CITY OF CARSON

PLANNING COMMISSION STAFF REPORT

CONTINUED PUBLIC HEARING: December 8, 2015 (Continued from October 13, 2015)

SUBJECT: Text Amendment No. 20-15

APPLICANT: City of Carson

REQUEST: To consider adoption of an Ordinance prohibiting hydraulic fracturing ("fracking"), acidizing and any other form of well stimulation, and a finding of a Class 8 Categorical Exemption under CEQA Guidelines §15308

PROPERTY INVOLVED: City-wide

COMMISSION ACTION

COMMISSIONERS' VOTE

AYE	NO		AYE	NO	
		Chairman Diaz			**Mitoma**
		Vice-Chairman Madrigal			**Pimentel**
		Andrews			**Post**
		Fe'esago			**Thomas**
		Guidry			

I. Introduction

This matter was considered by the Planning Commission on eight prior occasions. At the last meeting on October 13, 2015, the Planning Commission continued this matter to December 8, 2015. This Staff Report provides a status update and recommends Planning Commission take final action.

II. Background

On October 13, 2015, the Planning Commission continued this item to allow the City Manager to continue to meet with all stakeholders in order to ensure the community, environmental and other interested parties have been heard and have a full opportunity to consider and review all aspects of the proposed Ordinance. Staff have also assessed recent legislation and have examined options to ensure the public health and safety is protected.

III. Analysis

This project involves the consideration of an Ordinance to prohibit hydraulic fracturing, acidizing and any other form of well stimulation in conjunction with the production or extraction of oil, gas or other hydrocarbon substances in the city.

Components

The proposed Ordinance is comprised of three sections:

- Section 9535 "Operational Prohibitions" (1) prohibits the storage of certain volumes of acid on site; (2) limits the amount of water usage unless approved by the City Manager; and (3) regulates the amount of truck trips to the site for water deliveries. As a practical matter these regulations may have an impact on certain types of well stimulation practices.

- Section 9536 "Prohibited Uses," directly prohibits hydraulic fracturing, acidizing, or any other well stimulation treatment.[1] Certain exceptions are

[1] "Well stimulation treatment" is defined in the DOGGR Statutes and Regulations and means a treatment of a well designed to enhance oil and gas production or recovery by increasing the permeability of the formation. Well stimulation is a short term and non-continual process for the purposes of opening and stimulating channels for the flow of hydrocarbons. Examples of well stimulation treatments include hydraulic fracturing, acid fracturing and acid matrix stimulation. Except for operations that meet the definition of "underground injection project" under 14 CCR Section 1761(a)(2), a treatment at pressures exceeding the formation fracture gradient shall be presumed to be a well stimulation treatment unless it is demonstrated to DOGGR's satisfaction that the treatment, as designed, does not enhance oil and gas production or recovery by increasing the permeability of the formation. Except for operations that meet the definition of "underground injection project" under CCR Section 1761(a)(2), a treatment that involves emplacing acid in a well and that uses a volume of fluid equal to or greater than the Acid Volume Threshold for the operation shall be presumed to be a well stimulation treatment unless it is demonstrated to DOGGR's satisfaction that the treatment, as designed, does not enhance oil and gas production or recovery by increasing the permeability of the

noted, including a procedure where City Manager may issue a permit if the owner/operator can demonstrate (1) well stimulation, other than hydraulic fracturing, is necessary to recover the owner/operator's reasonable investment backed expectation; and (2) that such well stimulation will not create a nuisance due to an adverse impact on persons or property within the City.

- Section 9536.1 "Violations of Prohibited Uses" establishes enforcement proceedings for violations of prohibited uses. This includes paying the City a fine of $100,000 or more per day, depending on the severity of the violation, at the discretion of the City Manager. Additionally, the City Manager may also require an immediate shutdown of all operations at an oil and gas facility site, as long as the shutdown would not otherwise threaten public health, safety or welfare.

No Proposed Refinements

There are no substantive proposed refinements to the Ordinance at this time; clarifying language has been added. The proposed Ordinance and Resolution are attached as Exhibit "1."

Recent Legislation and Judicial Determinations

No legislation was enacted at the State level prohibiting hydraulic fracturing, etc. While there was proposed State legislation related to seismic activities and well stimulation treatments, emissions from well stimulation treatments, etc., these items were not approved. DOGGR has approved regulations titled SB4 requiring operators to provide notice to adjacent property located within 1,500 feet of the wellhead operations or 500 feet from the horizontal projection of the well path. In addition, SB4 places a number of requirements on well stimulation activities including ground water testing, well integrity testing and seismic monitoring.

Dialog With Interested Parties and Small Group Workshops

The City Manager, Staff, the City Attorney's office, and MRS have been actively moving forward on this matter, and have held or offered a series of separate meetings with members of the community, industry stakeholders and other interested parties at various times to address issues and concerns.

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formation. Well stimulation treatment does not include steaming, water flooding or cyclic steaming and does not include routine well cleanout work; routine well maintenance; routine treatment for the purpose of removal of formation damage due to drilling; bottom hole pressure surveys; routine activities that do not affect the integrity of the well or the formation; the removal of scale or precipitate from the perforations, casing, or tubing; a gravel pack treatment that does not exceed the formation fracture gradient; or a treatment that involves emplacing acid in a well and that uses a volume of fluid that is less than the Acid Volume Threshold for the operation and is below the formation fracture gradient.

Dominguez and Wilmington Field Conditions

Well stimulation techniques the Dominguez and the Wilmington fields would not be currently effective due to the nature of the fields and existing technology. This is primarily due to the level of sand in the formations or the natural "fracturing" already caused by pre-existing shifting of the formation due to seismic events along existing fault lines. Under these conditions, increasing the permeability of the formations through the use of high pressures which crack the rock, or acids which dissolve the rock formations, would not be effective based upon existing technology and market conditions. The oil and gas industry has indicated they have no current plans to utilize hydraulic fracturing to enhance recovery; however, they would not commit to a voluntary fracking ban.

IV. Environmental Review

Staff performed a preliminary environmental assessment of this project and has determined that it falls within the Class 8 Categorical Exemption set forth in CEQA Guidelines section 15308, which exempts actions by regulatory agencies for the protection of the environment. This Categorical Exemption is applicable as this Ordinance is intended to further regulate oil and gas production in the City in such a way as to better protect the environment. Additionally, prohibiting hydraulic fracturing, acidizing, or any other well stimulation treatment further limits – not relaxes – the environmental impacts these types of operations may potentially have on the environment including air quality, greenhouse gas emissions, water resources, geology, noise, traffic and public health and safety. By doing so, the Ordinance effectively strengthens environmental standards related to the prohibited uses, and thereby advances the protection of environmental resources within the City of Carson. Furthermore, none of the exceptions to Categorical Exemptions set forth in the CEQA Guidelines, section 15300.2 apply to this project.

V. Recommendation

If the Planning Commission is inclined to recommend approval of the Ordinance prohibiting hydraulic fracturing, etc., and the associated CEQA finding to the City Council with the staff additions, staff recommends the Planning Commission:

- **ADOPT RESOLUTION NO. ______:**
  - **RECOMMENDING APPROVAL** of a finding of a Class 8 Categorical Exemption under CEQA Guidelines §15308, as the Ordinance is an action taken by a regulatory agency for the protection of the environment; and
  - **RECOMMENDING APPROVAL** to the City Council an Ordinance to adopt Text Amendment No. 20-15 adding Sections 9535, 9536 and 9536.1 to, and amending Section 9501.B of, Chapter 5 of Article IV of

the Carson Municipal Code to prohibit well stimulation techniques, including hydraulic fracturing ("fracking") and acidizing, in conjunction with the production or extraction of oil, gas or other hydrocarbon substances in the city.

VI. Exhibits

1. Resolution with Ordinance
2. Correspondence

Note: Additional studies, comment letters, etc. can be found at: http://ci.carson.ca.us/department/communitydevelopment/oilcodeupdate.asp.

Prepared, Reviewed and Approved by: ______________________
Saied Naaseh, Planning Manager

CITY OF CARSON

PLANNING COMMISSION

RESOLUTION NO. 15 - ______

A RESOLUTION OF THE PLANNING COMMISSION OF THE CITY OF CARSON RECOMMENDING THE CITY COUNCIL TO ADOPT TEXT AMENDMENT NO. 20-15, ADDING SECTIONS 9535, 9536 AND 9536.1 TO, AND AMENDING SECTION 9501.B OF, CHAPTER 5 OF ARTICLE IV OF THE CARSON MUNICIPAL CODE TO PROHIBIT WELL STIMULATION TREATMENT INCLUDING HYDRAULIC FRACTURING ("FRACKING") AND ACIDIZING, IN CONJUNCTION WITH THE PRODUCTION OR EXTRACTION OF OIL, GAS OR OTHER HYDROCARBON SUBSTANCES IN THE CITY; AND RECOMMENDING APPROVAL OF A FINDING OF A CLASS 8 CATEGORICAL EXEMPTION UNDER CEQA GUIDELINES §15308

WHEREAS, all oil and gas operations have the potential for significant and immediate impacts on the health, safety, and welfare of the citizens of Carson through increased noise, odor, dust, traffic, and other disturbances, as well as the potential to significantly impact the City's air, water, soil, geology, storm water and wastewater infrastructure, transportation, noise exposures, emergency response plans and aesthetic values and community resources; and

WHEREAS, the City of Carson zoning and land use standards and regulations on oil and gas drilling have not been updated in several years, and have not been updated prior to various changes in oil and gas production practices and changes to state statutes and regulations; and

WHEREAS, the City Council held a variety of meetings regarding these and related issues associated with petroleum operations on March 18, 2014, April 15, 2014, April 29, 2014, and May 20, 2014; and

WHEREAS, on March 18, 2014, the City Council adopted Urgency Ordinance No. 14-1534U entitled "An Interim Urgency Ordinance of the City of Carson, California, Establishing a 45-Day Temporary Moratorium on the Drilling, Redrilling or Deepening of any Wells Within the Jurisdiction of the City of Carson that are Associated with Oil and/or Gas Operations, and Declaring the Urgency thereof," and

WHEREAS, on May 20, 2015, the City Council directed City Staff to commence a complete and comprehensive review to update the Municipal Code regarding oil and gas operations and to study and address all modern-day drilling issues and applications; and

WHEREAS, as part of this process, City Council directed City Staff to address regulation and prohibition of well stimulation including hydraulic fracturing ("fracking") and acidizing in conjunction with the production or extraction of oil, gas or other hydrocarbon substances in the city; and

WHEREAS, City Staff were also directed to have at least two workshops with the community to receive community input and feedback; and

WHEREAS, the Community Development Department also initiated Text Amendment No. 20-15 to facilitate this review; and

WHEREAS, the City of Carson has reviewed and studied revisions as necessary to the City's laws, rules, procedures and fees related to petroleum operations and facilities involving well stimulation, to enable the City to adequately and appropriately balance the rights of existing operators and future applicants who wish to develop oil and gas drilling and extraction facilities in the City, with the preservation of the health, safety and welfare of the communities surrounding the oil and gas drilling and extraction facilities in the city; and

WHEREAS, as part of this review process the City of Carson has engaged in significant community outreach regarding this matter, including sending mailed notices of community meetings to the approximately 30,000 resident addresses in the city, publishing notices in the newspaper, and holding three community meetings regarding oil and gas operation issues, including fracking and other well stimulation techniques; and

WHEREAS, City of Carson Staff prepared a proposed Ordinance prohibiting fracking and other well stimulation techniques, made it available on the internet on February 11, 2015, and received public feedback during the community meeting on February 18, 2015; and

WHEREAS, the Planning Commission of the City of Carson subsequently received and reviewed the proposed Ordinance prohibiting fracking and other well stimulation techniques at a duly noticed meeting held at 6:30 p.m. on February 24, 2015, at the Congresswoman Juanita Millender-McDonald Community Center, Community Halls ABC, 801 East Carson Street, Carson, CA 90745; and

WHEREAS, public testimony and evidence, both written and oral, was considered by the Planning Commission of the City of Carson; and

WHEREAS, the Planning Commission of the City of Carson continued the item to its regular meeting of April 14, 2015; and

WHEREAS, informal informational sessions were held with various members of the Planning Commission throughout the day on March 30, 2015; and

WHEREAS, City of Carson Staff provided additional refinements and made the updated proposed Ordinance and other studies, reports and documents available on April 7, 2015; and

WHEREAS, the City of Carson engaged in additional community outreach and met with interested members of the community, environmental groups, and oil and gas interests on April 8 and 28, 2015; and

WHEREAS, the Planning Commission of the City of Carson subsequently received and reviewed the updates to the proposed Ordinance at a duly noticed meeting at 6:30 p.m. on April 14, 2015, at City Hall, Helen Kawagoe Council Chambers, 701 East Carson Street, Carson, California, 90745; and

WHEREAS, the public comment portion was reopened, and public testimony and evidence, both written and oral, was considered by the Planning Commission of the City of Carson; and

WHEREAS, the Planning Commission of the City of Carson closed the public comment portion and continued the item to its regular meeting of May 12, 2015, with direction to City Staff to engage in further discussions with interested groups; and

WHEREAS, the City of Carson engaged in additional community outreach and met with interested members of the community, environmental groups, and oil and gas interests, including a meeting on May 12, 2015; and

WHEREAS, the Planning Commission of the City of Carson subsequently received and reviewed the revisions to the proposed Ordinance at a duly noticed meeting at 6:30 p.m. on May 12, 2015, at City Hall, Helen Kawagoe Council Chambers, 701 East Carson Street, Carson, California, 90745; and

WHEREAS, the public comment portion was reopened, and public testimony and evidence, both written and oral, was considered by the Planning Commission of the City of Carson; and

WHEREAS, the Planning Commission of the City of Carson closed the public comment portion and continued the item to its regular meeting of June 9, 2015, with direction to City Staff to further revise the proposed Ordinance and engage in further discussions with interested groups; and

WHEREAS, the City of Carson engaged in additional community outreach and had an additional meeting with representatives of oil and gas interests on May 26, 2015; and

WHEREAS, the Planning Commission of the City of Carson subsequently received and reviewed the proposed Ordinance at a duly noticed meeting at 6:30 p.m. on June 9, 2015, at City Hall, Helen Kawagoe Council Chambers, 701 East Carson Street, Carson, California, 90745; and

WHEREAS, the public comment portion was reopened, and public testimony and evidence, both written and oral, was considered by the Planning Commission of the City of Carson; and

WHEREAS, the Planning Commission of the City of Carson closed the public comment portion and continued the item to its regular meeting of July 28, 2015, with direction to City Staff to further revise the proposed Ordinance, set up small group workshops with the

Commissioners, engage in additional community outreach, and provide additional information to the Planning Commission; and

WHEREAS, the City of Carson held separate meetings with members of the community and industry stakeholders on July 6, 2015, three small group workshops with members of the Planning Commission throughout the day on July 7, 2015, and a teleconference was held with petroleum industry stakeholders on July 14, 2015; and

WHEREAS, the Planning Commission of the City of Carson subsequently received and reviewed the proposed Ordinance at a duly noticed meeting at 6:30 p.m. on July 28, 2015, at City Hall, Helen Kawagoe Council Chambers, 701 East Carson Street, Carson, California, 90745; and

WHEREAS, the public comment portion was reopened, and public testimony and evidence, both written and oral, was considered by the Planning Commission of the City of Carson; and

WHEREAS, the Planning Commission of the City of Carson closed the public comment portion and continued the item to its regular meeting of September 8, 2015, with direction to City Staff to set up small group workshops with the Commissioners and City Manager, engage in additional community outreach, and provide additional information to the Planning Commission; and

WHEREAS, the City of Carson engaged in additional outreach by holding additional small group workshops with members of the Planning Commission on August 24 and August 25, 2015, met with petroleum industry stakeholders on August 27th with petroleum industry stakeholders, and met with an environmental group representative on September 2, 2015; and

WHEREAS, the Planning Commission of the City of Carson subsequently held a duly noticed meeting at 6:30 p.m. on September 8, 2015, at City Hall, Helen Kawagoe Council Chambers, 701 East Carson Street, Carson, California, 90745; and

WHEREAS, upon recommendation by Staff, the Planning Commission of the City of Carson continued the item to its regular meeting of October 13, 2015, without reopening the public comment portion, to allow for noise studies, as well as to allow the City Manager to hold additional meetings with members of the community, industry stakeholders and other interested parties regarding the Ordinance; and

WHEREAS, the City of Carson engaged in additional community outreach and had an additional meetings with representatives of oil and gas, environmental and community group interests at various times on September 15th, 24th, and 29th of 2015; and

WHEREAS, Planning Commissioners were provided with the opportunity to tour existing oil and gas operations within the City of Carson in October of 2015; and

WHEREAS, the City mailed notices of the Planning Commission hearing on October 13, 2015, to the addresses in the city and published a notice in the newspaper regarding the same; and

WHEREAS, the Planning Commission of the City of Carson subsequently received and reviewed the proposed Ordinance at a duly noticed meeting at 6:30 p.m. on October 13, 2015, at City Hall, Helen Kawagoe Council Chambers, 701 East Carson Street, Carson, California, 90745; and

WHEREAS, the public comment portion was reopened, and public testimony and evidence, both written and oral, was considered by the Planning Commission of the City of Carson; and

WHEREAS, after closing the public comment period, upon recommendation by Staff the Planning Commission of the City of Carson continued the item to its regular meeting of December 8, 2015, to allow the City Manager to continue to meet with stakeholders and assess recent legislation; and

WHEREAS, the Planning Commission of the City of Carson subsequently received and reviewed the proposed Ordinance at a duly noticed meeting at 6:30 p.m. on December 8, 2015, at City Hall, Helen Kawagoe Council Chambers, 701 East Carson Street, Carson, California, 90745; and

WHEREAS, Planning Commission of the City of Carson has reviewed Text Amendment No. 20-15 for consistency with the General Plan and all applicable Specific Plans; and

WHEREAS, after considering public testimony and receiving information, the Planning Commission of the City of Carson desires to recommend approval of Zone Text Amendment No. 20-15, which prohibits well stimulation, including fracking and acidizing, in conjunction with the production or extraction of oil, gas or other hydrocarbon substances, to the City Council of the City of Carson; and

WHEREAS, the Planning Commission of the City of Carson has also reviewed and also desires to recommend approval of a finding of a Class 8 Categorical Exemption under CEQA Guidelines §15308, as the Ordinance is an action taken by a regulatory agency for the protection of the environment, to the City Council of the City of Carson; and

WHEREAS, it is the intent of the recommendation of the Planning Commission of the City of Carson that petroleum operations shall be permitted within the City of Carson, except where expressly prohibited, subject to the application the Carson Municipal Code and all other applicable laws, regulations and requirements; and

WHEREAS, it is a purpose of said recommendation of adoption to protect the health, safety, public welfare, physical environment and natural resources of the City of Carson, and to prevent nuisances, by the reasonable regulation of certain petroleum operations.

NOW, THEREFORE, THE PLANNING COMMISSION OF THE CITY OF CARSON, CALIFORNIA, HEREBY FINDS, RESOLVES AND ORDERS AS FOLLOWS:

Section 1. Text Amendment No. 20-15 was assessed in accordance with the authority and criteria contained in the California Environmental Quality Act (CEQA), the State CEQA Guidelines (the Guidelines), and the environmental regulations of the City. The Planning Commission hereby recommends a finding and determination by the City Council that the adoption of Text Amendment No. 20-15 is exempt from CEQA pursuant to Section 15308 of the Guidelines for actions taken by regulatory agencies to assure the maintenance, restoration, enhancement, or protection of the environment. This Categorical Exemption is applicable as this Ordinance is intended to further regulate oil and gas production in the City in such a way as to better protect the environment. Additionally, prohibiting hydraulic fracturing, acidizing, or any other well stimulation treatment, and regulating associated uses, further limits – not relaxes – the environmental impacts these types of operations may potentially have on the environment including air quality, greenhouse gas emissions, water resources, geology, noise, traffic and public health and safety. By doing so, the Ordinance effectively strengthens environmental standards related to the prohibited uses, and thereby advances the protection of environmental resources within the City of Carson. No exception to the exemption under CEQA Guideline Section 15300.2 applies.

Section 2. The Planning Commission of the City of Carson has reviewed Text Amendment No. 20-15, an Ordinance prohibiting well stimulation techniques within the City of Carson, and hereby finds it is consistent with the General Plan and all applicable Specific Plans.

Section 3. The Planning Commission of the City of Carson, based on its own independent judgment, finds that Text Amendment No. 20-15 promotes and protects the health, safety, welfare, and quality of life of City residents, including protection against nuisances, and adopts the Findings of Fact, attached as Exhibit "A" and incorporated in full by reference, any one of which findings would be sufficient to support adoption of this Text Amendment.

Section 4. The Planning Commission hereby recommends approval to the City Council of an Ordinance to adopt Text Amendment No. 20-15 adding sections 9535, 9536 and 9536.1 to, and amending section 9501.B of, Chapter 5 of Article IV of the Carson Municipal Code to prohibit any form of well stimulation. Including hydraulic fracturing and acidizing, in conjunction with the production or extraction of oil, gas or other hydrocarbon substances in the city (Exhibit "B").

Section 5. The Secretary shall certify to the adoption of the Resolution and shall transmit copies of the same to the City Council of the City of Carson.

PASSED, APPROVED AND ADOPTED THIS 8th DAY OF DECEMBER, 2015.

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CHAIRMAN

ATTEST:

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SECRETARY

EXHIBIT "A"

FINDINGS OF FACT

The Planning Commission of the City of Carson, based on its own independent judgment, finds that Text Amendment No. 20-15 promotes and protects the health, safety, welfare, and quality of life of City residents and reduces nuisances as set forth in these Findings of Fact, any one of which findings would be sufficient to support a recommendation to adopt this Text Amendment, and any one of which may rely upon evidence presented in the other, including as follows:

I. Well Stimulation Treatments Have More Intense Impacts Than Traditional Operations

Low-intensity traditional petroleum operations generally involve drilling wells through which oil or gas flows naturally or is pumped up to the surface. Well stimulation treatments are different. Hydraulic fracturing, acidizing, or any other well stimulation treatments typically include high-pressure injections of solvents, acids, and other chemicals, to fracture or dissolve underground formations. Well stimulation treatments threaten limited water resources in ways that low-intensity and traditional petroleum operations do not. While some well stimulation treatments have previously occurred, new advances in fracturing and stimulation technologies enable oil and gas recovery in fields and formations that were previously uneconomical to produce. Use of well stimulation treatments to extract oil and gas could give rise to an increase in the number of active wells in the City, leading to additional operational impacts on the City's residents including noise, odor, glare and other impacts. Additionally, there are currently dozens of inactive or plugged oil and gas wells scattered throughout the City and neighboring jurisdictions, many of which have not been abandoned to current State requirements. These wells have been drilled through, and penetrate, a groundwater basin relied upon by the City to provide potable water. Well stimulation treatments may be used not only to drill new wells but also to reactivate these old wells or cause abandoned wells to fail in ways that adversely impact the public health, safety and welfare. The impacts and risks associated with well stimulation treatments are too great for the City to accept.

II. Limited Water Supplies Should Be Preserved

A. Extreme Drought Conditions Throughout State Result In Water Shortages

The City, region and State of California are experiencing extreme drought conditions, and have been struggling to preserve potable water resources for most of the decade. On June 12, 2008, the Governor issued Executive Order S-06-08 calling for a State of Emergency regarding water shortages and availability. The State of Emergency was again called on February 27, 2009. Additionally, the Water Conservation Bill of 2009 SBX7-7 was passed, which requires every urban water supplier that either provides over 3,000 acre-feet of water annually, or serves more than 3,000 urban connections, to assess the reliability of its water sources over a 20-year planning horizon, and report its progress on 20% reduction in per-capita urban water consumption by the year 2020. Executive Order S-06-08 was not rescinded until March 30, 2011. Even then the Governor urged Californians to continue to conserve water.

Shortly thereafter extreme drought conditions once again resulted in water shortages. On January 17, 2014 the Governor again proclaimed a State of Emergency regarding water shortages and availability. On April 25, 2014, the Governor issued an executive order to speed up actions necessary to reduce harmful effects of the drought, and called on all Californians to redouble their efforts to conserve water. On December 22, 2014, Governor Brown issued Executive Order B-28-14, citing to the January 17, 2014 Proclamation and the April 25, 2014 Proclamation, and extending the operation of those proclamations until May 31, 2016.

During this period of time the State Water Resources Control Board (SWRCB) has been adopting new water conservation regulations. On July 15, 2014, SWRCB adopted emergency regulations prohibiting all individuals from engaging in certain water use practices and require mandatory conservation-related actions of public water suppliers during the current drought emergency. On March 17, 2015, the SWRCB amended and re-adopted the emergency drought conservation regulations, and they became effective on March 27, 2015.

Following the lowest snowpack ever recorded and with no end to the drought in sight, on April 1, 2015, the Governor directed the SWRCB to implement mandatory water reductions in cities and towns across California to reduce water usage by 25 percent. This is the first time in state history such drastic steps have ever been ordered due severe drought conditions. The SWRCB continues to adopt new water and emergency conservation regulations for all of California to address systemic water shortages.

B. Hydraulic Fracturing ("Fracking") Can Use Several Magnitudes More Water A Day Than Used By The Entire City of Carson

Between 100,000 and 1,000,000 gallons of water are required to perform a typical fracking operation for a single well, and the process is most successful when all wells in a particular field are fracked simultaneously. These numbers can vary according to the type of operation being conducted. For example, the U.S. EPA reports that fracturing shale gas wells requires between 2,300,000 to 3,800,000 gallons of water per well –not including 40,000 to 1,000,000 of water required to drill the well.[1] Water requirements within Texas' Eagle Ford Shale area can be even greater, where fracking can use up to 13,000,000 gallons of water per well excluding water required to drill the well.[2]

Even using the more conservative numbers, a fracking field of 200 wells can require 20,000,000 to 200,000,000 gallons of water, requiring approximately 3,300 to 33,000 round-trip deliveries by diesel trucks often occurring in as little as a 24-hour period – just for water.[3] Potential land use and nuisance activities from these operations include water shortages from

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[1] Cooley, Heather and Kristina Donnelly, "Hydraulic Fracturing and Water Resources: Separating the Frack from the Fiction," Pacific Institute, June 2012, p. 15; see also "Information on Shale Resources, Development, and Environmental and Public Health Risks," United States Government Accountability Office, September 2012 (showing average ranges of 3,000,000 gallons to 4,600,000 for certain oil fields).

[2] Cooley, Heather and Kristina Donnelly, "Hydraulic Fracturing and Water Resources: Separating the Frack from the Fiction," Pacific Institute, June 2012, p. 15.

[3] Use of trucks having a capacity of approximately 3,000 gallons would more than double this amount. See Shonkoff, Seth B, "Public Health Dimensions of Horizontal Hydraulic Fracturing: Knowledge, Obstacles, Tactics, and Opportunities," April, 2012. p. 3.

drought conditions, traffic, air emissions, noise, vibration, potential contamination of surface and subsurface water, and aesthetics. These impacts can increase by more than 130% -380% using the averages from the U.S. EPA.

The 2010 Urban Water Management Plan for the California Water Service Company - Dominguez District, which includes the City of Carson, sets district-specific targets of 193 gallons per capita day (gpcd) by 2015, and 171 gpcd by 2020.[4] The City of Carson had a 2010 population of 91,714,[5] which at target levels would result in a targeted consumptive use of water of about 18,000,000 gallons per day by 2015, and about 16,000,000 gallons per day by 2020. As a result, a single fracking operation for 200 wells could use more water in a one or two day period than the entire City of Carson would use more than 12 days under the Urban Water Management Plan. When recent drought reduction targets are added in, fracking a field of 200 wells could use more water in one or two day period than the entire City of Carson would use in about 14 days. If the U.S. EPA averages are used, fracking a field of 200 wells could use more water than the entire City of Carson would consume for a period of 26 to 42 days based on 2015 water consumption targets. With each well potentially expected to be fracked between one and ten times over its lifetime,[6] fracking a field of more 200 wells could use more water than the entire City would consume in a year.

Use of water for fracking operations could result in a significant impact on water resources for both the City and the surrounding area. Limited water supplies should be preserved municipal and other critical uses.

Based on these considerations and other impacts found in the administrative record, the Planning Commission finds Text Amendment No. 20-15 promotes and protects against potential pollution and water quality impacts and nuisances activities from oil and gas operations, including those articulated herein, for the benefit of the public health, safety, welfare, and quality of life.

III. Transportation of Water Required for Operations Creates Land Use and Nuisance Activities

As noted above, well stimulation techniques including hydraulic fracturing operations generate a significant amount of truck traffic. All of the materials and equipment needed for activities associated with hydraulic fracturing, including water and chemicals, are typically transported to the site by trucks. Additionally, wastewater from natural gas operations is usually removed by tanker truck to the disposal site or to another well for reuse. Truck trip for hydraulic fracturing of a horizontal well have been estimated at 3,950 truck trips per well during early development of the well field, which is two to three times greater than is required for conventional wells. Much of the truck traffic is concentrated over the first 50 days following

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4 The 2010 Urban Water Management Plan for the California Water Service Company - Dominguez District, http://www.water.ca.gov/urbanwatermanagement/2010uwmps/CA%20Water%20Service%20Co%20-%20Dominguez%20District/_DOM_UWMP_2010.pdf.

5 U.S. Census Bureau, 2015, Quick Facts –Carson California, http://quickfacts.census.gov/qfd/states/06/0611530.html.

6 See Shonkoff, Seth B, "Public Health Dimensions of Horizontal Hydraulic Fracturing: Knowledge, Obstacles, Tactics, and Opportunities," April, 2012. p. 3.

well development.[7] For an operation involving 200 wells, this would result in approximately 790,000 truck trips. Wastewater disposal may require additional trips.

One report has noted the increase in traffic associated with well stimulation techniques to be "the most constant source of aggravation, stress, and fear" for residents in the area.[8] Transport associated with well stimulation treatments operations through the City to well locations will result in potential adverse land use and nuisance activities include traffic loads, increased risk of truck accidents including releases chemical or wastewater spills, air emissions, noise, traffic congestion, degraded road quality, vibration, and aesthetics - each of which is detrimental to the public health, safety and welfare and a nuisance.

Hauling water for fracking from outside the City also impacts water resources. The City relies on groundwater water sources tracked by the Water Replenishment District. The City is primarily located within the West Coast Basin area, which underlies 160 square miles in Los Angeles County. Additionally, the City is located adjacent to the Central Basin, which also underlies much of the Los Angeles area west of the City. Both of these basins are located in areas subject to extreme drought conditions, and transporting water from other portions of a shared basin will also impact water resources available to the City and surrounding areas. Likewise, hauling water from other regions within the state, or even adjacent states, would be taking water resources from other areas experiencing extreme drought conditions and water shortages. Even use of saltwater or other non-potable sources of water in fracking and other well-stimulation activities increases nitrates and other chemicals in both groundwater and surface water supplies as a result of migration, spills, flow-back, and other factors related to petroleum operations and hydrocarbon extraction.

The City and the surrounding area rely upon groundwater and surface water supplies to provide potable and other types of water for its residences and businesses. Regardless of where water is proposed to be acquired for fracking operations, transporting the water to and through the City to well locations will result in potential land use and nuisance activities from these operations including water shortages from drought conditions, traffic, air emissions, noise, vibration, potential contamination of surface and subsurface water, and aesthetics.

Based on these considerations and other impacts found in the administrative record, the Planning Commission finds Text Amendment No. 20-15 promotes and protects against excessive use of potable water and impacts on potable water sources, for the benefit of the public health, safety, welfare, and quality of life of City residents and also reduces associated nuisances.

IV. City Cannot Afford the Risks of Groundwater Pollution or Negative Impacts on Water Quality

While water withdrawals directly affect the availability of water for other uses, water withdrawals in the volumes required for well stimulation techniques such as fracking can also

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[7] Cooley, Heather and Kristina Donnelly. "Hydraulic Fracturing and Water Resources: Separating the Frack from the Fiction," Pacific Institute, June 2012, p. 25.

[8] Bailin, Deborah, P. Rogerson, J. Agatstein, J. Imm and P. Phartiyal, "Toward an Evidence Based Fracking Debate: Science, Democracy, and Community Right to Know in Unconventional Oil and Gas Development," Union of Concerned Scientists, October 2013, p. 15.

affect water quality. For example, withdrawals of large volumes of water can adversely impact groundwater quality through a variety of means, such as mobilizing naturally occurring substances, promoting bacterial growth, causing land subsidence, and mobilizing lower quality from surrounding areas.[9] A number of studies reviewed by the United States Governmental Accountability Office indicate that shale oil and gas development pose risks to water quality from contamination of surface water and groundwater as a result of erosion from ground disturbances, spills and releases of chemicals and other fluids, or underground migration of gases and chemicals.[10] A study has also found dissolved methane at levels more than 17 times higher than those found in wells in areas without drilling.[11]

Groundwater contamination from oil and gas operations can occur through a variety of mechanisms. Oil and gas are located at varying depths, often below underground sources of drinking water. The well bore, however, must be drilled through these drinking water sources in order to gain access to the oil and gas. Vibrations and pressure pulses associated with drilling can cause short-term impacts to groundwater quality, including changes in color, turbidity, and odor. Chemicals and natural gas can escape the well bore if it is not properly sealed and cased. While there are state requirements for well casing and integrity, accidents and failures can still occur.[12] Further, wells that are hydraulically fractured have some unique aspects that increase the risk of contamination. For example, hydraulically fractured wells are commonly exposed to higher pressures than wells that are not hydraulically fractures. In addition, hydraulically fractured wells are exposed to high pressures over a longer period of time as fracturing is conducted in multiple stages, and wells may be re-fractured multiple times – primarily to extend the economic life of the well when production declines significantly or falls below the estimated reservoir potential.[13] An analysis has found that more than 6% of wells utilized for hydraulic fracturing had compromised structural integrity, and that the risk of water contamination from such failure may be significant.[14] Another study noted that wellbores used for enhanced oil recovery operations were particularly vulnerable to leakage problems.[15]

As an additional consideration, old, abandoned wells can also potentially service as migration pathways for contaminates to enter groundwater basins and systems.[16] There are currently large numbers of abandoned wells located within the City, and hundreds located in adjacent jurisdictions sharing a common groundwater basin. Natural underground fractures as

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[9] Cooley, Heather and Kristina Donnelly. "Hydraulic Fracturing and Water Resources: Separating the Frack from the Fiction," Pacific Institute, June 2012, p. 17.
[10] See "Information on Shale Resources, Development, and Environmental and Public Health Risks," United States Government Accountability Office, September 2012.
[11] "Blind Rush? Shale Gas Boom Proceed Amid Human Health Questions," Environmental Health Perspectives, Vol. 119, No. 8, 2011.
[12] Cooley, Heather and Kristina Donnelly. "Hydraulic Fracturing and Water Resources: Separating the Frack from the Fiction," Pacific Institute, June 2012, p. 17.
[13] "Information on Shale Resources, Development, and Environmental and Public Health Risks," United States Government Accountability Office, September 2012, p. 45.
[14] See Kiparsky, Michael and Jayni Foley Hein, "Regulation of Hydraulic Fracturing in California: A Wastewater and Water Quality Perspective," Berkeley Center for Law, Energy & the Environment, April 2013, p. 20.
[15] "Towards a Road Map for Mitigating the Rates and Occurrences of Long-Term Wellbore Leakage," University of Waterloo, Geofirma Engineering Ltd., May 22, 2014, 3.3.2.1.
[16] Cooley, Heather and Kristina Donnelly. "Hydraulic Fracturing and Water Resources: Separating the Frack from the Fiction," Pacific Institute, June 2012, p. 17; see also Jackson, Robert B., et al., "The Environmental Costs and Benefits of Fracking," Annual Review, 2014, 39:340.

well as those potentially created during the fracturing process could also serve as conduits for groundwater contamination. Wellbore leakage can lead to the deterioration of the quality of groundwater.[17]

Many well stimulation treatments involve the mixing, transport, or storage of toxic and hazardous chemicals for use in fracking or acidizing fluid. They also generate a considerable amount of wastewater that can contain these chemicals along with hydrocarbons, naturally occurring dissolved salts, and other elements harmful to human health and safety. The wastewater and chemicals from these operations could contaminate the City and surrounding region's groundwater through improper storage or disposal, surface spills, or other means. Given the City's heavy reliance on groundwater, groundwater contamination could have devastating impacts on the local economy and water supplies.

Based on these considerations and other impacts found in the administrative record, the Planning Commission finds Text Amendment No. 20-15 promotes and protects against excessive impacts on groundwater quality and or negative impacts on water quality, for the benefit of the public health, safety, welfare, and quality of life of City residents and also reduces associated nuisances.

V. Surface Spills and Leaks

All extraction activities come with some risk of surface or groundwater contamination from the accidental or intentional release of wasted. In the case of hydraulic fracturing, common wastes of concern including fracking fluid, additives, flowback and produced water. Fluids released into the ground from spills or leaks can fun off into surface water and/or seep into the groundwater.

Spills can occur at any stage during the drilling lifecycle. Chemicals are hauled to the site, where they are mixed to form the fracturing fluid. Accidents and equipment failure during on-site mixing of the fracturing fluid can release chemicals into the environment. Above-ground storage pits, tanks, or embankments can fail. Vandalism and other illegal activities can also result in spills and improper wastewater disposal. Given the large volume of truck traffic associated with hydraulic fracturing, truck accidents can also lead to chemical or wastewater spills.[18]

While there are reports of spills and leaks associated with well stimulation operations, the extent of the issue has yet to be quantified on a national basis. Given the uncertainty of the frequency, severity, cause and impact of spills associated with well stimulation techniques, prohibition and regulation of well stimulation treatments is warranted given the severity of the risks associated with such operations.

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[17] "Towards a Road Map for Mitigating the Rates and Occurrences of Long-Term Wellbore Leakage," University of Waterloo, Geofirma Engineering Ltd., May 22, 2014.

[18] Cooley, Heather and Kristina Donnelly. "Hydraulic Fracturing and Water Resources: Separating the Frack from the Fiction," Pacific Institute, June 2012, p. 27, see also Bailin, Deborah, P. Rogerson, J. Agatstein, J. Imm and P. Phartiyal, "Toward an Evidence Based Fracking Debate: Science, Democracy, and Community Right to Know in Unconventional Oil and Gas Development," Union of Concerned Scientists, October 2013, p. 10.

Finally, a recent study noted that reported wellbore leakage in active onshore drilling ranged from approximately 7% to 64% across a wide variety of locations.[19] The likelihood of leakage is significant given the potentially high level of risk that can associated with petroleum operations. Leakage can impact groundwater, air quality, cause odors, contaminate soil, and result in a variety of other nuisance, health, safety and welfare issues.

Given the uncertainty of the frequency, severity, cause and impact of spills associated with petroleum operations, prohibition and regulation of well stimulation techniques are warranted given the severity of the risks associated with such operations in order to protect the public health, safety, welfare and quality of life, as well as to address associated nuisances.

VI. Air Pollution, Particulate Matter and Odors

Odors, air pollution and particulate matter can be produced as a result of well stimulation activities, whether from mobile or stationary sources. These impacts are not localized, but can be spread by natural air flow cause by weather or physically generated outside a site by truck and other traffic. Odors have been known impact locations around an oil and gas site at distances of approximately 1,500 feet.

Significant methane emissions have been attributed to natural gas production activities.[20] In addition to land and water contamination issues, at each stage of production and delivery tons of toxic volatile compounds (VOCs), including BETX, other hydrocarbons and fugitive natural gas (methane) can escape and mix with nitrogen oxides (NOx) from the exhaust of diesel-fuel, mobile and stationary equipment, to produce ground-level ozone. This ozone can cause irreversible damage to the lungs.[21] The most commonly used air toxins in production involving well stimulation techniques include crystalline silica, methanol, hydrochloric acid, formaldehyde, amorphous silica, hydrofluoric acid, naphthalene, 2-butoxy ethanol, alumina/aluminum oxide, xylene and glutaral/pentanedial.[22] Each of these toxins can pose significant health and safety risks.[23] The pollutant of primary health concern emitted from the transportation component of hydraulic fracturing is fine diesel particulate matter (PM). A review by the California Air Resources Board indicated there is a 10% increase in the number of premature deaths per 10 ug/m^3 increase in $PM_{2.5}$ exposure.[24] A study has also found that residents living less than half a mile from unconventional gas well sites were at greater risk of

[19] See "Towards a Road Map for Mitigating the Rates and Occurrences of Long-Term Wellbore Leakage," University of Waterloo, Geofirma Engineering Ltd., May 22, 2014.
[20] See Allen, David T., V.M. Torres, J. Thomas, et al., "Measurements of Methane Emissions at Natural Gas Production Sites in the United States," Proceedings of the National Academy of Sciences, August 2013.
[21] Colborn, Theo, C. Kwiatkowski, K. Schultz and M. Bachran, "Natural Gas Operations from a Public Health Perspective," Human Ecological Risk Assessment, September 2011, pp. 1309-1056.
[22] See "Air Toxics One-Year Report: Oil Companies Used Millions of Pounds of Air-Polluting Chemicals in Los Angeles Basin Neighborhoods," Center for Biological Diversity, Physicians for Social Responsibility - LA, Communities for a Better Environment, Center on Race, Poverty and the Environment, June 2014, p. 4-5.
[23] Id.
[24] Shonkoff, Seth B, "Public Health Dimensions of Horizontal Hydraulic Fracturing: Knowledge, Obstacles, Tactics, and Opportunities," April, 2012. p. 3.

health effects from air pollution from natural gas development than those living farther away from well sites.[25]

Well stimulation can also create silica dust clouds. Large quantities of silica sand are used during hydraulic fracturing. Transporting, moving and refilling silica sand into and through sand hoppers can release dusts containing silica into the air. Breathing silica can cause silicosis, a lung disease. Acute silicosis nearly always leads to disability and death. The operational Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH) have issued a hazard alert for worker exposure to silica dust during hydraulic fracturing.[26]

Air quality in the City and region already falls below state standards for some of the pollutants related to production activities. Residents want to protect the air they breathe from these threats. Enactment of the Ordinance provides a regulatory framework to reduce these risks. Based on these considerations and other impacts found in the administrative record, the Planning Commission finds Text Amendment No. 20-15 promotes and protects against potential air pollution, particulate matter and odor impacts and nuisances activities from well stimulation techniques, including those articulated herein, for the benefit of the public health, safety, welfare, and quality of life of City, and to reduce nuisances.

VII. Deleterious Public Health Effects

Development and production of operations utilizing well stimulation techniques involve multiple sources of physical stressors such as noise, light, and vibrations, toxicants (e.g. benzene, constituents in drilling and well stimulation treatment fluids) and impacts on air emissions.[27]

Technology to recover natural gas depends on undisclosed types and amounts of toxic chemicals. Based on compilations of products used during natural gas operations, approximately 353 chemicals contained in these products have potential health effects. Of these, more than 75% of the chemicals could affect the skin, eyes and other sensory organs, and the respiratory and gastrointestinal systems. Approximately 40-50% could affect the brain/nervous system, immune and cardiovascular systems, and the kidneys; 37% could affect the endocrine system; and 25 % could cause cancer and mutations. These results indicate that many chemicals used during the fracturing and drilling stages of gas operations may have long-term health effects not immediately expressed.[28]

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[25] See Bailin, Deborah, P. Rogerson, J. Agatstein, J. Imm and P. Phartiyal, "Toward an Evidence Based Fracking Debate: Science, Democracy, and Community Right to Know in Unconventional Oil and Gas Development," Union of Concerned Scientists, October 2013, p. 11.

[26] "Hazard Alert: Worker Exposure to Silica during Hydraulic Fracturing," Occupational Safety and Health Administration, 2012.

[27] Macey, Gregg P., et al, "Air Concentrations Of Volatile Compounds Near Oil And Gas Production: A Community-Based Exploratory Study," Environmental Health, October 30, 2014, p. 2.

[28] Colborn, Theo, C. Kwiatkowski, K. Schultz and M. Bachran, "Natural Gas Operations from a Public Health Perspective," Human Ecological Risk Assessment, September 2011, pp. 1309-1056; See also "Chemicals Used in Hydraulic Fracturing," United States House of Representatives Committee on Energy and Commerce, April, 2011, p. 1.

Well stimulation treatments associated with development gas resources can result in direct and fugitive air emissions of a complex mixture of pollutants from the natural gas itself as well as diesel engines, tanks containing produced water, and on site materials used in production, such as drilling muds and fracking fluids. This complex mixture of chemicals and resultant secondary air pollutants, such as ozone, can be transported to nearby residences and population centers.[29]

Residents living less than ½ mile from wells are at greater risk for health effects from well stimulation treatments and other types of unconventional natural gas development. Multiple studies on inhalation exposure to petroleum hydrocarbons in occupational settings as well as residences near refineries, oil spills and petroleum stations indicate an increased risk of eye irritation and headaches, asthma symptoms, acute childhood leukemia, acute myelogenous leukemia, and multiple myeloma. Many petroleum hydrocarbons near wells include benzene, ethylbenzene, toluene, and xylene, all of which have known toxicity impacts. Assessments have concluded that ambient benzene levels demonstrate an increased potential risk of developing cancer as well as chronic and acute non-cancer health effects. Health effects associated with benzene include acute and chronic nonlymphoctic leukemia, acute myelogenous leukemia, acute myeloid leukemia, chronic lymphocytic leukemia, anemia and other blood disorders and immunological effects. Additionally, inhalation of xylenes, benzene and alkanes can adversely affect the nervous system.[30]

Enactment of the Ordinance provides a regulatory framework to reduce these risks. Based on these considerations and other impacts found in the administrative record, the Planning Commission finds Text Amendment No. 20-15 promotes and protects against potential deleterious public health effects from well stimulation operations, including those articulated herein, for the benefit of the public health, safety, welfare, and quality of life of City residents, and for the reduction of nuisances.

VIII. Risk of Induced Seismicity

While available research does not identify a direct link between hydraulic fracturing and increased seismicity, studies indicate that there could be an effect to the extent that increased use of hydraulic fracturing produces increased amounts of water that is disposed of through underground injection.[31]

In addition to requiring large amounts of water, well stimulation treatments also create large quantities of wastewater ("flowback" or "produced water") that contain contaminants which can reach toxic concentrations. Flowback and produced water are typically very saline and can contain heavy metals, organic contaminants and other materials from deep in the formation which makes treatment and recycling difficult. As a result, the wastewater produced during oil and gas extraction is either disposed of or reused for additional oil and gas extraction in a process called "secondary recovery" or "enhanced oil recovery." In California, the most

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[29] McKenzie, Lisa M., et al., "Human Health Risk Assessment Of Air Emissions From Development Of Unconventional Natural Gas Resources," Science of the Total Environment, February 2012.
[30] Id.
[31] "Information on Shale Resources, Development, and Environmental and Public Health Risks," United States Government Accountability Office, September 2012, p. 52.

common wastewater disposal method is trucking or piping the wastewater for injection into deep wastewater injection wells.[32] Approximately 90-95% of wastewater is re-injected either for reuse or disposal.[33]

The underground of injection of wastewater has long been documented to induce earthquakes. Wastewater injected into rock formations can build up significant pressure depending on a variety of complex factors. This pressure build-up can induce an earthquake if the pressure is relayed to a fault that is already stressed and close to failure. The pressure can reduce the natural friction on the fault enough to cause it to slip and trigger an earthquake. The larger the fault, the larger the magnitude of earthquakes it can host.[34]

Earthquakes can cause catastrophic levels of damage and are a threat to the public health, safety and welfare. The magnitude of earthquakes accompanying wastewater injection has been attributed up to 5.7 M_w.[35] Almost half of the 4.5 M or larger earthquakes to strike the interior of the United Sates in the past decade have occurred in regions of potential injection-based seismicity.[36] If a major earthquake such as a magnitude 7.8 were to occur along the Sand Andreas fault, it could cause 1,800 fatalities and nearly $213 billion in economic damages.[37]

One of the main areas of concern lies in Los Angeles County, where underground injection wells and oil and gas wells subjected to well stimulation techniques are located very near faults that have been shown to be active within 150 to 200 years.[38] The City of Carson is within Los Angles County and near a variety of faults in the area. Given the increased risk of inducing earthquakes, as well as the severity of the danger posed, the Planning Commission finds that operations utilizing well stimulation techniques are a nuisance and create a risk to the public, health, safety, and quality of life of City residents.

IX. Well Stimulation Operations Impact Aesthetics

Oil and gas operations utilize unsightly derricks and rigs for drilling, re-drilling, workovers and other operations. The number of unsightly derricks, rigs and other surface equipment would be increased in order to carry out operations involving well stimulation techniques, and lead to more wells for a sustained period of time to pump additional oil and gas resulting from the well stimulation operations. This is compounded by the large trucks and traffic traveling on the City's roadways through the community, dust, and stadium lighting from around-the-clock drilling rigs. The Planning Commission finds these aesthetic impacts are contrary to the urban nature of the City, are a nuisance and create a risk to the public, health, safety and quality of life in the City.

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[32] Arbelaes, J., et al., "On Shaky Ground: Fracking, Acidizing, and Increased Earthquake Risk in California," 2014, p. 6-9.
[33] Kiparsky, Michael and Jayni Foley Hein, "Regulation of Hydraulic Fracturing in California: A Wastewater and Water Quality Perspective," Berkeley Center for Law, Energy & the Environment, April 2013, p. 19.
[34] Id.
[35] Jackson, Robert B., et al., "The Environmental Costs and Benefits of Fracking," Annual Review, 2014, 39:345.
[36] Bailin, Deborah, P. Rogerson, J. Agatstein, J. Imm and P. Phartiyal, "Toward an Evidence Based Fracking Debate: Science, Democracy, and Community Right to Know in Unconventional Oil and Gas Development," Union of Concerned Scientists, October 2013, p. 13.
[37] Id., p. 22
[38] Id.

X. Well Stimulation Is Incompatible With Residential Uses

The City is urbanized[39] with a large residential population. The City's population in 2010 was 91,714 people,[40]in an area of approximately 19.2 miles.[41] Well stimulation operations and associated oil and gas operations are industrial operations that are incompatible with residential uses and quality of life. Well stimulation and resulting petroleum operations often generate noise, odor, visual effects, significant heavy truck traffic, and other impacts noted in these Findings that create safety and general welfare concerns in residential areas. For these reasons, the Planning Commission finds that all well stimulation operations should be directed away from populated areas, such as the City of Carson, to reduce adverse impacts on residents and the community.

XI. Well Stimulation Operations Are Not The Way To Grow A Health Economy

Operations utilizing well stimulation techniques do not provide the long-term local job opportunities that are necessary for a healthy, sustainable local economy. Rather, rapid development of oil resources can lead to "boom-and-bust" growth that is ultimately harmful to the local economy. It is debatable whether operations utilizing well stimulation techniques will create any new jobs in in the City in the long term—and they could degrade the assets and resources upon which a prosperous future for the City depends.

The City wishes to create modern job opportunities in clean energy, renewables, and green technology, which can be compatible with existing economic strengths and the quality of the community. A healthy, sustainable economy requires developing a diversity of energy resources, such as wind and solar. The City plans to meet California greenhouse gas reduction targets and stimulate local businesses and the economy by supporting new renewable energy development. Operations utilizing well stimulation techniques are non-renewable, carbon emitting, and extractive technologies that are incompatible with these goals and with preserving what makes the City a desirable place to live and work.

Based on these considerations and other impacts found in the administrative record, the Planning Commission finds Text Amendment No. 20-15 promotes and protects the goals of the City for the benefit of the public health, safety, welfare, and quality of life of City residents.

XI. Accidents and Risks

Accidents happen, and the nature of well stimulation and associated operations can cause unique and potentially significant impacts upon the community not associated with other uses as has been noted in the administrative record. The severity of the potential impacts can be high. Based on these considerations and other impacts found in the administrative record, the Planning Commission finds Text Amendment No. 20-15 promotes and protects against potential impacts

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[39] City of Carson 2004 General Plan, 2014-2021 Housing Element, p. 7.
[40] U.S. Census Bureau, 2015, Quick Facts –Carson California, http://quickfacts.census.gov/qfd/states/06/0611530.html.
[41] City of Carson 2004 General Plan, p. I-3.

and nuisances caused by well stimulation operations for the benefit of the public health, safety, welfare, and quality of life of City residents.

EXHIBIT "B" TO
PLANNING COMMISSION RESOLUTION

TEXT AMENDMENT NO. 20-15

AN ORDINANCE OF THE CITY COUNCIL OF THE CITY OF CARSON, CALIFORNIA, TO ADOPT TEXT AMENDMENT NO. 20-15, ADDING SECTIONS 9535, 9536 AND 9536.1 TO, AND AMENDING SECTION 9501.B OF, CHAPTER 5 OF ARTICLE IV OF THE CARSON MUNICIPAL CODE TO PROHIBIT WELL STIMULATION TECHNIQUES, INCLUDING HYDRAULIC FRACTURING ("FRACKING") AND ACIDIZING, IN CONJUNCTION WITH THE PRODUCTION OR EXTRACTION OF OIL, GAS OR OTHER HYDROCARBON SUBSTANCES IN THE CITY

Section 1. Article IX, Chapter 5, Section 9535 (Operational Prohibitions) of the Carson Municipal Code is hereby added to read, in its entirety, as follows:

9535 Operational Prohibitions

It shall be unlawful to perform or cause to be performed the following activities within the City for the purpose of the production or extraction of oil, gas or other hydrocarbon substance from any subsurface location within the City as follows:

A. No storage of acid on the oil and gas site shall occur in a volume in excess of 2,500 gallons.

B. No oil and gas operations shall utilize more than 25,000 gallons of water in a 24 hour period, or more than 100,000 gallons per week, unless during an emergency and as approved by the City Manager. This restriction does not apply to produced water, or waste water that originated from a petroleum reservoir, or uses authorized by this ordinance.

C. No more than 15 truck trips in a 24 hour period may be used for water deliveries, unless such water is used for a purpose other than extracting oil, gas, or any other hydrocarbon substance, unless for repairs or during an emergency and as approved by the City Manager.

Section 2. Article IX, Chapter 5, Section 9536 (Prohibited Uses) of the Carson Municipal Code is hereby added to read, in its entirety, as follows:

9536 Prohibited Uses

The operator shall not use or cause to be used any well stimulation treatment, including hydraulic fracturing or acidizing. Notwithstanding any other provision of this article, it shall be unlawful to use or cause to be used any land within the City for the purpose of conducting or enabling any well stimulation treatment, including hydraulic fracturing or acidizing, in conjunction with the production or extraction of oil, gas or other hydrocarbon substance from any subsurface location within the City, other than normal maintenance work that utilizes acidizing techniques. However, to the extent that any permittee demonstrates to the City Manager, that (1) well stimulation is necessary to recover the operator's reasonable investment backed expectation established through investment made before the effective date of this ordinance; and (2) that such well stimulation will not create a nuisance due to an adverse impact on persons or property within the City, then the City Manager may authorize such well stimulation pursuant to a permit issued pursuant to this ordinance. This Section shall remain in full force and effect unless otherwise required by any applicable State or Federal law, regulation or judicial determination.

Section 3. Article IX, Chapter 5, Section 9536.1 (Violation of Prohibited Uses) of the Carson Municipal Code is hereby added to read, in its entirety, as follows:

9536.1 Violations of Prohibited Uses

Any operator who violates Section 9536 of this ordinance shall be subject to the enforcement proceedings including those found in Sections 9512, 9513, and 9515 in addition to the following:

A. If an operator is found responsible for violation of Section 9536, the operator will be responsible for paying the City a fine of up to $100,000 per calendar day, as authorized by law, and depending on the severity of the violation, at the discretion of the City Manager.

B. In addition to fines, the City Manager may also require an immediate shutdown of all operations at a oil and gas site where violations of Section 9536 have been identified, as long as the shutdown would not otherwise threaten public health, safety or welfare.

Section 4. Article IX, Chapter 5, Section 9501 (Ordinance Applicability), Subsection B of the Carson Municipal Code is hereby amended to read, in its entirety, as follows:

9501 Ordinance Applicability

...

B. All portions of this ordinance are applicable to new or existing oil and gas sites and operators if they have or are required to obtain a CUP. For oil and gas sites lawfully existing at the time of adoption of this ordinance which do not have or are not required to obtain a new CUP, only the following sections are applicable:

9506 Well Drilling Permit

9507.4(B) Modifications and Extensions

9510 Facility Closure, Site Abandonment, and Site Restoration Procedures

9521(C) Setbacks

9522 Site Access and Operations

9523 Lighting

9526 Signage

9527 Steaming

9530 Safety Assurances and Emergency/Hazard Management (except 9530.4)

9531 Environmental Resource Management (except 9531.3 and 9531.5.1)

9532 Standards for Wells (except subsection G)

9535 Operational Prohibitions

9536 Prohibited Uses

Violations of these sections shall also be subject to enforcement mechanisms contained in this ordinance and Code.

To the extent the ordinance applies to existing oil and gas sites, it is not intended to apply in such manner as to interfere with any vested rights that have accrued to property owners.

Saied Naaseh

From: Lori Noflin <lnoflin@att.net>
Sent: Tuesday, November 24, 2015 3:16 PM
To: Ken Farfsing; Saied Naaseh
Subject: C:\Users\Lori\Desktop\November Email
Attachments: G3 LA Mantle He paper.pdf

I would like the attached G3 LA Mantle He report included as evidence for the Oil & Gas Code.

Sincerely,

Lori Noflin

EXHIBIT NO. 02

28

AGU PUBLICATIONS

Geochemistry, Geophysics, Geosystems

RESEARCH ARTICLE

10.1002/2015GC005951

Key Points:

- Fault-related helium (up to 66% mantle) occurs in oil wells of the LA basin
- Calculated flux up the fault is too low to cause a thermal anomaly
- A paleo-subduction zone maintains mantle connection for 30 Myr

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Citation:
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Mantle helium along the Newport-Inglewood fault zone, Los Angeles basin, California: A leaking paleo-subduction zone

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Abstract Mantle helium is a significant component of the helium gas from deep oil wells along the Newport-Inglewood fault zone (NIFZ) in the Los Angeles (LA) basin. Helium isotope ratios are as high as 5.3 Ra (Ra = $^3He/^4He$ ratio of air) indicating 66% mantle contribution (assuming R/Ra = 8 for mantle), and most values are higher than 1.0 Ra. Other samples from basin margin faults and from within the basin have much lower values (R/Ra < 1.0). The ^3He enrichment inversely correlates with CO_2, a potential magmatic carrier gas. The $\delta^{13}C$ of the CO_2 in the ^3He rich samples is between 0 and −10‰, suggesting a mantle influence. The strong mantle helium signal along the NIFZ is surprising considering that the fault is currently in a transpressional rather than extensional stress regime, lacks either recent magma emplacement or high geothermal gradients, and is modeled as truncated by a proposed major, potentially seismically active, décollement beneath the LA basin. Our results demonstrate that the NIFZ is a deep-seated fault directly or indirectly connected with the mantle. Based on a 1-D model, we calculate a maximum Darcy flow rate $q \sim 2.2$ cm/yr and a fault permeability $k \sim 6 \times 10^{-17}$ m^2 (60 microdarcys), but the flow rates are too low to create a geothermal anomaly. The mantle leakage may be a result of the NIFZ being a former Mesozoic subduction zone in spite of being located 70 km west of the current plate boundary at the San Andreas fault.

1. Introduction

For crustal fluids, ^3He enrichment relative to ^4He is the principal indicator of mantle degassing [*Lupton*, 1983] and the $^3He/^4He$ ratio is a measure of the proportion of mantle-derived ^3He mixed with continental derived ^4He. Mantle ratios as indicated by mid-ocean ridge basalt (MORB) values are generally 8 Ra (where R = $^3He/^4He$ and Ra = R_{air} = 1.4×10^{-6}) or higher [*Lupton*, 1983; *Lowenstern et al.*, 2014] and recent studies indicate old subcontinental lithospheric mantle values may be as low as 6 Ra [*Gautheron and Moreira*, 2002]. Continental crustal values are about 0.02 Ra due to abundance of ^4He from U-Th decay [*Andrews*, 1985]. Areas of continental crust with high mantle He values have been identified, but without evidence of recent magmatism [*Welhan et al.*, 1979; *Lupton*, 1983; *Oxburgh et al.*, 1986; *Kennedy and van Soest*, 2007]. These areas are characterized by Cenozoic crustal extension and shear that has been hypothesized as maintaining permeable pathways from the mantle to the crust. Tectonically active major strike-slip faults have been found with high (>13%) mantle component (i.e., R/Ra > 1.0) including the North Anatolian Fault in Turkey [*Güleç et al.*, 2002], the Karakoram fault in Tibet [*Klemperer et al.*, 2013], and the Niigata-Kobe tectonic zone in Japan [*Umeda et al.*, 2013], although most of the He values in these areas have less than 13% mantle component. In addition, most of these areas have elevated heat flow as indicated by hot springs at the surface.

The Newport-Inglewood fault zone (NIFZ) is one of the oldest and most westward faults that is part of the San Andreas fault system (SAFS) in California (Figure 1). The SAFS is a 1300 km strike-slip fault system, considered to be the most seismically active fault in the U.S. that developed in the early Miocene from a subduction zone, which was believed to be near or at the NIFZ [*Wallace*, 1990]. The San Andreas fault forms a single trace in Northern California, but in southern California multiple strands are considered part of the SAFS, including the NIFZ (Figure 1).

The San Andreas fault (SAF) proper, which is the current boundary between the Pacific and North American plates, has highly variable helium isotopic values from approximately 0.1 Ra to 6.5 times Ra $^3He/^4He$ values

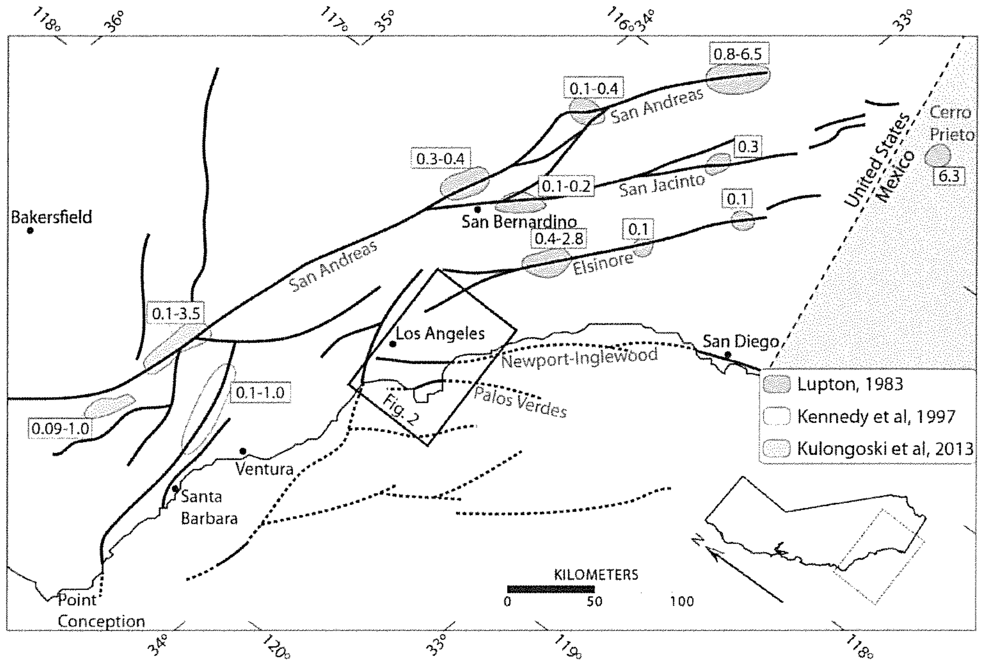

Figure 1. Fault map of southern California showing location of previous He isotopic studies and location of current study in the LA basin (Figure 2). Numbers are the range of R/Ra values from studies of *Lupton* [1983], *Kennedy et al.* [1997], and *Kulongoski et al.* [2013].

[*Lupton*, 1983; *Kennedy et al.*, 1997; *Kulongoski et al.*, 2013; *Wiersberg and Erzinger*, 2007], indicating varying degrees of mantle contribution along the length of the fault (Figure 1). Some of the highest values are found in the Salton Sea area (Figure 1), which is the southernmost part of the SAF, adjacent to the Gulf of California spreading center. Several geothermal or CO_2 wells in the area have R/Ra values exceeding 6.0 [see *Welhan et al.*, 1979; *Lupton*, 1983, Figure 10]. Areas north of the Salton Sea have been shown to have values not exceeding 0.44 Ra [*Lupton*, 1983]. More recently, a few values as high as R/Ra = 3.47 have been recorded on the SAF in the Big Bend area from groundwater well samples [*Kulongoski et al.*, 2013]. Further north, of the Big Bend area, the highest values are not on the main strike-slip segment but from hot springs on a fault strand in serpentinite, some 35 km to the east of the SAF [*Kennedy et al.*, 1997]. A relatively high 2.8 Ra is reported from Murrieta Hot Springs, approximately 75 km west of Newport Beach, from a sample close to the Elsinore fault and another nearby sample from a thermal spring was R/Ra = 0.72 [*Lupton*, 1983]. Clearly there is a lot of variability in mantle-crust communication along the SAF. There are no previous studies of He isotopes within the deep LA basin.

The LA basin encompasses 3200 km^2 with over 17 million people (Figure 1). The area is seismically active [*Hauksson*, 1987], with the most recent major event being the 1994 Northridge earthquake (M_W = 6.7). There is considerable concern about the earthquake potential of blind thrusts in the basin [*Davis et al.*, 1989; *Shaw and Suppe*, 1996] and a current USGS and California Division of Mines and Geology mapping initiative will improve our understanding of the seismic risk of the faults in the LA basin. Helium isotopic studies may be important to evaluate the role of mantle versus metamorphic fluids to fault weakening and seismicity [*Kennedy et al.*, 1997; *Güleç et al.*, 2002; *Umeda and Ninomiya*, 2009; *Umeda et al.*, 2013]. Evidence that the NIFZ has been a major pathway for fluid movement in the upper crust is the abundance and large vertical distribution of hydrocarbons along the NIFZ, largely generated and trapped within the last 5–10 million years [*Wright*, 1991; *Hunt*, 1995; *Jung et al.*, 2015]. As shown in this paper, He isotopes suggest that the lower crust is also a pathway from the mantle along the same fault.

The NIFZ has been a major structural feature of the LA basin since at least early Miocene time [*Wright*, 1991]. The fault zone extends southeast for approximately 65 km from the Santa Monica Mountains to Newport Beach, where it continues offshore [*Harding*, 1973, Figure 1]. At the surface, the fault is series of left-stepping fault segments, characterized by oblique right slip and associated anticlinal hills. The NIFZ has a relatively small slip rate (0.5 cm/yr) compared to faults directly eastward (Elsinore fault = 0.5–1.0 cm/yr; San Jacinto fault = 1.0–2.0 cm/yr; San Andreas fault = 2.0–3.0 cm/yr. See fault locations in Figure 1) [*Wallace*, 1990]. In spite of the low slip rate, five earthquakes of magnitude 4.9 or greater have occurred on the fault since 1920, the largest being the $M_L = 6.4$ Long Beach earthquake of 1933 [*Hauksson*, 1987, 1990]. Most earthquakes occur from 6 to 11 km depth, within the 28–30 km thick crust. Currently, the regional principal stress in the basin is north-south [*Heidbach et al.*, 2008] indicating the NIFZ is undergoing transpressional deformation.

The NIFZ zone separates blueschist basement on the southwest from meta-igneous basement rocks to the northeast and largely based on this, it has been proposed as a compressed Mesozoic subduction zone between Pacific and North American plates [*Hill*, 1971; *Wright*, 1991]. Little is known about the pre-SAFS history (pre-Miocene) of the LA basin, but it is clear that the NIFZ was in the vicinity of this subduction zone about 30 m.y.b.p. [see e.g., *Wallace*, 1990]. Miocene transpression and rotation of blocks has resulted in thinning of the crust [*Nicholson et al.*, 1994], and deposition of more than 8 km of Miocene and younger sediment in the central part of the LA basin [*Wright*, 1991]. Mid-Miocene volcanism occurs as a result of crustal thinning along the basin bounding faults, including some areas along the NIFZ. Our helium results suggest the NIFZ has retained a strong connection into the mantle, in spite of complex deformation and an 80 km eastward shift in the Pacific plate boundary to the present SAF [*Wright*, 1991].

In this study, we report numerous high $^3He/^4He$ ratios (R/Ra = 1.0–5.3) along the NIFZ, which is considered the western most part of the SAFS. The NIFZ is more than 80 km from the main trace of the San Andreas fault, more than 140 km from the Big Bend area, and between 90 and 230 km from the high He anomalies reported by *Welhan et al.* [1979] and *Lupton* [1983] in the Salton Sea area (Figure 1). After a discussion of the isotope data, we develop a 1-D mathematical model for helium mass transport to calculate fluid flow rates in the fault zone using the R/Ra data, explore the coupled effects of fluid flow on heat transport in the LA basin, and calculate fault permeability.

2. Samples

Helium samples were collected from active producing oil wells in stainless steel 500–1000 cc vessels (Table 1). The gas gauge pressure at the casing gas ports of these wells was 0.034–1.38 MPa (5–200 psi) greater than STP. The gases are mostly methane with some $\geq C_2$ gases and minor CO_2 that has degassed from the hydrocarbons and formation water at the perforation interval. At the NOAA laboratory in Newport, Oregon, the gas samples were subsampled into glass ampoules, and then subsequently analyzed for helium isotopes, and He and Ne concentrations on a 21 cm dual-collector mass spectrometer specially designed for helium isotope measurements. Splits of the samples archived in glass ampoules were analyzed for $\delta^{13}C$ and CO_2 concentration by Marvin Lilley at ETH in Zurich, Switzerland. We have also sampled the produced fluids associated with a number of these gases and these will be described in a later paper. The producing intervals are the deepest available production in each area (generally greater than 2 km) and are mainly from mid to upper Miocene sandstone, siltstone, and shale. These deep production zones have not been subjected to the fluid injection common to the shallow producers in the basin. Most helium isotopic studies sample surface fluids from springs or groundwater wells [e.g., *Oxburgh et al.*, 1986; *Güleç et al.*, 2002; *Du et al.*, 2006; *Kennedy and van Soest*, 2007; *Umeda and Ninomiya*, 2009; *Kulongoski et al.*, 2013]. The advantage of deep well sampling is the lack of surface air contamination, as the flux is principally vertical as opposed to potential lateral flow from groundwater movement, and there is a subsurface geologic context for the fluids. The disadvantage is limited numbers of costly (greater than $1M USD) deep wells for sampling, gaining access to regulated industrial sites, and shipping pressurized flammable gas for analysis.

3. Results

The $^3He/^4He$ ratios in Table 2 are given both as R/Ra, which is the empirical or measured value, and as Rc/Ra, which is the ratio corrected for atmospheric helium contamination. The correction is based on the He/Ne or He/Ar ratios in the samples, assuming that the Ne and Ar are atmospheric in origin. The He/Ne ratios and He/Ar ratios indicate that the samples have minimal atmospheric contamination, which is

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Table 1. Gas Samples From Miocene Sediments of the LA Basin[a]

Sample	Oil Field	Well ID	Latitude	Longitude	Sample Date	Mean Sample Depth (km)	Perforation Interval (km)	Temperature (°C)
1	Sawtelle (SW)	OF15-RD1	34.0586	−118.4567	1 Aug 2012	3.53	0.27	122
2	Beverly Hills (BH)	WP11RD2	34.0556	−118.3905	24 Apr 2014	2.51	0.56	84
3	Sansinena (S)	12A-5	33.9570	−117.9680	12 Feb 2014	1.15	0.20	44–49
4	Sansinena (S)	4H-53	33.9627	−117.9650	12 Feb 2014	1.01	0.27	51–61
5	Santa Fe Springs (SF)	C	33.9429	−118.0672	1 Jan 2013	1.93	2.03	47–100
6	Inglewood (I)	VIC-1–935	34.0057	−118.3765	1 Aug 2012	2.80	0.06	93–107
7	Inglewood (I)	VIC-1–845	34.0057	−118.3765	1 Aug 2012	2.58	0.14	93–107
8	Dominguez (D)	Dominguez #1	33.8635	−118.2432	12 Feb 2014	2.45	0.82	102–129
9	Dominguez (D)	Dominguez #2	33.8635	−118.2431	12 Feb 2014	3.73	0.24	151
10	Long Beach Airport (LBA)	LBA-1	33.8185	−118.1665	11 Feb 2014	2.75	0.45	120
11	Long Beach Airport (LBA)	C-37	33.8100	−118.1709	18 Jun 2014	2.56	0.36	116
12	Long Beach (LB)	B-14	33.8113	−118.1802	1 Aug 2012	2.37	0.34	102–109
13	Long Beach (LB)	B-14	33.8113	−118.1802	11 Feb 2014	2.37	0.34	102–109
14	Long Beach (LB)	23–25	33.8021	−118.1650	24 Apr 2014	3.57	0.31	153
15	Long Beach (LB)	D-81	33.8057	−118.1703	18 Jun 2014	3.56	0.30	154
16	Long Beach (LB)	ALA-49A	33.7993	−118.1568	11 Feb 2014	2.31	0.60	80–85
17	Long Beach (LB)	A-59	33.8126	−118.1825	18 Jun 2014	3.68	1.03	166
18	Wilmington (W)	C-348	33.7393	−118.1387	22 Apr 2014	3.06	0.06	167
19	Belmont (BL)	C-236	33.7395	−118.1383	22 Apr 2014	0.93	0.06	89
20	Huntington Beach (HB)	N. Bolsa	33.7027	−118.0238	12 Feb 2014	1.37	0.30	51–86
21	Huntington Beach (HB)	HB A001	33.6627	−118.0448	12 Feb 2014	0.33	0.09	31
22	Beta Field (B)	B-20	33.5957	−118.1416	30 Jan 2014	0.76	0.30	42
23	Newport Beach (NB)	C	33.6260	−117.9463	24 Apr 2014	1.07	0.50	43

[a]Samples arranged approximately north to south. C = commingled. Figure 2 shows sample locations.

Table 2. Isotopic and CO_2 Content of Gas Samples From Miocene Sediments of the LA Basin[a]

Sample	Distance to NIFZ (km)	R/Ra[b]	Rc/Ra[c]	ppmv He	He/Ne/air	He/^{36}Ar/air	CO_2[d] (mol. %)	d^{13}C CO_2[e] (±0.17)	Lab
1	6	0.324	0.322	8.5		256	2.38		LLBL
2	1	0.721	0.720	5.63	1122		2.01–0.85		NOAA
3	26.2	0.154	0.117	0.829	23.67		*2.47*	17.63	NOAA
4	26.8	0.144	0.135	0.531	94.4		*8.8*	16.13	NOAA
5	17.2	0.301	0.177	2.25		7.2	6.84–0.93		USGS
6	0	1.875	1.88	7.20		81	ND		LLBL
7	0.5	2.273	2.28	5.71		94	ND		LLBL
8	0	3.58	3.58	5.58	1344		*0.95*	−0.22	NOAA
9	0	5.30	5.31	13.1	1208		*1.21*	−10.64	NOAA
10	1	4.05	4.06	1.6	632		*0.26*	−8.21	NOAA
11	0	3.06	3.18	5.63	17.73		2.15		NOAA
12	0	3.065	3.07	6.96		80	ND		LLBL
13	0	3.62	3.62	9.62	1403		*0.57*	−10.87	NOAA
14	0	0.537	0.537	17.9	1556		ND		NOAA
15	0	0.553	0.552	7.33	596		9.45		NOAA
16	0.2	1.09	1.09	3.96	1028		*1.74*	1.96	NOAA
17	0	1.48	1.48	19.1	2729		8.02		NOAA
18	4	0.105	0.105	17.7	3024		ND		NOAA
19	3.6	0.561	0.549	0.380	37.8		ND		NOAA
20	1.8	2.81	2.81	7.41	934		*5.20*	−1.34	NOAA
21	4	0.527	0.527	2.67	665		*1.78*	16.00	NOAA
22	12.2	0.897	0.897	1.41	444		*2.53*	10.54	NOAA
23	0	0.111	0.104	4.33	134.4		2.41–2.48		NOAA

[a]See Table 1 and Figure 2 for sample locations. Newport-Inglewood fault zone (NIFZ) shown in Figure 2.
[b]Helium isotope ratio, R = $^{3}He/^{4}He$ and Ra = Rair = 1.4×10^{-6}.
[c]Helium isotope ratio corrected for atmospheric helium addition using the formula: Rc/Ra = ((R/Ra) X − 1)/(X − 1) where X = (He/Ne)/(He/Ne)air or X = (He/^{36}Ar)/(He/^{36}Ar)air.
[d]Values in italics determined on helium sample by Marvin Lilley, U of Washington. Other values are from produced gas analysis reports.
[e]Determined by Marvin Lilley, U of Washington.

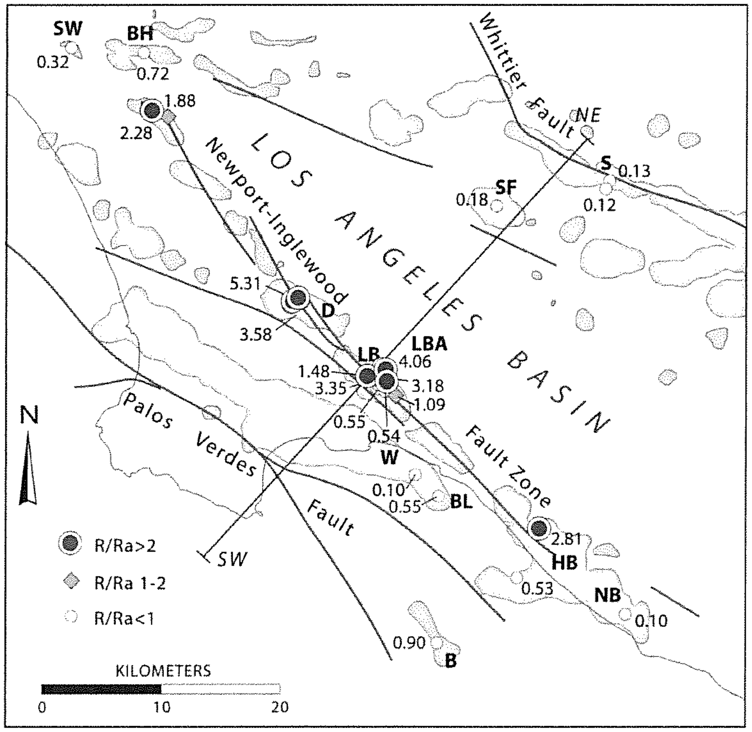

Figure 2. Map of Los Angeles basin and the Newport-Inglewood fault zone (NIFZ) showing high Rc/Ra values of most samples along the NIFZ. Numbers are Rc/Ra helium isotope values of sampled wells (purple areas are oil fields). See Figure 1 for map location. Oil fields abbreviations are B (Beta), BH (Beverly Hills), BL (Belmont), D (Dominguez), HB (Huntington Beach), I (Inglewood), LB (Long Beach), LBA (Long Beach Airport), NB (Newport Beach), S (Sansinena), SF (Santa Fe Springs), SW (Sawtelle), and W (Wilmington). Wells identification numbers and supporting data are given in Table 1. Cross-section line across the NIFZ from the Whittier fault (northeast NE) to the Palos Verdes fault (southwest SW) is shown in Figure 7.

consistent with little or no injection of surface water in these deep wells. Only two samples, Santa Fe Springs and Sansinena Well 12-5, required significant air correction (Table 2).

High Rc/Ra values along the NIFZ compared with other areas in the basin are obvious in Figure 2, with values exceeding ~3 Ra being common (Table 2). The affinity of the NIFZ helium with mantle helium is clear (Figures 2 and 3).

The highest value (5.3 Ra) indicates up to 66% mantle contribution to the He gas (assuming upper mantle helium averages 8 Ra). The Rc/Ra values appear to fit a Gaussian spatial trend along the NIFZ (Figure 3a), suggesting, perhaps, the possibility of a discrete source at the base of the crust. More samples would be required to confirm this. A number of shallow samples tend to have low R/Ra values whereas deep samples tend to have higher R/Ra values, which we interpret as an overprint of in situ produced crustal ^{4}He added to the shallower samples. However, deep samples (e.g., compare Sawtelle, Wilmington, Dominguez, and Long Beach field samples of Table 1) have considerable variability in R/Ra values, which indicate that there are real differences in fractions of mantle verses crustal helium within the deep basin.

Although the casing gas is principally methane with some heavier hydrocarbons, the CO_2 content of the sampled gas has a wide range of values (see Table 2; 0.5 to more than 9 mol % CO_2). CO_2 is believed to be a carrier gas for mantle helium [*Marty and Jambon*, 1987], and the origin of the CO_2 will be discussed in a later section of the paper.

The helium content of the ^{3}He-enriched samples is no greater than that in the ^{3}He poor samples, indicating that the strong mantle signature is not correlated with helium abundance (Table 2). We interpret the variation in helium content of the samples to largely be a result of variation in ^{4}He production in the crust due to U and Th heterogeneity. The helium content of gas from Well B-14 (Tables 1 and 2), which was sampled

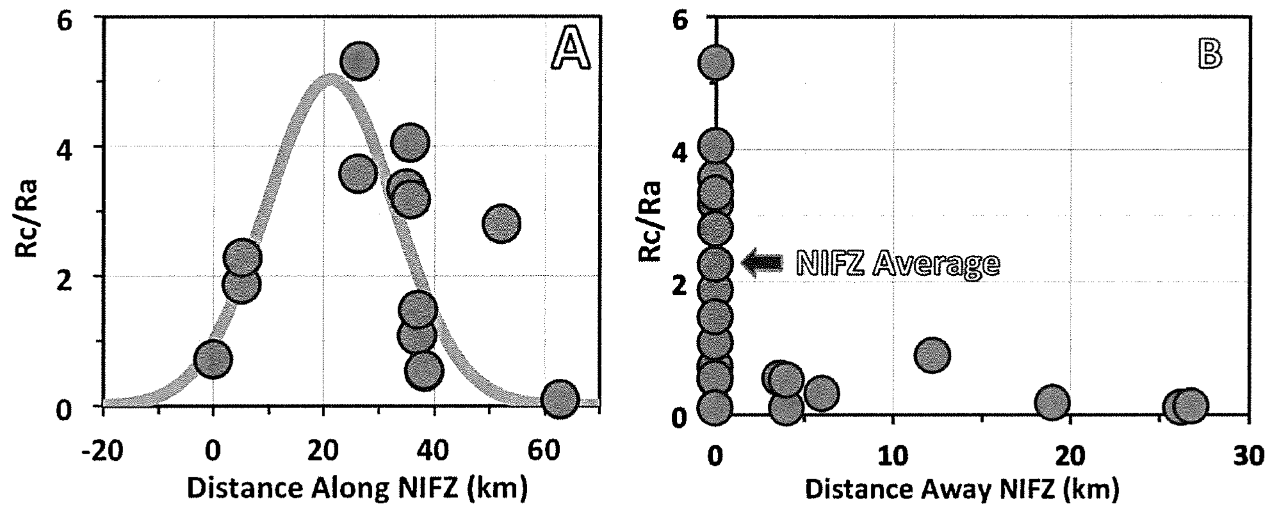

Figure 3. Rc/Ra values of this LA basin study (orange dots) relative to distance along (Figure 3a), and away from the NIFZ (Figure 3b). The dashed curve in Figure 3a shows a best fit regression of the data to a normal probability density function with spatial mean 21.2 km and standard deviation 11.8 km. The average of all values on the NIFZ is Rc/Ra = 2.2. The San Andreas fault values along the Mission Creek segment [*Lupton*, 1983] and the Big Bend segment [*Kulongoski et al.*, 2013] are generally lower than the NIFZ values from our study and average ~1.0 (see Figure 1). In Figure 3a, the Beverly Hills oil field position (see Figure 2) provides the arbitrary reference point for x = 0 km for distance along the NIFZ.

twice (18 month interval), dropped approximately 40% indicating significant variability in the amount of helium over time.

4. Data Analysis

4.1. Unexpected Helium Anomaly

The conspicuous mantle He enrichment along the NIFZ is unexpected compared to most other areas of continental crust with a mantle helium anomaly. First, the fault is in a transpressional rather than an extensional stress regime, thus faults would be expected to be overall sealing [*Oxburgh et al.*, 1986; *O'Nions and Oxburgh*, 1988; *Kennedy and van Soest*, 2007]. A number of recent studies, however, have shown that strike-slip faults or faults within the vicinity of active strike-slip faults may have variable but local high mantle helium anomalies in California [*Kennedy at al.*, 1997; *Kulongoski et al.*, 2013], in Tibet [*Klemperer et al.*, 2013], in Turkey [*Güleç et al.*, 2002], and in Japan [*Umeda and Ninomiya*, 2009]. In the case of Japan, reduced mantle helium leakage has been noted along thrust versus strike-slip components of faults [*Umeda et al.*, 2013]. Presumably discontinuous dilation segments along these faults could provide localized fluid pathways to the lower crust. We find high R/Ra values (R/Ra > 1.0–5.3) in most of the samples we have collected along the NIFZ, rather than in localized isolated areas along the fault or away from the main fault zone, suggesting the fault is a major conduit to the lower crust.

Second, there is no evidence for recent magmatism in the LA basin. Early-mid Miocene igneous activity from crustal extension is common along the NIFZ [*Wright*, 1991], but other faults in the basin, without strong mantle signatures, had similar igneous activity (e.g., Sansinena field samples of Table 1, along the Whittier fault [see *Bjorklund*, 2003]). Thus, the mantle signature does not appear to be related to the presence of Miocene igneous rocks or their deformation in the LA basin. In addition, mantle helium is believed to be largely degassed during igneous emplacement and cooling at time scales less than 1–10 million years [*Kamensky et al.*, 1990]. For example, in the Sacramento gas field, high R/Ra values are associated with Pleistocene volcanism [*Poreda et al.*, 1986; *Jenden et al.*, 1988]. However, in the LA basin, the high Rc values should not be due to *early-mid Miocene* igneous activity.

Third, most mantle helium anomalies are associated with locally elevated thermal gradients such as hot springs, geothermal anomalies, with or without recent volcanism [see *Polyak and Tolstikhin*, 1985; *Oxburgh and O'Nions*, 1987; *Torgersen*, 1993; *Umeda et al.*, 2007]. However, exceptions of strong mantle helium anomalies without correlation with surface spring temperature have been observed in some areas including the Sichuan earthquake zone of southwestern China [*Du et al.*, 2006], along faults of the Itoigawa-Shizuoka

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tectonic line in Japan [*Umeda et al.*, 2013], and along the North Anatolian Fault Zone of Turkey [e.g., *Güleç et al.*, 2002]. In the Big Bend area of the San Andreas fault, the highest value reported (R/Ra = 3.5) is apparently not associated with a hot spring [*Kulongoski et al.*, 2013]. The high R/Ra helium values (without the associated heat) could be explained, in most cases, by the unknown circulation path of shallow groundwater. In the case of our field study, the lack of a strong thermal signature is more difficult to explain, as we are sampling at depths where complex meteoric fluid circulation paths cannot be invoked. The fact is that, worldwide, most strong mantle helium anomalies are associated with surface hot springs.

The LA basin has a relatively average crustal geothermal gradient of about 32°C/km [*Price et al.*, 1999]. The central syncline, with the thickest sedimentary section, is typically about 28°C/km, whereas the Wilmington area, with relatively thin sedimentary crust, has a relatively high gradient of 55°C/km. The thermal gradient along the NIFZ is about 33°C/km, only slightly elevated compared to other areas in the basin [*Price et al.*, 1999]. This is a surprisingly low value considering the strength of the mantle helium signature at numerous localities (Figure 2).

From the previous considerations, there is no reason to suspect that the NIFZ would be a pathway for substantial mantle degassing along its length. The NIFZ R/Ra values are higher than observed along much of the SAF (Figure 3, average NIFZ R/Ra = 2.2; average SAF R/Ra = 1.0), the current boundary between the Pacific and North American plates. R/Ra values along the much of the SAF are between 0.4 and 2.0 [*Lupton*, 1983; *Kennedy et al.*, 1997; *Wiersberg and Erzinger*, 2007]. The highest SAF values are in the crustal shortened Big Bend segment of the fault, an area of transpression, where R/Ra values are between 1.0 and 3.5 (Figure 1) [*Kulongoski et al.*, 2013], similar to values we observe along the NIFZ, which is approximately 140 km to the southeast of the Big Bend area. It is interesting to note that in the vicinity of the Big Bend segment of the SAF, the fault dip at deep crustal levels is vertical [*Namson and Davis*, 1988; *Fuis et al.*, 2012]. To the north, however, the fault is west dipping whereas south of the Big Bend segment the fault is east dipping. A vertical dip plane in the Big Bend area, therefore, may allow for a more permeable pathway from the mantle, and explain the high R/Ra values reported there. Most depictions of the NIFZ also show it to be a nearly vertical fault at depth [*Wright*, 1991; *Romanyuk et al.*, 2007], perhaps enhancing its ability to transfer mantle components.

Helium isotopic studies of large fault zones including the SAFS, the North Anatolia Fault Zone in Turkey, and the Karakoram fault in Turkey show significant helium anomalies occur only within a distance of 1.0–1.5 times the crustal thickness of the area [see *Klemperer et al.*, 2013], indicating crustal-scale movement of fluid around these fault zones. In the case of the NIFZ anomaly, the fault is ~2.5 crustal thicknesses distance from the main SAF, yet it shows a large helium anomaly in multiple samples. The maximum value mantle anomaly (R/Ra = 5.3) is larger than any value measured within the current SAFS, except for the Salton Sea area where the San Andreas fault transitions into the Gulf of California (Figure 1). We think that the NIFZ anomaly is a residual of mantle communication from a paleo-subduction zone unrelated to the current SAF. If true, a paleo pathway still exists some 30 million years later, in spite of the eastward shift of the plate boundary and long intervening history of deformation.

4.2. Cause of Local Helium Isotopic Variability

Spatial variability of He anomalies has been previously noted, for example along the SAF [*Kennedy et al.*, 1997; *Kulongoski et al.*, 2013]. Helium variability is attributed to "release of radiogenic helium during episodic faulting and fracturing on short time scales" [*Torgersen and O'Donnell*, 1991]. Variability is also attributed to the differences in basement rock, groundwater flow paths, or residence time of mantle helium during transport through the crust [see *Kulongoski et al.*, 2013, p. 96]. In the case of the NIFZ, variability of isotopic ratios is in part due to variation in contribution of crustal ^{4}He. All of the shallow samples have low R/Ra values relative to the deep samples (Table 2). But some of the deep samples (e.g., Sawtelle and Sansinena fields) also have low R/Ra values indicating the variation in R/Ra values cannot be explained simply by sample depth. In addition, considerable variation in R/Ra may be due to lithological variation. For example, in the Long Beach field, Wells SHP 23–25 and D-81 have relatively low Rc/Ra values (0.54 and 0.55 Ra) compared to adjacent wells. These two wells are perforated over 0.3 km in U-Th enriched shale with up to 25 ppm U and 10 ppm Th, based on spectral gamma ray logs. Similarly, the perforations in Well ALA 49A are just above this zone and may explain the somewhat lower value of 1.0 Ra for this sample relative to most others along the NIFZ trend. U-Th values for the Miocene section in the vicinity of the NIFZ, based on modern spectral gamma ray logs, are typically 2–6 ppm. We interpret the relatively low value of $^3He/^4He$ (R/Ra = 0.54–0.55) in these wells to the production of abundant ^4He from the U-Th rich shale interval. The U-Th rich unit is either below the perforation interval or absent in other wells of our study.

The Newport Beach offshore sample is relatively shallow in the sedimentary section (approximately 1 km depth). Thus, for this sample we cannot determine if the relatively low R/Ra value is due to the lack of mantle communication (i.e., low permeability in the fault zone) or abundance of ^4He production within the sedimentary section between the mantle and the sample point.

Spatial variability of helium isotopic ratios exists in the Long Beach and adjacent Long Beach Airport fields where we have the greatest sample density. Helium isotopic ratios vary from about 1.0 to 4.0 Ra (excluding Well SHP 23–25 discussed above) over a distance of less than a few kilometers. Temporal variation of the helium anomalies, from duplicate samples of Well B-14, in the Long Beach field over an 18 month time interval, indicate similar values between the early sample (R/Ra = 3.06) and the later sample (R/Ra = 3.62), although the helium content drops by about 40% (Tables 1 and 2).

4.3. Fluids and Gases Associated With the Helium Isotopic Anomaly

Fluids associated with these gases are dilute Na-Cl fluids (TDS = 18,000–28,000 mg/L) that we interpret as seawater modified by water-rock reactions including clay diagenesis. As is typical of many waters associated with Miocene kerogen in southern California, the deep formation waters also have abundant organic acids [see e.g., *Fisher and Boles*, 1990]. These fluids may also contain unidentified mantle components, including CO_2 (see below). Oxygen isotopic ratios range from $\delta^{18}O_{SMOW} = -0.2$ to $+2.0‰$ and deuterium δD from -0.8 to $-15.6‰$. All water samples plot on the positive side of the meteoric water line and tend to form trends orthogonal to the line [*Boles et al.*, 2011]. Although our database is biased with fluids from the NIFZ, the formation fluids associated with mantle-enriched helium are similar to deep basin formation fluids where there is less mantle enrichment (e.g., Sawtelle field). The LA basin fluids are similar to the deep fluids in the San Joaquin basin but are less evolved from diagenetic reactions due to lower temperature [*Fisher and Boles*, 1990; *Boles et al.*, 2011].

4.4. Evidence for Mantle CO_2

CO_2 is thought to be the carrier gas for mantle helium into the crust based on relatively constant $CO_2/^3He$ values of about 2×10^9 to 10^{10} as measured from areas with mantle dominated fluids [*Marty and Jambon*, 1987; *Marty and Zimmermann*, 1999]. Fluids from continental crust that are corrected for nonmantle CO_2 sources and that have a high ^3He content, also have $CO_2/^3He$ values of about 10^{10} [*Crossey et al.*, 2014].

The CO_2 content of the wellhead gases for which we could obtain analyses vary from 0.2 to 9.5 mol. % (Table 2). These gases are largely methane generated during the maturation of the kerogen in the basin. Formation water, which is largely marine water altered by interaction with the rock, is also produced from most wells. The CO_2 content of casing gas in some wells varies over time and thus the values we report here should be interpreted with caution (see Table 2). Thus, the CO_2 concentrations determined from our sample splits are more comparable to the He values than CO_2 concentrations from company gas reports. The calculated ratios of $CO_2/^3He$ range from about 1.2×10^8 to 8.8×10^{11} and the gases with the most mantle-like values (e.g., Rc/Ra > 3.0) generally have $CO_2/^3He$ ratios less than 10^9, lower than predicted for a pure mantle helium sources. The $^3He/^4He$ ratio inversely correlates with $CO_2/^3He$ (Figure 4). *Burnard et al.* [2012] also report an inverse correlation between $^3He/^4He$ and $C/^3He$, but the carbon in this case is mostly methane. High mantle helium values are reported to positively correlate with CO_2 content of groundwaters in the Big Bend area [*Kulongoski et al.*, 2013], although potential underlying carbonate sources and sinks are not reported for this area. In the vicinity of the NIFZ, potential sources of CO_2 are thermogenic from kerogen (associated with methane production), breakdown of oxygen-bearing organic acids (e.g., methanogenesis), acidization of carbonate (not applicable to our deep sampled wells), and mantle CO_2. A potential sink for the CO_2 in this system is small amounts of distinctive Fe-rich calcite and dolomite cement found in the more deeply buried sandstones. These cements might account for the lower than expected CO_2 values associated with the mantle He. $CO_2/^3He$ ratios greater than 10^9 may result from an increasing thermogenic or methanogenic CO_2 relative to a background level of mantle He. In the following section we use $\delta^{13}C$ of the CO_2 to distinguish potential sources.

MORB CO_2 is reported as having a $\delta^{13}C_{PDB} = -6.5 \pm 2.5$ per mil [*Sano and Marty*, 1995], which is considerably more positive than thermogenic or bacterial CO_2 of $\delta^{13}C_{PDB} < -25$ to -30 [*Hunt*, 1995], but more

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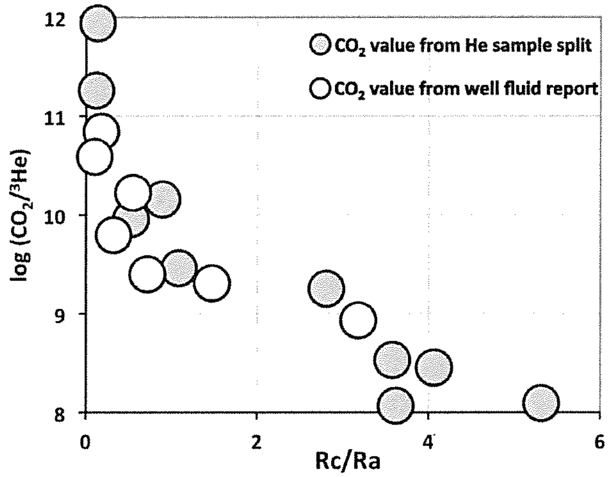

Figure 4. $CO_2/^3He$ ratio of gas (ppm) plotted against the Rc/Ra value of the gas. $CO_2/^3He$ ratios of 10^9 to 10^{10} are believed to represent mantle ratios for the carrier gas of CO_2 relative to the mantle-derived ^3He in other studies (see text). CO_2 concentration measured from split of ^3He sample (green dots). CO_2 concentration from well gas analyses reports (yellow spot). See Table 2 for listing of the data.

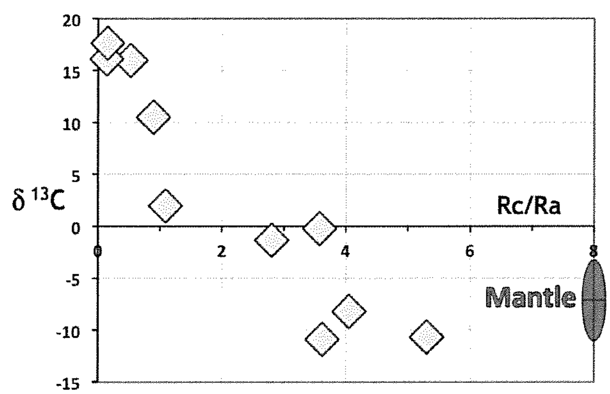

Figure 5. $\delta^{13}C‰$ of CO_2 in LA basin gases compared with Rc/Ra of the helium. Note that the low Rc/Ra values are associated with very positive $\delta^{13}C$. Mantle Rc/Ra = 8 [*Lupton*, 1983], mantle $\delta^{13}C = 6.5 \pm 2.5‰$ [*Sano and Marty*, 1995]. Data are listed in Table 2.

negative than CO_2 from methanogenic processes [*Carothers and Kharaka*, 1980]. The $\delta^{13}C_{PDB}$ of carbonate cements in Tertiary sandstones and fault cements of California, which can range from +10 to −40, reflect this wide range of CO_2 sources [see *Boles*, 1998; *Boles et al.*, 2004]. As shown below, the $\delta^{13}C$ of CO_2 in the gases of this study indicates a mixture of CO_2 sources.

Figure 5 shows that the Rc/Ra values are inversely correlated with the $\delta^{13}C$ of the CO_2. We interpret this relation as due to mixing between at least two CO_2 sources. At high Rc/Ra values, the CO_2 could be in part mantle derived as the $\delta^{13}C$ values are close to mantle values of $\delta^{13}C = -6.5 \pm 2.5‰$. These samples also have the lowest CO_2 content and occur in the deepest reservoirs (Tables 1 and 2). None of the samples with high Rc/Ra values appear to have an end-member thermogenic CO_2 source. In contrast, the very positive $\delta^{13}C$ values are interpreted to be due to methanogenesis, where the bacterial generation of isotopically light methane leaves a heavy carbon residue. These samples come from relatively shallow reservoirs (<80°C) and have very high CO_2 contents (Tables 1 and 2). *Carothers and Kharaka* [1980] have shown very heavy dissolved carbon ($\delta^{13}C$ up to +28‰) in southern California reservoirs at intermediate depths (<80°C) that they attribute to methanogenesis of organic acids. Another source of heavy carbon would be the oxygen-bearing functional groups associated with these acids [*Franks et al.*, 2001]. In summary the $\delta^{13}C$ values of the CO_2 indicates mantle CO_2 in the deep LA basin, which is mixed with methanogenic CO_2 in the shallower reservoirs. In the following section, we assume vertical flow and calculate the helium flux along this conduit, and quantify the effect of fluid flow on the thermal structure of the fault zone. We also compute an effective permeability for the NIFZ, based on the helium data signal and estimated fluid pressure gradients for the crust.

5. Helium Transport Model

5.1. Theory

We wish to mathematically model the concentrations of the helium isotopes [^{3}He] and [^{4}He] along a fluid flow path, as they are transported in the fluid phase, undergo exchange with the country rock, and advected up a fault zone due to a hydraulic gradient. The length of the flow path L is assumed to be approximated by the thickness of the Earth's crust H_c, which is estimated to be about 27–30 km in southern California [*Romanyuk et al.*, 2007]. The isotope ^{3}He is assumed to derived from magmatic fluids in the Earth's

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mantle, which may leak up along deep crustal fault zones with sufficient permeability [*Kennedy et al.*, 1997]. The isotope ^4He is mostly produced by radioactive decay reactions within various crustal minerals. The goal of this exercise is to mathematically model the helium isotope ratio in the fluid R_f, which will decrease (exponentially) as a mantle-derived fluid moves vertically up the fault zone and becomes increasingly "diluted" by ^4He generated by radiogenic reactions in the crust. Standard porous-flow theory for chemical solute mass balance with isotopic exchange and radiogenic generation is covered in numerous textbooks and journal articles, too many to review here. For the helium isotope pair, D. J. DePaolo, (personal communication, 2015) considers the 1-D mass balance, equating the time rate of change of helium mass accumulation/depletion (per unit volume of porous medium) to the advection of the helium isotopes (at a constant pore fluid velocity v) and reactive porous exchange and production. He writes this balance as

$$\frac{\partial C_{f3}}{\partial t}=-v\frac{\partial C_{f3}}{\partial z}+M[RC_{s3}+P_3], \tag{1a}$$

$$\frac{\partial C_{f4}}{\partial t}=-v\frac{\partial C_{f4}}{\partial z}+M[RC_{s4}+P_4], \tag{1b}$$

where t is time, z is distance, C_f is the concentration of the helium isotope species (^3He or ^4He) in the fluid at a given time and position, C_s is the concentration of the isotopes in the reactive solid phase, v is the average linear fluid velocity [*Freeze and Cherry*, 1979], M is the mass ratio of solid/fluid, R is the solid phase dissolution rate, and P is the rate of production or generation. It is common practice to combine (1a) and (1b) by assuming $P_3/P_4 \sim (C_{s3}/C_{s4})$ and define a new model parameter $P'_{He}=[RC_{s4}+P_4]$. The total helium production term J_{tot} (reactive flux of ^4He) can also be expressed as: $J_{tot}=M(P'_{He})=\frac{(1-\phi)\rho_s}{\phi\rho_f}P'_{He}$, where ϕ is fault porosity, ρ_s is density of crustal rocks (solid phase), and ρ_f is density of the fluid phase. *Johnson and DePaolo* [1994] provide a full derivation of this theory and mathematics and present an analytical solution for the special case of steady fluid flow, when $v \sim$ constant. In Appendix A we show that their analytical solution to (1) can be rewritten as

$$v=H_c\ \frac{\rho_s}{\rho_f}\frac{(1-\phi)}{\phi}\frac{P'(^4He)}{[He]_{f,m}}\left[\ln\left\{\frac{(R/R_a)_m-(R/R_a)_c}{(R/R_a)_f-(R/R_a)_c}\right\}\right]^{-1}, \tag{2}$$

after normalizing the fluid, crustal, and mantle isotopic ratios $R=[^3He]/[^4He]$ by the atmospheric helium ratio R_a and defining the helium concentration in the fluid at the mantle source $C_f=[He]_{f,m}$.

A similar expression, depicting the fluid velocity as a function of the helium ratio $(R/Ra)_f$, was first presented by *Kennedy et al.* [1997]. They used their equation to predict the fluid flow rate in the San Andreas fault zone, but did not present a derivation in their article. A similar equation for the fluid velocity is also presented in *Kennedy and van Soest* [2006], *Burnard et al.* [2012], and *Kulongoski et al.* [2013], but again without any published derivation. Appendix A provides more details on our derivation and a comparison of the equations.

5.2. Fluid Flow Rate Calculation

It follows from equation (2) that the predicted fluid velocity v is inversely proportional to the helium concentration in the source fluid (mantle) and the isotopic disequilibrium, for a given fault geometry and reactive flux of radiogenic helium from the crust. We use (2) to estimate the fault zone fluid velocity, based on the helium measurements and estimated physical parameters. For example, from Well Dominguez #2 (Table 1), assuming $H_c=27$ km, $\phi=0.03$, $\rho_s=2.60$ gm/cm^3, $\rho_f=1.026$ gm/cm^3, $(R/R_a)_m=8.00R_a$, $(R/R_a)_f=5.31R_a$, and $(R/R_a)_c=0.02R_a$,

$$v=\left(5.3471\times 10^8\right)\frac{P'(^4He)}{[He]_{f,m}}. \tag{3}$$

Our estimate for fault porosity ~3% represents a representative value, vertically averaged over the entire depth of the fault zone. *Rice* [1992] argued, based on theoretical grounds and magnetotelluric data, that a porosity of about 0.5–3% is necessary in the lower crust due to its low electrical resistivity. *Janssen et al.* [2011] measured an effective nano-porosity of 3% from core samples of the San Andreas fault zone (SAFOD site), and *Morrow et al.* [2014] report values of 1.9–7.1% for a suite of SAFOD core samples of sandstone,

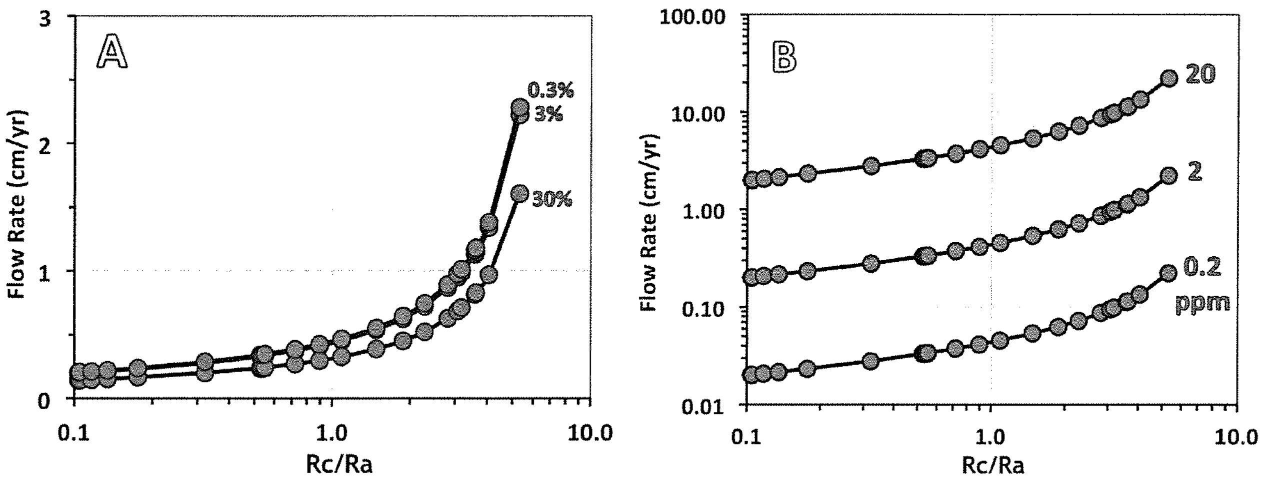

Figure 6. Fluid flow rate (cm/yr) versus air-corrected helium $^3He/^4He$ ratio, as predicted by a one-dimensional isotopic transport model and well field observations from the LA Basin. Figure 6a shows the effect of fault porosity over a range from 0.3 to 30%. Figure 6b shows the effect of radiogenic flux of ^4He, as controlled by the crustal uranium concentration over a range of [U] from 0.2 to 20 ppm. We assume the concentration ratio of [$^3He/^4He$] = 3 in all three scenarios.

sheared siltstone, cataclasite, and serpentinized clay gouge at a borehole-depth interval ~3190–3310 m. Based on these data, we adopted a value of 3% for the NIFZ porosity as a first approximation. Few data sets exist to constrain porosity in deeper fault zones, but we assume it could physically range from 0.03 to 30% depending on the lithology, effective stress, and amount of clay gouge present.

According to *O'Nions and Ballentine* [1993] and *Ballentine and Burnard* [2002], the ^4He production rate from radiogenic decay reactions in the crust can be estimated from the known bulk concentrations (ppm) of uranium [U] and thorium [Th]: $P'(^4He) = (1.207 \times 10^{-13}$ [U] + 2.867×10^{-14} [Th]). Based on crustal averages [*O'Nions and Oxburgh*, 1988; *O'Nions and Ballentine*, 1993], and gamma log data from the LA basin, we let [U] ~ 2 ppm and [Th] ~ 6 ppm, and therefore we can estimate a production rate, $P'(^4He) = 4.134 \times 10^{-13}$ cm^3 STP/gm yr. D. Graham (personal communication, 2015) provides an independent estimate of the "starting" mantle [^4He] concentration, as follows: the ocean crust production is about 21 km^3/yr, and the Earth's mantle ^3He flux is 1000 mol/yr [*Porcelli and Elliott*, 2008]. If we assume that the Earth's crust is produced by 10% partial melting, and ^3He is perfectly incompatible, this gives a mantle [^3He] of 3.2×10^{-11} cm^3 STP/g (8.7×10^8 atoms/g). For mantle sources $^3He/^4He$ = 8 Ra, this gives [^4He] = 3.0×10^{-6} cm^3 STP/g. Relatively gas rich mid-oceanic ridge basalts (MORBs) are reported to have [^3He] ~ 30 cm^3 STP/g, and so if they are derived by 10% partial melting, the value given above is internally consistent with what is observed in MORBs. After substituting $[He]_{f,m} \sim 3.0 \times 10^{-6}$ cm^3 STP/g into (3), we get an average fluid velocity in the fault,

$$v = \frac{2.2105E-04}{[He]_{f,m}} = 73.7\ cm/y, \tag{4}$$

or, as the Darcian flow rate (fluid volume discharge rate per unit area), $q = \phi\, v = 2.2$ cm/yr. Similar calculations were done for all of our helium gas sample locations in the LA basin (Figure 2), indicating a wide range of predicted flow rates from a low of 0.2 cm/yr (Wilmington and Newport Beach fields) to a high of 2.2 cm/yr (Well Dominguez #2), with flow rate increasing with increasing $(R/Ra)_f$ value and decreasing fault porosity (Figure 6a). The effects of variable fault porosity seem minor, given the likely range expected in the shallow and deep crust.

Based on equation (2), the fluid flow rate scales linearly with the rate of ^4He production in the crust (controlled by the U-Th concentrations), and so we have included results (Figure 6b) from a sensitivity study for variable [U] levels, assuming constant U/Th = 3. At constant flow rate the U-Th concentration has a marked effect on the R/Ra value, consistent with what we observe in the Long Beach field. The fluid velocity (and flow rate) also increases linearly with the flow path length (~*Hc*). We have assumed the thickness of the crust as the characteristic length for this model parameter, although one might visualize somewhat longer

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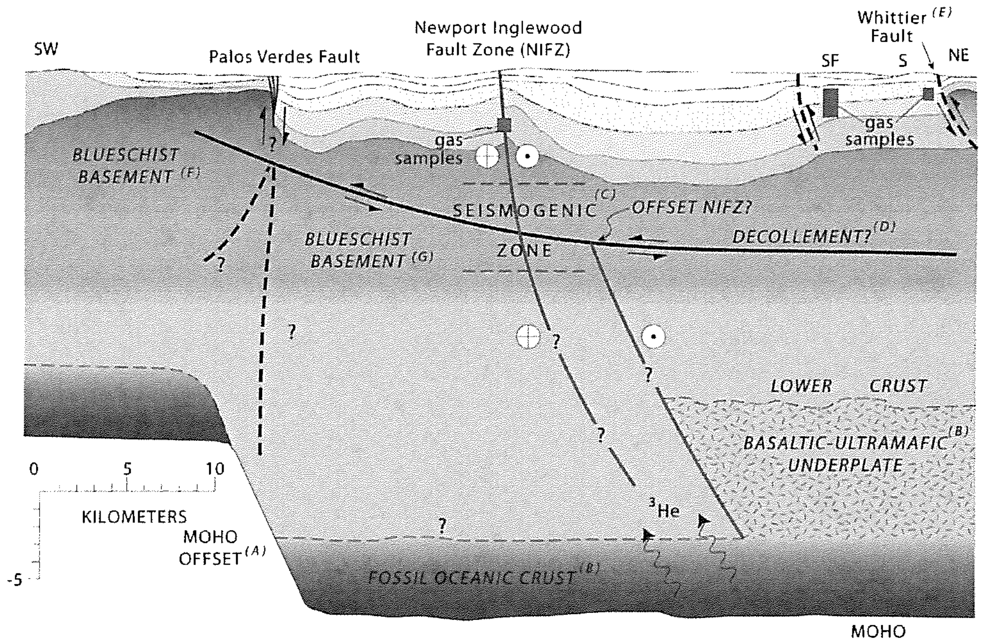

Figure 7. Geologic cross section of the Los Angeles basin, from the southwest to northeast. This profile intersects the NIFZ at Long Beach (see section line in Figure 2). The cross section is shown without vertical exaggeration. Deep basin features include (a) the offset Moho, (b) the basaltic-ultramafic under plating adjacent to the NIFZ, (c) seismogenic zone along the NIFZ, (d) the proposed décollement underlying the LA basin, including the offset of the NIFZ along the décollement, (e) the northern basin Whittier fault, and (f) the blueschist basement southwest of the NIFZ. See text for references and discussion of basin features. The helium isotopic data indicate that the NIFZ is a permeable connection to the mantle for this part of the crust.

flow paths, perhaps only by a factor of ~(1.5–2.0) × H_c (see Figure 7) if helium was being transported along interconnected vertical and lateral fault splays.

For the petroleum reservoir sites with the highest values of $(R/Ra)_f > 2$, the flow rate trend suggests that the Darcy velocity $q \sim 0.2$–2.2 cm/yr for the LA basin faults. This is twice as fast as the flow rate $q \sim 0.1$–1.0 cm/yr range estimated by *Kennedy et al.* [1997] for the San Andreas fault zone (SAFZ) near Parkfield, California (about 400 km northwest of Long Beach), but slower than the flow rate $q \sim 15$ cm/yr recently estimated by *Kulongoski et al.* [2013] for the Big Bend section of the SAFZ in the Cuyama Valley area (about 250 km northwest of Long Beach), all based on helium isotope data.

5.3. Thermal Effects of Flow

Given an upper estimate of flow rate $q \sim 2$ cm/yr, we compute a dimensionless "thermal Péclet Number" for the fault zone flow system, *Pe*, which expresses the ratio of convective heat transport by the fluid flow to bulk conductive heat transfer in the crustal rock [*Betcher*, 1977; *van der Kamp*, 1984; *van der Kamp and Bachu*, 1989; *Person and Garven*, 1992]. For any crustal profile where $Pe > 2$, convective heat flow exceeds conduction, and as a result, anomalous geothermal gradients develop and hot springs would appear in areas of groundwater/fluid discharge [*Anderson*, 2005]. Using the approach and notation of *van der Kamp* [1984], the ratio of convective to conductive heat flow in a basin with 3-D dimensions length *L*, width *W*, and mean height/depth *H*, can be simply represented as

$$Pe = \frac{\rho_f c_{vf} Q_f'}{\lambda_e \; (L/H)} = \frac{Q_f'}{D_e(L/H)}, \tag{5}$$

where ρ_f fluid density, c_{vf} specific heat capacity of the fluid (at constant volume), Q_f' volumetric fluid flow rate per unit width, λ_e bulk effective thermal conductivity, and D_e bulk thermal diffusion coefficient. We assign the representative fluid and rock parameters [*Ge*, 1998; *Anderson*, 2005]: $\rho_f = 1026$ kg/m^3, $c_{vf} = 4080$ J/kg °C, $\lambda_e = 3.0$ W/m °C, and $D_e = 7.17 \times 10^{-7}$ m^2/s ~ 23 m^2/yr. Given the local crustal geometry of the LA basin, $L \sim 60$ km, $H \sim 30$ km, then (5) simply yields $Pe \sim Q_f'/45$. For our system, the total volumetric flow rate per unit width of the basin can be expressed as

$$Q_f' = \frac{qA}{W} = \frac{q\ W\ b_f}{W} = q\ b_f. \tag{6}$$

The new parameter b_f = fault zone width. It follows from (5) and (6) that the Péclet Number for the basin domain can be expressed as a function of the Darcy flow rate and fault zone width, and given a representative Darcy flow rate $q \sim 0.02$ m/yr from the helium data, and assuming a fault width $b_f \sim 150$ m, we estimate thermal $Pe \sim qb_f/45 = 0.067$–0.1 for the NIFZ.

Because the disturbance of any conductive subsurface temperature field is due to forced convection (advection) of heat by the fluid phase, the thermal Péclet Number provides a good measure of the degree of thermal disturbance by a fluid flow regime [*van der Kamp and Bachu*, 1989]. It is clear from this dimensional analysis that a vertical flow rate of 2 cm/yr would not perturb the conductive temperature field, but flow rates above 30 cm/yr or higher might. Heat flow measured using idle petroleum wells along the NIFZ indicates a remarkably uniform heat flux of 63–66 mW/m^2 [*Price et al.*, 1999; *Williams et al.*, 2001], extending over 40 km from Seal Beach in the southeast to Inglewood in the northwest. Our low Péclet Number calculation confirms that the fluid flow rates in the fault zone, as estimated by the helium data, would be too low to perturb the nearly uniform conductive field in this section of the LA basin.

5.4. Fault Permeability Calculation

For a fractured medium, the fluid flow rate per unit area (specific discharge) q can be formally expressed by a one-dimensional form of Darcy's law, written out in terms of fluid pressure P and elevation Z above a datum [*Hubbert*, 1940]:

$$q = -\frac{k}{\mu_f}\left\{\frac{\partial P}{\partial Z} + \rho_f g\right\}, \tag{7}$$

where g is gravitational acceleration, μ_f dynamic viscosity of the fluid, and k the intrinsic permeability (fault zone permeability). This formulation of Darcy's law assumes a liquid phase fluid of uniform composition. Prepetroleum industry development of reservoirs in the LA basin indicate a slightly overpressured sedimentary basin [*Berry*, 1973; *Glassley*, 2015]. Pore pressures in the lower crust below the basin are unknown, but given this tectonic system is transpressional, one would expect pressure gradients well above hydrostatic of (~0.45 psi/ft), but below geostatic (~1.20 psi/ft), based on the geomechanical reasoning of *Rice* [1992] and *Neuzil* [1995, 2003], and the metamorphic geochemistry and thermal reasoning of *Manning and Ingebritsen* [1999]. Therefore, as a first approximation we assume $dP/dZ \sim -0.7$ psi/ft ($-15{,}835$ Pa/m), as a representative gradient over the thickness of crust. If we assign a Darcy velocity from the Well Dominguez #2, $q = 2.2$ cm/yr $= 0.909 \times 10^{-9}$ m/s, specific weight $\rho_f\,g = 10{,}055$ N/m^3, and dynamic viscosity $\mu_f = 0.001$ Pa s, then Darcy's law (7) yields an estimate of the intrinsic permeability:

$$k = -\frac{q\mu_f}{\left\{\frac{\partial P}{\partial Z} + \rho_f g\right\}} \sim 1.58 \times 10^{-16}\ \mathrm{m}^2, \tag{8}$$

or $k \sim 158$ microdarcys for the NIFZ at this site, vertically averaged over the thickness of the crust. We performed similar calculations for the other gas sample sites, which produces a root-mean-square average permeability $k \sim 57$ microdarcys ($=5.63 \times 10^{-17}$ m^2 or log k ~ -16.25). For comparison, *Bredehoeft and Ingebritsen* [1990] assigned values of porosity (1%) and compressibility (10^{-4} MPa^{-1}) to estimate a bulk crust permeability of $k \sim 10^{-21}$ m^2, needed to maintain high fluid pressures thought to exist in the ductile parts of the deep crust. *Morrow et al.* [2014] measured cm-scale lab permeabilities $k \sim 10^{-22}$ to 10^{-18} m^2 on core samples (depth ~2.7 km) of clay-rich gouge from the San Andreas fault at Parkfield, CA. *Rice* [1992], however, argued on theoretical grounds for a km-scale permeability $k \sim 10^{-18}$ m^2 (1 microdarcy) at the base of the seismogenic zone (depth ~ 15–20 km), by taking into account the depth dependency of bulk rock compressibility on stress. Our helium-based estimate for the NIFZ permeability range, $-16.7 < \log k < -15.7$ m^2, is higher than the exponential depth-dependent range ($-18.5 < \log k < -16.6$ m^2) cited by *Manning and Ingebritsen* [1999], as constrained by thermal data for the Coast Ranges, California, for depths <15 km. But more recently, *Ingebritsen and Manning* [2010] have proposed $\log k > -16$ m^2 for high-permeability transients ($t \sim 10^3$ years), particularly for fault and shear zones in the brittle crust (depths < 10 km), and an upper limit (constant) log $k \sim -16$ m^2 for the ductile crust (depths > 15 km). *Giger et al.* [2007] used hot-press high P-T experiments to show that, within the recurrence time interval of large earthquakes, quartz-rich fault zones in the middle to lower crust can evolve from high-permeability conduits to low-permeability seals. Under lower crustal temperatures of 600–800°C, permeability typically exceeds $\sim 10^{-19}$ m^2, and follows the well-known cubic law $k \sim \phi^3$, provided fault gouge porosity exceeds ~4%.

6. Discussion

Mantle seepage into the NIFZ has important implications with respect to structural models for the deep LA basin. Specifically, recent models using kinematic balanced cross sections propose that the NIFZ is cut off and offset from the deeper crust by a deep (8–10 km) subhorizontal thrust ramp that is part of a central basin décollement (see Figure 7) [*Davis et al.*, 1989; *Shaw and Suppe*, 1996]. However, our geochemical data indicate that the NIFZ is the only major fault in the basin that is connected to the very deep crust. If the structural interpretation of *Shaw and Suppe* [1996] is correct, the blind thrust, presumably a shortening feature, is a pathway for at least 4 km of lateral transport of helium. Alternatively, the model may be incorrect and the NIFZ may extend directly to the mantle unaffected by the proposed underlying faults.

Several lines of evidence, not necessarily consistent with each other, indicate the NIFZ is an area with some anomalous deep crustal features. These features may relate to the paleo-subduction zone (plate boundary) proposed by *Hill* [1971]. Analysis of teleseismic events in the Long Beach area from a 3-D seismic array at Signal Hill indicates the Moho may have 10 km of vertical offset approximately 10 km to the south of the NIFZ in the Long Beach area [*Schmandt and Clayton*, 2013]. The model projects a 65° north dipping surface to the offset, which would project about 30 km south of the NIFZ (Figure 7). The offset of the Moho at this locality may connect to thrusting along the Palos Verdes fault (see Figure 2) and if so, then the mantle communication between the Moho and the surface is weaker here than along the NIFZ, based on the strength of the R/Ra ratio in the two areas (Figure 2). Another study, based on gravity and seismic data, concludes the NIFZ is the southwest boundary between a thick section of ultramafic lower crust on the north and a thin section of oceanic crust to the south [see *Romanyuk et al.*, 2007, Figure 8]. The abrupt lateral change in lithospheric material in the deep crust adjacent to the NIFZ is consistent with a deep-seated conduit to the Moho along the NIFZ and the preservation of a paleo-subduction boundary.

7. Conclusions

Leakage of mantle helium into the lower crust without associated elevated heat may be explained by ~0.2–2.0 cm/yr fluid flux rates, sufficiently high enough to transport ^{3}He from the mantle, but at rates too slow to disturb conductive heat transfer. Transport of ^{3}He without dilution by ^{4}He from the crust requires relatively rapid movement of mantle gas along preferred pathways without long residence time. This also implies local transport of heat. Our calculations suggest flux rates of up to about 2 cm/yr, which would be insufficient to perturb the ambient conductive heat flow, due to the low thermal Peclet Number. Our geochemical modeling of helium transport also suggests a time-averaged fault permeability $k \sim 5.6 \times 10^{-17}$ m^2 (60 microdarcys) for the NIFZ, which compares well with estimates for deep crustal fluid flow from other geophysical data sets.

Sampling for mantle helium anomalies generally focuses on areas with thermal anomalies [*Oxburgh et al.*, 1986; *Hilton et al.*, 2002; *Kennedy and van Soest*, 2007; *Umeda et al.*, 2007]. The flux of mantle helium into the continental crust needs to be reevaluated by more extensive gas sampling in faulted areas with normal geothermal gradients. In addition, the importance of understanding local geology is demonstrated by the effects of elevated U-Th concentration on observed R/Ra values.

Our findings suggest that the NIFZ is a likely fluid conduit through the seismogenic zone and lower crust to the upper mantle. Although we cannot be certain that the NIFZ is not connected to other mantle-connected faults at depth, we believe the NIFZ itself, based on the evidence discussed above, including strength and consistency of the signal and geologic setting, is the likely primary pathway of mantle fluids in the area. This suggests the fault continues to be a fundamental boundary in the LA basin.

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The mantle connection along the NIFZ has apparently persisted since early Miocene time in spite of the eastward migration (80 km jump?) of the plate boundary and the proposed, potentially seismically active décollement within the deep LA basin. It appears to be an example of relatively "slow" seepage of mantle fluids from a paleo-subduction zone.

Appendix A: Derivation of the Helium Flow Rate Equation

Based on the theory and notation of *Johnson and DePaolo* [1994, 1997] and *DePaolo* [2006], the mass concentration ratio of an isotope pair (e.g., [^{3}He]/[^{4}He]) can be represented mathematically by combining the aqueous mass conservation equations for each isotope into a single partial differential equation, and casting the isotopic ratio in the fluid phase R_f as the sole dependent variable

$$\frac{\partial R_f}{\partial t'} = \frac{1}{P_e}\left(\frac{\partial^2 R_f}{\partial z'^2} + \frac{2}{c_f}\frac{\partial c_f}{\partial z'}\frac{\partial R_f}{\partial z'}\right) - \frac{\partial R_f}{\partial z'} + D_a[\bar{R}_d - R_f]. \tag{A1}$$

This equation describes mass conservation (per unit volume of bulk porous medium) of the helium isotope ratio, $R = [^3He]/[^4He]$, assuming a one-dimensional transport field (*z* distance along the flow path) where isotopic mass is advected by the flow field and undergoes diffusion (mixing) and isotopic exchange. We define the following variables and parameters in (A1): $z' = z/L$ dimensionless distance, L = length of the domain, $t' = \{(tv)/L\}$ dimensionless time, v average pore fluid velocity, R_f isotope ratio in the moving fluid phase, R_d isotope ratio of the radiogenic decay flux from the solid phase, c_f source concentration of the isotope in the fluid phase (mass/fluid volume), $P_e = \{(vL)/D\}$ chemical Péclet Number (ratio of advective mass flux/diffusive mass flux), $D_a = \{(L\ J_{tot})/(v\ c_f)\}$ Damköhler Number (ratio of reactive mass flux/advective mass flux), and J_{tot} total reactive flux (total mass of the radiogenic isotope delivered to a unit volume of fluid by all reactions per unit time). Generally speaking, in fault zones Pe >> 1, and advection greatly dominates over processes of diffusion [*Phillips*, 1991].

The full derivation of equation (A1) is given by *Johnson and DePaolo* [1994] and they assume: (i) one-dimensional mass transport by advection and diffusion, (ii) uniform and steady rate of advection of the isotopic species under a constant pore fluid velocity v in the fault zone, (iii) homogeneous and constant porosity, (iv) homogeneous fluid density and viscosity, and (v) uniform and constant reaction flux J_{tot} due to radiogenic production of ^{4}He. If we adopt the additional mathematical simplifications of *Johnson and DePaolo* [1994] and consider the special case of steady state mass transport (i.e., $\partial R_f/\partial t' \sim 0$), and assume negligible effects of diffusion of the isotopic mass (i.e., $D \sim 0$), then (A1) simplifies to

$$\frac{dR_f}{dz'} = -D_a[R_f - \bar{R}_c], \tag{A2}$$

where we have set $\bar{R}_d = \bar{R}_c$, the average "crustal" ratio, and assume this is nearly constant.

To solve for the unknown dependent variable R_f, *Johnson and DePaolo* [1994] integrate (A2) over the isotope ratio range on the boundaries for 1-D transport,

$$\int_{r_{f,o}}^{r_f} \frac{1}{[R_f - \bar{R}_c]} dR_f = ln\left\{\frac{[R_f - \bar{R}_c]}{[R_{f,o} - \bar{R}_c]}\right\} = -D_a[z']. \tag{A3}$$

With rearranging terms in (A3) to simplify, as done by *Johnson and DePaolo* [1994, equation (23), p. 1575], we get

$$R_f(z') = \bar{R}_c + [R_{f,0} - \bar{R}_c]\ \exp\{-D_a z'\}. \tag{A4}$$

For the outflow boundary, where $z' = 1$ (i.e., $z = L = H_c$), it follows from (A4) that

$$\frac{[R_f - \bar{R}_c]}{[R_{f,0} - \bar{R}_c]} = \frac{(R_f - \bar{R}_c)}{(R_m - \bar{R}_c)} = \exp\{-D_a\} = \exp\left\{-\frac{H_c\ J_{tot}}{v\ c_f}\right\}, \tag{A5}$$

where $R_{f,o} = R_m$ is the helium isotope ratio of the fluid at the inflow boundary $z' = 0$ (i.e., mantle/crust inflow boundary). Based on the closed-form solution (A5), the isotopic disequilibrium term $[\bar{R}_c - R_f]$ will decay exponentially with distance traveled, with the Damköhler Number D_a as the exponential factor (assumed constant), as correctly noted by *Johnson and DePaolo* [1994]. Solving (A5) for the average linear fluid velocity v [see *Bear*, 1972; *Freeze and Cherry*, 1979] in the fault zone yields,

$$v = -\frac{H_c\ J_{tot}}{c_f \ln\left\{\frac{(R_f - \bar{R}_c)}{(R_m - \bar{R}_c)}\right\}}. \tag{A6}$$

After bringing the minus sign into the logarithmic term and rearranging this equation,

$$v = \frac{H_c\ J_{tot}}{c_f \ln\left\{\frac{(R_m - \bar{R}_c)}{(R_f - \bar{R}_c)}\right\}} = \frac{H_c\ J_{tot}}{c_f}\left[\ln\left\{\frac{(R_m - \bar{R}_c)}{(R_f - \bar{R}_c)}\right\}\right]^{-1}. \tag{A7}$$

It is clear from this equation that the predicted fluid velocity v is inversely proportional to the helium concentration in the source fluid (mantle) and the isotopic disequilibrium, for a given fault geometry and reactive flux of radiogenic helium from the crust. Based on the notation in *Johnson and DePaolo* [1994] and *Kennedy et al.* [1997], the total helium production term J_{tot} (reactive flux of ^{4}He) can be expressed as

$$J_{tot} = M(P'_{He}) = \frac{(1-\phi)\rho_s}{\phi\rho_f} P'_{He}, \tag{A8}$$

where M is the mass ratio of solid to fluid phases (per unit bulk volume), P'_{He} = radiogenic helium production rate from the crust (~constant), ϕ = fault porosity, ρ_s = density of crustal rocks (solid phase), and ρ_f = density of fracture-zone fluid (fluid phase). Inserting this expression for J_{tot} into (A7), and redefining the parameter constant $c_f = [\mathrm{He}]_{f,m}$, to be consistent with *Kennedy et al.* [1997] notation, equation (A8) now can be reformatted, after normalizing the fluid, crustal, and mantle isotopic ratios by the atmospheric helium ratio R_a, such that

$$v = H_c\ \frac{\rho_s}{\rho_f}\frac{(1-\phi)}{\phi}\frac{Pr(^4He)}{[He]_{f,m}}\left[\ln\left\{\frac{(R/R_a)_m - (R/R_a)_c}{(R/R_a)_f - (R/R_a)_c}\right\}\right]^{-1}. \tag{A9}$$

Equations (A7) and (A9) are similar to the working equation first presented in *Kennedy et al.* [1997], but they appear to have simplified it further by assuming $(1-\phi) \sim 1$ for very small porosity, and they appear to have replaced the logarithm term with the Taylor Series approximation $\ln\{x\} \sim (1-x)$, which is mathematically valid for estimates of the argument $x \sim 1$. To verify their derivation and compare to ours, consider a Taylor Series expansion of a logarithmic function (centered at 1, for $0 < x < 2$): $\ln(x) = \frac{(x-1)^1}{1} - \frac{(x-1)^2}{2} + \frac{(x-1)^3}{3} - + \ldots$ If the argument $x \sim 1$, then $\ln(x) \sim (x-1)$ is the first-order Taylor approximation. Therefore, equation (A7) could be rewritten,

$$v = \frac{H_c\ J_{tot}}{c_f\left(\frac{r_m - \bar{r}_c}{r_f - \bar{r}_c} - 1\right)} = \frac{H_c\ J_{tot}}{c_f\left(\frac{r_m - \bar{r}_c - r_f + \bar{r}_c}{r_f - \bar{r}_c}\right)} = \frac{H_c\ J_{tot}}{c_f\left(\frac{r_m - r_f}{r_f - \bar{r}_c}\right)} = \frac{H_c\ J_{tot}}{c_f}\left(\frac{r_f - \bar{r}_c}{r_m - r_f}\right). \tag{A10}$$

Furthermore, based on the notation in *Johnson and DePaolo* [1994], the total helium production term J_{tot} (reactive flux of ^{4}He due to radiogenic reactions) can be expressed as

$$J_{tot} = M(P'_{He}) = \frac{(1-\phi)\rho_s}{\phi\rho_f} P'_{He} \sim \frac{\rho_s}{\phi\rho_f} P'_{He}, \tag{A11}$$

which assumes $(1-\phi) \sim 1.0$, or in other words that porosity ϕ is very small. Inserting this expression for J_{tot} into (A10), and redefining $c_f = [\mathrm{He}]_{f,m}$ as before, we get

$$v = \frac{H_c\ \frac{\rho_s}{\phi\rho_f} P'_{He}}{c_f}\left(\frac{R_f - \bar{R}_c}{R_m - R_f}\right) = \frac{H_c \rho_s\ P'_{He}}{\phi\rho_f [\mathrm{He}]_{f,m}}\left(\frac{R_f - \bar{R}_c}{R_m - R_f}\right). \tag{A12}$$

The Darcy velocity q, also known as the specific discharge (volumetric flow rate per unit area of porous medium), is defined by Forchheimer's formula [*Bear*, 1972], $q = v\phi$, and therefore we can rewrite (A12) as

$$q = \frac{H_c \rho_s\ P'_{He}}{\rho_f [\mathrm{He}]_{f,m}}\left(\frac{R_f - \bar{R}_c}{R_m - R_f}\right). \tag{A13}$$

This is the simplified equation format first presented by *Kennedy et al.* [1997]. We decided to use equation (A9) for our calculations of flow rates, because application of the Kennedy equation (A13) generated computational errors of up to 50% for the NIFZ physiochemical parameters.

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