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Illite and hydrocarbon exploration

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ABSTRACT Illite is a general term for the dioctahedral mica-like clay mineral common in sedimentary rocks, especially shales. Illite is of interest to the petroleum industry because it can provide a K-Ar isotope date that constrains the timing of basin heating events. It is critical to establish that hydrocarbon formation and migration occurred after the formation of the trap (anticline, etc.) that is to hold the oil. Illite also may precipitate in the pores of sandstone reservoirs, impeding fluid flow. Illite in shales is a mixture of detrital mica and its weathering products with diagenetic illite formed by reaction with pore fluids during burial. K-Ar ages are apparent ages of mixtures of detrital and diagenetic end members, and what we need are the ages of the end members themselves. This paper describes a methodology, based on mineralogy and crystallography, for interpreting the K-Ar ages from illites in sedimentary rocks and for estimating the ages of the end members.

Illite is a general term for the dioctahedral mica-like clay mineral common in sedimentary rocks, especially shales (1, 2). Although it has a strict mineralogical definition (3), the name illite is often loosely used for any clay mineral with a 1-nm repeat in the x-ray powder diffraction data (4). Because shale is abundant at the earth's surface, its typical clay mineral, illite, impacts human welfare in several ways. In the petroleum industry, illite is of interest for two reasons: (i) It can provide an isotope date constraining basin heating events, and (ii) it may precipitate in the pores of sandstone reservoirs, impeding fluid flow. Because it is a potassium aluminum phyllosilicate, its time of formation can be determined by using K-Ar isotope dating. Illite holds Ar tightly because of the difficulty of migration (diffusion) through the crystal structure layers (5) at low temperatures.

Of particular concern in resource exploration is the timing of hydrocarbon (HC) generation. When were the organic-rich source rock shales heated to $\approx 100^\circ\text{C}$, cracking the solid organic matter to oil and gas? It is critical to establish that HC formation and migration occurred after the formation of the trap (anticline, etc.) that is to hold the oil. We have long been able to find traps by using seismic methods, but we seldom are able to predict the presence of HC without expensive drilling. If integrated geologic evaluation of outcrops or nearby wells can show HC generation after trap formation, the risk of drilling a dry hole is reduced. Because illite forms in shales in response to heating in the same temperature range as oil formation (6), its K-Ar age is useful indeed.

It has been recognized for some time (7) that illite in shales is a mixture of detrital mica and its weathering products with diagenetic illite precipitated from pore fluids during burial. Two important lines of evidence support this conclusion. First, grain size vs. mineralogy relations show a mixture of $2M_1$ and $1M$ (including $1Md$) polytypes, with $1M$ increasingly abundant in the finer size fractions (7). Polytypes are a variety of

polymorph distinguished by various repeating stacking arrangements of identical layers (3). $1M$ means one layer, monoclinic, etc. The $2M_1$ polytype certainly is expected (8) for the large detrital micas eroded from slates, schists, and phyllites. As we shall see, diagenetic illite that grows in bentonites and sandstones is exclusively $1M$, which suggests that similar material mixed with $2M_1$ muscovite in shales is also diagenetic. Secondly, grain size vs. K-Ar age relations in shales invariably show age decreasing with grain size: The coarse fractions are typically older than the depositional (stratigraphic) age of the shale whereas the fine fractions are younger (9). The foregoing shows that illite in shales is a mixture of detrital and diagenetic components, with the latter more abundant in the fine fractions. But it also identifies the principal problem with practical use of K-Ar dating of illite in shales: The ages of bulk mixtures of detrital and diagenetic end members are rather meaningless, and what we need are the separate ages of the end members themselves. I describe a methodology, based on mineralogy and crystallography, for interpreting the K-Ar ages from illites in sedimentary rocks and for estimating the ages of the end members.

Illite in Sedimentary Rocks

One cannot discuss illite without touching the subject of mixed-layer illite/smectite (I/S), a mineral in which unit cell scale layers of illite and smectite are shuffled like a deck of cards. Clay mineralogists typically disaggregate a sample and prepare one or more grain size fractions as oriented aggregates (10) on a slide for x-ray powder diffraction (XRD) with a focusing diffractometer. Because the particles orient with $00l$ parallel to the slide, only the $00l$ reflections appear in the data. Illite has a series of $00l$ reflections based on a 1-nm periodicity; smectite, with interlayer water, has a 1.4-nm periodicity that can vary with humidity or treatment with organics. XRD patterns ($00l$ series) for I/S typically are nonperiodic (nonintegral; they do not obey Bragg's Law) and do not look like a physical mixture of illite and smectite. They are interpreted (6) to result from a single diffraction from a faulted layer structure composed of two types of unit cells. There is a mature technology (10) for quantifying and modeling XRD data from mixed-layer clay minerals.

I/S is common in shales; indeed, much of the illite in shales may be in the form of I/S. The percent of illite in I/S typically increases with depth and temperature in most of the world's sedimentary basins and with geologic age (6). This has been interpreted (or inferred) to indicate a progressive solid state or layer-by-layer transformation of smectite to illite in which the initial structure of the smectite is inherited by the illite (11). More recently, Nadeau (6, 10, 12) has introduced the dual concepts of fundamental particles and interparticle diffraction to explain mixed-layer clays. In this view, thin (2- to 10-unit

Abbreviations: HC, hydrocarbon; I/S, illite/smectite; XRD, x-ray powder diffraction; AFM, atomic force microscopy; IAA, Illite Age Analysis; my, million years.

cells) illite crystals precipitate in shales whereas smectite, feldspars, and other minerals dissolve. The diffraction effects of I/S result from coherent (in 00 ℓ) scattering amongst thin face-to-face illite crystals with hydrated interfaces that behave like smectite (are turbostratic). As crystals grow thicker, the number of interfaces decreases, which is seen in the XRD data as a decrease in smectite component of I/S. The observation of thin ideomorphic crystals of 1M illite with 1-nm surface growth steps in sandstones and shales (13) supports Nadeau's ideas. The subject of I/S remains controversial, but here I assume that increase in illite content of I/S with burial depth simply represents the growth of progressively thicker illite crystals.

To extract useful chronologic information from K-Ar dating of illite, I have found the concept of grain-size vs. age spectra (size-age spectra) useful (Fig. 1a). A sample is routinely divided into three clay-size fractions: coarse (C = 0.2–2.0 μm), medium (M = 0.02–0.2 μm), and fine (F = <0.02 μm), and, for each, a routine K-Ar age is obtained. Using the <2- μm fraction generally excludes feldspar, so that the only K-bearing phases are illite and micas. Plotting these as simple bar graphs has revealed three major spectra shapes for sedimentary rocks: inclined, flat, and benched. These are typical of shales, K-bentonites, and sandstones, respectively.

An inclined spectrum (Fig. 1a) is typical for shales, which are deposited with a wide initial size range of detrital micas. Usually the C fraction is older than the depositional age, but this depends on the proportion of diagenetic illite. The F fraction is typically younger than the depositional age because of the dominance of diagenetic illite. Importantly, as pointed out 35 years ago by Hower *et al.* (9), there is no way to use these dates, except as crude limits. All fractions appear to be physical mixtures, and we do not know the proportions. The mixture of old and young illite in shales can for some samples give K-Ar ages fortuitously close to depositional age (9). Note that K-Ar data from shales cannot be successfully interpreted by using the isochron method because shales are mixtures of things that formed at different times. They do, however, often give nice-looking, linear, but useless, "mixochrons."

Bentonites (stratigraphic definition) are an uncommon class of shale bed consisting of air-fall glassy volcanic ash altered to smectite (3). K-bentonites (3) are those that have undergone subsequent diagenesis to illite or I/S. They are of great value to illite studies because they do not contain detrital dioctahedral micas, only diagenetic illite. The size-age spectrum of a K-bentonite is typically flat (Fig. 1b); i.e., all size fractions have the same K-Ar age, younger than depositional age. Bentonites give the diagenetic age directly because they do not contain detrital illite.

FIG. 1. (a) Size-age spectrum for shale. The sample is divided into three clay-size fractions: coarse (C = 0.2–2.0 μm), medium (M = 0.02–0.2 μm), and fine (F = <0.02 μm). An inclined spectrum is typical for shales, which are deposited with a wide initial size range of detrital micas. Usually, the C fraction is older than the depositional age, but this depends on the proportion of detrital mica. The F fraction is typically younger than the depositional age because of the dominance of diagenetic illite. (b) Size-age spectrum for a K-Bentonite is flat; i.e., all size fractions have the same K-Ar age, younger than depositional age. Bentonites give the diagenetic age directly because they do not contain detrital illite.

give the mean diagenetic age directly. If bentonites were common in the stratigraphic record, we could forget about trying to get meaningful ages from ordinary shales. They are useful for our dating problem because they give us an idea of what the pristine diagenetic illite is like. Mineralogic studies of K-bentonites are numerous, and XRD shows the illite and I/S to be entirely 1M polytype with moderate amounts of 120° rotational disorder (14, 15). 2M₁ muscovite is never found as a diagenetic phase in K-bentonites of sedimentary basins. This is good news because it gives us a possible way to differentiate and quantify the diagenetic and detrital components in shales.

Atomic force microscopy (AFM) shows the K-bentonite illite crystals to be only a few nanometers thick (Fig. 2), with a predominance of 1-nm growth steps. The former is confirmed by XRD studies of the 00 ℓ reflections (16); the latter agrees with their 1M polytype. The extraordinary thinness likely explains the abundance of diagenetic illite in the fine fractions of shales.

Sandstones with a shale-like depositional matrix or abundant lithic grains have size-age spectra similar to shales and will not be discussed further. Clean sandstones consist only of sand-sized grains of quartz, feldspars, mica, etc., and lack depositional clay. They are deposited in a high-energy environment (like a beach) in which the fines are winnowed away. During diagenesis, feldspars and other rock constituents may react with pore fluids to precipitate illite or other diagenetic clays; hence, the fine material in these sandstones tends to be mostly diagenetic, and more so than for shales. A typical sandstone size-age spectrum (Fig. 3) is bench-shaped; i.e., the C fraction is older than depositional age whereas the M and F fractions have the same age, younger than depositional age. This flattening out in the finer fractions permits us to conclude that fine detrital mica is absent in these fractions and that we have measured the mean age of illite formation. Unfortunately, diagenetic illite is not so universally abundant in sandstones as it is in shales, and not all sandstones are clean sandstones.

There are many studies of pore filling illites, both mineralogic and K-Ar dating (2, 6, 10). The abundant literature is primarily due to the negative effect illite has on permeability

FIG. 2. AFM deflection image of illite crystals from the Tioga K-bentonite. Scale is in nanometers. Individual growth steps are 1 nm high; the largest crystal is 7 nm thick. The image was made in air, contact mode, on a Digital Instruments (Santa Barbara, CA) Multi-Mode Nanoscope IIIa.

FIG. 3. Size-age spectrum of sandstone. The spectrum is typically bench-shaped; i.e., the C fraction is older than depositional age whereas the M and F fractions have the same age, younger than depositional age. The flattening out in the finer fractions indicates that fine detrital mica is absent in these fractions and that we have measured the mean age of illite formation. Symbols are same as in Fig. 1.

of sandstone petroleum reservoirs. The illites are typically ideomorphic with a pronounced fibrous (lath) habit (long axis is crystallographic a axis) making them interesting subjects for microscopy (Fig. 4). They are often called “hairy illite” in the petroleum industry. The crystals are ideomorphic because they precipitate unconstrained from fluid in a relatively large pore. They are all 1M polytype, with a minor 120° rotational disorder. As in K-bentonites, they are thin (2–10 nm), with 1-nm growth steps and some evidence of spiral growth. Samples composed of especially thin crystals are I/S by XRD. There is no evidence for a smectite precursor. Individual laths may be intergrown at 120° to produce star-like aggregates or twins (Fig. 5). The twinning (a rotation of 120° with respect to the mirror plane containing the empty octahedral site) is after the “common mica twin law” (8) and likely accounts for much of the rotational disorder seen in the XRD data.

The preceding has established that thin diagenetic illite crystals grow in sedimentary rocks and that they have distinct mineralogical features, such as I/S XRD effects and 1M polytype, that distinguish them from $2M_1$ muscovite. Much of our knowledge of disordered illite polytypes and I/S comes from the use of the programs NEWMOD (10) and WILDFIRE (14), which permit easy calculation of the complete powder XRD patterns of clay minerals. These programs form the basis for “unmixing” the mixtures we have been discussing. In the process of matching calculated to experimental data on poly-

FIG. 4. Scanning electron micrograph of pore-filling fibrous illite in a sandstone.

FIG. 5. (A) AFM deflection image of sandstone illite. Laths are intergrown at 120° in a star-like aggregate or twin after the common mica twin law (a rotation of 120° with respect to the mirror plane containing the empty octahedral site) (8). Granular materials adhering to illite (especially on the right) are salts precipitated during sample preparation. The scale is in micrometers; the crystal is $\approx 1 \mu\text{m}$ long. This and subsequent images were made in air, contact mode, on a Universal AFM (ThermoMicroscopes, Sunnyvale, CA). (B) Close-up of the center in A. Lines show measurements of step height made on the height image (not shown). Note interlaced growth of 1-nm (10-Å) growth steps. Individual laths have a thickness of 6–8 nm. By powder XRD, this sample is 1M, with a minor 120° rotational disorder. Only the center will contribute to the disorder; the projecting laths (A) will not. The scale is in angstroms.

types and disorder in illite, some generalizations have emerged. Bentonites and fibrous (sandstone) illites are similar in many respects (1M with some 120° rotational disorder) but differ in that the cis-vacant form (15, 17) is more common in bentonites and the trans-vacant form (the traditional 1M structure) is more typical of fibers [discussion of nomenclature (14)].

Shales are different in that most shale illites (excluding the $2M_1$ component) show nearly maximum rotational disorder, including both 120° and 60° rotations (14) and are therefore the 1Md polytype (8). This means that each successive 1-nm layer is unrelated to the layer below it except that the hexagonal oxygen rings align to accommodate K. On the basis of AFM morphological observations, bentonite and sandstone illites

grow primarily by spiral or step mechanisms whereas shale illites grow by nucleation (birth and spreading). Illites in shales (Fig. 6) show many small 1-nm-thick nuclei on the 00 l of a larger substrate that may be detrital mica. These appear to be randomly placed epitaxial growths. Continued similar growth would create a 1Md illite. Bentonite and fibrous illites have nearly featureless 00 l faces with one or more parallel growth steps. The contrasting mechanisms (growth vs. nucleation) are roughly in accord with the early discussion on the origin of polytypes (8).

Transmission electron microscopy paints an apparently somewhat different view of shale illite (18), but it is not clear to me how much of that difference is related to the method of investigation (transmission electron microscopy vs. XRD). For example, the requirements for coherency are likely more stringent for XRD than for transmission electron microscopy. The predominance of 2M₁ polytype in ion-milled whole-rock samples (18) is possibly due to detrital muscovite; at least, that is what shale K-Ar data (older than depositional age) suggest. Further discussion is beyond the scope of this review, but the questions raised by the transmission electron microscopy work on illite offer exciting directions for future research.

Illite Age Analysis

Returning to the shale size-age spectrum (Fig. 1a), it is obvious that a simple way to estimate the ages of the detrital and diagenetic end members is to quantitatively determine (by XRD) the proportions of the end members in each of the three size fractions, plot the points (normalized to 100%) as apparent K-Ar age vs. percent of detrital illite, and linearly extrapolate to 0 and 100% detrital to get the end member ages (Fig. 7). I call this Illite Age Analysis (IAA), and it is the subject of an Exxon patent (19). The extrapolated "diagenetic age" is the mean (integrated) age of the time interval over which illite grew. This could be a nearly instantaneous event in the case of illite formed in response to an igneous intrusion, or a 50-million-year (my) interval of burial in a sedimentary basin. Similarly, the "detrital age" is the mean age of the coarse micas, which may themselves be a mixture. Ideally, the detrital age corresponds to the mean time of uplift and cooling of the source terrain below the so-called blocking temperature for

FIG. 6. AFM deflection image of a shale illite crystal. The surface is covered with small, 1-nm-thick growths or nuclei, possibly on the 00 l of a larger substrate that may be detrital mica. These appear to be randomly placed epitaxial growths. Continued similar growth would create a 1Md illite. XRD shows 60% 1Md, with the rest 2M₁. The XRD pattern for this sample is in Fig. 9b (C). The scale is in angstroms.

FIG. 7. IAA plot of a shale sample. To estimate the ages of the detrital and diagenetic end members, we quantitatively determine (XRD) the proportions of the end members in each of three size fractions, plot the points (normalized to 100%) as apparent K-Ar age vs. percent of detrital illite, and linearly extrapolate to 0 and 100% detrital to get the end member ages. Lower diagram is XRD pattern (oriented aggregate, Cu radiation) showing discrete illite (detrital) and diagenetic I/S.

muscovite (250–300°C), below which Ar no longer diffuses out of the structure (20).

Some distinctly questionable assumptions are made in using this method. First, can we treat the complex mixture that is shale as a two-component system with respect to illite? For example, what if there is detrital (recycled) 1M illite? Where we have had an independent test, such as a convenient bentonite interbedded with shale (21), or a date on large micas physically separated from the rock, the method works. Diagenetic illite is likely more easily weathered because of fine grain size; it may not survive as detritus. What if illite grew during two heating events 50 my apart? As we will see, for calibrating the thermal history of basins, only the integrated age is important. Certainly, two separate ages could not be extrapolated from IAA data alone. Could Ar leak out of the tiny illite crystals so the age would be too young? Illite formed by contact metamorphism gives the same age as the pluton, showing illite to be retentive of Ar (22). Small crystals often have fewer defects than large ones, and defects may control Ar loss (atom hopping vs. migration down tubes and cracks). Also, if a crystal is disrupted so it loses Ar, it will likely also lose K from the same region because it is in contact with a Na-rich pore fluid, in which case the K-Ar age will be unaffected. As long as the samples have not been heated above the generally accepted 250°C muscovite-blocking temperature, thermal argon diffusion is unlikely, but we really have few data on illite itself. Fortunately, drill holes in most sedimentary basins seldom get close to 200°C. How do we know that the relation in Fig. 7 is linear? It is not, really, but if the K content of both end members is similar, it is close enough. This is suggested by the observation that most of our many data sets fit a straight line rather well.

In practice, there are two approaches to quantify the end members using XRD. The first uses the 00 l peaks and assumes the diagenetic illite is in I/S, and the detrital end member is discrete mica. These two can be distinguished on an XRD pattern (Fig. 8*a*). Quantification is the critical step and the source of most of the uncertainty in the IAA method. We calculate, from first principles, XRD patterns to match the experimental pattern (Fig. 8*b*). The basic method is that of NEWMOD (10), but the actual calculation and matching are controlled by a genetic algorithm (23). From the range of calculations that have a good fit, we estimate an uncertainty for each point on the IAA plot and use a Monte Carlo method to project these uncertainties into the extrapolated end member ages. For samples that have data points mostly at one end or the other of the IAA plot, the uncertainty in estimating the age at the opposite end can be quite large.

The second method uses polytypes (1Md and 2M₁; see Fig. 9*a*). Because shales contain large amounts of rotationally disordered illite with a few, broad XRD peaks (Fig. 9*b*), anything resembling a real quantitative analysis was not easily done until WILDFIRE became available (14). Using an approach similar to the first, for each fraction, a calculated XRD pattern is optimized to the experimental data (Fig. 10). The polytype method is especially useful for samples lacking I/S, in which the peaks for illite and mica are superimposed. A similar routine was applied to a Paleozoic shale from Illinois (24).

FIG. 8. (a) Calculated XRD patterns (oriented aggregate, Cu radiation) for discrete illite and I/S made with NEWMOD. Patterns like these are added to match an experimental pattern. Blocks on the left show basic structural 2:1 layers. (b) This illustrates how an experimental XRD pattern (oriented aggregate, Cu radiation) is matched, and thus quantified, by a calculated mixture of discrete illite and I/S. Calculated pattern at the top is for 40% discrete (detrital) illite.

FIG. 9. (a) XRD patterns (assuming random powder sample, Cu radiation) calculated with WILDFIRE of nondisordered 1M and 2M₁ polytypes of dioctahedral mica. Note the distinguishing peaks in the central part of the patterns. At the left is the a-b projection of the unit cell showing the stacking sequences that characterize each polytype. (b) XRD patterns for the shale shown in Fig. 6. Size fractions are same as Fig. 1. K-Ar ages are C = 151, M = 110, and F = 78 my. The F pattern is typical for maximum disordered 1Md illite. The C pattern shows modulations for 2M₁, and the model indicates 40% 2M₁. Random powder mount, Cu radiation.

The IAA technique permits only estimation of the component ages. Precision, calculated as above, averages $\approx \pm 15\%$ of the estimated value (e.g., 20 ± 3 my) based on our experience, and can be larger where the diagenetic age is < 10 my. Accuracy is unknown, but where tested (21) is almost as good as precision. Certainly, the diagenetic age from IAA is a much better choice for calibrating basin thermal history than a whole rock K-Ar age from shale or the age of an arbitrary fine fraction. The $^{40}/^{39}\text{Ar}$ dating technique has been used as an

FIG. 10. Experimental XRD pattern (Upper) and a calculated match (Lower) of a sample containing 15% 2M₁ and the rest moderately disordered 1M.

alternative for separating diagenetic from detrital ages in mixtures (25). Although at present this is not as effective as IAA, continued progress on methodology and diffusion models may ultimately make this the method of choice.

Applications

Models are the key to using illite in basin thermal history calibration. The petroleum industry typically uses burial history, based on the stratigraphy (age and depth) in a well, to estimate thermal history (26). Other geologic data are used to estimate the amount of sediment eroded from unconformities, timing of uplift events, and basal heat flow. A computational model, which includes compaction, estimated rock thermal conductivity, and radiogenic heat generation, computes the temperature of each sedimentary layer through time as it is buried. The modeled results, such as present-day thermal gradient, are then compared with measured well temperatures, which define the real thermal gradient, and the model is adjusted to fit the measured data. Once the model is calibrated to data, kinetic expressions for thermal generation of oil and gas can be applied to the thermal history to give timing of HC generation.

Unfortunately, present-day conditions may not tell us much about when a particular shale bed generated oil tens of millions of years ago. Present thermal gradient may not be a guide to past conditions. We need paleothermometers, rock properties that tell us about past thermal events, to properly constrain the model. The most widely used paleothermometer is based on vitrinite reflectance (%R), the increase in reflectivity of a coaly material found in rocks as a function of time and especially temperature (26). The thermal history is applied to a kinetic expression for %R, and model %R values are obtained; these are compared with measured values from rocks obtained from the well, and the model is adjusted to give a reasonable fit. But there is a problem: %R really gives only the maximum temperature; it tells us nothing about when that temperature was reached, and that is when the HCs were generated.

A downhole increase in shale diagenetic illite (%I in I/S) is observed in many basins of the world (6, 20, 26), and this relation has been used as a paleothermometer in the same way as %R (27). We use experimental kinetics developed by Exxon (27); see ref. 28 for a comparison of several published kinetic expressions. The measured values of %I in I/S are compared with the modeled curve (Fig. 11), and the model is adjusted to optimize the fit. This alone does not give us much more than %R, but the age of the diagenetic illite can also be easily modeled by using the kinetic expression and can be calibrated

FIG. 11. Plot of decimal fraction of illite in I/S from shales in a typical well. Individual points are sample measurements; the line is calculated from a burial history by using an experimental kinetic expression (23).

with the measured diagenetic age from IAA. This gives us a powerful piece of chronologic information that is independent of assumptions about burial history. Note that a modeled age, like the IAA diagenetic age, will be an integrated age—the mean age of an illite-forming time interval.

The integration of paleothermometers is shown on a schematic thermal history in Fig. 12. Illite data constrain the burial or heating phase of a basin's thermal history, %R records maximum temperature, and apatite fission track analysis constrains timing of uplift and cooling. Discussion of the last technique is beyond the scope of this review.

A diagrammatic example application is given in Fig. 13. The cross section shows petroleum source rocks separated from a structural trap by an unconformity at A. Did the source rocks mature (get heated) before or after deposition of the upper units containing the trap? If they produced oil before time A, then it is much less likely that they will be able to act as source for the trap. The question is one of amount of missing (eroded) section at A. If there was a large amount of uplift and erosion, then the source rocks could have been deep (hot) enough before A to produce oil. To solve the problem, samples are obtained from the source shales from outcrops or nearby wells (Fig. 13A, 1) and IAA (Fig. 13B, 2) is done to get the diagenetic age (Fig. 13B, 3). The thermal history plot (Fig. 13B, 4) is now anchored by a real date (IAA), which constrains the source heating and HC yields to post A time (Fig. 13B, 5). This indicates that HC supply to the trap will not be a risk factor for this prospect. IAA is especially useful in areas of complex structure, like fold and thrust belts, in which thermal history is not just a function of simple burial.

Variants of the methods described have been used to successfully date normal and thrust faults (time of trap formation) and to predict growth of permeability-reducing illite in reservoir sandstones (29, 13). Growth of illite in shales, as in sandstones, appears to be a pore-filling process, but the pores are smaller and flatter. Shale permeability, like that of sandstones, is likely reduced by illite growth. This could improve the quality of a shale seal above a trap or could otherwise effect the mechanical properties of the shale.

Clay-rich fault gouge typically has a flat size–age spectrum or an inclined spectrum with all ages younger than depositional age (29). It appears that upper crustal faulting (low temperature) can reset the illite K-Ar clock, but the mechanism is unclear. Heating seems unlikely, as %R indicates low temperatures. Crystal growth under conditions of deformation and unique fluid chemistry are likely involved. It is not clear that deformation alone can cause total Ar loss from illite. Fault gouge illites are an area of evolving research.

FIG. 12. Thermal history schematic showing integration of paleothermometers. Illite data constrain the burial or heating phase of a basin's thermal history, %R records maximum temperature, and apatite fission track analysis constrains timing of uplift and cooling.

FIG. 13. (A) Cross section showing petroleum source rocks separated from a structural trap by an unconformity at A. Did the source rocks get heated before or after deposition of the upper units containing the trap? If they produced oil before time A, then it is much less likely that they will be able to act as source for the trap. The question is one of amount of missing (eroded) section at A. If there was a large amount of uplift and erosion, then the source rocks could have been deep (hot) enough before A to produce oil. (B) To solve the problem in A, samples are obtained from the source shales (1), and IAA (2) is done to get the diagenetic age (3). The thermal history plot (4) is now anchored by a real date (IAA), which constrains the source heating, and HC yields to post-A time (5). Sharp peaks on 5 show model generation of oil and gas, respectively. HC supply to the trap will not be a risk factor for this prospect.

Conclusions

Illite is a common mineral in sedimentary rocks, especially shales. Careful mineralogical analysis using new techniques developed by the clay mineral research community permits the extraction of quantitative information on the time and temperature of diagenetic illite formation. In hydrocarbon exploration, these data are used to calibrate the heating history of sedimentary basins to ascertain that oil or gas generation from source shales postdated trap formation. If generation preceded trap formation, the oil or gas would presumably have leaked off, and the well should not be drilled. Application of the mineralogical work reported here will decrease the risk of drilling a dry hole, reducing not only the expense but also any disturbance that might be caused by drilling. Further, because thermal conditions partly control the likelihood of the trap being filled with gas vs. oil, the illite work helps us find the particular type of HC we are looking for. Application to fault dating is useful not only to estimate HC trap timing but also may have potential in evaluating earthquake hazards.

The price of oil and gas has remained low because of the combined effects of open competition and applied technology.

Although three-dimensional seismic is often featured by the media, many less dramatic advances also contribute to improving the efficiency of exploration and production. Because the earth is made of minerals, it is not surprising that mineralogy plays an essential role.

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