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Shale Tectonics: A Preface

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INTRODUCTION

The phenomenon of rocks moving under their own means has always fascinated both scientists and the nonscientists. Salt is known to extrude and flow as a result of differences in density of the material and surrounding sediments. However, movement of fine-grained clastics as intrusive injectites or diapirs or as extrusive eruptive sand blows or mud volcanoes has captured the public's imagination and given scientists the impetus to reconsider the physics of how sediments behave in the subsurface.

The 2006 AAPG Hedberg Conference on Mobile Shale Basins was held in response to a need to gather industry and academic communities in a common forum to address the very existence of mobile shales. Because this question involved integrated understanding of argillokinesis from the grain scale to the basin-gravity scale, the forum attracted a broad cross section of the geoscience community. These attendees presented a wide variety of topical presentations that ranged from geochemistry of modern fluid-mud extrusions to gravity studies in basins characterized by mobile shales. An ongoing topic of debate at this forum was the very term "mobile shales." The attendees decided at the meeting that this term was a misnomer and that a more appropriate term to be used to describe this phenomena was shale tectonics, thus the title of this volume. Stimulating and informative discussions at the Hedberg conference led to this special volume on shale tectonics, with contributions from researchers in industry, academia, and government covering diverse aspects of shale tectonics from grain to basin scale.

In addition, to works from authors who attended the Hedberg conference, this book also contains articles from authors who did not have an opportunity to present their work at the meeting. We hope this volume presents a representative cross section of the most current research and understanding regarding shale tectonics. The volume documents shale tectonics from a variety of basins around the world, including the southern Beaufort Sea (Elsley and Tieman, 2010), the Krishna-Godavari Basin, India (Choudhuri et al., 2010), the Niger Delta (Wiener et al., 2010), eastern offshore Trinidad (De Landro Clarke, 2010), offshore Brunei (Warren et al., 2010), and along the Spanish arm of the Mediterranean Sea (Soto et al., 2010).

Publication of this memoir coincides with a growing interest in shales as hydrocarbon reservoirs. Because of the burgeoning of shale gas and shale oil research, geoscientists are gaining a better understanding of the petrographic framework of shales, as well as their behavior under various pressure and temperature regimes and the manner in how fluids move thorough these strata (for a review, see Day-Stirrat et al., 2010). Advances in seismic imaging and processing technologies illuminate stratal geometries associated with shale tectonics that have led to a new understanding of the processes responsible for the geometries we observe in shale strata (see Day-Stirrat et al., 2010; Elsley and Tieman, 2010). In addition, advances in modeling and understanding of how both muds and shales behave after burial have led to new geodynamic models for interpreting process from response reflected in stratal packages (Albertz et al., 2010). Field geoscientists have added to our understanding of the geochemistry and physical character of extrusive mud features and their relationship to the overall basin hydrocarbon system (Battani et al., 2010;

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Delisle et al., 2010; McNeil et al., 2010; Warren et al., 2010). As with mobile salt, shale-cored structures are commonly closely associated with hydrocarbons in many basins around the world. In Henry et al. (2010), information on the character of these strata can be found as well as documentation on drilling into mobile mud-cored anticlinal features (diapirs) in southern Trinidad.

TERMINOLOGY: THE QUESTION THAT WON'T GO AWAY

To develop a working classification of shale tectonics, recognition that two primary classes of features occur is critical: (1) those associated with extrusion of fluids and material that does not involve grain-to-grain contact (Battani et al., 2010; Delisle et al., 2010), and (2) those associated with larger scale deformation of apparent highly overpressured mud or shale substrates involving grain-to-grain plastic flow (Elsley and Tieman, 2010; Wiener et al., 2010). In addition, several varieties of highly fractured seep features exist (Warren et al., 2010). These features allow fluid leakage from overpressured beds, but they do not always involve plastic or fluid-mud extrusion. Shales form a variety of nonextrusive structures, many of which resemble features generated through mobile salt movement, such as domes, welds, and walls. In contrast, muds form a variety of extrusive features, such as volcanoes, ponds, and flows and can erupt explosively as seen in the Piparo mud volcano video included on the CD attached to the back cover of this book.

Several terms are used to describe the processes and features of shale mobility. These include shale tectonics, mud diapirism, shale diapirism and diapirs, mobile shales, mud volcanoes, mud diatremes, mud flows, and finally, from the Greek, argillokinesis and pellitokinesis. Although many scientists continue to argue against the existence of mobile shale, the term is well entrenched in the lexicon and unlikely to go away. A GeoRef search on the topic of mobile shale resulted in 34 instances of the combined term present in the peer-reviewed literature. Mobile shale and mud are the primary subject of a 2003 publication from the Geological Society of London, *Subsurface Sediment Mobilization* (Van Rensbergen et al., 2003). This single publication accounts for 36 additional articles on the subject, quadrupling the previous literature offering. Likewise, the 2006 AAPG Hedberg Conference on the subject of mobile shale basins resulted in 33 abstracts and extended abstracts on the subject of shale tectonics and mobile muds (Wood et al., 2006). Papers in the resulting publication of full-length manuscripts (this volume) show pervasive use of the term mobile shale(s).

Argillokinesis is a broadly applied, all-encompassing term used to describe the dynamics of uncompacted flexible clays. With broad consideration of previous literature, as well as numerous conversations with the scientific community of subsurface researchers, we propose herein to use the term shale tectonics to define the structuring within a basin associated with shale or mudstone plasticity or mobility, either as the cause of such mobility or as a result of such mobility. Mobile shales are defined as any manifestation of clay constituents (indurated or not) that show evidence of microscopic-scale fluid or plastic movement. We acknowledge that such mobility is currently poorly understood and may be some manifestation of microscopic shearing or as a reconstitution of partly indurated muds through diagenetic alteration.

HOW IS MOBILE SHALE IDENTIFIED IN THE SUBSURFACE?

Setting is a very important factor in the possible occurrence of mobile shales. Because shale mobility is caused by an imbalance of hydrostatic and lithostatic pressures, anything that varies the balance of forces within or around a shale mass, such as compressive tectonics, or rapid loading, will affect this balance and may initiate movement. Undeniably, the most influential variable in shale tectonics is fluid pressure. Two conditions commonly exist in regions of tectonically active muds or shales: (1) the presence of undercompacted mud at depth within the basin (this mud is presumed overpressured and held at depth by an overlying low permeability material) and (2) a triggering of overburden breach by some process that passes a critical threshold, causing sudden or gradual release of fluids, either with or without sediments. Triggers might be the gradual buildup of pressure beyond confining stresses of the overburden, sudden mass failure downslope of the overburden, regional compression, or seismicity.

Graue (2000) published a set of criteria that, when met, are conducive to shale tectonics and mud extrusion. These criteria are as follows.

1) Rocks that have low mechanical strength, that are commonly undercompacted, and that have a low degree of consolidation.
2) Compressive tectonic stress to provide ductile deformation and increased pore pressures.
3) Structural culminations that focus decompacted water and hydrocarbons.
4) Carrier beds for migrating fluids and gases.

In AAPG Memoir 8, *Diapirs and Diapirism*, Musgrave and Hicks (1968) provided a set of characteristics for what appear to be displaced shale masses in the Gulf of Mexico:

(1) low-velocity sound transmission, in the range of 6500–8500 ft/s (1981.2–2590.8 m/s) with very little increase in velocity with depth; (2) low density, estimated to be in the range of 2.1–2.3 g/cm^3; (3) low resistivity, approximately 0.5 ohm m; and (4) high fluid pressure, about 90% of the overburden pressure. Other authors (Henry et al., 2010) have documented sonic velocities in near surface (~0–3500 ft [~0–1070 m] below surface) mobile muds of onshore Trinidad to be lower than that of water! Authors from a range of disciplines have attributed these behaviors to high fluid pressure within the shales. At times, these densities are reduced to the point that the shales will rise as a mass in a diapiric fashion that is similar to that of salt. However, such behavior is not widely documented.

Improved seismic technologies have allowed a step change forward in the interpretation of shale tectonics in the subsurface with many previously interpreted mobile masses now much better defined. In some instances, improved imaging techniques have shown features previously interpreted as shale diapirs to be tightly folded anticlinal cores (Elsley and Tieman, 2010). However, other instances exist in which shale substrates do appear to show inflation and upward mobility (Wiener et al., 2010). Because criteria for interpreting mobile shales are not well documented in literature, many of the characteristics that were developed for interpreting mobile salts have been applied to shale basins, albeit with mixed success. In addition, in basins where both salt and shale occur, geoscientists commonly fail to differentiate mobile shales from mobile salts in seismic images. To rectify this deficiency, the following criteria for differentiating salt and shale are provided.

1) Shale welds are less prevalent in shale systems than salt welds are in salt systems.
2) Shales have a much slower velocity than salt. Salt will be underlain by seismic pull-up versus no pull-up beneath shale features.
3) Salt requires a pipe several kilometers wide to facilitate vertical migration. In contrast, fluids migrating through shales will crack and hydraulically fracture a zone through which they will migrate upward.
4) Shale may flow laterally but will develop overhangs of less than 6 km (3.7 mi). In contrast, salt overhangs may be on the order of tens of kilometers.
5) Ductile behavior of shales is unlikely above 80°C (176°F), and brittle behavior is more likely. Therefore, this temperature will provide a plasticity basement within a basin to constrain interpretation of tectonically active shales.
6) Salt volumes tend to be underestimated in interpretations of seismic data. In contrast, shale mass volumes are commonly overestimated by geophysical interpreters (Van Rensbergen and Morley, 2000) because of the manner in which geophysical data are processed. The apparent pull-up of beds around shale diapirs is caused by overmigration of the shale mass and treating its velocity as one would a salt.

FUTURE DIRECTIONS

Areas remain in which additional advances can be made in the study of shale tectonics. As exploration and development of hydrocarbons move into deeper waters along continental margins, our ability to seismically image shale versus salt must improve if we are to deduce the role that these very different materials play in deep-water fold-belt evolution. Improved understanding of how muds behave at grain-to-grain scale when buried will inform modelers and improve our understanding of diagenetic processes in shales.

At present, many intriguing questions remain regarding shale tectonics and mobile muds. How do we get fluid and plastic muds extruded at the sea floor that appear on seismic data to have originated well below the lithifaction depth of shales (see Day-Stirrat et al., 2010, for a review)? What is the physical interaction between mud-volcano pipes and underlying hydrocarbon reservoirs? Some researchers have shown that no hydraulic links between these crosscutting strata exist (DeVille et al., 2006). Do shales truly inflate as salts do above a regional stratigraphic datum? Evidence in Nigeria seems to suggest that they do (see Wiener et al., 2010). Why have we not identified more basins in which such regional inflation of shale occurs? Is there truly such a thing as a shale diapir or is this term a misdirected application of terminology? And of course, there is always the terminology itself. Although a laborious task to standardize, because this is the language by which scientific communities communicate their ideas, some attention must be paid to its clarification.

CONCLUSIONS

Hollis Hedberg was fascinated by mud volcanoes. He spent a good part of his career in eastern Venezuela and Trinidad examining and publishing on the phenomenon that was mobile shale. Today, the same phenomenon is documented in basins and settings all over our planet, as well as on other planets in our solar system. Like any geologic phenomenon, understanding will come with examination, and examination will come with a growing realization of the role that this phenomenon plays in the evolution of a planet's systems. We hope that this volume will add to the body of literature that significantly

addresses both extrusive and intrusive phenomena and generates as many new questions as the answers it provides. These questions are what will drive the next generation of understanding.

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