Title

Decrease in natural marine hydrocarbon seepage near Coal Oil Point, California, associated with offshore oil production

Journal

Geology, 27(11)

ISSN

0091-7613

Authors

Quigley, Derek C
Hornafius, J Scott
Luyendyk, Bruce P
et al.

Publication Date

1999

DOI

10.1130/0091-7613(1999)027<1047:dinmhs>2.3.co;2

Peer reviewed

Decrease in natural marine hydrocarbon seepage near Coal Oil Point, California, associated with offshore oil production

Derek C. Quigley Geco-Prakla Field Processing, 1325 South Dairy Ashford, Houston, Texas 77077, USA, and Institute for Crustal Studies, University of California, Santa Barbara, California 93106, USA
J. Scott Hornafius Mobil Oil Corporation, 1250 Poydras, New Orleans, Louisiana 70113, USA, and Institute for Crustal Studies, University of California, Santa Barbara, California 93106, USA
Bruce P. Luyendyk Department of Geological Sciences, University of California, Santa Barbara, California 93106, USA, and Institute for Crustal Studies, University of California, Santa Barbara, California 93106, USA
Robert D. Francis Department of Geological Sciences, California State University Long Beach, 1250 Bellflower Boulevard, Long Beach, California 90840, USA
Jordan Clark Department of Geological Sciences, University of California, Santa Barbara, California 93106, USA
Libe Washburn Department of Geography, University of California, Santa Barbara, California 93106, USA

ABSTRACT

Prolific natural hydrocarbon seepage occurs offshore of Coal Oil Point in the Santa Barbara Channel, California. Within the water column above submarine vents, plumes of hydrocarbon gas bubbles act as acoustic scattering targets. Using 3.5 kHz sonar data, seep distribution offshore of Coal Oil Point was mapped for August 1996, July 1995, and July 1973. Comparison of the seep distributions over time reveals more than 50% decrease in the areal extent of seepage, accompanied by declines in seep emission volume, in a 13 km^2 area above a producing oil reservoir. Declines in reservoir pressure and depletion of seep hydrocarbon sources associated with oil production are the mechanisms inferred to explain the declines in seep area and emission volume.

NATURAL MARINE HYDROCARBON SEEPAGE

Hydrocarbon seepage from the world's continental shelves affects ocean chemistry (Dando and Hovland, 1992) and provides a natural source of petroleum pollution (Landes, 1973; Wilson et al., 1974; Kvenvolden and Harbaugh, 1983). Submarine venting of methane, a greenhouse gas (Watson et al., 1990), may provide a significant and overlooked source of methane in the environment (Hovland et al., 1993; Hornafius et al., 1999). Natural marine hydrocarbon seeps offshore of Coal Oil Point in the northern Santa Barbara Channel, California, are among the largest and best documented seeps in the world (Allen et al., 1970; Wilson et al., 1974; Kvenvolden and Harbaugh, 1983; Hornafius et al., 1999). At a regional scale, the Coal Oil Point seeps represent a significant source of gaseous hydrocarbons (Killus and Moore, 1991; Cynar and Yayanos, 1992) and residual asphaltic hydrocarbons (beach tar) (Hartman and Hammond, 1981). The Miocene diatomaceous shale and siltstone of the Monterey Formation are the source for the seep emissions (Reed and Kaplan, 1977; Hartman and Hammond, 1981).

The nearshore seeps at Coal Oil Point (Allen et al., 1970) are predominantly oil exuded directly from the outcrop of the Monterey Formation exposed in the axis of the Coal Oil Point anticline (Fischer, 1977) (Fig. 1). Farther offshore, seepage passes through overlying Sisquoc Formation cap rock and includes both oil and gas (Fischer, 1977). The offshore gaseous seepage is controlled

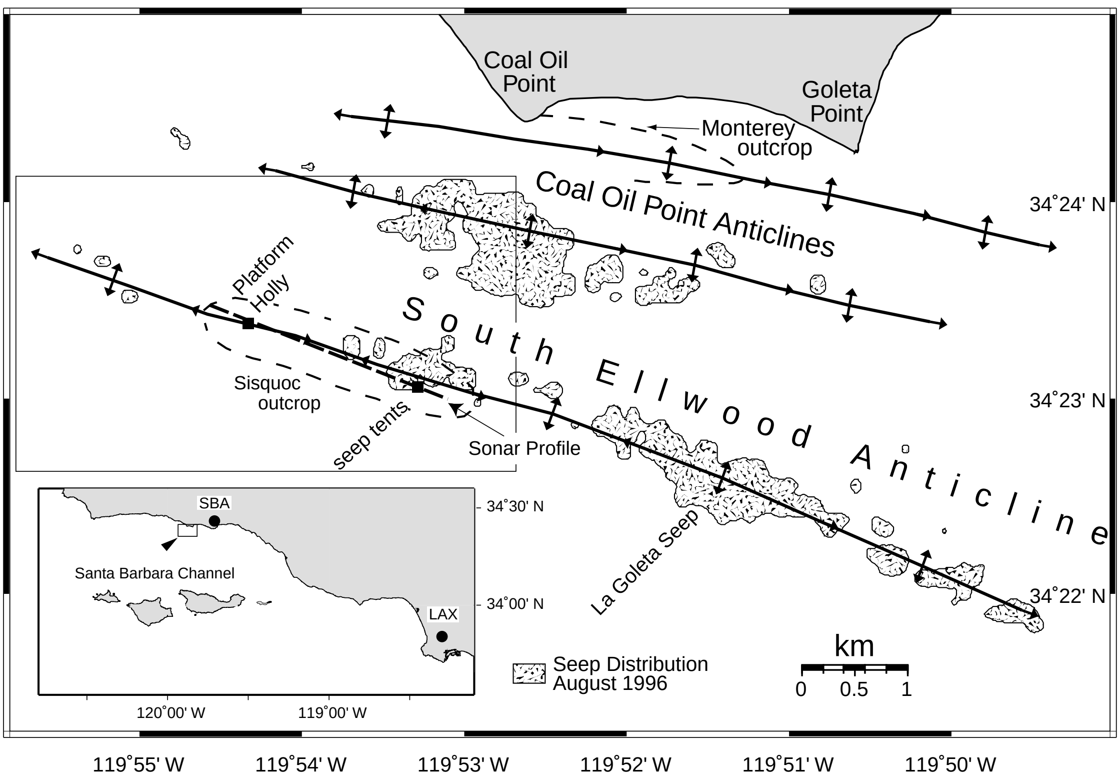

Figure 1. Offshore Coal Oil Point study area. Fault locations and anticline-syncline pairs in Monterey and Sisquoc Formations of northern Santa Barbara Channel shelf determine seep distribution. Mapped distribution of seepage is from 3.5 kHz sonar survey during August 1996. Area of seepage comparison is boxed 13 km^2 area surrounding Platform Holly. Arrow points to sonar profiles in Figure 2. SBA—Santa Barbara Airport. LAX—Los Angeles International Airport.

by the local geologic structure, which trends west-northwest. Seepage is most intense at submarine fault conduits and at structural closures along anticline axes (Fischer, 1977; Quigley, 1997). At one structural closure along the South Ellwood anticline, a site of intense historical seepage (Fischer, 1977; Fischer and Stevenson, 1973), offshore oil production occurs at Platform Holly (Fig. 1). At a second closure 1.5 km east of Platform Holly, prolific gaseous seepage is captured by a pair of seep tents (steel pyramids covering 1900 m^2 of sea floor) installed by ARCO in 1982 (Rintoul, 1982; Guthrie and Rowley, 1983). The areal distribution and volume of seep emissions have varied (Fischer and Stevenson, 1973; Fischer, 1977; Quigley, 1997). Time variation in the seep emissions is a significant issue. It implies variability in the local background levels against which pollution from industrial activities is measured, and is relevant at a global scale if seepage from continental margins represents a significant source of atmospheric methane (Hovland et al., 1993; Hornafius et al., 1999).

SONAR SURVEYS OF SEEP DISTRIBUTION

Gas hydrocarbon seepage offshore Coal Oil Point was mapped with 3.5 kHz sonar (Sweet, 1973; Tinkle et al., 1973) during July 26–27, 1995, and August 15–17, 1996. A 3.5 kHz acoustic transducer was towed at a depth of 9 m and a cruising speed of ~5 knots and navigated by a differential global positioning system (GPS). Analog records were recorded on a 19 in (48 cm) thermal paper recorder. The sonar transceiver was operated without time-varied gain. A Krone-Hite filter band-passed the signal from 3.0 to 4.0 kHz to eliminate excess noise. The analog acoustic data display a cross section or profile of the water column and sea bottom along the ship tracks (Fig. 2). The travel-time of each successive acoustic return is related to the depth by the sound speed, ~1500 m/s for the seawater and water-saturated sea-floor sediments. Dark vertical bands within the water column are sonar backscatter from gas bubbles. To evaluate changes in seep distribution near Platform Holly over a 22 yr period, 3.5 kHz records acquired by Peter Fischer in July 1973 were obtained for comparison. A comparison between two sonar records along a survey line between Platform Holly and the seep tents in July 1973 and July 1995 reveals a large decrease in seep activity (Fig. 2).

The 1973 and 1995 3.5 kHz analog records were digitally scanned to compare seep distribution and intensity. Profiles of relative seep intensity along each survey track were constructed by scaling the mean values of pixel darkness within a 20–30 m depth window relative to mean background values, normalized by the saturation level of the paper (Quigley, 1997). The sonar beam is ~25 m wide within the depth window. Relative seep-intensity data were subsequently gridded at 100 m, contoured by using a tension-spline surface algorithm (Smith and Wessel, 1990), and displayed as a relative-intensity map of seep distribution (Fig. 3). The threshold level of noise was arbitrarily selected as 0.1 (10% of the saturation level). The comparison is limited because navigational coverage is similar only within a restricted 13 km^2 area in the vicinity of Platform Holly (outlined by the box in Fig. 1). Change in seep distribution farther from Holly is unknown. Errors in the navigational data are on the order of a few meters for the differential GPS survey in 1995, but as great as 15 m for the 1973 data (Fischer, 1977). The total area of seeps mapped decreased from 0.9 km^2 to 0.4 km^2 between 1973 and 1995; the most significant disappearance of seepage occurred immediately adjacent to the platform (Fig. 3).

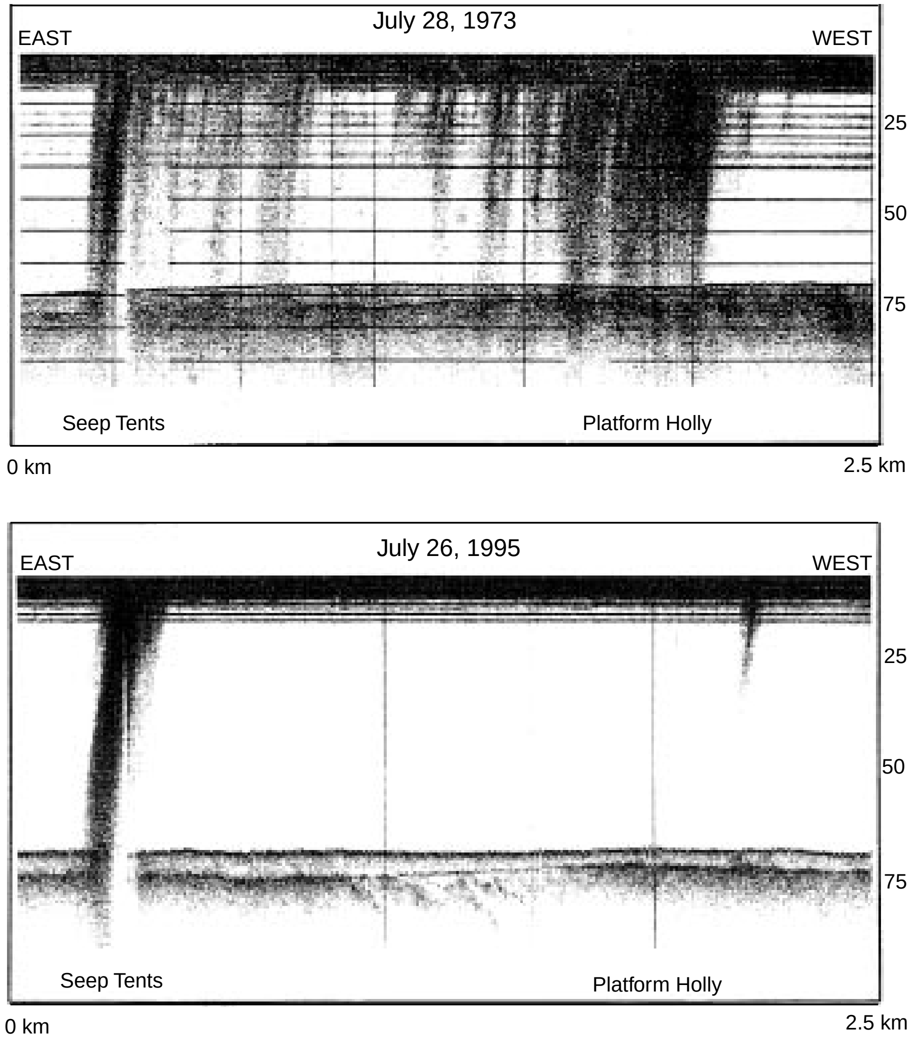

Figure 2. Sonar profiles on track line between Platform Holly and seep tents comparing seepage in July 1973 with July 1995 and illustrating drastic reduction in seepage adjacent to Platform Holly. Profile location is shown in Figure 1.

SEEP EMISSION VOLUMES

A time series of average monthly seep gas emission volumes collected at the seep tents (Fig. 4) illustrates variability in the seep emissions (Mobil Oil Corporation data supplied in 1997). The initial rate of gas collection at the seep tents following their installation was 30 000 m^3 (1 050 000 ft^3) of gas per day (Guthrie and Rowley, 1983). Subsequently, collection volumes increased. The sharp increase in 1986 was due to the addition of flaps to the seep tent structures. Gas collection remained steady until a long-term decline in collection rate began in 1989. Other variations are second order in comparison to this dominant trend of decline, and they are of unknown origin. By 1994, emissions had declined to about half of the peak collection from 1987 to 1989, and the collection rate stabilized. The sharp drop in collection volume after 1994 was caused by a failure of a pipe from one of the seep tents, which was subsequently repaired, but again failed. The temporary repair caused the upward spike in the time series in 1995. The dashed line in Figure 4 represents our estimate of seepage volumes after accounting for the changes in area of the seep tents.

SEEP TIME VARIATION

Some variations in seepage could result from natural effects, e.g., changes in the fracture migration pathways due to viscous tar sealing (Vernon and Slater, 1963) or seismic activity (Fischer, 1977). Although these effects may account for second-order variations (illustrated in Fig. 4), the dominant trend is most likely attributable to the effect of oil production on the reservoir pressure that drives seepage. The disappearance of seepage around Platform Holly and decline in emission volumes collected at the adjacent seep tents indicate a long-term decline in seepage. The similarity in seep distribution near Platform Holly in the July 1995 and August 1996 data suggests that changes in seep distribution are negligible on a time scale of 1 yr. That the observed reductions in seepage are spatially associated with oil production from Platform Holly suggests that decline in seepage between 1973 and 1995 is associated with effects of oil production.

Oil production affects seepage as reservoirs of hydrocarbons are drawn down by producing wells (Landes, 1973; Wilson et al., 1974; Kvenvolden and Harbaugh, 1983), leading to reduction in reservoir pressure. The seepage rate is proportional to the pressure gradient based on Darcy's law (Craft and Hawkins, 1959). Since production from Platform Holly began in 1967, more than 50 million barrels of oil, an equal volume of water, and more than 30 billion cubic feet of natural gas have been produced by wells drilled from the platform. This withdrawal of subsurface fluids is reflected in a recorded decrease in subsurface pressure (Fig. 4). Prior to 1977, gas was reinjected, which may have increased formation pressures and could have increased seepage rates (Kvenvolden and Harbaugh, 1983). Pressure in the Monterey Formation reservoir beneath Platform Holly began to drop below hydrostatic levels in 1983 (Fig. 4; Mobil Oil Corporation data supplied in 1997). By 1994, the total pressure drop was about 35%. There is a lag of several years between the pressure drop under Holly and the drop in collection rates at the seep tents beginning in 1989. This can be explained as due to the low permeability of the Monterey Formation migration pathways (Isaacs and Peterson, 1987). The reduction in reservoir pressure is inversely correlated with distance to Platform Holly (Quigley, 1997). Near the platform, subsurface pressure was approximately hydrostatic at 11.9 MPa in 1972, about the time of the earlier 3.5 kHz sonar survey. By 1994, the pressure had decreased to 7.54 MPa. At 1.5 km east of the platform under the seep tents, the pressure was 9.65 MPa in 1994, suggesting that pressure decrease was greater near Platform Holly.

Although mechanisms other than pressure, such as gravity flow of meteoric recharge waters or buoyancy of gaseous hydrocarbons (Hunt, 1979), can potentially drive seepage, the seepage at Coal Oil Point is most likely pressure driven (Quigley, 1997). If the fracture pathways, which serve as seepage conduits, are gas charged, then the pressure gradient between the reservoir source and the sea-floor vents would be equivalent to the hydrostatic pressure, providing a considerable driving force. However, if the fracture pathways are liquid filled, then the pressure gradient would need to be above hydrostatic to drive seepage. This characteristic would pertain only to the early production history of the reservoir, which could explain the decrease of some seepage. In addition, if fracture pathways are liquid filled and the fracture apertures are too small (submillimeter), capillary pressure would oppose hydrocarbon expulsion (Hunt, 1979; England and Fleet, 1991). Thus, water intrusion into the fracture network could augment the effect of declining reservoir pressure and contribute to the disappearance of seepage.

Time variation in seepage would affect estimates of methane leakage from continental margins (Hovland et al., 1993; Hornafius et al., 1999). This has important repercussions, because methane is a greenhouse gas (Watson et al., 1990). A larger global estimate for natural seepage rates would help to explain the unknown source of isotopically heavy methane in the global methane budget (Crutzen, 1991; Lacroix, 1993).

CONCLUSIONS

The distribution of seepage observed in maps of 3.5 kHz sonar data reveals a significant reduction in the area of seepage within 13 km^2 of Platform Holly between 1973 and 1995. The seepage area has decreased by more than 50% over a 22 yr time period, and declines in volume emissions of gas collected at the seep tents declined by more than 50% from 1989 to 1994. Lacking sonar surveys between 1973 and 1995, we cannot say whether sea-floor discharge decreased at the same time as tent collection volumes.

The spatial coincidence between offshore oil production at Platform Holly and the observed decrease in seepage around Holly are probably related and attributable to the impact of oil pro-

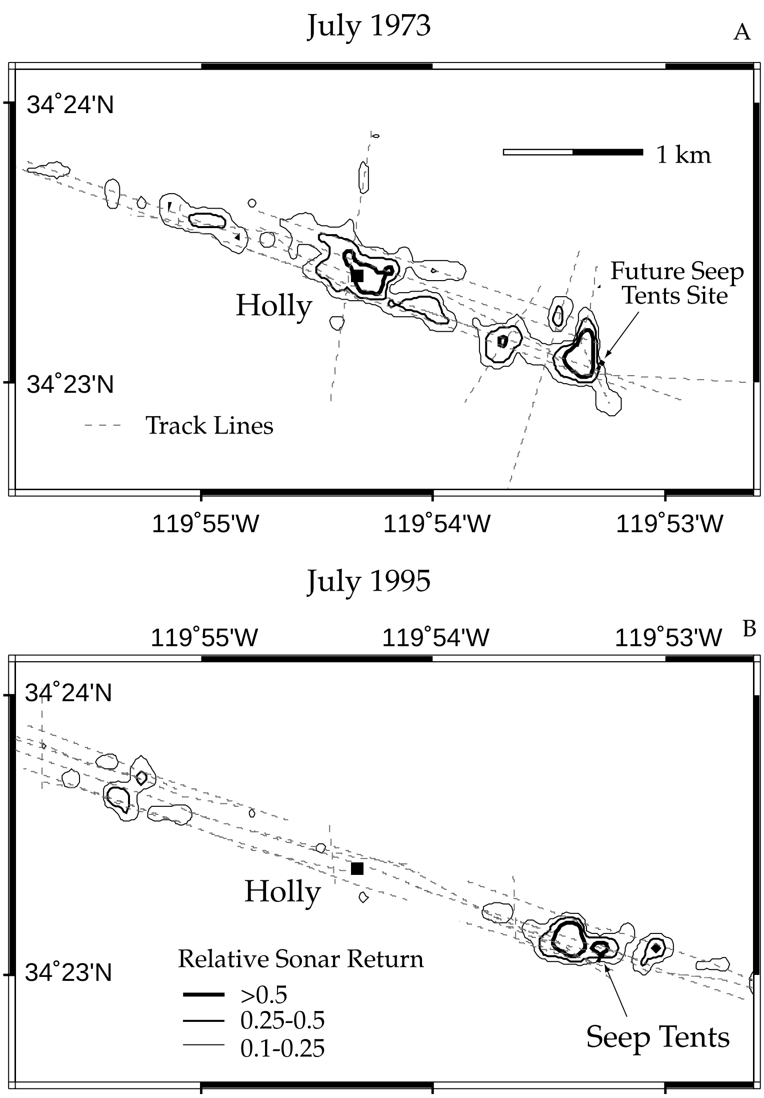

Figure 3. Comparison of distribution of gaseous hydrocarbon seepage in vicinity of Platform Holly in (A) 1973 and (B) 1995. Note nearly complete disappearance of seepage immediately adjacent to Holly in 1995. Map location is box in Figure 1.

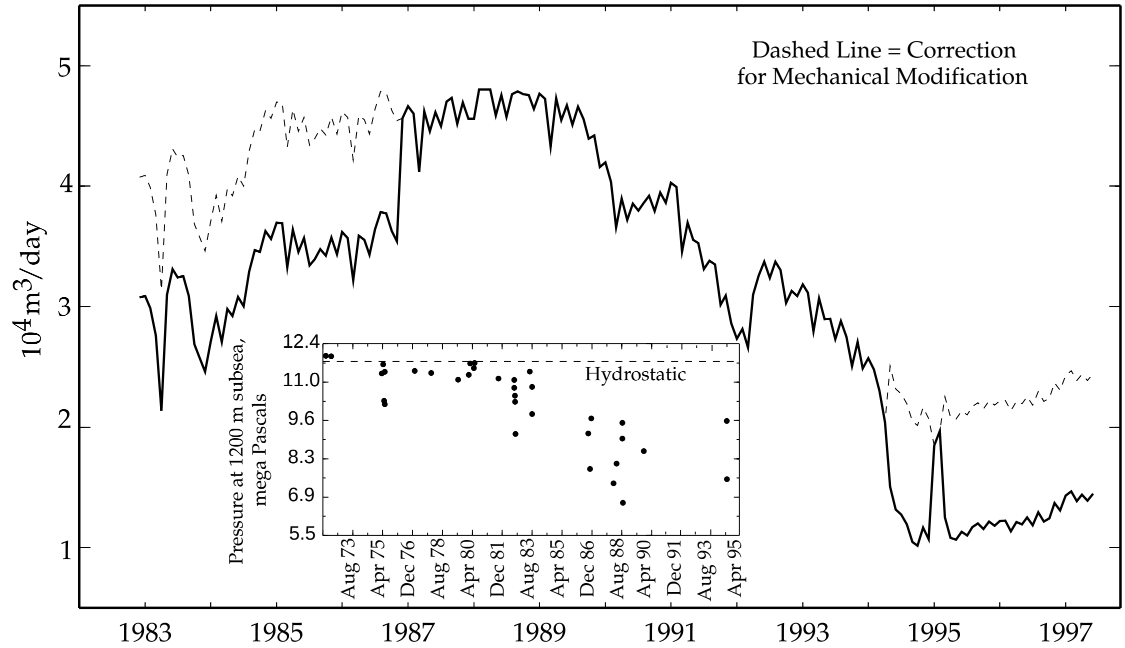

Figure 4. Time series of seep-gas volumes collected at seep tents. Dashed line provides estimated correction due to changes in seep tent areas (see text). Dominant trend is long-term decline in gas collection beginning in 1989. Inset shows reservoir pressure in Holly wells since 1973.

duction on reservoir pressure. Oil production from the Monterey Formation oil and gas reservoirs caused subsequent declines in reservoir pressure, thus removing the primary driving mechanism of the seepage. This finding implies that worldwide oil production may lead to declines in natural emissions of hydrocarbons on a global scale.

ACKNOWLEDGMENTS

This work was supported by grants from the University of California Energy Institute, California Energy Studies Program, and by the Minerals Management Service (MMS), U.S. Department of the Interior, under MMS Agreement no. 14-35-0001-30758. The views and conclusions contained in this document are ours and should not be interpreted as necessarily representing the official policies, either express or implied, of the U.S. Government. We thank Peter Fischer for supplying the historical data used in this work. Institute for Crustal Studies contribution number 0344-96TC.

REFERENCES CITED

Allen, A. A., Schlueter, R. S., and Mikolaj, P. G., 1970, Natural oil seepage at Coal Oil Point, Santa Barbara, California: Science, v. 170, p. 974–977.

Craft, B. C., and Hawkins, M. F., 1959, Applied petroleum reservoir engineering: Englewood Cliffs, New Jersey, Prentice-Hall, 437 p.

Crutzen, P. J., 1991, Methane's sinks and sources: Nature, v. 350, p. 380–381.

Cynar, F. J., and Yayanos, A., 1992, The distribution of methane in the upper waters of the Southern California bight: Journal of Geophysical Research, v. 97, p. 11,269–11,285.

Dando, P. R., and Hovland, M., 1992, Environmental effects of submarine seeping natural gas: Continental Shelf Research, v. 12, p. 1197–1207.

England, W. A., and Fleet, A. J., 1991, Petroleum migration: Geological Society [London] Special Publication 59, 280 p.

Fischer, P. J., 1977, Oil and tar seeps, Santa Barbara basin, California, *in* California offshore gas, oil, and tar seeps: State of California, State Lands Commission Staff Report, p. 1–62.

Fischer, P. J., and Stevenson, A. J., 1973, Natural hydrocarbon seeps along the northern shelf of the Santa Barbara basin, *in* Fischer, P. J., ed., Santa Barbara Channel revisited: American Association of Petroleum Geologists Annual Meeting Guidebook, Field Trip 3, p. 17–28.

Guthrie, L. D., and Rowley, P. R., 1983, Containment of naturally occurring subsea hydrocarbon emissions—A project review: Offshore Technology Conference, 15th, Paper 4446, p. 33–38.

Hartman, B., and Hammond, D., 1981, The use of carbon and sulfur isotopes as correlation parameters for the source identification of beach tar in the Southern California borderland: Geochimica et Cosmochimica Acta, v. 45, p. 309–319.

Hornafius, J. S., Quigley, D. C., and Luyendyk, B. P., 1999, The world's most spectacular marine hydrocarbons seeps (Coal Oil Point, Santa Barbara Channel, California): Quantification of emissions: Journal of Geophysical Research Oceans (in press).

Hovland, M., Judd, A. G., and Burke, R. A., 1993, The global flux of methane from shallow submarine sediments: Chemosphere, v. 26, p. 559–578.

Hunt, J. M., 1979, Petroleum geochemistry and geology: San Francisco, W. H. Freeman, 617 p.

Isaacs, C. M., and Peterson, N. F., 1987, Petroleum in the Miocene Monterey Formation, California, *in* Hein, J. R., ed., Siliceous sedimentary rock-hosted ores and petroleums: New York, Van Nostrand Reinhold, p. 83–116.

Killus, J. P., and Moore, G. E., 1991, Factor analysis of hydrocarbon species in the south central coast air basin: Journal of Applied Meteorology, v. 30, p. 733–743.

Kvenvolden, K. A., and Harbaugh, J. W., 1983, Reassessment of the rates at which oil from natural sources enters the marine environment: Marine Environmental Research, v. 10, p. 223–243.

Lacroix, A. V., 1993, Unaccounted-for sources of fossil and isotopically-enriched methane and their contribution to the emissions inventory: A review and synthesis: Chemosphere, v. 26, p. 507–557.

Landes, K. K., 1973, Mother nature as an oil polluter: American Association of Petroleum Geologists Bulletin, v. 57, p. 637–641.

Quigley, D. C., 1997, Spatial and temporal quantification of gaseous natural marine hydrocarbon seepage in the Santa Barbara Channel, California [Master's thesis]: Santa Barbara, University of California, 95 p.

Reed, W. E., and Kaplan, I. R., 1977, The chemistry of marine petroleum seeps: Journal of Geochemical Exploration, v. 7, p. 255–293.

Rintoul, B., 1982, ARCO Caps Santa Barbara Channel seep: Pacific Oil World, v. 74, no. 11, p. 6–9.

Smith, W., and Wessel, P., 1990, Gridding with continuous curvature splines in tension: Geophysics, v. 55, p. 293–305.

Sweet, W. E., 1973, Marine acoustical hydrocarbon detection: Offshore Technology Conference, 5th, Paper 1803.

Tinkle, A. R., Antoine, J. W., and Kuzela, R., 1973, Detecting natural gas seeps at sea: Ocean Industry, v. 8, p. 139–142.

Vernon, J. W., and Slater, R. A., 1963, Submarine tar mounds, Santa Barbara County, California: American Association of Petroleum Geologists Bulletin, v. 47, p. 1624–1627.

Watson, R. T., Rodhe, H., Oeschger, H., and Siegenthaler, U., 1990, Greenhouse gases and aerosols, *in* Houghton, J. T., et al., eds., Climate change, the IPCC scientific assessment: New York, Cambridge University Press, p. 41–68.

Wilson, R. D., Monaghan, P. H., Osanik, A., Price, L. C., and Rogers, M. A., 1974, Natural marine oil seepage: Science, v. 184, p. 857–864.

Manuscript received April 12, 1999
Revised manuscript received August 5, 1999
Manuscript accepted August 11, 1999