Analyzing the Thermal History of Sedimentary Basins: Methods and Case Studies

Edited by Nicholas B. Harris and Kenneth E. Peters
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ABSTRACT: Bottom-hole temperatures (BHT) from well log headers are common, but they require correction because they are biased lower than true formation temperature. Care must be taken to avoid short static times, recirculation between measurements, and spurious records of times or temperatures from logs. Criteria for reliable Horner-corrected BHT data include a minimum of three logging runs that record time and temperature for each run, temperature extrapolation less than the range of temperature data, and deviations from the least-squares regression line that are less than measurement uncertainty (±1–3°C or ±2–5°F).

Based on published comparisons of drill-stem test (DST) and Horner-corrected BHT data from the same depths, the standard deviation of corrected bottom-hole temperatures is about ±8°C (±14°F). Some studies show that corrected data may still be systematically biased lower than true formation temperature. For a one-dimensional PetroMod® basin and petroleum system model of the upper Cook Inlet in Alaska, error of ±8°C resulted in calculated depth to top of the oil window in the Jurassic Tuxedni Group source rock of as much as 305 m (1001 ft) above and 6.2 million years earlier or 231 m (758 ft) below and 4.5 million years later than that calculated using a corrected BHT formation temperature of 92.4°C. Error in maturity assessment associated with shallow BHT data can propagate to the greater depth of the source rock where temperature and thermal maturity are to be estimated. In summary, BHT data are an important source of uncertainty that needs to be considered when calibrating basin and petroleum system models.
ABSTRACT: Many basin simulators include the option to use calculated biomarker ratios from published first-order kinetic parameters as a means to calibrate thermal history. Published kinetic parameters for many biomarker reactions are based on simplistic and unfounded assumptions of reaction pathways, lack the needed precision, or have insufficient documentation to evaluate their effectiveness. We believe that calibrations of thermal history based on biomarker ratios are less reliable than those based on more common methods, such as vitrinite reflectance and corrected bottom-hole temperatures, because of uncertainty in the reaction mechanisms and kinetic parameters. Some research indicates that certain reactions, such as cyclization of ortho-substituted biphenyls and thermal decomposition of alkyl esters, could provide useful kinetics with which to calibrate basin models, but these efforts have not been pursued by the geochemical community.
ABSTRACT: The effect of thermal maturation on the δD values of individual petroleum hydrocarbons (n-alkanes and regular isoprenoids) from sedimentary organic matter over geological timescales has been explored in six different sedimentary sequences covering a wide range of maturities; i.e., 0.53%–1.6% vitrinite reflectance (Ro or equivalent; i.e., Re, Rc). These include new data and recently reported literature data on formations ranging in age from the Early Cretaceous to the Permian. The application of Deuterium/Hydrogen (D/H) of biomarkers as a maturity proxy for Devonian source rocks from the Western Canada Sedimentary Basin is also presented here, extending this application to much older sediments than previously studied. In each case, pristane and phytane are predominantly derived from the lipid side chain of chlorophyll a present in most photosynthetic organisms, with an additional (but minor) contribution to pristane from tocopherol of land plants in selected cases. The n-alkanes represent contributions of algae, bacteria, and in certain cases higher plants. In general, the n-alkanes, pristane, and phytane from relatively immature sediments have δD values that retain the isotopic signature of their natural product precursors; i.e., biosynthesized lipid components made up of acetyl and isoprene subunits, respectively. With increasing maturity, pristane and phytane become more enriched in deuterium (D), while the n-alkanes generally remain at a constant isotopic composition until an overmature level is reached, at which point there is a significant enrichment of D in n-alkanes. The enrichment of D in pristane and phytane with increasing maturity correlates strongly with changes in traditional maturity parameters, including vitrinite reflectance, T_max and molecular parameters, providing evidence that D enrichment is associated with thermal maturation.
ABSTRACT: Fluid inclusion geothermometry is useful for establishing detailed thermal histories of sedimentary rocks that cannot be gleaned from other techniques. The fluid inclusion technique requires careful attention to petrography and evaluation of thermal reequilibration. The fluid inclusion assemblage approach (FIA) is most important in evaluating the extent to which fluid inclusions have been altered.

Fluid inclusion geothermometry can be accomplished in both low- and high-temperature sedimentary systems. At low temperature, it can be used in paleoclimate work by generating bubbles from metastable inclusions, using cooling and femtosecond laser techniques. At elevated paleotemperature, homogenization temperatures (Th) can be measured from inclusions composed of high-temperature aqueous liquid without dissolved gas, high-temperature aqueous liquid with dissolved gas, gas, and petroleum. Given consistent FIA and an understanding of the pressure–volume–temperature (PVT) relations for the inclusions, fluid inclusion Th data can be pressure-corrected given certain constraints.

Inclusions can be used to evaluate the detailed spatial, temporal, tectonic, and fluid composition history of a system that cannot be determined in other ways. Fluid inclusions are used as a tool for determining the maximum temperature achieved in a sample, but this commonly would be an under-utilization of the data generated. Unlike other techniques, fluid inclusions can link thermal history to fluid flow, as a means of evaluating whether heating was associated with normal burial conditions, hydrothermal systems, or cool fluids flowing into warmer rocks. Hydrothermal systems can be identified when geothermometry indicates: (1) repeated increases and decreases in temperature inconsistent with the burial and unroofing history; (2) paleotemperatures higher than what the most liberal burial history analysis will allow; (3) paleogeothermal gradients or pressure–temperature data inconsistent with normal burial; (4) evidence for locally increased temperature at the same depth within a region; and (5) geothermometric evidence that higher temperatures are focused in fracture, fault, or stratigraphic conduits for paleofluid flow.
ABSTRACT: While several methods have been developed for assessing the magnitude of postdepositional heating of sedimentary rocks, apatite fission track analysis (AFTA®) can also define the time at which a sedimentary rock cooled from its maximum postdepositional temperature, up to ~110° C. This information is particularly important in hydrocarbon exploration, e.g., in defining the timing of hydrocarbon generation and identifying regions where the main phase of generation postdates formation of potential trapping structures.

Based on analysis of naturally occurring radiation damage features (fission tracks) in detrital apatite grains, the foundation of the technique is a detailed understanding of the kinetics of fission-track “annealing,” incorporating observations from both laboratory and geological field conditions and making explicit allowance for apatite composition (chlorine content), which exerts a crucial influence over fission-track annealing kinetics. The thermal response of fission tracks is dominated by the maximum postdepositional paleotemperature, and this fundamental aspect of the technique imposes strict limitations on the information that can be obtained. In particular, no information can be obtained on the thermal history prior to the onset of cooling from the maximum postdepositional temperature. However, one or possibly two additional episodes of heating and cooling can often be resolved following the paleo-thermal maximum. Integration of AFTA data with paleotemperature estimates from other methods, in particular vitrinite reflectance (VR), provides additional support for thermal history interpretations and can often help to refine solutions from AFTA.

Most importantly, the combined use of AFTA and VR in a vertical sequence allows construction of profiles of paleotemperature with depth (or elevation), enabling quantitative determination of paleogeothermal gradient, which in turn allows identification of the mechanisms of heating and cooling. Heating due to deeper burial produces a linear paleotemperature profile with a similar gradient to the present temperature profile, whereas heating due primarily to increased basal heat flow will produce a profile with a higher gradient than the present temperature profile. Extrapolation of such profiles above the appropriate unconformity identified from AFTA to a suitable paleo-surface temperature allows determination of the magnitude of additional burial responsible for the observed heating. Estimations of additional burial in this way depend on assumptions concerning the lithology (i.e., thermal conductivity) of the eroded sequence and wherever possible should be combined with estimates of burial based on nonthermal processes, such as sonic velocity, in order to provide consistent constraints on the burial history. Nonlinear profiles are produced by contact heating around intrusive bodies and by passage of hot fluids within confined aquifer horizons. More complex situations that involve nonlinear profiles resulting from thick sequences with extreme thermal conductivities (e.g., coal or salt) can also be assessed by inspection of the variation of paleotemperature with depth. AFTA has been applied to hydrocarbon exploration in a wide variety of settings. Some of the most important outcomes of AFTA analysis, in terms of events that affect regional hydrocarbon prospectivity, are: (1) the recognition of regional kilometer-scale exhumation (implying earlier deeper burial), often in areas that have traditionally been considered stable; (2) definition of major Phanerozoic paleo-thermal events in Proterozoic basins; and (3) revelation of the importance of hot fluids in transporting heat in sedimentary basins. In basins with complex histories, for example, exhumed basins or those in which heat flow was higher in the past, AFTA can provide unique constraints on the timing of hydrocarbon generation, which can significantly reduce exploration risk in such areas.
ABSTRACT: The (U-Th)/He technique is based on the accumulation and diffusive loss of helium generated by alpha decay. The temperatures required to drive diffusion vary with mineral type and characteristics and can range from <50° C to >200° C, an ideal range for basin thermal history analysis. Although promising due to its conceptual simplicity and capacity for quick analysis, (U-Th)/He has proven to be quite challenging in practice due to a variety of complications, such as alpha particle ejection and implantation, grain-size effects, and the influence of radiation damage on helium diffusivity. Recent research has begun to quantitatively characterize many of these processes and their effects, allowing the technique to be applied with increasing confidence and robustness. This paper reviews the current state of knowledge of the physics and chemistry underlying the (U-Th)/He system, and the modeling approaches that allow thermal history information to be extracted from various kinds of data. A new approach for simultaneously accounting for grain-shape effects on both diffusion and alpha particle ejection is proposed. Various examples of basin and other field studies employing (U-Th)/He are reviewed and in some cases reinterpreted using up-to-date tools and approaches. As the (U-Th)/He system is further explored and tested in the field and laboratory, it will become an increasingly robust and versatile tool for basin analysis.
THERMAL HISTORY ANALYSIS OF SEDIMENTARY BASINS: AN ISOTOPIC APPROACH TO ILLITIZATION

NORBERT CLAUER
Laboratoire d’Hydrologie et de Géochimie de Strasbourg, (CNRS/UdS), 1 rue Blessig, 67084 Strasbourg, France
e-mail: nclauer@unistra.fr

AND

ABRAHAM LERMAN
Department of Earth and Planetary Sciences, Northwestern University, Evanston, Illinois, USA

ABSTRACT: The postdepositional history of clay minerals is critical to understanding the diagenetic evolution of sedimentary rocks. Diagenetic changes occurring in sedimentary K-bearing clay minerals, known as illitization, are routinely identified by a changing trend in the mineralogy from smectite to illite. This change is typically gradual, with the smectite-rich components changing into illite-rich components affected by the addition of K, generally occurring during progressive burial. Understanding of illitization is also germane to the use of authigenic illite as temperature and age indicators of the thermal history of sedimentary rock sequences. Oxygen and hydrogen isotope geothermometry and radiogenic isotope dating (by K-Ar or other methods) of authigenic illite represent tools that can potentially help decipher the thermal histories of sedimentary basins.

For these analytical techniques to be meaningful, a particularly adequate mineral separation and an accurate mineral identification are necessary, which may be difficult and not systematically successful because of the small sizes and varied origins of the studied minerals. Combined with detailed X-ray analyses and electron microscope observations, stable and radiogenic isotopic data have proven useful in distinguishing burial-induced from hydrothermally-induced temperature increases in sedimentary sequences. Some of the difficulties in the application of isotopic methods to separate clay-sized materials (which may also contain other silicates of identical size) can arise from uncertain values of the isotope fractionation factors of oxygen and hydrogen and from mixtures of detrital and authigenic components in the analyzed size fractions.

Conflicting isotopic data from illite-rich size fractions may also result from difficulties associated with demonstrating chemical and isotopic equilibrium between minerals and fluids, especially in the low-temperature domain. The intimate physical association of detrital and authigenic illitic particles of varied sizes, which may not be physically separated, can also contribute to the drawbacks. In order to provide a coherent overview of the input of isotope studies to the understanding of illitization—and therefore of the thermal history of sedimentary basins—burial-induced and more sporadic rock–hot fluid interactions, such as those of Northern Germany, Paris, East Slovak, and of the Mahakam Delta, are evaluated on the basis of combined mineralogical and isotopic databases of the illitic and associated materials.
APPLICATION OF GAS ISOTOPES TO THE THERMAL HISTORY ANALYSIS OF BASINS

XINYU XIA AND YONGCHUN TANG
Power Environmental Energy Research Institute, 738 Arrow Grand Circle, Covina,
California 91722, USA
e-mail: tang@peeri.org

ABSTRACT: Carbon isotope composition can be used to derive natural gas generation temperature and source rock maturity by applying a rigorous parallel first-order reaction model based on quantum chemistry and microkinetics. In gas generation reactions, the breaking of $^{13}$C–$^{12}$C and $^{12}$C–$^{12}$C bonds has different frequency factors and activation energies. After the optimizing of these kinetic parameters with laboratory experiments, we can use the model to derive natural gas formation temperature and source rock maturity with given carbon isotope composition data. This method is useful for analyzing the thermal history of a basin along with petroleum generation and accumulation history of reservoirs, especially for strata that lack vitrinite for reflectance measurements.
EVALUATION OF THE HEAT FLOW IN THE SOUTHERN ALPS DURING MESOZOIC EXTENSION: IMPLICATIONS FOR HYDROCARBON EXPLORATION IN THE PO PLAIN FOREDEEP

PAOLO SCOTTI AND ROBERTO FANTONI
Eni S.p.A.–Exploration and Production Division, Via Emilia 1, 20097 San Donato Milanese, Milan, Italy
e-mail: paolo.scotti@eni.com

ABSTRACT: We reconstructed the thermal history, and therefore the evolution of heat flow in the southern Alps region (northern Italy), using organic matter (OM) maturity data obtained from samples of sedimentary units outcropping along the entire mountain chain. Regional OM maturity patterns are largely controlled by a high geothermal gradient and differential burial during the Norian–Liassic extensional phase. Good results for thermal history calibrations from several locations were obtained using a large database of measured OM maturity, consisting of different maturity parameters, often all in agreement, for a wide range of lithostratigraphic sequences.

One-dimensional thermal modeling was applied to selected successions that were not overprinted by alpine evolution. Resulting heat-flow values were high and relatively uniform (85 to 105 mW/m²) throughout the southern Alps during the Lias–Early Dogger, and they progressively decreased after the Bajocian–Bathonian to values similar to the present-day heat flow (50 to 55 mW/m²) by the end of the Cretaceous. This heat-flow reconstruction is consistent with the known tectonic evolution of Mesozoic extension in the southern Alps, characterized by a rifting stage lasting to the Lias, followed by a drifting stage beginning in the Middle Jurassic.

Elevated heat flow in the southern Alps has important implications for hydrocarbon exploration. Upper Triassic source rocks in basinal successions attained high maturity during the Jurassic, and this is even more likely for the deeper Middle Triassic source rocks.

Improved definition of the heat-flow peak in the Jurassic helps to define the hydrocarbon charge risk associated with leads and prospects in the Po Plain subsurface, where traps formed in the Cenozoic. In areas characterized by little Rhaetian–Liassic burial, the source rocks retained their original petroleum potential prior to strong Neogene–Quaternary burial and heating.
PALEOBURIAL, HYDROCARBON GENERATION, AND MIGRATION IN THE CÓRDOBA PLATFORM AND VERACRUZ BASIN: INSIGHTS FROM FLUID INCLUSION STUDIES AND TWO-DIMENSIONAL (2D) BASIN MODELING

ESMERALDA GONZALEZ
Pemex Exploration and Production, Veracruz, Mexico and Direction Géologie–Géochimie–Géophysique, IFP Energies nouvelles, 1–4 Avenue de Bois-Préau, F-92852 Rueil-Malmaison Cedex, France

HELGA FERKET
Direction Géologie–Géochimie–Géophysique, IFP Energies nouvelles, 1–4 Avenue de Bois-Pré’au, F-92852 Rueil-Malmaison Cedex, France and Mexican Petroleum Institute (MPI), Mexico DF, Mexico and VITO, Boeretang 200, 2400 Mol, Belgium

JEAN-PAUL CALLOT*
Direction Géologie–Géochimie–Géophysique, IFP Energies nouvelles, 1–4 Avenue de Bois-Pré’au, F-92852 Rueil-Malmaison Cedex, France.
Present address: UMR CNRS TOTAL 5150 “Laboratoire des Fluides Complexes et leurs Réservoirs,: Université de Pau et des Pays de l’Adour I.P.R.A. Avenue de l’Université BP 1155 64013 PAU Cedex, France
e-mail: jean-paul.callot@univ-pau.fr

NICOLE GUILHAUMOU
MNHN, Muséum National d’Histoire Naturelle, Laboratoire d’étude de la matière extra-terrestre, 57 rue Cuvier, F-75005 Paris, France

SALVADOR ORTUNO
Mexican Petroleum Institute (MPI), Mexico DF, Mexico

AND

FRANÇOIS ROURE
Direction Géologie–Géochimie–Géophysique, IFP Energies nouvelles, 1–4 Avenue de Bois-Pré’au, F-92852 Rueil-Malmaison Cedex, France and Vrije Universiteit Amsterdam, The Netherlands

ABSTRACT: One-dimensional and two-dimensional basin modeling has been performed along a regional transect crossing the Córdoba Platform allochthons and the autochthonous Veracruz Basin in order to infer the burial and kinematic evolution and to determine timing of hydrocarbon migration and charge in this famous Mexican petroleum province. Vitritine reflectance, Rock-Eval data, and bottom-hole temperatures have been used to calibrate the heat flow and thermal evolution of the Veracruz Basin, where no erosion occurred.

The Córdoba Platform and Veracruz Basin in Eastern Mexico comprise the southernmost extent of the Laramide foreland fold-and-thrust belt, which developed along the eastern border of the North American Cordillera from Late Cretaceous to Eocene. Unlike in the Canadian Rockies, where pre-orogenic strata are relatively isopachous, this segment of the North American craton has been strongly affected by the Jurassic rifting and opening of the Gulf of Mexico. Substantial thickness and facies changes between...
horsts and grabens control the lateral and vertical distribution of Mesozoic source rocks and hydrocarbon reservoirs.

In the east, thick Paleogene and Neogene sequences in the Cordilleran foreland provide a continuous sedimentary record in the Veracruz Basin. In the west, however, the Middle Cretaceous carbonates of the Córdoba Platform generally constitute the main outcropping horizon in the adjacent thrust belt, making it difficult to reconstruct its burial evolution from the Laramide orogeny onward.

Cemented veins were sampled in reservoir intervals of the thrust belt. Petrography, stable isotope analyses, and fluid inclusion studies (microthermetry, Synchroton Fourier Transform Infra-Red analyses) on these samples revealed the diagenetic history of the reservoirs. Where diagenetic phases could be constrained in time and with respect to the tectonic evolution, fluid inclusion temperatures provide an additional paleothermometer in areas where major erosion occurred. Pressure–temperature modeling of simultaneously entrapped aqueous and oil-bearing inclusions indicates more than 4.5 km of erosion of Late Cretaceous–Paleocene sequences in the thrust belt, which can be accommodated in palinspastic sections only by restoring a hypothetical foredeep basin. This implies that the current east-dipping attitude of the basement beneath the Córdoba Platform developed after Laramide deformation, accounting for a major change in paleofluid dynamics. Fluid flow and basin modeling of the Veracruz section has been performed using CERES2D to infer the paleofluid dynamic associated with the petroleum system evolution. Following the initial phase of geometric model building and calibration against the thermal and burial history inferred, the modeling accounted for the past migration pathways for both water and oil and gas fluids. Unlike in most other foreland fold-and-thrust belts, hydrocarbons generated in Jurassic source rocks from the Veracruz foreland are currently migrating westward toward the thrust belt, accounting for a post-Laramide charge of the frontal duplexes of the Cordilleran thrust belt.
ABSTRACT: Measurements of dispersed vitrinite in several exploration wells within the Tertiary and Quaternary rift sediments of the northern Upper Rhine Graben indicate a complex thermal history. While most wells show “normal” increasing maturity trends with depth, some lack any obvious trend. One of the investigated wells, Nordheim-1, even features a bell-shaped downhole anomaly having an inverse maturation trend. Abnormal maturation effects, such as oxidation, reworking, or deposition of previously coalified material from the hinterland, are ruled out as a result of the relative position of the well with respect to the graben shoulders or active fault systems. Thus, secondary maturation caused by focused, lateral hydrothermal fluid flow has been proposed.

To verify the measured maturity anomaly organic (Rock-Eval pyrolysis, methylphenanthrene distribution), geochemical analyses were used to obtain independent data for comparison. T_{max} values from Rock-Eval pyrolysis and various ratios of methylphenanthrene isomers indicate abnormally high maturities at shallow depth. Like the vitrinite reflectance values, these techniques show maturities that are inconsistent with their present burial depth but support enhanced convective hydrothermal heat flow in these strata. The consistency of results obtained using independent techniques verifies a hydrothermal origin of the maturity anomaly and excludes other modes of alteration.
THERMAL MATURATION HISTORY OF ARCTIC ALASKA AND THE SOUTHERN CANADA BASIN

DAVID W. HOUSEKNECHT AND W. MATTHEW BURNS
US Geological Survey, Reston, Virginia 20192 USA
e-mail: dhouse@usgs.gov

AND

KENNETH J. BIRD
US Geological Survey, Menlo Park, California 94025 USA

ABSTRACT: The emerging global focus on the oil and gas potential of the Arctic underscores the importance of understanding petroleum systems with limited data. Geohistory modeling of Arctic Alaska (including the Chukchi shelf) and the southern Canada basin indicates that regional patterns of thermal maturity and timing of petroleum generation reflect geologic processes associated with rift-opening of the Canada basin and collision orogenesis along the Brooks Range–Herald arch from Jurassic through Tertiary time. The base of the Cretaceous–Tertiary Brookian sequence provides a regional reference horizon because most oil generation occurred as the result of Brookian burial.

In Arctic Alaska, basal Brookian strata on the Beaufort rift shoulder grade from immature in the west to overmature in the east. From the crest of the rift shoulder, thermal maturity of basal Brookian strata increases southward into the oil window on the north flank of the Colville foreland basin and into the gas window in the foredeep. A >200-mile-wide area of immature to mature strata in the Chukchi Sea narrows eastward as the Brooks Range converges with the rift shoulder in the eastern North Slope. These patterns reflect generally low Jurassic to Tertiary sediment accommodation on the rift shoulder, large Cretaceous sediment accommodation in the Colville foredeep, and northward impingement of the Brooks Range onto the eastern part of the rift shoulder during the Tertiary.

Fewer geologic data in the Canada basin increases the uncertainty of modeling. Projection of stratigraphy from the rift shoulder, reconstruction of regional sediment dispersal patterns, and consideration of source rocks in Arctic Alaska and Canada indicate the potential for four source rocks in the Cretaceous and Paleogene. Model results indicate that all four source rocks are mature or overmature across much of the southern Canada basin. The highest thermal maturity occurs in depocenters immediately north of the rift shoulder and on the eastern margin of the study area, which is the distal Mackenzie delta. The lowest thermal maturity occurs at the northern limit of modeling, more than 200 miles north of the rift shoulder and on the western margin of the study area, adjacent to the Chukchi borderland. A potential source rock in the Lower Cretaceous likely matured during the Early Cretaceous in a western depocenter related to sediment by-pass of the Chukchi shelf, but maturation of all source rocks elsewhere occurred during the Paleogene when large volumes of sediment were shed from the Brooks Range and through the Mackenzie delta.