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Migration of Hydrocarbon and Nonhydrocarbon Gases From the Deep Crust—Composition, Flux, and Tectonic Setting

By Robert C. Burruss

GEOLOGIC CONTROLS OF DEEP NATURAL GAS RESOURCES IN THE UNITED STATES

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ABSTRACT

Hydrocarbon and nonhydrocarbon gases are generated in the deep crust by fluid-rock interactions. The trend of increasing nonhydrocarbon gas content with depth in most commercial reservoirs at depths of 14,000 ft (>4,270 m) or greater is consistent with the trend of compositions of fluid inclusions in metamorphic rocks buried to very great depth (>30,000 ft, >9,144 m). Methane is present and stable in graphite-bearing metasedimentary rocks at these great depths. The potential flux of gases from the deep crust can be estimated from the volume of water necessary to produce regionally extensive quartz vein systems in metamorphic terranes. These estimates are in the range of tens to hundreds of trillion cubic feet of methane in a single deeply buried, metamorphic terrane.

INTRODUCTION

The composition of nonhydrocarbon and hydrocarbon gases in deep >14,000 ft (>4,270 m) natural gas reservoirs yields evidence of migration of gases from deep crustal levels of more than 30,000 ft (>9,144 m) to shallower sedimentary levels. Any indication of migration of gases from great depth to drillable depths in sedimentary basins is significant for two reasons. First, it expands our knowledge of the source of gases beyond conventional concepts of gas generation, and second, the presence of nonhydrocarbon gases can have a significant impact on the economics of gas production from deep reservoirs.

Comparison of gas compositions in deep reservoirs with those of gases generated in the deep crust yields three types of information. First, the comparison can demonstrate if there are similarities between the gases in the two crustal regimes. Second, evidence for volumetric fluxes of nonhydrocarbon and hydrocarbon gases in metamorphic rocks presently exposed at the surface can be used to estimate the potential flux of gases to shallow crustal levels currently accessible to the drill. Third, identification of crustal environments (tectonic and metamorphic terranes) that generate significant quantities of gas can be coupled with analysis of structural style and setting (Perry, this volume) to identify basins in which deep crustal sources may have contributed to the hydrocarbon resource base.

GASES IN DEEP RESERVOIRS AND METAMORPHIC ROCKS

DEEP RESERVOIRS

Initial analysis of trends in gas composition versus depth and reservoir lithology was performed on all available gas data in the NRG Associates Significant Field File (NRG Associates Inc., 1991) for reservoirs at depths of 14,000 ft or greater. This file contains gas data for 120 reservoirs: 44 from the Permian Basin, 38 from the Midcontinent (mostly Anadarko Basin), 15 from the Gulf Coast North, 14 from the Gulf Coast South, and 9 from basins in the Rocky Mountains region. If the fraction of total nonhydrocarbon gases is plotted as a function of reservoir temperature (to eliminate significant variations in geothermal gradient) (fig. 1), two trends are apparent. Trend A consists of gradually increasing nonhydrocarbon gas content with depth up to about 10 percent of total gas content and is common to both carbonate and sandstone reservoirs from all basins. Trend B consists of rapidly increasing nonhydrocarbon gas content with depth and is present in a small number of carbonate reservoirs with the exception of two cases. Trend A is due to fluid-rock interactions involving organic matter and dissolution and reprecipitation of carbonate cements. Trend B is present in carbonate reservoirs of the Permian Basin (Lower Ordovician Ellenberger Group) and carbonate and sandstone reservoirs in the Upper Jurassic Smackover Formation and related strata (Upper Jurassic Norphlet Formation) of the

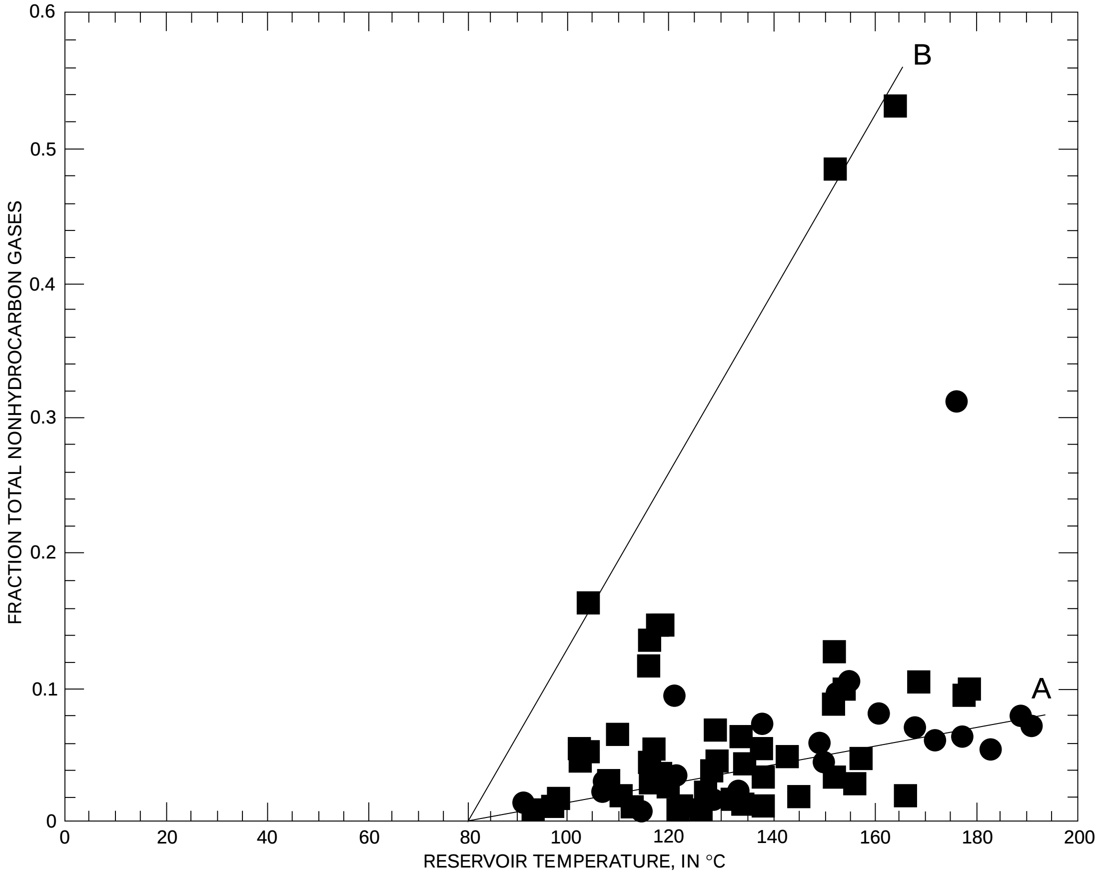

Figure 1. Fraction of total nonhydrocarbon gases ([N_2+CO_2+H_2S+He]/[sum of all gases]) versus reservoir temperature for all production from depths greater than 14,000 ft (4,270 m) cited in the NRG Associates Inc. (1991) data file. Fields are divided into sandstone (circles) and carbonate (squares) reservoir lithologies. Lines A and B define general trends in the data (see discussion in text) and are not mathematical fits to the data.

Gulf Coast. Although the dominant nonhydrocarbon gas in these reservoirs is CO_2, H_2S is also important (as much as 25 percent of total). The presence of large amounts of nonhydrocarbon gases in carbonate reservoirs and the presence of H_2S indicate that thermochemical sulfate reduction and simultaneous oxidation of hydrocarbons to CO_2 may be the dominant control on gas composition in these reservoirs.

There is some danger in overinterpreting the trends in the data from the NRG Associates field file. Because this file only contains data on reservoirs that contain greater than 1 million BOE or 6 BCFG ultimate production, the range of compositions represented is limited by the economics of production.

FLUIDS IN DEEP CRUSTAL ROCKS

Most of the evidence for the composition of fluids in the deep crust comes from observations on fluid inclusions in metamorphic and igneous rocks, and extensive reviews of the topic have been made by Hollister and Crawford (1981) and Roedder (1984). Most of the information that is relevant to gas generation is related to metasedimentary rocks that contain graphitic carbon and carbonate minerals that can act as a source of the carbon-bearing gas components, CH_4 and CO_2 (Hollister and Burruss, 1976; Burruss, 1977; Duke and Rumble, 1986). Although igneous rocks can be important sources of CO_2 (Murck and others, 1978; Roedder, 1984), they are not considered in this discussion. An additional source of information on fluids in crustal rocks is provided by fluid inclusions in quartz veins associated with ore mineralization. Reviews of fluid inclusions in ore deposits have been recently prepared by Landis and Hofstra (1991) and Kerrich and Feng (1992), and related observations from a nonmineralized setting are given by Ferry (1992). All of this information is important because it records the flux of fluids from deep to shallower levels of the crust and provides a basis for quantitative estimates of the flux of gases to shallow crustal levels as discussed in the following section.

The trends in nonhydrocarbon gas content of natural gases shown in figure 1 can be extended to deeper crustal levels by including data from fluid inclusions in rocks of well-constrained burial. Figure 2 shows the data of figure 1, together with fluid-inclusion compositions in metasedimentary rocks from three different terranes, two of which have different temperatures of equilibration at different sample localities. Although an individual locality may show a significant range in composition, it is obvious that even the highest temperature rocks still contain some methane and the compositions tend to lie along the extension of trend A, for sandstone reservoirs, from figure 1. Clearly, the "early burnout" of hydrocarbon gases that one would predict from trend B, for carbonate reservoirs, does not occur in all crustal rocks. In fact, work by van den Kerkhof (1991) on a siliceous marble that equilibrated at 800°C documents the occurrence of about 1 mole percent methane in carbon dioxide at this temperature. Although not shown in figure 2, this occurrence would plot much closer to trend A than to trend B, clearly showing that methane is stable to great depths in the crust.

Metamorphic rocks that contain more than about 10 mole percent methane in fluid inclusions tend to be graphite bearing. The compositions of the inclusions tend to be generally consistent with calculated compositions of aqueous fluids in equilibrium with graphite (Ohmoto and Kerrich, 1977; Duke and Rumble, 1986), especially if the possibility of hydrogen diffusion (loss) from inclusions is taken into account (Burruss, 1977). This observation, together with the textural evidence for precipitation of graphite from fluids (Duke and Rumble, 1986), clearly documents the generation and migration of CH_4- and CO_2-bearing fluids in the deep crust. It also suggests that identification of geologic environments in which carbon-rich sediments have been incorporated into metamorphic terranes will help define areas in which there is the greatest probability of deep crustal sources contributing to shallower natural gas resources.

GAS FLUX FROM DEEP CRUSTAL LEVELS

Estimates of the flux of gases from the deep crust are based on the measured solubility of quartz in water as a

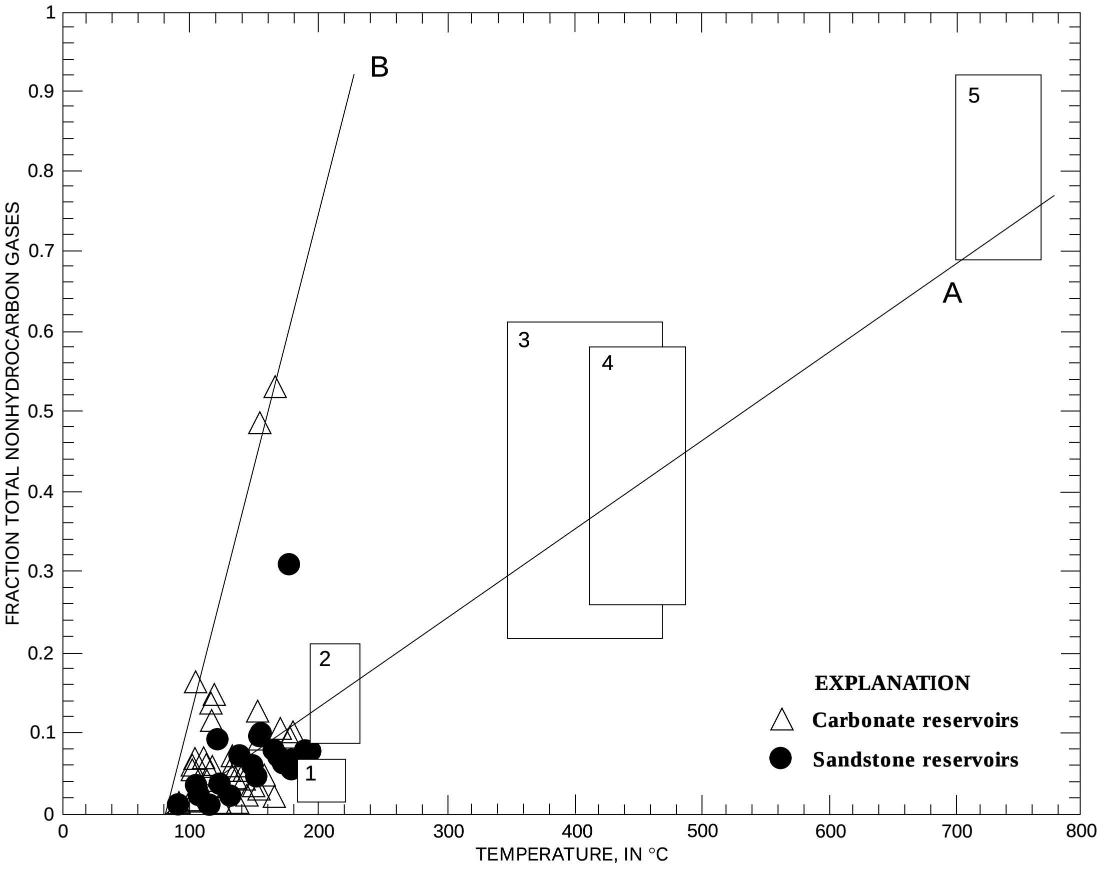

Figure 2. Data from figure 1 plotted over a wide range of composition and subsurface temperature for comparison with the composition of fluid inclusions in metamorphic rocks. The numbered boxes define the range of temperature and composition of inclusions from five sample localities: 1, 2, anthracite belt of the Valley-and-Ridge province, Pennsylvania (Kisch and van den Kerkhof, 1991); 3, 4, retrograde rocks in the granulites of Rogaland, Norway (van den Kerkhof and others, 1991); 5, prograde granulite rocks of Khtada Lake, British Columbia, Canada (Hollister and Burruss, 1976; Burruss, 1977). Lines A and B are approximate extensions of the lines shown in figure 1.

function of temperature, pressure, and salinity, which can be translated into a quantity of quartz precipitated per volume of water in a vein system at a given depth in the crust. From the volume of quartz veins that can be measured in the field, we can estimate the volume of water necessary to form the vein system. The ratio of hydrocarbon and nonhydrocarbon gases to water can be determined from fluid-inclusion measurements (Burruss, 1981; van den Kerkhof, 1988; Landis and Hofstra, 1991). Therefore, we can estimate the volume of gases that is transported with the water that is necessary to form quartz veins at depth in a given tectonic setting.

An extensive series of studies by Kerrich and his students (see review paper, Kerrich and Feng, 1992, and references therein) documents the geochemical processes and tectonic setting of formation of "giant quartz vein systems," which in many cases have associated gold mineralization (see Goldfarb and others, 1991). In one example of a giant vein system, Kerrich and others (1987) estimated that 6×10^{18} g of aqueous fluid (6×10^{3} km^{3}) deposited about 6×10^{15} g of quartz and in the process transported 3×10^{15} g of CO_2. This is 1,500 TCF of CO_2. Based on the range of methane to carbon dioxide ratios observed in fluid inclusions in quartz from one of these giant vein systems (1:3–1:40 [Landis and Hofstra,1991] for "southern Alaska mesothermal veins," which are part of Kerrich's "Cretaceous-Tertiary Coast Range Megalineament, Juneau belt, Alaska," which extends south into British Columbia, with similar observations made by Hollister and Burruss, 1976), a single giant vein system may transport on the order of 50–500 TCF of CH_4 to shallow crustal levels. Twelve giant vein systems have been documented by Kerrich and Feng (1992), and they range in age and location from Late Archean (2,700–2,600 Ma) in the Canadian and Australian shields to Tertiary (38–27 Ma) in the Alps. These twelve are only the systems documented in the literature and are biased by the fact that they are now exhumed and exposed at the surface where they can be easily studied. Fluid fluxes of similar magnitude have been documented in recent work by Ferry (1992) in giant vein systems of more common dynamothermal metamorphic terranes.

DISCUSSION AND SIGNIFICANCE

Kerrich's giant quartz-vein systems are an important component of any consideration of deep crustal sources of hydrocarbon and nonhydrocarbon gases for several reasons. First, quartz veins are direct evidence of focused flow of fluids from deep to shallow crustal levels. Second, giant vein systems are present at convergent plate margins, especially those associated with transpressive tectonic regimes (Kerrich and Feng, 1992), a geologic environment in which major hydrocarbon accumulations are present. In fact, the giant vein systems may be the best evidence to support earlier suggestions of natural gas accumulations in "accretionary" terranes (Gwilliam and Cohen, 1986).

The association of giant vein systems and convergent, transpressive plate margins may have both positive and negative aspects for potential hydrocarbon gas accumulations. On the positive side, major gas accumulations are associated with such tectonic settings, for example, the deep Anadarko Basin of Oklahoma and Texas and the Arkoma Basin of Arkansas. On the negative side, convergent, transpressive tectonic regimes tend to have a component of very active vertical tectonism that can lead to rapid erosional exhumation of potential reservoir rocks and loss of accumulations. For example, there is a large amount of fluid inclusion evidence for methane generation and transport through the Alpine quartz veins, but any sedimentary cover that could have provided reservoirs has been stripped off this young terrane.

REFERENCES CITED

Burruss, R.C., 1977, Analysis of fluid inclusions in graphitic metamorphic rocks from Bryant Pond, Maine, and Khtada Lake, British Columbia—Thermodynamic basis and geologic interpretation of observed fluid compositions and molar volumes: Princeton, N.J., Princeton University Ph. D. dissertation.

———1981, Analysis of phase equilibria in C-O-H-S fluid inclusions, *in* Hollister, L.S., and Crawford, M.L., eds., Fluid inclusions—Applications to petrology: Mineralogical Association of Canada Short Course Notes, v. 6, p. 39-74.

Duke, E.F., and Rumble, D., III, 1986, Textural and isotopic variations in graphite from plutonic rocks, south-central New Hampshire: Contributions to Mineralogy and Petrology, v. 93, p. 409-419.

Ferry, J.M., 1992, Regional metamorphism of the Waits River Formation, eastern Vermont—Delineation of a new type of giant metamorphic hydrothermal system: Journal of Petrology, v. 33, p. 45-94.

Goldfarb, R.J., Snee, L.W., Miller, L.D., and Newberry, R.J., 1991, Rapid dewatering of the crust deduced from ages of mesothermal gold deposits: Nature, v. 354, p. 296-298.

Gwilliam, W.J., and Cohen, K.K., 1986, Deep source gas potential along west coast of North America [abs.]: American Association of Petroleum Geologists Bulletin, v. 70, p. 924.

Hollister, L.S., and Burruss, R.C., 1976, Phase equilibria in fluid inclusions from the Khtada Lake metamorphic complex: Geochimica et Cosmochimica Acta, v. 40, p. 163-175.

Hollister, L.S., and Crawford, M.L., eds., 1981, Fluid inclusions—Applications to petrology: Mineralogical Association of Canada Short Course Notes, v. 6.

Kerrich, R., and Feng, R., 1992, Archean geodynamics and the Abitibi-Pontiac collision—Implications for advection of fluids at transpressive collisional boundaries and the origin of giant quartz vein systems: Earth-Science Reviews, v. 32, p. 33-60.

Kerrich, R., Fryer, B. J., King, R. W., Willmore, L. M. and Van Hees, E., 1987, Crustal outgassing and LILE enrichment in major lithosphere structures, Archean Abitibi greenstone belt—Evidence on the source reservoir from strontium and carbon isotope tracers: Contributions to Mineralogy and Petrology, v. 97, pp. 156-168.

Kisch, H.J., and van den Kerkhof, A.M., 1991, CH_4-rich inclusions form quartz veins in the Valley-and-Ridge province and the anthracite fields of the Pennsylvania Appalachians: American Mineralogist, v. 76, p. 230-240.

Landis, G.P., and Hofstra, A.H., 1991, Fluid inclusion gas chemistry as a potential minerals exploration tool—Case studies from Creede, CO, Jerritt Canyon, NV, Coeur d'Alene district, ID and MT, southern Alaska mesothermal veins, and mid-continent MVT's: Journal of Geochemical Exploration, v. 42, p. 25-59.

Murck, B.W., Burruss, R.C., and Hollister, L.S., 1978, Phase equilibria in fluid inclusions in ultramafic xenoliths: American Mineralogist, v. 63, p. 40-46.

NRG Associates Inc., 1988, The significant oil and gas fields of the United states (through December 31, 1988): Available from Nehring Associates, Inc., P.O. Box 1655, Colorado Springs, Colorado 80901.

Ohmoto, H., and Kerrich, D., 1977, Devolatilization equilibria in graphitic systems: American Journal of Science, v. 227, p. 1013-1044.

Roedder, E.,1984, Fluid inclusions: Mineralogical Society of America Reviews in Mineralogy, v. 12, 644 p.

Van den Kerkhof, A.M., 1988, The system CO_2-CH_4-N_2 in fluid inclusions—Theoretical modeling and geological applications: Amsterdam, Free University Press, 206 p.

———1991, Heterogeneous fluids in high-grade siliceous marbles of Pusula (SW Finland): Geologische Rundschau, v. 80, p. 249-258.

Van den Kerkhof, A.M., Touret, J.L.R., Maijer, C., and Jansen, J.B.H., 1991, Retrograde methane-dominated fluid inclusions from high-temperature granulites of Rogaland, southwestern Norway: Geochimica et Cosmochimica Acta, v. 55, p. 2533-2544.

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