<u>**2015 DOE-BES Final Report**</u>

Award No.: DE-SC0003676 (UCSB) and DE-FG02-96ER14620 (Tufts)

Co-Recipient: University of California, Santa Barbara, CA

Co-Recipient: Tufts University, Medford, MA

Project Title: *"Fault-related CO_2 degassing, geothermics, and fluid flow in southern California basins---Physiochemical evidence and modeling"*

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Report contains no patentable or protected material.

Executive Summary

Our studies have had an important impact on societal issues. Experimental and field observations show that CO_2 degassing, such as might occur from stored CO_2 reservoir gas, can result in significant stable isotopic disequilibrium. In the offshore South Ellwood field of the Santa Barbara channel, we show how oil production has reduced natural seep rates in the area, thereby reducing greenhouse gases. Permeability is calculated to be ~20-30 millidarcys for km-scale fault-focused fluid flow, using changes in natural gas seepage rates from well production, and poroelastic changes in formation pore-water pressure. In the Los Angeles (LA) basin, our characterization of formation water chemistry, including stable isotopic studies, allows the distinction between deep and shallow formations waters. Our multiphase computational-based modeling of petroleum migration demonstrates the important role of major faults on geological-scale fluid migration in the LA basin, and show how petroleum was dammed up against the Newport-Inglewood fault zone in a "geologically fast" interval of time (less than 0.5 million years). Furthermore, these fluid studies also will allow evaluation of potential cross-formational mixing of formation fluids. Lastly, our new study of helium isotopes in the LA basin shows a significant leakage of mantle helium along the Newport Inglewood fault zone (NIFZ), at flow rates up to 2 cm/yr. Crustal-scale fault permeability (~60 microdarcys) and advective versus conductive heat transport rates have been estimated using the observed helium isotopic data. The NIFZ is an important deep-seated fault that may crosscut a proposed basin decollement fault in this heavily populated area, and appears to allow seepage of helium from the mantle sources about 30 km beneath Los Angeles. The helium study has been widely cited in recent weeks by the news media, both in radio and on numerous web sites.

Comparison of Accomplishments vs Goals

Our original study planned a detailed time analyses of seep rates into the offshore seep tents that collect natural gas in the shallow off-shore of the Santa Barbara basin (SB basin) near Goleta, CA. At the time we began to install the monitoring equipment, the natural seepage from the tent stopped, due to a new well drilled beneath the tent in the South Ellwood reservoir. Seepage has not returned. We were able to continue sampling of fluids coming into the under pressured reservoir along faults from the sea bed.

Our original study proposed to leverage a well drilling the Newport-Inglewood fault to be paid for and drilled by Signal Hill petroleum (SHP). The well was to be sited on the California State Long Beach (CSLB) campus. We had planned extensive sampling and monitoring of the Newport Inglewood fault zone (NIFZ) from this well. For various reasons the well was not drilled (lack of a suitable site being the main reason, other well priorities by SHP being another, change in oil prices being a third). We were, however, able to conduct a major survey (both isotopic and elemental analyses) of formation water composition over a wide range of depths in the basin.

To analyze the field observations, we also proposed to construct 2-D finite element models of the both the Santa Barbara and Los Angeles basins, using well-known and stable numerical algorithms. Parameter sensitivity studies were conducted to better understand the effects of ancient sedimentation, geothermal history, and fault permeability on the rates and patterns of petroleum migration and accumulation (LA basin), and to better characterize the effects of fault properties on the poroelastic behavior of deep formation fluids subjected to tidal loading on the sea floor (SB basin). This research was competed as planned, and resulted in the completion of one Master's Thesis (SB basin) and one Doctoral Dissertation (LA basin) at Tufts University.

Not specified in the original proposal, we initiated a first-time study of helium isotopes and associated CO_2 in the deep LA basin wells, including a number of samples obtained along the NIFZ. This study led to new findings of significant importance to the study of helium migration in the Earth's crust, and potentially to new studies of seismicity and plate tectonics in southern California.

Summary of Project Activities

Rapid leakage of gas from sequestered CO_2 reservoirs and pressure drops from the formation into the production tubing can result in precipitation of carbonate. This carbonate scale can be a problem in producing fluids and in the case of CO_2 reservoirs can be indicative of leakage. We have found that rapid leakages results in extreme isotopic disequilibrium, specifically the light isotopes of ^{16}O and ^{12}C are concentrated in the carbonate phase. We were able to document disequilibrium values that were 7 to 13 ‰ lighter for $\delta^{18}O$ and 25 to 30 ‰ lighter for $\delta^{13}C$ than predicted equilibrium. To quantify the effect of extremely rapid crystallization rate on isotopic disequilibrium we began a series of controlled lab experiments on rapid crystallization in collaboration with Dr. Sidney Omelon, University of Toronto. Experiments involve rapid CO_2 degassing and mixing. The results of this work are ongoing at this date.

The South Ellwood fault seep studies, Santa Barbara channel, include an analysis of the sea floor natural gas seep capture rate as a function of production history of Platform Holly wells. Our work shows the decline in seep rate occurs when certain wells are activated. From changes in seep rates we were able to calculate unique kilometer scale fault permeability between the production wells and the sea floor. Unfortunately the demise of flux into the seep tent (due to a new exploration well being drilled) prevented any further study of this unique location. But the data set we obtained before the seep tent demise was sufficient to constrain the first-ever direct Darcy calculations of fault permeability at the km scale, and furthermore allowed us to calculate the first-ever value of specific storage (bulk compressibility) for a single fault zone using pore-pressure changes induced by tidal loading on the sea floor. This work was also clear documentation than hydrocarbon production can reduce natural seepage.

The Los Angeles basin/Newport Inglewood fault zone studies include collection and analyses of the formation waters in deep wells, many of which have been recently drilled. The analyses shows the waters are only about 70-80% sea water salinity. Stable isotopic analyses indicate theses formation fluids are not being diluted by meteoric water, but rather by diagenetic clay reactions. The deep waters are distinct from the shallow waters indicating that basin-scale mixing does not occur. This was confirmed mathematically by 2-D numerical models, which showed how petroleum tends to favor fault zone conduits for both lateral and vertical migration. Vertical strike-slip faults such as the NIFZ created very rich "stacked" petroleum reservoirs in the LA basin. We also collected casing gas samples of 23 wells for helium and CO_2 isotopic analyses from the deepest and most pristine wells that are available. The Newport-Inglewood fault showed a major mantle helium anomaly (up to 66% mantle helium) along its entire length through the LA basin, in contrast to other areas in the basin. The CO_2 data indicated that the CO_2 associated with the mantle helium-rich samples wells is mantle derived whereas the more abundant CO_2 associated with the shallow wells is derived from methanogenic processes. New equations were developed to calculate flow rates through the crust, which are mathematically more rigorous than previous estimates of helium flow rates. The lack of a geothermal signature (anomaly) along the NIFZ was explained from calculations of the Péclet number, and a quasi-3D dimensional analysis of the field data. Findings of the helium isotopic study are our most significant immediately exciting result from this grant, but long term we believe the basin fluid flow modeling has provided clearer insight as to the origin of the richest accumulation of petroleum in the Earth's crust, and helped quantified the hydraulics of faults and their fundamental role in fluid migration, vertical leakage, and multiphase fluid sequestration. Our calculations for the large-scale permeability of large fault zones are also new and unique.

Products

Published Conference Abstracts

2015

"Fault-related mantle helium Los Angeles basin, California": AAPG-SEPM Pacific Section Meeting, May 4, Oxnard, CA.

"Formation water composition as a guide to fluid flow and diagenetic processes in three southern California basins": AAPG National Meeting, June 1, Denver, CO.

"Leakage of mantle helium along the Newport-Inglewood fault zone, Los Angeles basin": GSA Annual Meeting, Nov. 3, Baltimore, MD, abstract 258065.

2014

"Geofluid dynamics of faulted sedimentary basins": AGU Fall Meeting, Dec. 17, San Francisco, CA, abstract H32F-04.

2013

"Comparison of helium isotopes in Tertiary basins of Southern California: evidence of fault related mantle helium": AGU Fall Meeting, Dec 9, San Francisco, CA, abstract V13G-2702.

"Tidal fluctuations in a deep fault extending under the Santa Barbara Channel, California": AGU Fall Meeting, Dec 10, San Francisco, CA, abstract H51O-02.

2012

"Comparison of formation water composition in the San Joaquin and Los Angeles basin: Implications for types of water-rock interaction and fluid transfer": AAPG Annual meeting, April 23, Long Beach, CA.

"Effects of faults on petroleum fluid dynamics, Borderland basins of southern California": AGU Fall Meeting, Dec. 3, San Francisco, CA, abstract T11E-05.

2011

"Vertical changes in formation water composition in arkosic California basins: Implications for types of water-rock interaction and fluid transfer": AGU Fall Meeting, Dec 9, San Francisco, CA, abstract H13A-1187.

"Large-scale multiphase flow modeling of hydrocarbon migration and fluid sequestration in faulted Cenozoic sedimentary basins, southern California": AGU Fall Meeting, Dec. 6, San Francisco, CA, abstract H12A-06.

Student Theses

Jung, B. (2013) "*Geohydrology of Multiphase Flow and Petroleum Migration in the Los Angeles Basin*": Ph.D. dissertation (Tufts University), May 2013.

Stone, J. (2013) "*An Investigation of Fault Zone Hydrogeology and Geomechanical Tidal Behavior, South Ellwood Field, California*": Master's thesis (Tufts University), May 2013.

Journal Articles

Boles, J.R., Horner, S. and Garven, G. (2010) Permeability Estimate for the South Ellwood Fault: Society of Petroleum Engineers, SPE 133613, 9 p.

Boles, J.R., Edwards, M., Kamerling, M., and Valentine, D. (2012) Oil Seeps and Geology of the Santa Barbara Channel: 2012 AAPG Annual Convention Field Trip Guide Book, Pacific Coast Geological Society, 67 p.

Jung, B., Garven, G., and Boles, J.R. (2014) Effects of episodic fluid flow on hydrocarbon migration in the Newport-Inglewood fault zone, southern California: Geofluids, v. 14, p. 234-250.

Jung, B., Garven, G. and Boles, J.R. (2015) The geodynamics of faults and petroleum migration in the Los Angeles basin, California: American Journal of Science, v. 315, p. 412-459.

Boles, J.R., Garven, G., Camacho, H., Lupton, J.C. (2015) Mantle helium along the Newport-Inglewood fault zone, Los Angeles basin, California -- A leaking paleo-subduction zone: Geochemistry, Geophysics, Geosystems, July 2015 (in press).

Websites

None.