General Model for Delivery of Asphaltenes to Tar Mats*

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Abstract

A tar mat can be understood only in relation to the history of the hydrocarbon system of the entire basin. The following facts and assumptions should underlie any tar mat model. 1) Source: all asphaltene molecules are derived from the source, not created in the reservoir; early-generated oil has low API gravity and abundant asphaltenes; late-generated oil has high API gravity and rare to nonexistent asphaltenes.
2) Migration occurs as threads or blobs of oil tracing only the highest crest of the nose leading to the crest of the reservoir.
3) Fill: early, asphalting-rich oil fills the attic of the reservoir and is pushed downward by later, asphalting-poor, high-API oil; assume asphaltene molecules diffuse slowly so oil volume remains stratified during fill; late oil causes gas-deasphaltinization (light molecules migrate from asphalting-rich to asphalting-poor oil); although gas deasphaltinization occurs at the point of contact between migrating light oils and already-reservoired heavy oils, tar is produced in very small volumes localized at the very crest of the nose leading to the crest of the reservoir because the heavy oil is constantly pushed downward in the reservoir.
4) Spill: the first oil to reach the contemporaneous spill point will be heavy oil, which will start to spill to the next trap updip; lateral migration of the heavy oil toward the spill point will be slow in comparison to vertical migration of overlying light oil, so a heavy oil layer will persist around most of the field; light oil migrating into and through the now-stationary heavy oil will form tar, blocking the nose-crest migration pathway and causing the migration pathway to become convoluted and expanding the area of tar formation; light oil rapidly migrating up a high-perm streak may "drag" asphalting-rich heavy oil along with it, causing tar to finger up the high-perm streak until perm is blocked by tar and the preferred migration pathway moves to another part of the heavy-oil/water contact.

Differences in surface chemistry of carbonate vs. siliciclastic minerals probably result in different rates of tar formation vs. asphaltene diffusion so the same basin-wide history may produce more tar in carbonate reservoirs than in siliciclastic reservoirs. To the extent that "all" tar mats are formed by gas deasphaltinizaton, then "all" tar mats must be formed when reservoirs are filled to contemporaneous spill. Assumptions in this model can, in theory, be lab tested.

Reference

Tissot, B.P., and D.H. Welte, 1984, Petroleum Formation and Occurrence: Springer-Verlag, Berlin, Heidelberg, New York, Tokyo, 699p.

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Abstract

A physico-chemically precipitated tar mat in a field can be understood only in relation to the history of the hydrocarbon system of the entire basin. The following facts and assumptions should underlie any tar mat model. 1) Source: all asphaltene molecules are derived from the source, not created in the reservoir; early-generated oil has low API gravity and abundant asphaltenes; late-generated oil has high API gravity and rare to nonexistent asphaltenes. 2) Migration: occurs as threads or blobs of oil tracing only the highest crest of the nose leading to the crest of the trap. 3) Fill: early, asphaltene-rich oil fills the attic of the trap and is pushed downward by later, asphaltene-poor, high-API oil; assume asphaltene molecules diffuse slowly so oil volume remains stratified during fill; late oil causes gas-deasphaltinization (light molecules migrate from asphaltene-rich to asphaltene-poor oil); although gas deasphaltinization occurs at the point of contact between migrating light oils and already-reservoired heavy oils, tar is produced in very small volumes localized at the very crest of the nose leading to the crest of the trap because the heavy oil is constantly pushed downward in the reservoir. 4) Spill: the first oil to reach the contemporaneous spill point will be heavy oil, which will start to spill to the next trap updip; lateral migration of the heavy oil toward the spill point will be slow in comparison to vertical migration of overlying light oil, so a heavy oil layer will persist around most of the field; light oil migrating into and through the now-stationary heavy oil will form tar, blocking the nose-crest migration pathway and causing the migration pathway to become convoluted and expanding the area of tar formation; light oil rapidly migrating up a high-perm streak may drag asphaltene-rich heavy oil along with it, causing tar to finger up the high-perm streak until perm is blocked by tar and the preferred migration pathway moves to another part of the heavy-oil/water contact.

Differences in surface chemistry of carbonate vs. siliciclastic minerals probably result in different rates of tar formation vs. asphaltene diffusion so the same basin-wide history may produce more tar in carbonate reservoirs than in siliciclastic reservoirs. To the extent that all tar mats are formed by gas deasphaltinizaton, then all tar mats must be formed when traps are filled to contemporaneous spill. Assumptions in this model can, in theory, be lab tested.

1

Introduction and Caveats

I contend that it is impossible to understand, much less adequately model, a physico-chemically precipitated tar mat in an oil reservoir without understanding the history of emplacement of the tar as a part of the overall history of the complete hydrocarbon system of the entire basin. Thus, the components of the tar must by followed through maturation and expulsion from the source; migration from source to trap; evolution during fill of the trap; timing and evolution of spill from the first trap updip from the source; and dynamic evolution of the path of migration of late hydrocarbons into the trap.

The following discussion is based on a few generally accepted concepts of hydrocarbon-system evolution and some testable assumptions about how hydrocarbons and hydrocarbon systems act during evolution of the basin. It contains no data from individual fields or from tests of how individual hydrocarbon molecules and components act in nature or in the lab. Acquisition of such data is left to the reader with access to more field data and more laboratory and library facilities than the author has available.

The following discussion is delivered in terms of asphaltene molecules, but is probably applicable to any other high-molecular-weight hydrocarbon molecules that might make up a significant percentage of some physico-chemically precipitated tar deposits.

The impetus for developing these ideas came from my frustrations in trying, ultimately relatively unsuccessfully, to predict the geometry and characteristics of tar in one of Saudi Aramco's large fields. I ultimately decided that there were no studies that I found that adequately explained how the necessary asphaltene molecules could be delivered to the tar mat location. Asphaltene molecules settling out of the overlying oil, what I think of as the "pin-ball" approach with individual asphaltene molecules gravitationally bouncing downward from sand grain to sand grain, seemed to have insufficient density difference between asphaltenes and the surrounding oil to result in a timely accumulation of the necessary volumes of asphaltenes, even if it could be assumed that few molecules would be trapped during their descent. Circulation of tens of pore volumes of the overlying oil through the ultimately tar-blocked pores seemed to require too much energy differential across the height of the oil column, even if the reduction of permeability caused by precipitation of each asphaltene molecule were ignored.

2

Source Maturation

My first assumption is that asphaltene molecules are evolved from (or created in) the source rock and experience little if any chemical change once they arrive in the trap. It is widely accepted (e.g., Tissot & Welte, 1984) that a hydrocarbon source rock, in evolving from early oil to late gas generation (Fig. 1), will generate heavy oil in the early stages, lighter and lighter oil with increased maturation, mixed hydrocarbon gases in the transition from oil- to gas-generation, and ultimately only methane. As a result, the vast majority of the asphaltenes that will ultimately make up the tar deposit in a field are most likely present in the early-generated oil (Fig. 2).

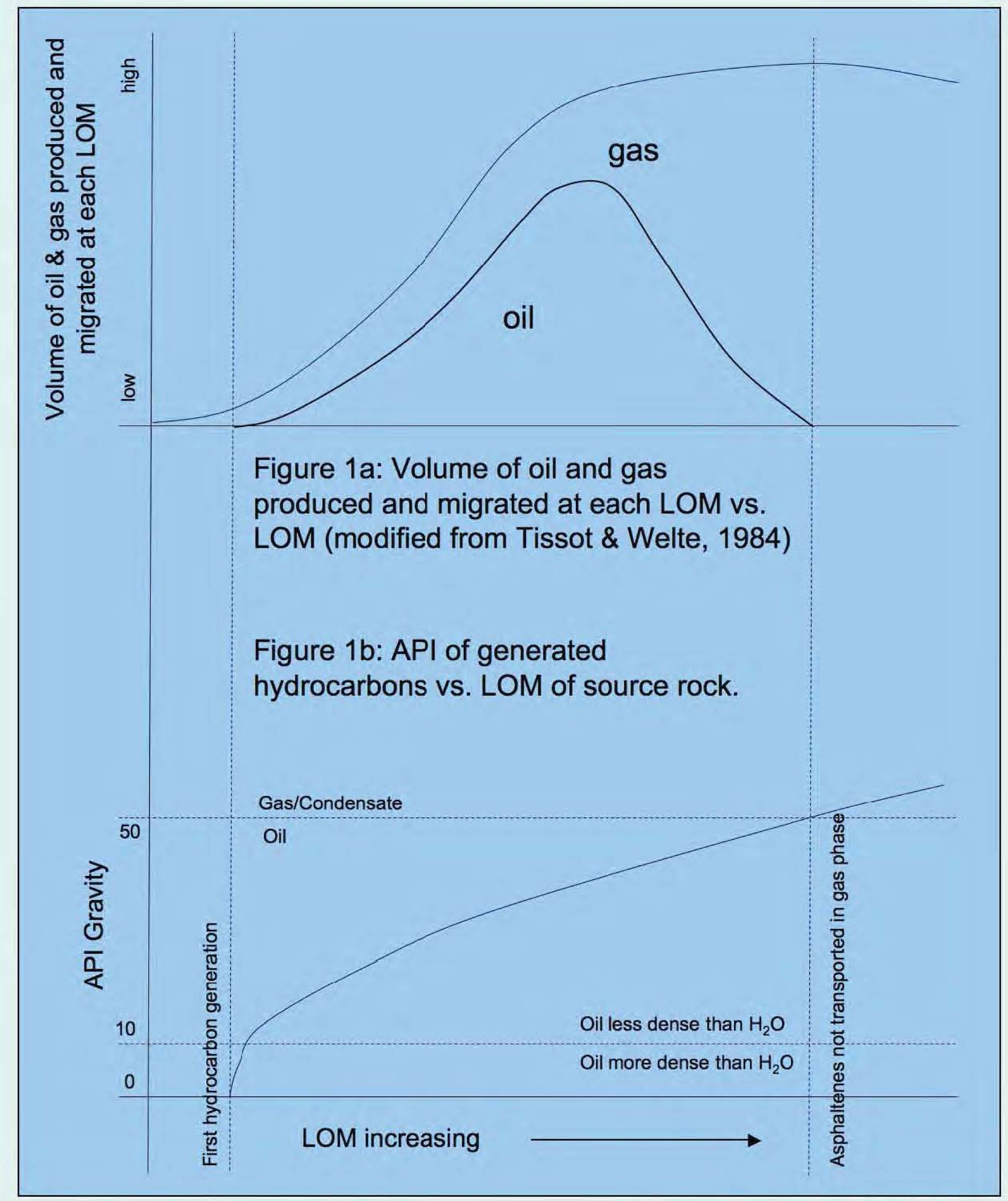

Figure 1a: Volume of oil and gas produced and migrated at each LOM vs. LOM (modified from Tissot & Welte, 1984)

Figure 1b: API of generated hydrocarbons vs. LOM of source rock.

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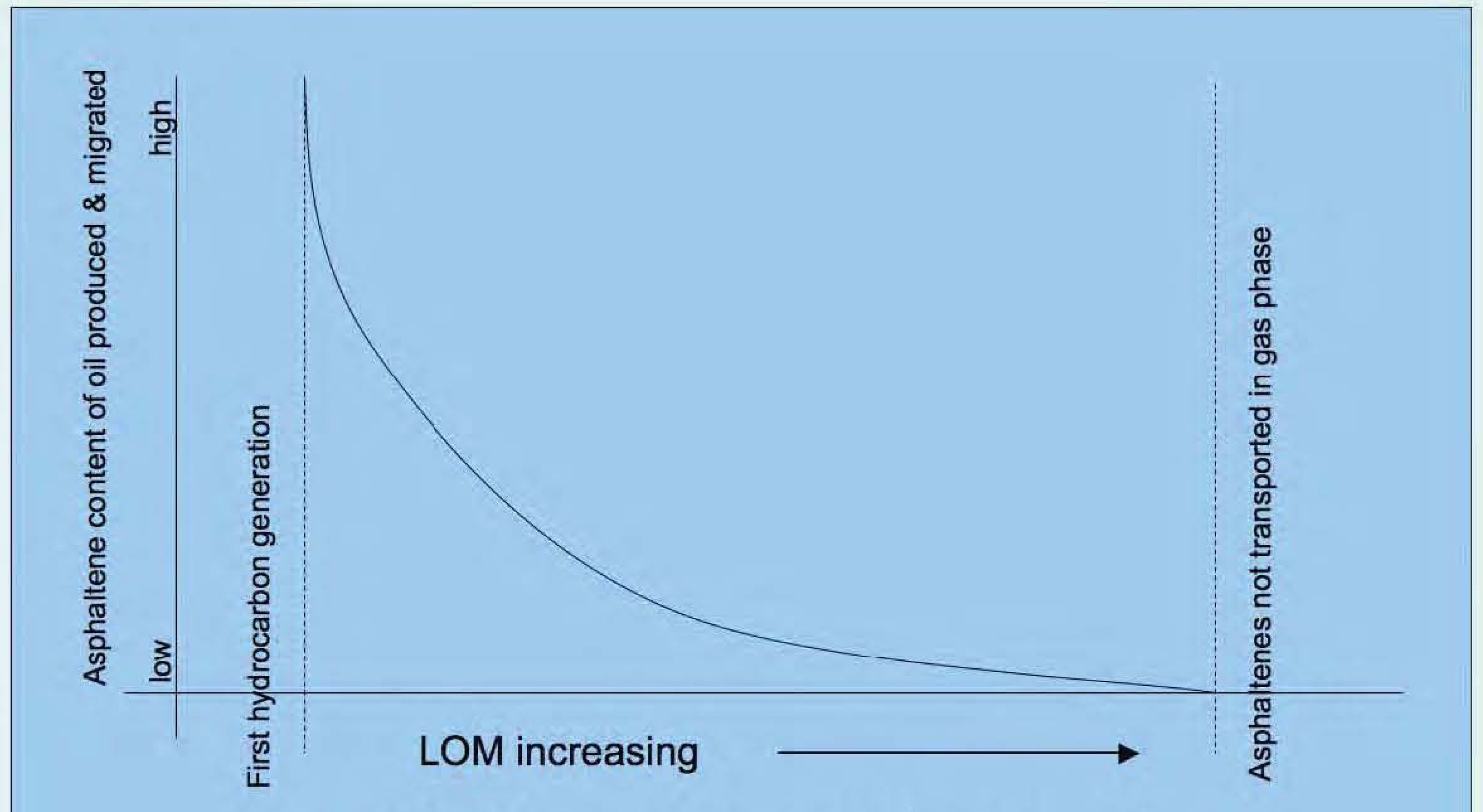

Figure 2: Asphaltene content of migrating oil vs. LOM of source rock.

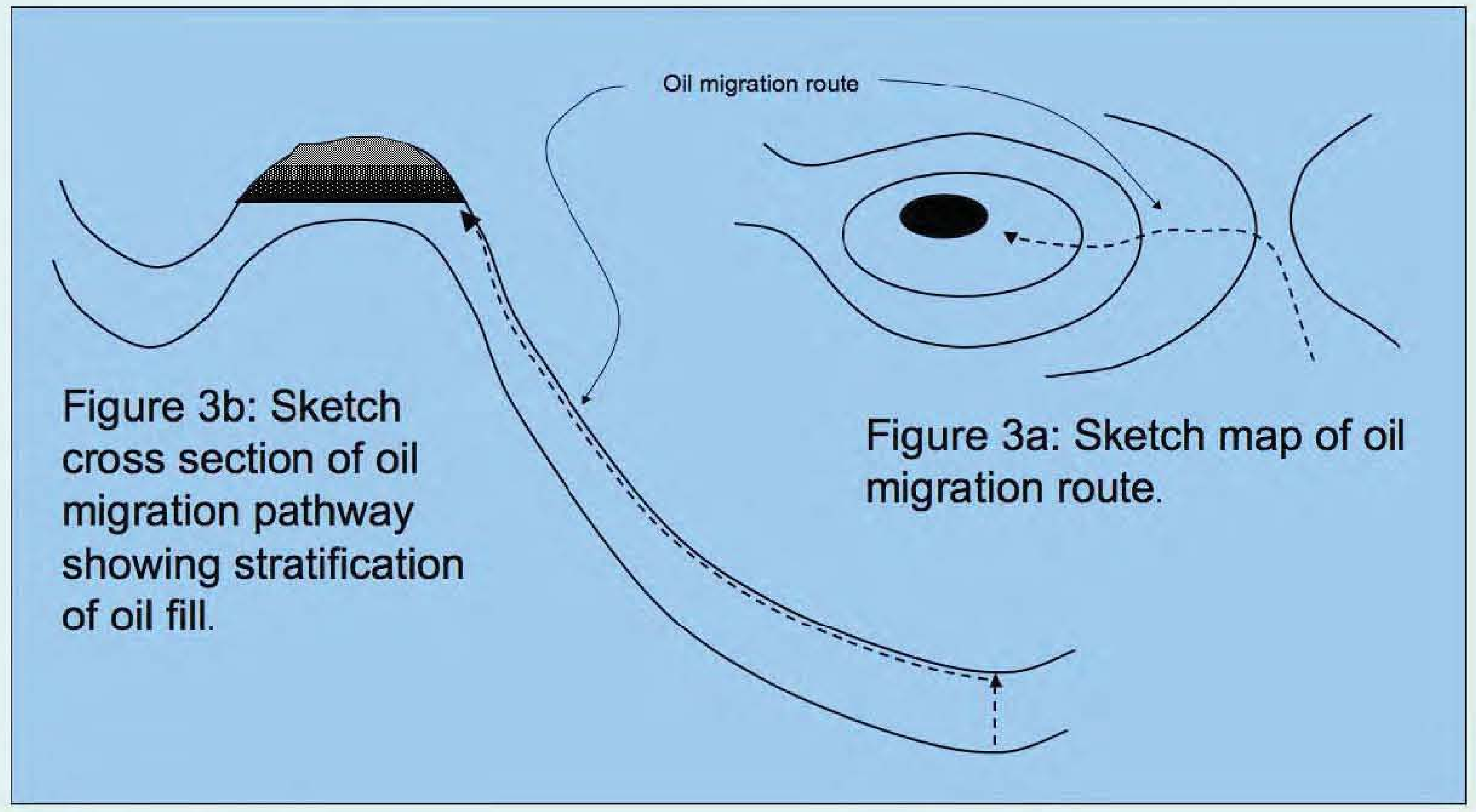

Figure 3b: Sketch cross section of oil migration pathway showing stratification of oil fill.

Figure 3a: Sketch map of oil migration route.

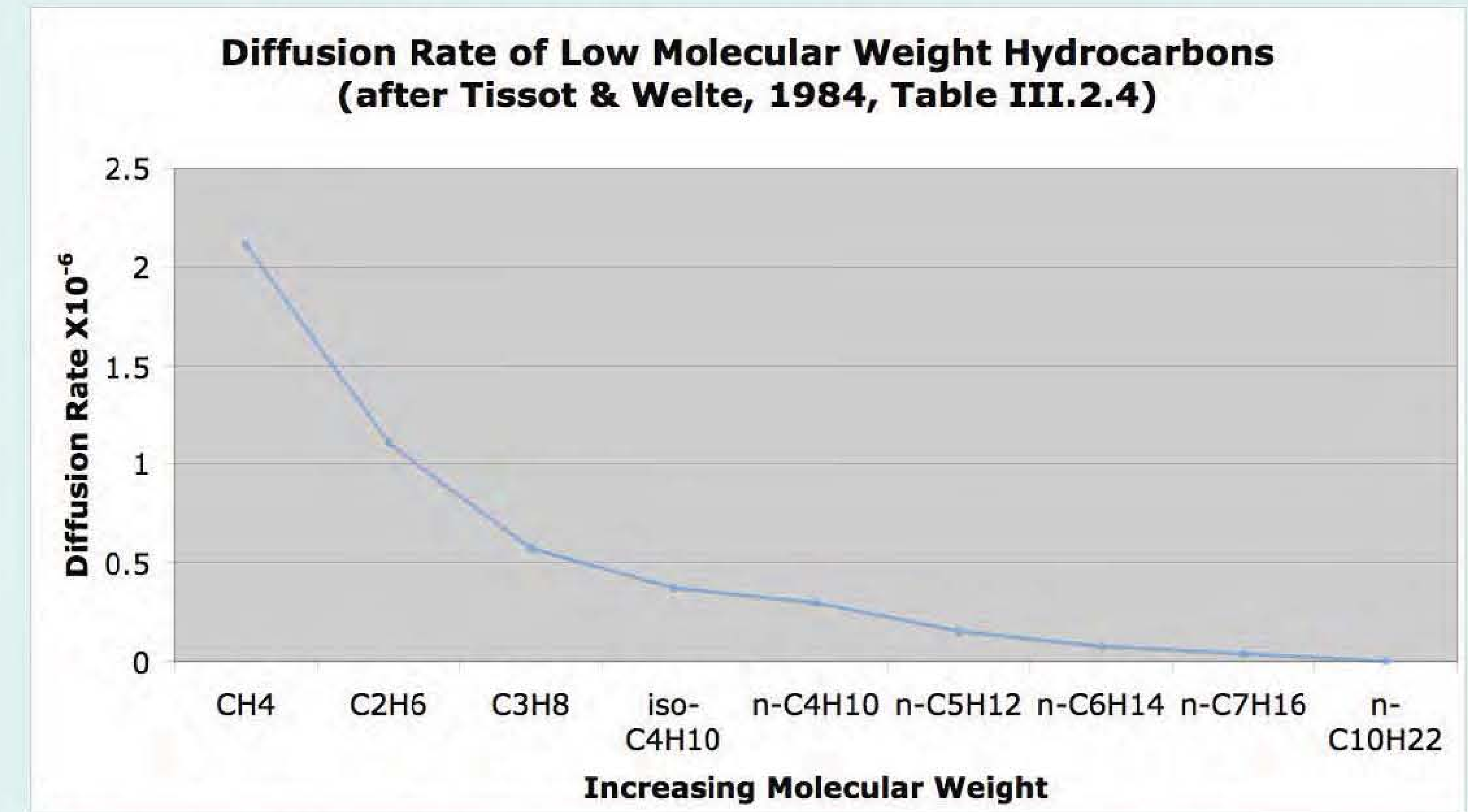

Figure 4: Relative diffusion rates of low molecular wiight hydrocarbons (after Tissot & Welte, 1984, Table III.2.4)

3

Expulsion from Source

Thus, the first liquids available for expulsion from the source will be rich in asphaltenes and each subsequent volume will be poorer in asphaltenes (Fig. 2).

Migration

If the first oil generated and expelled from the source has an API gravity of less than 10 (that is, density greater than that of water), the first-expelled oil, richest in asphaltenes, will be too dense to migrate upwards toward the ultimate trap. I assume that this oil will remain in the vicinity of the source until the expelled oil achieves an API gravity greater than 10, but still including a high percentage of asphaltenes, resulting in a buoyancy sufficient to drive migration to the ultimate trap. The earlier-expelled oil, lying in the pathway of the lighter oil, will be commingled with the newer oil and the resulting mix, with a density still less than that of water, will start to migrate toward the ultimate trap.

In general, the migrating oil will move straight up dip to the nearest nose, then updip along that nose (Fig. 3a). I assume that the rate of migration is sufficiently rapid as compared with the rate of expulsion from the source that it is unlikely that any significant hydrocarbon saturation would develop more than a few centimeters below the overlying seal rock or more than a few meters (or perhaps tens of meters) either side of the nose crest (Fig. 3b). Even if some of the asphaltenes precipitate onto some of the rock surfaces along this migration pathway, it is extremely unlikely that a well will penetrate that thread of hydrocarbon saturation, even less likely that anyone would notice the extremely thin zone of saturation.

4

Trap Fill

The first oil to arrive in the trap will be the asphaltene-rich early-generated oil. It will fill the attic of the trap (Fig. 3a). Oil arriving later will have a higher API gravity (lower density) and so will displace the asphaltene-rich oil downward through the reservoir (Fig. 3b). I assume that the diffusion rate for the extremely-high-molecular-weight asphaltene molecules will be very low (Fig. 4) so the layer of asphaltene-rich oil will remain distinct from the later oil.

Note that the later, lighter oil – the oil that might be capable of causing precipitation of asphaltenes by "gas stripping" – will contact the asphaltene-rich oil dynamically only along the migration pathway at the crest of the migration nose (as discussed above, an extremely narrow area of contact) and the point of contact between the two oils will move constantly downward with further fill of the trap. As a result, there will be little precipitation of asphaltenes at any one point along the migration pathway, and the string of points with potential asphaltene precipitation will be extremely narrow. Likewise, the relatively static plane of contact between the layer of high-asphaltene oil below and low-asphaltene oil above will be constantly moving downward in the reservoir and will have no buoyancy-driven gas-deasphaltinazation interaction, so any tar precipitated along that surface will be minor and distributed more-or-less evenly through the reservoir.

5

Trap Spill

Once the trap is filled to spill, two significant changes occur in processes. First, the dynamic factors restricting precipitation of tar during fill of the trap become inoperative. That is, there is continued migration of light oil along the crest of the nose leading to the crest of the trap, but the zone of interaction between this light oil and the asphaltene-rich heavy oil at the base of the oil column will remain in essentially one place. As a result, any tar precipitated as a result of that interaction will accumulate in one place.

Second, spill of oil from the filled trap toward unfilled traps updip will take on a dynamic character. Initially, the oil available for spill will be asphaltene-rich heavy oil. However, the rate at which the high-viscosity heavy oil will be able to migrate laterally to the spill point will be significantly less than the rate at which the overlying low-viscositty lighter oil will be able to migrate vertically downward to the spill point. As a result, the character of the oil filling the next trap updip will follow the same evolution as did the first trap updip from the source. The implication here is that each successive trap in an updip direction will have access to less asphaltene-rich oil than the one below it. Thus, if there are enough traps or if the traps are sufficiently large in comparison to the volume of the source, tar mats will get thinner "downstream" (that is, in the direction of migration), and ultimately there may not be enough asphaltene-rich oil to form tar mats in the shallowest traps.

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6 ***Formation of Tar through Dynamic Evolution of Migration Path***

Once the trap is filled to spill, the actual mechanics of creating a tar mat that covers much if not all of the contemporaneous oil/water contact become somewhat convoluted. With the layer of asphaltene-rich heavy oil essentially stationary, the migrating lighter oil is capable of causing precipitation of asphaltenes at the fill point for the trap, an area that might initially be only a few centimeters to a few meters thick and a few meters to a few tens of meters wide. As the pore throats become more and more restricted by tar precipitation, the migrating light oil will start to go to nearby locations that provide greater permeability. Areas or beds with low permeability will become clogged with tar relatively rapidly whereas areas or beds with high permeability will experience higher flow rates, will take longer to become clogged, and will likely experience some "dragging" of the asphaltene-rich oil updip, so that high permeability beds will have tar fingering higher into the trap. Given enough light oil migrating to the base of the reservoired oil, this constantly moving locus of passage through the contemporaneous oil/water contact will ultimately cause tar precipitation around the entirety of the contemporaneous oil/water contact.

Likewise, with the plane of contact between the overlying light oil and the underlying heavy (asphaltene-rich) oil remaining stationary, any tar precipitation caused by interaction between those two different fluids will be localized and accumulate along and near that stationary plane.

This leads to the conclusion that once the tar mat is complete, late generated oil might bypass the first trap entirely.

Note that all of the above implies that a physico-chemically precipitated tar mat will occur only when the trap is filled to contemporaneous spill.

7 ***Relative Process Rates***

In the light of the discussion above, it is possible to order the processes that are involved in creation of a tar mat from fastest to slowest as follows:

1. Interaction between glob of late oil and pool of early oil through which the glob is passing – that is, exchange of light hydrocarbon molecules from early oil to late oil and perhaps exchange of asphaltene molecules from late oil to early oil.
2. Diffusion of light hydrocarbon molecules within the oil column.
3. Dispersal of a glob of late oil while traversing a pool of early oil.
4. Generation and migration of hydrocarbons or, looked at in a different way, fill of the reservoir.
5. Formation of tar.
6. Diffusion of asphaltenes.

8 ***Note to the Reader***

It is clear that the discussion above includes a minimum of data (derived either from field studies or laboratory studies) and is supported by only a minimum number of references. I, being retired, am currently not in the position of being able to rectify either of these deficiencies. You are encouraged to provide any comments that may improve this discussion. I would, of course, be gratified to receive any positive comments but would really appreciate any negative or cautionary comments that might improve the discussion.

Acknowledgements

Some of the ideas discussed in this report were refined in discussions with Bill Carrigan, Jan Buiting, Ed Clerke, Henry Halpern, and Peter Jones of Saudi Aramco. Their assistance is gratefully acknowledged but any inadequacies either in the ideas themselves or in their expression are solely the responsibility of the author.

Reference

Tissot, B. P., & Welte, D. H., 1984, Petroleum Formation and Occurrence: Springer-Verlag, Berlin, Heidelberg, New York, Tokyo, 699 p.