7°C)
%Chert OCS Well = 61.3%

Well P-0446-2
Average Temperature = 171°F
%Chert OCS Well = 88.5%

Well P-0450-1
Average Temperature = 225°F (107.2°C)
%Chert OCS Well = 100%

Well P-0446-1
Average Temperature = 169°F (76.1°C)
%Chert OCS Well = 88.5%

Well P-0411-1
Average Temperature = 118°F (47.7°C)
%Chert OCS Well = 87%

Well P-0446-2
Average Temperature = 171°F (77.2°C)
%Chert OCS Well = 100%

Well P-0452-1
Average Temperature = 160°F (71.1°C)
%Chert OCS Well = 100%

Well P-0451-2
Average Temperature = 212°F (100°C)
%Chert OCS Well = 100%

Well P-0450-1
Average Temperature = 197°F (91.6°C)
%Chert OCS Well = 88.5%

Well P-0452-1
Average Temperature = 160°F (71.1°C)
%Chert OCS Well = 87%

Well P-0451-2
Average Temperature = 212°F (100°C)
%Chert OCS Well = 100%

MUDLOGS: Porcelaneous chert white to dark brown, conchoidally fractured, and brittle. Generally, porcelaneous chert is described as vein material and/or laminated filled with chalcedony or quartz.
Glassy Cherts and Porcelaneous Cherts are associated with highest geothermal gradients, the highest average temperatures in Monterey Formation, and highest Methane gas concentrations.
Three Dimensional Perspective of Vertical Distribution of % Glassy Chert in Monterey Formation from OCS Wells

Glassy Cherts and Porcelaneous Cherts are associated with highest geothermal gradients, the highest average temperatures in Monterey Formation, and highest Methane gas concentrations.
MUDLOGS: Glassy chert is exceedingly pure chert with little clay or detritus type material. It is 95% silica dioxide. Described as amber color, yellow to brown to translucent and transparent, conchoidally fractured in cuttings.

The Monterey Formation rock is known as a “glassy” chert, known for its tendency to shatter like glass. Geological processes cause it to shatter, forming cracks that may lead to the surface (Saenz, 2002).

Oil changes as it travels up these cracks from deep oil reservoirs to the surface; it is these changes that allow chemists to differentiate between naturally seeping oil and produced oil (MMS, 2007).
Oil Isopleths Showing °API Gravity Related to Thermal Degradation of Monterey Formation Crude Oil (Saenz, 2002)

• Degree API (°API) gravity crude oil collected from drill stem tests from 60 exploratory wells of the SMB study area.

• As shown in the Figure, the isopleths of °API gravity oil decrease to the northwest of Point Arguello.

• In Federal Waters, about 20-25 miles (32-40 km) between Purisima Point and Point Sal are the lowest gravities in the study area. Area N-1 is located in this area of minimum API gravity area.

• Heavy oil is (low API gravity) due to escape of volatiles during migration from predominantly thermogenic degradation in the northern and central areas, but in the southern area due to microbial action. Microbial action is also responsible for the high sulfur content of heavy oils. Some conditions must be met to carry out sub-surface biodegradation. Meteoric waters, which contain oxygen and bring bacteria to the oil to aid biodegradation are important. Degradation is less where meteoric water circulation is limited by shale seals. Waters that induce degradation must contain dissolved oxygen at least at 8 ppm in order to maintain aerobic bacteria.

The waters must contain nutrients and the reservoir temperature must not exceed 80°C in order for the bacteria to survive. Hydrogen sulfide, which kills them, should not be present. The breaking up of heavy oil molecules into lighter fractions by the use of high temperature without the aid of catalysts.
Three Dimensional Perspective
Showing three dimensional perspective of °API Gravity for Monterey Formation

Surfer by Golden Software, 2020
Differences among seeps and seep features are related to the difference in tectonic regimes of Santa Maria and Santa Barbara Basins

• In the northern and central study area, strike-slip tectonics of the Hosgri, Purisima, and Lompoc fault zones are associated with numerous active and episodic gas vent craters.

• In the southern-most portion of the study area, compressional tectonics of the North Channel Fault zone are associated with heavy oil-tar seeps.
Hydrocarbon seep area (N-IIIN) containing active seeps

(OCS P-0396-1)

Probable Gas Cap

Franciscan Complex

(Tf)

Ts

Tm

K-T

Sea Level

Scale: X = Y

(TD = 8055 ft)

6880 ft 7540 ft

790 ft

7450 ft

2000 ft

1000 ft

0 ft

OCS P-0397-2

Probable Gas Cap

Franciscan Complex

(Tf)

Ts

Tm

K-T

Hosgri Fault

(TD = 8055 ft)

7220 ft 7940 ft

645 ft

6880 ft

790 ft

3050 ft

2790 ft

6880 ft

790 ft

7940 ft

6980 ft

6880 ft

7940 ft

7940 ft

6880 ft

(OCS P-0397-2)

Probable Gas Cap

Franciscan Complex

(Tf)

Ts

Tm

K-T

Hosgri Fault

(TD = 8055 ft)

7220 ft 7940 ft

645 ft

6880 ft

790 ft

3050 ft

2790 ft

6880 ft

790 ft

7940 ft

6980 ft

6880 ft

7940 ft

7940 ft

6880 ft

(TD = 8055 ft)

7220 ft 7940 ft

645 ft

6880 ft

790 ft

3050 ft

2790 ft

6880 ft

790 ft

7940 ft

6980 ft

6880 ft

7940 ft

7940 ft

6880 ft

(TD = 8055 ft)
Hydrocarbon seep area (N-II) containing active seeps

Hydrocarbon seep area (N-IIIC) containing active seeps

Franciscan Complex

Franciscan Complex

Hosgri Fault

Sea Level

OCS P-0408-1

OCS P-0409-2

Sea Level

Seafloor

Qtd

Foxen

Sisquoc

T. Monterey

B. Monterey

K-T

TD = 6110 ft

TD = 6110 ft

TD = 8400 ft

TD = 8400 ft

Probable Gas Cap

1133 ft

3150 ft

5315 ft

5875 ft

1300 ft

3028 ft

5570 ft

7795 ft

8150 ft

Strike-slip Tectonics
Cross Section B-B’

Scale: X = Y

(Saenz, 2002)
Strike-slip Tectonics
Cross Section C-C’ and Cross Section D-D’

Hydrocarbon seep area (N-V) containing active seeps

Hydrocarbon seep area (C-IVN) containing active seeps

(Saenz, 2002)
Strike-slip Tectonics
Cross Section E-E’

(Saenz, 2002)
Compressional Tectonics

- In the southern-most portion of the study area, compressional tectonics of the North Channel Fault zone, bring the Monterey Formation to the surface resulting in a loss of volatiles and biodegradation of the oil to tar at the surface. The heavy oil-tar seeps form tar sheets and growing tar mounds.

- The hydrocarbon seeps in the SBB along the North Channel fault and east-west trending fold trends have tapped into various reservoir rocks; including the Monterey, Vaqueros, Sespe, and Sacate Formations.

- The compressional tectonics of the North Channel Fault zone, brings the Monterey Formation to the surface resulting in a loss of volatiles and biodegradation of the oil to tar at the surface in the southern area. The occurrence of these features is generally limited to the Arguello Slope. The heavy oil-tar seeps form tar sheets and growing tar mounds found near the seep vent structures, and in one case associated with Beggiatoa, a chemosynthetic bacterium that metabolizes petroleum was found near a seep in area S-II.
Cross section (F-F’) showing structure, and hydrocarbon seeps for the southern portion of the offshore SMB study area (Saenz, 2002).

Location of this section is south of Point Conception.
Case Study - Conclusions

• The mechanism for thermal degradation of Monterey Formation oil are associated with the highest Geothermal Gradients (3°F/100 ft), and high Monterey Formation temperatures (250°F).

• Glassy Chert’s and Porcelaneous Chert’s are associated with highest geothermal gradients, the highest average temperatures in Monterey Formation, and highest Methane gas concentrations.

• Presence of thermogenic hydrocarbons at depth results in the vertical migration of gas in major fault zones to the seafloor (high resolution seismic surveys, mud logs-gas chromatograph trends, well cores, and SNIFFER surveys).

• Loss of volatiles or lighter–end fractions (C1–C8) have resulted from thermal cracking in the northern and central areas and correlate to low °API gravities in Monterey Formation oil, highest gas concentrations in shallow horizons (0-3000 ft subsea), and highest # of gas vent craters on the seafloor (+1500).

• Differences among seeps and seep features are related to the difference in tectonic regimes of Santa Maria and Santa Barbara Basins.

• The primary seep controls are the northwest-trending active faults of the Hosgri system (strike-slip tectonics), including the Purisima and Lompoc faults all tapping into one major reservoir rock.

• In the southern-most portion of the study area, the North Channel Fault zone (compressional tectonics) is the primary seep control tapping into several major reservoir rocks.

• Tar mounds/sheets or seeping oil on seafloor may be inhibiting the upward migration of hydrocarbons acting as a “secondary seal” in the North Channel Fault zone. Leading to slower gas-seepage rates and higher °API gravities in Monterey Formation oil. Low concentrations of craters are located in the southern area and are associated with tar mounds/sheets.